



**MECHANICAL PROPERTIES, RADIATION SHIELDING AND THERMAL
RESISTANCE OF UHPC CONTAINING COLEMANITE AGGREGATE AND
PVA FIBERS**

By

MUHD AFIQ HIZAMI BIN ABDULLAH

**Thesis Submitted to the School of Graduate Studies, Universiti Putra
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Doctor of Philosophy**

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Abstract of thesis presented to the Senate of Universiti Putra Malaysia in
fulfilment of the requirement for the degree of Doctor of Philosophy

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Nuclear energy provides a vast application which includes energy generation and medical imaging that benefits hugely on our livelihood. However, this energy emits harmful radiation which requires shielding material for safe handling. Concrete has been widely used in nuclear-related structures and there is a gap of knowledge in the application of ultra-high performance concrete (UHPC) as radiation shielding concrete, especially in terms of shielding against neutron sources and thermal resistance. Colemanite and polyvinyl alcohol fibre (PVA) improve the neutron shielding and thermal resistance of UHPC but the combined effect of these materials requires further investigation. Hence, this research aimed to study this effect and coined the term ultra high-performance dense concrete (UHPdC) for UHPC with radiation shielding properties. Based on previous studies that produced UHPC against radiation shielding, three types of UHPdC are studied which include magnetite, barite and sand UHPdC. Aggregate of these UHPdCs are replaced with

colemanite by 1, 5 and 10 %. Results show highest compressive strength and neutron shielding are achieved with 5 % replacement with colemanite in magnetite, barite and sand UHPdC despite the reduction in gamma radiation. Based on this mixture, PVA is introduced in the composition of each UHPdCs and exposed to heat of 800 °C. The inclusion of 0.5 % PVA fibre by-volume improve thermal resistance of all UHPdCs with reductions in residual mechanical and radiation shielding properties. Based on the survivability of a certain mix of UHPdCs at 800 °C, a new batch of samples is exposed to 400 °C and tested for flexural and splitting tensile strength. Samples are also scanned using X-ray computed tomography (X-ray CT) to evaluate the effect of heat on the internal structure of UHPdC. Computer simulations using ANSYS and PHITS are conducted to validate the experiment and its application as dry cask storage. Results are compared with experimental based on the deflection and radiation shielding trend among the different type of UHPdCs.

Keywords: Gamma Ray, Neutron, Radiation Shielding, UHPC, Thermal Durability

SDG: GOAL 9: Industry, Innovation and Infrastructure

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia
sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

**SIFAT MEKANIKAL, PENEBATAN RADIASI DAN KERINTANGAN
TERMA UHPC MENGANDUNGI AGREGAT COLEMANITE DAN SERAT
ALKOHOL POLIVINIL**

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Tenaga nuklear menyediakan aplikasi yang luas termasuk penjanaan tenaga dan pengimejan perubatan yang memberi manfaat besar kepada kehidupan kita. Walau bagaimanapun, tenaga ini mengeluarkan radiasi berbahaya yang memerlukan bahan pelindung untuk pengendalian yang selamat. Konkrit telah digunakan secara meluas dalam struktur berkaitan nuklear dan terdapat jurang pengetahuan dalam aplikasi konkrit berprestasi tinggi ultra (UHPC) sebagai konkrit pelindung radiasi, terutamanya dari segi perlindungan terhadap sumber neutron dan rintangan termal. Colemanite dan serat alkohol polivinil (PVA) meningkatkan perlindungan neutron dan rintangan haba UHPC tetapi kesan gabungan bahan-bahan ini memerlukan penyelidikan lanjut. Oleh itu, kajian ini bertujuan untuk mengkaji kesan ini dan mencipta istilah konkrit padat berprestasi tinggi ultra (UHPdC) untuk UHPC dengan sifat pelindung radiasi. Berdasarkan kajian terdahulu yang menghasilkan UHPC terhadap perlindungan radiasi, tiga jenis UHPdC dikaji termasuk magnetit, barit dan

pasir UHPdC. Agregat UHPdC ini digantikan dengan colemanite sebanyak 1, 5 dan 10 %. Keputusan menunjukkan kekuatan mampatan dan perlindungan neutron tertinggi dicapai dengan penggantian 5 % colemanite dalam magnetit, barit dan pasir UHPdC walaupun terdapat pengurangan dalam radiasi gamma. Berdasarkan campuran ini, PVA diperkenalkan dalam komposisi setiap UHPdC dan didedahkan kepada haba 800 °C. Penambahan 0.5 % serat PVA mengikut isipadu meningkatkan rintangan haba semua UHPdC dengan pengurangan dalam sifat mekanikal dan perlindungan radiasi sisa. Berdasarkan ketahanan campuran tertentu UHPdC pada 800 °C, satu kumpulan sampel baru didedahkan kepada 400 °C dan diuji untuk kekuatan lenturan dan tegangan memisah. Sampel juga diimbis menggunakan tomografi berkomputer sinar-X (X-ray CT) untuk menilai kesan haba pada struktur dalaman UHPdC. Simulasi komputer menggunakan ANSYS dan PHITS dijalankan untuk mengesahkan eksperimen dan aplikasinya sebagai penyimpanan kering. Keputusan dibandingkan dengan eksperimen berdasarkan lenturan dan trend perlindungan radiasi antara jenis UHPdC yang berbeza.

Kata Kunci: Ketahanan Termal, Neutron, Sinaran Gamma, Tebatan Radiasi, UHPC,

SDG: MATLAMAT 9: Industri, Inovasi dan Infrastruktur

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LIST OF ABBREVIATIONS

PVA	Polyvinyl Alcohol
UHPC	Ultra-high Performance Concrete
UHPdC	Ultra-high Performance dense Concrete
OPC	Ordinary Portland Cement
UPV	Ultrasonic Pulse Velocity
XRF	X-ray Fluorescent
XRD	X-ray Diffraction
HVL	Half Value Layer
TVL	Tenth Value Layer
mfp	Mean Free Path
$\mu\rho$	Mass Attenuation Coefficient
μ	Linear Attenuation Coefficient
ρ	Density
$\Sigma_R (E_n)$	Macroscopic Removal Cross Section
PHITS	Particle and Heavy Ion Transport code System

CHAPTER 1

INTRODUCTION

1.1 Introduction

Nuclear energy is produced through fission or fusion reactions that cause the splitting of atoms or through the decay of radioactive elements. This energy is utilised to generate steam that produces electricity via turbine rotation which is considered more sustainable and environmentally friendly compared to fossil-fueled or hydrocarbon-fueled power plants (Nordin et al., 2019). Besides that, agriculture, manufacturing and healthcare have largely benefited from this energy source in terms of X-ray imaging and non-destructive tests (Baharuddin et al., 2020). However, nuclear energy also emits nuclear radiation which is defined as all elementary particles with energy over 100 eV (Choppin et al., 2002). This includes elementary particles that acquire energy apart from nuclear reactions which are electrostatic accelerators. As the radiation is able to penetrate certain objects, it has harmful effect on any organisms. Nuclear radiation could cause skin burns and also cancer due to a reduction in white blood cells and cell destruction (Centers for Disease Control and Prevention, n.d.). Nausea and skin burns are classified as deterministic effects which are due to destruction of cells and the lag of cell division rate. Cancer is termed as stochastic effects which is due to cell modification that resulted in malignancies (Valković, 2000). This is hereditary and detected in mammals that are exposed to radiation which eventually could lead to the destruction of the ecosystem. Hence, protection against radiation exposure is imperative and this is done by utilising dense material as shield.

Conventionally, lead is used as shielding material. However, as the material is hazardous to humans, there is a strong justification to opt for a better alternative material (Ogawa et al., 2008). Concrete is one of the materials that has been used in the construction of nuclear power plants since before 1975 (Naus et al., 1992). The advantages of concrete are the low diffusivity which protects the embedded steel reinforcement, the resistivity against fire, the wide availability of material forming the concrete and the mouldability to form any shape of structure. Concrete is mostly utilised in primary containment as a dome that accommodates the ionising facility and also as a shielding wall in secondary containment (Hendrie, 1983). It is also constructed as dry cask storage that stores spent nuclear fuel to prevent nuclear waste contamination (Attar et al., 2016). Concretes are also constructed as trenches in managing radioactive waste in India (Raj et al., 2006). Overall, wide application of concrete in nuclear radiation-structures and these types of concrete are classified as radiation shielding concrete.

Current researches that utilise concrete as a radiation shielding material aims at enhancing its ability to attenuate harmful radiation through various alterations of its composition. There are four types of radiation which are alpha, beta, gamma and neutrons. Alpha is a type of particle that made of two protons and two neutrons which are emitted from naturally occurring elements such as uranium or radium (Hore-Lacy, 2007). While beta is particles that can either be positrons or electrons and emitted by many radioactive elements. These two radiations are blocked by a sheet of paper which is considered less harmful. However, the other two radiations which are gamma and neutrons

are more penetrative hence there is extensive discussion on these two radiations in studies of radiation shielding concrete.

1.2 Problem Statement

Recent research shows that concrete can block 99 % of radiation with a thickness of 7.6 cm (Horszczaruk & Brzozowski, 2019). This is achieved by replacing sand with a heavyweight aggregate of magnetite. However, the maximum compressive strength recorded in the study is only 56 MPa which reflects its durability against elevated temperature or external impacts due to acts of terrorism on sensitive infrastructure. Nuclear-related facilities are sensitive structures as they contain radioactive material. Any damage to the structure may cause radiation leakages which could lead to nuclear contamination. Therefore, concrete that is used in nuclear facilities should possess high durability such as ultra-high performance concrete (UHPC). UHPC has a compressive strength of at least 120 MPa and research shows that it has superior properties compared to normal-strength concrete against impact and projectile forces (Máca et al., 2014). Research on UHPC as a radiation shielding material is very few and more investigation is needed to improve its radiation shielding properties.

The conventional aggregate used in UHPC is silica sand but this produces low-density concrete which results in low gamma ray shielding. The incorporation of heavyweight aggregate is needed to improve its shielding as the aggregate contains heavy elements such as iron and barium. However, research indicates that the replacement of silica with heavy-weight aggregate

resulted in lower compressive strength. Furthermore, concrete used for nuclear-related structures should also be durable against extreme temperatures as radiation sources also emit heat. While this heat is important for the power generation of nuclear power plants, it reduces concrete strength. Current research using normal-strength concrete indicates more than 70 % of compressive strength loss due to 800°C exposure (Horszczaruk et al., 2015). Research on UHPC's durability against heat conclude that it requires fibre to dissipate internal pressure due to heating. This incorporation of fibre in UHPC also requires further investigation, especially on the effect of radiation shielding. Furthermore, fibre in UHPC evaporated at a temperature above 230°C which leaves pores and channels. Even though these voids are beneficial in dissipating internal pressure due to heat, further investigation into their effect on radiation shielding is needed.

As mentioned before, another type of penetrative radiation besides gamma rays is neutron and there is a dearth of research regarding concrete shielding properties against neutron radiation. As opposed to gamma ray shielding, neutron shielding requires more neutron-absorbing elements besides heavy elements in concrete. This includes cadmium, gadolinium and boron. Boron is found in colemanite and few research that incorporate colemanite in concrete indicate its regressive effect on setting time and strength. Due to that, ultra-high mechanical properties of UHPC can offset this reduction in strength due to colemanite incorporation. This would produce UHPC with neutron shielding capability with workable mechanical performance.

Besides the boron element that affects the neutron shielding property of concrete, the presence of heavy elements such as iron, Fe, and barium, Ba, also influence the shielding of concrete against gamma radiation. Commonly, UHPC are made up of silica sand or river sand and these aggregates contain mostly silicon, Si which is lighter compared to Fe and Ba. Heavy elements of Fe and Ba are found in heavyweight aggregate of magnetite and barite and these aggregates have been investigated in producing UHPC with radiation-shielding properties (Rashid et al., 2020). However, there is a lack of information on the incorporation of boron element especially via colemanite in UHPC even with magnetite and barite.

Furthermore, it is found that at elevated temperatures, UHPC is vulnerable to explosive spalling due to its densely packed microstructure and low permeability. This requires the incorporation of fibre that can melt at elevated temperatures such as PVA fibre to control the spalling effect (Y. Li et al., 2019). Conventionally, steel fibre make up the composition of UHPC which provides UHPC with high flexural strength compared to normal concrete (Yu et al., 2015). The addition of PVA fibre into the composition of UHPC is not aimed to improve its mechanical properties but rather to provide channels that dissipate vapour pressure due to elevated temperature (Hiremath & Yaragal, 2018). However, combining PVA fibre with heavyweight aggregate and colemanite has not been extensively investigated especially in terms of radiation shielding. This requires further study to produce better form of UHPC for radiation shielding applications.

Studying the performance of concrete at elevated temperatures is important in nuclear infrastructure as it involves radioactive materials that produce heat continuously and at higher temperatures, especially in power-generating facilities. Furthermore, this type of facility is sensitive as any compromise would lead to a nuclear catastrophic event. Hence, shielding material should possess high resistance against elevated temperatures to better protect the facility and prevent any unwanted chain disasters. Current research is mostly on normal-strength concrete as a radiation shielding material and the studies found that the residual strength is less than 20 % of the original strength after being heated to 800 °C (Ismail Ahmed Ali & Lublóy, 2022).

1.3 Objectives of Research

This research aimed to improve the radiation shielding properties and thermal resistance of three different UHPC that are to be denoted as UHPdC. This is achieved by completing the following objectives:

- i. To elucidate the effect of colemanite replacement in UHPdC on its linear attenuation coefficient, macroscopic removal cross-section and compressive strength.
- ii. To investigate the effect of PVA fibre addition towards UHPdC spalling resistance and residual compressive strength
- iii. To study the effect of elevated temperature on linear attenuation coefficient, macroscopic removal cross-section and mechanical strength of UHPdC
- iv. To validate the experimental work with computer-aided simulation using ANSYS for flexural properties and Particle and Heavy Ions Transport code system (PHITS) for radiation shielding properties.

1.4 Organisation of the Thesis

This thesis begins with Chapter 1 which explains the background of the research, the problem statement, the significance of the study and its objective. This is followed by Chapter 2 which reviews past works of literature that are related to this study. This includes an depth review of concrete's radiation shielding performance, mechanical strength and durability. These are all summarised at the end of the chapter and used to develop a method of research which is detailed in Chapter 3. In this chapter, overall flow process of research work including sampling and testing is elaborated in detail. Experimental data collected based on the methodology are presented in Chapter 4. Data are analysed and discussed extensively in this chapter and further validated using computer simulation. All findings elaborated in this chapter are concluded in Chapter 5 which also includes proposed future works relevant to this area of research.

1.5 Significant of Study

Concrete has been studied and adopted as a radiation-shielding material. However, the use of denser ultra-high-performance concrete as radiation shielding or UHPdC is still new and many recent researchers are investigating its performance in terms of radiation attenuation and mechanical properties. This study further investigates the viability of UHPdC to include colemanite in the mixtures. This study will elucidate the effect of colemanite on the physical, mechanical and radiation attenuation properties of concrete being produced.

Besides that, there is a dearth of experimental data on UHPdC's neutron attenuation which is beneficial for ionising facilities such as nuclear power generation plants. Most researchers test concrete or UHPdC on gamma attenuation or x-ray radiation shielding. Data on neutron attenuation are mostly produced from simulations such as Monte Carlo Neural Programming. Hence, one of the significant contributions of this study is that it produced experimental data on UHPdC's neutron shielding performance. Furthermore, this study elucidates the effect of colemanite presence and elevated temperature on neutron attenuation performance.

Despite much research on the effect of elevated temperature on concrete and UHPC, few works produce data on the correlation between increasing heat exposure on concrete and radiation attenuation; specifically neutron attenuation. This study adds more data related to this topic especially neutron attenuation performance of UHPdC due to heat exposure. Furthermore, the study also investigates the effect of PVA fibre in UHPdC with colemanite which aimed to improve the durability of UHPdC under extreme heat exposure. The study will help elucidate the performance of mechanical and radiation attenuation of UHPdC with colemanite which provides indicators of the durability of UHPdC. Microstructure analysis of produced UHPdC and heated UHPdC will provide a better understanding of the response of the new UHPC mixture against heat exposure. This would pave the way for future research on UHPdC durability.

1.6 Scope of Study

This study is limited to concrete with characteristics of UHPC with the inclusion of radiation shielding element and coined as UHPdC. This includes the size of the binder and aggregates comprising the mixture of UHPdC which is finer than 1.18 mm and a high portion of binder used per cubic meter of concrete. Furthermore, the water-to-binder ratio is minimised to be less than 0.25 to produce concrete with a compressive strength of more than 120 MPa with a very low percentage of voids.

Current studies on UHPC as radiation shielding material mostly investigate the shielding effectiveness against gamma radiation (Gökçe et al., 2018). There is a dearth of studies involving shielding against neutron radiation which is beneficial for its application in nuclear power generation facilities and medical units (Hawk et al., 2004). In this study, colemanite is replacing the main aggregate to improve the neutron shielding capability of produced UHPdC.

There are three variations of UHPdC which depend on the type of aggregate used in the mixture. These are UHPdC-Sand, UHPdC-Barite and UHPdC-Magnetite. The based mixtures are based on previous studies (Azreen et al., 2018, 2020). In this study, the mixtures are further investigated by replacing the main aggregate with colemanite on the physical and mechanical performance of the concretes. The replacement is limited to 10% of the total weight of sand in the UHPC-Sand mixture. This would improve the neutron shielding efficiency of the three types of UHPdC.

The optimum mixtures of three different UHPdC with colemanite replacement are selected based on the performance of compressive strength, gamma ray shielding of Caesium-137, shielding of Cobalt-60 and neutron source of Americium-Beryllium. The mixtures are further studied with the addition of PVA fibre to improve the thermal resistance of the UHPdCs and this is limited to 0.75% by volume of the fibre. The starting percentage is set at 0.25% which is based on a previous study (Rashid et al., 2020).

In this study, the effect of elevated temperature is also limited. The maximum temperature is limited to 800 °C which is the highest temperature adopted in a previous study related to this topic (Horszczaruk & Brzozowski, 2019; Rashid et al., 2020).

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter critically reviews the literature related to UHPC and radiation-shielding concrete. This chapter will first present the historical background of UHPC and PVA fibre in UHPC. This is followed by an introduction to two types of radiation which are gamma and neutron. Discussion on these topics includes fundamentals of radiation, test setup in measuring the radiation and shielding performance of concrete based on past literature. Safety guidelines on radiation protection are also discussed to provide a better understanding of radiation shielding parameters. Furthermore, the mechanical properties and durability of radiation-shielding concrete are also reviewed. This only includes literature that investigates radiation shielding concrete. This chapter also discussed the simulation work on dry cask storage and empirical equations developed by past literature. The overall discussion is summarised at the end of the chapter.

2.2 Ultra-high Performance Concrete

UHPC or ultra-high performance concrete has been developed since the 1930s by applying pressure to improve the strength packing density (Richard & Cheyrezy, 1995). It has been known by many terms such as Reactive Powder Concrete, High-Performance Fibre Reinforced Composite, ultra-high strength fibre reinforced concrete and Ultra High-Performance Fiber Reinforced Concrete (Benson & Karihaloo, 2005). Japan Society of Civil

Engineering recommended that UHPC be composed of cement, aggregate, steel fibre, high-range water-reducing agents and admixtures of silica fume. The water-to-binder ratio in UHPC is reduced to less than 0.2 which reduces free water and voids (Liang et al., 2018; Yu et al., 2014). Furthermore, the workability of UHPC measured using the flow table test is more than 220 mm in diameter despite a low water-to-binder ratio which is due to the presence of high-range water-reducing admixture (S. L. Yang et al., 2009). Past research found that 2 % by volume of steel fibre in UHPC presents the optimum percentage in providing its flexural strength (Máca et al., 2014; Rossi, 2000). In terms of compressive strength, most of the research on UHPC recorded more than 120 MPa with more than 8 MPa of flexural strength (Beglarigale et al., 2021; Voo, 2010).

Overall, UHPC possesses better quality compared to normal-strength concrete in terms of physical properties and mechanical properties. UHPC has been investigated as radiation shielding material with the replacement of silica or river sand with heavyweight aggregate which reported high radiation shielding properties (Azreen et al., 2018; Gökçe et al., 2018; Khan et al., 2020). The composition of UHPC used in the study involves high density aggregate but does not include neutron attenuating mineral such as colemanite (Table 2.1). This study aimed to improve the mixture further by incorporating colemanite and PVA fibre which is effective against neutron radiation and elevated temperature. UHPC that contained these materials is denoted as UHPdC.

Table 2.1 : Composition of UHPC in radiation shielding study

Binder	Aggregate	Fiber	Author
Cement/Silica Fume	Silica Sand/ Barite/ Amang/ Lead Glass	Steel Fiber	(Azreen et al., 2018)
Cement/Silica Fume	Silica Sand/ Barite/ Hematite	Steel Fiber	(Azreen et al., 2020)
Cement/Silica Fume	Silica Sand/ Magnetite	Steel Fiber / Polivynil Alcohol Fiber	(Rashid et al., 2020)
Cement/Silica Fume	Quartz/ Barite	Steel Fiber	(Gökçe et al., 2018)
Cement/Silica Fume	Sand/ Hematite	Steel Fiber	(Khan et al., 2020)

2.2.1 PVA Fibre in Ultra-high Performance Concrete

PVA has been used with cement and steel fibre to produce electromagnetic interference shields (Wen & Chung, 2004). PVA is added to the mixture at 0.4 % by mass of cement to help disperse steel fibre as it is hydrophilic. A study reported a slight increase in compressive strength at a smaller percentage of PVA fibre (Noushini et al., 2013). Control concrete samples were designed to 50 MPa of compressive strength and the presence of PVA improves the strength by 110 % at 2.5 % of fibre while strength is reduced by 25 % at 0.5 % PVA fibre. Recent studies incorporate PVA fibre in concrete to improve its thermal properties. A study using PVA at 2.5 % by volume fraction in ultra-high toughness cementitious composite reported a compressive strength of 85 MPa and a flexural strength of 26 MPa (Q. H. Li et al., 2019). The study also found that the presence of PVA fibre in the concrete composition prevented any explosive spalling. Another study reported higher compressive and flexural strength of reinforced cement-based composite with the presence of steel fibre and PVA fibre (L. Li et al., 2020). The study also indicates that

internal vapour pressure buildup due to elevated temperature is released by channels left by melted PVA and crack propagation was restricted by the presence of steel fibre. This is based on the thermogravimetric analysis of the fibre done in the study. Reduced vapour pressure and mitigation on thermal crack propagation resulted in better residual compressive and flexural strength of cement composite with PVA fibre compared to plain cement composite at 800 °C of thermal exposure. In another study of UHPC with PVA fibre, a sample of sand UHPC shows severe cracking compared to magnetite UHPC after heating at 800 °C (Rashid et al., 2020). Compressive strength shows a 66 and 68 % reduction after heating compared to the original strength of sand and magnetite UHPC respectively. This is 49 MPa of residual compressive strength of sand UHPC compared to original strength of 154 MPa. However, this is higher compared to other studies that recorded residual compressive strength of 26 MPa (Q. H. Li et al., 2019). Overall, PVA fibre is more beneficial in preventing explosive spalling and improving strength after thermal exposure compared to improving the mechanical properties of UHPC. Other types of fibre such as steel fibre are more effective in improving the mechanical properties of UHPC due to their superior tensile strength.

2.3 Gamma Radiation

Gamma radiations are emitted by radioactive elements throughout the decaying process. This type of radiation possesses high energy beams which are highly intrusive. Gamma radiation is similar to x-ray in terms of electromagnetic radiation but it has shorter wavelengths (Bayliss & Langley, 2003). This gives higher penetrative properties on the radiation as indicated

by densification and omission of pores in concrete microstructure being exposed to gamma source (Rezaei Ochbelagh et al., 2011).

2.3.1 Test Setup for Radiation Shielding

In the investigation of gamma-ray shielding in concrete, the quality of shielding is measured by linear attenuation coefficient. This coefficient indicates the chances of a particle in a material interacting with a photon per unit path length (Bashter, 1997). The linear attenuation coefficient is determined by beaming a concrete sample to gamma rays which are mostly sourced from Cesium-137 or Cobalt-60 (Lotfi-Omran et al., 2019)(Nikbin et al., 2019)(H. Liu et al., 2019)(Tyagi et al., 2020)(LIU et al., 2019)(K. Singh et al., 2015). Cesium-137 produced 0.662 MeV of photons while Cobalt-60 emitted photons with energy of 1.173 and 1.333 MeV (Lotfi-Omran et al., 2019)(Nikbin et al., 2019). Generally, the test setup in measuring this coefficient is as shown in Figure 2.1, where a radioactive source is placed in a line of a certain distance from the sodium iodide NaI (TI) detector that is connected to the channel analyser (Table 1). However, there are other radioactive sources with gamma radiation used in the study such as Barium-133 and Technetium-99m which emit 140.511 and 80.99 keV respectively (Akbulut et al., 2015)(Oto et al., 2013). The distance between the sample to the source and detector also is different for each research (Table 2.2). The farthest distance of the sample to the source of radiation is 79 cm while the shortest is 2 cm. This resulted in the distance of the source to the detector counter varying from 7 – 85 cm. However, the distance between the source and the detector is insignificant for gamma rays as there is no absorption of radiation by air due to its high

penetration (Valković, 2000). The selection of the sample's thickness is incremental up to 150 mm and some studies used fixed thickness. To eliminate the effect of radiation coefficient damping by specimen thickness, 80 – 100 mm is recommended by the literature (Horszczaruk & Brzozowski, 2019)(Gencel et al., 2011). This is also shown in the study of test samples with incremental thickness which indicates average coefficient is attained at 100 mm thickness (Mostofinejad et al., 2012). As most of the detector type used is NaI (TI), quite several studies used a stilbene scintillator to obtain readings for neutron and gamma absorption simultaneously. Measurement of gamma-ray counts in a stilbene scintillator is done indirectly by the transfer of energy to electrons through Compton's scattering (Masoud, El-Khayatt, et al., 2020). This method enables concurrent measurement for neutron and photon exposure in a setup of one source. The observation period of gamma ray counting also varies from 90 seconds to 120 minutes. At 120 minutes and 90 seconds of measurement duration, the statistical uncertainty of data is found to be at $\pm 2\%$ and $\pm 0.3\%$ respectively (Masoud, El-Khayatt, et al., 2020)(Xu et al., 2010).

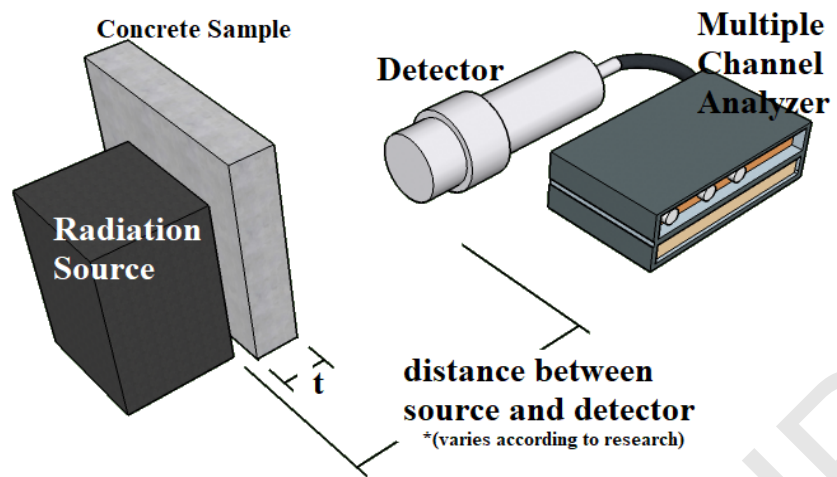


Figure 2.1 : Common linear attenuation coefficient test setup

Table 2.2 : Test setup of gamma radiation

Ref.	Radiation Source	Distance from source to specimen (cm)	Distance from detector to specimen (cm)	Thickness of sample (mm)	Detector Type	Collimator opening	Duration of count observation (min)
(Rasoul Abdar Esfahani et al., 2021)	Cs137, Co60	2	5	150	2"x2" NaI(Tl)		
(Abdo et al., 2003)	Cs137, Co60				3"x3" NaI (TL)	18mm dia.	
(Sakr & El-Hakim, 2005)				20 - 100	4" dia. NaI(Tl)		15min
(N. Singh et al., 2006)	Cs137	33	31	11 - 16	Berthold LB-6411	2.8mm dia.	
(Kharita et al., 2009)	Cs137	50	50				
(Kharita et al., 2010)							
(Kharita et al., 2011)							
(Xu et al., 2010)	Cs137, Co60	14.7	28.6		2"x2" NaI(Tl)	26mm dia.	1.5min
(Akkurt et al., 2010a)	Cs137, Co60			20 - 100	3"x3" NaI(Tl)		
(F. Demir et al., 2011)	Cs137	10	10	10 - 90	2"x2" NaI(Tl)	5mm dia.	
(Yilmaz et al., 2011)	Co60	10	5	12 - 36	HPGe detector		
(Alwaeli & Nadziakiewicz, 2012)	Co60	79	6	26 - 182			
(Oto et al., 2013)	Ba133, Am241	10	5		NaI(Tl)	Pin hole	
(Oto & Gür, 2013)							
(Yaltay et al., 2015)	Co60					1 cm ²	
(Hassan et al., 2015)	Cs137, Co60	2	5	10 - 40	3"x3" NaI(Tl)	10 mm slit	
(Akbulut et al., 2015)	Tc99m, Am241, Cd109, I131						
(Horszczaruk & Brzozowski, 2019)	Cs137		35	80	Scintillation type detector		60min
(Gencel et al., 2011)	Co60	20	20	20	HPGe type detector		
(Masoud, El-Khayatt, et al., 2020)	Cs137, Co60,	5	40	40 - 120	stilbene scintillator (40 x 40 mm)		120min

2.3.2 Linear Attenuation Coefficient

From the setup, several counts detected by multi-channel analyser during time of observation indicates the number of photons that passed through the sample. Counts recorded without samples are denoted as background counts. Therefore, the actual number of counts for each thickness of the sample is attained by subtracting the observed counts from background counts. This is ratioed to the initial count to determine the linear attenuation coefficient based on Beer-Lambert Law as indicated by Eq. 2.1 (Lotfi-Omran et al., 2019):

$$\mu = \frac{1}{t} \ln \frac{D_0}{D} \quad (\text{Eq. 2. 1})$$

where μ is the linear attenuation coefficient (cm^{-1}), t is the thickness of the sample (cm), D_0 and D is the background subtracted number of counts recorded by the detector without and with concrete sample respectively. The average value of μ is determined from the plot of t and μ .

Based on the value of μ , the value of half value layer, HVL and the tenth value layer, TVL can be determined. HVL and TVL values are the thickness required for concrete or any absorbing material to attenuate the intensity of gamma radiation by half and a tenth of its intensity respectively. HVL and TVL can be calculated using Eq. 2.2 and Eq. 2.3 (Akkurt & Canakci, 2011):

$$HVL = \frac{\ln 2}{\mu} \quad (\text{Eq. 2. 2})$$

$$TVL = \frac{\ln 10}{\mu} \quad (\text{Eq. 2. 3})$$

where HVL and TVL is the half value layer and tenth value layer respectively which are expressed in unit cm.

Furthermore, the mean free path, mfp which is defined as the average distance between two successive interactions of photon can be calculated using Eq. 2.4 (Nikbin et al., 2019)(Ouda, 2015):

$$mfp = \frac{1}{\mu} \quad (\text{Eq. 2.4})$$

Linear attenuation coefficient is also expressed in mass attenuation coefficient as an indicator for shielding effectiveness by obviating the effect of varied density in concrete on the value of μ . Mass attenuation coefficient, μ_p is calculated using Eq. 2.5 (Kaplan, 1989)(Oto & Gür, 2013):

$$\mu_p = \frac{\mu}{\rho} \quad (\text{Eq. 2.5})$$

where ρ is the density of concrete.

Parameters such as mfp , TVL and HVL, are calculated based on μ which serves as an indicator for the actual production of the material as a radiation shield. Therefore, the linear attenuation coefficient, μ is the basic parameter determining the efficiency of material in reducing the energy of nuclear radiation. Further analysis μ into μ_p is also useful in gauging the shielding efficiency with disregard for its density.

2.3.3 Effect of Aggregate of Linear Attenuation Coefficient of Concrete

Gamma-ray absorption which is represented by linear attenuation coefficient is influenced by atomic number of shielding material and density (Valković, 2000). In concrete, a combination of aggregates and binders gives concrete a variety of components made of different elements of varied densities. By increasing the percentage of high-density elements in concrete, the absorption rate of gamma rays is also increased. This is achieved by increasing the amount of aggregate and also by using heavyweight minerals. Increasing the amount of heavyweight aggregate leads to an increase in the density of the concrete and concrete with a density of more than 2600 kg/m^3 is categorised as heavyweight concrete (Azeez et al., 2019). However, the use of common natural aggregates such as limestone and granite which have a density of less than 3000 kg/m^3 in concrete samples of past research indicates the viability of these aggregates to form radiation shielding concrete.

Natural aggregate such as limestone, granite and silica sand has a density of less than 2800 kg/m^3 (Tung-Chai & Chi-Sun, 2013)(K. H. Yang et al., 2013). Granite and sand contained a large percentage of SiO_2 while limestone contained mostly CaCO_3 (Akkurt et al., 2007)(Alwaeli, 2016)(Saidani et al., 2015). These compounds which are formed of elements with small atomic weight resulted in low gamma attenuation of natural aggregate concrete. The computed value of the linear attenuation coefficient for granitic rock indicates the value to be between $0.4 - 0.455 \text{ cm}^{-1}$ (Akkurt et al., 2007).

Figure 2.2 shows the correlation between μ measured in samples containing natural aggregate and their density based on past research. The μ value is observed on control sample that is subjected to 0.662 MeV of gamma ray. Maximum concrete density produced using natural aggregate is 2990 kg/m³ which recorded μ value of 0.184 cm⁻¹ (Çullu & Ertaş, 2016). The highest μ value is reported by concrete with density of 2231 kg/m³ which is 0.267 cm⁻¹ (Rasoul Abdar Esfahani et al., 2021). This sample contained the highest percentage of ground-granulated blast furnace slag in the study. The study found that enhancement in linear attenuation coefficient is due to the densification of pore structure which is attributed to the micro-filling ability of the slag. Furthermore, the pozzolanic reaction from the slag also contributed to reducing pores and improving density.

A comparison on a mixture of samples indicates that a higher percentage of natural aggregate in the mixture resulted in a higher μ value even though the density of concrete is lower. A huge percentage of aggregate provides a higher amount of SiO₂ and CaO in concrete that led to a spike in μ value. Based on all data presented in Figure 2.2, The average density and μ value of concrete with natural aggregate is 2434.87 kg/m³ and of 0.1855 cm⁻¹ respectively which equals to mass attenuation coefficient, μ_p of 0.0762 cm²/g.

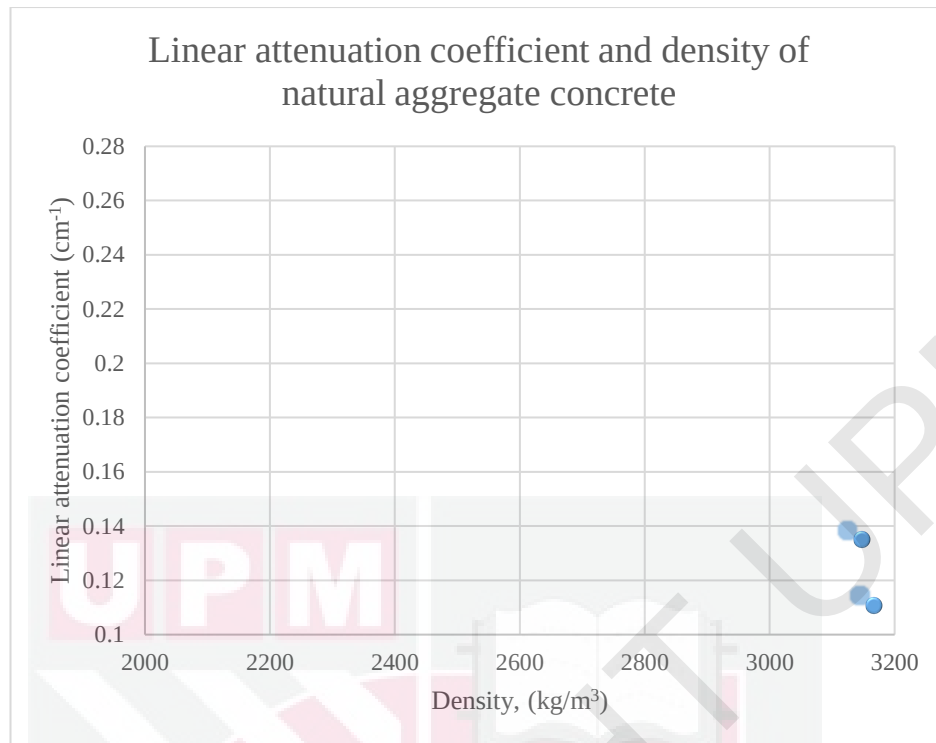


Figure 2.2 : Correlation between linear attenuation coefficient and concrete's density of sample containing only natural aggregate (kg/m³)
(Source : Akkurt et al., 2007; Azeez et al., 2019; Azreen et al., 2018, 2020; Demir et al., 2020; Gökçe et al., 2018; Horszczaruk & Brzozowski, 2019; Rasoul Abdar Esfahani et al., 2021)

Naturally occurring heavyweight aggregate is denser compared to commonly used aggregate in concrete that has a bulk density of more than 3000 kg/m³. This includes hematite, magnetite, limonite, barite, goethite and ilmenite (Miller, 2003). Figure 2.3 shows the relationship between μ value and mass of heavyweight aggregate per cubic meter of concrete mixture. The value of μ is recorded based on exposure to gamma ray at 0.662 MeV. The mass of heavyweight aggregates shown is based on their composition in the concrete mixture. This illustrates the effect of mass for each type of aggregate on the gamma radiation shielding of the produced concrete. Overall, lead shows the highest influence on enhancing the radiation shielding of concrete. This is indicated by the value of linear attenuated coefficient recorded by concrete

with 408 kg of lead per cubic meter that recorded an almost similar shielding coefficient with concrete with magnetite (K. Singh et al., 2015)(Rashid et al., 2020).

Recent research mostly used magnetite and barite in investigating radiation shielding concrete as shown in Figure 2.3. Few studies used hematite, iron ore, siderite and lead in forming the concrete and reported maximum μ value at 0.22 cm^{-1} (El-Samrah et al., 2018)(Azreen et al., 2020)(Azeez et al., 2019)(Demir et al., 2020)(K. Singh et al., 2015).

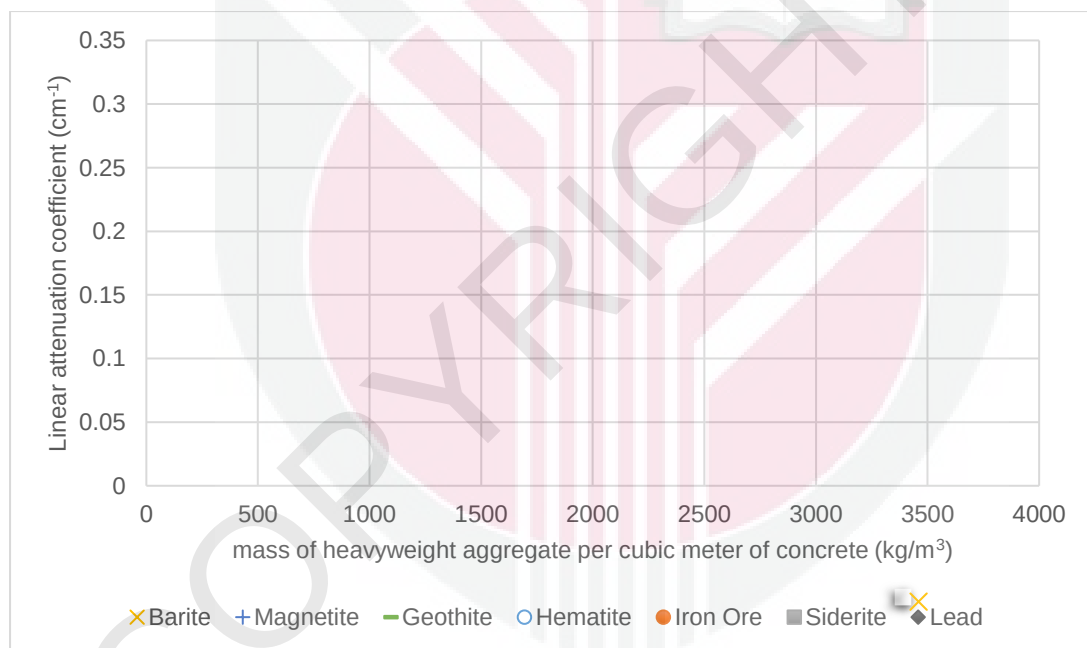


Figure 2.3 : Graph of linear attenuation coefficient (cm^{-1}) and the amount of heavyweight minerals in concrete (kg/m^3)

(Source : Akkurt et al., 2007; Azeez et al., 2019; Azreen et al., 2020; Cullu & Ertas, 2016; Demir et al., 2020; El-Samrah et al., 2018; Gökçe et al., 2018; Horszczaruk & Brzozowski, 2019; H. Liu et al., 2019; Lotfi-Omran et al., 2019; Nikbin et al., 2019; Rashid et al., 2020; K. Singh et al., 2015)

Barite which contains a large percentage of barium sulphate (BaSO_4) that varies according to its purity and has a density of 4000 to 4200 kg/m^3 (Miller,

2003)(Ouda, 2015)(F. Demir et al., 2010). The use of barite aggregate with 90% purity will result in 3400 kg/m³ of concrete's density (Miller, 2003). The combination of fine and coarse barite aggregate resulted in 3950 kg/m³ of concrete density (Çullu & Ertaş, 2016). The linear attenuation coefficient of barite ore having 90% BaSO₄ is around 0.75 cm⁻¹ which indicates the high radiation shielding quality of barite (Akkurt et al., 2010b). Samples containing barite reported an average μ value of 0.244 cm⁻¹ which is 31.3% higher compared to the μ value reported by natural aggregate concrete (Figure 2.3). The high atomic weight of barium in barite increased shielding as compared to silicon or calcium in natural aggregate. Overall analysis also indicates that improvement in the radiation shielding value of concrete is recorded with an increase in barite percentage. Based on available concrete density data, the average density of barite concrete is 3366.121 kg/m³ hence μ_p value of 0.066 cm²/g. The existence of barium in BaSO₄ influenced the high absorption value of barite concrete hence high purity of barite would result in large μ value.

Another type of heavyweight mineral is magnetite which contains mostly iron oxide, Fe₃O₄ that ranges from 49.6 to 90 % (Miller, 2003)(K. H. Yang et al., 2013)(Horszczaruk & Brzozowski, 2019). This resulted in varied concrete density of between 2860 – 4800 kg/m³ (Miller, 2003)(K. H. Yang et al., 2013)(Horszczaruk & Brzozowski, 2019). Based on Figure 2.3, the maximum recorded μ value is 0.295 cm⁻¹ which is from a sample containing only magnetite with a density of 3320 kg/m³ (Horszczaruk & Brzozowski, 2019). However, lower μ value of 0.228 cm⁻¹ is observed on a sample containing a marginally higher amount of magnetite at 3378.3 kg per cubic meter of

concrete (Lotfi-Omran et al., 2019). This could be due to the lower purity of magnetite used in the study which is 72.1 - 78.2 % of Fe_3O_4 compared to 90 % in a study by E. Horszczaruk & P. Brzozowski (2019) (Horszczaruk & Brzozowski, 2019) (Lotfi-Omran et al., 2019). A study on the influence of the ratio of water to cement on radiation attenuation of magnetite concrete indicated that μ value is inversely proportional to the ratio (Lotfi-Omran et al., 2019). However, the mix composition of samples indicated that besides the increment of the water-to-cement ratio of the sample, the percentage of magnetite is also being reduced across all the samples. This indicates that the lowering of μ value may also be due to a reduction of magnetite aggregate in the concrete as shown by samples that contained only 700 kg/m^3 of magnetite and recorded the lowest μ value of 0.185 cm^{-1} (LIU et al., 2019). Based on data in Figure 2.3, the average density and μ value of magnetite concrete is 3618.7 kg/m^3 and 0.217 cm^{-1} respectively which equals to μ_p value of $0.060 \text{ cm}^2/\text{g}$. The presence of iron, Fe as a heavy element in magnetite influences the μ value of produced concrete. This influence also depends on the purity of the magnetite aggregate used in the concrete.

Another type of ore that contains similar heavy element of iron, Fe is hematite which contributes to gamma-ray shielding. Hematite has a density of $2900 - 2967 \text{ kg/m}^3$ with a major percentage of Fe_2O_3 at 27 – 81.13 % (Azreen et al., 2020)(Miller, 2003)(Gencel et al., 2011). A study on various gamma radiation shielding properties of ore reported that hematite ore containing 27 % Fe_2O_3 recorded μ_p value of $0.263 \text{ cm}^2/\text{g}$ at 0.081 MeV of radiation (Oto, Yildiz, Akdemir, et al., 2015). This is 687% lower compared to barite and 97% lower

compared to magnetite ore which indicates that gamma attenuation is hugely affected by the percentage of heavy elements in ore as magnetite and barite contained 93.1% of BaSO₄ and 85.74% of FeO respectively.

In terms of hematite performance as aggregates in concrete, hematite concrete reported μ value of 0.165 cm⁻¹ at 0.662 MeV of gamma radiation (Azreen et al., 2020). Based on the study, hematite used in the concrete contained 71.71% of Fe₂O₃. Another study of hematite concrete reported 0.189 and 0.160 cm⁻¹ of μ value at 0.662 and 1.25 MeV respectively (Kharita et al., 2008). Slightly higher μ for hematite concrete is reported at 0.212 cm⁻¹ at 0.662 MeV of Cs-137 (Kharita et al., 2009).

Another type of aggregate used in the study of radiation shielding concrete is ilmenite which is a type of ore that contains titanium beside iron as a heavy element. Ilmenite contains 35.55 – 65.74 % Fe₂O₃ and 21 - 23.08 % of TiO₂ with a density of 4.2 g/cm³ (Abo-El-Enein et al., 2014)(Sakr & El-Hakim, 2005). The attenuation coefficient per cent of ilmenite concrete exposed to 660 keV of photon energy was recorded at 9.81 % which is higher than the value recorded by barite concrete at 9.73 % (Sakr & El-Hakim, 2005). This is due to the density of ilmenite which is the highest in the study compared to barite and gravel.

Another type of heavyweight aggregate of limonite contained iron oxide (hydrated), 2Fe₂O₃.3H₂O with 60% of iron, Fe (Miller, 2003). A study on limonite ores with 70.94% of Fe₂O₃ recorded μ_p value of 0.368 cm²/g which is 3.4% higher than hematite but 29.2% lower than magnetite(Oto, Yildiz,

Akdemir, et al., 2015). Goethite is also another type of heavyweight aggregate which contains 63% iron, Fe in iron oxide (hydrated), and $\text{FeO}(\text{OH})$ (Miller, 2003). The combination of goethite as coarse aggregate with natural sand and limonite as fine aggregate resulted in μ value of 0.0822 cm^{-1} (El-Samrah et al., 2018). The study shows that goethite aggregate used in concrete contained 67% of Fe_2O_3 yet the result of μ value is lower by 12% compared to barite concrete with limonite and sand as fine aggregate. This may be due to the heavier element of barium in barite which is 66.77 % of barium oxide, BaO presence in barite aggregate. Another type of aggregate called zeolite that contains alumina silicate has also been studied as aggregate for radiation shielding concrete. Zeolite contained 72.09 % of SiO_2 and 13.612 % of Al_2O_3 (Kurudirek Murat et al., 2010). An increase in the percentage of zeolite replacing natural aggregate in concrete of up to 50 % resulted in a reduction of μ value of about 40 % (Akkurt et al., 2010a). The lowest value of μ at 0.156 cm^{-1} was recorded by concrete with a 50 % concentration of zeolite aggregate and this is due to the high porosity of zeolite which resulted in lower density and radiation shielding. Hence, the study concluded that zeolite is not viable as aggregate replacement in radiation-shielding concrete.

Table 2.3 summarises the comparison between various studies of different aggregates used in radiation-shielding concrete. The table also shows the percentage of heavy components such as Fe_2O_3 , Fe_3O_4 and Ba_2SO_4 present in aggregates of the concrete. There is a correlation between the percentage of the component and the resulting μ value of the concrete. The higher the percentage of heavy components in aggregate, the higher the μ value of the

concrete. This is shown in concrete with barite aggregate that shows a higher μ value with a high percentage of Ba_2SO_4 (Gökçe et al., 2018) (El-Samrah et al., 2018). This is also shown in the varied purity of magnetite and other type of ore such as hematite and goethite used in concrete. Overall, the element comprising the aggregate heavily influences the outcome of gamma radiation shielding efficiency. The purity of ores used as aggregate determined the percentage of heavy elements possessed by the mineral hence affecting the μ value of the concrete.

Table 2.3 : List of major comprising elements in radiation shielding concrete reported by reviewed papers

Sample Name	Aggregate	Fe_2O_3 (%)	Fe_3SO_4 (%)	$\text{BaSO}_4 / \text{BaO}$ (%)	Linear Attenuation Coefficient, μ (cm^{-1})	Aggregate volume by weight in mix (kg/m^3)	Ref.
B-UHPC	Barite			58.69	0.208	1630	(Azreen et al., 2020)
BL	Barite			20.84	0.0918	1798.3	(El-Samrah et al., 2018)
B	Barite			74.31	0.241	1444	(Gökçe et al., 2018)
BC	Barite			90.3	0.265	2920	(Horszczaruk & Brzozowski, 2019)
MC	Magnetite		90.8		0.295	3320	(Horszczaruk & Brzozowski, 2019)
S1	Magnetite	72.1			0.228	3378.3	(Lotfi-Omran et al., 2019)
H-UHPC	Hematite	71.71			0.165	1100	(Azreen et al., 2020)
G.L	Goethite	67.0			0.0822	1651.3	(El-Samrah et al., 2018)

2.3.4 Effect of Aggregate Size on Linear Attenuation of Concrete

Difference sizes of heavyweight or natural aggregate were studied and this influences the μ value of radiation shielding concrete. Research using magnetite as aggregate in concrete shows an increase of μ value by 12% with an increase in the highest aggregate size from 12.5 to 25 mm (Lotfi-Omran et al., 2020). This result of μ is based on gamma-ray radiation at 0.662 MeV. This is also reported by barite concrete with the highest value of μ at 0.266 cm^{-1} which has a larger percentage of coarse-size aggregate compared to fine aggregate (Akkurt et al., 2006). The use of fine-sized barite aggregate reported a lower μ value of 0.241 cm^{-1} at 0.662 MeV of gamma radiation (Gökçe et al., 2018).

Another study which also used fine-sized barite as aggregate recorded an even lower μ value of 0.208 cm^{-1} at a similar energy level (Azreen et al., 2020). Comparison of concrete samples with natural aggregate also indicates the influence of aggregate sizes on radiation shielding efficiency. Sample with a 1.6 ratio of coarse-to-fine aggregate recorded higher μ compared to samples with a 0.8 - 1.18 ratio of coarse-to-fine aggregate. (Akkurt et al., 2006)(Han et al., 2018)(Demir et al., 2020). This may be due to the higher surface area of fine-sized aggregate compared to coarse aggregate which created a larger interfacial transition zone. The increase in the interfacial transition zone leads to a reduction of μ value. In terms of variation in the water-to-cement ratio of radiation shielding concrete, no significant impact on μ value is observed. This is shown by a sample of natural aggregate concrete with a 0.16 water-to-cement ratio having almost similar μ value with a sample of 0.4 ratio. This is

further proved by samples with similar constituents but varied water-to-cement ratios of 0.43 - 0.63. Samples reported no significant changes in μ value which is around 0.19 cm^{-1} (Kharita et al., 2010).

2.3.5 Use of Industrial Waste in Radiation Shielding Concrete

Industrial waste has also been utilised as radiation-shielding concrete. It produces more sustainable concrete by reducing waste and reducing dependency on natural occurring minerals such as barite and magnetite. Figure 2.4 shows the reported μ value for different types and masses of waste incorporated per cubic meter of concrete. The reported μ value is based on exposure to gamma radiation at 0.662 MeV. Most data indicates that waste is utilised at about $100 - 1500 \text{ kg/m}^3$ of concrete mixture (Figure 2.4). The sample consists of only steel shot as aggregate with dune sand as fine aggregate recorded 0.2 cm^{-1} of linear attenuation coefficient (Azeez et al., 2019). This is higher compared to samples with steel slag or a combination of coarse limestone and steel shot. Based on the study, the highest amount of steel shot in mix constituent produced concrete with the highest unit weight hence the highest μ value. The μ value is 3% higher than the maximum value reported by magnetite concrete with 420 kg/m^3 of cathode ray tube (LIU et al., 2019). This implies that the improvement in μ value due to steel shot as aggregate is comparable to heavyweight aggregate such as magnetite.

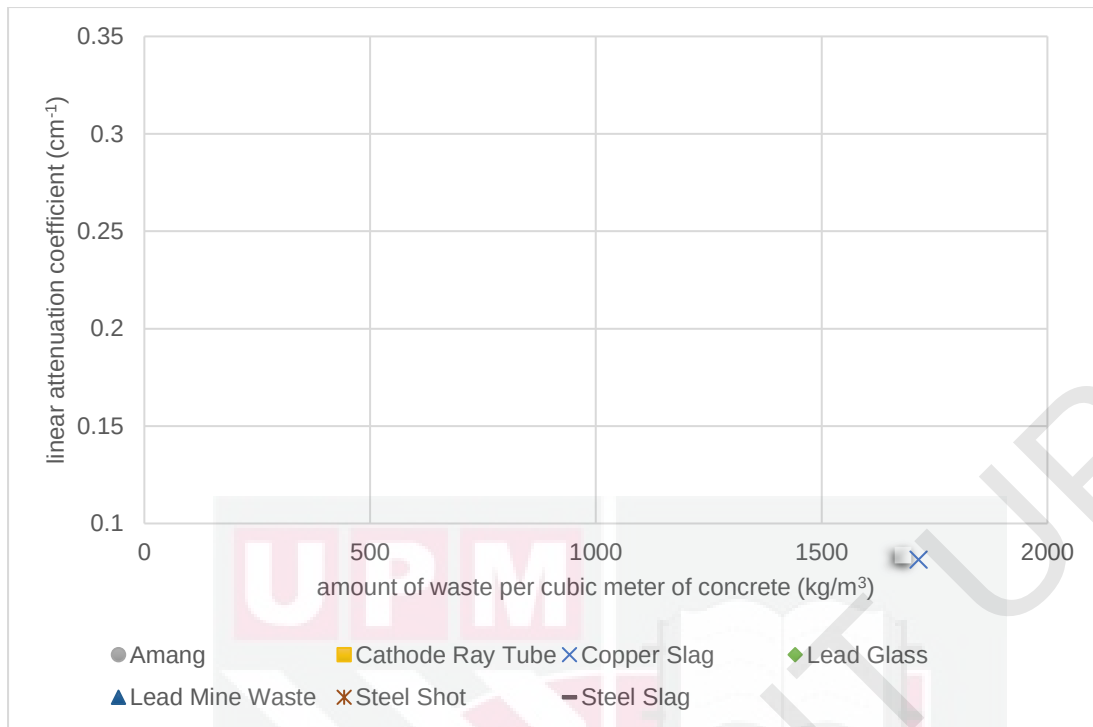


Figure 2.4 : Relationship between linear attenuation coefficient (cm^{-1}) and the amount of waste per cubic meter of concrete (kg/m^3)

(Source : Ameri et al., 2020; Azeez et al., 2019; Azreen et al., 2018; Cullu & Ertas, 2016; LIU et al., 2019; Nikbin et al., 2019; Rasoul Abdar Esfahani et al., 2021)

Replacement of heavy minerals with cathode ray tube in radiation shielding concrete reduces the weight of high-density concrete hence resulting in lower μ value as low as 0.168 cm^{-1} (LIU et al., 2019). The utilisation of waste containing lead glass recorded μ value of 0.175 cm^{-1} which is almost similar to the value recorded by concrete with cathode ray tube as this material contained mostly SiO_2 . By-products of the mining process such as amang and lead mine waste reported μ values of 0.182 and 0.175 cm^{-1} respectively (Azreen et al., 2018)(Çullu & Ertaş, 2016). The high value of μ in concrete with amang is due to the presence of TiO_2 and Fe_2O_3 that make up most of amang's composition as compared to lead mine waste that contained mostly CaO .

Concrete with copper slag shows the highest attenuation coefficient among all other concrete with waste which recorded μ value of 0.32 cm^{-1} (Rasoul Abdar Esfahani et al., 2021). The study indicates that copper slag as fine aggregate combined with coarse natural aggregate increased the value of μ by 30.6 %. The utilisation of lead slag in concrete recorded a lower coefficient of 0.204 cm^{-1} at 60% aggregate replacement (Yadollahi et al., 2016a). The study indicates that the replacement of aggregate with lead slag from 40 to 60% increased μ by 5 %. This is in line with a study investigating the effect of lead-zinc slag as fine aggregate in concrete which also shows improvement in μ value by 17 % with incorporation of the slag (Alwaeli, 2017). However, steel slag in concrete recorded an inverse proportionality between its percentage in concrete mixture and the resulting μ value which may be due to lack of heavy element presence in this type of slag (Azeez et al., 2019). Another research that investigates the replacement of steel shot with electric arc furnace slag in concrete also indicates a reduction in μ with increasing replacement (Maslehuddin et al., 2013). At maximum replacement of steel shot with slag which is 65%, concrete density is 14.6 % lower compared to concrete with 100 % steel shot as aggregate. This shows that the density of slag is lower compared to steel shot due to the lack of heavy elements in its composition hence resulting in a lower attenuation coefficient.

In general, copper and steel slag contain Fe_2O_3 at different percentages and some steel slag is reported to contain Al_2O_3 (Rasoul Abdar Esfahani et al., 2021)(Beaucour et al., 2020)(Pomaro et al., 2019). Lead-zinc slag contained mostly nickel, Ni element which is heavier compared to iron, Fe which

explained the high recorded μ value (Alwaeli, 2017). The type and amount of element influence the efficiency of overall gamma radiation attenuation which could enable slag to perform similarly to heavyweight minerals. This is shown by a study on the sample with electric arc furnace slag as aggregate in concrete that recorded a similar μ value with barite concrete at 0.182 cm^{-1} based on exposure of 1.25 MeV (Pomaro et al., 2019). The slag aggregate is denser compared to barite aggregate which is due to the presence of the high amount of magnetite and hematite. These ores contribute Fe_xO_y elements hence resulting in high gamma ray attenuation. Overall, the variations in the composition of industrial waste affect the shielding coefficient which could outperform heavyweight aggregate hence producing more sustainable radiation-shielding concrete.

2.3.6 Effect of Pozzolanic Material on Linear Attenuation Coefficient of Concrete

In gamma ray attenuation studies, few researchers investigated the effect of pozzolanic additives such as silica fume and ground granulated blast furnace slag (GGBS) and also another heavyweight additive such as Bi_2O_3 on linear attenuation coefficient of concrete. This is shown by Figure 2.5 which shows the relationship between μ value (cm^{-1}) and weight of additive added per cubic meter of concrete (kg/m^3). The value of μ shown in Figure 2.5 is based on exposure to photon at 0.662 MeV of energy level. Additives such as silica fume, GGBS and fly ash are part of cement replacement which aims to reduce the carbon footprint in concrete. An increase in the percentage of fly ash replacing cement in concrete by 60 % reduced the value of μ by 10 % (K. Singh et al., 2015). The study also reported that no reduction in μ for fly ash

replacing cement by 20 % which indicates the optimum percentage. This is in line with other researches that limit the percentage of fly ash in the mix design by 20 % (Skarżyński, 2020)(LIU et al., 2019)(H. Liu et al., 2019).

Silica fume is added to the concrete at 19.5 – 23.1 % of total binder weight (Azreen et al., 2020)(Abid et al., 2017). An increment in the percentage of silica fume-to-total binders by 13 % resulted in a reduction of μ value between 2.5 – 4.3 % (Yadollahi et al., 2016a). Another study that used 2.8 % of silica fume also reported a reduction of the gamma-ray attenuation coefficient (Mostofinejad et al., 2012). This is due to the lower density possessed by silica fume compared to cement which resulted in lower concrete density and μ value. However, a 1 % addition of silica fume in copper slag concrete recorded a 15% increment in μ value(Rasoul Abdar Esfahani et al., 2021).

A combination of silica fume and fly ash which summed up to 20 % of binder weight resulted in an increment of 3 – 15 % in μ value (El-Samrah et al., 2018). However, this result is influenced by the different types of aggregate used in the experiment. Replacement of cement with GGBS by 15 – 60 % resulted in a 1.6 – 9.0 % increment of μ value (Rasoul Abdar Esfahani et al., 2021). This is due to the micro-filling ability and pozzolanic reactivity possessed by GGBS that leads to densification of pore structure hence better attenuation (Rasoul Abdar Esfahani et al., 2021).



Figure 2.5 : Relationship between linear attenuation coefficient (cm^{-1}) and amount of additive in concrete (kg/m^3)

(Source : Ameri et al., 2020; Nikbin et al., 2019; Rashid et al., 2020; Rasoul Abdar Esfahani et al., 2021; K. Singh et al., 2015; Yadollahi et al., 2016a)

The use of Bi_2O_3 in radiation shielding concrete showed a 2.6 - 5.7% increment in μ value with 2 – 6 % of cement replacement (Nikbin et al., 2019). Replacement of cement with WO_3 by 2 – 6 % caused a 2.6 – 4.0 % increment in value of μ (Nikbin et al., 2019). The gain recorded by Bi_2O_3 is higher compared to WO_3 as the latter is lower in density due to the lower atomic number of the elements in the component (Nikbin et al., 2019). The heavier element of bismuth (Bi) in Bi_2O_3 produced denser concrete compared to WO_3 .

The combination of the two additives at 2 – 6 % of cement replacement resulted in a slightly higher gain of 3.7 – 6.6 % in the value of μ . This is due to the compound effect provided by both additives in the ability of neutron and photon absorption (Nikbin et al., 2019). In the overall observation, the μ value recorded by these additives is below 0.2 cm^{-1} which is low compared to

concrete with GGBS additive as shown in Figure 2.5. However, the percentage of μ increment for each percentage of additive is larger for Bi_2O_3 and WO_3 combination compared to GGBS. This further demonstrates the influence of heavy elements on gamma shielding.

The incorporation of additives in concrete affects its microstructure. Pozzolanic additives provide additional calcium silicate hydrate in concrete's matrix through a secondary pozzolanic reaction while heavyweight fillers increase radiation attenuation properties. These changes in concrete's constituent and microstructure which are aimed towards improving the shielding properties of concrete also affect its mechanical strength which is the governing parameter in defining its practicality as a structural member.

2.4 Neutron Radiation

2.4.1 Macroscopic Removal Cross Section

For neutron radiation, sources of radiation can either be plutonium-beryllium sources (PuBe) or americium-beryllium sources (AmBe). PuBe emits energy of 3.92 and 4.43 MeV while AmBe emits about 4.5 MeV (Malkapur et al., 2017)(Masoud, Kansouh, et al., 2020). The test setup to irradiate samples using a neutron source is similar to Figure 2.1 with the only difference being the type of scintillating detector to detect neutron flux. As neutrons have no charge, their detection is done indirectly through nuclear reactions that produce charged particles (Korkut et al., 2010). The detector produced pulses based on neutron reactions within it.

The total intensity of neutrons with and without shielding concrete is used to determine the total neutron cross-section or macroscopic removal cross-section, $\sum_R(E_n)$ in cm^{-1} which can be calculated using Eq. 2.6 (Malkapur et al., 2017)(Masoud, Kansouh, et al., 2020):

$$\sum_R(E_n) = \frac{1}{t} \ln \frac{I_0}{I} \quad (\text{Eq. 2. 6})$$

where t is the thickness of the sample (cm), and I_0 and I are the total intensity of fast neutron flux emitted without and with the sample respectively. Total macroscopic removal cross-section, $\sum_R(E_n)$ is the probability a fission or fast neutron had a first collision that would displace it from the group of penetrating neutrons (El-Sayed Abdo, 2002).

The higher the value of $\sum_R(E_n)$, the larger the number of neutron collisions which is equivalent to the absorption of neutron. This value depends on the target nucleus of the shielding material and also the energy possessed by the neutrons. High-energy neutrons called fast neutron is attenuated by elastic collisions with nuclei of light elements such as hydrogen. The attenuation is also caused due to inelastic collision with nuclei of heavy elements (Zalegowski et al., 2020). These slowed-down neutrons called thermal neutrons are captured by absorber atoms in compounds such as boron or gadolinium (Choppin et al., 2002)(Zalegowski et al., 2020).

Similar to gamma-ray attenuation, $\sum_R(E_n)$ is used to determine HVL and relaxation length, λ using Eq. 2.7 and Eq. 2.8 (Masoud, Kansouh, et al., 2020):

$$HVL = \frac{\ln 2}{\sum_R(E_n)} \quad (\text{Eq. 2.7})$$

$$\lambda = \frac{1}{\sum_R(E_n)} \quad (\text{Eq 2.8})$$

Table 2.4 summarises the value of macroscopic removal cross-section for concrete samples from previous studies. The highest $\sum_R(E_n)$ value recorded by concrete with light natural aggregate is 0.133 cm^{-1} based on exposure to 0.025 MeV of energy (Demir et al., 2020). Concrete with granite aggregate recorded a lower value of $\sum_R(E_n)$ at 0.104 cm^{-1} based on exposure to the higher energy level of 4 MeV (Malkapur et al., 2017).

Another study using natural aggregate in the concrete sample recorded a lower $\sum_R(E_n)$ value of 0.075 cm^{-1} at 4 MeV (Malkapur et al., 2015). Analysis of the mix composition of concretes used in the studies indicates that an increase in the amount of cement used in the sample caused a gain in neutron shielding. This is due to hydrogen in chemically bound water of cement hydrates that slow down fast neutrons due to elastic collision (Masoud, El-Khayatt, et al., 2020). A study indicates a 1% increment in cement's moisture resulted in an increment of $\sum_R(E_n)$ value by 15% (Piotrowski et al., 2015).

Table 2.4 : Macroscopic removal cross section value concrete sample with different types of aggregate

Sample	Source	Energy (MeV)	$\Sigma_R(E_n)$ (cm ⁻¹)	Aggregate	Mass of aggregate per m ³ of concrete (kg/m ³)	Ref.
CC1	Am-Be	4	0.075	Natural	1762.7	(Malkapur et al., 2015)
CC	Am-Be	4	0.104	Granite	1363.9	(Malkapur et al., 2017)
NC	Am-Be	0.025	0.133	Natural	1746	(Demir et al., 2020)
PC00	Am-Be		0.13954	Limestone	1812.5	(Gencel et al., 2011)
BC	Am-Be	0.025	0.15	Barite	2673	(Demir et al., 2020)
B100	Am-Be	4.5	-	Barite		(Korkut et al., 2010)
M	Pu-Be		0.0996	Magnetite	2078	(Zalegowski et al., 2020)
B85C15	Am-Be	4.5	-	Barite (85-95 %) +Colemanite (5-10 %)		(Korkut et al., 2010)
N85C15	Am-Be	4.5	-	Natural (85-95 %) + Colemanite (5-15 %)		(Korkut et al., 2010)
FCL	Am-Be	4.5	0.148	Limonite	2369.28	(Oto, Yildiz, Korkut, et al., 2015)
HC50	Am-Be	-	0.14112	Limestone+Hematite	1254.7	(Gencel et al., 2011)
Peridotite Concrete	Am-Be	-	0.1445	Peridotite	1703	(Wang et al., 2014)
A	Pu-Be	4	0.0922	Serpentine	1556.1	(Masoud, Kansouh, et al., 2020)
ABC	Pu-Be	0.8-11	0.0702 - 0.0922	Serpentine	1856.1	(Masoud, El-Khayatt, et al., 2020)
AB 25, AB50	Pu-Be	4	0.1226 - 0.1484	Serpentine +Barite (25 – 50 %)	1538.61	(Masoud, Kansouh, et al., 2020)
AH25, AH50	Pu-Be	4	0.1105 - 0.1398	Serpentine +Hematite (25 – 50 %)	1429.05	(Masoud, Kansouh, et al., 2020)
SC	Am-Be	0.025	0.1525	Siderite+Barite	2520	(Demir et al., 2020)
L1	Am-Be	4	0.069 - 0.09	Natural aggregate + SBR	1765.2	(Malkapur et al., 2015)
MP1-MP9	Am-Be	4	0.1077 - 0.1103	Granite + HDPE	1274.7	(Malkapur et al., 2017)
CFM	Reactor ET-RR-1	2 - 15	0.196	SBR + Magnetite + Boron Carbide		(El-Sayed Abdo et al., 2003)
MPCC1G1.0	Pu-Be		0.1034	Magnetite + acrylic + gadolinium	2078	(Zalegowski et al., 2020)

2.4.2 Effect of Aggregate on Macroscopic Removal Cross Section

Heavyweight aggregate provides heavy elements which caused inelastic collision with neutron. This collision precipitated energy and affects neutron shielding property. A study on magnetite cement composite indicates that heavyweight aggregate is not effective against fast neutrons as a lower number of thermal neutrons counted after passing through the magnetite composite sample compared to the granite composite sample (Piotrowski et al., 2015). However, heavyweight aggregate absorbed higher percentage of thermal neutron at 90% compared to granite sample at 70% absorption. This is also shown by another study that reported 16 – 20 % lower HVL of magnetite concrete compared to granite concrete (Zalegowski et al., 2020). However, the study credited the superior performance of magnetite compared to granite to better attenuation of fast neutrons by iron, Fe element in magnetite compared to silica, Si in granite.

The positive impact of heavyweight aggregate on neutron shielding is also shown by barite which recorded lower dose transmission of 0.862 compared to 0.864 recorded by natural aggregate concrete (Korkut et al., 2010). This reduction of neutron dose is also translated in terms of $\sum_R (E_n)$ which barite concrete recorded a higher value of 0.15 cm^{-1} compared to natural aggregate concrete at 0.13 cm^{-1} (Demir et al., 2020).

However, a study on the replacement of limestone with hematite revealed no significant impact of hematite presence on neutron shielding properties of concrete sample (Gencel et al., 2011). Concrete sample with 50 % hematite

replacing limestone aggregate recorded 0.14112 cm^{-1} of $\sum_R(E_n)$ value which is a marginal increase compared to 100 % limestone concrete at 0.13954 cm^{-1} . This may be due to the low amount of heavy element presence in hematite and also the low percentage of replacement. Overall, the presence of heavy elements in the aggregate caused precipitation of energy due to inelastic collision. However, the moderation of fast neutrons due to inelastic collision is not very effective which resulted in a slight gain in $\sum_R(E_n)$.

The presence of light elements such as hydrogen provides a cross-section for elastic collision with neutrons which contributes to the overall increment of $\sum_R(E_n)$. Colemanite is a type of mineral that contains hydrogen elements. Furthermore, its monoclinic crystal structure has a chemical formula of $2\text{CaO} \cdot 3\text{B}_2\text{O}_3 \cdot 5\text{H}_2\text{O}$ and also contains boron element which makes colemanite a prime source for the production of borax and boric acid (Içelli et al., 2011). The atom of boron element has a large cross-section which is beneficial for neutron absorption and interaction (Mesbahi et al., 2013).

Previous research includes colemanite in concrete's mix constituent by 0.25 – 15 % (Oto et al., 2013)(F. Demir et al., 2010). A study revealed that the replacement of natural aggregate and barite aggregate with colemanite in concrete by 15 % resulted in a reduction of neutron dose transmission by 1 % and 1.7 % respectively (F. Demir et al., 2010). Concrete with natural aggregate replaced by 15 % of colemanite recorded 0.855 of neutron dose transmission while concrete with barite aggregate replaced by 15 % of colemanite recorded lower neutron dose transmission at 0.846 (Korkut et al.,

2010). This indicates the positive effect of combining heavyweight aggregate and colemanite in concrete composition on its neutron shielding.

Serpentine also contain hydrogen elements as it is a hydrate aggregate that is able to retain crystallised water at temperatures of up to 500 °C (Kaplan, 1989). Serpentine is a metamorphic mineral with a chemical formula of $\text{Mg}_3\text{Si}_2\text{O}_5(\text{OH})_4$. Serpentine concrete recorded $\Sigma_R(E_n)$ of 0.0922 cm^{-1} at exposure of 4 MeV which contributed largely by chemically bound water in serpentine (Masoud, El-Khayatt, et al., 2020).

The combination of serpentine and heavyweight minerals as aggregate in concrete resulted in better neutron shielding. This is reported in a study on serpentine replacement with barite or hematite as an aggregate of concrete with exposure to Pu-Be (Masoud, Kansouh, et al., 2020). The study shows that the replacement of serpentine with 50 % of barite recorded the highest $\Sigma_R(E_n)$ in the study at 0.1484 cm^{-1} . This is higher compared to $\Sigma_R(E_n)$ value of 0.1398 cm^{-1} which is recorded by concrete with 50% hematite replacing serpentine. Both types of aggregate replacement showed a gain in $\Sigma_R(E_n)$ value by 51 – 61 % compared to the control sample of serpentine concrete. This is due to the inelastic collision between fast neutrons and heavy elements in barite or hematite that contributed to the numbers of moderated fast neutrons apart from the amount of neutrons being moderated by serpentine in the concrete sample.

Limonite is another type of hydrated aggregate with a chemical formula of $2\text{Fe}_2\text{O}_3.3\text{H}_2\text{O}$ (Miller, 2003). Replacement of normal aggregate with limonite

in concrete an increased effective macroscopic removal cross-section Σ_R (Oto, Yildiz, Korkut, et al., 2015). The Highest Σ_R -value of 0.148 cm^{-1} was recorded by 100 % replacement of natural aggregate with limonite. This is due to the highest partial density value of hydrogen in the limonite concrete sample which is contributed by crystallised water in limonite aggregate.

The incorporation of another type of aggregate containing crystallised water which is peridotite in concrete resulted in a higher neutron attenuation rate compared to ordinary concrete (Wang et al., 2014). Peridotite aggregate contained mostly MgO and SiO_2 but also contained 12.95 % of crystal water. Based on exposure to the Am-Be source, peridotite concrete recorded an Σ_R value of 0.1445 cm^{-1} which is almost 50 % higher compared to ordinary concrete at 0.0671 cm^{-1} . The presence of crystal water in peridotite concrete provides hydrogen element with a high cross-section hence resulting in an increase of removal cross-section value.

2.4.3 Effect of Neutron Absorbing Element on Macroscopic Removal Cross Section

Neutron-absorbing elements such as hydrogen and boron are integral in producing neutron shielding concrete. Other materials with hydrogen elements besides minerals such as styrene-butadiene (SBR) and high-density polyethylene (HDPE) have also been studied as aggregate in concrete. SBR is a latex polymer that can act as a binder and mould it into various shapes. It has been used to form shielding material by adding lead oxide or lead ore minerals into the elastomer matrix (Abdel-Aziz & Gwaily, 1997)(Gwaily, 2002). Recent research used SBR as cement replacement by 10 – 20 % to increase

the amount of hydrogen in the concrete (El-Sayed Abdo et al., 2003)(Malkapur et al., 2015). Concrete with 15 % SBR replacing cement recorded the highest $\Sigma_R(E_n)$ value of 0.09 cm^{-1} (Malkapur et al., 2015). This is based on exposure of Am-Be source at 4 MeV energy level.

In terms of dose transmission value, an increase in hydrogen loading due to SBR replacing cement reduces the dose transmission value by 5.3 % on average. This improvement in neutron shielding is due to the increased presence of hydrogen presence from SBR in the concrete sample. Collision between fast neutron and hydrogen resulted in a scattering reaction hence reducing the transmission value (Malkapur et al., 2015).

In the utilisation of HDPE as concrete's additive, a sample of concrete containing HDPE and natural aggregate recorded around $0.108 - 0.11 \text{ cm}^{-1}$ of $\Sigma_R(E_n)$ which is higher compared to concrete with SBR (Malkapur et al., 2017). This is due to the amount of hydrogen loading in the HDPE concrete mix is higher by 217 % compared to the SBR concrete mix (Malkapur et al., 2017). In comparison to a control sample, the replacement of fine aggregate with HDPE by 50.4% increased to $\Sigma_R(E_n)$ value by 5.7 % while 15 % of cement replacement with SBR resulted in a 20 % increment in $\Sigma_R(E_n)$ value.

Another study reported an increase in $\Sigma_R(E_n)$ value with the addition of acrylic and gadolinium into the concrete composition (Zalegowski et al., 2020). Acrylic is a polymer dispersion which is rich in hydrogen while gadolinium has the highest thermal neutrons capture cross-section. The addition of acrylic by 10% and gadolinium by 1% of cement mass in the concrete mix resulted in 5.99 cm

of measured HVL and 0.1034 cm^{-1} of calculated $\Sigma_R(E_n)$ (Zalegowski et al., 2020).

2.4.4 Boron on Macroscopic Removal Cross Section

Besides being incorporated into concrete via colemanite, boron element is also included in concrete through infusion with heavyweight ores or as an additive through material with boron element. In a study using barite as heavyweight fibre in normal concrete, boron oxide is infused with the barite fibre to improve neutron shielding of the concrete (Skarżyński, 2020). Infused barite fibre that contains 12% B_2O_3 is added to the concrete composition at 5kg per cubic meter. Exposure to Pu-Be neutron source revealed an increase of 25 % in neutron shielding for a sample thickness of 10 cm with a current transmission rate of 0.48. This increment in shielding is based on a comparison to normal concrete without barite-infused fibre which recorded a higher current transmission rate of 0.62.

Boron wastes were also studied as an additive in concrete through the usage of borogypsum and colemanite wastes (Ozturk et al., 2020). These boron wastes are by-products from the production of boric acid and borates. Borogypsum and colemanite wastes contained 1.05 - 4.2 and 6.3 – 33.99 % of B_2O_3 respectively. A study using borogypsum and colemanite waste as additives in concrete indicates an increase in the shielding of electromagnetic waves and photon rays (Ozturk et al., 2020)(D. Demir & Keleş, 2006). Another type of boron source, boron carbide also shows improvement in neutron shielding with its presence. At 11.43 % addition of boron carbide of overall

magnetite concrete weight resulted in a 20 % increase of Σ_R of fast neutrons which is 0.128 cm^{-1} (El-Sayed Abdo et al., 2003). In terms of slow neutrons cross-section, magnetite concrete with boron carbide recorded 0.196 cm^{-1} which is a 35 % increment compared to normal concrete. These values of neutron shielding are measured in the study using research reactor ET-RR-1. Boron carbide is a ceramic material used as an additive in nuclear protective material and a good slow neutron absorber as it contains ^{10}B atom. ^{10}B has a high cross section to capture thermal neutron which is 3837 Barns (Sarıyer et al., 2015)(Huang et al., 2013).

Overall, a combination of heavyweight aggregates, neutron moderator and neutron absorber resulted in higher neutron shielding efficiency as indicated by $\Sigma_R(E_n)$ value. This is due to the collision of fast neutron particles in the radiation with heavyweight elements in the aggregate through inelastic collision that moderates the particles into thermal neutrons. Furthermore, neutron moderators such as hydrogen that possessed high removal cross-section moderates fast neutron through elastic collision. The moderated neutrons are absorbed by neutron-absorbing elements such as boron which results in attenuation of neutron radiation. Adopting these elements in concrete's composition is beneficial towards its radiation shielding property yet these combinations also affect its mechanical strength and durability.

2.5 Safety Guidelines on Radiation Protection

The performance of radiation shielding concrete is usually measured in linear attenuation coefficient and macroscopic removal cross-section for gamma-ray

and neutron radiation respectively. However, authority in radiation protection regulation regulates the protection procedure based on the dose limit. The International Atomic Energy Agency (IAEA) specify that occupational exposure to dose shall be limited to 20 mSv per year averaged for five consecutive years (IAEA, 2014). This is adopted by the Department of Atomic Energy Malaysia in its requirements for licensing under ACT 304 (AKTA PERLESENAN TENAGA ATOM, 1984). The value is recommended by the International Commission on Radiological Protection (ICRP) based on Publication 103 (Tsapaki et al., 2021).

Based on the recommendation, the dose limit is the maximum value of an effective dose that should not be exceeded. While effective dose depends on the type of tissue or organ absorbing the dose of radiation in unit Sievert, Sv. As the type of tissue would be different according to types of work being carried out using radioactive sources, the absorbed dose remains the same as it is based on the source of radiation.

The absorbed dose depends on the mean energy imparted by the ionising radiation source. The energy relies on the type of source and its activity. A typical activity concentrations of Uranium-238 are 1500 Bq kg⁻¹ (Abbady et al., 2005). The higher energy of the radiation source would lead to a higher absorbed dose. This can be reduced by using shielding material that could absorb part or the entirety of the energy imparted by the source. The use of μ and $\sum_R (E_n)$ determine the HVL and TVL of shielding material which indicates the thickness required to shield half of the energy or the entire energy of the

radiation respectively. This allows efficient estimation of shielding thickness required according to the demand of the facility.

2.6 Mechanical Strengths

The practicality of concrete as a structural member is defined by its mechanical strengths which include compressive, tensile and flexural strength. Alteration of concrete's composition to improve its radiation shielding properties affects these strengths. Table 2.5 lists the radiation shielding concretes with compressive strength of less than 50 MPa from previous studies. The value of linear attenuation coefficient, μ listed in the tables is based on exposure to 0.662 MeV of photon radiation. Concrete with natural sand and limonite with a high percentage of steel slag recorded the highest compressive strength in the list at 49 MPa (El-Samrah et al., 2018). Barite and magnetite concrete recorded lower compressive strength yet higher gamma radiation shielding.

This is also indicated by a study that indicates a lower μ value but higher compressive strength of limestone concrete compared to concrete with 50 % barite replacing limestone as aggregate (Çullu & Ertaş, 2016).

Table 2.5 : List of radiation shielding concrete with compressive strength less than 50 Mpa

Sample	Densi	Compress	μ	Aggregat	Ref
50B50L	3270	33.1	0.211	Barite	(Çullu & Ertaş, 2016)
100B	3610	32.95	0.236	Barite	(Cullu & Ertas. 2016)
BC	3441	49	0.265	Barite	(Horszczaruk & Brzozowski,
CB-FA-	3230	32	0.175	Barite	(H. Liu et al., 2019)
CB-0	3410	35	0.185	Barite	(H. Liu et al., 2019)
B.L	2963	38	0.091	Barite	(El-Samrah et al., 2018)
G.L	2906	41	0.082	Geothite	(El-Samrah et al., 2018)
IO100	3029	40	0.16	Iron ore	(Azeez et al., 2019)
BW6	3740	44.1	0.197	Magnetite	(Nikbin et al., 2019)
			9	+ Bi ₂ O ₃ (3	
M-4	2620	34.1	0.194	Magnetite	(LIU et al., 2019)
O	3708	40.7	0.185	Magnetite	(Nikbin et al., 2019)
100MW	3040	43.84	0.196	Mine	(Cullu & Ertas, 2016)
LSA10	2435	42	0.12	Natural	(Azeez et al., 2019)
100LS	2990	37.7	0.184	Natural	(Cullu & Ertas, 2016)
s4	3687	41	0.221	Natural	(Lotfi-Omran et al., 2019)
G0C0	2296	35.7	0.245	Natural	(Rasoul Abdar Esfahani et
G60C1	2845	32.4	0.333	Slag	(Rasoul Abdar Esfahani et
7		46.5	0.201	Slag	(Yadollahi et al., 2016a)
S.L	2994	49	0.083	Slag	(El-Samrah et al., 2018)
SA100	2790	45	0.14	Slag	(Azeez et al., 2019)
SS100	3563	30	0.2	Steel shot	(Azeez et al., 2019)

Table 2.6 lists radiation-shielding concrete with records of compressive strength above 50 MPa. The highest compressive strength recorded in the list is 218 MPa which is a natural aggregate concrete with μ value of 0.202 cm⁻¹ (Gökçe et al., 2018). This type of concrete having compressive strength above 180 MPa is considered ultra-high performance concrete (UHPC) (Uchida et al., 2006; Voo, 2010). High compressive strength is achieved by using a very low water-to-cement ratio of less than 0.2 to reduce free water in concrete paste resulting in fewer pores of hardened concrete (Rashid et al., 2020)(Gökçe et al., 2018)(Rossi, 2000)(Kolias & Georgiou, 2005).

Replacement of natural aggregate with barite in UHPC concrete resulted in a 12.8 - 21.1 % reduction of compressive strength (Gökçe et al., 2018)(Azreen et al., 2020). This is due to the lack of enhancement on the interfacial transition zone between barite and cement paste and the disintegration of barite during the mixing process (Gökçe et al., 2018)(González-Ortega et al., 2015).

The use of magnetite in UHPC also recorded a reduction of 12.9 % in compressive strength compared to natural aggregate (Rashid et al., 2020). However, at the coarser size of magnetite aggregate, a lower reduction of 6.7 % in compressive strength is recorded compared to natural aggregate (Horszczaruk & Brzozowski, 2019). However, UHPC is mostly made up of fine-sized aggregate which allows for more compact packing of its composition that results in higher mechanical strengths (Uchida et al., 2006). Goethite concrete recorded higher compressive strength compared to barite concrete but lower than natural aggregate concrete. At similar concrete density, goethite concrete recorded 41 MPa of compressive strength which is 3 MPa higher than barite concrete but 10 MPa lower than natural aggregate concrete (El-Samrah et al., 2018). This research indicates that natural aggregate in radiation shielding concrete has higher compressive strength compared to concrete with heavyweight aggregate.

However, a study shows that the replacement of natural aggregate with hematite powder resulted in higher compressive by 6.3 % (Khan et al., 2020). This is achieved at 50 % replacement of dune sand with hematite powder and the sample reported 170 MPa of compressive strength. This is due to the very fine size of hematite powder which resulted in higher packing density and its

angular morphology increased the interlocking strength between components of the concrete (Khan et al., 2020). Overall, the resulting compressive strength of radiation shielding concrete relies on the interaction between components of its composition and their strength. The selection of a more robust aggregate with more angular morphology would enhance the compressive strength of radiation-shielding concrete.

Table 2.6 : List of radiation shielding concrete with compressive strength more than 50 Mpa

Sample	Density (kg/m ³)	w/c	Compressive Strength (Mpa)	μ (0.662 Mev)	Aggregate	Ref.
BC	3311.85	0.4	58.1	0.234	Barite	(Demir et al., 2020)
B-UHPC	3112	0.16	138	0.208	Barite	(Azreen et al., 2020)
B	2943	0.18	172	0.241	Barite	(Gökçe et al., 2018)
Q+B	2684	0.18	190	0.221	Barite	(Gökçe et al., 2018)
D.C	2570	0.43	51	0.0797	Dolomite	(El-Samrah et al., 2018)
H-UHPC	2602	0.19	149	0.165	Hematite	(Azreen et al., 2020)
HP-50	2900	0.17	170	0.022	Hematite + Silica	(Khan et al., 2020)
SC	3158.85	0.4	63.75	0.22	Siderite	(Demir et al., 2020)
M-U		0.16	134	0.197	Magnetite	(Rashid et al., 2020)
MC	3939	0.35	56	0.295	Magnetite	(Horszczaruk & Brzozowski, 2019)
70NCA	2398	0.23	87	0.1849	Natural	(Han et al., 2018)
s1	3871	0.4	62	0.228	Natural	(Lotfi-Omran et al., 2019)
M-0.35/CS0	2542	0.35	67.38	0.15914	Natural	(Ameri et al., 2020)
SS-UHPC	2401	0.16	165.7	0.155	Natural	(Azreen et al., 2018)
Q	2438	0.18	218	0.202	Natural	(Gökçe et al., 2018)
SS-UHPC	2401	0.16	166	0.155	Natural	(Azreen et al., 2020)
HP-0	2500	0.14	160	0.0187	Natural	(Khan et al., 2020)

Table 2.6 : Continued

70RCA	2321	0.23	80	0.1743	Recycled aggregate	(Han et al., 2018)
40RCA	2289	0.37	50	0.1723	Recycled aggregate	(Han et al., 2018)
M-0.35/CS60/SF	2668	0.35	78.62	0.23771	Slag	(Ameri et al., 2020)
LG-UHPC	2479	0.17	170.1	0.175	Lead glass	(Azreen et al., 2018)
A-UHPC	3036	0.16	157.5	0.182	Mine waste	(Azreen et al., 2018)

Colemanite replacement in ordinary concrete reported a reduction of compressive strength of 14.51 – 51.61%. The reduction is due to the replacement of natural aggregate at 10 – 50 % by volume with colemanite (Gencel et al., 2010). The highest compressive strength of concrete with colemanite recorded is 50 MPa at 10 % replacement of aggregate. This is also exhibited by barite concrete with colemanite replacement which showed 33.33 and 46.67% reduction in compressive strength due to 5 and 10% replacement respectively (Mesbahi et al., 2013). The adverse effect of colemanite presence on compressive strength of concrete is due to a reaction between cement paste and colemanite which resulted in melting and flocculation. This flocculation leads to the formation of deep and wide cracks at the interfacial zone between colemanite and cement paste hence weak adhesion and low overall compressive strength (Gencel et al., 2010).

This weakness at the interfacial transition zone is also reported for goethite and serpentine concrete which leads to a reduction of the compressive strength of the sample. The use of goethite as coarse aggregate resulted in a compressive strength of 39 – 42 MPa which is about 38 % lower compared to

magnetite concrete (Ouda, 2015). For concrete with serpentine aggregate, compressive strength is even lower at around 32 MPa. Researchers noted that serpentine and goethite coarse aggregate has high water absorption rate which caused internal bleeding at the aggregate surface. This led to the formation of a porous interfacial transition zone hence weakening the bond between aggregate and concrete matrix (Ouda, 2015).

Waste as aggregate in concrete has a varied impact on the compressive strength which depends on the physical and mechanical properties of the waste. The total replacement of fine barite aggregate with a cathode ray tube resulted in a 29 % of reduction in compressive strength (H. Liu et al., 2019). This is also shown in a study replacing magnetite sand with cathode ray tubes up to 60 % (LIU et al., 2019). Although the replacement resulted in a higher μ value, compressive strength was reduced by 12.6 % with 60 % replacement. This may be due to the smooth surface of the tube which provides less traction and adhesion with binder and other aggregates (Ling et al., 2012). Furthermore, the tube is weaker in terms of mechanical strength compared to heavyweight concrete and there is lead leaching from the tube which adversely affects cement hydration hence resulting in lower compressive strength (H. Liu et al., 2019).

A study on replacing 80% of limestone with steel shot as aggregate in concrete recorded a 38.1 % reduction in compressive strength (Azeez et al., 2019). The adverse effect shown due to the replacement of aggregate indicates the steel shot's poor strength and is also proven by another study that replaces steel shot with an electric arc furnace as aggregate in radiation shielding concrete

(Maslehuddin et al., 2013). Result of compressive strength indicates an increase of 22.5 % in compressive strength with 50 % replacement of steel shot with electric arc furnace slag which indicates weaker strength of steel shot compared to the slag. Hence, the incorporation of waste with high strength in concrete composition contributes to its overall strength.

Another type of high-quality waste is copper slag a study conducted on replacing natural aggregate with copper slag in concrete reported an increment in the compressive strength of the concrete sample. Replacement of washed river sand with copper slag at 60 % resulted in a 13.9% gain in compressive strength (Ameri et al., 2020). This is due to the angular form of copper slag particles which enhanced adhesion with binder and other aggregates. This influence of particle angularity was also shown by another study using a spherical form of copper slag which resulted in lower compressive strength of concrete compared to natural aggregate concrete (Rasoul Abdar Esfahani et al., 2021).

The addition of hydrogen elements such as SBR and HDPE in concrete composition has no significant impact on compressive strength. An increasing percentage of SBR-to-cement resulted in varied compressive from 26 – 34 MPa (Malkapur et al., 2015). The variation of compressive strength is also affected by a water-to-cement ratio that is also varied for individual samples. A sample with a 10% SBR-to-cement ratio and 0.35 water-to-cement ratio recorded the highest compressive strength at around 34 MPa which is an almost similar value to the sample with no SBR at 0.4 ratio of water-to-cement. For concrete with HDPE replacing sand as fine aggregate, the highest

compressive strength is recorded by concrete with 30.9 % sand replacement which is 31.2 MPa (Malkapur et al., 2017). This value is only 8 % lower than a sample containing natural aggregate only.

Overall, the influence of aggregate on the compressive strength of concrete is determined by its inertness, shape, surface condition and strength (Akçaoğlu, 2017). Aggregate that is not inert and susceptible to chemical reaction, especially with cement would affect the overall matrix of hardened concrete. Besides that, the shape and surface condition of aggregate affects the interlocking friction between aggregates and also the strength of the interfacial transition zone between aggregate and cement paste. Lastly, the strength of aggregate contributes to the overall strength by resisting the deformation of the concrete matrix. Table 2.7 shows a list of radiation-shielding concrete with linear attenuation coefficients and splitting tensile strength values. The value of the attenuation coefficient shown in the table is based on irradiation of 0.662 MeV energy level. The highest splitting tensile strength was recorded at 8 MPa while the lowest value was 2.6 MPa. Mostly, radiation shielding concrete attained a splitting tensile strength between 3 – 5 MPa. A study on the effect of aggregate size on magnetite concrete recorded a maximum splitting tensile strength of 5.06 MPa with a maximum aggregate size of 12.5 mm (Lotfi-Omran et al., 2020). The study indicates that an increase in aggregate size resulted in lower tensile strength of concrete due to an increase in porosity and weakened interfacial transition zone. Using micro-size barite as aggregate also resulted in a reduction of splitting tensile strength. A study on barite powder replacing sand as fine aggregate shows a 53% reduction of tensile

strength due to a 50% replacement of sand with barite powder (Saidani et al., 2015). This is explained by the friability of barite and weaker interfacial transition zone due to the powder form of barite.

Table 2.7 : List of radiation shielding concrete with tensile strength value

Name	Steel fibre (%)	LAC (cm ⁻¹)	Aggregate	Tensile strength (MPa)	Ref.
s1	0	0.228	Natural	4.82	(Lotfi-Omran et
M-	0	0.159	Natural	3.79	(Ameri et al.,
CB-0	0	0.185	Barite	3.6	(H. Liu et al.,
CB-CA-10	0	0.183	Barite + CRT 10 %	3.375	(H. Liu et al., 2019)
D12.5W0.4	0	0.211	Magnetite	5.06	(Lotfi-Omran et
G30C0	0	0.254	Natural + GGBS	4.93	(Rasoul Abdar Esfahani et al.,
G0C100	0	0.32	Copper slag	4.18	(Rasoul Abdar
G30C100	0	0.328	Copper slag +	3.9	(Rasoul Abdar
M- 0.35/CS60/ SF	1	0.2377	Natural + Copper slag (60 %)	5.79	(Ameri et al., 2020)
M- 0.40/CS60/ SF	1	0.2296	Natural + Copper slag (60 %)	5.46	(Ameri et al., 2020)
A-UHPC	1.5	0.182	Amang	7	(Azreen et al.,
LG-UHPC	1.5	0.175	Lead Glass	6.9	(Azreen et al.,
H-UHPC	1.5	0.165	Hematite	6.28	(Azreen et al.,
B-UHPC	1.5	0.208	Barite	6.12	(Azreen et al.,
SS-UHPC	1.5	0.155	Silica sand	8	(Azreen et al.,

Based on Table 2.7, samples with splitting tensile strength that is higher than 5 MPa would contain steel fibre of at least 1 % of concrete volume. A study on concrete with natural aggregate and copper slag indicates that addition of 1 % by volume of steel fibre resulted in 22.9 % increment in splitting tensile strength (Ameri et al., 2020). The study also noted that increase in copper slag content by 60 % resulted in 25% increment in splitting tensile strength which indicates its superiority over natural sand. Increase in percentage to 1.5 % by volume of steel fibre resulted in higher splitting tensile strength of 8 MPa for concrete with natural aggregate (Azreen et al., 2020). Based on the same study,

hematite and barite concrete recorded lower splitting tensile strength of 6.28 and 6.12 MPa respectively. Another study using waste in UHPC which are among and lead glass reported splitting tensile strength of 7 and 6.9 MPa respectively which are also lower compared to silica sand UHPC (Azreen et al., 2018). However, this is higher compared to other samples with no steel fibre as listed in Table 2.7.

The effect of steel fibre in improving tensile property of concrete is reflected in the flexural performance. Table 2.8 shows radiation shielding concrete's flexural value and μ value based on 0.662 MeV energy level. Radiation shielding concrete recorded up to 40 MPa of flexural strength with incorporation 143.3 kg/m³ or 2 % by volume of steel fibre in the concrete (Gökçe et al., 2018). Superior tensile and flexural property of concrete containing steel fibre is due to bridging of cracks by steel fibre that leads to restriction in deformation and overall higher tensile and flexural strength (B. Li et al., 2018)(Lu et al., 2018).

Table 2.8 : List of radiation shielding concrete with flexural strength value

Name	Steel fibre (%)	LAC (cm ⁻¹)	Aggregate	Flexural strength (MPa)	Ref.
M-0.35/CS60/SF	1	0.2377	Natural + Copper slag (60 %)	8.27	(Ameri et al., 2020)
M-0.40/CS60/SF	1	0.2296	Natural + Copper slag (60 %)	7.65	(Ameri et al., 2020)
A-UHPC	1.5	0.182	Amang	28.8	(Azreen et al., 2018)
LG-UHPC	1.5	0.175	Lead Glass	28.3	(Azreen et al., 2018)
H-UHPC	1.5	0.165	Hematite	30	(Azreen et al., 2020)
B-UHPC	1.5	0.208	Barite	38.7	(Azreen et al., 2020)
SS-UHPC	1.5	0.155	Silica sand	30.7	(Azreen et al., 2018)
Q	2	0.202	Quartz	40	(Gökçe et al., 2018)
B	2	0.241	Barite	25.5	(Gökçe et al., 2018)
HP-0	1.9	0.187	Dune sand	20.5	(Khan et al., 2020)
HP-50	1.9	0.22	Natural + Hematite (50 %)	24.5	(Khan et al., 2020)

Replacement of natural aggregate with waste or heavyweight aggregate resulted in various effect on flexural performance of concrete. A study on replacing 50 % of dune sand with hematite reported 4 MPa gain of flexural strength while another study with 100 % hematite as aggregate reported reduction of 0.7 MPa in strength compared to silica sand concrete (Khan et al., 2020)(Azreen et al., 2020). For barite, replacement of quartz with barite as aggregate in concrete resulted in reduction of flexural strength up to 36 % at 100 % replacement (Gökçe et al., 2018). However, another study producing barite concrete reported a flexural strength of 8 MPa higher compared to silica sand concrete (Azreen et al., 2020). This is due to varied morphology and

robustness of heavyweight aggregate used in these studies which resulted in varied trend of changes in flexural performance. The study that indicates increase in flexural strength due to hematite replacement credited the significant gain to fine size and angular morphology of the heavyweight aggregate (Khan et al., 2020). This resulted in increase in compactness and improved interlocking among compositions of concrete matrix. For study that indicates loss in flexural strength due to barite replacement, the drop in flexural performance is due to the lack of robustness of barite compared to quartz which contributed less in resisting the flexural deformation (Gökçe et al., 2018).

Overall, the mechanical properties of radiation shielding concrete is influenced by the material comprising the concrete matrix which is also affected by the amount of water used for the binder. Having superior mechanical properties in radiation shielding concrete will increase its durability against various possible threat on nuclear related structure. Improvement in strength leads to improvement in security of nuclear structure and boosting public confidence on wide application of nuclear energy in daily lives.

2.7 Durability

The durability of nuclear-related structures is crucial to ensure its long life span of operation. The nuclear power plant is expected to operate within 60 years of design life and continue to operate beyond this span life (C et al., 2013). Furthermore, dry cask storage is expected to securely store spent fuel core throughout its entire lifetime. However, environmental effects on these

structures caused degradation of concrete hence reducing its span life (Attar et al., 2016). Besides that, external forces such as earthquakes, tsunamis and projectile impacts may compromise the structures' integrity which leads to radiation contamination such as in the Fukushima Nuclear Power Plant. Thus, it is essential to increase the durability of concrete, particularly in nuclear-related structures, to guarantee both the surrounding area's safety and that of the surrounding material.. Research on the durability of radiation shielding concrete involves its durability against elevated temperature, freeze-thaw cycle and chemical reactions.

2.7.1 Elevated Temperature

Studying the behaviour of radiation shielding concrete at elevated temperatures provide indications of its durability. Concrete structures of primary containment in nuclear-ionising facilities or in the secondary containment of nuclear power generation are always exposed to elevated temperatures. Thenuclear reactor of boiling water reactor type typically operates at 287°C – 304°C and increasing the operating temperature would increase the thermal efficiency of the reactor in power generation (Hendrie, 1983). Hence, this indicates the need for radiation-shielding concrete with high thermal resistance.

Table 2.6 shows the relationship between μ value exposed to 0.662 MeV of gamma-ray and temperature based on previous studies. In general, an increase in temperature beyond 100°C resulted in a reduction of the linear attenuation coefficient of concrete, μ . Barite concrete recorded a 12.5 and 6.4

% reduction in μ value after being exposed to 450°C and 800°C respectively (El-Samrah et al., 2018)(Horszczaruk & Brzozowski, 2019). In magnetite concrete, the reduction is minimal at 0.8 and 3.7 % after exposure to 600°C and 800°C respectively (Nikbin et al., 2020)(Horszczaruk & Brzozowski, 2019).

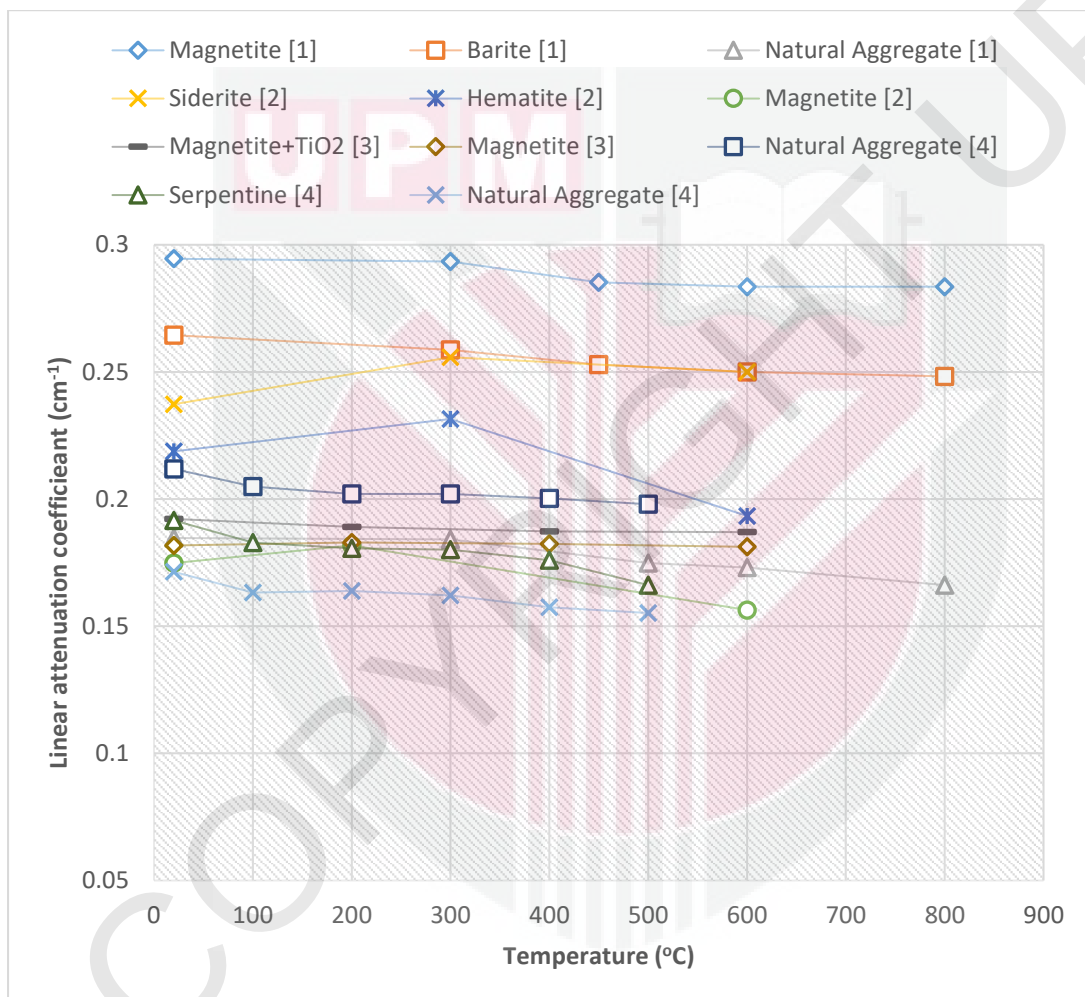


Figure 2.6 : Relationship between linear attenuation coefficient (cm^{-1}) and temperature ($^{\circ}\text{C}$) of different types of concrete

(Source : Horszczaruk & Brzozowski¹, Demir et al. ², 2020; Nikbin et al., 2020³; El-Samrah et al., 2018⁴)

Larger reduction reported by barite concrete compared to magnetite concrete may be due to expansion of barite aggregate which leads to cracking and

spalling of concrete sample (Horszczaruk & Brzozowski, 2019)(Tung-Chai & Chi-Sun, 2013). Comparison in terms of the coefficient of thermal expansion indicates that barite has almost 3 times the value of natural aggregate and more than 1.5 times the value of magnetite (Tung-Chai & Chi-Sun, 2013)(Witte & Backstrom, 1954)(Horszczaruk & Brzozowski, 2019). Expansion of barite created cracks which resulted in loss of μ value (Tung-Chai & Chi-Sun, 2013). For hematite concrete, exposure to 500 °C resulted in a reduction of μ value by 6.6 % to 0.198 cm⁻¹ (Yousef et al., 2008). This is the lowest reduction as compared to serpentine and dolomite concrete which reported 9.4 and 13.1 % respectively after exposure to 500°C. Serpentine and dolomite concrete reported residual μ values of 0.155 and 0.166 cm⁻¹ respectively. The high reduction in μ value of dolomite concrete could be attributed to the combustion of organic compounds inside it and the evaporation of water at a temperature of 100 – 600°C (Yousef et al., 2008). For serpentine concrete, the reduction in μ value is due to the loss of bonded water at a temperature of 500°C as serpentine is a type of hydrated aggregate (Kaplan, 1989). Another type of hydrated aggregate which is goethite also reported a loss of water that led to a reduction of μ value at elevated temperature. Goethite concrete recorded a 15.6 % reduction in μ value after exposure to 450 °C which is also the lowest residual μ value compared to serpentine and dolomite concrete (El-Samrah et al., 2018). This is due to de-hydroxylation and transformation of goethite which is indicated by the largest weight loss of 11.25 % after exposure to 450°C (El-Samrah et al., 2018).

Natural aggregate in concrete recorded a loss of 10.3 % in μ value which is due to the crystalline transition of quartz that leads to loss of density hence reduction in attenuation property (Horszczaruk & Brzozowski, 2019). This is also shown by a large reduction of μ value in a sample containing a combination of fine-sized natural aggregate and coarse barite compared to pure barite concrete (El-Samrah et al., 2018)(Horszczaruk & Brzozowski, 2019).

In the study of using nano-titanium as an additive, a study using 6% nano-titanium replacing cement magnetite concrete reported a 2.5 % reduction in μ value compared to 0.8 % recorded by the control sample after an exposure of 600 °C (Nikbin et al., 2020). However, the study showed that an increase in the percentage of nano-titanium resulting an increased residual μ value. This is due to the non-porous structure of the concrete matrix due to the presence of nano-titanium and the ability of nano-titanium to withstand high temperatures.

Few studies reported an increment in μ value with increasing temperature exposure. At 300°C, concrete samples recorded an increment at 3.4 – 8.0 % of μ value with heavyweight aggregate recording the largest increment compared to natural aggregate (Demir et al., 2020). This is also shown in the sample with coarse barite and fine natural aggregate exposed to 100°C which showed a 1.9 % increase in μ value. This may be due to the desiccation of capillary water and expansion of aggregates during the heating regime which promotes compactness (Demir et al., 2020)(Liang et al., 2018).

In contrast to normal strength concrete, UHPC reported huge losses of μ value due to elevated temperature. UHPC with magnetite aggregate recorded a reduction of 44.2% in μ value while UHPC with a natural aggregate reported a lower percentage of loss at 43.2% of μ value (Rashid et al., 2020). This large percentage of loss in μ value as compared to lower strength concrete may be due to dense packing of UHPC matrix that induced micro cracks hence loss in attenuating ability (Y. Li et al., 2019)(Liang et al., 2018). Furthermore, additional cracks due to expansion of steel fibre and pores left by vaporised polyvinyl alcohol fibre in UHPC may also contributed to the huge loss of μ value in UHPC (J. C. Liu & Tan, 2018).

In terms of neutron attenuation, a maximum loss of 30% on $\sum_R(E_n)$ value is recorded by the concrete sample with coarse barite aggregate exposed to 600°C (Demir et al., 2020). Lowest $\sum_R(E_n)$ reduction is recorded by the sample with natural aggregate which is 21% and this is followed by a sample with siderite aggregate at 27.5% (Demir et al., 2020). The study also reported large losses in neutron attenuation as compared to gamma-ray attenuation of similar samples and temperature exposure. This is due to the depleted hydrogen element in concrete as this element contributes largely to slowing down and absorption of free neutrons (Hiremath & Yaragal, 2018)(Algourdin et al., 2020)(Demir et al., 2020). During heating, high temperature desiccates pore water and results in the removal of chemically bound water from hydration products that contribute to the amount of hydrogen elements in the concrete composition (Gökçe, 2019)(Luo et al., 2000). Depletion of this element in concrete leads to a reduction of its neutron attenuation property.

Reduction of $\sum_R(E_n)$ value due to loss of hydrogen element is also reported in serpentine and goethite concrete. Concrete with goethite as coarse aggregate which recorded the largest percentage of weight loss due to heat in the study reported a 35.3% reduction in $\sum_R(E_n)$ the value after exposure to 450°C (El-Samrah et al., 2018). The lowest reported residual $\sum_R(E_n)$ value in the study is 0.0717cm⁻¹ which is due to the loss of hydrogen nuclei in goethite due to the evaporation of water and goethite transformation to ferric oxide. Serpentine concrete which recorded about 15% loss of weight at exposure above 500°C reported a 0.07cm⁻¹ of residual $\sum_R(E_n)$ value based on exposure of the same temperature (Yousef et al., 2008). This is a 26% loss of $\sum_R(E_n)$ value based on exposure to the Am-Be source.

High-temperature exposure towards radiation shielding concrete not only reduces its shielding property but also its mechanical properties (Figure 2.7). Exposure to 800°C caused 79.6 % and 84.8 % loss in compressive strength of barite concrete and natural aggregate concrete respectively (Horszczaruk & Brzozowski, 2019). The residual compressive strength of barite concrete and natural aggregate concrete after the heat exposure is 10 and 8 MPa respectively. Magnetite concrete recorded the highest residual compressive strength after exposure to 800°C which is 11MPa but the percentage of loss compared to original strength is the highest that is 80.4%. The results of residual compressive strength indicate the very low serviceability possessed by these concretes as structural members once exposed to temperatures beyond 800°C.

To have sufficient residual compressive strength after heat exposure, concrete needs to have higher original compressive strength. This is shown by goethite and barite concrete having low original strength of 38 – 42MPa ended up having low residual compressive strength of 17 – 19MPa after being exposed to only 400°C (El-Samrah et al., 2018). Hence, concrete with ultra-high strength such as UHPC would possess more practical residual strength after exposure to elevated temperature.

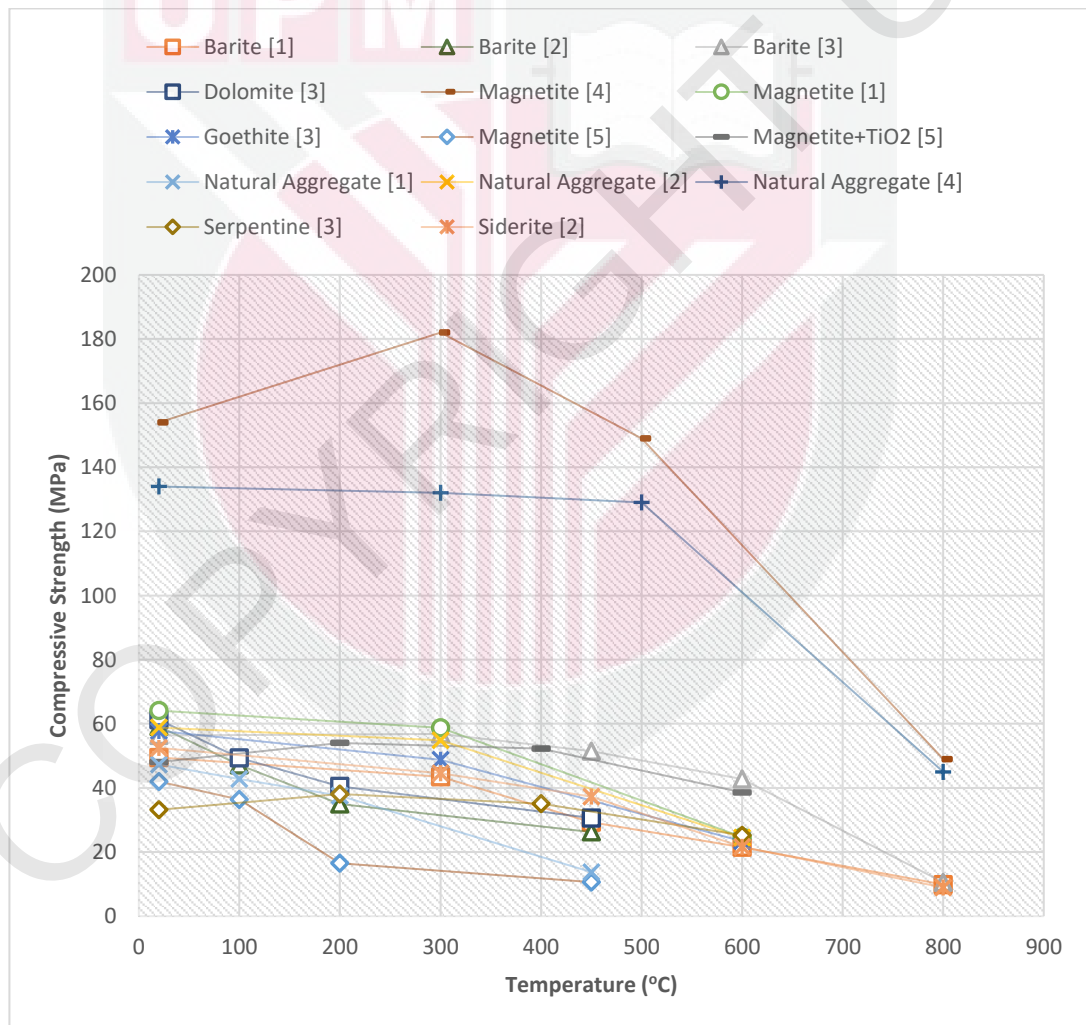


Figure 2.7 : Relationship between compressive strength (MPa) and temperature (°C) of different types of concrete

(Source : Horszczaruk & Brzozowski, 2019¹; Demir et al., 2020²; El-Samrah et al., 2018³; Rashid et al., 2020⁴; Nikbin et al., 2020⁵)

Research on UHPC reported natural and magnetite aggregate concrete having a practical residual compressive strength of 49 and 45 MPa respectively (Rashid et al., 2020). This is recorded after the samples are exposed to 800°C despite the loss of 66 – 68 % of compressive strength. Even though UHPC possess higher residual compressive strength after heat treatment, the loss in μ value is highest among the reviewed studies. Hence, further research towards producing higher residual compressive strength and radiation attenuation coefficient is required. Radiation shielding concrete should be able to withstand external threats as well as internal heat or combustion due to any mishap while containing the radiation from polluting the surroundings.

UHPC has been studied to outperform normal-strength concrete under impact and blast but suffers more spalling incidents at elevated temperatures (F. Zhang et al., 2016)(Máca et al., 2014)(Zhu et al., 2011)(D. Zhang, Zhang, et al., 2021)(D. Zhang & Tan, 2020). Furthermore, there is a dearth of research on UHPC's radiation attenuation ability. Future research in improving its performance in shielding radiation at higher temperatures may provide a superior alternative material for nuclear-related structures.

2.7.2 Freeze-thaw

The performance of radiation shielding concrete in terms of freeze-thaw resistance is evaluated based on its residual linear attenuation coefficient after being exposed to freeze-thaw cycles. A study using barite concrete indicates about 25 – 39 % reduction in μ value after 50 cycles of freeze-thaw (Basyigit

et al., 2006). The value of μ is based on exposure of barite concrete with 0.43 - 0.65 water-to-cement ratio to a Co-60 source of 1.25 MeV of average energy.

This is almost similar to natural aggregate concrete performance which reported a 25 - 43 % reduction of μ value at the same range of water-to-cement ratio. Based on the study, the highest residual μ value recorded after 50 cycles by natural aggregate concrete is 0.07 cm^{-1} while barite concrete recorded 0.1 cm^{-1} . It is revealed in the study that a higher ratio of water-to-cement could minimise the adverse effect of the freeze-thaw cycle on μ value. This is based on a lower reduction of μ value being observed in a sample with a higher water-to-cement ratio. The high ratio of water-to-cement in concrete reflects the amount of free water in the capillary and porosity of concrete. Freezing of concrete caused water in the pores to freeze and expand. The expansion of water creates internal hydraulic pressure which can be dissipated through nearest voids. If this pressure exceeds the tensile strength of the paste, cracks will appear from the point of failure (Shang et al., 2009).

Cracks appearance increases and expands for every freeze-thaw cycle which results in a reduction of shielding properties. Having higher porosity due to a high water-to-cement ratio in the sample could dissipate the expanding water and reduce the internal pressure. This would minimise the formation of cracks hence mitigating the reduction of shielding properties.

2.7.3 Chemical Resistance

Reports on radiation shielding concrete performance in resisting chemical attack is very few. A study on barite concrete reported a reduction in shielding properties due to immersion in sodium sulphate and sodium hydroxide (Akkurt et al., 2012). The study shows that barite concrete possessed about 17 % of the original μ value after being immersed in sodium hydroxide solution for 6 months. The value of μ is based on 662 keV of Cs-137 source which recorded 0.35 cm^{-1} . It is also revealed that sodium sulphate had a slightly larger adverse effect on the shielding properties of barite concrete. This is shown in the 28.6 % reduction in μ value to about 0.25 cm^{-1} . The study concludes that intrusive chemical media adversely affect radiation shielding concrete.

However, it is worth noting that concrete samples that were used in the study were produced with a 0.5 water-to-cement ratio. This high ratio resulted in more porous concrete and prone to chemical attack. Sulphate attacks on concrete cause expansion and higher permeability in concrete results in higher expansion (Khatri et al., 1997). The expansion is caused by the formation of gypsum at the interfacial transition zone which is a product of the reaction between external sulphate and calcium hydroxide in concrete (Wu et al., 2018). This leads to the formation of cracks originating from the interfacial transition zone which caused a reduction in shielding properties.

Another research investigating the effect of chemical exposure to radiation shielding concrete indicates 20.5 and 59.5 % of reduction on compressive and flexural strength of concrete mortar respectively due to immersion in sodium

sulphate for 90 days (Binici et al., 2015). The study also shows that eggshell replacing sand by up to 50 % resulted in a reduction of 51.8 and 10.5 % in compressive and flexural strength. This larger reduction observed in eggshell mortar is due to the susceptibility of eggshells to sulphate attack compared to sand which is also indicated by a sizeable mass loss of 25.7 % compared to 6.3 % recorded by sand mortar. In terms of μ value, 50 % of eggshells replacing sand in mortar was recorded at 3.66 cm^{-1} which is higher compared to sand mortar at 1.49 cm^{-1} . The μ value is measured based on exposure to 26 keV of Am-241.

Overall, the radiation shielding concrete could be susceptible to chemical attack should the material comprising the concrete's matrix is also prone to react with the deteriorating chemical. Furthermore, concrete with high porosity is also prone to chemical attack as the pores provide passage for the deteriorating chemical substances.

2.8 Simulation Work of Cask Storage Structure

Simulating the cask storage for storing nuclear waste is done using available shielding material and radioactive sources on computer-aided software. This helps estimate the suitability of the model as cask storage without conducting costly experiments. A study on serpentin cask for Ghana research reactor was done using Monte Carlo Neural Programming 5 with excess reactivity estimation based on fresh core operated at power levels of 30 kW (Abrefah et al., 2014). From the simulation, dose rates were measured at the cask surface in grey per hour. The study concluded that an increase in layers at the cask

wall would give the best results for neutron and gamma dose rate. Another study used WinXcom to simulate the gamma-ray shielding of concrete with four different types of aggregate which include dolomite, calcium magnesium carbonate, barite and ilmenite (El-samrah et al., 2022). The study found the large influence of Compton scattering on gamma-ray shielding depending on the type of concrete and spectrum of energy level. In terms of neutron shielding, simulation using OpenMC shows the large impact of strontium, Sr on improving neutron shielding of cask storage. The study concluded that 500 mm wall thickness made of barite or celestite concrete is needed to limit total dose rates to slightly above 0.20 – 4 mSv/hr. A study on cask storage for Korea Radioactive Waste Management Corporation also reported results on dose rate (Ko et al., 2014). The study used a fuel model of that emits gamma and neutron radiation that is simulated using Monte Carlo Neural Programming and SCALE 5.1 respectively. The simulation shows the peak dose rate at the lower part of cask storage which is 0.3207 mSv/hr. The study also highlights that the dose rate at 280 m distance from cask storages is 0.25 mSv/hr and the actual dose rate will be lower due to the decaying of nuclear waste. A study on UHPC replicates this dimension of cask storage using an aggregate of barite, hematite, sand and amang. A study found that a dry cask made of hematite UHPC with a dose rate of 1×10^{-4} Sievert per hour. Another simulation work using concrete containing magnetite and lead oxide reported an exposure rate of 1.73×10^{-53} mR/hr which is very low compared to ordinary concrete that recorded 1.3×10^{-53} mR/hr (Waly & Bourham, 2015). The study highlights that increase in concrete density leads to a lower exposure rate. Overall, the simulation of radiation

shielding for concrete produces data on dose rate and exposure rate. The comparison is made between the simulated result and the guideline provided by the IAEA and ICRP.

2.9 Empirical Equations on Radiation Shielding Thickness of Concrete

Few past research produce empirical equations to the required shielding thickness of concrete. The equations are developed based on the experimental data gathered from the study. A study on heavyweight concrete made of either steel slag, steel shot, iron ore or a combination of all proposes equation Eq. 2.9 which is based on regression analysis with $R^2 = 0.95$ (Azeez et al., 2019). This equation can be used to estimate the required thickness to shield 99 % of radiation of Caesium-137. Another study that developed an empirical equation used UHPC with hematite powder. The study proposed Eq. 2.10 has a high degree of fit with $R^2=0.97$. Overall, the proposed equations are based on experimental data and a trendline is developed to fit all the experimental data.

Hence, the proposed equations are accurate if the elements of the concrete and gamma ray source are similar to the experimental work. Furthermore, there is yet an equation proposed to estimate shielding thickness against neutron sources or high energy levels of gamma radiation.

$$t_c = \frac{8 \times 10^7}{W_c^{1.564}} \quad (\text{Eq. 2. 9})$$

$$t_c = \frac{8.39 \times 10^5}{W_c^{1.04}} \quad (\text{Eq. 2. 10})$$

where t_c is the optimum thickness of concrete required for 99% radiation shielding in mm and W_c is the unit weight of concrete in kg/m^3 .

2.10 Summary

In conclusion, nuclear radiation shielding of concrete involves shielding of highly penetrative gamma ray and neutron radiation. Sources for this radiation differ according to the type of radiation and their energy which requires different detectors and thicknesses to shield off the radiation. The development of concrete as radiation shielding involves alteration of its mix composition and inclusion of materials with heavy element and neutron moderators. This influenced the resulting mechanical properties of the concrete which affected its structural practicality and durability. Hence, UHPC which possesses higher strength and thermal resistance is viable to investigate as a radiation shielding material. Application of UHPC as radiation shielding material would produce a shield with superior mechanical and durability. There are recent research on utilising UHPC as radiation shielding but there is still a lack of investigation on neutron shielding and thermal resistance of UHPC. In a study of neutron shielding, colemanite is found to cause a degrading effect on the setting time of concrete and mechanical properties of concrete but it contains boron element which is effective in shielding neutrons. For thermal resistance, UHPC shows better thermal resistance based on superior residual strength compared to ordinary concrete yet it requires PVA fibre in the composition. Hence, it is important to study the effect of incorporating colemanite into UHPC on its mechanical properties

along with PVA fibre in producing UHPC with complete radiation shielding and thermal resistance.



CHAPTER 3

RESEARCH METHODOLOGY

3.1 Research Design

This research is a joint effort of two agencies which are the Malaysian Nuclear Agency and Dura Technologies Sdn Bhd along with Universiti Putra Malaysia.

Three types of UHPdC are being studied which are UHPdC with sand as main aggregate, UHPdC with barite as main aggregate and UHPdC with magnetite as main aggregate. The three types of UHPdC is based on the previous study of UHPC as radiation-shielding concrete (Azreen et al., 2018, 2020; Rashid et al., 2020). This study aimed to further improve the mixture with neutron shielding and thermal resistance with the incorporation of colemanite and PVA fibre. In total, there are three types of UHPdC which are sand UHPdC, barite UHPdC and magnetite UHPdC. These UHPdCs are investigated for replacement of the main aggregate with colemanite and the addition of PVA fibre into the composition. In objective 1, the three types of aggregate is replaced with colemanite to study the impact on compressive strength and radiation shielding properties. The optimum mixture of the three UHPdCs is then investigated for the effect of PVA fibre addition on the thermal behaviour of their compressive strength and radiation shielding properties. At the end of the research, three new mix compositions of sand UHPdC, barite UHPdC and magnetite UHPdC with optimum content of colemanite and PVA fibre are produced. A total of 24 mixtures are investigated to determine the optimum mixture of colemanite and PVA fibre. The addition of colemanite and PVA fibre

is aimed to improve neutron shielding and heat durability of UHPdC respectively.

This research work can be divided into 5 parts which begin with the characterisation of materials used in this work using X-ray Diffraction (XRD) analysis, X-ray Fluorescence (XRF) analysis and Scanning Electron Microscope (SEM). This is followed by objective 1 which is to study the effect of colemanite replacing main aggregate in UHPdC. Based on data from the flow table, compressive strength, gamma and neutron attenuation radiation, an optimum mixture of the three different types of UHPdC is selected to become a control sample in the following part which is objective 2. In Objective 2, the effect of PVA fibre addition is investigated for all types of UHPdC. Similar to the previous part, data from the flow table, compressive strength, and gamma and neutron radiation shielding are the parameters for determining the optimum mixture. Furthermore, samples are also heated to 800°C to study their durability hence defining the optimum mixture. The fourth part which is Objective 3 is the development on the UHPdC based on data provided from the previous objectives. In this part of the research, optimum mixtures are tested on additional parameters which are flexural strength, splitting tensile strength and overall response towards heat exposure of 400°C. The final part of the study is to verify the experimental data of radiation shielding with the computer simulation program of Particle and Heavy Ion Transport code System (PHITS). Furthermore, a mathematical equation is produced based on research data and previous works to estimate the attenuation coefficient of UHPdC based on mix design. The flow of research work is shown in Figure

3.1. A detailed research framework is given in Figure 3.2, Figure 3.3 and Figure 3.4.

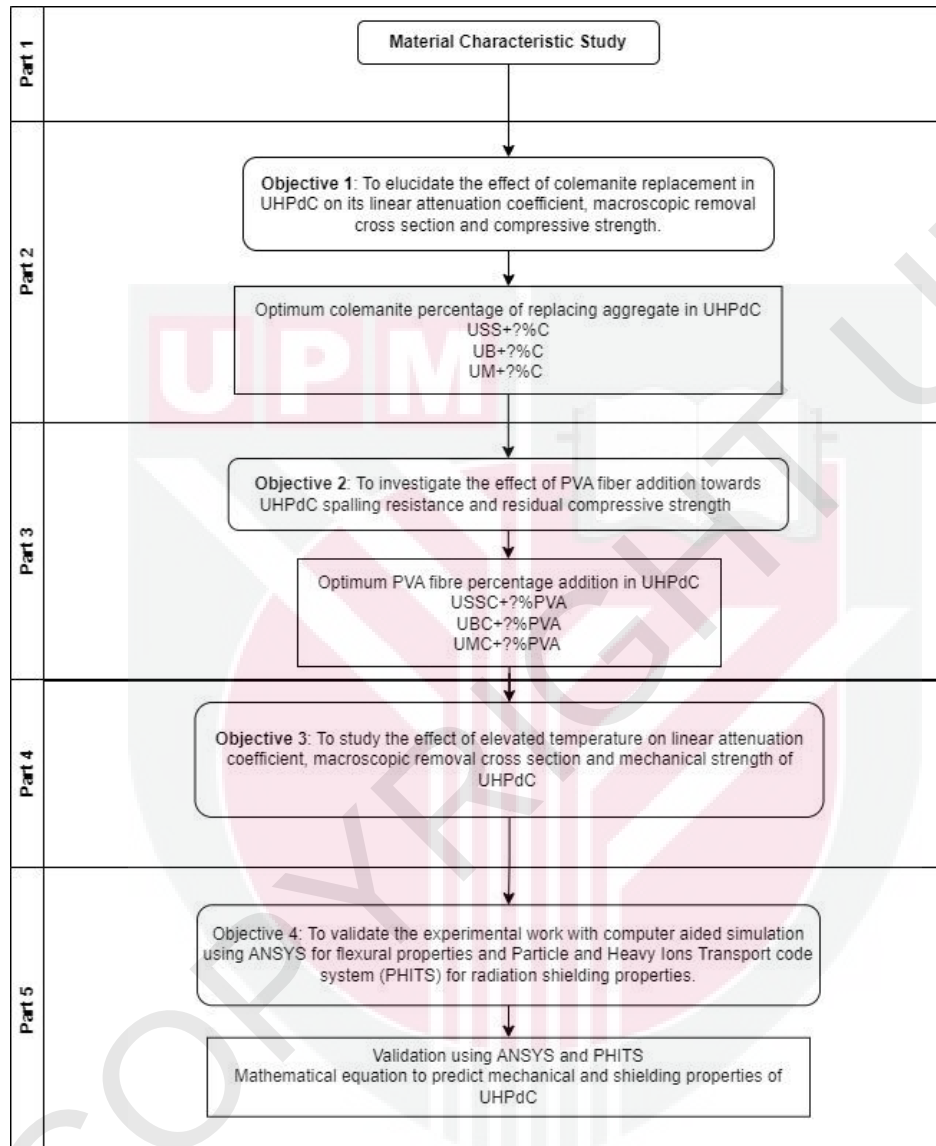


Figure 3.1 : Overall flow diagram of research

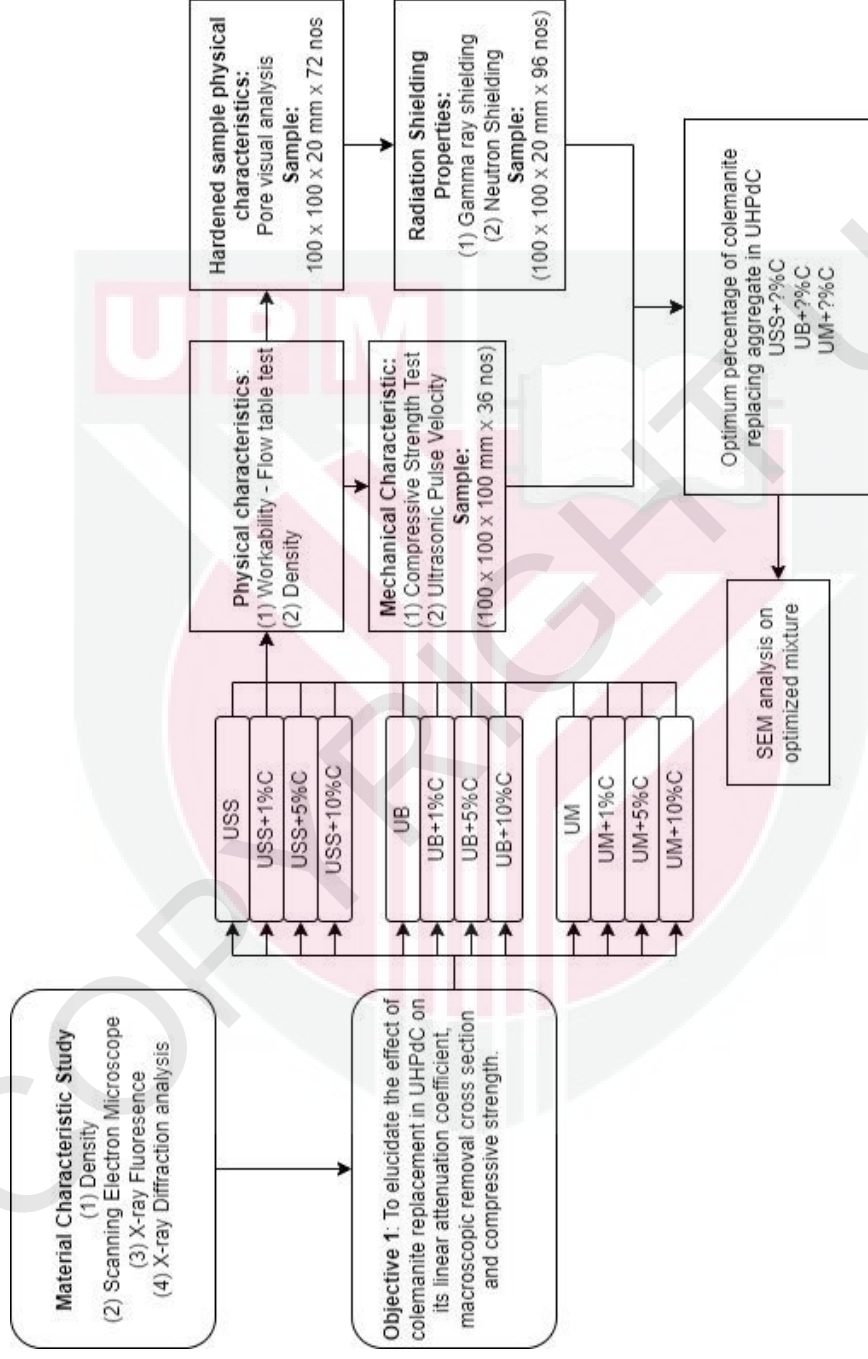


Figure 3.2 : Flowchart of objective 1

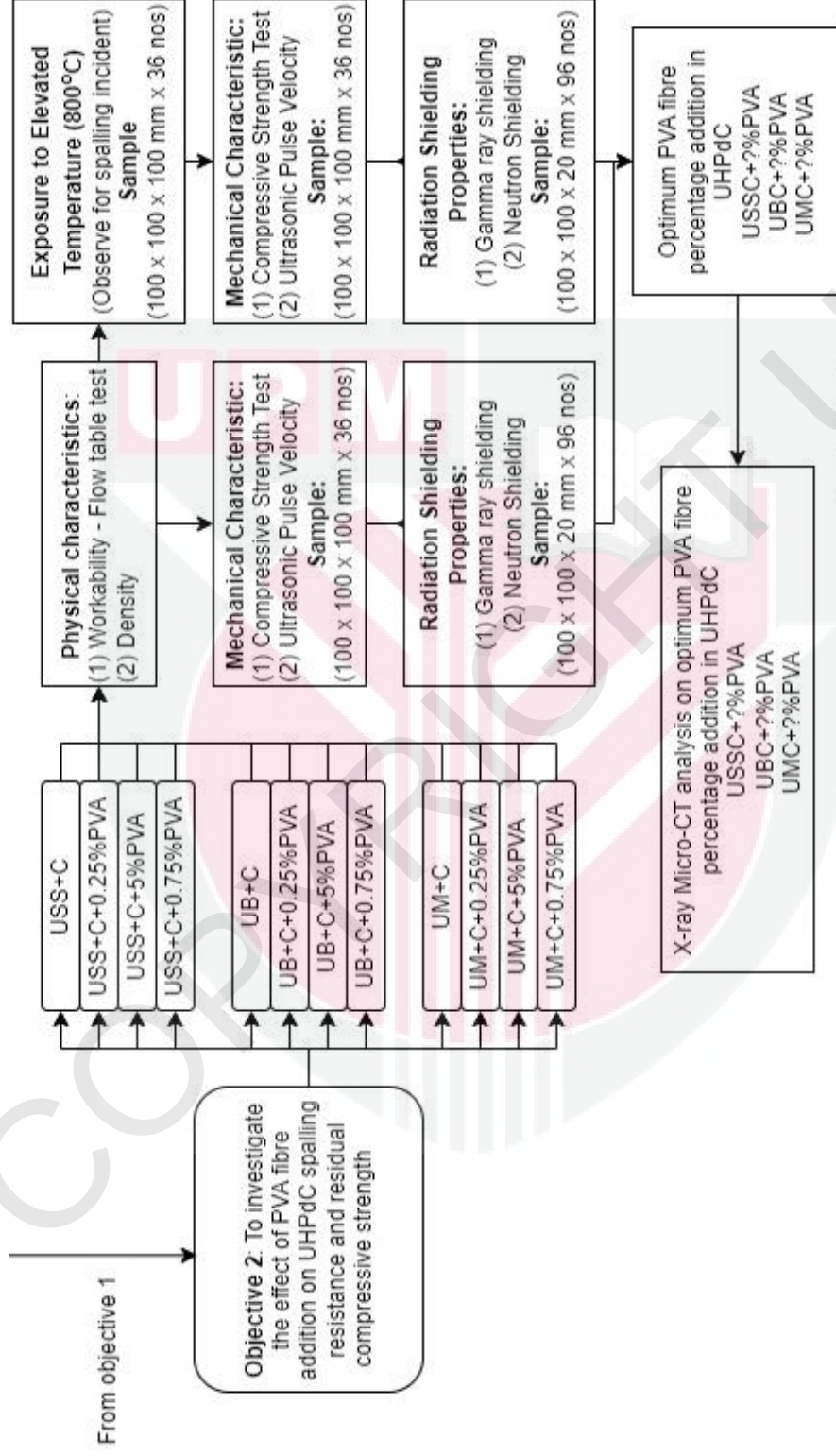


Figure 3.3 : Flowchart of objective 2

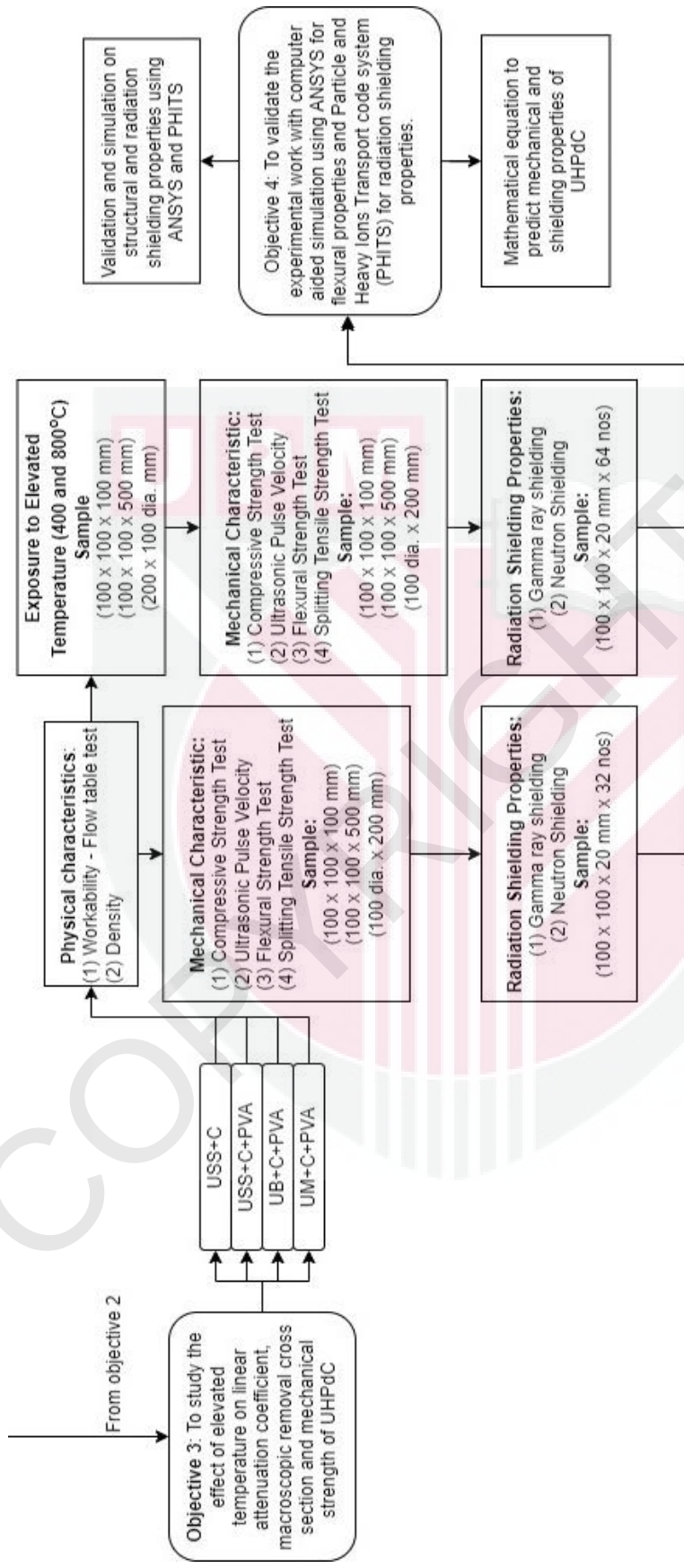


Figure 3.4 : Flowchart of objective 3 and 4

3.2 Materials

UHPdC mixture consists of cement, silica fume, fine aggregate, superplasticiser and water. The cement used in this study is Ordinary Portland cement (OPC) Type 1 manufactured by Tasek Corporation Berhad. This type conforms to MS EN 197-1:2014.

There are three types of fine aggregate used in this study which are sand, barite and magnetite. Only fine aggregate is used in producing UHPdC as it promotes homogeneity within the microstructure. Each type of fine aggregate is used to produce each type of UHPdC. There are three types of UHPdC being investigated which are sand UHPdC, barite UHPdC and magnetite UHPdC. Each UHPdC contains a single type of aggregate which is then replaced by colemanite at percentages. Sand UHPdC contains sand as its main fine aggregate. Sand is the ordinary river sand sieved to three sizes of 0.065 – 0.3 mm, 0.3 – 0.6 mm and 0.6 – 1.18 mm (Figure 3.5). Each size of sand made up 1/3 of the total composition of sand aggregate in sand UHPdC. For barite UHPdC, the barite is obtained from Malaysia, which is crushed to less than 1.18 mm. For magnetite UHPdC, the magnetite is obtained from the steel ore mine of Bestagold Sdn. Bhd. in Sungai Petani, Kedah with a particle size of less than 1.18 mm. The main replacing aggregate is colemanite and was sourced from Türkiye in powder form.

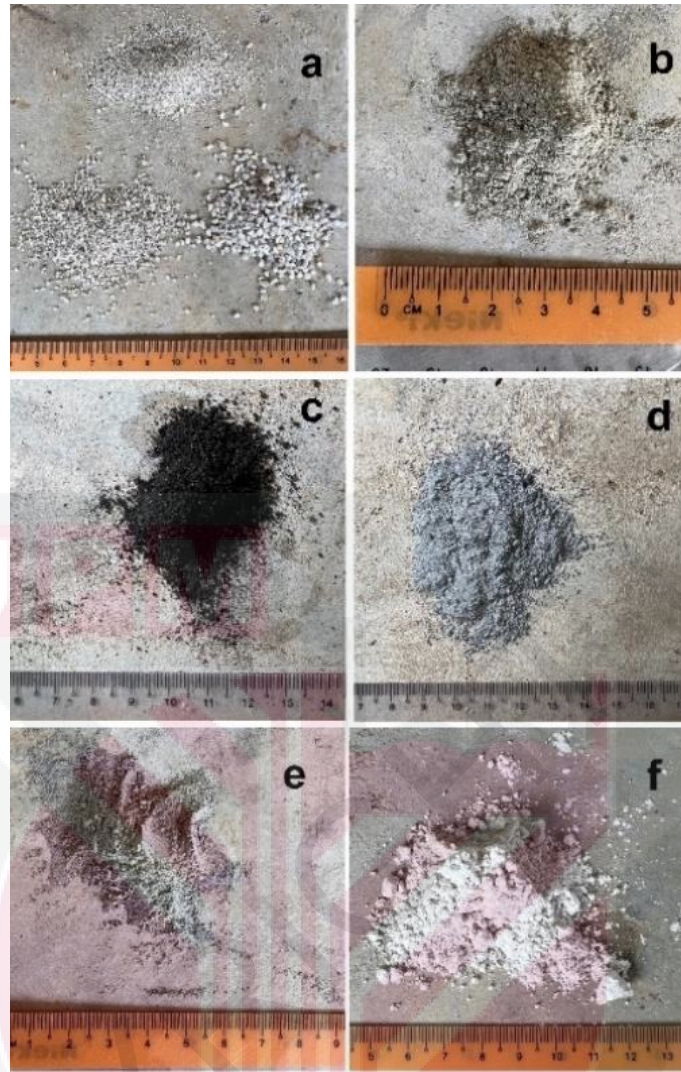


Figure 3.5 : Photo of a. sand, b. barite c. magnetite, d. silica fume, e. cement, and f. colemanite

Figure 3.6 shows the microstructure of barite with particle size ranging from 8.033 – 288.5 μm . Generally, the barite particles are angular and most are sized between 40 – 66 μm which is shown in 200 $\times$ and 1000 $\times$ magnification. A few areas in 200 $\times$ magnification photo shows particles with size less than 15 μm . There are also particles of barite having large sizes of 141 – 288.5 μm but at a small percentage. Figure 3.6b shows the magnification at 1000 $\times$ which indicates a large portion of particles with a range size of 43.1 – 66.23 μm . This further proves that a large portion of barite particles are within this

range of sizes. Finer sizes of barite particles are shown in detail in Figure 3.6c which is at 4000 × magnification. Based on the figure, barite particles are also sized at finer than 1 μm among other larger-size particles. These fine-sized particles are the particles that appear in a large population in 200 × magnification (Figure 3.6a).

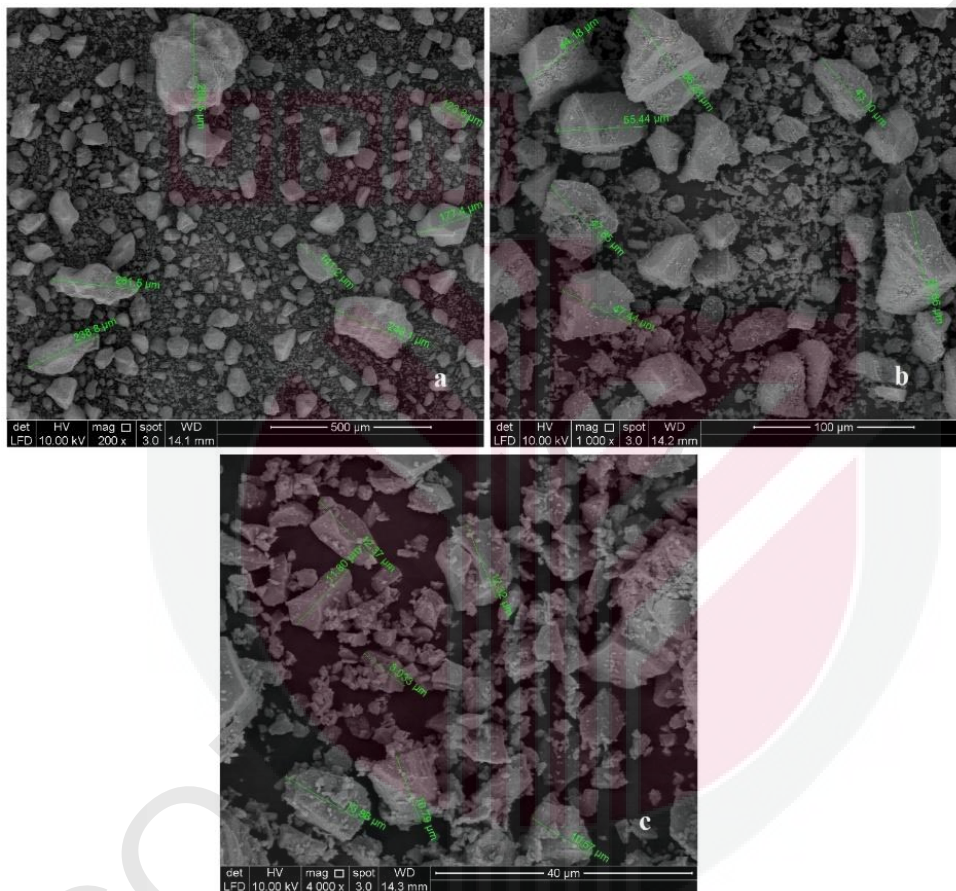


Figure 3.6 : SEM analysis of barite at a. 200 × magnification b. 1000 × magnification and c. 4000 × magnification

For magnetite, particles are also angular but quite a few particles have cylindrical and elongated shapes. This is shown in all magnifications where particles of magnetite appear to have one long side and a thin section. In terms of particle size, magnetite is larger compared to barite. This is shown in 200 ×

and 1000 × magnification where most particles are between 37 – 339 μm (Figure 3.7b). Few particles with a size less than 40 μm are visible in 200 × magnification compared to the barite sample.

At 4000 × magnification, most of the particles are larger than 5 μm with very few particles sized at less than 1 μm which indicates that the particle size of magnetite is larger compared to barite based on the same magnification. These nano-sized particles of magnetite are low in percentage and some are attached to larger particles. Particles of magnetite also show variation in morphology as some particles show flakiness while others show rough surfaces. This indicates the mixture of minerals present in magnetite particles as this material is taken from iron ore mines.

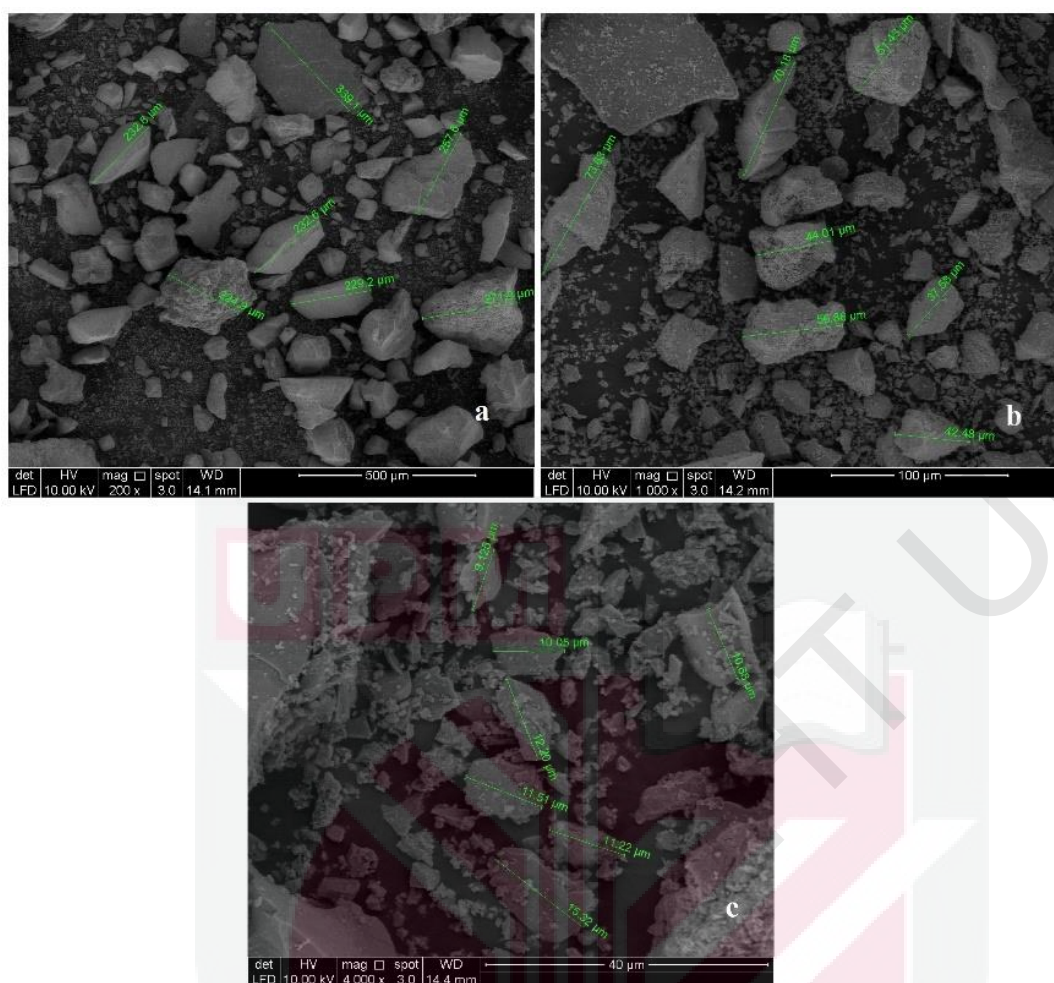


Figure 3.7 : SEM analysis of magnetite at a. 200 × magnification b. 1000 × magnification and c. 4000 × magnification

Colemanite particles are finer in size compared to barite and magnetite. This is shown in 200 × magnification which indicates a large area with particles of size less than 25 μm (Figure 3.8a). Side by side comparison between this figure and barite or magnetite will reveal that colemanite is finer based on the same magnification of the SEM. Large particles of size more than 60 μm are present in the observation but most of the colemanites are small than this measurement. These particles are even smaller than 40 μm which also populated most areas in Figure 3.8b of 1000 × magnification.

Figure 3.8c shows the magnification at 4000 × magnification which detailed the sizes of these particles. Based on the measurement, these particles are between 12 – 23 µm which is almost similar in size to barite particles that are observed at the same magnification. However, the percentage offine-sized particles is more pronounced in colemanite compared to barite. Furthermore, the amount of particles having smaller size than this is very scarce compared to barite. This indicates that the colemanite contained almost no nano-sized particles.

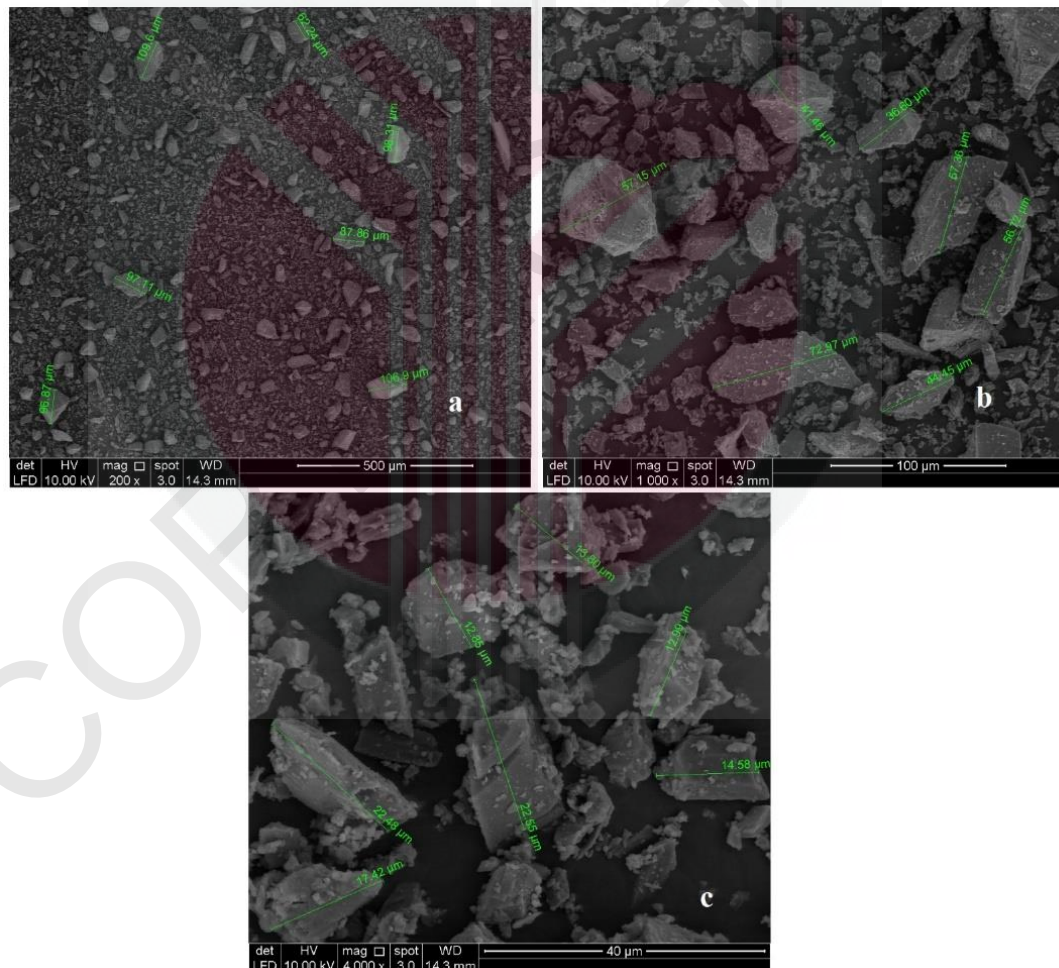


Figure 3.8 : SEM analysis of colemanite at a. 200 × magnification b. 1000 × magnification and c. 4000 × magnification

Analysis of all the materials used in this study by XRF is shown in Table 3.1. The result indicates the presence of heavy elements in heavyweight concrete. Barite consists of 58.69% of BaO while magnetite recorded a higher percentage of Fe₂O₃ at 83.93%. Composition of sand is similar to silica fume with a large percentage of SiO₂. Analysis on colemanite is also done using XRD which indicates the presence of boron (Figure 3.9).

Table 3.1 : XRF result of the used materials

	Cement	Silica Fume	Sand	Barite	Magnetite	Colemanite
CaO	54.57	3.22	0.03	1.01	0.1	52.01
SiO ₂	22.66	85.37	97.32	3.08	6.26	5.46
Fe ₂ O ₃	6.64	5.66	0.84	0	83.93	1.86
SO ₃	5.05	0.85	0.02	35.01	0.8	0.21
BaO	0	0	0	58.69	0	0
K ₂ O	0.28	1.13	0.06	0.05	0.23	0
ZnO	0	0.03	0	0	0	0
MnO	0.09	0.19	0.003	0.02	0	0
SrO	0.03	0.02	0	1.42	0	2.39
CuO	0	0	0	0.02	0	0
TiO ₂	0.61	0	0.08	0	0.37	0
ZrO ₂	0.01	0	0.18	0	0	0
MoO ₃	0	0	0	0	0	0
Tm ₂ O ₃	0	0	0	0	0	0
Na ₂ O ₃	0.16	0	0.03	0.17	0.57	0
Al ₂ O ₃	6.82	0.55	1.36	0.45	2.41	0.09
Cr ₂ O ₃	0	0	0	0	0.04	0
ThO ₂	0	0	0	0	0.04	0
MgO	2.89	0	0.05	0.03	0	3.11
Cl-	0.02	0	0.01	0.02	0	0
Rb ₂ O	0.02	0	0.001	0	0	0
Total	99.85	97.02	99.984	99.97	94.75	65.13

Figure 3.10 shows the fibres used in this research. There are two types of fibre used in this study which are micro steel fibre and polyvinyl alcohol (PVA) fibre. Micro steel fibre is sourced from Ganzhou Daye Metallic Fibres Co., Ltd. which is a copper-coated steel fibre with a 20 mm length and 0.2 mm diameter. This type of steel fibre provides 2850 MPa of tensile strength at 6000 kg/m³ of density. Steel fibre is added to the composition of each UHPdC at 2 % by volume. PVA fibre used in this study is 0.015 mm in diameter and 12mm of length. The fibre has 1600 MPa of tensile strength with a density of 1300 kg/m³.

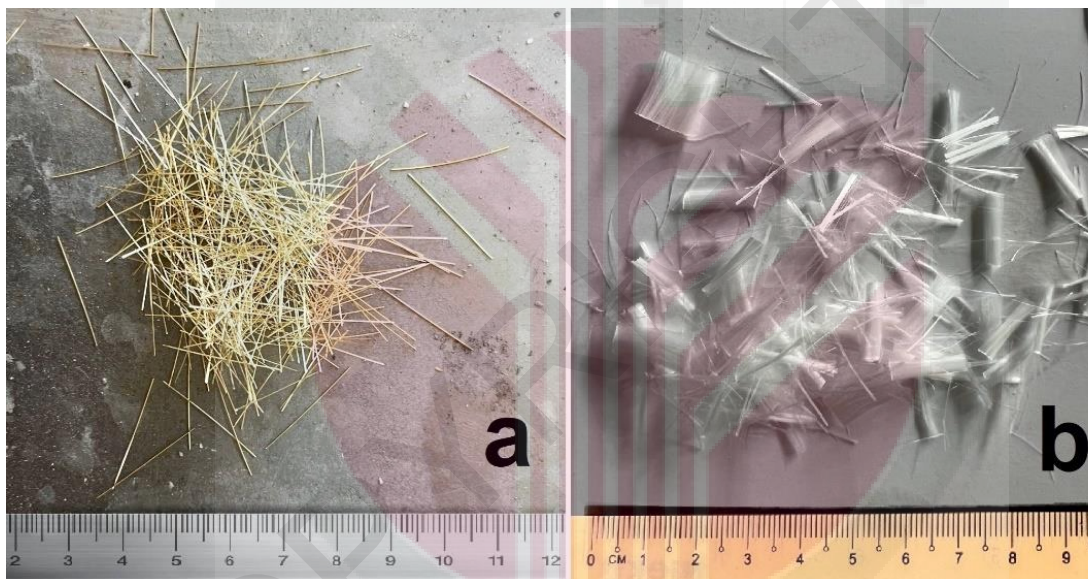


Figure 3.10 : Photo of a. steel fibre and b. PVA fibre

3.3 UHPdC Mix Proportion and Samples Preparation

In this study, three different types of UHPdC are being investigated which are Sand UHPdC (USS), Barite UHPdC (UB) and Magnetite UHPdC (UM). Colemanite is added incremental into each type of UHPdC by replacing the mass of the main aggregate. This is to study its effect on the mechanical and shielding properties of the concrete. The replacement of main aggregate with

colemanite is between 1 – 10% where the amount is initially based on sand UHPdC. The percentage is based on previous studies which limit to 10% due to flocculation, retardation on setting time and weakened adhesion of cement paste (Gencel et al., 2010; Mesbahi et al., 2013; Yadollahi et al., 2016b). Hence, incremental replacement of aggregate with colemanite is done by 10, 50 and 100g. This amount is replicated in barite and magnetite UHPC to enable direct comparison of the result, especially in terms of neutron shielding. The mix design for each type of sample which follows objective 1 is given in Table 3.2.

Table 3.2 : Mix design for objective 1

Sample	Cement (kg/m ³)	Silica Fume (kg/m ³)	Sand/ Barite/ Magnetite (kg/m ³)	Colemanite (kg/m ³)	Super plasticiser (kg/m ³)	Steel Fibres (kg/m ³)	Water (kg/m ³)
USS100	825	200	1000	0	28	120	168
USS99C1	825	200	990	10	28	120	183
USS95C5	825	200	950	50	28	120	183
USS90C10	825	200	900	100	28	120	183
UM100	825	200	1915	0	33	120	220
UM99C1	825	200	1905	10	33	120	232
UM95C5	825	200	1865	50	33	120	232
UM90C10	825	200	1815	100	33	120	236
UB100	825	200	1630	0	33	120	223
UB99C1	825	200	1620	10	33	120	225
UB95C5	825	200	1580	50	33	120	225
UB90C10	825	200	1530	100	33	120	236

For objective 2, the optimum mix design from objective 1 which is mixed with 5 % colemanite replacing aggregate is used as a based design. This selection is based on the experimental data of maximum compressive strength and maximum radiation shielding performance of each type of UHPdC. In this objective, the effect of PVA fibre addition towards UHPdC's mechanical and

shielding properties and also its durability against elevated temperature. PVA fibre is added at 0.25, 0.5 and 0.75 % by-volume into the mix composition of each UHPdC. The percentage of PVA fibre is based on a previous study which used 0.25 % in the UHPC mix (Rashid et al., 2020). Past research also highlights the reduction of workability due to fibre addition which limits the percentage to 1.5 % of polypropylene and polyethylene fibre (Maluk et al., 2017; D. Zhang, Liu, et al., 2021). The mix design for this objective is shown in Table 3.3.

UHPdC is mixed using a pan mixer with a 300 kg mixing capacity. Dry components of the composition are mixed at low speed for 2 minutes before adding 1/3 part of the mixing water. After the water is added, the mixing speed is increased and the mixing continues for another 4-6 minutes. The remaining mixing water is added with superplasticiser and half part of the solution is added gradually into the mixture while the blade is still running. The mixture is further blended until it begins clumping and forms balls of mixture with a seemingly shiny surface Figure 3.11. Another half of the remaining solution is added to the mixture, followed by fibres. Mixing is complete after another 2 minutes of blending and fibres are well-dispersed throughout the concrete based on observation.

Table 3.3 : Mix design for objective 2

Sample	Cement (kg/m ³)	Silica Fume (kg/m ³)	Sand/ Barite/ Magnetite (kg/m ³)	Colemanite (kg/m ³)	PVA (kg/m ³)	Super plasticiser (kg/m ³)	Steel Fibres (kg/m ³)	Water (kg/m ³)
USS95C5	825	200	950	50	0	28	120	183
USS95C5P0.25	825	200	950	50	3.25	28	120	191
USS95C5P0.5	825	200	950	50	9.75	28	120	191
USS95C5P0.75	825	200	950	50	29.25	28	120	199
UB95C5	825	200	1580	50	0	33	120	225
UB95C5P0.25	825	200	1580	50	3.25	28	120	225
UB95C5P0.5	825	200	1580	50	9.75	28	120	226
UB95C5P0.75	825	200	1580	50	29.25	28	120	241
UM95C5	825	200	1865	50	0	33	120	232
UM95C5P0.25	825	200	1865	50	3.25	28	120	248
UM95C5P0.5	825	200	1865	50	9.75	28	120	236
UM95C5P0.75	825	200	1865	50	29.25	28	120	240

A small batch of samples is then taken for a flow table test which follows EN 1015-3 that measures the workability. Disc and mould of flow table test are wiped clean before each test and then lubricated before receiving fresh UHPdC sample. Mould is then placed in the centre of the disc and UHPdC is introduced in two layers before being compacted by at least 10 short strokes of the temper. Excess mortar is skimmed from the top of the mould with a palette knife and the surface of the disc is wiped clean before being unmolded. The mould is then removed vertically and the disc is jolted 15 times at a constant frequency within 15 seconds. The diameter of the resulting spread is measured in two directions at right angles.

The process is then followed by a moulding process which commences on the vibrating table. The mixture is placed in a mould and compacted in three layers on the vibrating table. The curing compound is sprayed on top of the exposed surface of the specimen to prevent dehydration. Specimens are de-mould after 24 hours and cured in water of 90 °C for three days. Heat treatment during curing or “heat-curing” is commonly used in curing UHPC as the method

promotes high early strength and higher mechanical properties compared to UHPC cured at room temperature (S. L. Yang et al., 2009). This is due to microstructure enhancement due to the acceleration of pozzolanic activity while the cement hydrates remain amorphous at an early stage of the hydration process (Richard & Cheyrezy, 1995). This method has been reviewed and adopted in producing UHPC (Akeed et al., 2022). The curing regime is followed by air curing for another 25 days.

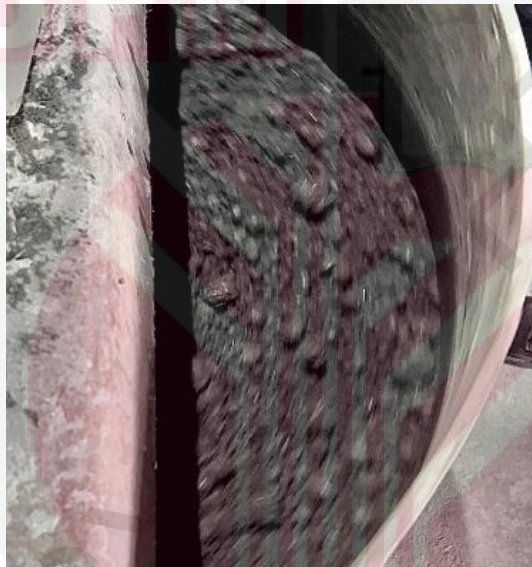


Figure 3.11 : Mixture is clumping and forming balls

3.4 Samples type and dimension

A total number of specimens is presented according to the objective. Table 3.4 shows the total specimen produced for each test in objective 1. Two types of samples are produced in this objective which are cubic samples (100×100×100 mm) and prism samples (100×100×500 mm) (Figure 3.12 and Figure 3.13). Cubic samples are tested for UPV and compression strength tests while prism samples are cut to 20×100×100 mm dimension using a

concrete cutter before being tested for radiation tests (Figure 3.14). Figure 3.15 shows sliced samples for radiation tests. These tests involved two types of sources: neutron and gamma sources to determine neutron radiation shielding and gamma radiation shielding respectively.

Table 3.4 : Tests and samples allocated for objective 1

Test	Standard	Total sample	Age Tested	Size (mm)
Compression Strength	BS EN 12390-3	36 cubes	28 days	100 × 100 × 100
UPV	BS EN 12504-4:2021			
Radiation Absorption Test for Gamma and Neutron Radiation	-	84 prisms	28 days	20 x 100 x 100



Figure 3.12 : Cubic samples of 100×100×100 mm



Figure 3.13 : Prism samples of 100×100×500 mm



Figure 3.14 : Photo of concrete cutter used in this study

For objective 2, the total specimen produced is given in Table 3.5. A total of two types of samples are produced in this objective which are cubic and prismatic samples that have similar dimensions to samples in objective 1. In

this objective, tests are compression strength, UPV and radiation shielding. These tests were carried out on the sample at room temperature and heated samples.

Table 3.5 : Tests and samples allocated for objective 2

Test	Standard	Total sample	Age Tested	Size (mm)
Compression Strength	BS EN 12390-3	54 cubes	28 days	100 × 100 × 100
UPV	BS EN 12504-4:2021			
Linear Attenuation Coefficient and Macroscopic Removal Cross section	-	168 prisms	28 days	20 x 100 x 100

Table 3.6 shows the total number of samples produced for objective 3. In this objective, only 3 mixtures of optimised UHPdC are used to produce the samples. The optimised mix composition is based on the results of objectives 1 and 2. Produced samples of optimised sand, barite and magnetite UHPdC are tested for compressive, flexural and splitting tensile strength. Furthermore, the samples are also tested at 400°C temperature exposure to investigate the heat durability property. Three types of dimensions for samples are produced in this objective which are cubic, prism and cylindrical. Cubic and prism samples are similar to the dimensions used in objectives 1 and 2 while cylindrical samples are 100 mm by diameter and 200 mm by height. These types of sample are tested for splitting tensile test (Figure 3.16). For prismatic samples (100×100×500 mm), a total of 9 samples are tested for flexural strength test.

Table 3.6 : Tests and samples allocated for objective 3

Test	Standard	Total sample	Age Tested	Size (mm)
Compression Strength	BS EN 12390-3	9 cubes	28 days	100 × 100 × 100
UPV	BS EN 12504-4:2021			
Flexural Strength	BS EN 12390-5	9 prisms	28 days	100 × 100 × 500
Linear Attenuation Coefficient and Macroscopic Removal Cross section	-	24 prisms	28 days	20 x 100 x 100
Splitting Tensile Test	BS EN12390-13	9 cylinders	28 days	100 (dia) × 200



Figure 3.15 : Prism samples of 20×100×100 mm



Figure 3.16 : Cylindrical samples of 100 mm (diameter) × 200 mm (height)

3.4.1 Density Test

The density of hardened UHPdC follows BS EN 12390-7 (British Standards Institution BSI, 2009b). Hardened samples of cubic dimension in objectives 1 and 2 are used as specimens in this test. Samples that have completed the curing process are dried in a ventilated oven at $105 \pm 5^\circ\text{C}$ until mass changes by less than 0.2 % in 24 hours. The value of oven-dried mass is recorded in kg. The density of the sample is calculated based on the ratio of oven-dried mass to the volume of the specimen which is 0.001 m^3 . The average density of the triplicate samples for each mixture is calculated and recorded.

3.4.2 Mechanical Strength Test

Mechanical strength tests include compressive, flexural and splitting tensile strength test. For compressive strength, samples are tested using a hydraulic compressing machine with 2500 kN compressive force at a loading rate of 6 kN/s (Figure 3.17). This is in accordance with BS EN 12390-3 (British Standards Institution BSI, 2002). Only cube samples of 100 x 100 x 100 mm

are used for this test. Samples are tested at 28 days of age. Compressive strength is calculated using Eq. 3.1;

$$f_c = \frac{F}{100^2} \quad (\text{Eq. 3.1})$$

where f_c is the compressive strength in MPa and F is the peak load in N.



Figure 3.17 : Hydraulic compressive machine with maximum compressive force of 2500 kN

For the flexural strength test, prism samples of 100 x 100 x 500 mm are used and tested at 28 days of concrete age. This test is carried out in three-point bending tests at a rate of 1 kN/s in accordance with BS EN 12390-5 (British Standards Institute, 2009)(Figure 3.18). Supporting rollers are placed at a distance of 300 mm between each other with a centre point loading. This test

is only carried out in objective 3 on optimised UHPdC mixtures. Flexural strength is calculated using Eq. 3.2;

$$f_{cf} = \frac{3 \times F \times 300}{2 \times 100^3} \quad (\text{Eq 3.2})$$

where f_{cf} is the flexural strength in MPa and F is the peak load in N.



Figure 3.18 : Flexural testing machine

Another test that is carried out on an optimised UHPdC mixture is the Splitting tensile test which follows BS EN 12390-6 (British Standards Institution BSI, 2009a). It is carried out on cylinder samples of 100 dia. x 200 mm after 28 days of concrete age using a compressive testing machine with casing to ensure the load is applied perpendicularly to the sample longitudinal length (Figure

3.19). The loading rate is applied at 1 kN/s. Splitting tensile strength is calculated using Eq. 3.3;

$$f_{ct} = \frac{2 \times F}{3.142 \times 200 \times 100} \quad (\text{Eq. 3.3})$$

Where f_{ct} is the tensile strength in MPa and F is the peak load in N.



Figure 3.19 : Casing used for splitting tensile test which is placed in the hydraulic compressive machine

3.4.3 Ultrasonic Pulse Velocity Test (UPV)

UPV test is carried out on a cube sample before the sample is tested for compressive strength. The test is based on BS EN 12504-4:2021 using a direct measurement pulse (British Standards Institution BSI, 2004)(Figure 3.20).

UPV testing device is calibrated with standard material before testing begins.

The dimension of the cube sample is set up in the device at the beginning of the test. The hardened sample's surface is ensured free from debris and the

area of contact is covered in a thin layer of heavy-duty grease. The transducer and receiver are placed in a single file with the sample in between them. This is considered a direct measurement. Wave velocity is measured at the end of each measurement. This test is conducted on all cube samples in objectives 1 and 2. Specification for UPV testing machine is mentioned in Table 3.7.

Table 3.7 : Specification of UPV testing device

Brand	Proceq Pundit Lab+ UPV Instrument
Range	0.1–7930 μ s
Resolution	0.1 μ s (< 793 μ s), 1 μ s (> 793 μ s)
Temperature Range	-10°C - 50°C (Non-charging) Humidity: < 95% RH, non-condensing
Power Supply	Lithium Polymer, 3.6V, 14.0Ah
Product Dimensions	9.8 x 6.4 x 2.4in (250 x 162 x 62mm), WxDxH
Weight	3.0lb (1.36kg)



Figure 3.20 : UPV measurement by direct method

3.4.4 Radiation Absorption Test

Test for radiation absorption is conducted at the Malaysia Nuclear Agency. There are two types of radiation absorption tests in this study which are gamma radiation attenuation and neutron attenuation. Samples are aligned between the source of radiation and the detector. The source of radiation for gamma attenuation is Cesium-137 and Cobalt-60 with reactivity of 2 mCi and 1.14 mCi respectively. For the neutron absorption test, the source of the neutron is Ameryllium-Berillium with a reactivity of 23.8 mCi.

Prism samples of 20 x 100 x 100mm are used in this test. Each mixture is represented by 8 nos of prism samples. This dimension is produced by cutting the prism sample of 100 x 100 x 500mm by 20mm thickness using a concrete cutter as shown in Figure 3.14. A total of 8 prisms with 20mm thickness are cut from each sample. The radiation absorption test begins by measuring the count detected without sample for 6 seconds, I_0 . This is followed by placing the first prism at the specified distance and the number of counts detected is recorded. Then, the second prism is placed next to the first prism and reading is taken again. This process is repeated until a full set of eight prisms has been measured for the count by the detector. The number of counts with a sample is denoted with I_n . The test setup is shown in Figure 3.21 and Figure 3.22 shows the actual test setup with lead protection.

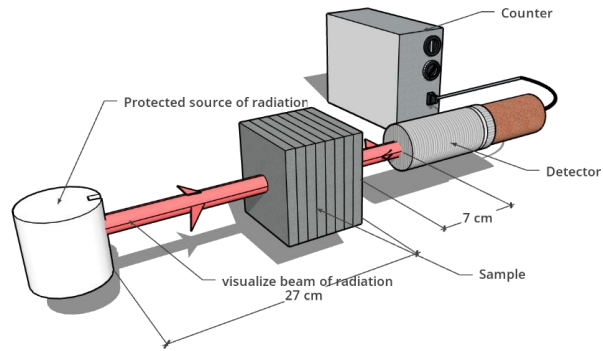


Figure 3.21 : Drawing of test setup

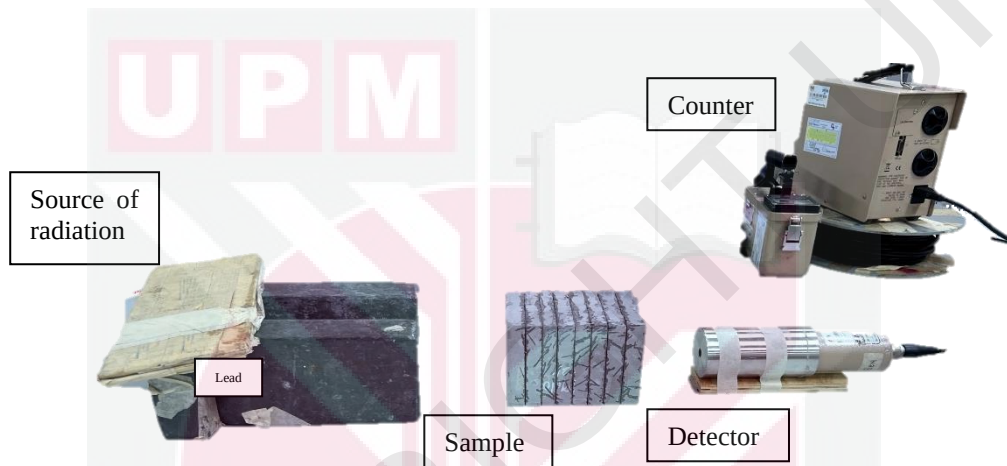


Figure 3.22 : Actual test setup

By rearranging the Beer-Lambert equation, the value of radiation is acquired from the slope of data trend of $\ln \frac{D_0}{D}$ plotted against the thickness of the sample as in Eq. 3.4 and Eq. 3.5.

For gamma attenuation, μ ;

$$\ln \frac{D_0}{D} = \mu t \quad (\text{Eq. 3.4})$$

For neutron attenuation, $\sum_R(E_n)$;

$$\ln \frac{D_0}{D} = t \sum_R (E_n) \quad (\text{Eq. 3.5})$$

where $y = \ln \frac{D_0}{D}$, $x = t$, and m (slope of the data trend) = μ or $\sum_R(E_n)$, D_0 is the count observed without the sample and D is the count with a sample.

In measuring the effectiveness of radiation shielding, the minimum thickness is calculated for each type of radiation source using Eq. 3.6;

$$TVL = \frac{\ln 10}{\mu} \quad (\text{Eq. 3. 6})$$

where TVL = tenth value layer or the minimum thickness to shield 99 % of the radiation and μ is replaced with $\sum_R(E_n)$ for a neutron source.

3.4.5 Image Analysis

There are three methods of image analysis being carried out in this study which are using stereomicroscope, scanning electron microscope (SEM) and X-ray micro-computed tomography scan (X-ray μ -CT). Stereomicroscope and SEM are used on samples of objective 1 while X-ray μ -CT is used on samples of objective 2. Each method provides different types of images and produces different outcomes of analysis which contribute towards the findings of this study. Samples taken for each type of image scanning differ according to the objective of the study. In objective 1, the effect of colemanite towards the mix composition of UHPdC is investigated. Increase in number of pores and effect on quality of interfacial transition zone between aggregate and cement paste is expected due to attribute of colemanite. This type of images can be shown by stereomicroscope and SEM scanning. For X-ray μ -CT, the analysis is suited for objective 2 as the effect of PVA fibre addition is investigated. Presence of PVA fiber is expected to prevent spalling due to thermal exposure. Cracks and

empty channel is expected to be formed after heating and evaporation of PVA fiber which is best analysed using X-ray μ -CT due to its level of sensitivity and penetrability.

SEM image produced from SEM requires a sample of less than 5 grams and sized less than 1 cm in diameter. The sample for analysis is dehydrated and coated with a thin layer of gold which serves as a conductive material. Before analysis begin, SEM is warmed up for at least 30 minutes and set to 10 kV of working voltage. Once the microscope is operated, the working distance is adjusted to achieve optimal focus and resolution. A secondary electron detector is used to map out the surface morphology of the sample and images captured are stored in the linked computer.

For the stereomicroscope, samples are taken from objective 1 to observe the effect of colemanite addition on the formation of pores (Figure 3.23). Samples used in the study are prism samples which are also used in radiation shielding tests. All samples of UHPdC are analysed under the stereomicroscope. Total of 6 samples are observed for each type of UHPdC mixture. The area of 100 mm² that is located at the centre of the prism surface is analysed by measuring the diameter and number of pores with the observed area. A total of 600 mm² of area is analysed for each type of UHPdC. Based on the observed size and number of pores in each sample provide a base of analysis on the effect of colemanite presence in UHPdC.



Figure 3.23 : Photo of stereomicroscope for pore analysis of sample

For SEM, a fraction of samples are taken from objective 1 to observe the effect of colemanite addition on the microstructure of each UHPdC. Samples of size less than 5mm are taken to the lab for analysis on SEM. These samples include the optimised composition of sand, barite and magnetite UHPdC. Samples are observed for homogeneity, quality of interfacial transition zone and pores. Overall, SEM and stereomicroscope analysis is used to study the effect of colemanite presence in UHPdC. Based on a previous study, the presence of colemanite affects the workability, and quality of hardened cement paste and the interaction between hydrated cement and aggregate. This is visualized in pore formation and interfacial transition zone images that are obtained from stereomicroscope and SEM analysis respectively.

For the X-ray μ -CT scan, a fraction of samples is collected from objective 3 to observe the effect of heating to 800°C on the microstructure of each optimised

sand, barite and magnetite UHPdC (Figure 3.24). Samples taken for analysis are smaller than 5 mm in diameter as it is limited by the size of the sample holder and penetration X-ray energy.

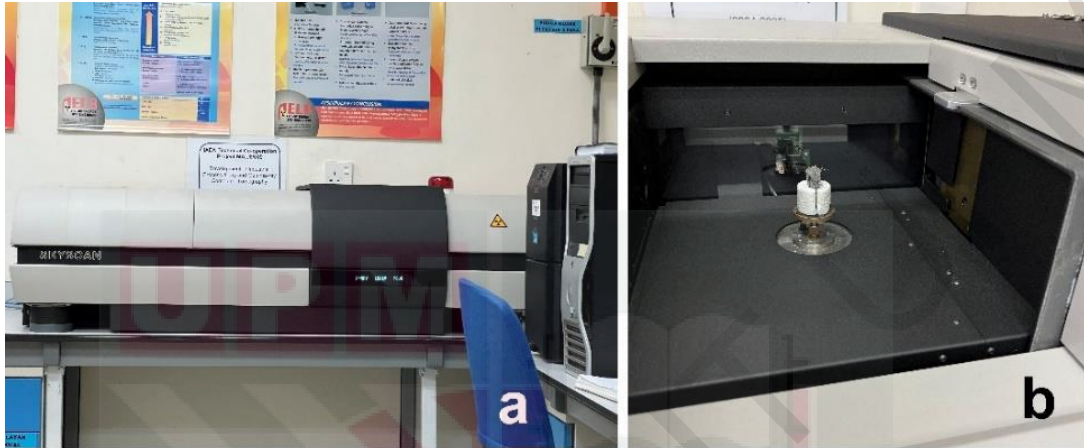


Figure 3.24 : Photo X-ray μ -CT scan with maximum voltage setting of 104kV and b. sample holder with sample inside the scanner

3.4.6 Elemental Analysis on Aggregate

X-ray Fluorescence (XRF) is used to analyse the elemental composition of materials. In this study, elements present in aggregate which includes magnetite, barite, sand and colemanite are analysed using XRF. Representative samples of the aggregate which are fine-sized particles are collected and mounted on the sample mount. A thin backing material of polypropylene is placed behind the sample to help support it and allows X-rays to pass through. X-rays are passed through for three minutes before readings are recorded.

X-ray Diffraction (XRD) is also used to determine elements' presence in aggregate. this is used to specifically determine the presence of colemanite as

element boron, B, is light and hard to be traced using XRF. XRD identifies the element based on the diffraction pattern of X-ray that bounced off the element in the aggregate. This test is done using a powder-sized sample which is mounted on a sample holder. The sample is firmly pressed and levelled on the sample holder and then locked with a lid before being placed in the XRD machine. It is scanned at 2θ with a scanning speed of 0.5 s. Results of counts are recorded to determine the presence of the element.

3.4.7 Heat Exposure and Spalling Probability

Part of the samples in objectives 2 and 3 are exposed to heat to investigate the effect of PVA fibre addition towards the thermal resistance of UHPdC. Heat-treated samples are then tested for mechanical strength and radiation shielding properties. In objective 2, samples are heated to 800°C and the optimum mixture is used in objective 3. For objective 2, cubic and prismatic samples are heated with increasing percentages of PVA fibre. Samples are observed for any spalling due to heat exposure. Samples are then tested for compressive and radiation-shielding properties. Based on a previous study, UHPC exposed to elevated temperature tends to explode due to spalling. Major spalling and cracking may render the sample to be unsuitable for mechanical strength test due to the deformation of the sample's dimension. In objective 3, samples are heated to 400 and 800°C before being tested for mechanical and shielding properties. This includes cubic, prismatic and beam samples. It is expected that no occurrence of spalling will be observed in objective 3 as all of the mixtures used can survive up to 800°C.

In exposing the heat towards the sample, the electric furnace is used with a steel cage to prevent any damage to the heating element in the case of explosive spalling. Samples are heated 5°C/min and maintained at the target temperature for 1 hour. Samples are taken out of the furnace once their temperature is viable for handling.

Spalling probability, **P** is calculated in objective 2 to analyse the effect of PVA fibre addition towards the thermal resistance of UHPdC. This is calculated using Eq. 3.7:

$$P = \frac{S}{S_T} \% \quad (Eq. 3.7)$$

where **P** is the spalling probability, **S** is the number of spalled samples and **S_T** is the total sample. A total of 8 prism samples and 3 cubic samples are heated for each mixture in objective 2. A total of 12 mixtures are produced in objective with variation in PVA fibre presence. This method of analysing the thermal resistance of fibre based on increments in temperature and the occurrence of spalling in the concrete samples is used in previous studies (K. Y. Kim et al., 2013; Liang et al., 2018; D. Zhang et al., 2018). The occurrence of spalling is due to the buildup of internal vapor pressure within the concrete at temperatures beyond 400 °C. This method provides a quantitative measurement of the effect of PVA fibre on the thermal resistance of UHPdC.



Figure 3.25 : Furnace used to heat the sample

3.5 Structural simulation on beam and dry cask storage

Based on data gathered in objective 3, a sample of unoptimised sand UHPC along with optimised sand, barite and magnetite UHPdC are simulated using ANSYS to validate the flexural data recorded in the experimental work. This is done using a beam sample of the same dimension and flexural modulus value calculated using the Eq. 3.8 listed in ASTM D790:

$$E_B = \frac{L^3 m}{4bd^3} \quad (\text{Eq. 3.8})$$

where E_B is the modulus of elasticity in bending in MPa, L is the support span in mm, b is the breadth of the beam in mm, d is the depth of the beam in mm and m is the slope of the initial straight line in the load-deflection curve (N/mm). Experimental work is validated by comparing the value of deflection calculated

in the simulation and recorded in the experimental work. Support for the sample is simulated as per the experimental procedure with a similar distance between roller supports. Peak load is applied on the sample according to the actual value recorded from the experimental work. The resulting deflection on each UHPdC beam sample is recorded from the simulation to be compared with deflection measured from the experiments. Models are also simulated for peak load based on deflection recorded by the software. Samples are simulated with incremental load until a similar deflection is observed on the sample. This peak load value is compared with the experimental peak load value for analysis.

Further simulation is carried out using data of compressive strength recorded for optimised sand, barite and magnetite UHPdC to produce dry cask storage with the capacity to sustain self-weight due to stacking of the cask.

The modulus of elasticity is calculated using Eq. 3.9 suggested by Castro et al. (2010);

$$E_c = 4069 \sqrt{f'_c} \quad (\text{Eq. 3.9})$$

where E_c is the modulus of elasticity in MPa and f'_c is the compressive strength.

Based on the value of E_c , dry cask storage is simulated and it is modelled based on the dimension used in research on radiation shielding of dry cask storage (Ko et al., 2014). Detailed dimension is shown in Table 3.8. Models are simulated with fixed support at the bottom of the cask and imposed with

load from a stacked cask. From ANSYS simulation, all simulated models of optimised UHPdCs are checked for any large deformation due to loadings. Idealised model of cask which is a circular hollow section is simulated. Load is calculated from the density of UHPdC that is recorded from the experimental work. An additional assumed loading of 1000 kg from the spent fuel rod is also included in the simulation (Table 3.9). The combined load is applied uniformly across the surface area of the circular hollow section of the model. The boundary condition for the model is set with a fixed support at the bottom of the cask.

Table 3.8 : Dimension of concrete dry cask storage based on previous research

Height (mm)	5240
Inner diameter (mm)	2240
Outer diameter (mm)	2890
Wall thickness (mm)	325

(Source : Ko et al., 2014)

Table 3.9 : Density and applied weight on simulated dry cask model

Sample	Density (kg/m ³)	Weight of top cask (kg)	Weight of Spent Fuel Cell (kg)
Unoptimised Sand UHPC	2444	4251	1000
Sand UHPdC	2374	4130	1000
Barite UHPdC	2776	4829	1000
Magnetite UHPdC	2991	5203	1000

3.6 Radiation Shielding Simulation on Dry Cask Storage

Similar to structural simulation, simulation of radiation shielding is also carried out optimised UHPdC of sand, barite and magnetite. This simulation is carried

out using a Particle and Heavy Ion Transport code System (PHITS) and the dry cask model is the same dimension used in the structural simulation.

The design of dry cask storage is cylindrical with a 2240 mm diameter with 325 mm wall. Its height is 5240 mm and is designed to carry 21 nos of fuel cells (Ko et al., 2014)(Figure 3.26). Based on this dimension, the cask is coded into PHITS using two nested right circular cylinder macrobodies. For the material of this cask, the value of density and its element composition is defined based on the experimental data.

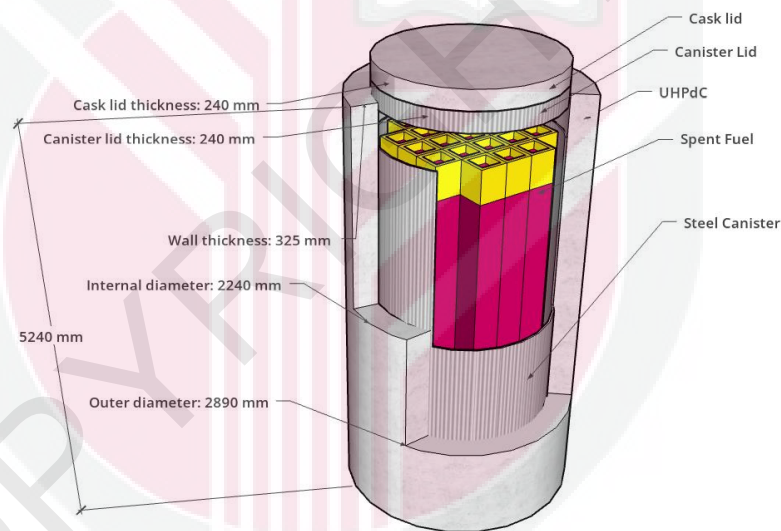


Figure 3.26 : 3D model of simulated dry cask storage with spent fuel assembly

The limit of the analysis is set by a sphere of radius 3500 mm that covers the whole cask (Figure 3.27). Any particle that crosses the outer surface of the cask and into the sphere is added to the tally. Furthermore, any movement of particles beyond the sphere is not analysed.

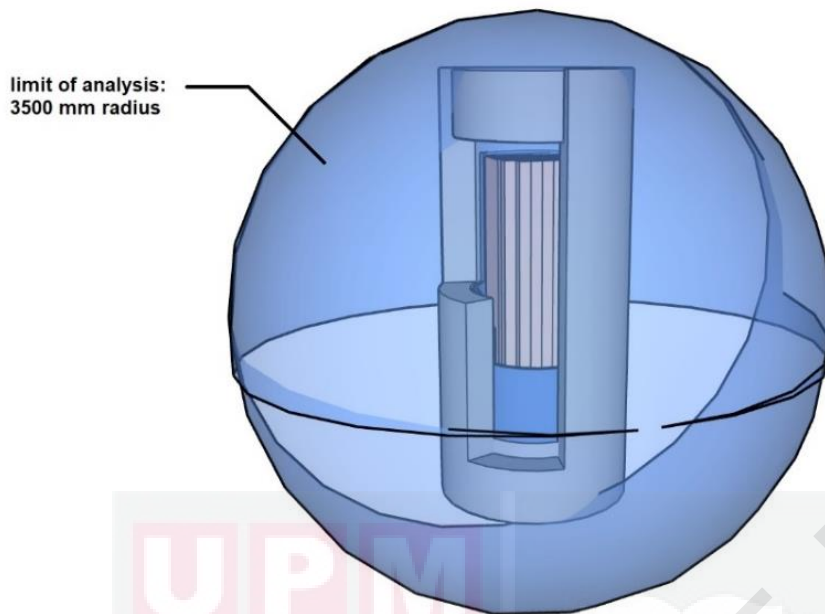


Figure 3.27 : 3D model of limit and surface simulated in code PHITS

The source of photon and neutron is set as the point source which is placed at 2620 mm from the base of the cask along the cask's axis. The source is defined as a point isotropic source with energies for photon and neutron as shown in Table 3.9 and Table 3.10 respectively.

A maximum of 10,000 numbers of source particle history is defined in the code. This number also defines the execution time produced by the acceptable relative error. Output from this simulation is presented as dose rate, calculated using the flux value simulated and the conversion coefficient of the International Commission on Radiological Protection (ICRP) 74.

Table 3.10 : Photon source

Energy (MeV)	Gamma Flux (photons/s)
0.01~0.05	9.56E+14
0.05~0.10	2.67E+14
0.10~0.20	1.94E+14
0.20~0.30	5.71E+13
0.30~0.40	3.74E+13
0.40~0.60	1.53E+14
0.60~0.80	1.72E+15
0.80~1.00	7.96E+13
1.00~1.33	4.60E+13
1.33~1.66	6.18E+12
1.66~2.00	1.26E+11
2.00~2.50	4.65E+10
2.50~3.00	2.83E+09
3.00~4.00	2.68E+08
4.00~5.00	7.26E+06
5.00~6.50	2.92E+06
6.50~8.00	5.72E+05
8.00~10.0	1.21E+05

(Source : Ko et al., 2014)

Table 3.11 : Neutron source

Energy (MeV)	Neutron Flux (Neutron/s)
0.0000001~0.000001	3.19E-04
0.000001~0.00001	1.11E-02
0.00001~0.0001	7.65E-02
0.0001~0.001	6.70E+00
0.001~0.01	5.48E+02
0.01~0.1	8.84E+04
0.1~1	1.77E+07
1~10	4.09E+07
10~100	4.79E+06

(Source : Ko et al., 2014)

3.7 Summary

Overall, there are three main research works aimed at the three objectives in the previous chapter. After characterisation work on the materials used in this study, the first part of the research determined the optimum percentage of colemanite replacing the main aggregate based on their mechanical and

shielding properties. Based on the optimum percentage, the work continues with part two which adds pva fibre that aims to improve the heat durability of uhpdc. The optimum percentage is also determined based on the spalling resistance, and mechanical and shielding properties. Part three of this study continues the test on the optimum mixes with flexural and splitting tensile strength tests. Uhpdc's are also tested at lower heat exposure of 400 °C to further investigate the effect of temperature on the uhpdc's. All of the data gathered during experimental work are validated using simulation work which consists of ansys and phits. Furthermore, the simulation work also includes the application of the uhpdc as dry cask storage to demonstrate their practicality.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Introduction

In this chapter, results of the research work are presented. The chapter begins with presenting and discussing the results of the research in relation to effect of colemanite replacing main aggregate of UHPdC on its physical, mechanical and radiation shielding properties. The discussions revolves around the work done in objective 1. This continues with data gathered in objective 2 which focuses on the effect of adding PVA fiber in composition of UHPdC. The discussion includes the effect of PVA fiber's presence on UHPdC's physical, mechanical and radiations shielding properties. Discussion continues on the effect of PVA fiber presence towards thermal resistance of UHPdC. This includes analysis on spalling probability, residual mechanical strength and radiation shielding properties of UHPdC. Based on these discussion, optimum mix composition is presented for each type of UHPdC. The chapter continues with analysis on the effect of elevated temperature on the optimum mix of UHPdCs. The data presented includes heat exposure of 400 and 800 °C which presents incremental degree of temperature. Discussion continues on simulation work in terms of structural and radiation shielding that validate the experimental work and application as dry cask storage. Equations are also proposed based on the experimental data to predict the radiation shielding properties of UHPdC.

4.2 Effect of Colemanite Replacing the Main Aggregate on Workability, Density and UPV Test

In studying the workable and paste-form mixture of UHPdC with colemanite, the ratio of water-to-binder of the mix composition is adjusted. This ratio is adjusted to maintain a high workability of at least 200 mm throughout all the mixes. Overall, the replacement of the main aggregate with colemanite shows an increase in water demand in the mixture which is shown by the water-to-binder ratio and workability. The water-to-binder ratio of sand UHPdC had to be increased from 0.165 to 0.18 due to aggregate replacement with 1-10% of colemanite (Figure 4.1). Even though the ratio is maintained as the percentage of replacement is increased, the workability of sand UHPdC with 10% replacement is reduced by 12.2% compared to 5% replacement.

For magnetite UHPdC, a slight increment in the water-to-binder ratio from 0.22 to 0.23 and resulted in an increase in workability from 240 to 265mm. In the barite UHPdC mixture, the ratio increased from 0.218 to 0.23 and maintained a workability of 270 to 280mm. The replacement of the main aggregate with colemanite resulted in a higher water-to-binder ratio in sand UHPdC as opposed to barite and magnetite UHPdC. This is due to fine sand-sized 0.3–0.6mm being replaced with finer colemanite which has a higher surface area that resulted in a higher demand of free water by the mix to achieve paste-form (Khalaf et al., 2021). The amount is relatively smaller in magnetite and barite UHPdC as the percentage of replacement is based on the weight of sand in sand UHPdC. This was to ensure the amount of colemanite present in all types of UHPdC with the same percentage is similar. Hence, the effect of lower workability is less presence in magnetite and barite UHPdC. The reduction in

terms of workability is also shown by limestone concrete containing more than 30% colemanite which is due to agglomeration that occurred during mixing with an increase in colemanite ratio (Gencel et al., 2010)

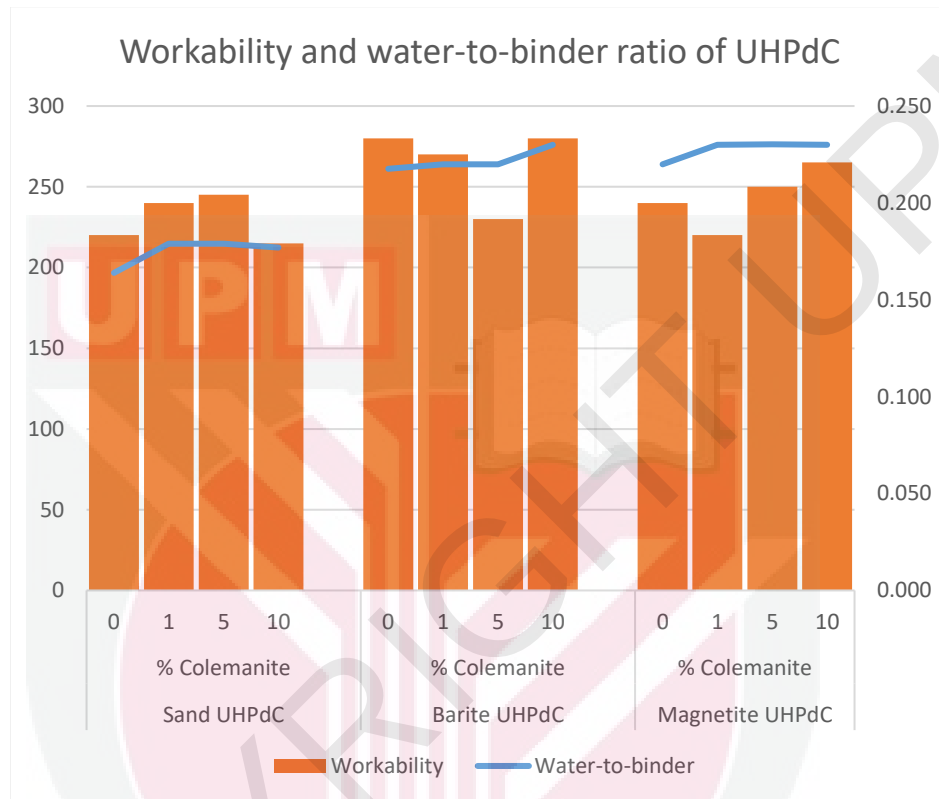


Figure 4.1 : Graph of workability and water-to-binder ratio versus percentage of colemanite replacement of varied UHPdC

In terms of density, colemanite replacing the main aggregate resulted in denser UHPdC up until the optimum percentage. Beyond this percentage of replacement, lower density in UHPdC produced is observed. Sand UHPdC recorded an optimum percentage of colemanite replacing sand at 1% at 2453 kg/m³ (Figure 4.2). Reduction in density is recorded at 5% replacement which is 2403kg/m³. For barite UHPdC, the optimum percentage is observed at 5% replacement which equals 3001kg/m³ in density. At 10% replacement of barite with colemanite, barite UHPdC recorded 2911 kg/m³ in density which is 3.0%

lower compared to 5% replacement. The reduction is similar to another study that reported a 5% reduction in density with increase in colemanite replacing fine-sized barite in concrete from 5 to 10% (Mesbahi et al., 2013). In magnetite UHPdC, the optimum percentage of replacement is also observed at 5% which is 3215kg/m³ in density. In comparison to sand UHPdC, magnetite and barite UHPdC show a higher percentage of optimum aggregate replacement which indicates the less compactness of the UHPdCs without colemanite. This is also shown by the particle size distribution of sand UHPdC which consists of more wider range of particle sizes compared to barite and magnetite UHPdC. The presence of colemanite in the mix composition fills the gap between the main aggregate which resulted in a denser microstructure. However, an excessive amount of colemanite would result in a porous microstructure as it requires more free water to become a paste-like form. This is shown by the value of the water-to-binder ratio with increasing colemanite replacement. The higher the ratio of water-to-binder would result in more free water and pores formed in the microstructure which resulted in lower density.

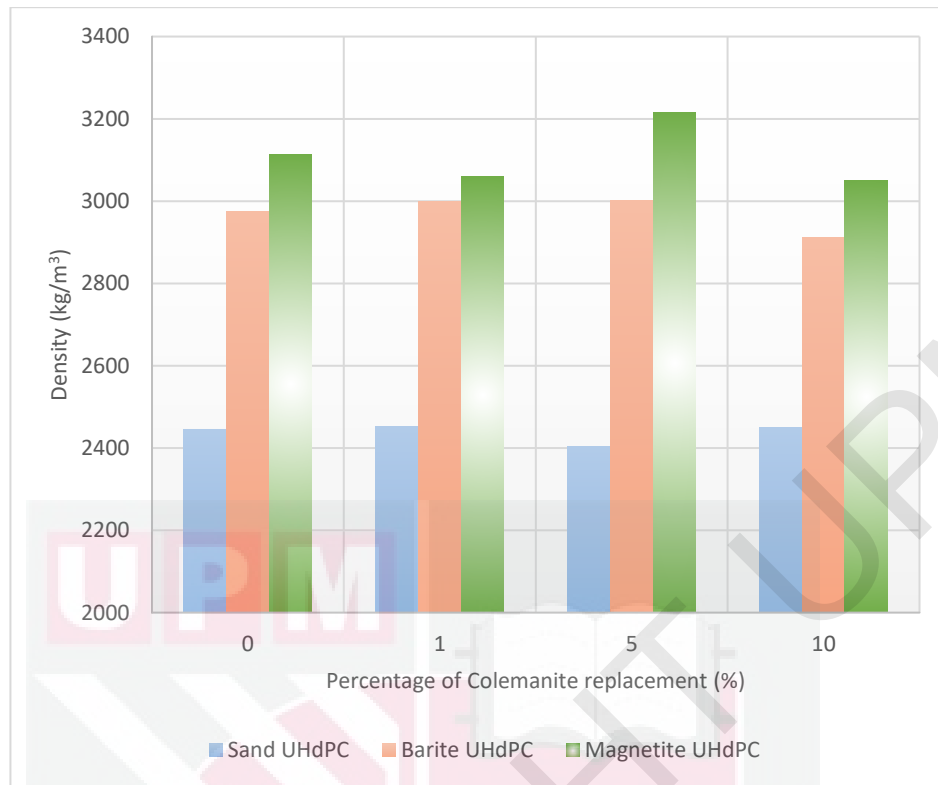


Figure 4.2 : Graph of density versus percentage fo colemanite replacement

In comparison among all three types of UHPdC, the density of hardened magnetite UHPdC is the highest followed by barite and sand UHPdC. Magnetite UHPdC recorded a density of 3051 – 3215 kg/m³ while barite UHPdC recorded a density of 2911 – 3001 kg/m³. This is 22 % higher compared to sand UHPdC which recorded a density of 2403 – 2453 kg/m³. Overall, the density of barite and magnetite UHPdC is larger than 2600 kg/m³ which is considered heavyweight concrete. Sand UHPdC is about 2500 kg/m³ which is slightly lower than the required value to be considered as heavyweight concrete. This relatively higher density observed in barite and magnetite UHPdC is due to the heavyweight aggregate of barite and magnetite in the mix compared to sand.

In terms of concrete quality which is based on UPV value, sand UHPdC shows the highest value at 4800 – 4900 m/s (Figure 4.3). This indicates a dense microstructure that allows the ultrasonic wave to propagate faster which is due to the wide range of particle size distribution of sand aggregate and low water-to-binder ratio. This is followed by magnetite UHPdC in the range of 4425 - 4545 m/s and then barite UHPdC with UPV value of 4016 – 4167 m/s. Overall, the replacement of the main aggregate with colemanite shows improvement in UPV value, especially for barite and magnetite UHPdC but it is up to the optimum percentage of replacement. Barite and magnetite recorded the highest UPV value at 5 % aggregate replacement but the difference is 2-3% only. Sand UHPdC shows improvement in UPV value at 10 % colemanite replacement but the difference is 1.5 % compared to 0% colemanite replacement. This may be due to an increase in compactness due to the fineness of colemanite particles which filled up voids between aggregates. Samples also show a reduction in UPV value by 0.6 and 2.5% at 1 and 5% aggregate replacement. It can be concluded that the replacement of aggregate with colemanite up to the optimum percentage resulted in a higher quality of UHPdC microstructure.

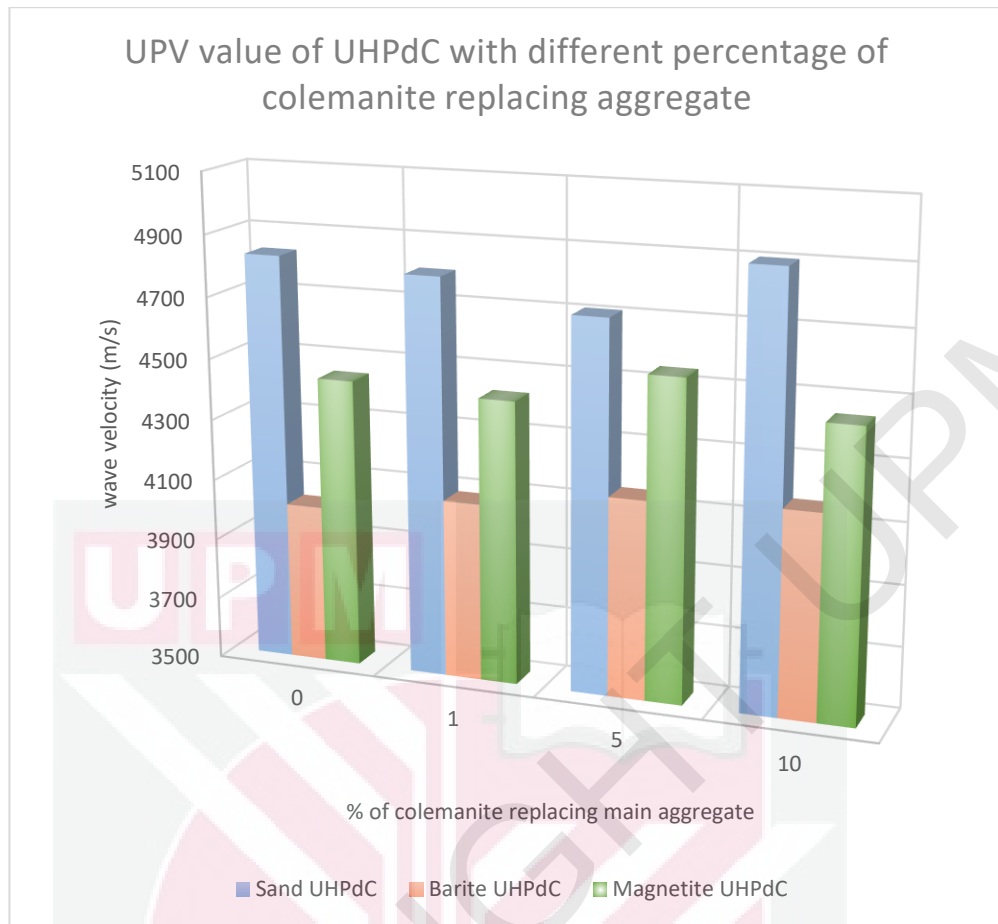


Figure 4.3 : Graph of UPV versus percentage of colemanite replacing the main aggregate in UHPdC

UPV value recorded in this study is slightly lower compared to steel slag heavyweight concrete (SSHWC) which is between 4800 – 5200 m/s (Khalaf et al., 2021). This is due to the denser material of steel slag and the wide range of particle size of steel slag with nano slurry which resulted in higher compactness. However, the UPV value reported in this study is higher compared to other concrete with colemanite such as colemanite coated pumice concrete (Sallı Bideci, 2016). Concrete with colemanite-coated pumice aggregates shows UPV of 3760 – 3950 m/s with increasing colemanite percentage up to 18 % (Figure 4.4). The study also shows the optimum addition of colemanite-coated pumice aggregates at 7.5% based on the

maximum value of UPV and compressive strength. However, the UPV value of the concrete is lower compared to UHPdC which indicates less compactness and this is also shown in low compressive strength that recorded a maximum value of only 29.4 MPa. Overall, UHPdC with colemanite shows higher quality of microstructural hence superior mechanical performance.

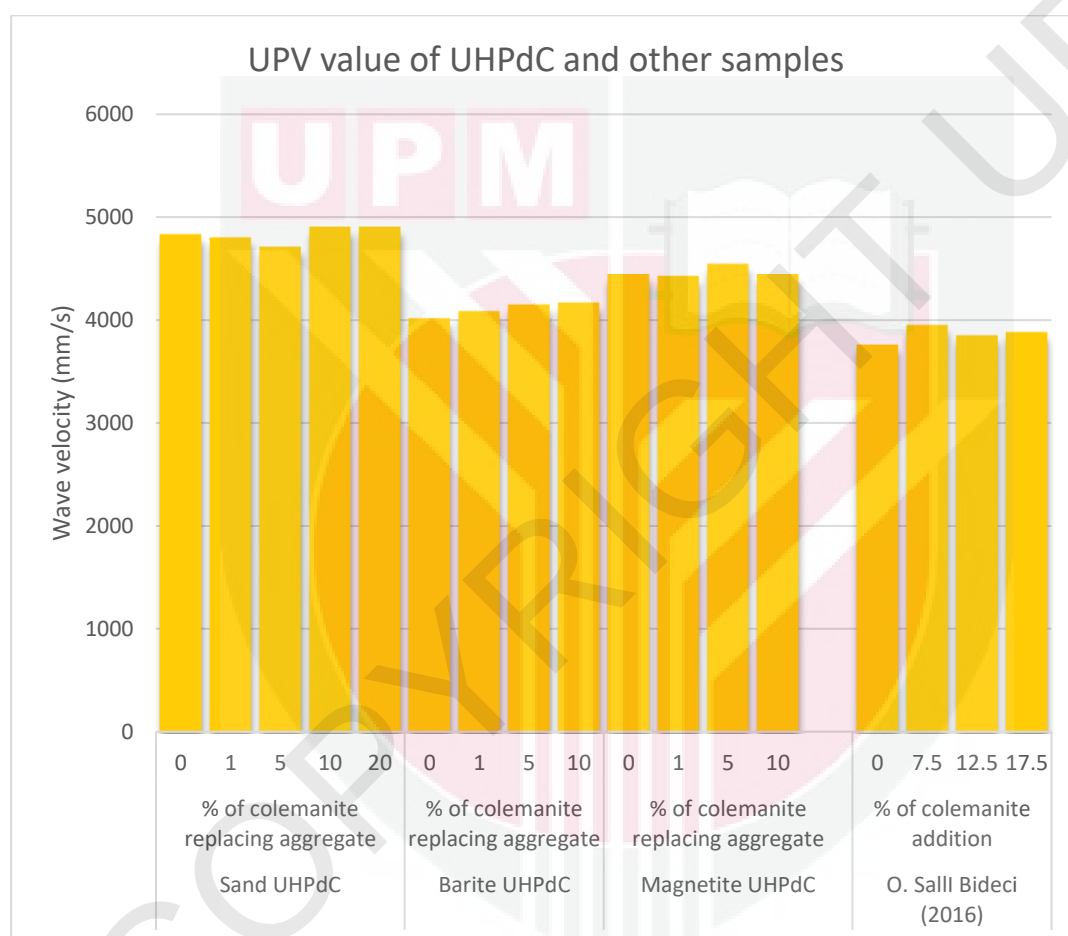


Figure 4.4 : UPV result comparison between this study and Bideci (2016)
(Source : Sallli Bideci, 2016)

Figure 4.5 shows an SEM photo of magnetite UHPdC with 5 % colemanite replacement. Circular-shaped pores are detected having a diameter of 0.2 – 0.3 mm which could be due to entrapped air or steel fibre (Figure 4.5a). A smaller pore sized at 0.164 mm is detected between magnetite particles which

indicates a lack of fine-sized particles of the aggregate and the inability of cement paste to remove entrapped air and form better adhesion to the aggregate. Furthermore, clumping of coarse magnetite prevented better adhesion with cement paste hence leading to the creation of pores (Figure 4.5c). Wider distribution of particle size of magnetite would result better microstructure. However, the adhesion between magnetite and cement paste is dense and solid with no visible pores (Figure 4.5c)

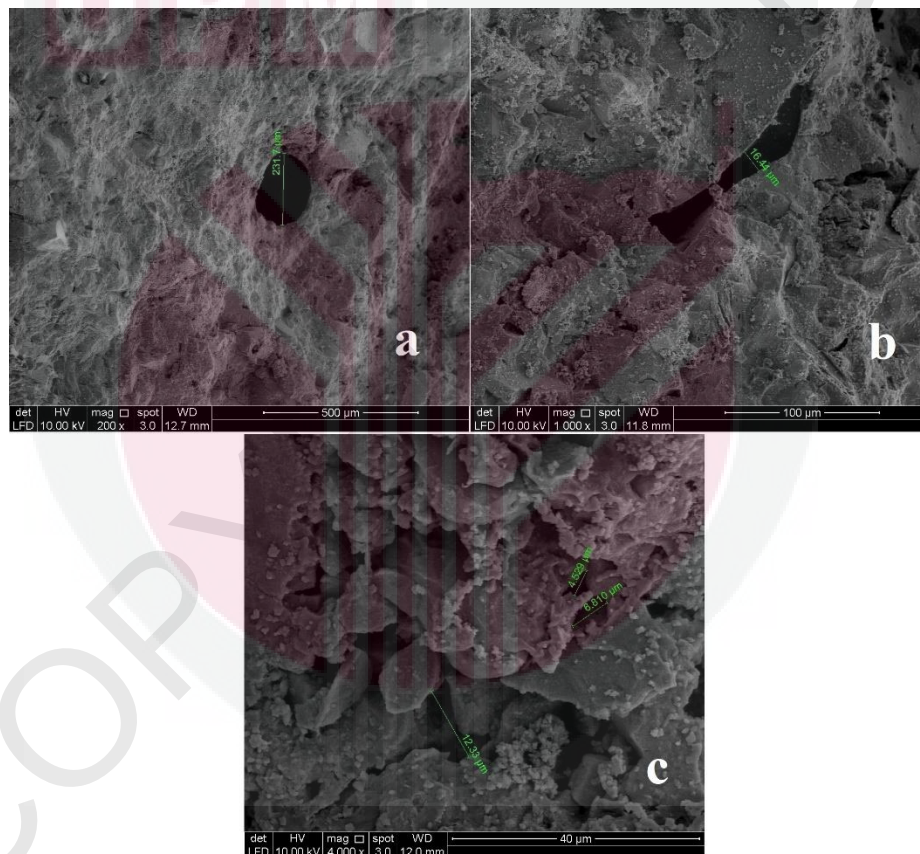


Figure 4.5 : SEM photo of Magnetite UHPdC with 5% colemanite replacement (UM95C5)

At the same percentage of colemanite replacement, barite UHPdC also shows a good interfacial transition zone with dense adhesion between cement paste and aggregate (Figure 4.6) This is indicated in 200 × and 1000 × magnification

where barite and cement paste are mixed homogeneously with good adhesion (Figure 4.6a and b). There are no visible voids between hardened cement paste and barite aggregate. However, at $4000\times$ magnification, micropores are found between cement paste and barite with a diameter of $2\text{--}6\text{ }\mu\text{m}$ which may be due to external forces from the sampling effort (Figure 4.6c). This is based on the localised position of micropores and the surrounding areas show a solid interfacial transition zone between barite and cement paste. However, larger pores with diameters between $200\text{--}300\text{ }\mu\text{m}$ are observed at lower magnification ($200\times$) which could be due to entrapped air (Figure 4.6a). This is due to perfectly round shape of these pores which are most likely formed by air.

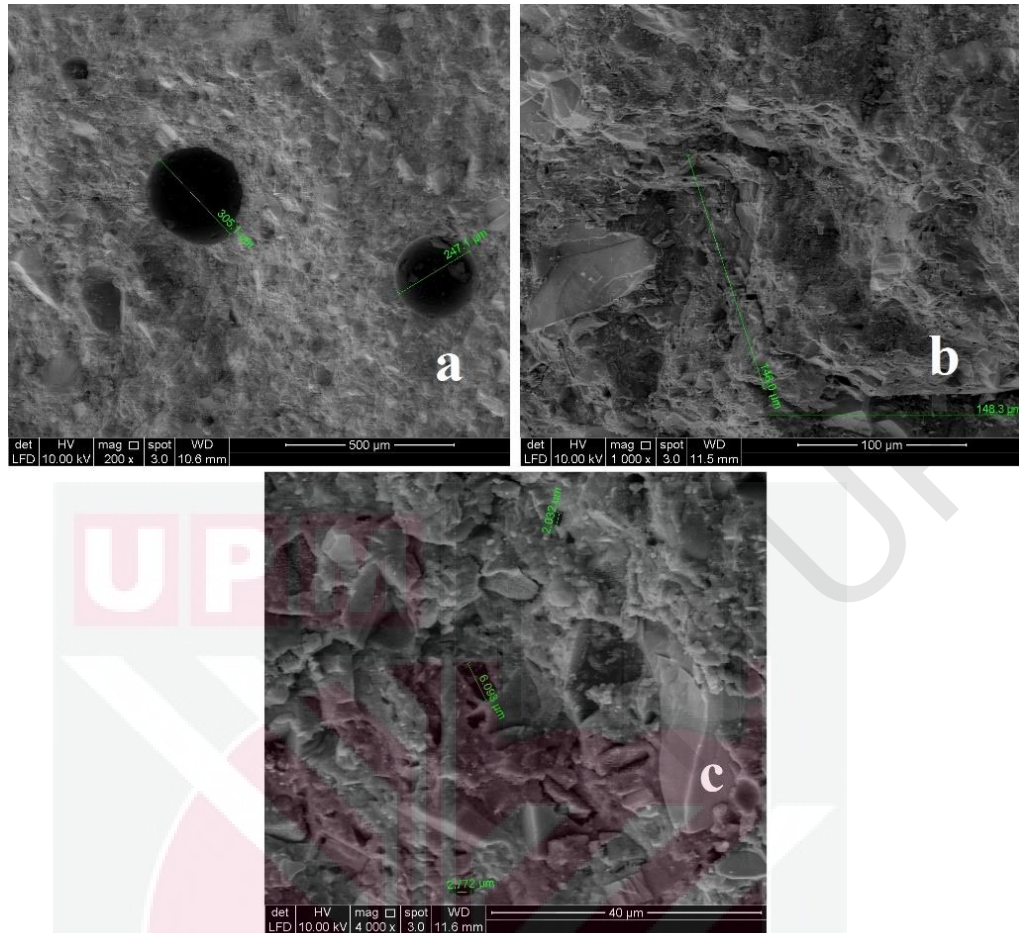


Figure 4.6 : SEM photo of barite UHPdC with 5 % colemanite replacement

For sand UHPdC, pores are observable at 200 × magnification only which indicates compactness and better adhesion between cement paste and sand (Figure 4.7a). This is also proved by the image at 1000 × magnification which shows no pores at the interfacial transition zone between the smooth surface of large sand particles and cement paste (Figure 4.7b). However, Figure 4.7c indicates huge numbers of very fine-sized particles that are not shown in magnetite and barite UHPdC. This could be fragments of colemanite which indicate a relatively high amount of colemanite in sand UHPdC composition compared to other UHPdC. These fine particles formed a solid microstructure

with cement and sand as shown in Figure 4.7d but the adhesion is weak due to the excessive presence of colemanite (Gencel et al., 2010).

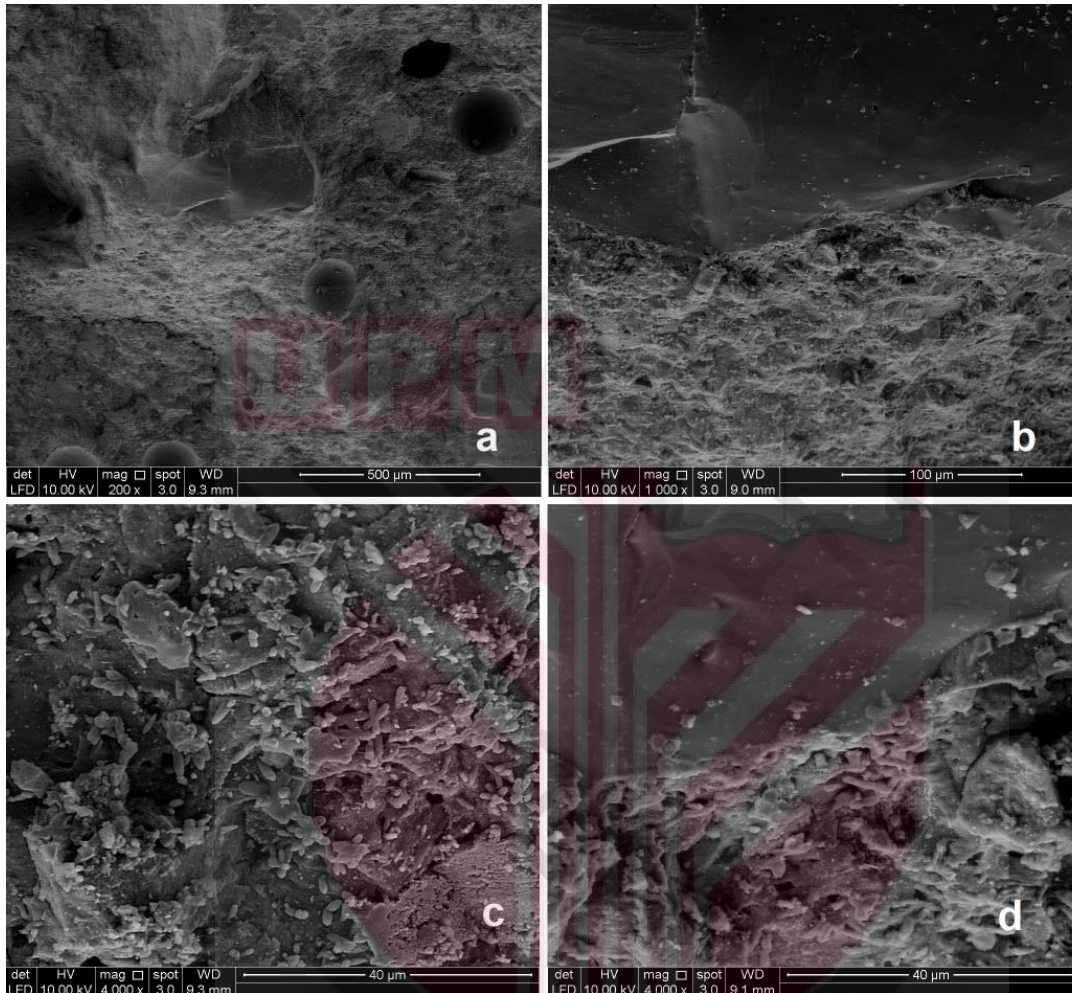


Figure 4.7 : SEM photo of sand UHPdC with 5 % colemanite replacement

4.3 Effect of colemanite replacing the main aggregate on compressive strength

Colemanite replacing the main aggregate at the optimum amount resulted in an improvement of compressive strength. Replacement of sand with colemanite by 1 % resulted in the highest compressive strength in sand UHPdC at 160.3 MPa (Figure 4.8). Further increment of colemanite replacement resulted in reduced compressive strength of sand UHPdC which

indicates the optimum percentage of sand replacement by colemanite at 1%. For magnetite UHPdC, the optimum percentage is at 5% which recorded the highest compressive strength of 162.8 MPa. Further increase in aggregate replacement resulted in lower compressive of magnetite UHPdC at 119 MPa. Barite UHPdC recorded the overall lowest compressive strength. At 5% replacement of barite with colemanite resulted in the highest compressive strength in barite UHPdC at 138.7 MPa .

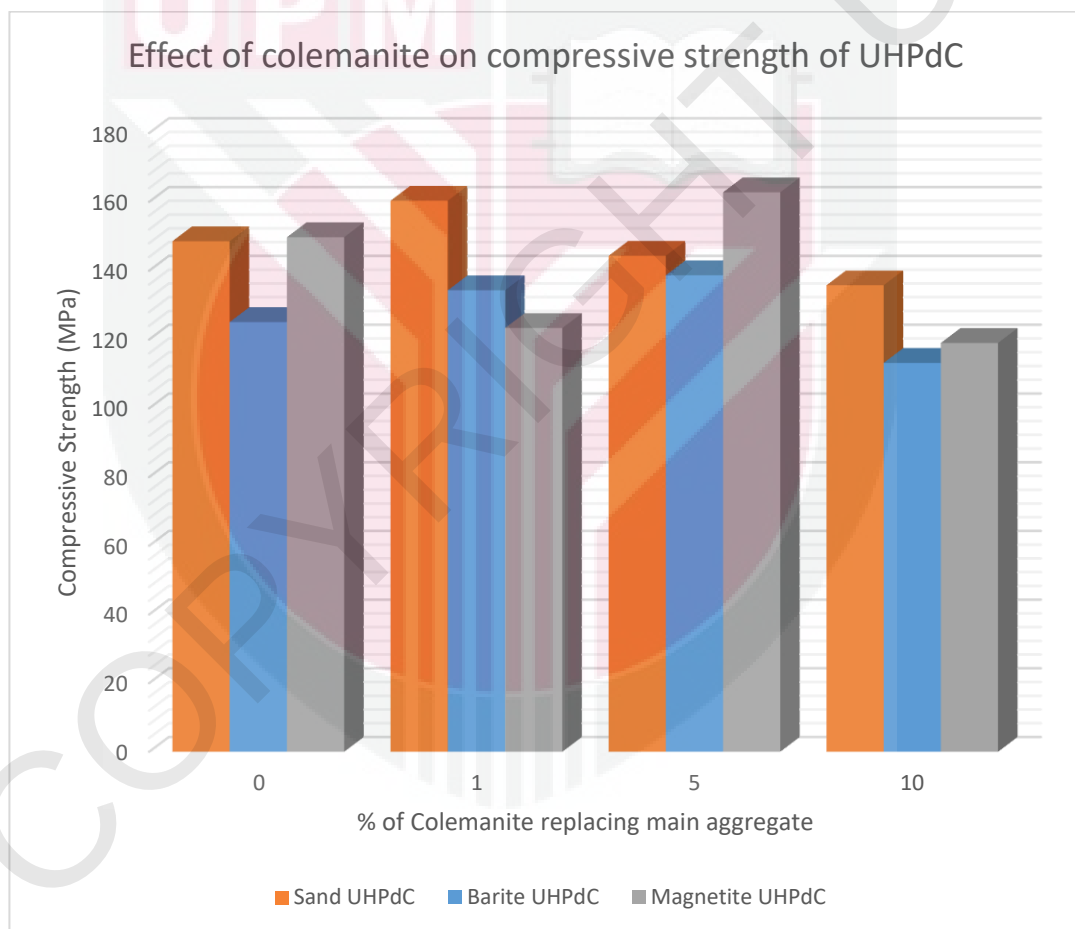


Figure 4.8 : Overall effect of colemanite replacing the main aggregate on compressive strength of UHPdC

Improvement of compressive strength in UHPdC with aggregate replacement is due to the presence of colemanite at the optimum amount. Colemanite

particles are powder-sized based on SEM analysis which is between 12 – 27 μm . These particles act as fillers in the microstructure of UHPdC due to their fine size. Colemanite fills the gap between large aggregates which leads to better interlocking and friction between aggregates which results in higher compressive strength of UHPdC (Akçaoğlu, 2017).

Lower compressive strength that is observed at 10% aggregate replacement in UHPdC is also recorded in study of barite-colemanite concrete with coarser aggregate (Mesbahi et al., 2013). The study recorded a 47% reduction in compressive strength due to 10 % of colemanite addition which is caused by weak adhesion between colemanite aggregates and cement paste. Furthermore, another study indicates that the presence of colemanite in concrete leads to flocculation which forms voids at the interfacial zone between colemanite and cement paste which weakens the adhesion hence reducing the overall compressive strength (Gencel et al., 2010).

In comparison between the three different types of UHPdC, magnetite UHPdC recorded the highest compressive strength followed by sand and barite UHPdC. Magnetite UHPdC recorded 1.6 % higher compressive strength compared to sand UHPdC with 5% colemanite replacing aggregate. The optimum amount of aggregate replacement in magnetite UHPdC is higher compared to sand UHPdC at 1% replacement due to the lack of compactness in magnetite UHPdC. This may be due to a lack of breadth in the particle size distribution of magnetite UHPdC compared to sand UHPdC. The composition of magnetite UHPdC requires a higher amount of colemanite as filler to achieve

maximum compressive strength. However, sand UHPdC able to achieve maximum compressive strength with only 1% aggregate replacement.

For barite UHPdC, its compressive strength is lowest due to the friability of barite compared to sand and magnetite. This is caused by the highly crystalline structure of barite that is susceptible to fragmentation or abrasion (Bodenlos, 1949). A study of barite friability shows that barite aggregate recorded a 40% loss based Los Angeles Abrasion test (González-Ortega et al., 2015). Overall, the compactness of particles' packing in the composition of UHPdC and the strength of the aggregate itself has huge influence on the resulting compressive strength of UHPdC.

4.4 Pore Image Analysis

The surface of the prism sample used in the radiation shielding test is analysed using stereomicroscopes for the distribution of pores. The area of 100 x 100 mm which is located at the centre of the prism as shown in Figure 4.9 is analysed and the percentage is shown in Figure 4.10 and is based on a total of 600 mm² of areas.

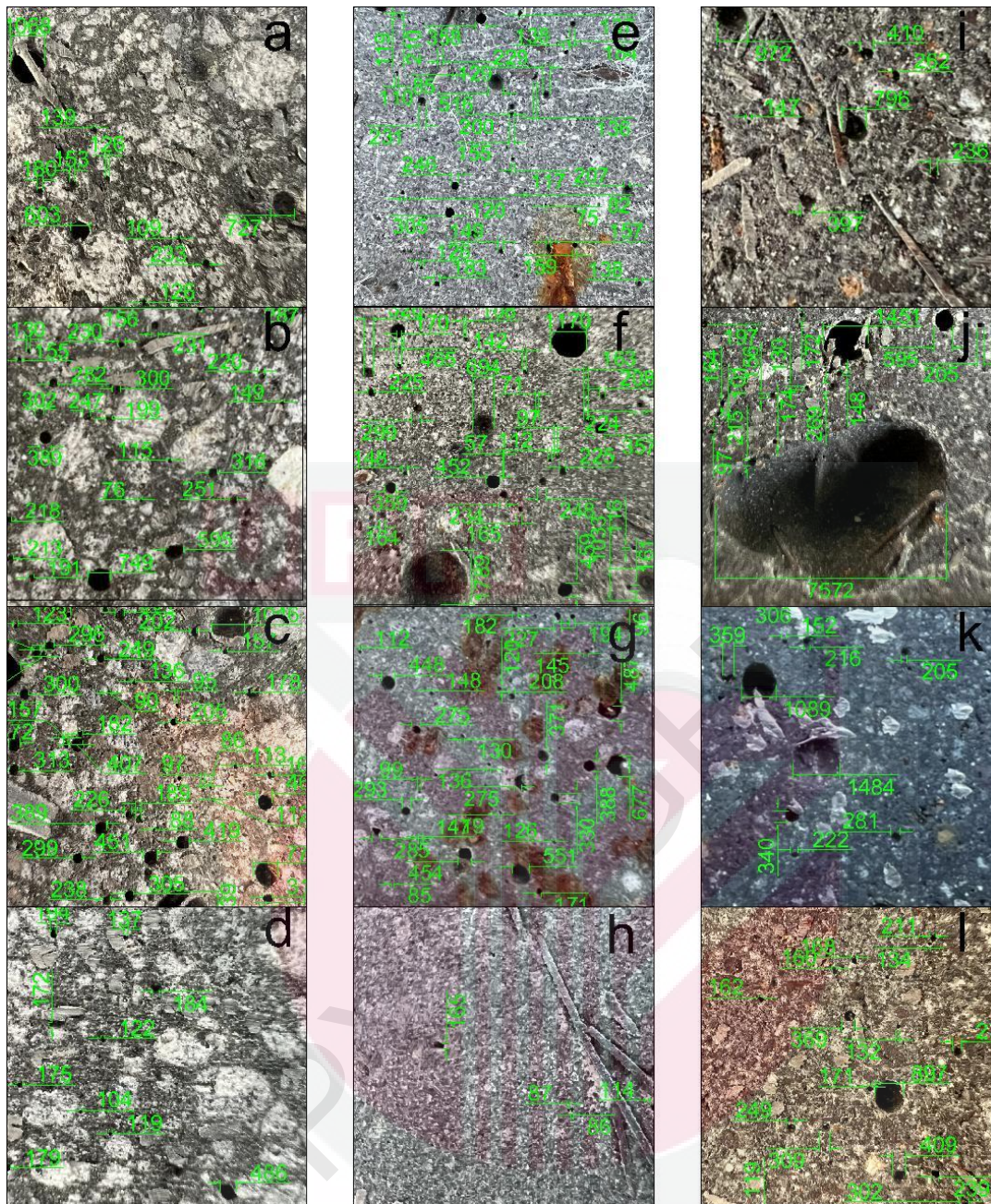


Figure 4.9 : Photos of pores in Sand UHPdC with 0% (a), 1% (b), 5% (c) and 10% (d) colemanite replacement. Photos of pores in Barite UHPdC are shown with 0% (e), 1% (f), 5% (g) and 10% (h) colemanite replacement. This is followed by Magnetite UHPdC with 0% (i), 1% (j), 5% (k) and 10% (l) colemanite replacement

In magnetite UHPdC, the sample with no aggregate replacement shows 3.08% of the pore area (Figure 4.10). Replacement of 1% magnetite with colemanite increased pore area to 10.04%. This sample also shows the largest pore

diameter of 7.572mm. An increase in aggregate replacement by 5% resulted in a reduction of pore area to 1.33 %. A reduction in pore diameter is also observed in the sample which is 1.089 mm. Further colemanite replacement at 10% resulted in a marginal increase in pore percentage to 3.08 % which indicates an optimum replacement of magnetite with colemanite in UHPdC is at 5 %. Furthermore, the total number of pores observed in this mix is the lowest among all samples (Figure 4.11).

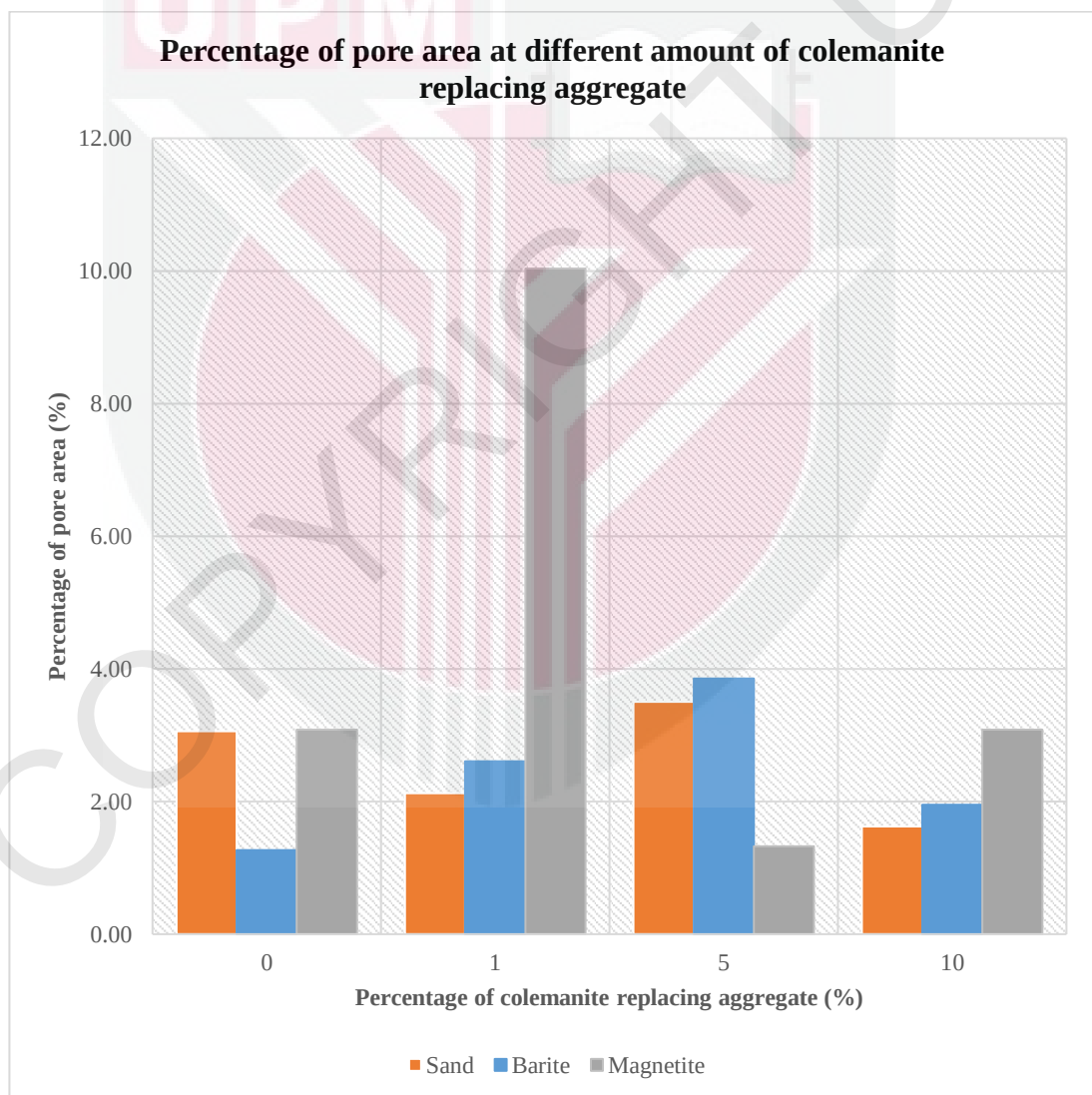


Figure 4.10 : Percentage of pore per area of magnetite, barite and sand UHPdC

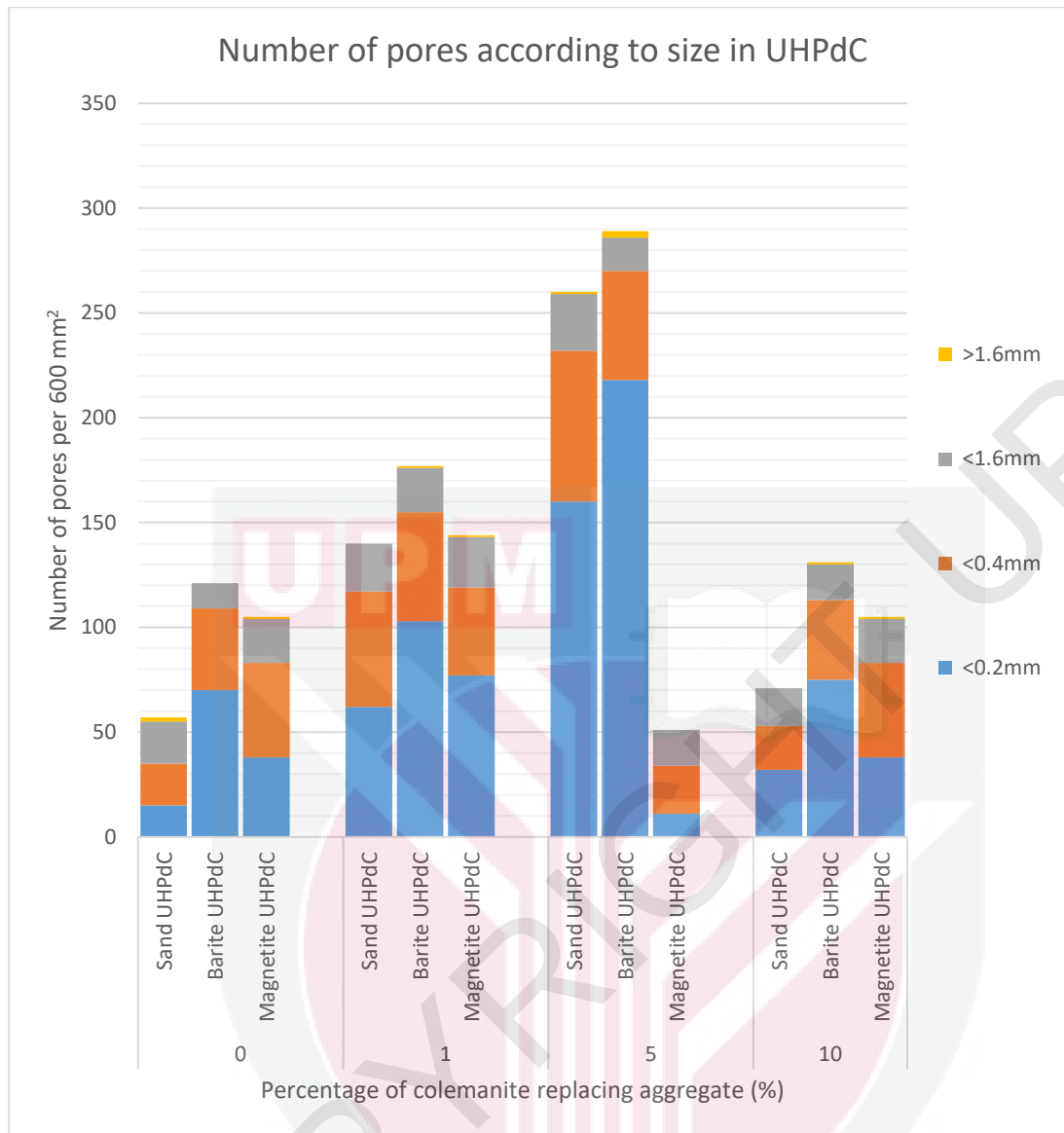


Figure 4.11 : Number of pores per 600 mm² observed in different type of UHPdC based on percentage of aggregate replacement

For barite UHPdC, the lowest percentage of pore area is recorded at 1.27% with 0% colemanite replacement. An increase in colemanite replacing barite in the mix increased the percentage to 3.85% at 5% barite replacement (Figure 4.10). However, at 10% replacement, the percentage of pore area is reduced to 1.95%. Most of these pores have having diameter that is less than 0.2 mm and the number of these small-sized pores is the most in barite UHPdC with 5% colemanite replacing barite. The high percentage of pores may be due to

low workability with the increased presence of fine-sized colemanite. An increase in colemanite percentage increased the surface area of particles that require more free water to form a paste. As a result, the workability of the mix is reduced hence resulting in more air being entrapped during mixing of UHPdC..

In sand UHPdC, the replacement of sand with colemanite by 10% in the mix resulted in the lowest pore percentage at 1.62%. This is followed by 1% replacement which recorded 2.12% of pore area. The sample with 5% replacement recorded almost similar percentage of pore with 0% replacement which is at 3.50%. However, the number of pores in the sample with 5% replacement is higher due to a large number of small-sized pores. The maximum average pore diameter observed with no sand replacement in sand UHPdC is 482.32 mm which is 106.7% larger than sand UHPdC with 5% replacement at 233.33mm (Figure 4.12). Colemanite replacing the finest size of sand in sand UHPdC caused a reduction in several large-sized pores hence lowering the pore area percentage. This is observed up to 5% aggregate replacement. Further replacement resulted in a lower pore area and smaller pore diameter. Based on sand UHPdC alone, the replacement of fine sand with finer-sized particles of colemanite allows the gap between large sand particles to be filled with colemanite which creates a denser microstructure. This is because the gap between particles of the mixture contributes to entrapment of air and pores creation (Janković et al., 2016).

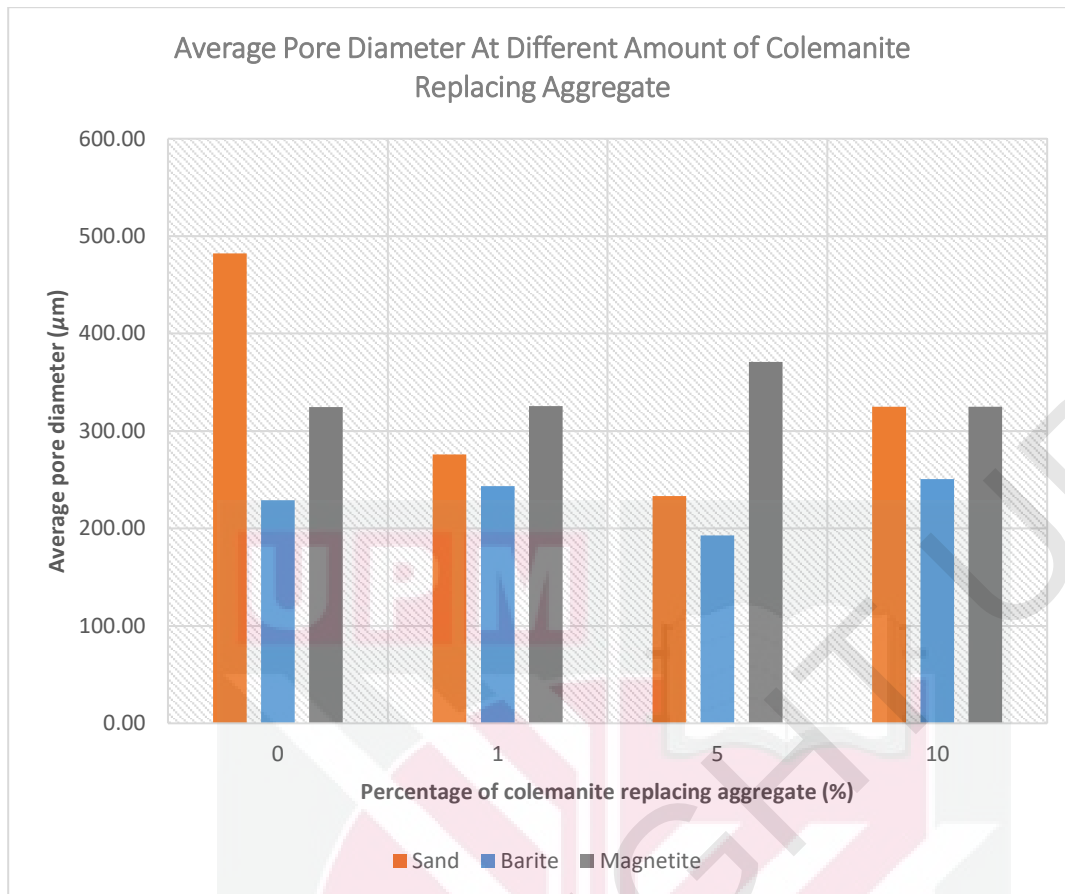


Figure 4.12 : Average pore diameter observed in different type of UHPdC based on percentage of aggregate replacement

A study that is related to this area is a study on the effect of boron-basalt fibre addition in concrete which also analyzes the pore produced in the concrete due to fibre addition (Skarżyński, 2020). Based on the percentage of large-diameter pores that is observed in the study, the value is much higher compared to UHPdC (Figure 4.13). Concrete with boron-basalt fibres shows 83% of the pores observed have a diameter of more than 0.5mm and 48.15% of these are sized larger than 1.6mm. This is large compared to UHPdC which recorded the maximum value at 3.5% by sand UHPdC with no aggregate replacement. Hence, UHPdC shows better compactness due to fewer pores in the microstructure and this is also reflected in better compressive strength. This is shown by the low compressive strength recorded in concrete with

boron-basalt fibre which is at 41.29MPa. The study indicates that the presence of boron-basalt fibre in concrete resulted in more pores hence lower compressive strength.

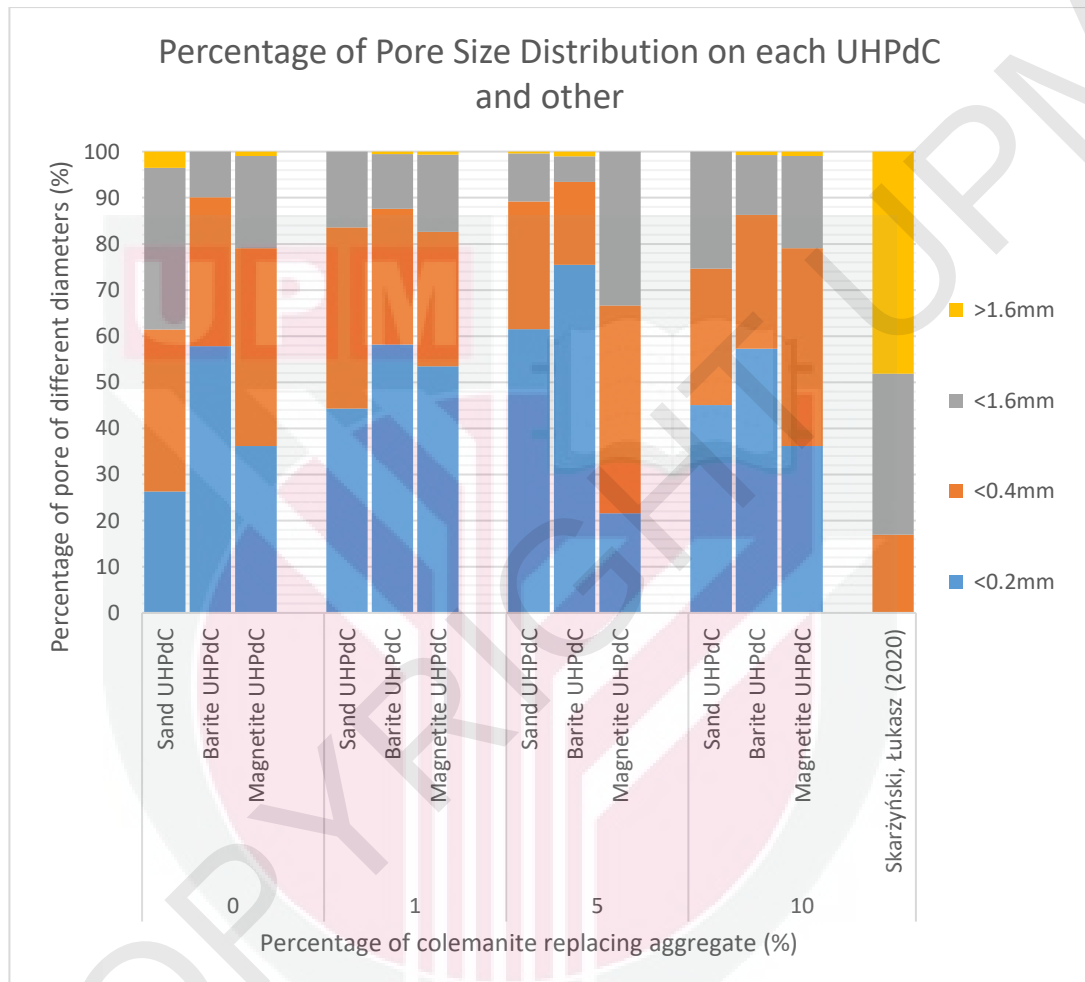


Figure 4.13 : Comparison of percentage by pore diameter with previous study
(Source : Skarżyński, 2020).

Overall, colemanite replacing main aggregate increased pore area. The resulting pores formation in UHPdC correlates with its compressive strength. The highest pore area observed in magnetite UHPdC with 1% replacement correlates with lowest compressive strength recorded. This high percentage of pore area combined with large number of pores and large average pore sizes

contribute to weak points throughout the microstructure. This resulted in poor strength to restrain compressive deformation. In opposition to this, magnetite UHPdC with 5% aggregate replacement recorded the lowest pore area with the lowest number of pore and this sample recorded the highest compressive strength among all magnetite UHPdC samples.

For barite UHPdC, the replacement of barite with 5% colemanite resulted in the highest compressive strength as the average pore diameter is the lowest in this mixture despite having a large number of pores. This is because most of the pores are less than 0.2mm diameter which prevents concentration of weak points as posed by large pores. This is indicated by barite UHPdC with 10% replacement which recorded the lowest compressive strength due to a larger average pore diameter despite having a lower percentage of pore area. Furthermore, denser colemanite presence between barite and cement paste weakened the adhesion and strength of the UHPdC (Gencel et al., 2010). This is also observed in magnetite and sand UHPdC at the same percentage of aggregate replacement which recorded the lowest compressive strength despite having a small pore area. For sand UHPdC, 1% replacement recorded the highest compressive strength which correlates with low pore area, low average of pore diameter and a small number of large-size pores. It can be concluded that the formation of pores in terms of number and size affects the overall compressive strength of UHPdC.

4.5 Effect of Colemanite Replacing Aggregate on Radiation Shielding Properties

Shielding properties are measured against gamma and neutron radiation. Gamma ray is sourced from Cs-137 and Co-60 while neutron ray is sourced from AmBe. Cs-137 possesses a lower energy level compared to Co-60 while AmBe emits neutron particles which is different compared to gamma radiation. Overall, the presence of colemanite is beneficial in reducing neutron radiation.

4.5.1 Linear Attenuation Coefficient

In terms of gamma-ray shielding, the replacement of the main aggregate with colemanite improves shielding properties at an optimum amount. Figure 4.14 shows the linear attenuation coefficient, μ (cm⁻¹) recorded based on exposure to Cs-137 for each type of UHPdC with increasing colemanite replacement. At 10% colemanite replacement, sand UHPdC recorded a slight increment of μ value which is from 0.1791 to 0.1844 cm⁻¹. However, a slight reduction of 5% in μ value is recorded in sand UHPdC with 5% colemanite replacing sand which is 0.1701 cm⁻¹. Barite UHPdC also recorded a marginal reduction of μ value at 5 % barite replacement which is 6.2%. Maximum replacement of barite with colemanite resulted in 0.2147 cm⁻¹ which differs by 2.1% compared to 0% replacement. In magnetite UHPdC, μ value is increased from 0.2155 to 0.2195 cm⁻¹ with 1% replacement of magnetite which is a 1.9% increment. However, a further increase in magnetite replacement resulted in a very small reduction in shielding to 0.2179 and 0.2177 cm⁻¹ at 5 and 10% of replacement respectively. This is a 0.1% difference compared to the 0% replacement of magnetite. Overall, shielding changes between 0.1 – 6.2% with the

replacement of the main aggregate with colemanite in all types of UHPdC. A similar trend is also observed in the shielding of Co-60.

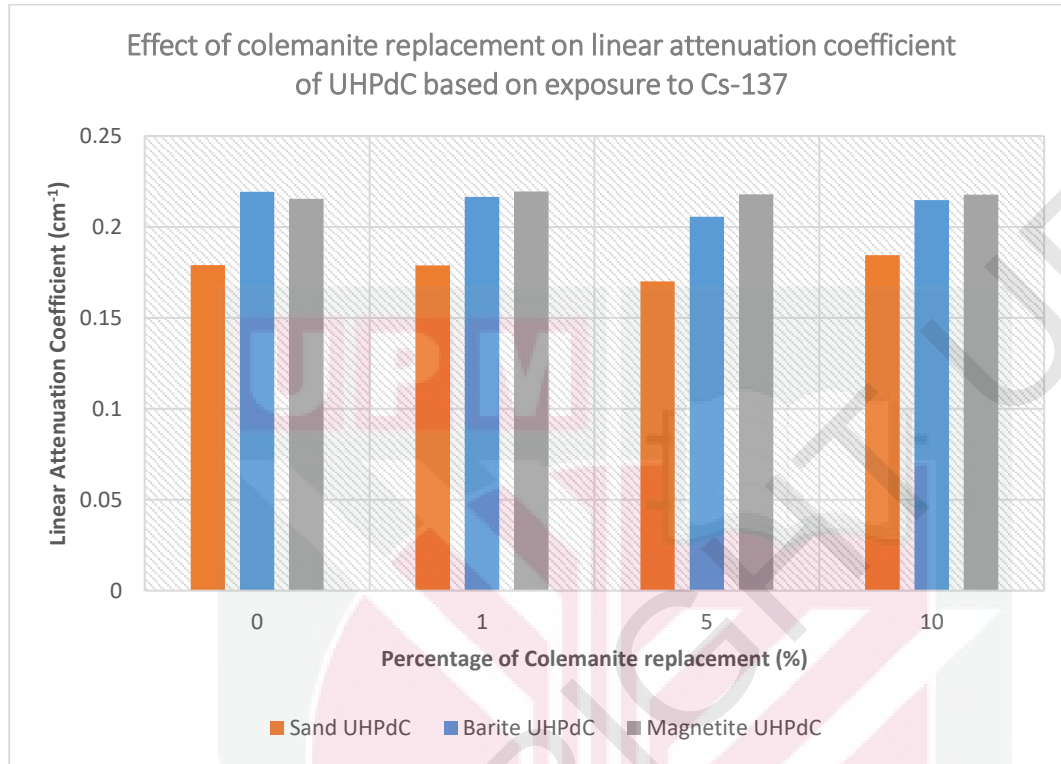


Figure 4.14 : Graph of Linear Attenuation Coefficient based on exposure to Cs-137 versus percentage of colemanite replacement in various UHPdC

Overall, the linear attenuation coefficient, μ value recorded based on Co-60 source by all UHPdC is lower by 30 – 35% compared to Cs-137 which is due to the higher energy level of the gamma source (Figure 4.15). As observed with the Cs-137 source, the changes in μ value is small with an increase in the replacement of the main aggregate with colemanite. Sand UHPdC recorded 0.1222 cm^{-1} of μ value with no colemanite and recorded the highest value of 0.1246 cm^{-1} at 10 % replacement which is 0.2 % increment. At 1% and 5 % replacement of sand with colemanite recorded μ values of 0.1162 and

0.1171 cm⁻¹ respectively which is a reduction of around 5% compared to the sample with no colemanite.

Barite UHPdC recorded a 4.5% reduction of μ value to 0.1361 cm⁻¹ at 5 % aggregate replacement. At 10 % replacement, Barite UHPdC recorded a slight increment of μ value by 0.7 % to 0.1425 cm⁻¹ compared to 0% replacement at 0.1415 cm⁻¹. Magnetite UHPdC recorded the highest μ value at 0.1491 cm⁻¹ with 1% replacement of aggregate which is a 3% increment compared to 0% replacement. Further increment of aggregate replacement recorded a 1.5% higher value of 0.1468 and 0.1467cm⁻¹ at 5 and 10% aggregate replacement respectively.

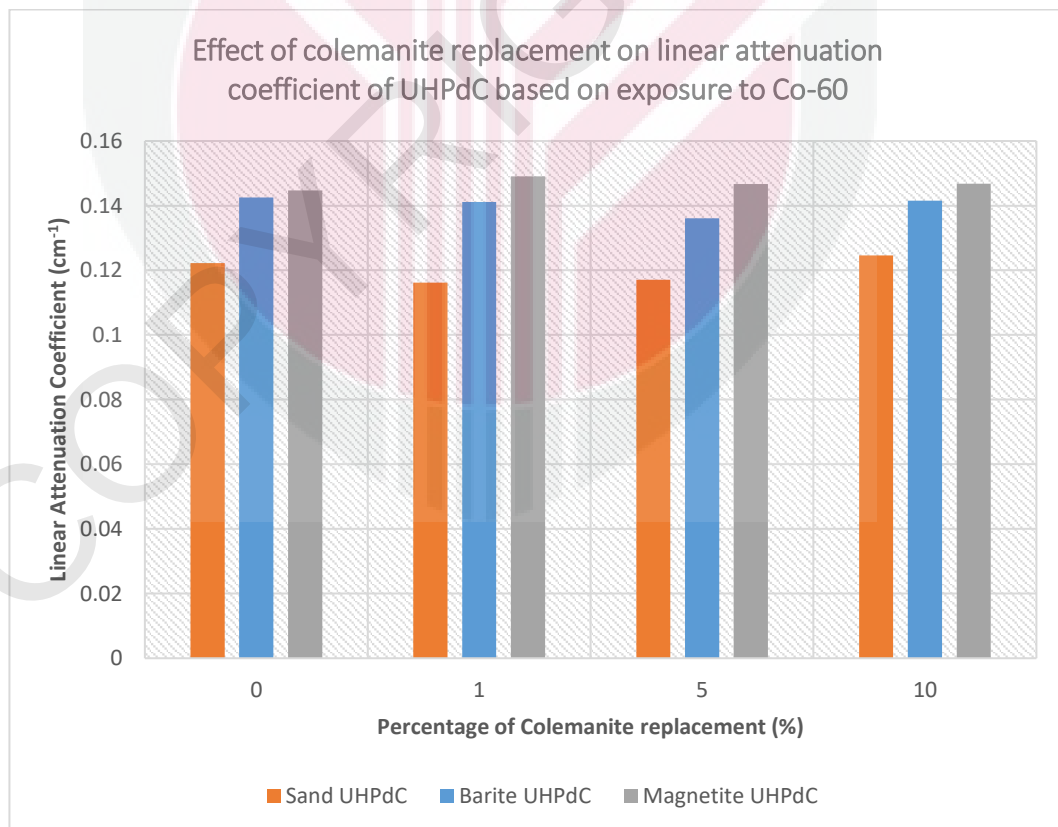


Figure 4.15 : Graph of Linear Attenuation Coefficient based on exposure to Co-60 versus percentage of colemanite replacement in various UHPdC

Both sources of gamma ray show a visible reduction in shielding with 5% aggregate replacement in barite and sand UHPdC compared to magnetite UHPdC. Barite and sand UHPdC with 5% aggregate replacement recorded up to 6.2% reduced in μ value compared to 0% aggregate replacement. This may be due to the combined effect of high numbers of pores per area and fine particle size of the main aggregate. It is observed that barite UHPdC with 5% colemanite-replacing has 289 nos. of pore per 600 mm² which is also observed in sand UHPdC which recorded a total of 260 nos. of pore per 600 mm² (Figure 4.14). On average, this is 91% higher compared to magnetite UHPdC which recorded a maximum of 144 nos.

A total 75% and 62 % of pores observed in barite and sand UHPdC respectively are sized less than 0.2mm and scattered across the internal structure of concrete. Pores reduced gamma ray shielding properties and high numbers of pores increase the probability of the radiation passing through less dense section during experimental work. This resulted in higher radiation count and lower shielding recorded. Furthermore, finer barite particles compared to magnetite being replaced with finer colemanite particles lead to more micropores created hence lower gamma shielding property. As shown in SEM analysis, barite has a maximum diameter of 66 μ m compared to a maximum size of 339 μ m observed in magnetite and this is replaced with colemanite with a maximum diameter of 22 μ m.

Overall, it is observed that the replacement of aggregate with colemanite between 1 – 10% has a slightly reducing effect on radiation shielding as opposed to the large negative impact shown in physical and mechanical

properties. This may be due to the amount being very small with a very fine particle size of colemanite and scattered uniformly throughout the concrete matrix that leads to minimal effect on the gamma shielding of UHPdC. Heavier and larger aggregate of magnetite, barite and sand compared to colemanite dominates the volume of concrete structure hence providing a shielding effect against gamma rays. A study on colemanite replacing barite in normal-strength concrete also recorded a minimal reduction between 3.4 – 4.9% of μ value due to 5 – 15% barite replacement (F. Demir et al., 2011). However, the study also recorded a higher value of gamma-ray shielding in samples with a coarser and wider range of particle size of barite aggregate.

In comparison between all types of UHPdC studied Magnetite recorded the highest μ value of 0.2195 cm⁻¹ with 1% aggregate replacement. While barite UHPdC recorded the highest value at 0.2193cm⁻¹ with 0% aggregate replacement. These values are 19% higher compared to the highest recorded μ value by sand UHPdC. This is due to the presence of heavyweight aggregate of either magnetite or barite in the UHPdC which resulted in denser concrete hence higher gamma ray attenuation.

At a higher energy level of gamma source, magnetite UHPdC also recorded the highest μ value which is 0.1491cm⁻¹. This is followed by barite UHPdC and sand UHPdC which recorded the μ value of 0.1425 and 0.1246cm⁻¹ respectively. These values are translated into the thickness required to shield 99% of gamma rays as in Figure 4.16. The thickness required is based on TVL and it is calculated using Eq. 3.6.

As shown in Figure 4.16, there is a strong correlation between the shielding thickness required and density of UHPdC for each source of gamma-ray. As the density increases, the thickness required to shield 99% of gamma ray from Cs-137 and Co-60 is reduced with steep changes shown between sand UHPdC and heavyweight UHPdC. Figure 4.16 also shows that sand UHPdC requires at least 12.5 and 18.5cm of concrete thickness to fully shield against Cs-137 and Co-60 respectively. Barite UHPdC requires at least 10.5 and 16cm of thickness against Cs-137 and Co-60 respectively. Magnetite UHPdC requires slightly thinner sections of at least 10.5 and 15.5cm against Cs-137 and Co-60 respectively. It can be concluded that denser UHPdC resulted in higher shielding properties.

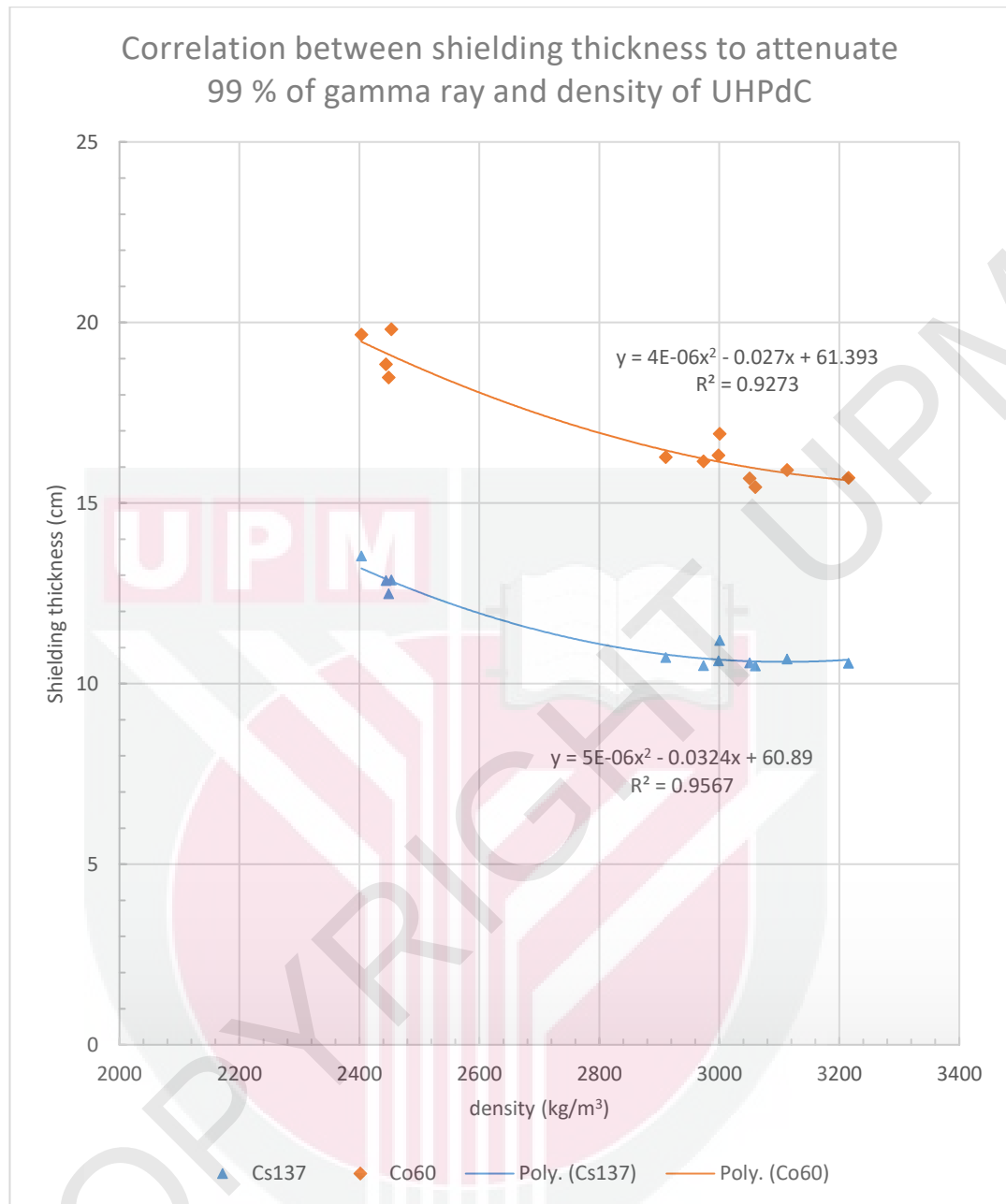


Figure 4.16 : Correlation between shielding thickness required to attenuate 99 % of gamma ray and UHPdC density

4.5.2 Macroscopic Removal Cross Section

For neutron shielding, an increase in the percentage of colemanite replacing the main aggregate resulted in an increment of neutron shielding. This is shown in Figure 4.17 with an upward trend in $\Sigma_R(E_n)$ with an increase in the percentage of aggregate replacement. Sand UHPdC recorded the lowest Σ_R

(E_n) value at 0.0265 cm^{-1} . The presence of 1 % colemanite in the mixture resulted in a 7% increment of removal cross section to 0.0284 cm^{-1} . The highest recorded value is at 10 % sand replacement at 0.036 cm^{-1} which is a 35.8 % increment.

At 10% colemanite replacing barite aggregate, barite UHPdC recorded 0.0452 cm^{-1} which is a 66.2 % increment compared to 0% replacement that recorded $\Sigma_R (E_n)$ value at 0.0272 cm^{-1} . Reduction in the percentage of colemanite replacing barite resulted in lower $\Sigma_R (E_n)$ values which is 0.0365 and 0.0292 cm^{-1} at 5 and 1% of colemanite replacing barite respectively.

Magnetite UHPdC recorded the highest $\Sigma_R (E_n)$ at 0.0474 cm^{-1} with 10% aggregate replacement. This is 54.9% higher compared to the sample with 0% colemanite in the mixture. Overall, the presence of colemanite improves the neutron shielding property of UHPdC even at 1%. This is due to the presence of boron in colemanite which is a neutron absorber that captures thermal neutrons hence resulting in higher neutron radiation shielding (Piotrowski et al., 2015).

The neutron radiation source used in this test emits fast neutrons which are moderated to thermal neutrons by elastic collision with hydrogen atom. Hydrogen exists in UHPdC mostly in cement paste of C-S-H gel and as UHPdC contains a high amount of cement in the mixture, this provides a high amount of hydrogen element hence more collisions and moderation of neutrons to thermal neutrons. As the presence of colemanite in the mixture increases, the absorption of thermal neutrons is also increased which leads to high neutron

shielding properties. Fast neutrons emitted from the AmBe source are also moderated to thermal neutrons due to inelastic collision with heavy elements of barite and magnetite in UHPdC. This resulted in higher shielding recorded in barite and magnetite UHPdC.

Overall, the highest $\sum_R(E_n)$ is recorded by magnetite UHPdC at 0.0474 cm^{-1} . This is followed by barite and sand UHPdC at 0.0452 cm^{-1} and 0.036 cm^{-1} respectively. It is shown that the presence of a heavyweight aggregate of either magnetite or barite resulted in higher neutron shielding. This is due to more moderation of neutron provided by heavyweight aggregate compared to sand along with elastic collision of neutron and hydrogen. A study also found magnetite concrete recorded a 9.0% higher $\sum_R(E_n)$ value compared to ordinary concrete which is due to the heavy iron element in magnetite (Zalegowski et al., 2020). The study recorded 0.0996 cm^{-1} of $\sum_R(E_n)$ value by magnetite concrete which is higher compared to this study. This may be due to the different source used in the study which is Pu-Be. The study also used a thicker dimension of the test sample which is a $500 \times 500 \times 500 \text{ mm}$ slab and the value of $\sum_R(E_n)$ is calculated using computer programs.

Another study that used an Am-Be source recorded a range of $\sum_R(E_n)$ values between $0.065 - 0.095 \text{ cm}^{-1}$ with increasing latex presence in the concrete samples (Malkapur et al., 2015). This is higher compared to UHPdC's $\sum_R(E_n)$ value despite using the same type of source which is Am-Be. However, the detector used in the study is the REM counter detects dose rate values which is different compared to this study. However, the study indicates that an increase in hydrogen presence in the concrete improves its neutron shielding.

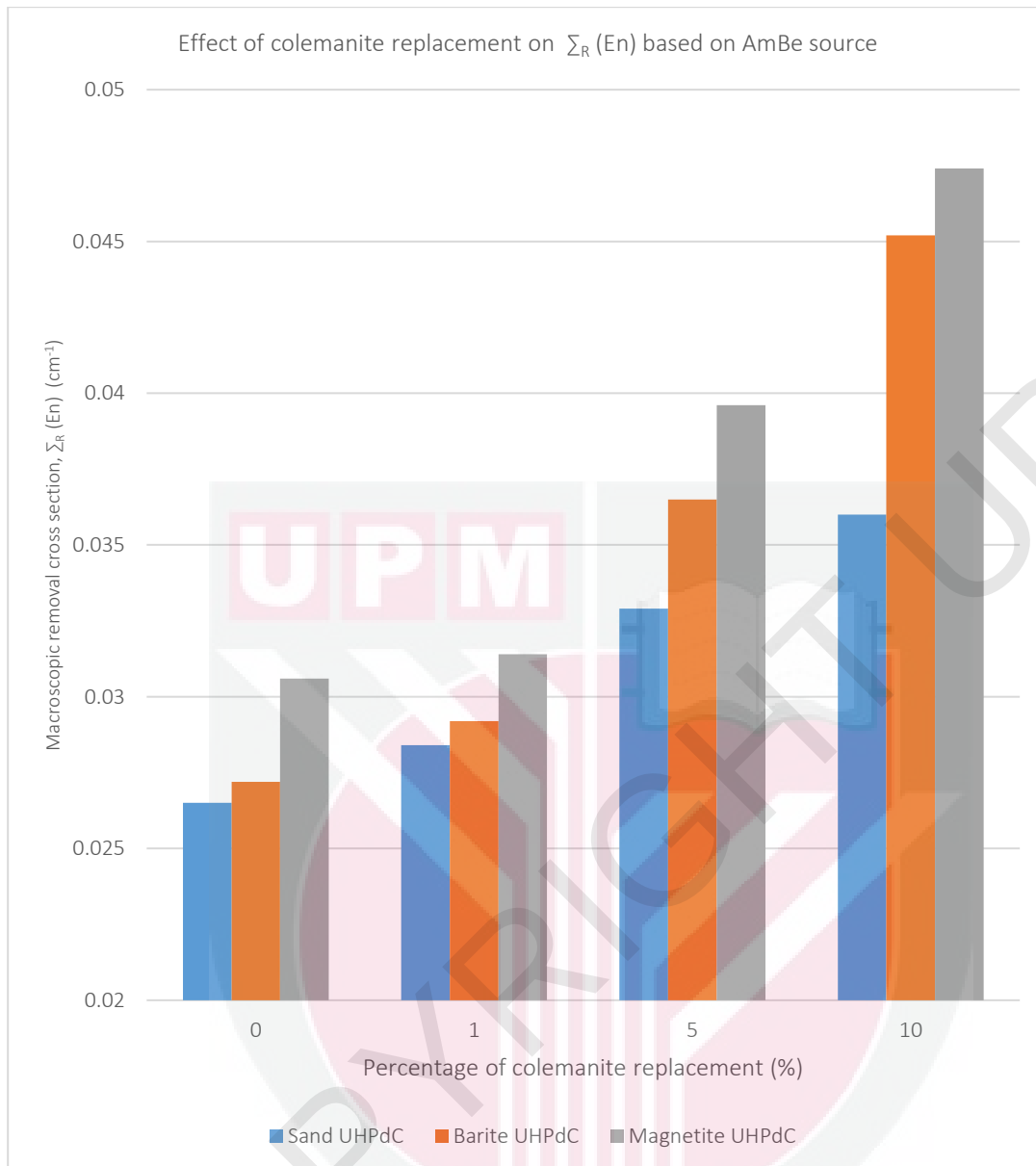


Figure 4.17 : Effect of colemanite replacing aggregate on $\Sigma_R (E_n)$ value of UHPdC based on AmBe source

The value of $\Sigma_R (E_n)$ in this study is further analysed into the required shielding thickness of UHPdC to remove 99% of neutrons radiation or the tenth value layer, TVL (Figure 4.18). A higher value of $\Sigma_R (E_n)$ resulted in lower TVL. Magnetite UHPdC shows the lowest thickness required followed by barite and sand UHPdC. At 5% magnetite replacement with colemanite, only 58cm of required thickness compared to 63 and 70 cm required by barite and sand

UHPdC with the same amount of colemanite respectively. The least thickness of magnetite UHPdC is only 49cm with 10% of colemanite replacing aggregate which allows for wide application as a biological shield.

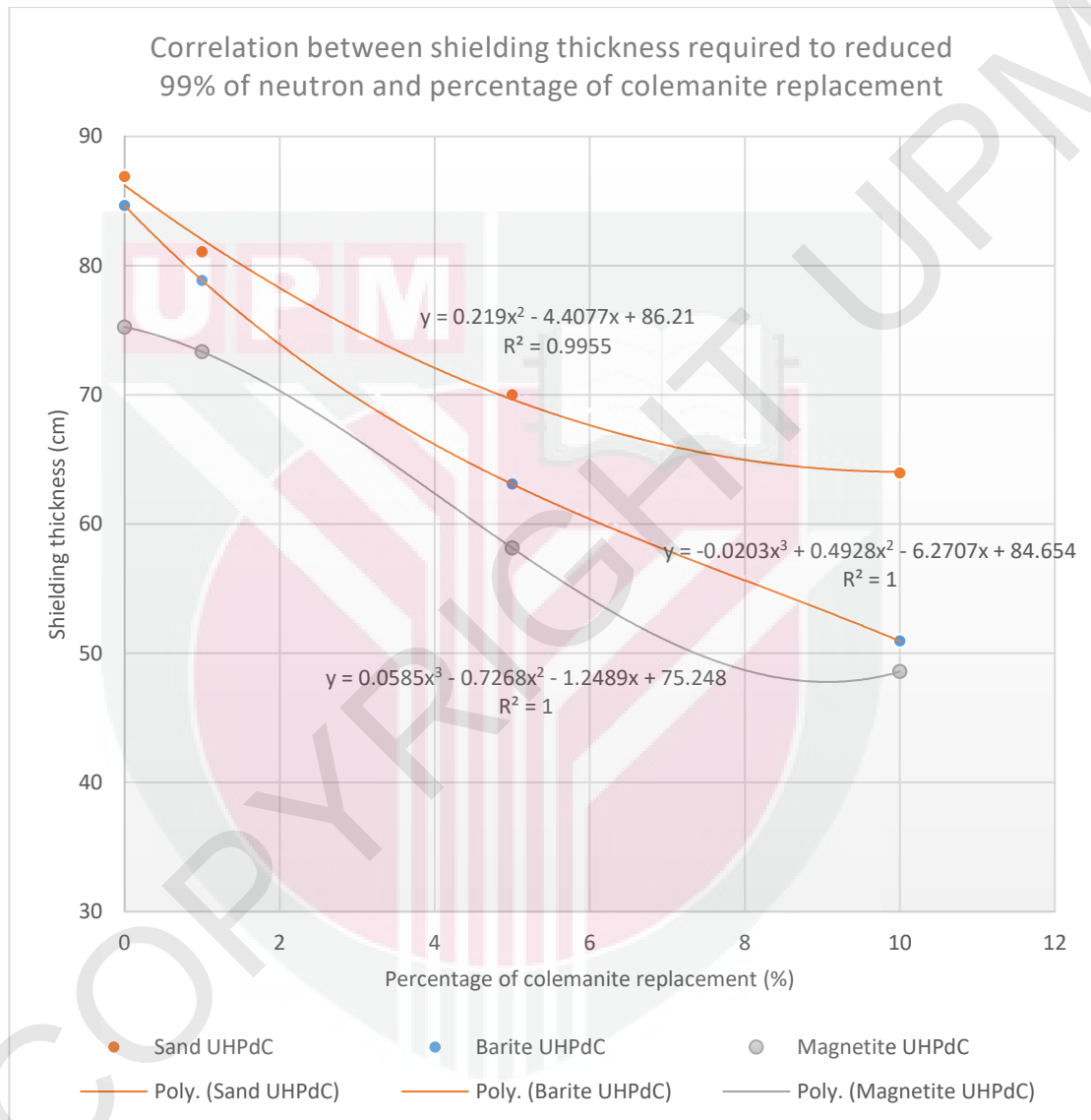


Figure 4.18 : Shielding thickness required for sand, barite and magnetite UHPdC to attenuate 99 % neutron from AmBe source

4.6 Effect of PVA Fibre Addition on Workability, Density and UPV Test

The addition of PVA fibre in UHPdC with 5% aggregate replacement resulted in an increase in water demand in dry mixture and lower workability. (Figure 4.19). Addition of 0.25 – 0.5% by volume of PVA fibre in sand UHPdC increased of 5% in the water-to-binder ratio. Further addition of PVA to 0.75% by volume resulted in a 9% increase in water-to-binder ratio in this type of UHPdC.

For barite UHPdC, addition of 0.25 – 0.5% by volume of PVA fibre resulted in an increase in the water-to-binder ratio from 0.21 to 0.22. Further increase of PVA percentage to 0.75 % resulted in a 9% higher in terms of water-to-binder ratio which is 0.24. This staggered increasing trend of water-to-binder ratio due to the increase addition of PVA fibre is observed only in sand and barite UHPdC but not in magnetite UHPdC. Ratio of water-to-binder in magnetite UHPdC is around 0.23 with increasing addition of PVA fibre.

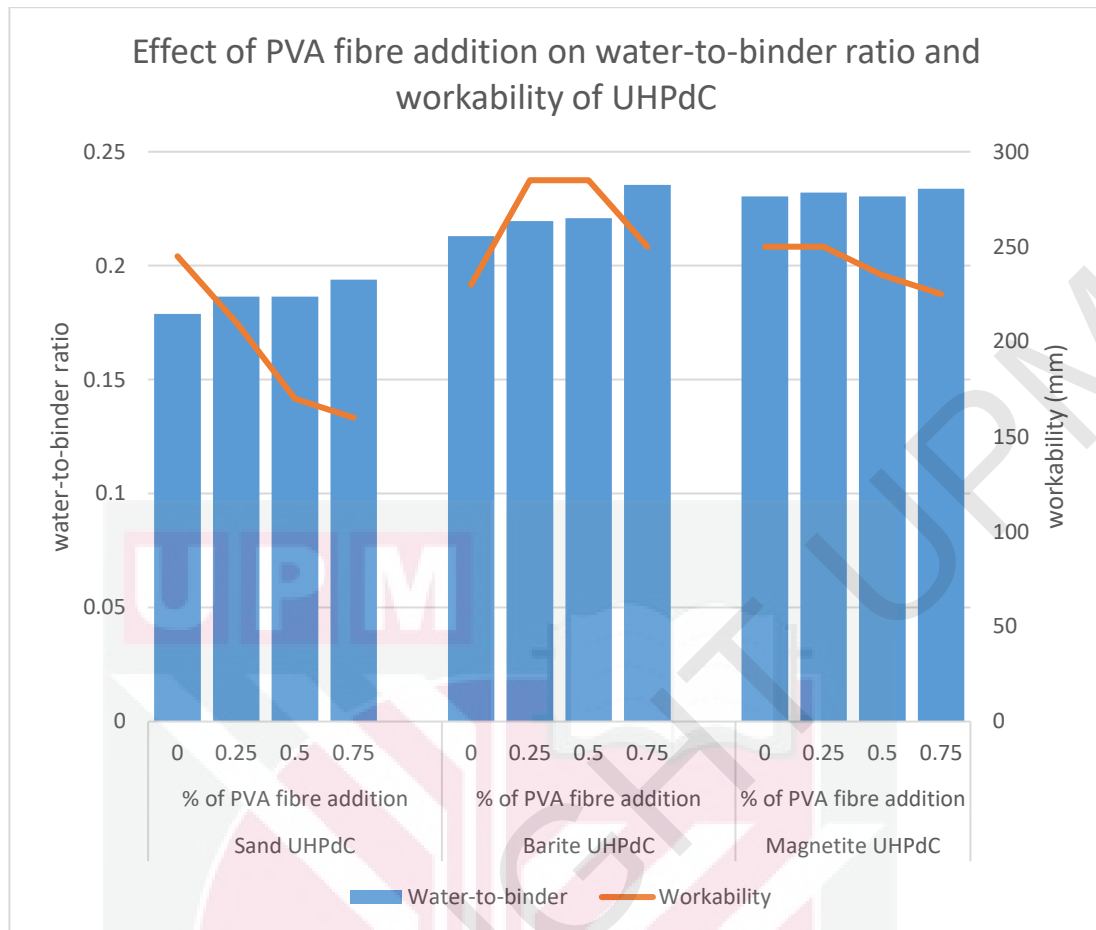


Figure 4.19 : Graph of water-to-binder ratio and workability versus percentage of PVA fibre addition in various UHPdC

Even though the mixes can form UHPdC, the workability of magnetite UHPdC is decreasing with increasing PVA addition. This is shown in 0.5 and 0.75% PVA in magnetite UHPdC which recorded 14 and 10% lower workability respectively compared to 0 % PVA fibre addition. Workability of sand UHPdC decreases with increasing amount of PVA fibre in the mix composition despite the increased ratio of water to cement. This indicates that presence of PVA fibre greatly reduced the workability of sand UHPdC compared to magnetite UHPdC. The effect of fibre on the workability of UHPdC depends on the type of aggregate as different aggregate has different indices of physical and geometric (Zeyad et al., 2022). More angular and coarser aggregate in sand

UHPdC compared to magnetite UHPdC caused more friction between fibre and aggregate. This leads to lower workability and higher water demand in the dry mixture. Less angular and smaller aggregate such as barite resulted in higher workability as shown in barite UHPdC. An increase of 24% in workability is recorded by barite UHPdC with 0.25 – 0.5% PVA fibre addition which resulted from only a 3% increase in the water-to-binder ratio. This slight increase in ratio indicates the minimum amount of water required by barite UHPdC to form a workable paste. Overall, sand UHPdC recorded the lowest water-to-binder ratio, followed by barite and magnetite UHPdC. In terms of workability, barite UHPdC recorded the highest value, followed by magnetite and sand UHPdC. Overall, the effect of PVA fibre addition in UHPdC composition varies according to particle size and morphology.

In terms of density, the addition of PVA fibre in UHPdC resulted in lower density for all UHPdC. However, sand UHPdC recorded a reduction in density with 0.5% PVA fibre addition but an increase in density with 0.75% addition (Figure 4.20). The changes range from 0.5 – 1.4%. For magnetite UHPdC, the addition of PVA fibre resulted in huge reduction in density. At 0.25% PVA fibre addition, an 8% reduction in density is recorded in magnetite UHPdC and this value remains the same with increasing PVA fibre addition. For barite UHPdC, the reduction in density is smaller but the downward trend continues at 0.5% PVA fibre which recorded a density of 2776 kg/m³ which is the lowest recorded in this type of UHPdC. This downward trend in density due to the addition of PVA fibre is caused by the displacement of aggregate and cement paste in the matrix of UHPdC. With a high aspect ratio of 800 that is based on the fibre's length and diameter, the fibres displace denser aggregate hence reducing the

amount of aggregate per volume. This resulted in lower density as the density of PVA fibre is very low compared to aggregate.

The percentage of reduction in density is lower in sand UHPdC compared to barite and magnetite UHPdC. This is due to a smaller difference in density between PVA fibre and sand compared to barite and magnetite. The density of PVA fibre is 48.1% of sand's density compared to 31.4 and 32.4% of magnetite's and barite's density respectively. Hence, the reducing effect of aggregate displacement by PVA fibre on density is less pronounced in sand UHPdC compared to denser UHPdC of barite and magnetite.

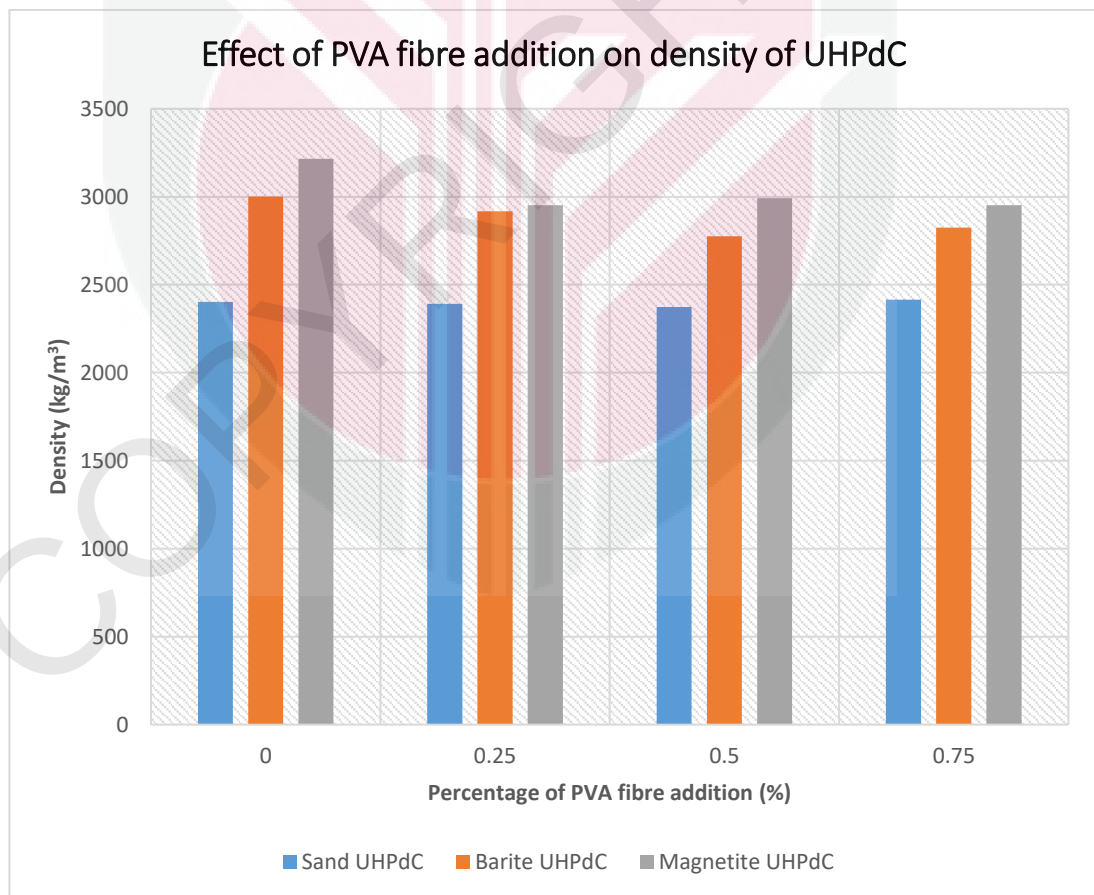


Figure 4.20 : Graph of density versus percentage of PVA fibre addition in various UHPdC

In terms of the UPV value, the increase in PVA fibre addition to UHPdC composition resulted in a lower UPV. Sand UHPdC's UPV value recorded a reduction from 4710 m/s to 4676 m/s with the addition of a 0.25% PVA fibre which is a 0.7% reduction (Figure 4.21). Further addition of fibre to a 0.5 and 0.75% resulted in a lower UPV value between 0.7 – 1.4%. For barite UHPdC, the reduction is larger which is between 3.6– 4.2% as the value is reduced from 4149 m/s to 3974 m/s. However, magnetite UHPdC recorded a larger reduction in UPV value with the addition of PVA fibre. With a 0.25 – 0.75% of PVA fibre addition, a 4.3 - 6.0% lower in UPV value compared to control sample is recorded. This could be due to the elongated shape of magnetite in the UHPdC which allows pores to form in between particles with the presence of PVA fibre.

PVA fibre addition in UHPdC composition caused the displacement of aggregate and mortar as the material is being added to the mixture instead of replacing any existing element. This may cause pores to form between fibre and aggregate especially aggregate with one longer side. This is shown by sand UHPdC which recorded the lowest UPV reduction compared to the control sample as the sand is more angular with a wide range of particle sizes. Sand UHPdC also recorded the highest UPV value which is followed by magnetite and barite UHPdC. Overall, the presence of PVA fibre altered the matrix of UHPdC and resulted in less dense microstructure.

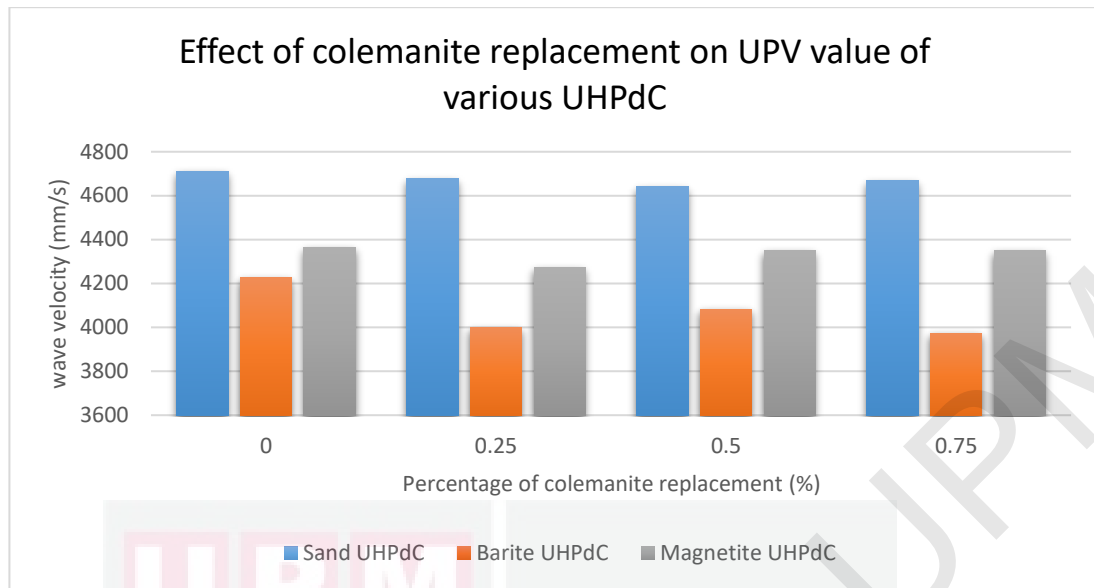


Figure 4.21 : Graph of UPV value versus percentage of PVA fibre addition

4.7 Effect of PVA Fibre Addition on Compressive Strength of Ultra-High Performance Dense Concrete

PVA fibre addition in UHPdC resulted in lower compressive strength. This is shown in all of UHPdC and the largest reduction in strength is recorded in magnetite UHPdC (Figure 4.22). Magnetite UHPdC recorded a 27.9% reduction in strength with 0.2% PVA fibre. This is equal to 117.3 MPa and the strength fluctuates with increasing PVA fibre. Maximum compressive strength in magnetite UHPdC is recorded at 118.7 MPa with 0.5% PVA fibre addition. However, this value is 27.1% lower compared to magnetite UHPdC with no PVA fibre. Further increment in PVA fibre addition to 0.75% by-volume resulted in 117.3 MPa of compressive strength which is similar to 0.25% PVA fibre addition in magnetite UHPdC. This indicates a downward trend in compressive strength with the increased addition of PVA fibre. Furthermore, the results indicate that the optimum percentage of PVA fibre addition is achieved at 0.5% by-volume.

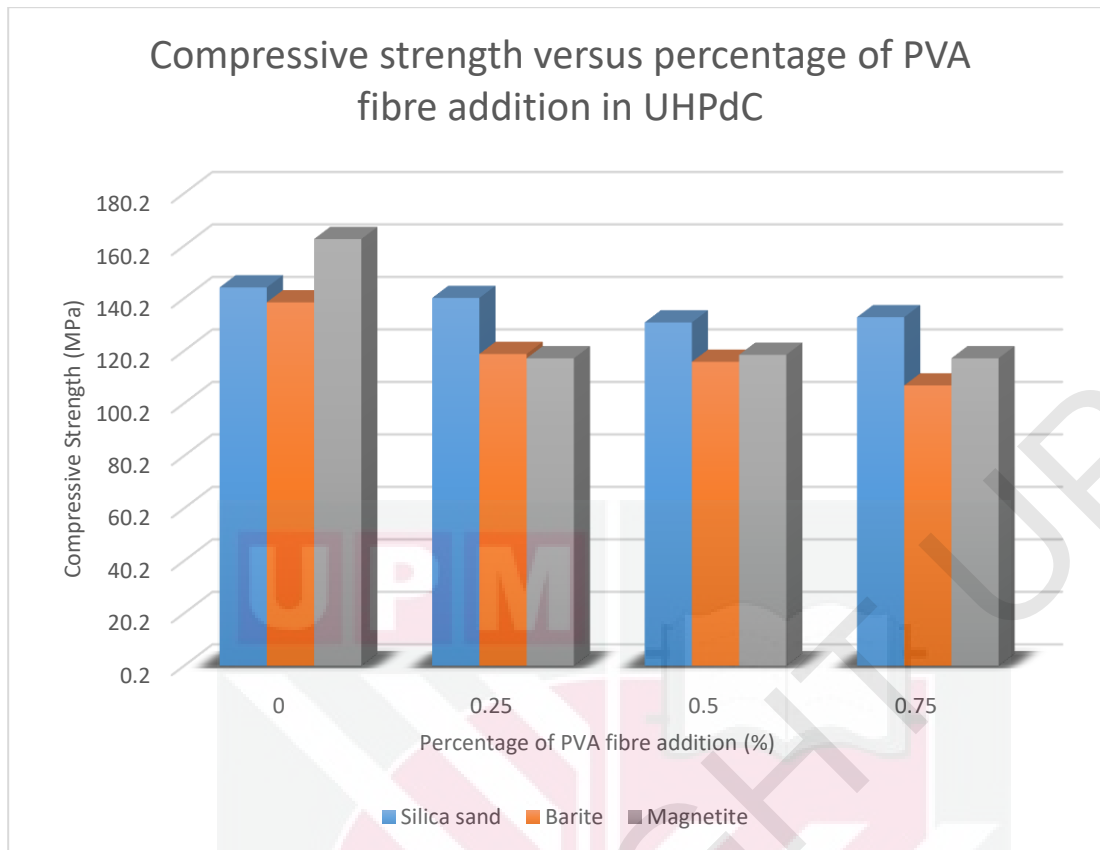


Figure 4.22 : Graph of compressive strength versus percentage of PVA fibre addition in various UHPdC

Barite UHPdC recorded 119 MPa of compressive strength with 0.25% PVA fibre which is a 14.2% reduction compared to the control sample. The slight reduction is recorded as the percentage of PVA is increased in the UHPdC. At 0.5 and 0.75% PVA fibre, barite UHPdC recorded 116 and 107 MPa of compressive strength respectively.

The trend of compressive strength versus fibre addition for barite UHPdC is almost similar to magnetite UHPdC except that it recorded a further reduction of 7.7% at 0.75% PVA fibre addition. Sand UHPdC recorded the least reduction in compressive strength which is only 2.8% with 0.25% PVA fibre

addition. The value further decreased to 131 and 133 MPa at 0.5 and 0.75% of PVA addition respectively.

Overall, the presence of PVA fibre in UHPdC resulted in a reduction of compressive strength and a huge reduction is recorded in magnetite and barite UHPdC compared to sand UHPdC. This may be due to different particle size distributions in each UHPdC composition. Particle sizes of magnetite range from 37 – 339 μm and mostly are larger than 100 μm with an elongated morphology. The presence of PVA may reduce the interlocking between aggregates especially with elongated and cylindrical shape. Furthermore, the presence of fibre in between magnetite and cement paste would reduce adhesion and the overall compressive strength of magnetite UHPdC.

Barite UHPdC experienced less reduction in compressive strength as the aggregate used is more angular in shape and sized smaller than magnetite which is 40 – 66 μm . This allows aggregate to fill around PVA fibre which enables aggregate to interlock and bond with cement paste that provides strength to the UHPdC. However, the use of more wider range of particle size distribution as shown by sand UHPdC shows more resilience against the detrimental effect of PVA fibre addition on compressive strength. The combination of coarse sand -ized between 600 – 1180 μm with fine sand-sized between 300 – 600 μm allows better interlocking and adhesion of mortar and aggregate despite the presence of PVA fibre.

The result of compressive strength correlates with UPV value where the highest compressive strength and the UPV value are recorded by sand

UHPdC. This is followed by magnetite and barite UHPdC. This indicates that the value of UPV for UHPdC is viable to estimate its compressive strength.

4.8 Effect of PVA Fibre Addition on Radiation Shielding of Ultra-high Performance Dense Concrete

The presence of PVA fibre alters the microstructural arrangement of the UHPdC which affects the mechanical properties and also the radiation shielding properties. Alteration of the structure reduces the compactness and density of produced UHPdC. Results of gamma and neutron shielding which are represented by linear attenuation coefficients and macroscopic removal cross sections, respectively, provide a better understanding on the impact of PVA fibre addition on UHPdC.

4.8.1 Linear Attenuation Coefficient

The addition of PVA fibre in UHPdC resulted in lower gamma ray shielding. Overall downward trend in μ value is observed in all types of UHPdC with the largest reduction observed in magnetite UHPdC. This is also observed in barite UHPdC but not in sand UHPdC. However, the lowest μ value is recorded by sand UHPdC despite minimal adverse impact of PVA fibre addition on gamma-ray shielding efficacy.

Sand UHPdC with 0.25% PVA fibre recorded μ value of 0.1687 cm^{-1} which is a 0.8% reduction compared to the control sample (Figure 4.23). The largest reduction in μ value due to PVA fibre addition in sand UHPdC is recorded at 2.5 % with 0.75 % fibre addition. Barite UHPdC recorded a larger reduction of μ value due to fibre addition which is 4.9 % with the same amount of PVA fibre

addition. This is due to the difference in density between PVA fibre and aggregate which resulted in the overall density of the UHPdC. The larger the difference in density between PVA fibre and aggregate, the larger the effect it has on the resulting shielding of UHPdC.

The difference in density is much larger between PVA and barite as compared to PVA and sand. This amount of difference resulted in a larger reduction in μ value of UHPdC. This is also shown by magnetite UHPdC which recorded an even larger reduction due to the presence of PVA fibre. At a 0.25% addition of PVA fibre in magnetite, UHPdC resulted in a 9.3% reduction of μ value which is 0.1975cm^{-1} . The lowest μ value recorded in magnetite UHPdC is 0.1933 cm^{-1} which contained 0.75% PVA fibre addition.

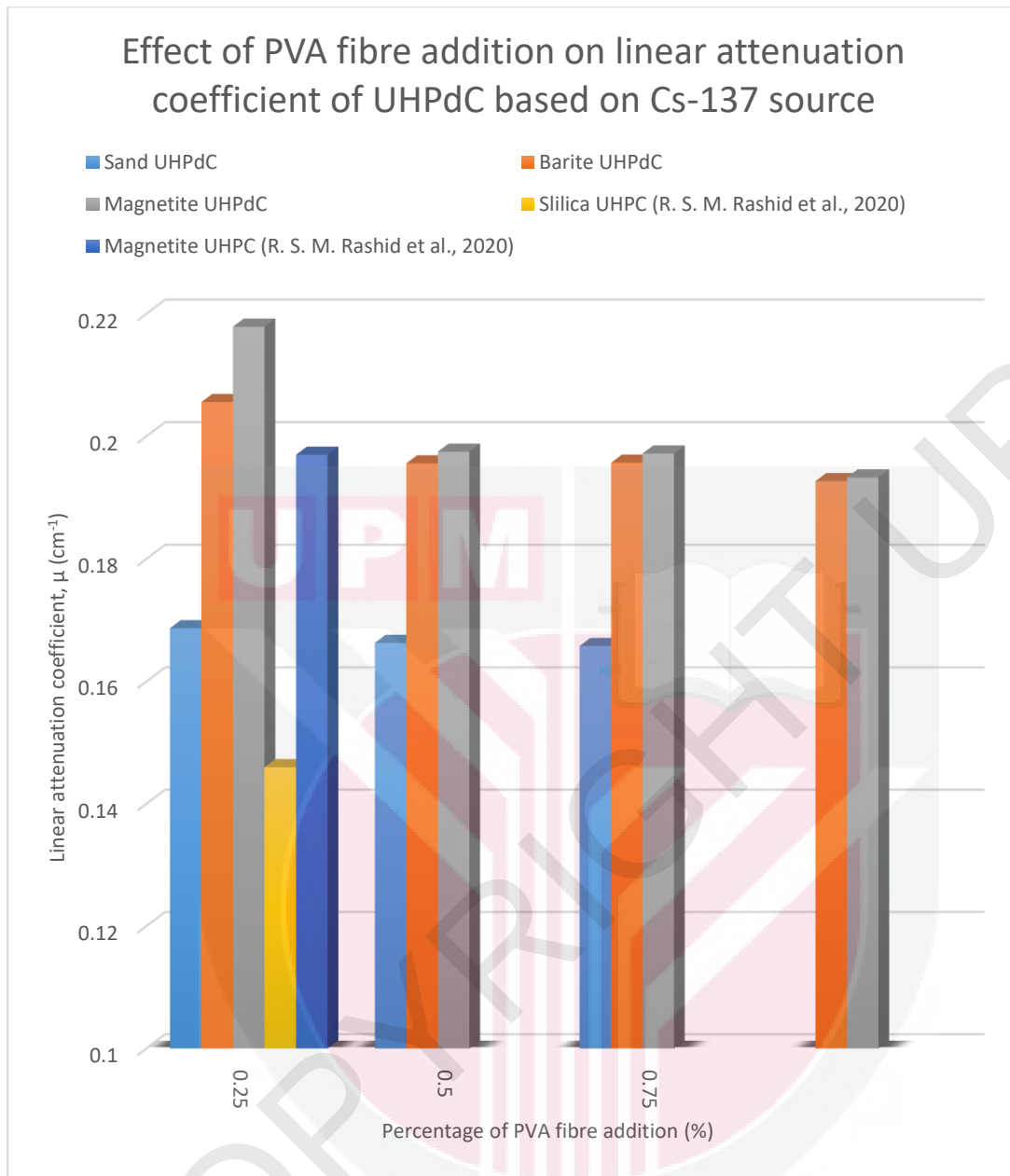


Figure 4.23 : Graph of linear attenuation coefficient versus percentage of fibre addition in UHPdC based on Cs-137 source

The steep drop in shielding value of magnetite UHPdC due to the addition of PVA fibre may be due to the morphology of magnetite aggregate that caused the formation of UHPdC microstructure with lower density when added with PVA fibre. As the fibre displaced the magnetite throughout the UHPdC lattice, the density of UHPdC is also reduced as the volume occupied by heavyweight magnetite is replaced with PVA fibre that has lower density. This resulted in

an overall lower density of magnetite UHPdC with PVA fibre hence a lower shielding coefficient.

Furthermore, a coarser particle of magnetite in the UHPdC also contributes to producing a less dense and compact microstructure due to the presence of PVA fibre. This is due to the gap between the large particles being further increased with the presence of fibre between the particles. This resulted in the formation of a low-density gap between the magnetite particles which resulted in lower shielding. This is also proved by smaller particles of barite which recorded a lower reduction in shielding coefficient of barite UHPdC. Fine particles of barite allow the particles to surround the fibre and reduce the gap produced due to the presence of the fibre. However, the use of a wider range of particle size distribution as in sand UHPdC proves that the reduction of shielding due to the addition of PVA fibre can be even smaller

This overall trend shown by magnetite, barite and sand UHPdC is similar at higher energy exposure of Co-60 (Figure 4.24). Sand UHPdC recorded the lowest value of μ which is followed by barite and magnetite UHPdC. Furthermore, sand UHPdC recorded a 1.3 – 2.5% lower μ value with an increasing percentage of fibre. Barite UHPdC recorded a larger reduction of 1.7 – 4.0% in terms of μ value which is similar to exposure at lower energy. This is also observed in magnetite UHPdC which indicates the largest reduction in shielding as shown in lower energy exposure. Magnetite UHPdC recorded a lower μ value by 17.5 – 19.5 % compared to the control sample.

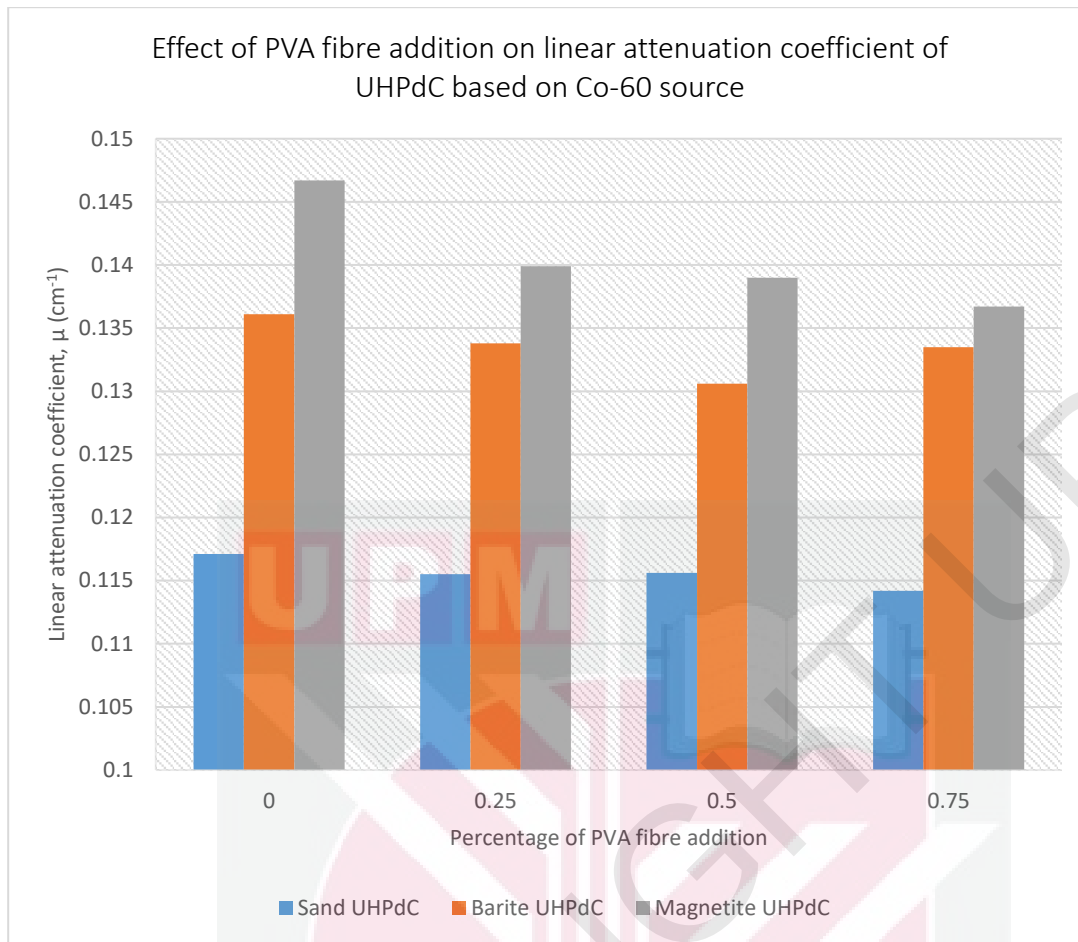


Figure 4.24 : Graph of linear attenuation coefficient, μ versus percentage of fibre addition in UHPdC based on Co-60 source

Overall, denser UHPdC of magnetite and barite with 0.5 % PVA fibre addition possessed a high μ value and this is followed by sand UHPdC with 0.25 % PVA fibre. Sand UHPdC which recorded 0.1687 cm^{-1} of μ value is higher compared to another study using silica and PVA fibre in UHPC that recorded 0.146 cm^{-1} of μ value (Rashid et al., 2020). The study also shows a similar μ value of magnetite UHPC at 0.197 cm^{-1} but at a lower amount of PVA fibre. Overall, an addition of PVA fibre in UHPdC reduced the gamma ray shielding property of UHPdC.

4.8.2 Macroscopic Removal Cross Section

In terms of neutron shielding, an increase in PVA fibre addition resulted in a lower $\Sigma_R(E_n)$ value in all UHPdCs. Magnetite UHPdC recorded a huge reduction in $\Sigma_R(E_n)$ value with the addition of PVA fibre (Figure 4.25). At 0.25 % PVA fibre addition, magnetite UHPdC recorded a 15.4 % reduction from 0.0396 to 0.03335 cm^{-1} . A larger reduction in $\Sigma_R(E_n)$ value is observed with the addition of 0.5 and 0.75 % of PVA fibre which recorded $\Sigma_R(E_n)$ values of 0.0307 and 0.0252 cm^{-1} respectively. This is equal to 22.5 and 36.3 % reduction in $\Sigma_R(E_n)$ value based on 0.5 and 0.75 % of PVA fibre addition respectively.

Barite UHPdC recorded a lower overall shielding coefficient compared to magnetite UHPdC. Barite UHPdC with 0.25, 0.5 and 0.75 % of PVA fibre recorded $\Sigma_R(E_n)$ value of 0.0297, 0.027 and 0.0248 cm^{-1} respectively. In comparison to the control sample, barite UHPdC also recorded a huge reduction in neutron shielding coefficient due to PVA fibre addition. The addition of PVA fibre at 0.25, 0.5 and 0.75 % in barite UHPdC resulted in a lower $\Sigma_R(E_n)$ value of 18.6, 26.0 and 32.1 % respectively.

Sand UHPdC recorded the lowest $\Sigma_R(E_n)$ value among all types of UHPdC studied. Furthermore, the addition of PVA fibre into the mix composition also resulted in a lower value of $\Sigma_R(E_n)$. At 0.25, 0.5 and 0.75 % of fibre addition, sand UHPdC recorded $\Sigma_R(E_n)$ values of 0.0277, 0.0262 and 0.0238 cm^{-1} respectively. In comparison with sand UHPdC with 0 % fibre addition which

recorded removal cross-section at 0.0329 cm^{-1} , the reduction of shielding coefficient is between 15.8 – 27.7 %.

Overall, denser UHPdC of magnetite and barite UHPdC recorded a higher $\Sigma_R(E_n)$ value compared to sand UHPdC due to the heavy element in magnetite and barite. These heavy elements in the form Fe_2O_3 and Ba_2SO_4 in magnetite and barite respectively caused an inelastic collision with fast neutrons from the source which reduced a large part of its energy and became thermal neutrons (Akkurt & El-Khayatt, 2013). Thermal neutron is then absorbed by boron in colemanite which is a neutron absorber. This resulted in a higher $\Sigma_R(E_n)$ value hence higher shielding against neutron radiation.

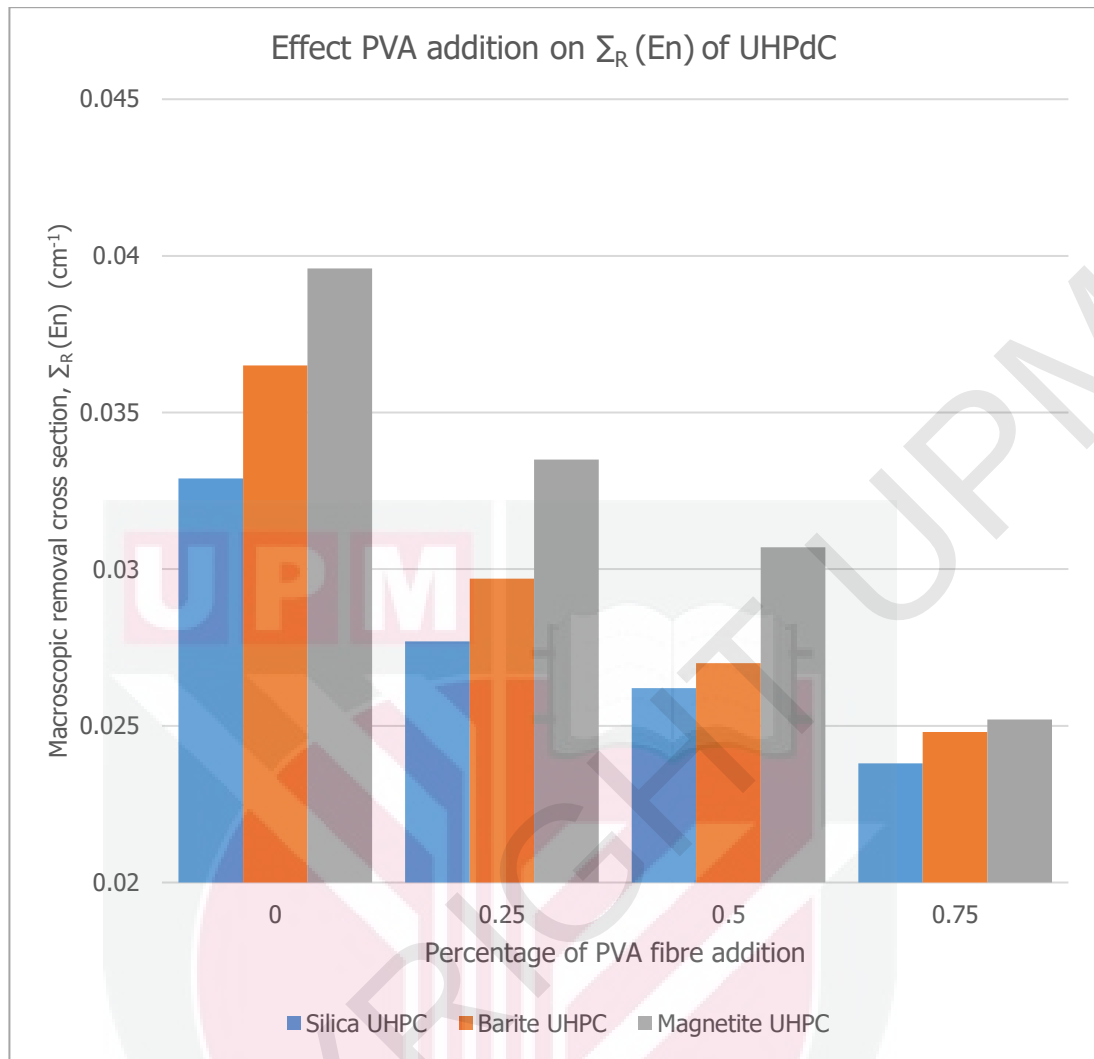


Figure 4.25 : Graph of $\Sigma_R (E_n)$ value versus percentage of PVA fibre addition in various UHPdC

The addition of PVA fibre resulted in lower shielding against neutrons as shown by the downward trend of $\Sigma_R (E_n)$ value. This is due to the element of hydrogen in PVA fibre that moderates fast neutrons into thermal neutrons which is then absorbed by boron in the UHPdC (Daungwilailuk et al., 2022). However, due to the constant amount of boron in all mix compositions of UHPdC, the amount of neutron being captured is similar and more thermal neutrons are passed through UHPdC with an increasing amount of PVA fibre. This resulted in a

higher count of thermal neutrons observed by the detector and a lower value of macroscopic removal cross-section in UHPdC.

4.9 Thermal Durability of Ultra-high Performance Dense Concrete with PVA Fibre Addition

The effect of PVA fibre addition on the thermal resistance of UHPdC is measured based on percentage of weight loss, spalling probabilities, residual compressive strength, residual gamma ray shielding and neutron shielding. The thermal resistance discussed is based on exposure to 800 °C heat on UHPdC.

4.9.1 Effect of PVA Fibre Addition on Percentage of Weight Loss of Ultra-high Performance Dense Concrete

Exposure to temperature at 800 °C on UHPdC resulted in spalling and weight loss. Loss in weight in this condition is due to loss of bonded water and decomposition of cement hydration product. Vaporisation of PVA fibre also contributes to this weight loss and left pores that help dissipate internal pressure (Q. H. Li et al., 2019). The largest reduction of weight after heat exposure which is 17.6 % is recorded by barite UHPdC with 0.25 % PVA (Figure 4.26). At a higher percentage of PVA addition, barite UHPdC recorded a lower weight loss percentage of 10.2 – 10.7 %. The higher weight loss percentage recorded by barite UHPdC may be due to the large thermal expansion coefficient of barite which caused cracking between aggregate and cement paste (Witte & Backstrom, 1954). This cracking resulted in a larger area being affected with heat exposure hence a higher volume of cement paste

being dehydrated and decomposed. Sand UHPdC recorded a slightly lower weight loss percentage which is 12.1 % with 0.25 % PVA fibre addition.

However, the trend is similar to barite as sand UHPdC also recorded a lower percentage of weight loss which is 10.2 and 10.0 % with 0.5 and 0.75 % fibre addition respectively. This indicates that 0.25 % of PVA fibre addition is not enough to dissipate internal pressure buildup due to heat exposure. This leads to microcracking hence the larger volume of UHPdC is affected by the decomposition of cement hydration product and vaporisation of bonded water. This is also shown by magnetite UHPdC which recorded 9.14 and 9.18 % weight loss with an adequate amount of PVA fibre at 0.5 and 0.75 % respectively.

At 0.25 %, magnetite UHPdC recorded a higher percentage of 9.60 %. However, these percentages are lower compared to barite and sand UHPdC which indicates better thermal resilience of magnetite UHPdC. This is due to the higher thermal conductivity of magnetite compared to sand (Ismail Ahmed Ali & Lubl6y, 2022). Furthermore, magnetite also has a low thermal expansion coefficient compared to barite which resulted in less cracking hence lower weight loss (Levy et al., 2004)

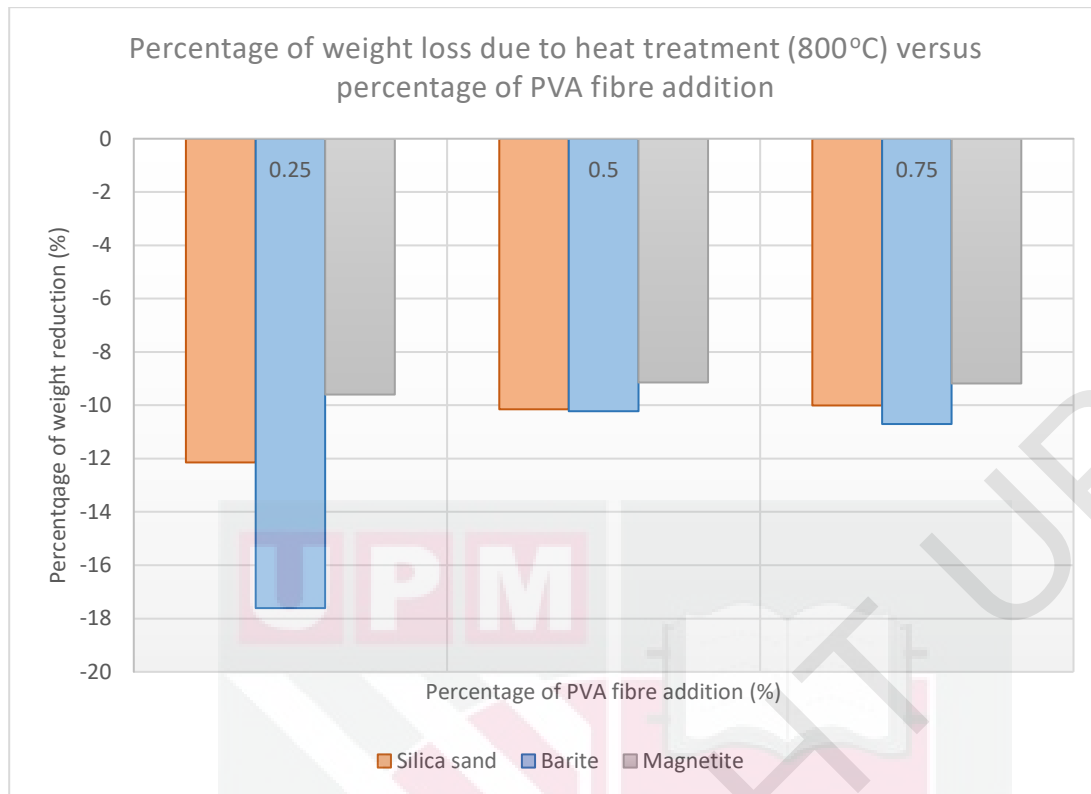


Figure 4.26 : Graph of percentage of weight loss due to 800 °C heat versus percentage of PVA fibre addition in various UHPdC

4.9.2 Effect of PVA Fibre Addition on Spalling Probability of Ultra-high Performance Dense Concrete

The presence of PVA fibre in UHPdC improves its spalling resistance as UHPdC with no fibre suffers explosive spalling (Figure 4.27). Furthermore, the minimum amount of fibre to prevent spalling in UHPdC varies according to the type of aggregate and its particle size distribution. This is indicated by barite UHPdC with 0.25 % fibre that recorded 23% chances of spalling (Table 4.1).

After heat exposure, only 2 out of 3 cube samples and 7 out of 8 prism samples of the mixture survived the heat. Major spalling that occurred to the samples renders the samples unsuitable for compressive and shielding tests. Furthermore, the cubes that survived the heat suffered major cracking (Figure 4.27e).

At percentage of 0.5 – 0.75 % of PVA fibre addition, barite UHPdC recorded no spalling probability. Sand and magnetite UHPdC recorded no spalling for the sample with PVA fibre addition. Presence of PVA fibre creates a network of pores which helps diffuse internal pore pressure buildup during heating. PVA fibre melted at 300 °C and fully evaporated at 800 °C which left channels in the internal structure of UHPdC (L. Li et al., 2020). This resulted in more permeable UHPdC which reduces internal autoclaving pressure that causes spalling. Furthermore, the channels also provide expansion space for aggregate due to heating which prevents additional cracking. However, the adequacy of voids provided by the fibre differs based on the thermal expansion of aggregate. This is shown by barite UHPdC that recorded spalling despite containing 0.25 % PVA fibre. This is due to large thermal expansion coefficient of barite aggregate at $20.6 \times 10^{-6} \text{K}^{-1}$ which is almost twice the magnetite's coefficient (Levy et al., 2004). Barite UHPdC shows lower chance of spalling at 0.5 % PVA fibre addition.

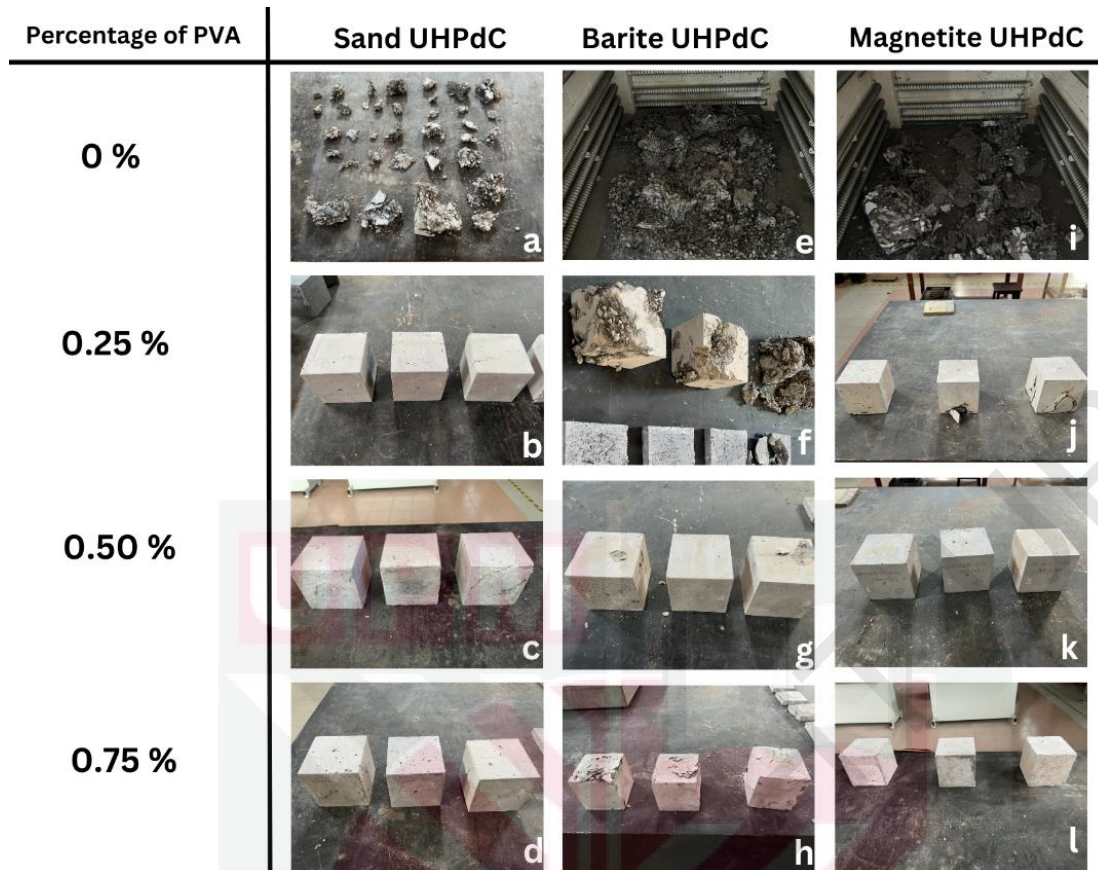


Figure 4.27 : Photo of sand UHPdC with a. 0 %, b. 0.25 %, c. 0.5 % and 0.75 % PVA fibre addition . Barite UHPdC is shown in 2nd column with e. 0 %, f. 0.25 %, g. 0.5 % and h. 0.75 % PVA fibre addition . Magnetite UHPdC is shown in third column with i. 0 %, j. 0.25 %, k. 0.5 % and l. 0.75 % PVA fibre addition

Table 4.1 : Effect of PVA fibre addition on spalling probability of UHPdC

Sample	Type of UHPdC	Percentage of PVA fibre addition	Percentage of Spalling Probability
USS95C5	Sand UHPdC	0	100
USS95C5P0.25	Sand UHPdC	0.25	0
USS95C5P0.5	Sand UHPdC	0.5	0
USS95C5P0.75	Sand UHPdC	0.75	0
UM95C5	Magnetite UHPdC	0	100
UM95C5P0.25	Magnetite UHPdC	0.25	0
UM95C5P0.5	Magnetite UHPdC	0.5	0
UM95C5P0.75	Magnetite UHPdC	0.75	0
UB95C5	Barite UHPdC	0	100
UB95C5P0.25	Barite UHPdC	0.25	23
UB95C5P0.5	Barite UHPdC	0.5	0
UB95C5P0.75	Barite UHPdC	0.75	0

4.9.3 Effect of PVA Fibre Addition on Residual Compressive Strength of Ultra-high Performance Dense Concrete

Overall, the addition of PVA fibre at an optimum amount resulted in higher residual compressive strength after being heated to 800 °C. This is shown in magnetite UHPdC which recorded higher residual compressive strength at 0.5 % PVA fibre addition compared to 0.25 % (Figure 4.28). For sand UHPdC, the optimum percentage is indicated by 0.25 % fibre addition based on the maximum value shown in strength. A higher amount of PVA fibre addition in sand UHPdC resulted in lower residual compressive strength. In barite UHPdC, 0.5 % fibre addition in the composition resulted in the maximum residual compressive strength which indicates the optimum percentage. The presence of fibre in concrete matrix creates channels and connects pores when melted which helps the dissipation of internal stress from heating. This leads to less internal cracking and better structural integrity in the concrete matrix hence higher residual compressive strength at an optimum amount of fibre. However, excessive pores and channels form due to melted fibre resulting in lower residual strength due to deteriorated microstructure.

Overall comparison between the three types of UHPdC, magnetite UHPdC shows the highest residual compressive strength followed by sand and barite UHPdC. This indicates that magnetite UHPdC possesses the highest thermal resilience in terms of compressive strength. This is due to the higher initial compressive strength possessed by the composition and also the strength of magnetite aggregate which a study found that magnetite could achieve 218 MPa of compressive strength (Grosu et al., 2017). This is followed by sand UHPdC with 0.25 % fibre and barite UHPdC with 0.5 % fibre.

In terms of the percentage of reduction in compressive strength due to heat at 800 °C, magnetite UHPdC also recorded the lowest percentage of strength reduction which further proves the thermal resilience of the UHPdC. This is followed by sand and barite UHPdC. Magnetite UHPdC recorded a 59.2 – 63.3 % reduction while sand and barite UHPdC recorded a reduction of 76.6 – 77.7 and 74.0 – 87.8 % respectively.

The thermal resilience of magnetite compared to barite and sand is indicated by the thermal expansion of magnetite at $7.5 \times 10^{-6} \text{ K}^{-1}$ which is less than half of barite's (Levy et al., 2004; Witte & Backstrom, 1954). Less thermal expansion of aggregate will prevent cracking with the microstructure of UHPdC hence higher residual strength. Furthermore, concrete with magnetite shows lower thermal capacity and conductivity compared to sand in concrete which indicates higher thermal resistance (Ismail Ahmed Ali & Lublóy, 2022). It can be concluded that thermal durability in terms of residual compressive strength is superior in magnetite UHPdC followed by sand and barite UHPdC.

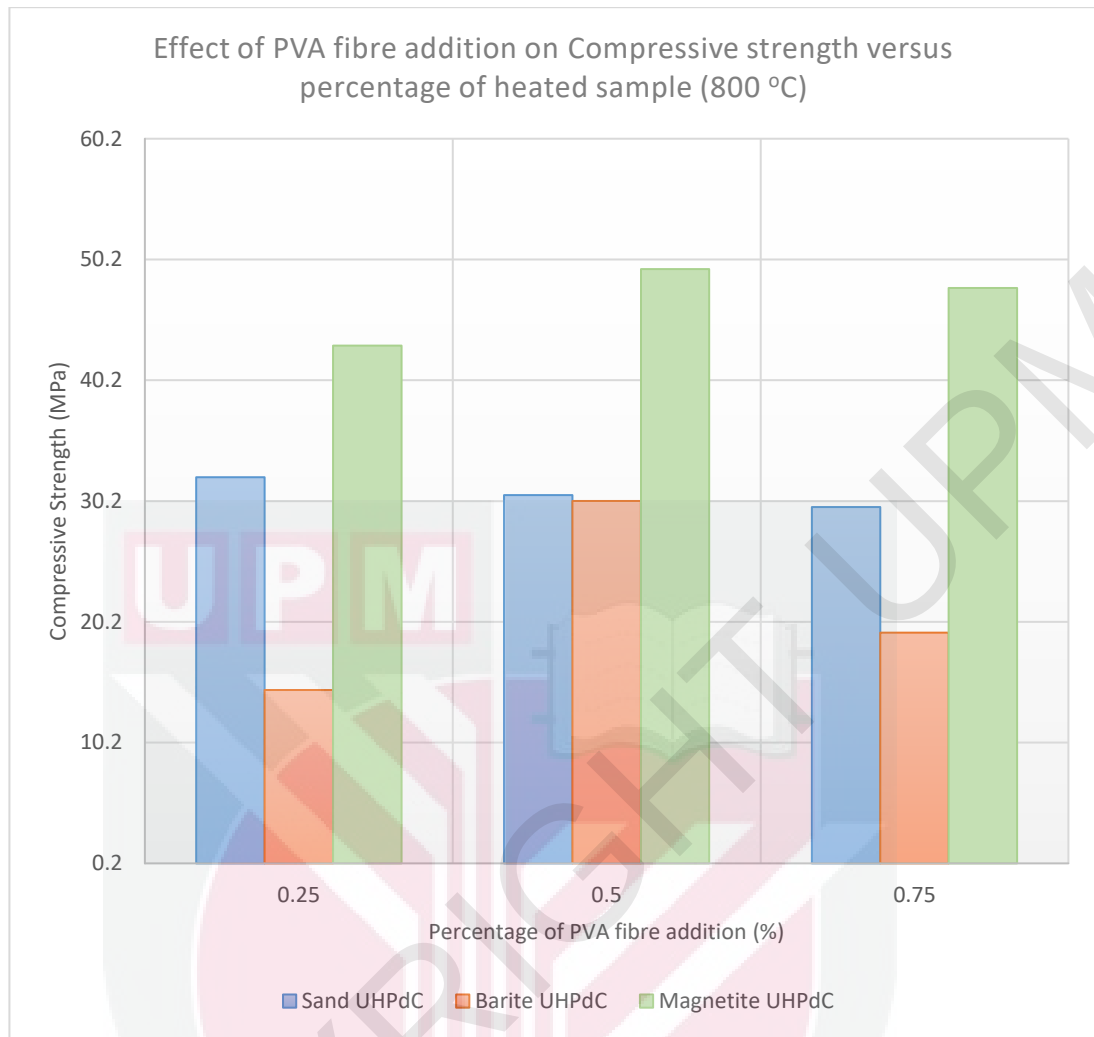


Figure 4.28 : Graph of compressive strength versus percentage of PVA fibre addition of various heated UHPdC

4.9.4 Effect of PVA Fibre Addition on Residual Gamma Ray Shielding of Ultra-high Performance Dense Concrete

Based on exposure to the gamma-ray source of Cs-137, the addition of PVA fibre in UHPdC resulted in lower residual gamma-ray shielding of UHPdC. This is shown in barite and sand UHPdC which recorded the lowest μ value with 0.75 % PVA fibre addition (Figure 4.29). Barite UHPdC recorded the highest μ value at 0.25 % fibre addition which is 0.1902 cm^{-1} . This was followed by a sample with 0.5 and 0.75 % fibre which recorded 0.1811 and 0.1748 cm^{-1} respectively. In comparison with the initial μ value, barite UHPdC recorded a

2.8 – 9.3 % of reduction in value with increasing PVA fibre addition from 0.25 – 0.75 %.

This trend of increasing reduction in μ value due to heating on the sample with a higher percentage of fibre addition is also observed in sand UHPdC. Sample of sand UHPdC with 0.25, 0.5 and 0.75 % PVA fibre addition recorded 6.8, 9.8 and 9.9 % of reduction in shielding value respectively. This trend indicates that μ value is reduced with the increasing amount of PVA fibre addition due to the increase in channels and pore network formation after heating. As these channels reduced the internal pore pressures in UHPdC, they created void which reduced density that attenuated penetration of gamma rays.

Furthermore, cracking also occurred in aggregate due to thermal expansion which also contributed to lower shielding value. However, magnetite UHPdC recorded a slight variation in reduction of shielding value despite the increasing amount of PVA fibre. Magnetite UHPdC with 0.25, 0.5 and 0.75 % PVA fibre recorded 5.1, 4.3 and 5.6 % of reduction in μ value respectively. This may be due to the higher thermal stability possess by magnetite UHPdC compared to sand and barite UHPdC.

In terms of residual μ value, magnetite UHPdC recorded the highest value at 0.5 % PVA fibre addition which is 0.1887 cm^{-1} . This is followed by 0.25 and 0.75 % PVA fibre addition which recorded 0.1873 and 0.1825 cm^{-1} respectively.

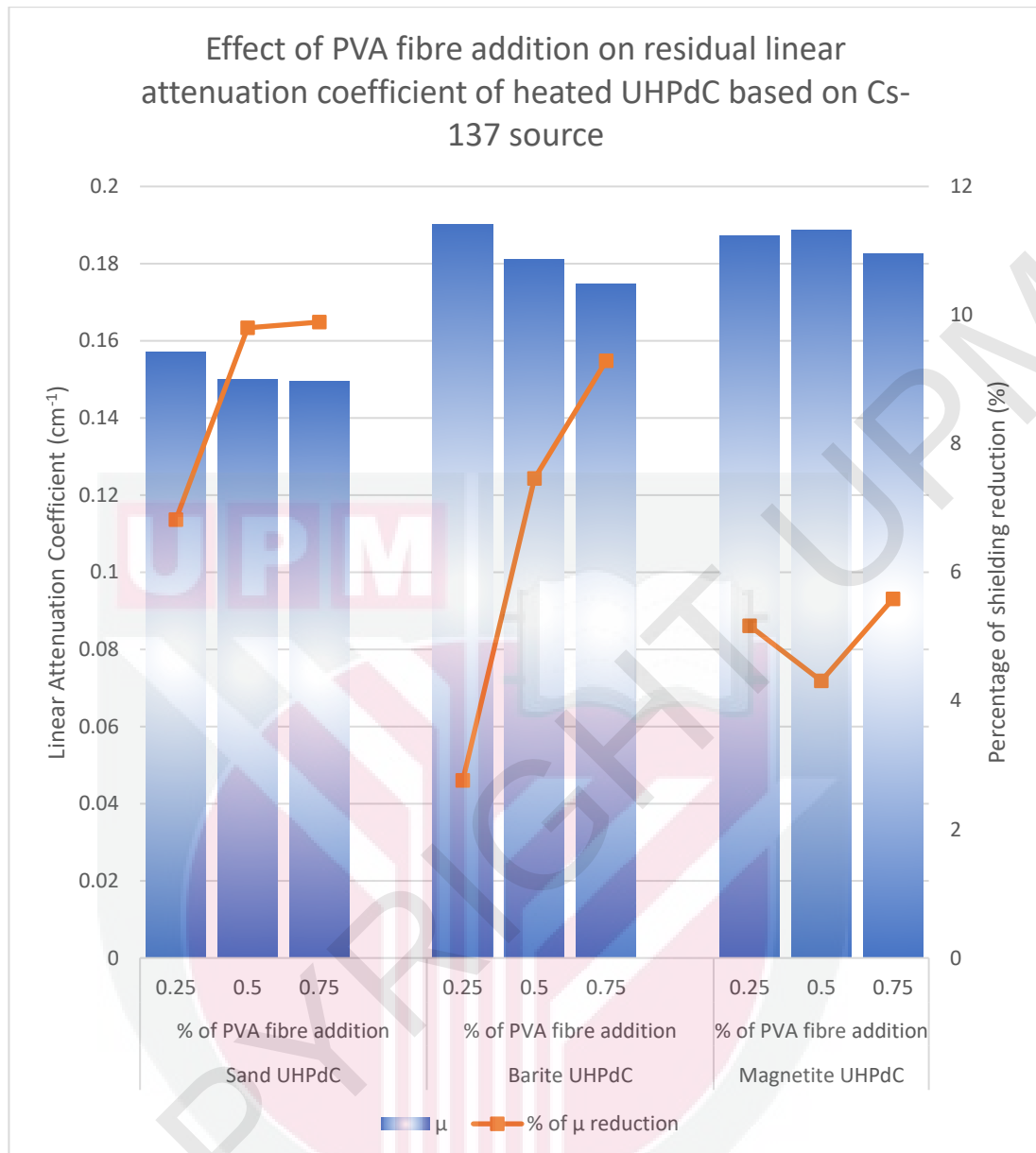


Figure 4.29 : Effect of PVA fibre addition on residual linear attenuation coefficient of UHPdC based on exposure to Cs-137

This large reduction of linear attenuation coefficient due to heating in the sand and barite UHPdC is also observed in μ value based on the Co-60 source (Figure 4.30). Sand UHPdC recorded a 5.6 – 10.4 % reduction which is 0.109 – 0.1023 cm^{-1} in terms of residual μ value. While barite UHPdC recorded a slightly lower reduction of 4.3 – 7.0 % which equals to 0.128 – 1241 cm^{-1} in terms of residual μ value. Magnetite recorded the highest value of residual

linear attenuation coefficient of 0.1305 cm^{-1} at 0.25 % PVA fibre addition. This is followed by 0.5 and 0.75 % PVA fibre addition which recorded residual linear attenuation coefficient at 0.1302 and 0.1283 cm^{-1} respectively. In comparison to the value recorded with the Cs-137 source, the residual μ value recorded by samples is lower as the energy of Co-60 is higher.

The superior thermal durability of magnetite UHPdC in terms of μ value is also shown by a study which recorded a 8.3 % reduction of μ value for magnetite concrete after heat exposure at 800°C (Horszczaruk & Brzozowski, 2019). This is very low compared to ordinary concrete which recorded a 39.0 % reduction of μ value after being exposed to the same temperature. The study also shows that barite concrete recorded a 13.7 % reduction of μ value which is higher than magnetite concrete. Overall, an increase in PVA addition in UHPdC resulted in lower gamma ray shielding.

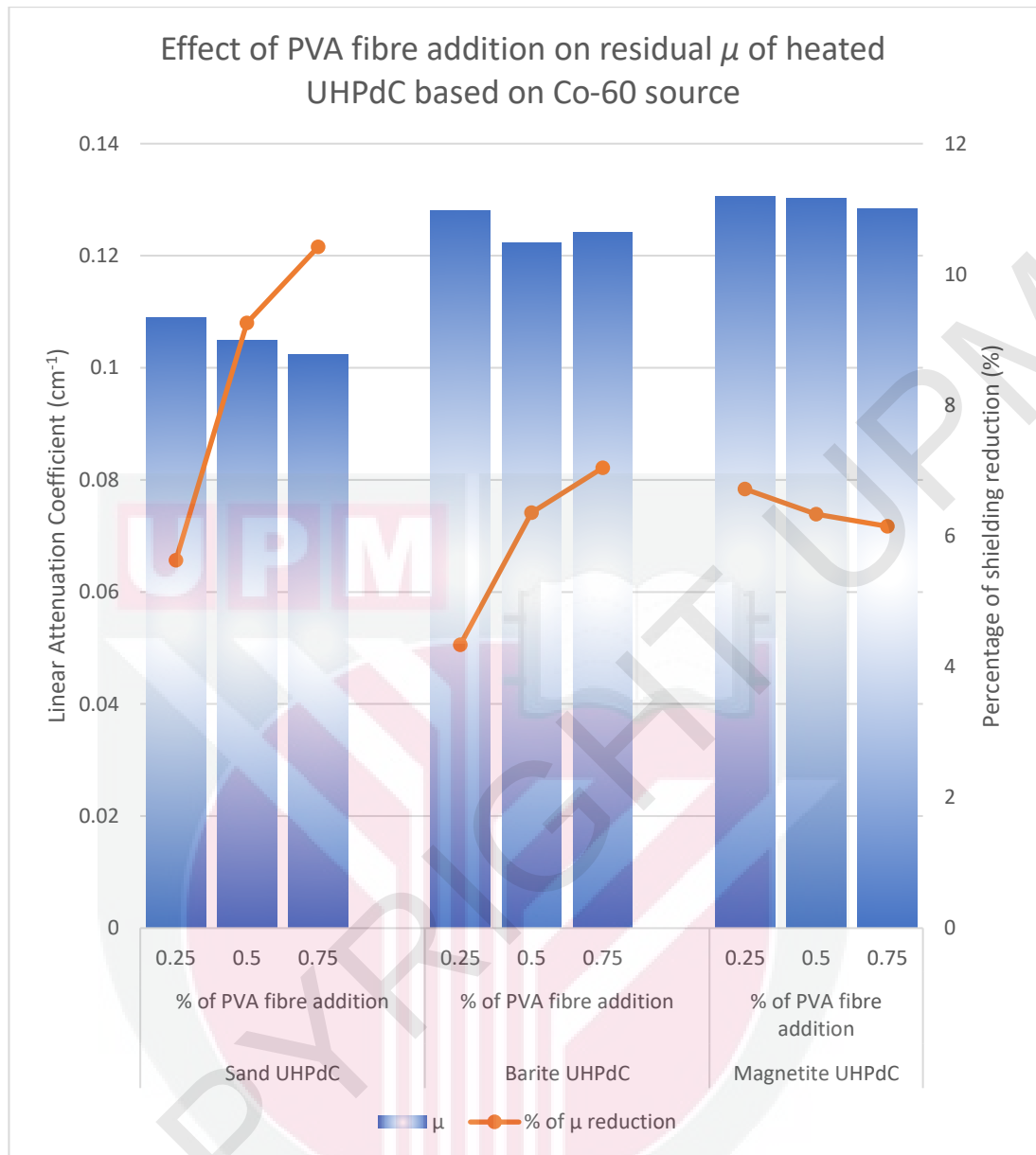


Figure 4.30 : Effect of PVA fibre addition on residual linear attenuation coefficient of UHPdC based on exposure to Co-60

4.9.5 Effect of PVA Fibre Addition on Residual Neutron Shielding of Ultra-high Performance Dense Concrete

In terms of residual neutron shielding, PVA fibre presence in the composition of UHPdC resulted in a larger reduction of $\sum_R(E_n)$ value after heat damage at 800 °C. As shown in Figure 4.31, the percentage of reduction in $\sum_R(E_n)$ value

recorded by all sample of UHPdC is increasing with an increase in PVA fibre addition.

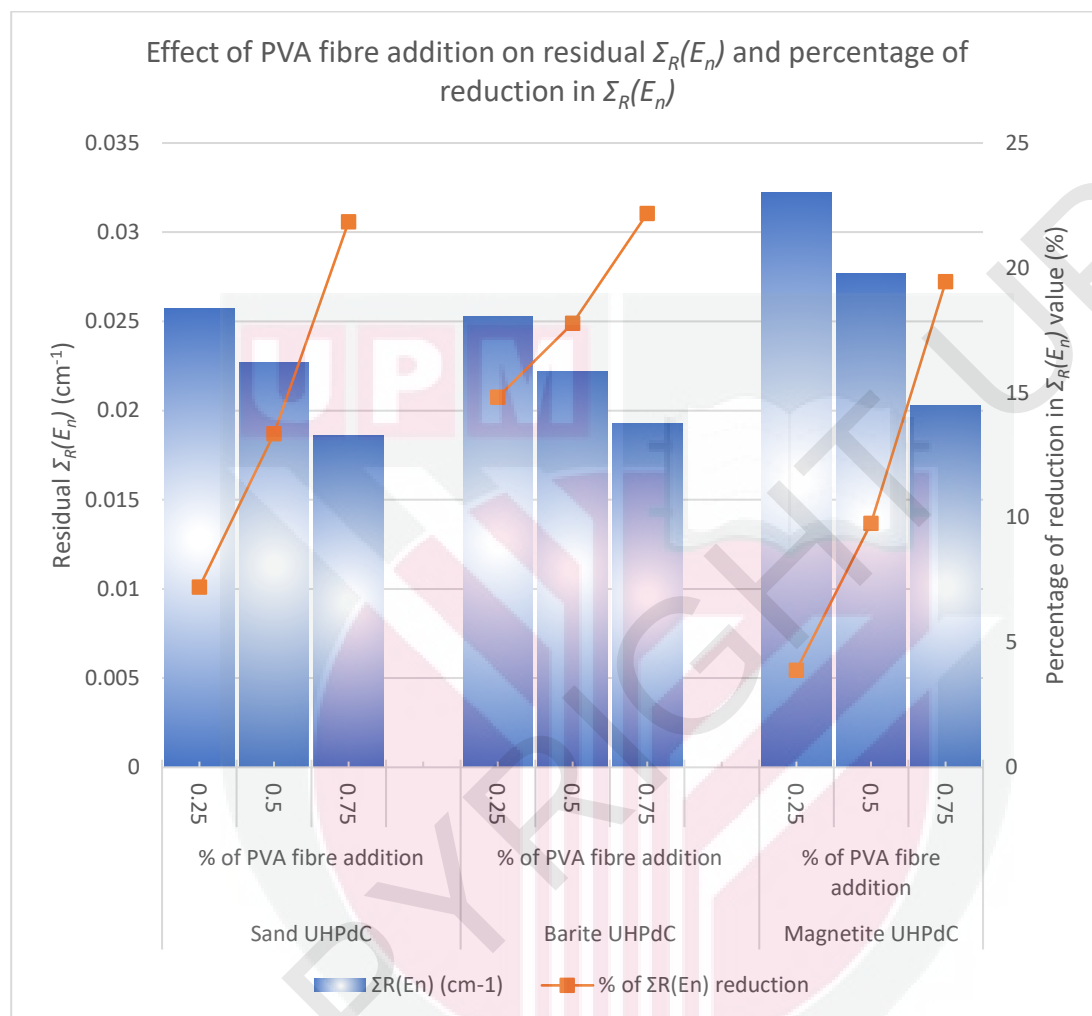


Figure 4.31 : Graph of residual $\Sigma_R(E_n)$ value and percentage of fibre addition in heated UHPdC

For sand UHPdC with 0.25 % PVA fibre, a 7.2 % reduction of $\Sigma_R(E_n)$ value is recorded which is 0.0277 cm⁻¹ compared to 0.0257 cm⁻¹ recorded by the unheated sample. The percentage of reduction increased to 15 % and 18.6 % at 0.5 % and 0.75 % PVA fibre addition in sand UHPdC respectively. Barite UHPdC recorded an even larger reduction in residual $\Sigma_R(E_n)$ value which is 17.8 – 22.2 %. This reduction in $\Sigma_R(E_n)$ value after heat exposure is due to the

formation of channels and cracks from the evaporation of PVA fibre which resulted in more void hence lower shielding against neutrons. Furthermore, the formation of voids and channels also resulted in larger evaporation of bonded water in cement hydration products that contained hydrogen.

Loss in hydrogen in UHPdC decreases its capacity to moderate fast neutrons hence lower $\Sigma_R(E_n)$ value. This is proved by magnetite UHPdC which has higher thermal stability and recorded the least reduction in $\Sigma_R(E_n)$ value after heat exposure. Due to the thermal stability of magnetite in the UHPdC, fewer cracks form during heat exposure hence reducing the amount of chemically bonded water being evaporated and cement hydrate being decomposed (Ismail Ahmed Ali & Lublóy, 2022). This leads to better neutron shielding of magnetite UHPdC. Furthermore, magnetite UHPdC also recorded the highest $\Sigma_R(E_n)$ value with 0.25 % PVA fibre addition which is 0.0322 cm^{-1} .

4.10 Properties of Optimised Ultra-high Performance Dense Concrete

Based on data from objective 1 and objective 2, the optimum mix composition for sand, barite and magnetite UHPdC is decided with 5 % colemanite replacing the main aggregate and 0.5% PVA fibre addition. From objective 1, replacing the main aggregate in UHPdC with colemanite improves the neutron shielding properties of UHPdC. Furthermore, its presence resulted in a more compact microstructure hence improvement in compressive strength. However, this is limited to 5 % of aggregate replacement. Replacing the main aggregate with colemanite also resulted in lower gamma ray shielding which is due to the lower density of colemanite. The presence of colemanite is

important in improving neutron shielding and microstructure. Hence, 5 % is selected as the optimum values based on these considerations. PVA fibre is integral in preventing the spalling of UHPdC. At 0.5 % PVA fibre addition, all UHPdCs show less chance of spalling and better thermal resiliency in terms of weight loss and residual mechanical properties. Hence, optimised composition of UHPdC contained 5 % colemanite replacing main aggregate with 0.5 % PVA fibre addition.

The mixes were further evaluated for compressive strength, flexural strength, splitting tensile strength and radiation shielding with additional heat exposure at 400 °C. Sand UHPdC recorded the highest compressive strength at 131 MPa and this is followed by magnetite and barite UHPdC (Figure 4.32). Comparison is being made with a control sample of sand UHPdC in objective 1 and denoted as “unoptimised sand UHPC”. The sample contains no colemanite and no PVA fibre. The data presented for unoptimised sand UHPC is the data from the control sample of sand UHPdC in objective. In comparison with unoptimised sand UHPC, sand UHPdC is 11.8 % lower which may be due to the presence of colemanite and PVA fibre in the mix.

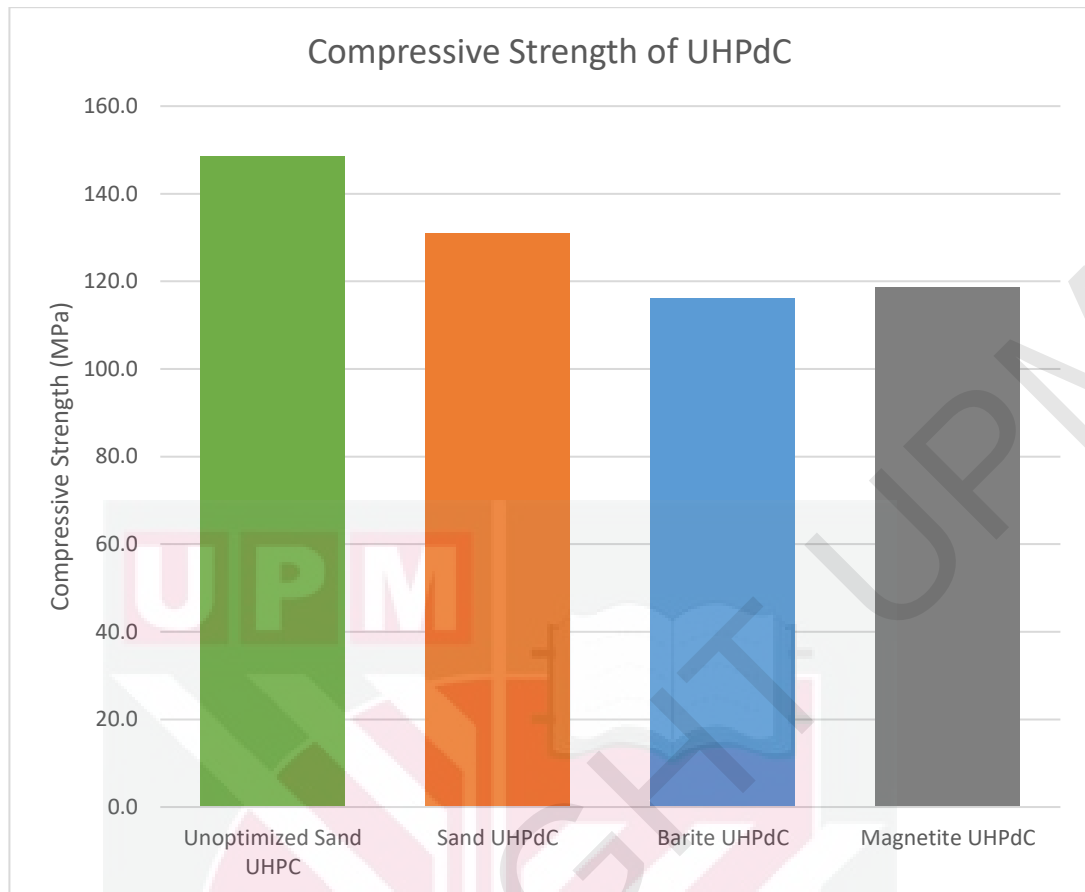


Figure 4.32 : Compressive strength of UHPdC and comparison with unoptimised sand UHPC

In terms of flexural strength, sand UHPdC also recorded the highest flexural strength at 20.0 MPa (Figure 4.33). This is followed by magnetite and barite UHPdC at 17.0 and 14.0 MPa respectively. However, the maximum flexural strength recorded by sand UHPdC is lower if it is compared to unoptimised sand UHPC. Unoptimised sand UHPC recorded a flexural strength of 20.2 MPa which is 0.1 % higher. This unoptimised sand UHPC does not contain any colemanite or PVA fibre. This resulted in denser sand per volume in this UHPC compared to sand UHPdC which contributed to the overall flexural strength of the UHPC.

Overall, the high flexural strength possessed by UHPdC is contributed by steel fibre that resists flexural deformation. Hardened cement paste and aggregate in strong contact with steel fibre in the matrix also contributed to the overall better flexural strength of UHPdC. Angular morphology of sand and denseness of microstructure in sand UHPdC provide better interlocking with steel fibre hence higher flexural resistance. Lack of compactness in magnetite and barite UHPdC resulted in poorer interlocking with steel fibre that contributes to the lower flexural strength.

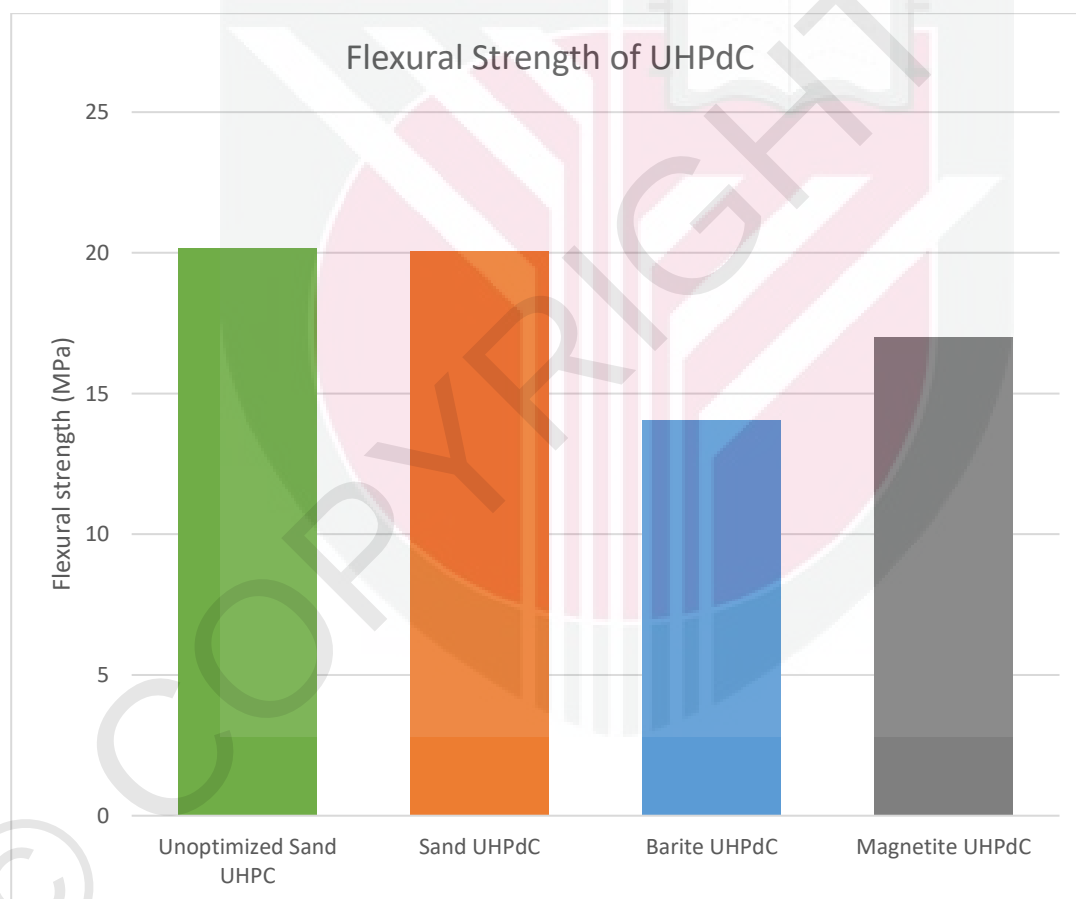


Figure 4.33 : Flexural strength of UHPdC and comparison with unoptimised sand UHPC

The result of splitting tensile strength is almost similar to flexural strength as sand UHPdC recorded the highest value at 17.6 MPa. This is followed by

magnetite and barite UHPdC which recorded the strength value at 15.2 and 14.4 MPa respectively. However, the result is lower than the splitting tensile strength recorded by unoptimised sand UHPC which is 18.8 MPa. This is 7.4 % higher than the tensile strength recorded by sand UHPdC. This indicates the adverse effect of colemanite presence and PVA fibre addition on the splitting tensile strength of UHPdC. The presence of PVA fibre and colemanite in UHPdC may have reduced the interaction between concrete matrix with steel fibre which leads to a reduction in tensile restraining of UHPdC.

However, in the comparison among all UHPdC sand UHPdC recorded the highest splitting tensile strength which indicates that sand UHPdC possessed better interaction between steel fibre and aggregate compared to magnetite and barite UHPdC.

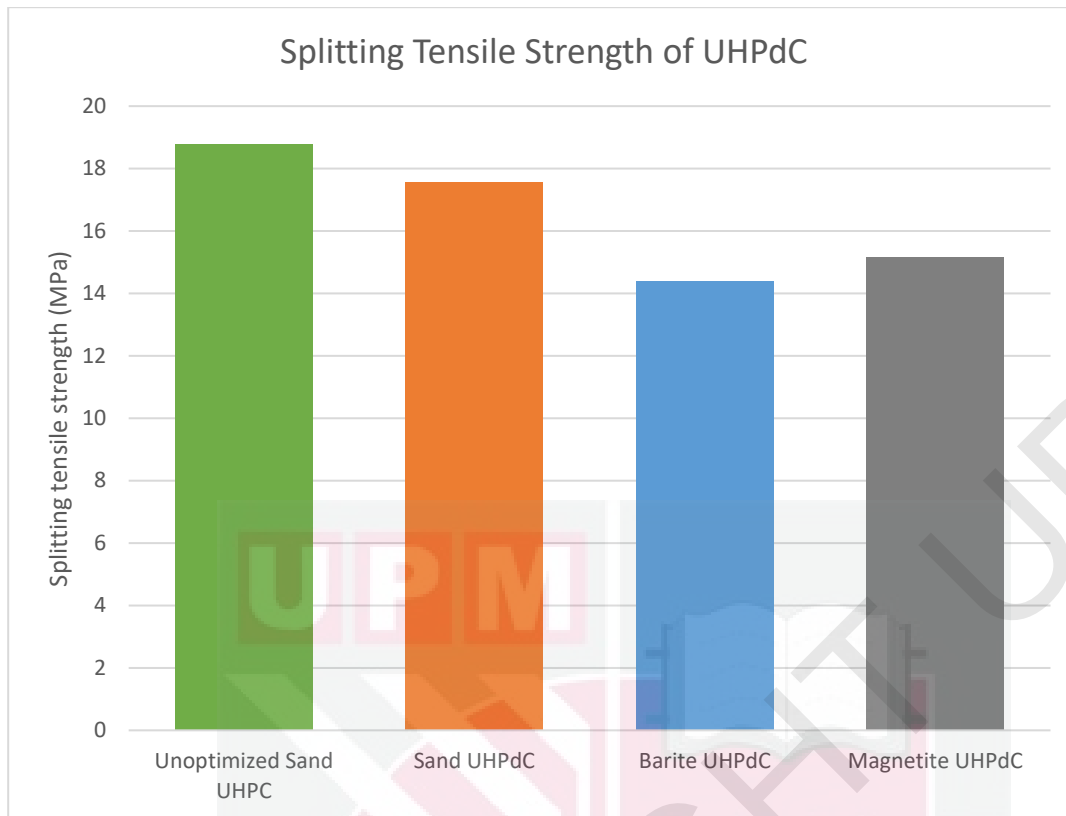


Figure 4.34 : Splitting tensile strength of UHPdC and comparison with unoptimised sand UHPC

In terms of radiation shielding, magnetite UHPdC recorded the highest μ value at 0.1972 and 0.139 cm^{-1} based on exposure to Cs-137 and Co-60 respectively. This is followed by barite and sand UHPdC. In comparison to unoptimised sand UHPC, sand UHPdC recorded a 7.1 % lower μ value which is due to the presence of colemanite and PVA fibre. However, magnetite and barite UHPdC recorded 10.1 and 9.3 % higher values compared to unoptimised sand UHPC due to each heavyweight aggregate.

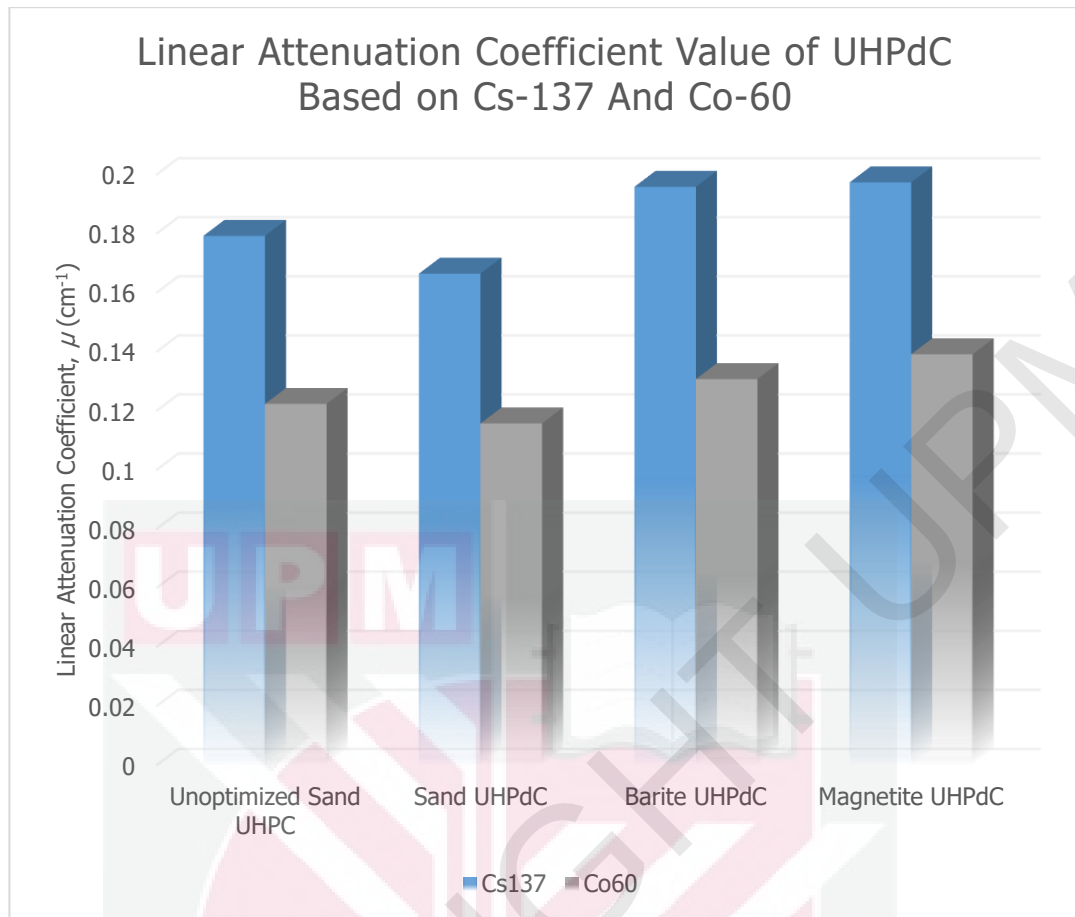


Figure 4.35 : Value of linear attenuation coefficient of UHPdC and unoptimised sand UHPC

In terms of neutron shielding, the highest value of $\sum_R(E_n)$ is recorded by magnetite UHPdC at 0.0307 cm^{-1} . This is followed by barite and sand UHPdC which recorded 0.027 and 0.0262 cm^{-1} of $\sum_R(E_n)$ value respectively. The presence of heavyweight aggregate influenced the value as fast neutrons are moderated by inelastic collision with the heavy element in the aggregate (Piotrowski et al., 2015). This resulted in more thermal neutrons that is absorbed by boron in UHPdC. Furthermore, barite UHPdC shows a lower $\sum_R(E_n)$ value compared to magnetite UHPdC which is due to a lower thermal neutron cross-section of barium, Ba in barite UHPdC compared to iron, Fe in magnetite UHPdC (Schmidt, 1970). Ba has 1.2 and 8.1 barns for absorbing

cross section and scattering cross-section respectively. This is much lower compared to Fe which has 2.55 and 10.6 barns of absorbing and scattering cross section respectively.

In comparison with unoptimised sand UHPC, the value of $\sum_R(E_n)$ recorded by magnetite UHPdC is 15.9 % higher, However, sand UHPdC recorded almost slightly lower value compared to unoptimised sand UHPC which is due lower amount of sand which act as neutron moderator.

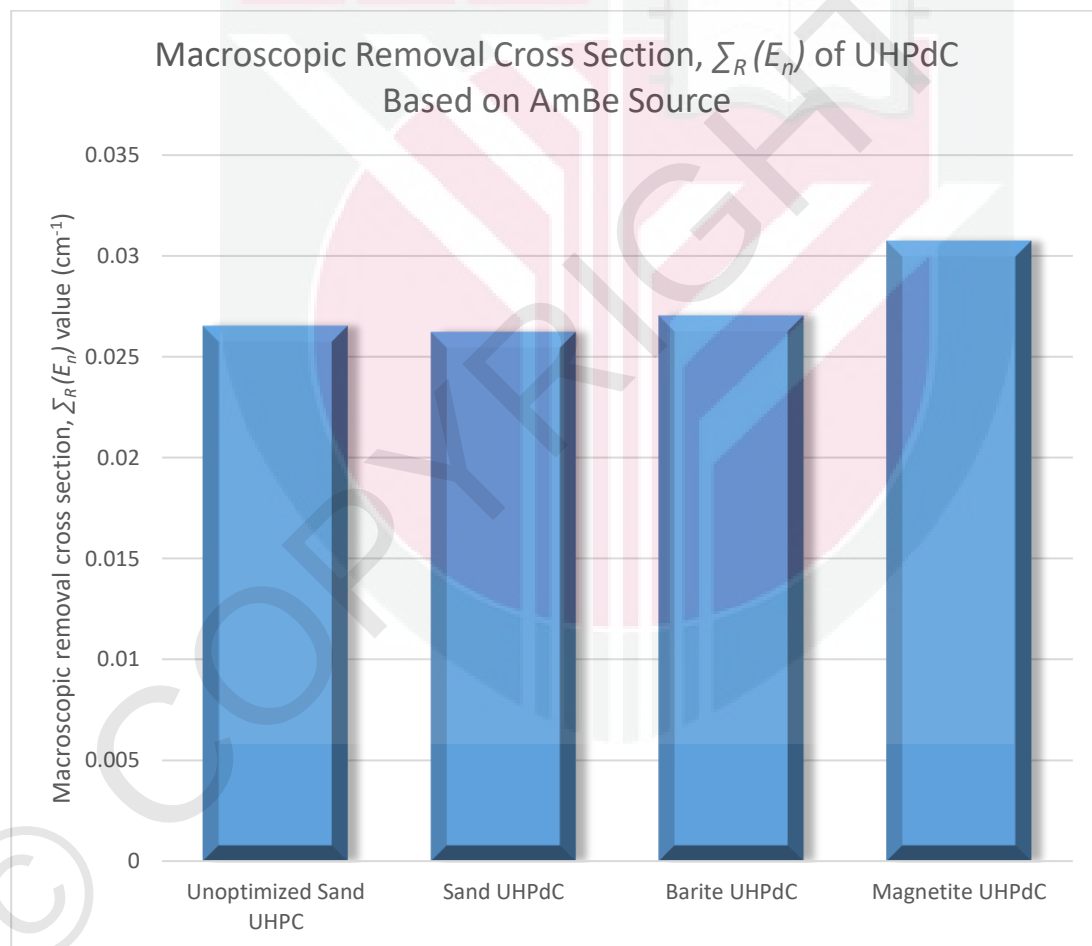


Figure 4.36 : Value of $\sum_R(E_n)$ value for UHPdC and unoptimised sand UHPC

4.11 Thermal Durability of Optimised Ultra-high Performance Dense Concrete

The thermal durability of optimised UHPdC is analysed based on the residual strength and shielding properties after being exposed to high temperatures of 400 and 800 °C. An image of the internal structure of UHPdC is also analysed which is scanned using X-ray micro-CT.

4.11.1 Residual Compressive Strength

Overall, increasing temperature resulted in lower compressive strength. At 400 °C exposure, sand and barite UHPdC recorded 19.4 and 8.8 % reductions in compressive strength respectively (Figure 4.37). Further increase in heat exposure resulted in a larger reduction of strength. However, magnetite UHPdC shows a constant strength at exposure to 400 °C which indicates the thermal stability of magnetite UHPdC. Magnetite which contains Fe_3O_4 would keep its phase stability at a temperature below 570 °C (Grosu et al., 2017). Expansion of sand and barite resulted in the formation of cracks on hardened cement paste around the aggregate which led to lower compressive strength.

However, sand UHPdC recorded a higher percentage of loss in compressive strength at 400 °C compared to other UHPdC. This indicates low thermal resistance of sand UHPdC at 400 °C which may be due to higher heat capacity and thermal conductivity of sand compared to denser aggregate (Ismail Ahmed Ali & Lublóy, 2022).

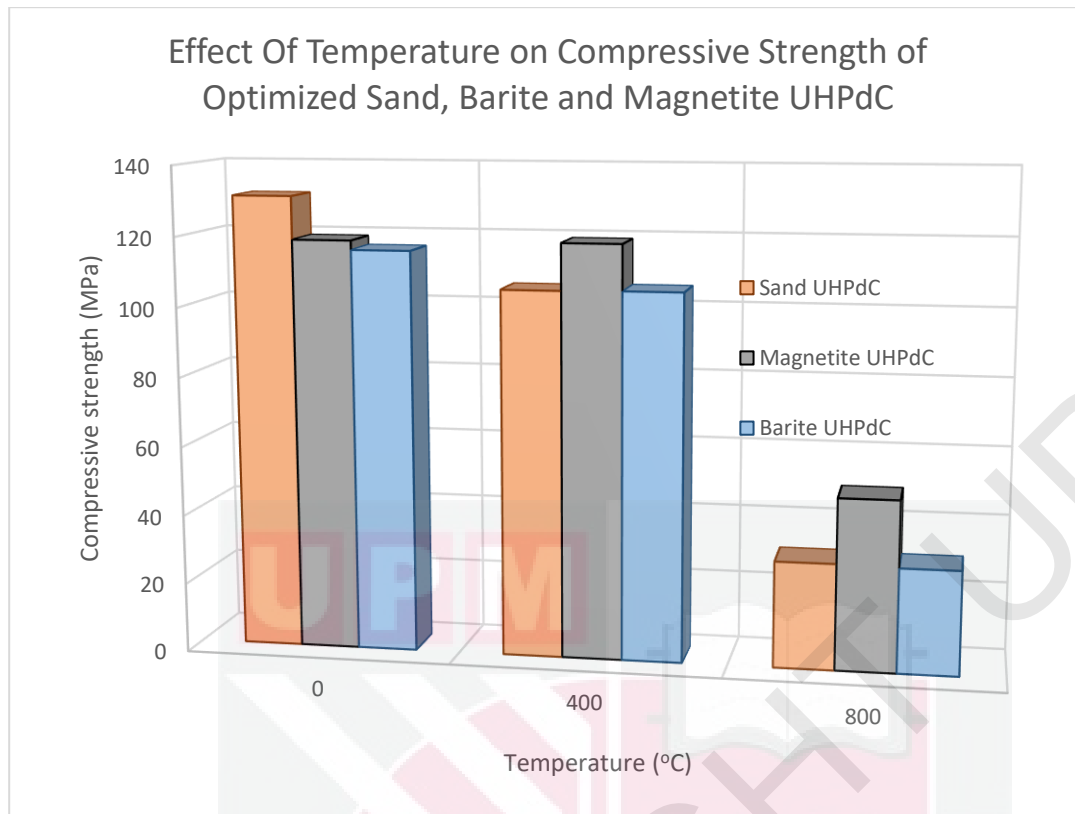


Figure 4.37 : Effect of temperature on compressive strength of optimised sand, barite and magnetite UHPdC

4.11.2 Residual Flexural Strength

Exposure to 400 °C resulted in lower flexural strength recorded in UHPdC. Sand recorded the highest residual flexural strength which is 14.8 MPa which is a 26.4 % reduction (Figure 4.38). This is followed by magnetite and barite UHPdC which both recorded a strength of 12.3 MPa with varied percentages of flexural strength reduction (Figure 4.39).

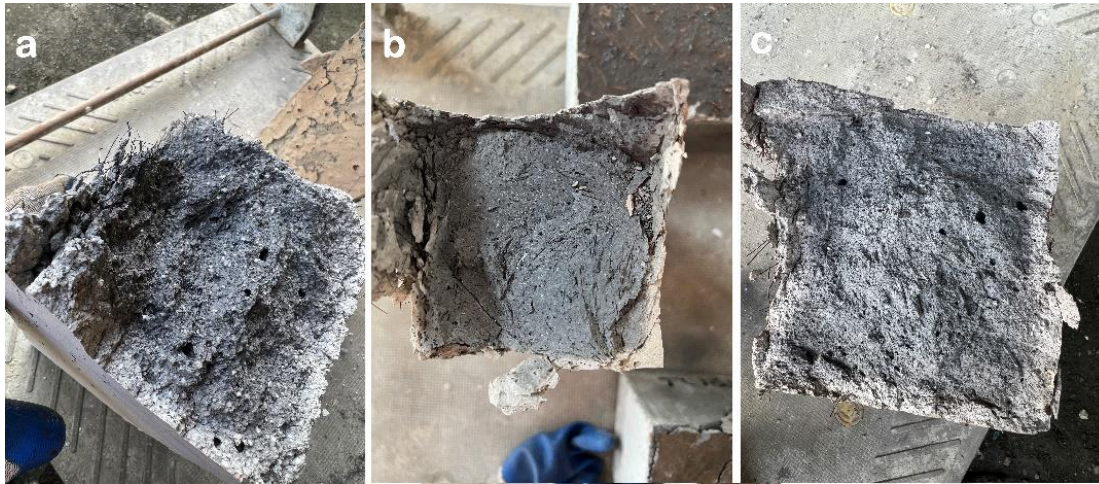


Figure 4.38 : Photo of 800 °C heated sample of a. sand UHPdC, b. barite UHPdC and c. magnetite UHPdC

At 800 °C, magnetite recorded the highest residual flexural strength at 7.0 MPa which is a reduction of 58.6 % compared to the the unheated sample (Figure 4.39). This is followed by sand and barite UHPdC which recorded 4.7 and 3.4 MPa respectively. Sand and barite UHPdC recorded higher reduction compared to magnetite UHPdC which is 76.3 and 75.5 % of strength reduction respectively.

The overall reduction in flexural strength of UHPdC due to thermal exposure is due to the expansion of aggregate that caused internal cracking hence reducing contact around steel fibre. Furthermore, a high temperature of 800 °C deteriorated the integrity of steel fibre further reducing the flexural strength of UHPdC. Figure 4.38 shows a change in the colour of steel fibres inside sand, barite and magnetite UHPdC. Steel fibres appear black due to severe oxidation which is also observed in a study of steel fibre's morphologies at a high temperature (L. Li et al., 2020). The study also reports that steel fibre loses its structural integrity at this temperature due to cracking and peeling

from the oxidation process. This resulted in a lower reinforcing effect from steel fibre hence lower flexural strength of UHPdC.

Exposure to 400 °C only caused oxidation on copper coating of steel fibre which explained the smaller reduction of flexural strength compared to exposure at 800 °C. However, the reduction in flexural strength of UHPdC is due to the expansion of steel fibre which resulted in cracking and loss in adhesion between the fibre and cement paste of aggregate (Zheng et al., 2013).

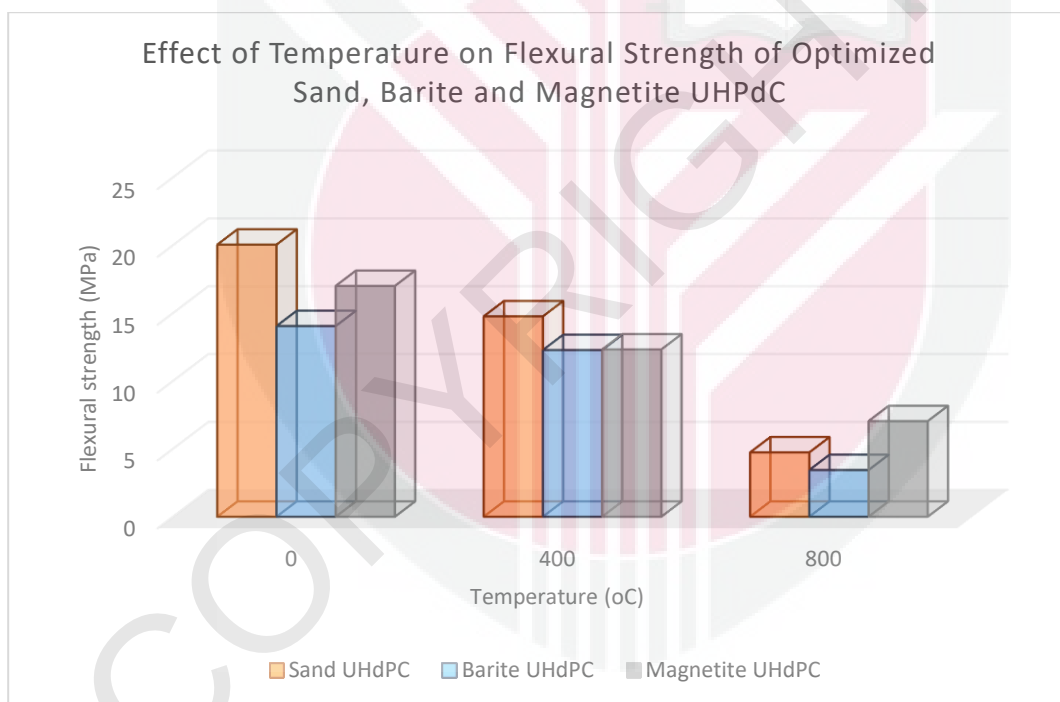


Figure 4.39 : Effect of temperature on flexural strength of optimised sand, barite and magnetite UHPdC

At 400 °C of heat exposure, sand UHPdC recorded high thermal resistance compared to sand UHPdC exposed to 800 °C based on residual flexural strength (Figure 4.39). This is due to the transition of quartzite crystal only

occurring at temperatures higher than 570 °C that resulting in intensive cracking and an increase in volume (Horszczaruk & Brzozowski, 2019; Yao & Hatta, 1995). Formation of cracks and increased void volume in sand UHPdC resulted in deterioration of structural integrity and friction between steel fibre and aggregate hence lowering the overall flexural strength. However, barite UHPdC shows better thermal resistance at 400 °C compared to sand UHPdC based on the percentage of flexural strength reduction. This may be due to the higher density of barite which resulted in higher thermal resistance at this temperature (Ismail Ahmed Ali & Lublóy, 2022).

However, the expansion of barite at 800 °C resulted in a large reduction of flexural strength compared to exposure at 400 °C. The expansion of barite resulted in cracking in hardened cement paste which led to poor contact with steel fibre hence the overall reduction in flexural capacity. Based on the percentage of flexural strength reduction, magnetite UHPdC shows better thermal resilience up to 800 °C.

4.11.3 Residual Splitting Tensile Strength

In terms of residual splitting tensile strength, sand UHPdC recorded the highest value at 14.2 MPa followed by magnetite UHPdC at 13.5 MPa after being exposed to 400 °C (Figure 4.40). The lowest splitting tensile strength recorded at the same temperature exposure is barite UHPdC which recorded 11.9 MPa. In terms of reduction percentage in strength due to heat of 400 °C, sand, magnetite and barite UHPdC recorded 19.2, 10.9 and 17.5 % respectively.

At 800 °C, sand, magnetite and barite UHPdC recorded an even larger reduction percentage of splitting tensile strength which is 80.2, 74.9 and 81.9 % respectively. In terms of residual splitting tensile strength after 800 °C heat exposure, sand, magnetite and barite UHPdC recorded 3.5, 3.8 and 2.6 MPa respectively.

Overall, the trend is similar to the flexural strength result as the reduction in strength is higher for sand UHPdC after 800 °C exposure compared to 400 °C exposure which is due to the phase transition of quartzite in sand that occur beyond 570 °C (Yao & Hatta, 1995). Furthermore, barite UHPdC also shows a large reduction in strength due to an increase in heat exposure which is linked to the high thermal expansion coefficient possessed by barite aggregate that deteriorates the microstructural integrity. Magnetite also shows the highest thermal stability based on residual strength value which concurs with results in flexural strength.

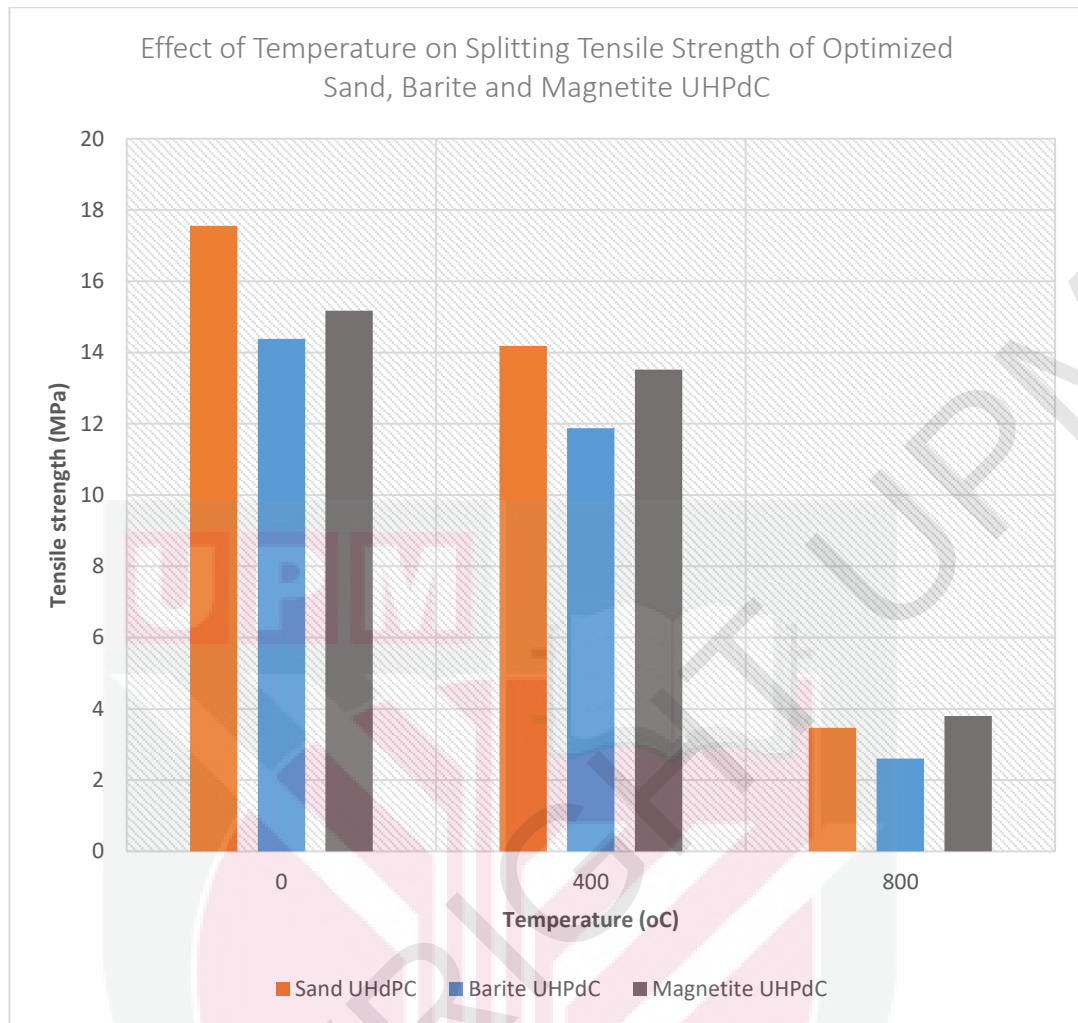


Figure 4.40 : Effect of temperature on splitting tensile strength of optimised sand, barite and magnetite UHPdC

4.11.4 Residual Linear Attenuation Coefficient

In terms of linear attenuation coefficient, magnetite UHPdC recorded the highest residual shielding value based on exposure to Cs-137 after heat exposure of 400 °C which is 0.1889 cm^{-1} (Figure 4.41). This is a 4.2 % reduction compared to an unheated sample which is the lowest reduction recorded among all UHPdC. Barite and sand UHPdC recorded 7.5 and 7.5 % reduction respectively which indicates the poor thermal durability of these UHPdC compared to magnetite UHPdC.

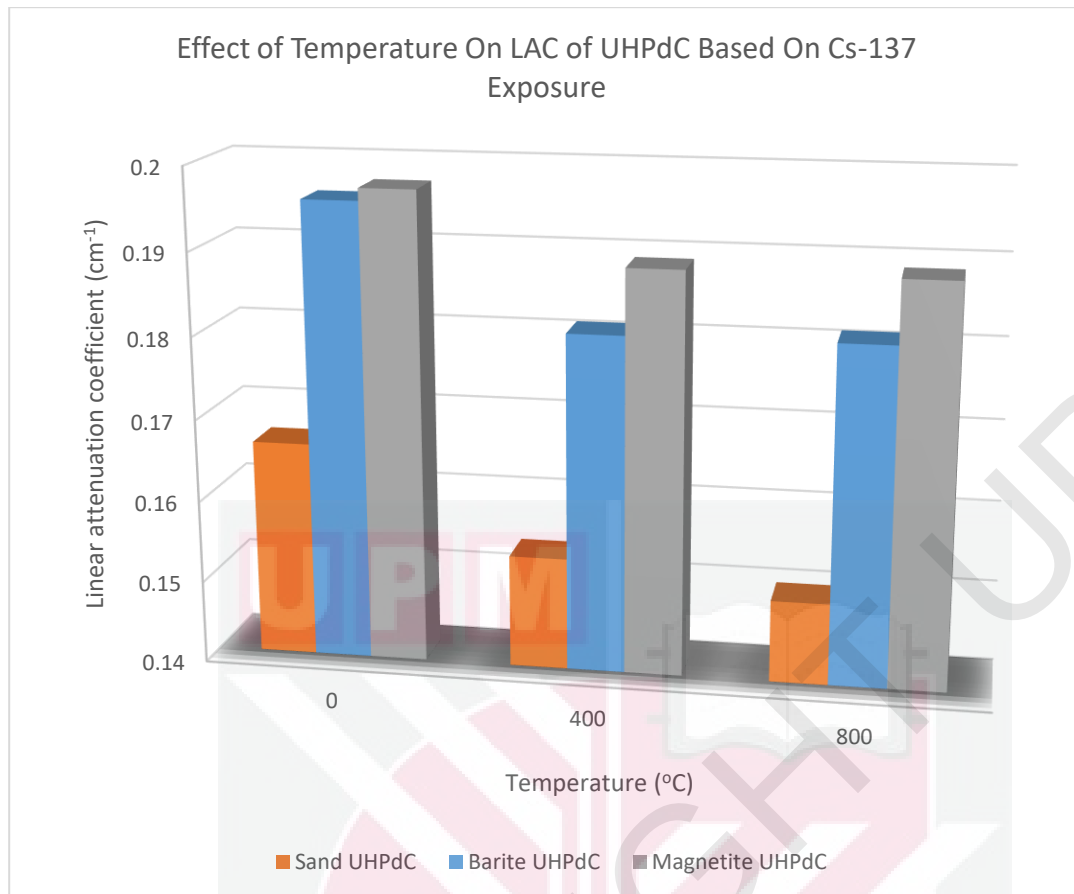


Figure 4.41 : Linear attenuation coefficient values recorded based on increasing temperature and Cs-137 exposure

Further increase in temperature exposure to 800 °C resulted in a further decrease of linear attenuation coefficient recorded by sand UHPdC. The sample recorded 0.15 cm⁻¹ which is 2.4 % lower compared to the value recorded by the sample exposed to 400 °C . However, barite and magnetite UHPdC recorded only 0.06 and 0.11 % reductions which indicates that temperatures beyond 400 °C would further deteriorate sand UHPdC's shielding value. This may be due to intensive cracking in sand and the phase transition of quartzite in sand aggregate leading to reduced density and overall shielding properties.

Based on the Co-60 source of radiation in the shielding test, a larger percentage of reduction in linear attenuation coefficient is also observed in samples up to 400 °C of heat exposure (Figure 4.42). Magnetite, barite and sand UHPdC recorded 6.4, 6.1 and 6.7 % of reductions in linear attenuation coefficient respectively. Further reduction in shielding value due to heat at 800 °C is only observed in sand UHPdC which is 2.8 % which is similar to records showed by radiation test with Cs-137.

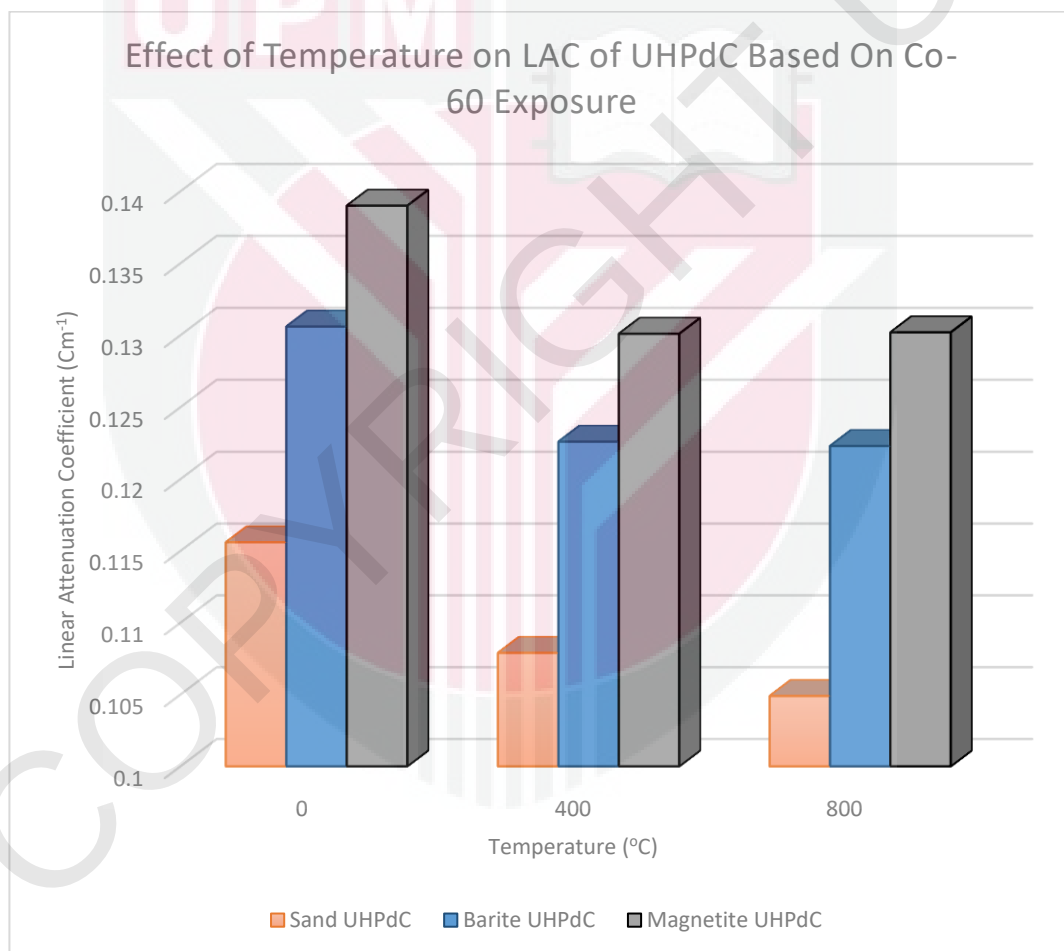


Figure 4.42 : Linear attenuation coefficient values recorded based on increasing temperature and Co-60 exposure

4.11.5 Residual Macroscopic Removal Cross Section

In terms of neutron shielding, magnetite UHPdC recorded the highest value throughout the temperature exposure. Heat at 400 °C caused a reduction in neutron shielding of magnetite UHPdC by 8.1 % which is 0.0282 cm⁻¹ in terms of macroscopic removal cross-section, $\Sigma_R(E_n)$ (Figure 4.43). Sand and barite UHPdC recorded 9.5 and 15.9 % of reduction in $\Sigma_R(E_n)$ value which is linked to lower thermal stability of these UHPdCs compared to magnetite UHPdC. Expansion of sand and barite in the UHPdC creates cracks and allows larger evaporation of bonded water and deterioration of colemanite which resulted in lower neutron shielding (Masoud, El-Khayatt, et al., 2020).

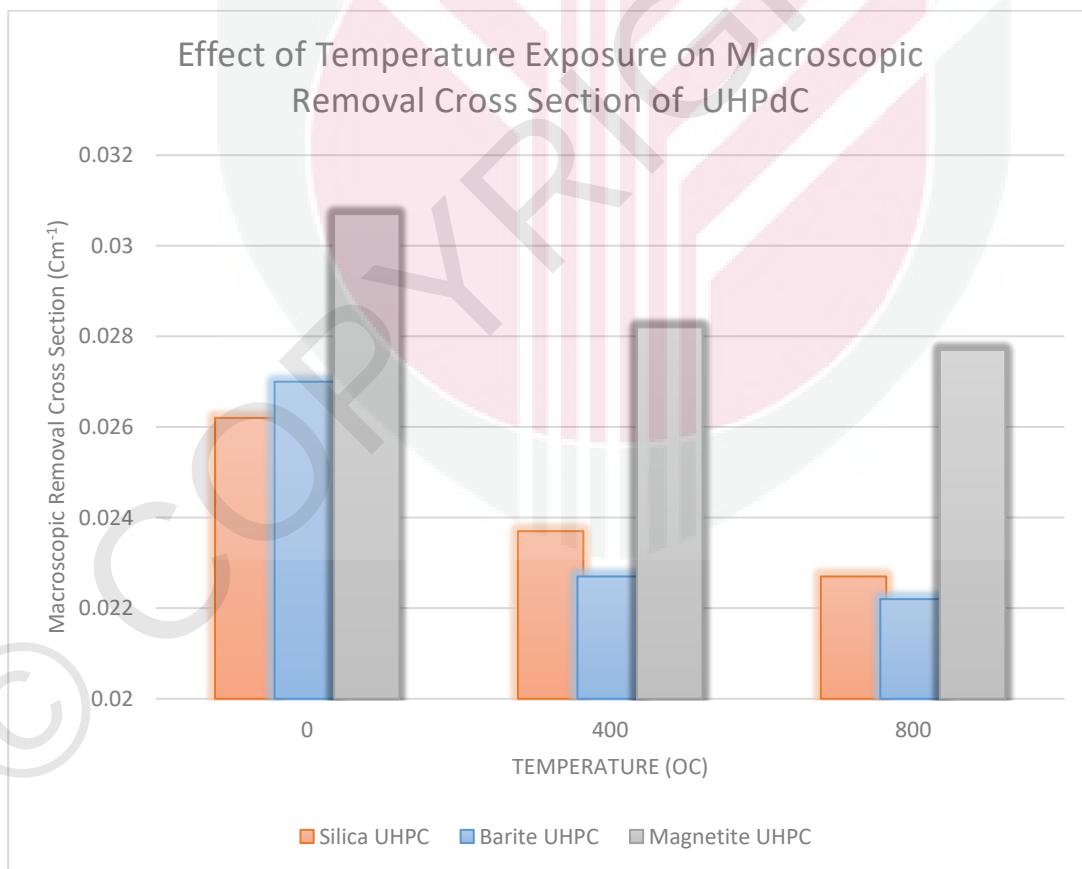


Figure 4.43 : Effect of temperature exposure on macroscopic removal cross section of UHPdC

At a higher temperature of 800 °C, all samples show lower reduction which indicates that most of the neutron moderator and absorber were removed at 400 °C. At 800 °C exposure, magnetite UHPdC recorded only a 1.8 % lower removal cross-section value compared to sample exposed to 400 °C. This is also observed in barite UHPdC which recorded 2.2% while sand UHPdC recorded the largest reduction of 4.2%.

Overall, magnetite UHPdC shows the most durable UHPdC against temperatures of up to 800 °C based on neutron shielding value. This is followed by sand UHPdC and lastly barite UHPdC.

4.11.6 Result of micro-CT Scan

A sample of optimised UHPdCs are analysed using an x-ray micro-CT scan for non-intrusive analysis. Based on the x-ray scan of the sample, internal structure and reconstruction of three-dimensional models are produced for analysis. However, only magnetite and sand UHPdC produced viable results while barite UHPdC shows indistinguishable internal structure from the x-ray scan (Figure 4.44). This is due to the absorption edge of barite in the lower energy region that may absorb large amounts of x-rays which prevents any detection (S. C. Kim & Jung, 2013). Furthermore, the fine size of barite in comparison to magnetite reduces the gap between high-density aggregate which prevents x-rays penetration that produces images (Mungpayaban et al., 2022).

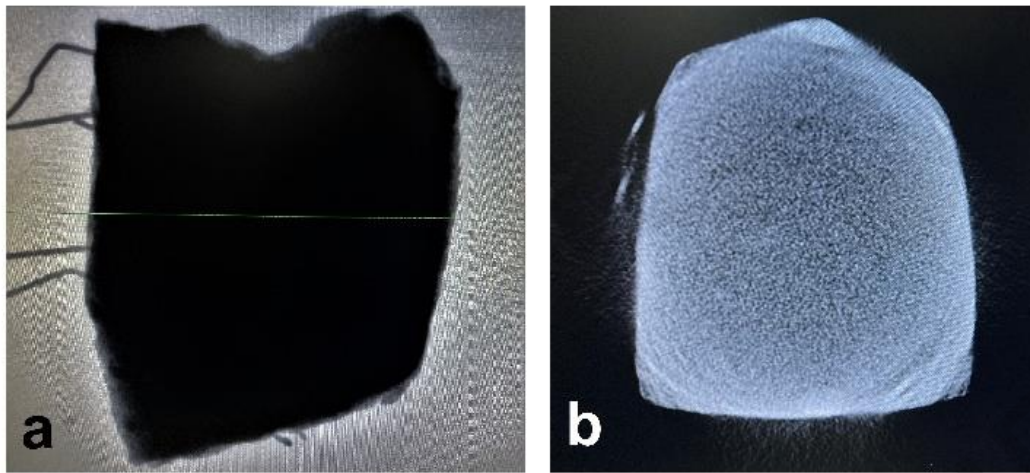


Figure 4.44 : Photos of a. x-ray scanned and b. constructed slice of barite UHPdC

Figure 4.45 shows the reconstructed 3-D model of unheated and heated sand UHPdC. Based on the model, steel fibres are well oriented as indicated by red and green lines. Heated sand UHPdC indicates a large amount of steel fibres oriented perpendicular to the direction of casting which is beneficial in resisting flexural deformation. This is also shown in magnetite UHPdC which most of the steel fibres in unheated and heated samples are positioned perpendicular to direction of casting (Figure 4.46). This resulted in higher strength of flexural members such as beam and slab. The 3-D model of magnetite UHPdC also shows a slightly lighter grey of concrete in the heated sample compared to the unheated sample. This indicates a reduction in the density of magnetite UHPdC due to heating at 800 °C which is congruent with the lower shielding properties of the heated sample compared to the unheated sample.

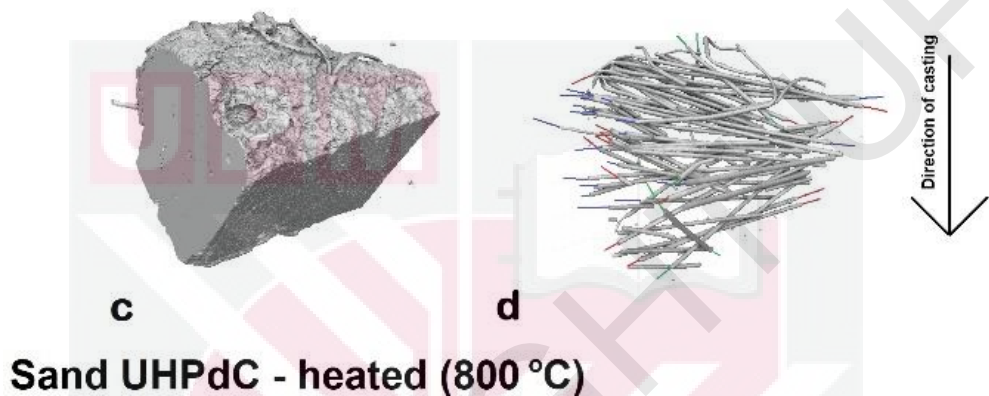
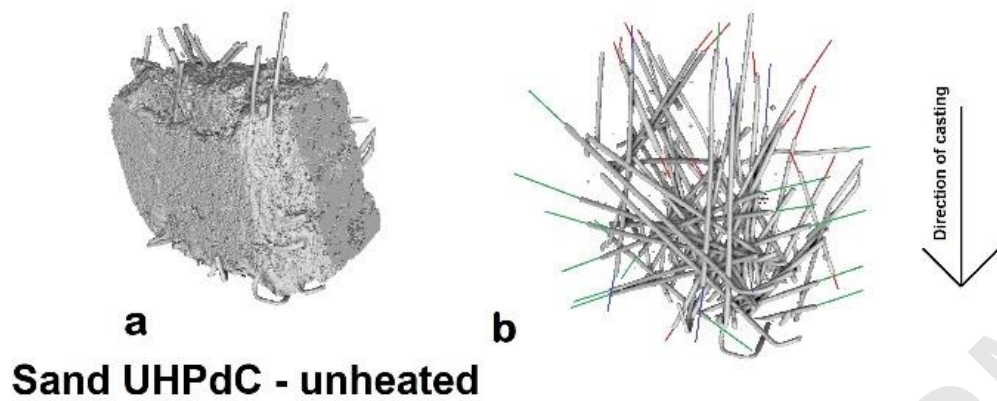


Figure 4.45 : 3-d reconstructed image of unheated (a and b) and heated (c and d) sample of sand UHPdC

Analysis of the constructed cross-section of unheated sand UHPdC shows pores formation adjacent to steel fibres (Figure 4.47a). This indicates that fibres in UHPdC contribute to the formation of pores which leads to lower strength. Furthermore, pores are also formed along the orientation of steel fibres which would affect adhesion between cement paste and steel fibre (Figure 4.47b). For the heated sand UHPdC sample, a slice image from the side of the sample shows intensive cracking formed around the sand which is due to the expansion of sand at 800 °C (Figure 4.48a). Furthermore, these cracks are also found to be connected between pores which help diffuse internal pressure due to heat hence preventing spalling. Formation of cracks is also found along steel fibre orientation which may be due to the expansion of the fibre and

deterioration of cement paste (Figure 4.48b). This resulted in less adhesion between fibres and hardened cement paste hence congruent with lower flexural strength observed in the heated sample compared to the unheated sample.

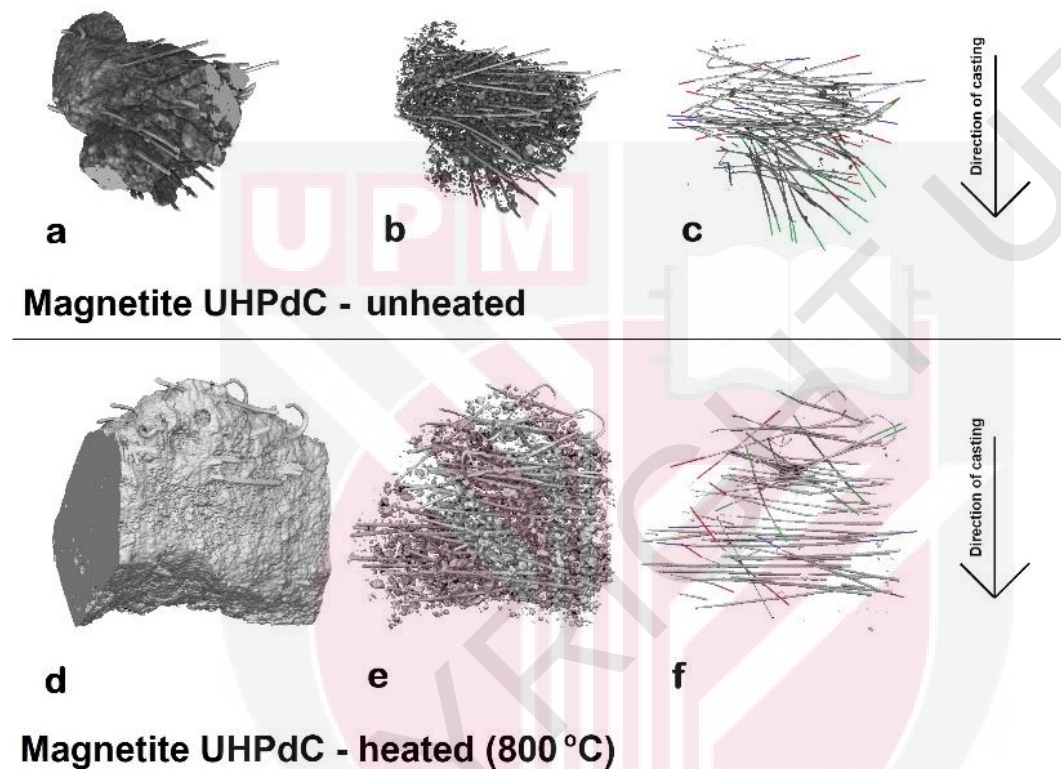


Figure 4.46 : 3-d reconstructed image of unheated (a, b and c) and heated (d, e and f) sample of magnetite UHPdC

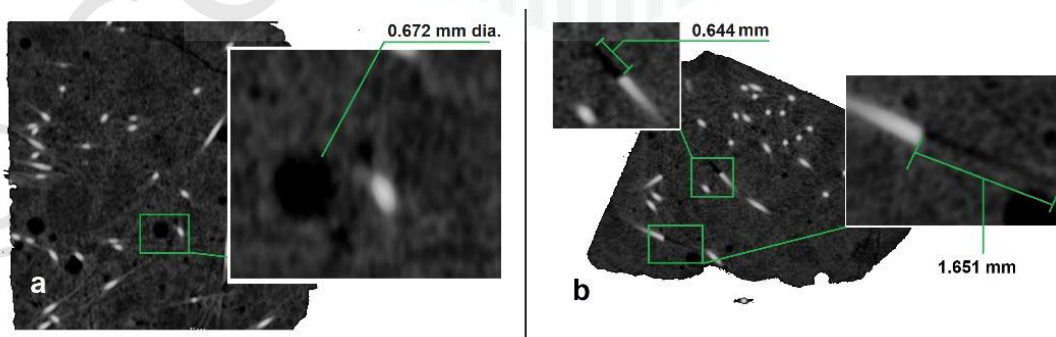


Figure 4.47 : CT image of a. side and b. top cross section of unheated sand UHPdC

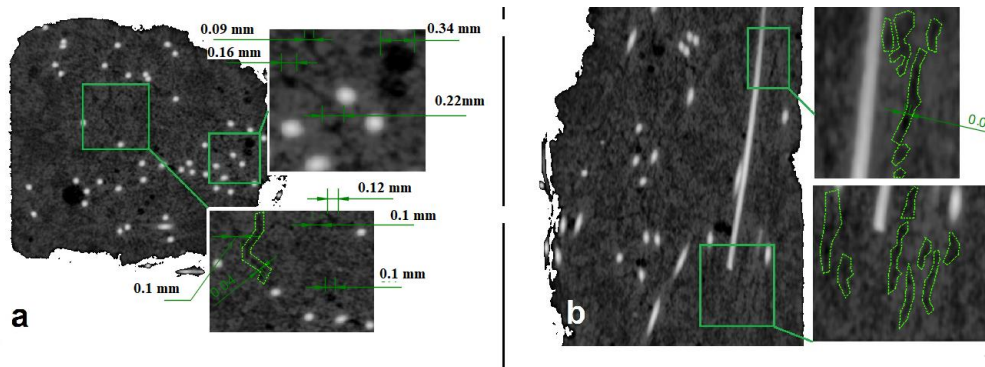


Figure 4.48 : CT image of a. side and b. top cross section of 800 °C heated sand UHPdC

For magnetite UHPdC, crack formation is less observed but the cracks are also formed connecting the pores as observed in sand UHPdC (Figure 4.49c). However, the cracks are less visible compared to sand UHPdC which indicates the severity of the cracks. This may be due to the higher thermal stability possessed by magnetite compared to sand. However, the slice image also shows cracks formed originating from pores which indicate an expansion of pores. Pores could expand as pressure builds up due to increasing heat which leads to cracking. This cracking near pores is not visible in unheated samples of magnetite UHPdC as shown in Figure 4.49a.

Analysis of the unheated magnetite sample also shows pores forming adjacent to steel fibres as observed in sand UHPdC (Figure 4.49b). This indicates that the incorporation of fibres leads to higher pore volume. Furthermore, magnetite aggregate is more visible compared to sand aggregate in the image as the density of magnetite is higher compared to other elements in UHPdC. Based on the image of the heated sample, cracks are formed around the magnetite hence indicating no visible cracking occurred in the magnetite due to heating at 800 °C.

Heating of UHPdC resulted in cracks formation due to aggregate expansion, cement paste deterioration and fibre evaporation. Based on CT-scan results, magnetite UHPdC shows higher thermal durability compared to sand UHPdC due to less visible cracking in the images.

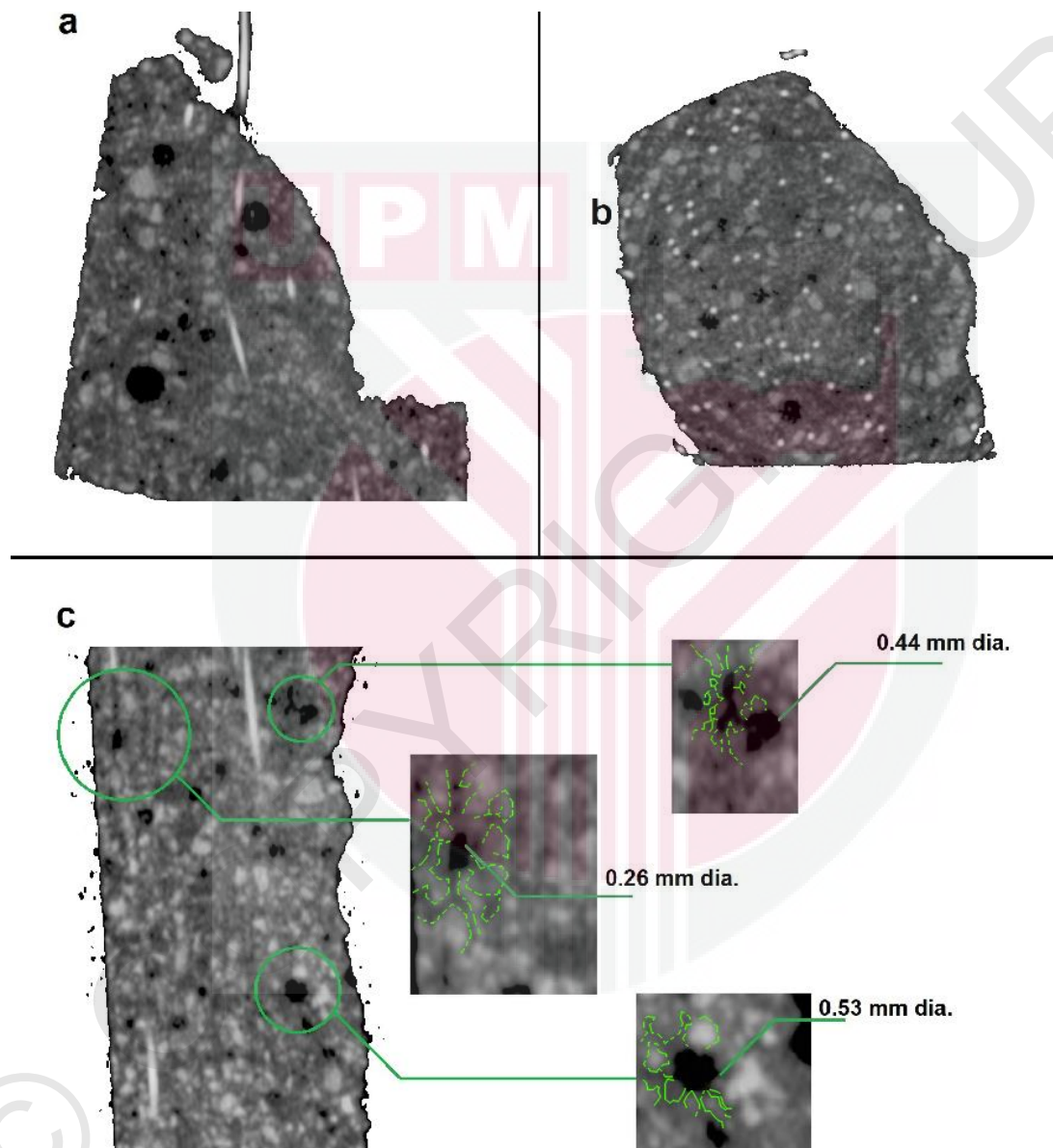


Figure 4.49 : CT image of a. top and b. side cross section of unheated magnetite UHPdC along with c. image of front cross section of 800 °C heated magnetite UHPdC

4.12 Simulation of Dry Cask Storage for Spent Fuel Cell

Based on the experimental data, simulations of structural and radiation shielding performance are carried out to validate the experimental work and also to investigate its viability as dry cask storage for spent fuel cells.

4.12.1 Structural Simulation Using ANSYS

Simulations are carried out using ANSYS software and modelled on flexural tests that were carried out on unoptimised sand UHPC and optimised UHPdC of sand, barite and magnetite. Based on the calculated flexural modulus and peak load recorded for each sample, the model of the beam is simulated to produce displacement on the z-axis as a point of validation (Figure 4.50).

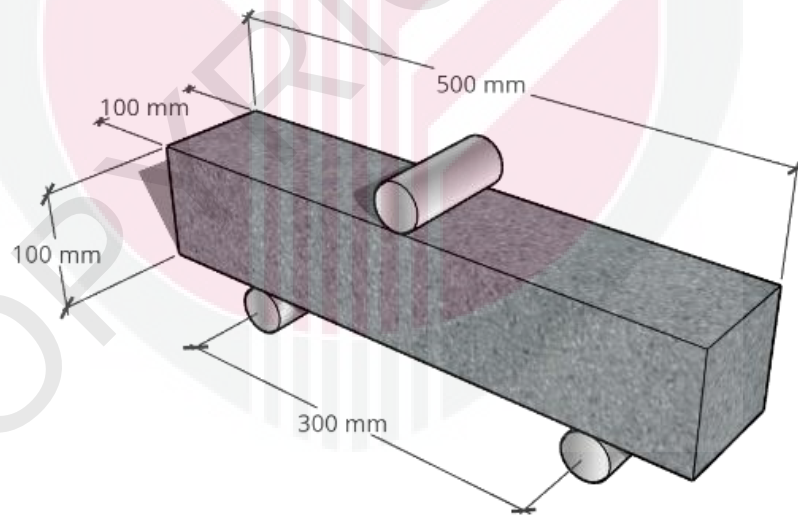


Figure 4.50 : 3d model used in simulation of UHPdC beam

Unoptimised sand UHPC recorded the highest flexural modulus and based on the simulation, it deflected to 4.52 mm on the z-axis (Figure 4.51). This is slightly lower compared to recorded the deflection of 5 mm. For optimised sand UHPdC, the model produced 4.52 mm of deflection which is also slightly lower

compared to the experimental deflection of 5 mm (Figure 4.52). Simulation for optimised barite UHPdC shows a slightly larger difference compared to experimental work which is 4.46 mm compared to 5 mm of deflection from the experimental work (Figure 4.53). The optimised magnetite UHPdC model shows the lesser difference in deflection between simulation and experimental work which is 4.51 mm compared to 5 mm of actual deflection (Figure 4.54).

Simulation is repeated using increasing load applied on the model until the displacement measured at the centre of the beam is similar to the experimental which is 5 mm. Unoptimised sand UHPC recorded 5 mm displacement with 57 kN of peak load which is 6.6 kN higher than the experimental value. Sand UHPdC recorded a 6.5 kN higher peak load at 5 mm displacement. This is almost similar to unoptimised sand UHPdC. Barite and magnetite UHPdC recorded 4.5 and 5.6 kN higher than the experimental peak load value. The small difference in terms of peak load simulated based on the displacement of the model indicates validation of the experimental data gathered in this study.

Overall data regarding simulation work on the beam is summarised in Table 4.2 and Table 4.3. The difference in terms of displacement value and simulated peak load is small as observed in both parameters. It can be concluded that the simulations validated the data gathered in the experimental work.

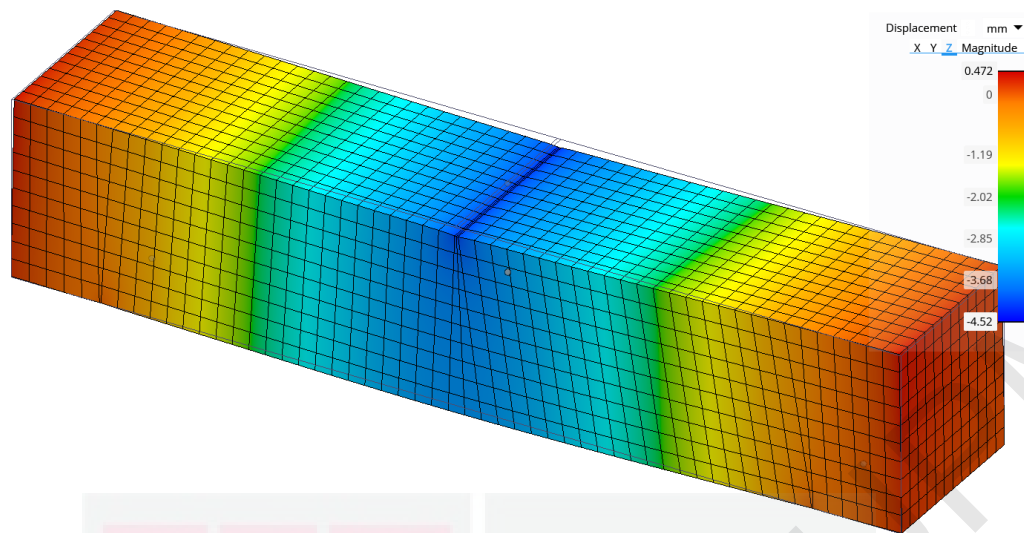


Figure 4.51 : Simulated beam deflection of unoptimised sand UHPC

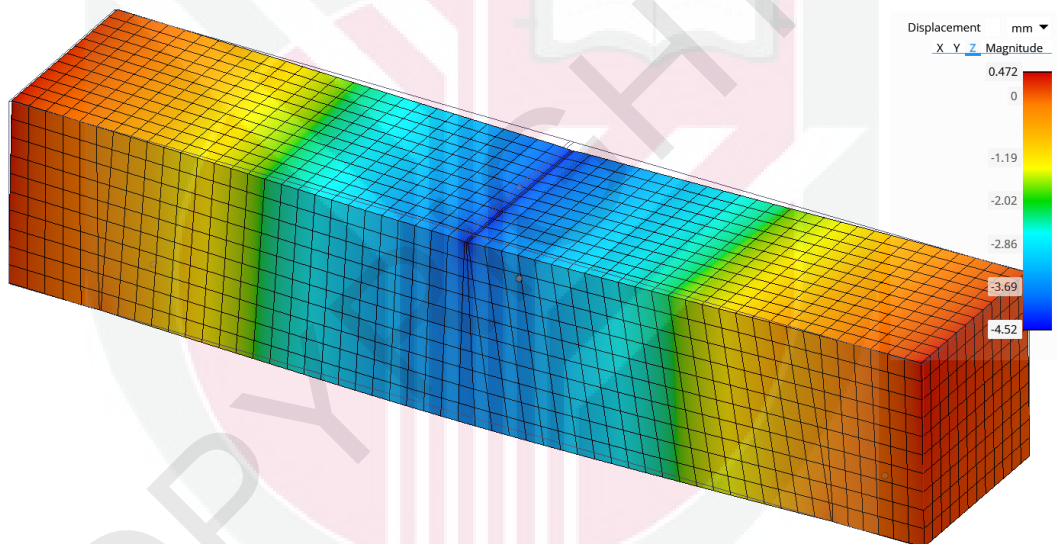


Figure 4.52 : Simulated beam deflection of sand UHPdC

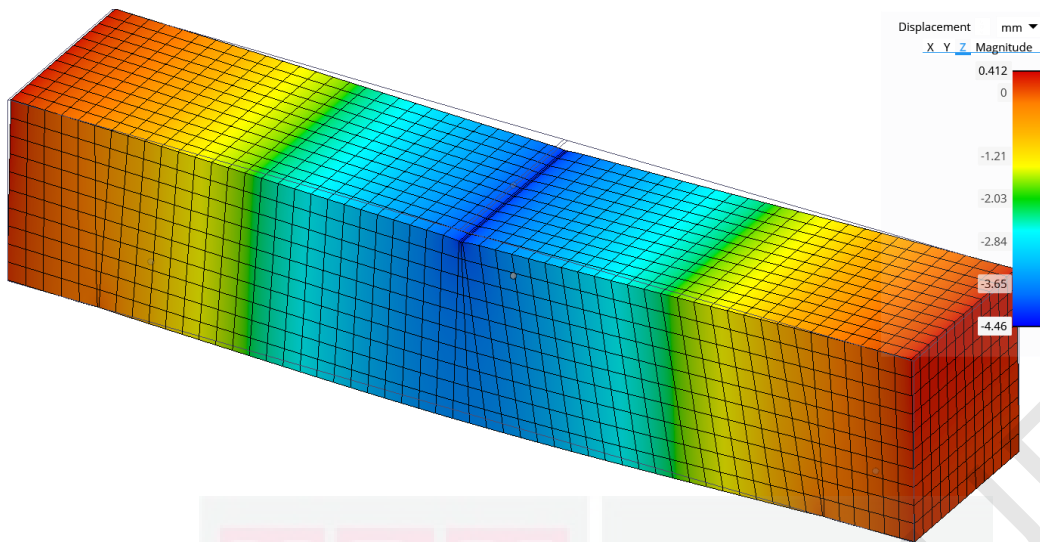


Figure 4.53 : Simulated beam deflection of barite UHPdC

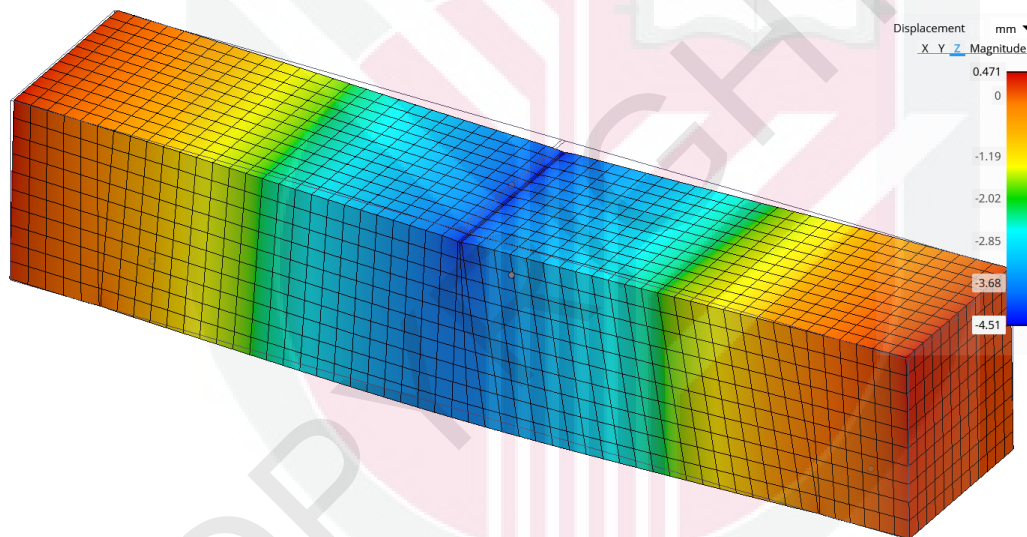


Figure 4.54 : Simulated beam deflection of magnetite UHPdC

Table 4.2 : Summarised data on samples simulated in ANSYS

Model ID	Flexural modulus (GPa)	Peak load (kN)	Peak load - simulation (kN)	Deflection – Experimental (mm)	Deflection – simulation (mm)
Unoptimised sand UHPC	1.61	50.4	57.0	5	4.52
Optimised sand UHPdC	1.60	50.1	56.6	5	4.52
Optimised barite UHPdC	1.12	35.1	39.6	5	4.46
Optimised magnetite UHPdC	1.36	42.5	48.1	5	4.51

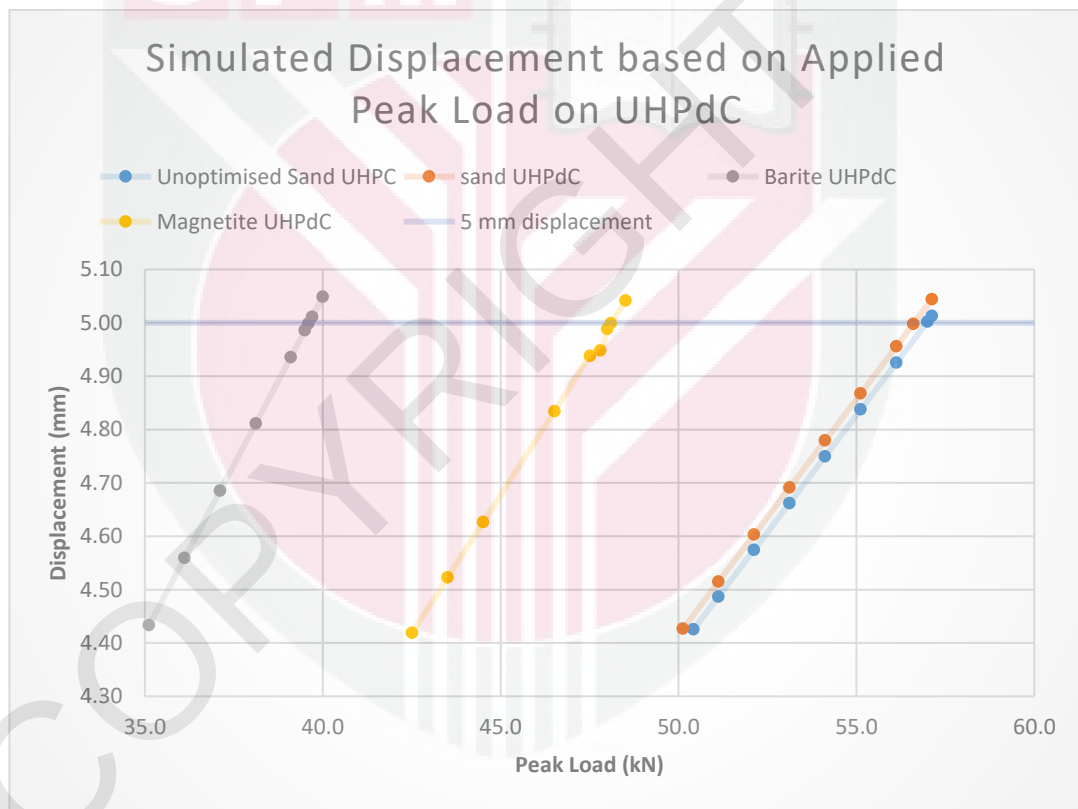


Figure 4.55 : Simulated displacement of beam model based on applied peak load

Table 4.3 : Peak load, maximum displacement and maximum Von Mises Stress of UHPdC

	Peak Load (kN)	Max. Displacement (m)	Max. Von Mises Stress (Pa)
Unoptimised Sand UHPC	50.4	4.43	118597710.1
	51.1	4.49	120236222.0
	52.1	4.57	122588149.1
	53.1	4.66	124940076.8
	54.1	4.75	127292004.4
	55.1	4.84	129643936.1
	56.1	4.92	131995861.4
	57.0	5.00	134065559.3
	57.1	5.01	134347793.7
sand UHPdC	50.1	4.43	117884129.0
	51.1	4.51	120236062.3
	52.1	4.60	122587987.8
	53.1	4.69	124939916.6
	54.1	4.78	127291843.0
	55.1	4.87	129643774.6
	56.1	4.96	131995700.6
	57.1	5.04	134347632.3
	56.6	5.00	133124626.8
Barite UHPdC	35.1	4.43	82598277.0
	36.1	4.56	84950209.1
	37.1	4.69	87302137.5
	38.1	4.81	89654066.3
	39.1	4.94	91966795.1
	40.0	5.05	94083533.1
	39.5	4.99	92907567.3
	39.7	5.01	93377953.7
	39.6	5.00	93142761.4
Magnetite UHPdC	42.5	4.42	99994420.3
	43.5	4.52	102346349.1
	44.5	4.63	104698277.4
	46.5	4.83	109402136.5
	47.5	4.94	111754068.2
	47.8	4.95	111954068.2
	48.0	4.99	112754068.2
	48.1	5.00	113134651.9
	48.5	5.04	114105994.6

Data from compressive strength are also used for the simulation of dry cask storage. Dimension of dry cask storage is based on previous work which follows the Nuclear Regulatory Commission on spent fuel storage and handling (Ko et al., 2014). Figure 4.56 shows the reproduced 3d model that is

used in the simulation. However, the simulated model is designed to be stacked and hence designed to resist distributed loading of another similar dry cask storage (Figure 4.56b).

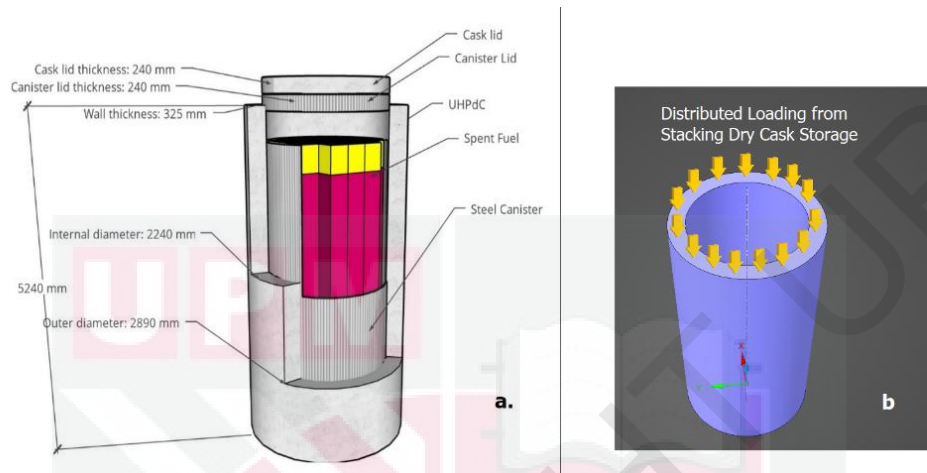


Figure 4.56 : Reproduced 3d model of dry cask storage from previous study (Ko et al., 2014) (a) and the applied loading on the cask (b)

Due to this, the modulus of elasticity is calculated using Eq. 3.9 which requires the compressive strength data recorded from the experimental work. Simulations revealed that all optimised UHPdC are capable of withstanding axial loading due to stacking with no significant deformation. Sand, barite and magnetite UHPdC recorded maximum deformation of 0.0381, 0.0467 and 0.0498 mm respectively (Figure 4.57). Larger deformations shown in barite and magnetite UHPdC are due to their denser property which imposed larger axial loading when stacked.

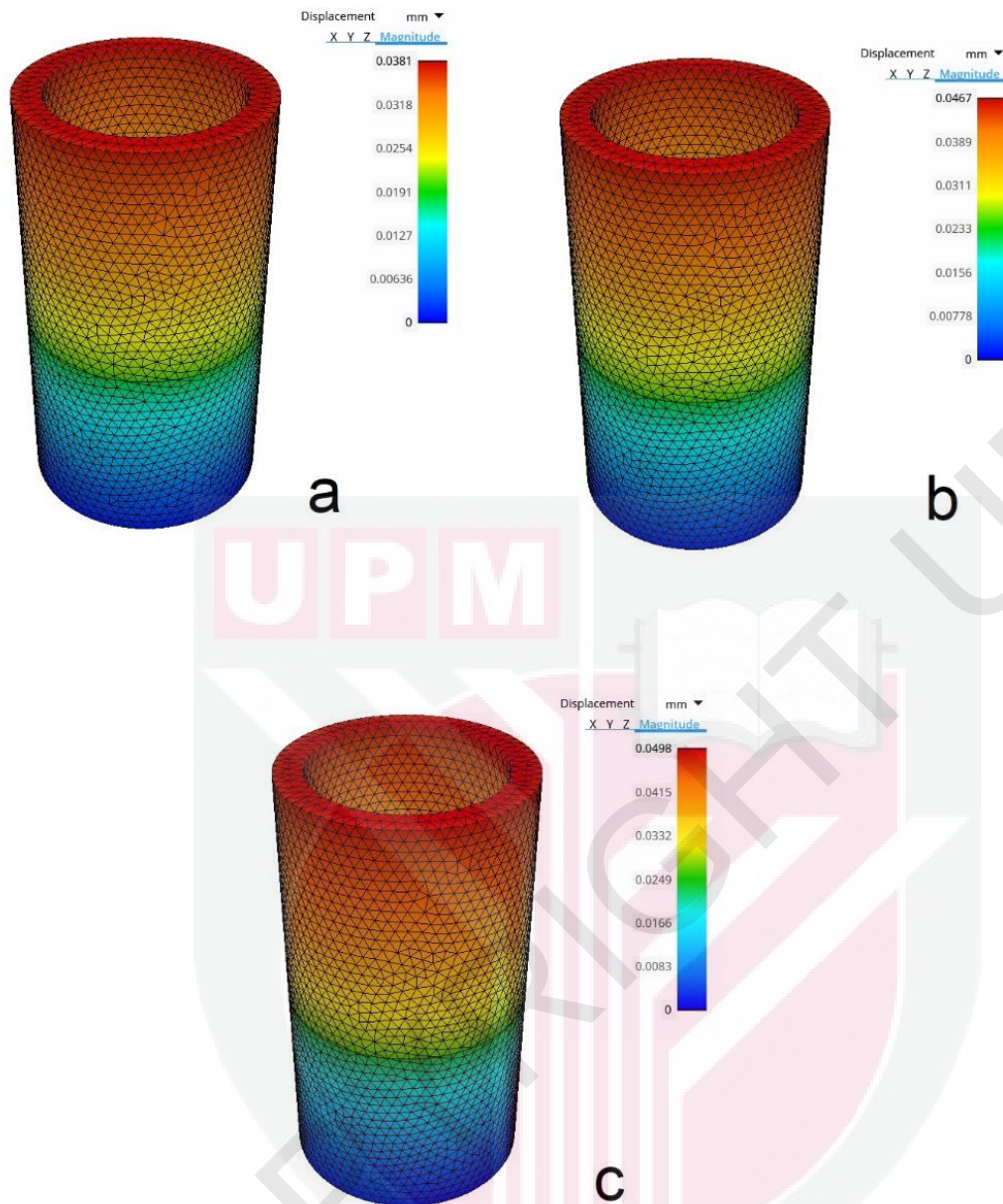


Figure 4.57 : Simulated dry cask storage of a. Sand UHPdC, b. Barite UHPdC and magnetite UHPdC

The dry cast storage model is also simulated with residual compressive strength of UHPdC to evaluate its durability. The result of the simulation shown in Figure 4.58 indicates an increase in deflection by more than 40 % as the strength deteriorated due to heat. Due to heating, the weight of UHPdCs is also reduced which resulted in lower loading due to stacking. The largest deflection is recorded by barite UHPdC cask which is 0.0758 mm and this is followed by sand and magnetite UHPdC at 0.062 and 0.064 mm respectively.

The superior thermal durability of magnetite UHPdC is reflected in this simulation as it recorded the lowest deflection despite sustaining larger loading due to denser material.

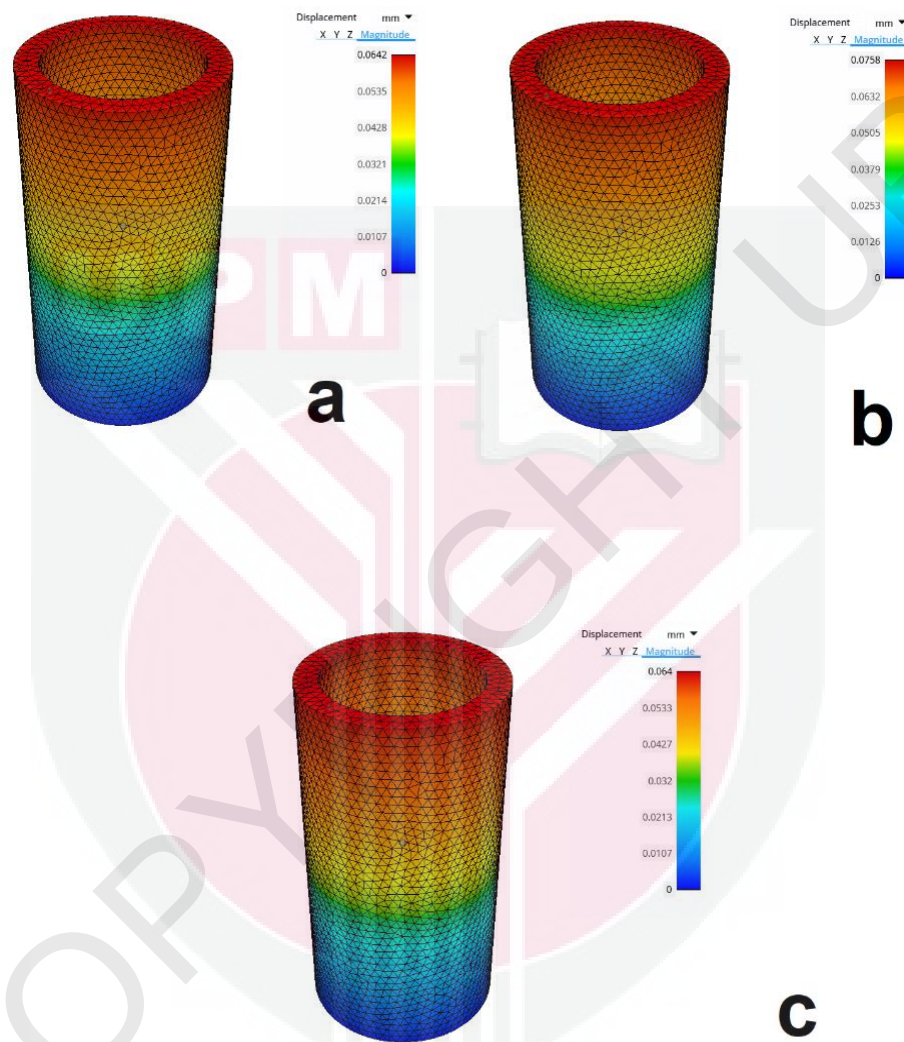


Figure 4.58 : Simulated dry cask storage based on deteriorated strength due to 800 °C of a. sand UHPdC, b. barite UHPdC and magnetite UHPdC

Based on the simulation, the wall thickness of 325 mm is sufficient for all types of optimised UHPdC to be stacked during the storage of spent fuel cells. This will result in less footprint imposed by the dry cask storage with no compromise on structural integrity. Overall the values indicate that the dimension of cask

storage is sufficient for vertical stacking arrangement which proves economical in terms of material and footprint usage.

4.12.2 Radiation Shielding Simulated Using PHITS

Based on similar dimensions used for models in structural simulation, a model is developed for radiation shielding simulation using PHITS software. PHITS is a software on particle transport simulation using Monte Carlo that can analyse in three-dimensional phase space of transport and collisions of nearly all particles that including heavy ions in the energy range of up to 100 GeV/u. In setting up the simulation of dry cask storage made from UHPdC materials, there are three sections of input needed which are parameters, geometry and tally. Parameters defined the source used in the simulation which is based on sources used study of dry cask storage developed for Korea Radioactive Waste Management Corporation (KRMWC) in Korea (Ko et al., 2014).

In this simulation, two types of sources are used gamma-ray and neutron radiation. These sources are defined by their energy distribution, shape and direction of the source. Materials used in the simulation are based on XRF analysis of materials used in the composition of sand, barite and magnetite UHPdC. Geometry defined the dimension of the cask while tally defined the type of tracking used in the simulation. In tally, t-track is defined as a tally parameter which tracks the transport of particles within the area of simulation. The accuracy of simulation work is based on statistical error which is generally accepted at the value of less than 10%. In this simulation, a total of 10000

histories per batch and 10 batches are defined in the code which achieved the required accuracy.

Figure 4.59 shows the quadrant of dry cask storage for each optimised UHPdC. It also shows the intensity of flux detected from the centre of the cask towards 200 cm from the centre of the cask. As depicted by the blue colour at the outer edge of the cask wall, the intensity of flux from gamma radiation is very low compared to the green colour at the inner side of the wall. All UHPdCs show low intensity of flux detected beyond the cask wall. This indicates that the thickness of the cask storage made from optimised UHPdCs shows a large attenuation of gamma radiation.

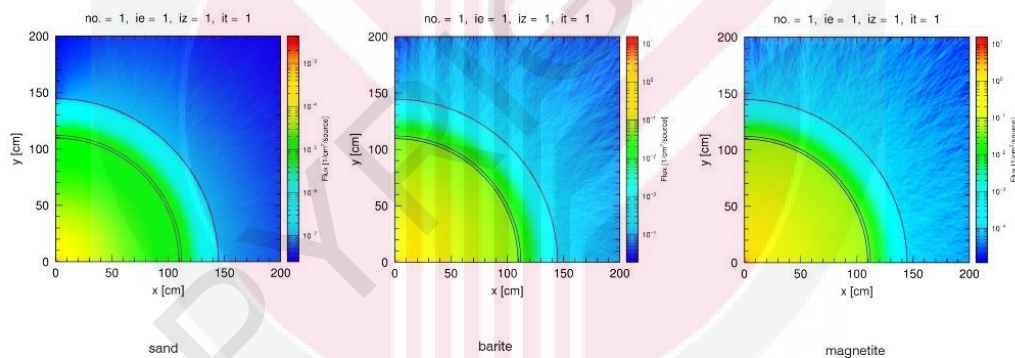


Figure 4.59 : Gamma ray shielding simulated result of dry cask storage using a. sand UHPdC, b. barite UHPdC and c. magnetite UHPdC

This is further demonstrated by Figure 4.60 which shows the effective dose rate declines sharply from the inner edge of the dry cask wall towards the outer face of the wall. Sand UHPdC shows the highest dose rate and this is followed by barite and magnetite UHPdC. The dose rate detected outer edge of the dry cask wall of sand UHPdC is 2.06×10^{-7} $\mu\text{sv}/\text{hour}/\text{source}$ while for barite and magnetite UHPdC is 9.99×10^{-8} and 7.09×10^{-8} $\mu\text{sv}/\text{hour}/\text{source}$ respectively.

Based on these values, magnetite UHPdC has the highest gamma-ray attenuation and this is followed by barite UHPdC and sand UHPdC. This validates the founding in experimental work on gamma-ray attenuation of UHPdCs.

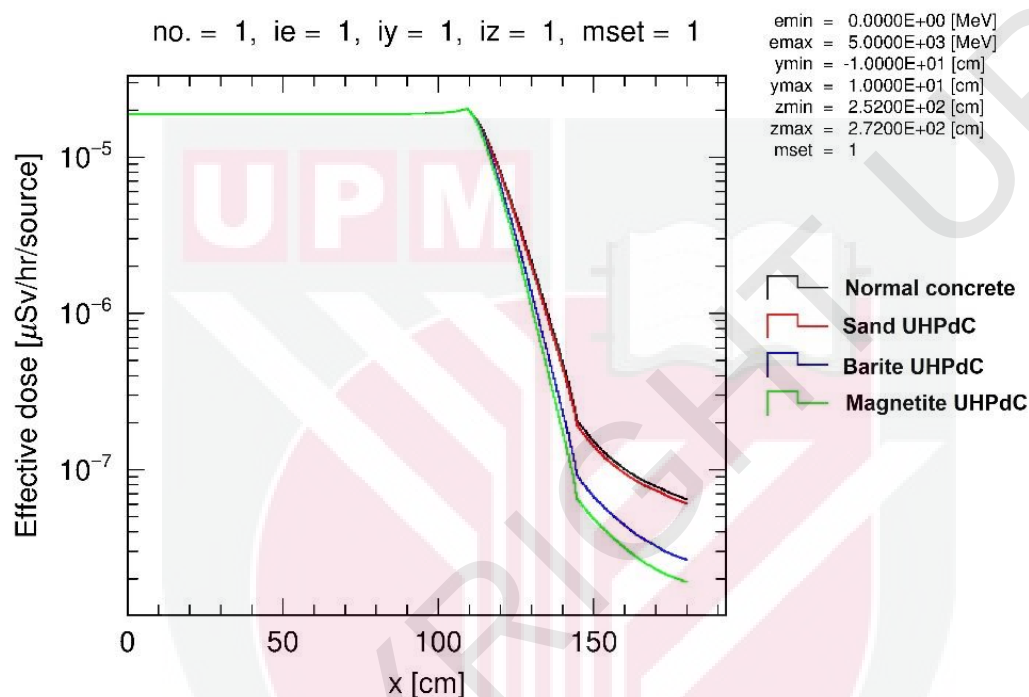


Figure 4.60 : Simulated effective dose of gamma ray for dry cask of normal concrete and optimised UHPdC

Overall, the resulting simulated gamma-ray effective dose of UHPdC correlates with its density. Further analysis by using the effective dose value to calculate the linear attenuation coefficient shows a similar trend of increased gamma-ray shielding with an increase in the density of UHPdC (Table 4.4). Comparison between simulated and experimental values shows a small difference between the simulated linear attenuation coefficient and the value obtained from exposure to Co-60. A lower effective dose was detected in UHPdC with higher density and this is also shown by experimental data. This

is because the attenuation of gamma radiation is highly influenced by the density of the shielding material.

The highest density shown by magnetite UHPdC is due to the high percentage of iron, Fe element in magnetite aggregate as shown by XRF results. Fe possess high atomic weight which largely contributes to gamma ray shielding of magnetite UHPdC. Hence, the simulated data validates the experimental data based on this correlation.

Table 4.4 : Summary of density, effective dose and linear attenuation coefficient of all UHPdCs

Type of UHPdC	Density (kg/m ³)	Effective dose (μsv/hours/source)	Simulated Linear attenuation coefficient based on effective dose (cm ⁻¹)	Linear attenuation coefficient from experiment of Co-60 (cm ⁻¹)	Linear attenuation coefficient from experiment of Cs-137 (cm ⁻¹)
Sand UHPdC	2374	2.06×10^{-7}	0.1200	0.1156	0.1663
Barite UHPdC	2776	9.99×10^{-8}	0.1381	0.1306	0.1957
Magnetite UHPdC	2991	7.09×10^{-8}	0.1458	0.139	0.1972

For exposure to neutron radiation, the simulated flux value shows that all types of UHPdC could shield the radiation to less than 10^{-5} cm⁻²/source with the specified cask thickness (Figure 4.61). Magnetite UHPdC shows a lower amount of flux based on the gradient of colour and this is followed by sand and barite UHPdC. In Figure 4.61c, turquoise lines are more visible compared to Figure 4.61a due to higher amount of blue colour.

Blue colour indicates flux value of less than $1 \times 10^{-6}/\text{cm}^2/\text{source}$. This lower compared to turquoise colour that indicate flux of $1 \times 10^{-5}/\text{cm}^2/\text{source}$. High concentration of turquoise colour near the surface of the cask for each type of UHPdC indicates sharp reduction of flux due to attenuation by UHPdC.

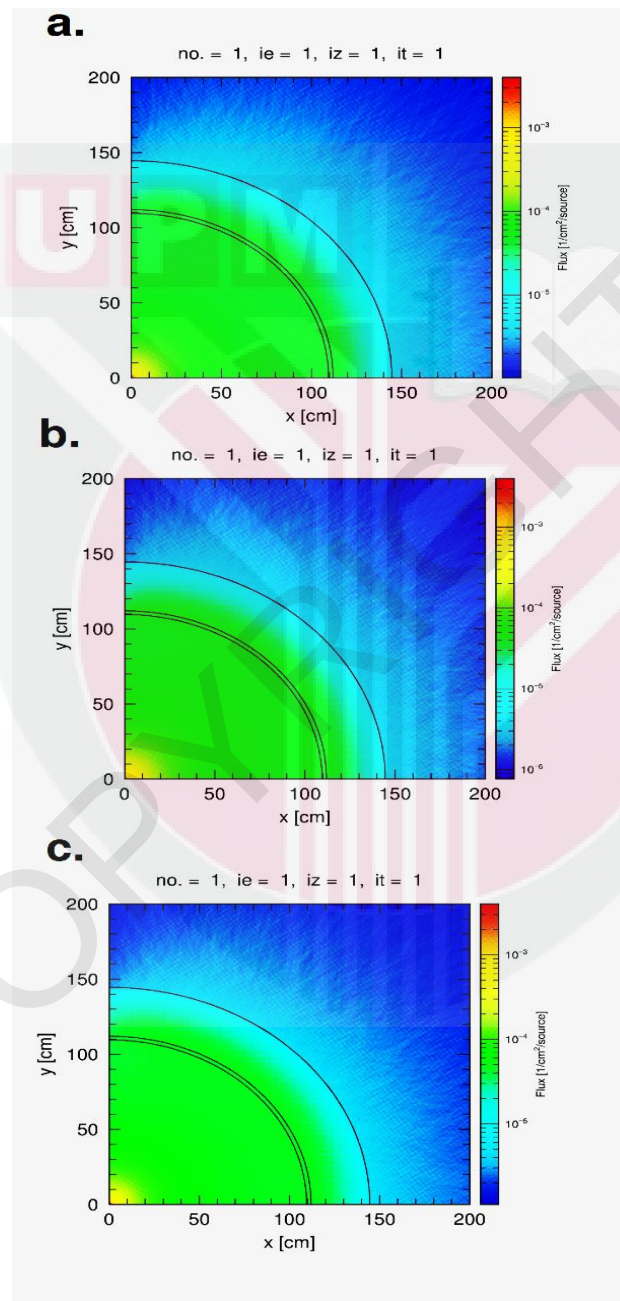


Figure 4.61 : Simulated flux from neutron radiation of dry cask storage using a. sand UHPdC, b. barite UHPdC and c. magnetite UHPdC

In terms of effective dose, magnetite UHPdC shows the lowest effective dose value followed by sand and barite UHPdC (Figure 4.62). This indicates the high neutron shielding property of magnetite UHPdC compared to other UHPdC as the amount of radiation absorbed by the material is the lowest. This validates the founding in experimental work on neutron shielding of UHPdC which shows that magnetite UHPdC possesses the highest neutron shielding property.

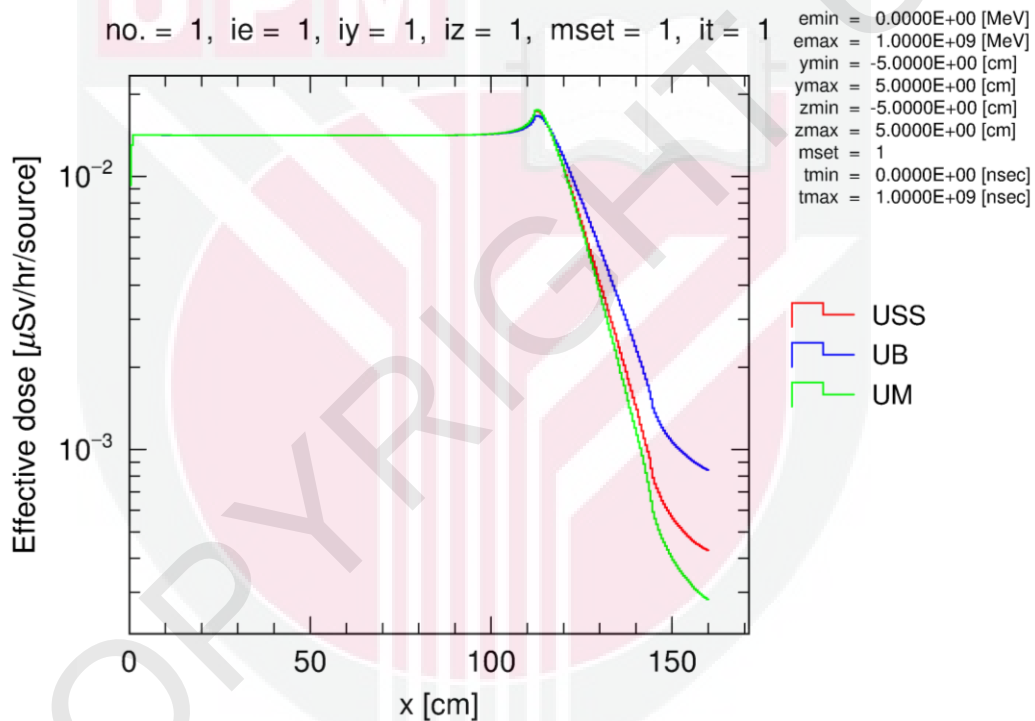


Figure 4.62 : Simulated effective dose of spent fuel neutron radiation for dry cask of optimised UHPdC

Barite UHPdC shows the highest value of effective dose which is due to the high amount of flux with a high energy level at the outer face of the dry cask model compared to other types of UHPdC (Figure 4.63). This indicates more neutrons with high energy passed through barite UHPdC which signifies lower neutron shielding. Overall, initial flux with a lower energy of less than 0.1 MeV

is attenuated by all types of UHPdC. However, at higher energy of initial flux, barite UHPdC shows the lowest amount of flux being attenuated compared to other UHPdC. Furthermore, the amount of flux detected after shielding with energy that is less than 0.1 MeV is almost none in barite UHPdC compared to other UHPdC which indicates less flux being attenuated to lower energy level hence signifies lower neutron shielding.

The highest neutron shielding property shown by magnetite UHPdC validates the experimental result. However, the simulated shielding of barite UHPdC differs slightly from the experimental result as the simulation indicates lower neutron shielding of barite UHPdC compared to sand UHPdC. In experimental results, barite UHPdC's neutron shielding is slightly higher compared to sand UHPdC. The discrepancy between experimental and simulated results is due to the different types of sources used in both works. The source used in the simulated work is based on a spent fuel cell with neutrons generated by alpha and neutron reaction of fissile material while the AmBe source is used in the experimental work. This simulated source possesses a higher energy level compared to the source used in experimental work. Furthermore, the detector used in the experimental work only detects thermal neutrons while the simulation work tracks all radiations including fast neutrons.

However, the results of the simulation and experimental are comparable as the difference in attenuation of the neutron is small. The result of simulated data is congruent with heated experimental data as the neutron shielding coefficient of heated barite UHPdC is lower compared to heated sand UHPdC. Reduction in simulated neutron shielding property due to barite is also

highlighted by a study that theoretically calculated neutron attenuation of barite in normal strength concrete and reactive powder concrete (Akkurt & El-Khayatt, 2013)(Gökçe et al., 2018). The presence of barite reduced the amount of neutron moderator in concrete which reduced the neutron shielding efficacy of the concrete.

Overall, the simulation highlights the effect of different elemental combinations in each UHPdC which resulted in the overall attenuation of neutrons. A combination of neutron moderators, absorbers and heavy elements in magnetite UHPdC proves better neutron shielding compared to barite UHPdC despite containing Ba in the composition. Furthermore, a comparison between magnetite UHPdC and sand UHPdC indicates the positive effect of heavy element (Fe) on neutron shielding properties.

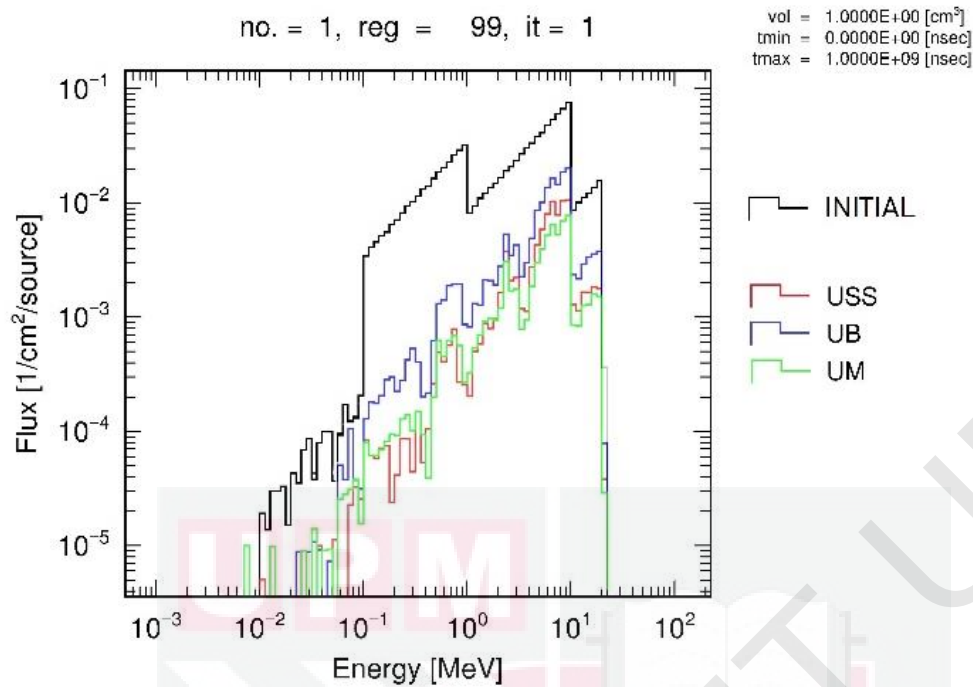


Figure 4.63 : Simulated initial flux value (INITIAL) and flux value at the outer face of dry cask of sand UHPdC (USS), barite UHPdC (UB) and magnetite UHPdC (UM)

4.13 Proposed Equation

Based on all the data gathered from this study, equations are proposed on the minimum required thickness to shield against 99% of radiation sources used in this study which are Cs-137, Co-60 and AmBe. This value of thickness is calculated based on the shielding coefficient recorded from the experiment using Eq. 3.6 which is denoted as the Tenth Value Layer (TVL).

TVL represents the minimum thickness required to shield 99 % of certain radiation based on the radiation shielding coefficient. The proposed equations are based on the relation between minimum required thickness and temperature exposure. Figure 4.64 shows the plotted value of the minimum required thickness of all data gathered from an experiment in regard to density

and temperature exposure. Strong correlations are shown for each equation based on the value of R-squared which is almost 1.

Overall, the proposed equation for minimum required thickness against Cs-137 is given as follows;

$$TVL_{25} = -0.0046x + 24.729 \quad (\text{Eq. 4. 1})$$

$$TVL_{400} = -0.006x + 29.416 \quad (\text{Eq. 4. 2})$$

$$TVL_{800} = -0.005x + 27.14 \quad (\text{Eq 4. 3})$$

where TVL, TVL_{400} and TVL_{800} are the minimum required thickness in cm for exposure to 25, 400 and 800 °C while x is the density of UHPdC in kg/m^3 .

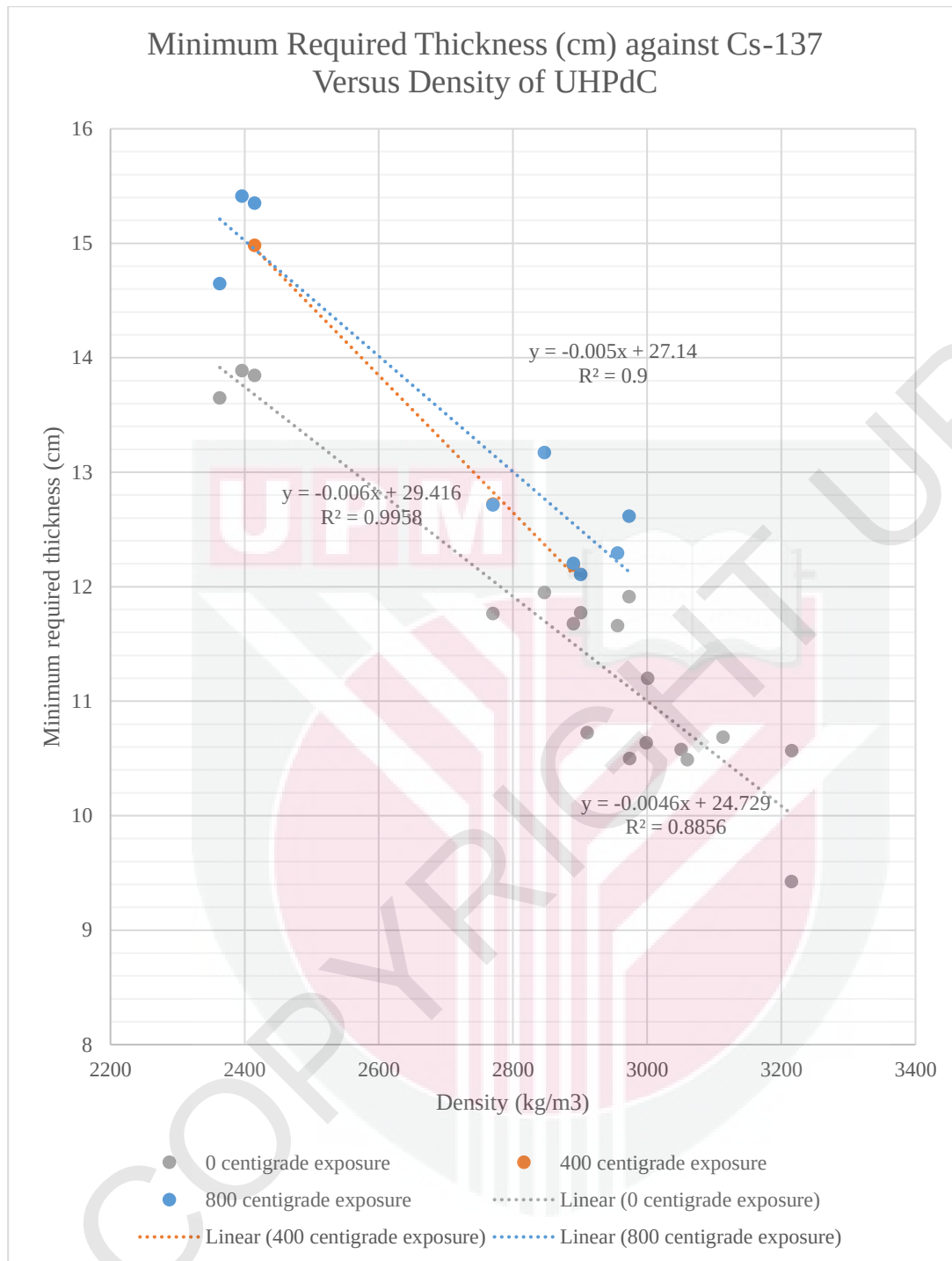


Figure 4.64 : Correlation between minimum required thickness to shield Cs-137 based on the density of the material and temperature exposure

The values for minimum required thickness against Co-60 and AmBe source are given in Figure 4.65 and Figure 4.66 respectively. Similar to the correlation of the Cs-137 source, the R-squared value is almost 1 and equals 1 for Co-60

and AmBe sources respectively. This indicates that all equation is based on strongly correlated data.

For shielding against Co-60, the equation for minimum required thickness is given as follows;

$$TVL_{25} = -0.0063x + 35.053 \quad (\text{Eq. 4.4})$$

$$TVL_{400} = -0.0076x + 39.627 \quad (\text{Eq. 4.5})$$

$$TVL_{800} = -0.0074x + 39.392 \quad (\text{Eq. 4.6})$$

where TVL_{25} , TVL_{400} and TVL_{800} are the minimum required thickness in cm for exposure to 0, 400 and 800 °C while x is the density of UHPdC in kg/m³.

For shielding against the AmBe source, the proposed equation is given based on temperature exposure;

$$TVL_s = -2 \times 10^{-5}x^2 + 0.0324x + 87.086 \quad (\text{Eq. 4.7})$$

$$TVL_B = -5 \times 10^{-5}x^2 + 0.0636x + 83.722 \quad (\text{Eq. 4.8})$$

$$TVL_M = -2 \times 10^{-5}x^2 + 0.0254x + 74.738 \quad (\text{Eq. 4.9})$$

Where TVL_s , TVL and TVL_M are the estimated minimum required thickness in cm for sand, barite and magnetite UHPdC respectively while x is the temperature in °C.

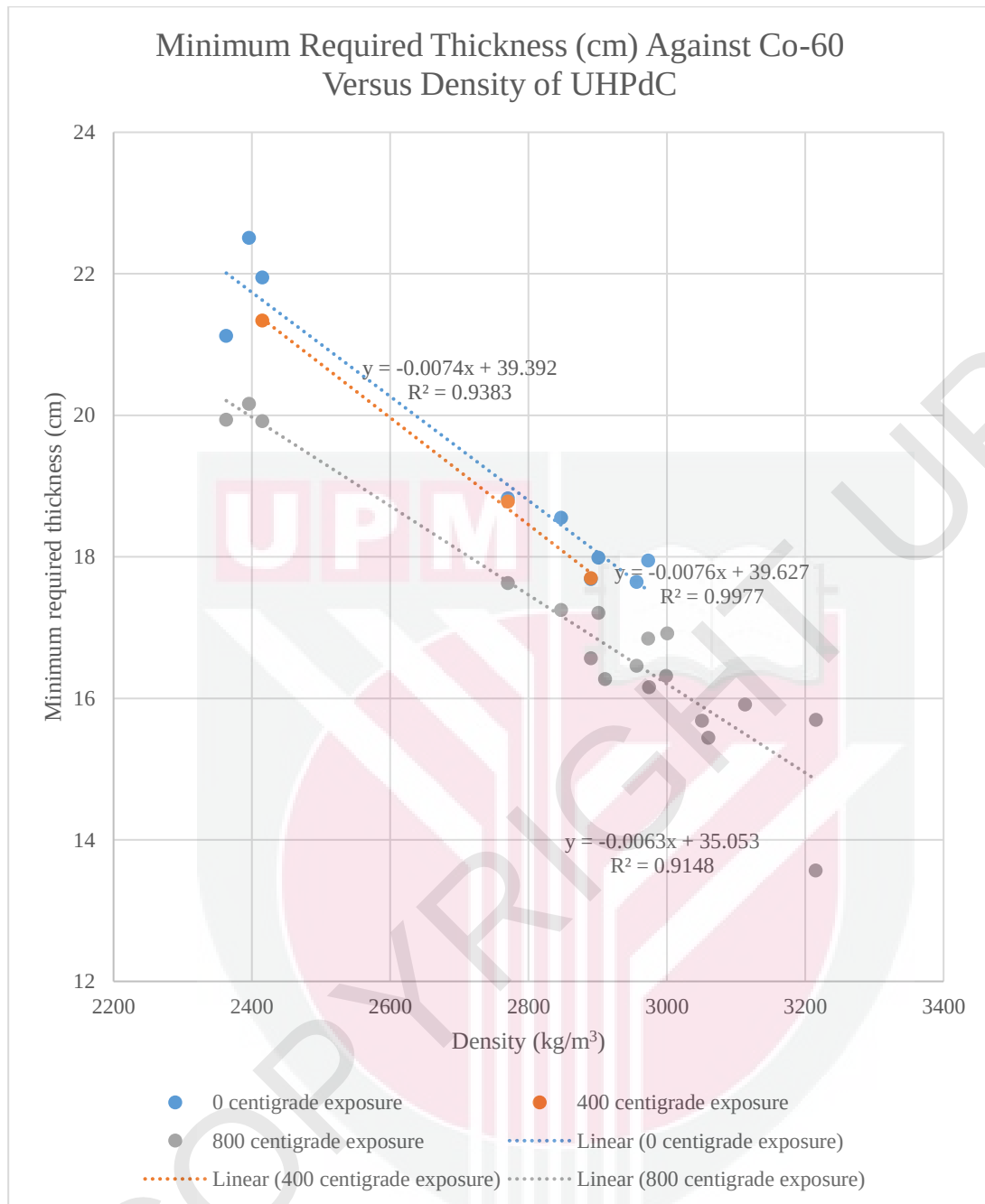


Figure 4.65 : Correlation between minimum required thickness to shield Co-60 based on the density of the material and temperature exposure

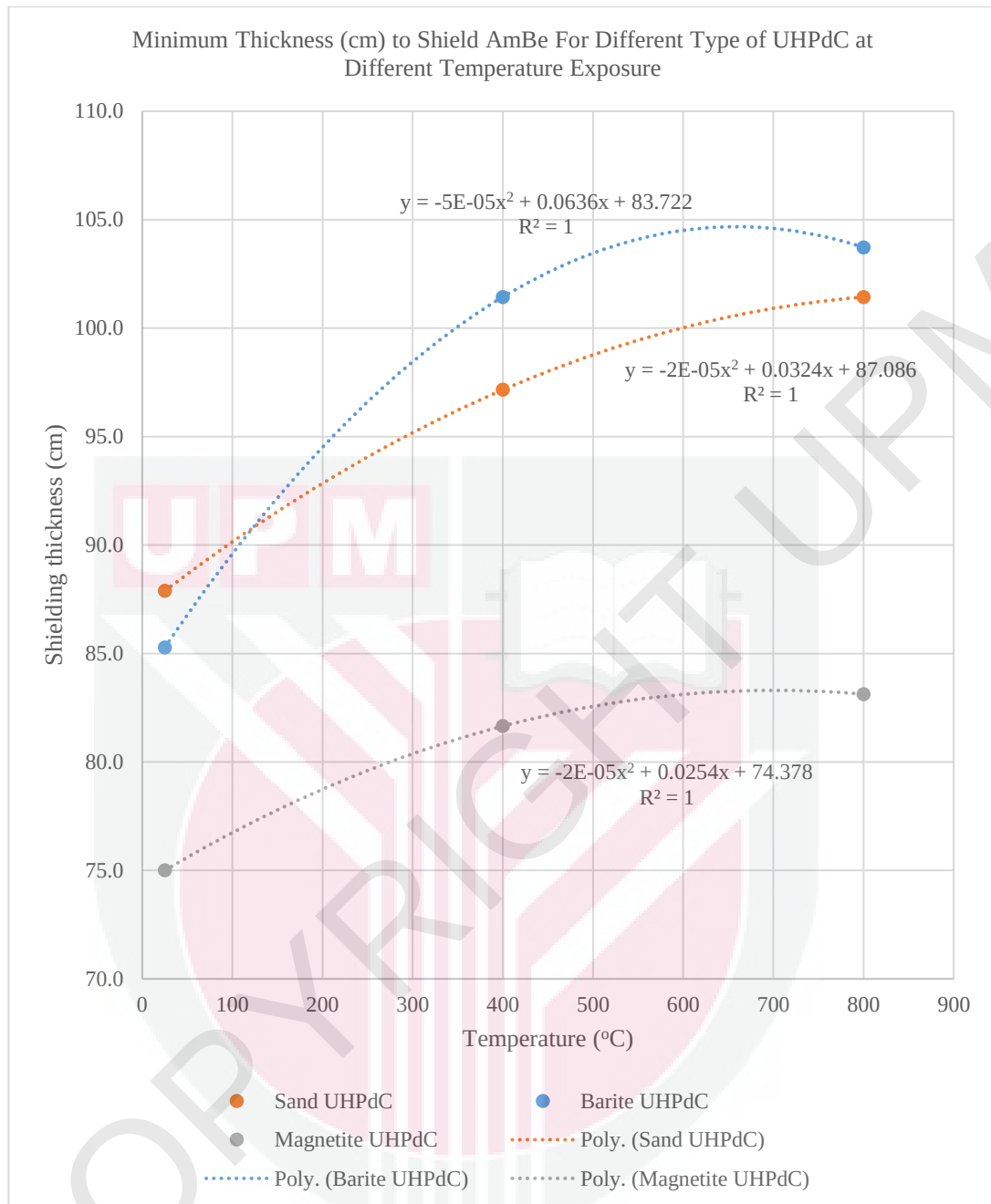


Figure 4.66 : Correlation between minimum required thickness to shield AmBe based type of UHPdC and temperature exposure

The values between experimental and calculated using the equation are presented in Table 4.5, Table 4.6 and Table 4.7 to show the amount of differences between these values. For the equation related to the Cs-137 source, the differences are very small for temperatures 0 and 400 °C which is between 0.4 – 2.1 %. Larger differences is recorded for UHPdC at 800 °C

which is up to 4.5 % This is in line with the value of r-squared which is lower for Eq. 4.3 compared to Eq. 4.1 and Eq. 4.2.

For data of shielding against Co-60, the trend is similar as the difference between experimental and calculated data of TVL is lower for temperatures 0 and 400 °C compared to differences in TVL values at a temperature of 800 °C. This is also congruent with the value of r-squared which is lower for 800 °C data.

In terms of minimum required thickness against AmBe source, no difference is reported for value at 0 °C while TVL values at 400 °C differ by 2.56 – 6.83 %. For 800 °C, values of TVL differ at an even larger percentage which is between 9.83 – 26.7 % which the largest percentage is recorded by barite UHPdC.

Overall, the presented equation is viable to estimate the required thickness in designing radiation shielding structures which complement the structural design. However, the estimation of the thickness of UHPdC for use at 800°C of heat exposure would involve at least 9.83 % over-estimation.

Table 4.5 : Comparison between experimental and calculated shielding thickness required (TVL) for Cs-137 source

UHPdC	TVL ₂₅ exp (cm)	TVL ₂₅ pred (cm)	Diff. (%)	TVL ₄₀₀ exp (cm)	TVL ₄₀₀ pred (cm)	Diff (%)	TVL ₈₀₀ exp (cm)	TVL ₈₀₀ pred (cm)	Diff. (%)
Sand UHPdC	13.846	13.62	-1.6	14.981	14.926	-0.4	15.351	15.065	-1.9
Barite UHPdC	11.766	11.987	1.9	12.721	12.796	0.6	12.714	13.29	4.5
Magnetite UHPdC	11.676	11.435	-2.1	12.189	12.076	-0.9	12.202	12.69	4.0

Table 4.6 : Comparison between experimental and calculated shielding thickness required (TVL) for Co-60 source

UHPdC	TVL ₂₅ exp (cm)	TVL ₂₅ calc (cm)	Diff. (%)	TVL ₄₀₀ exp (cm)	TVL ₄₀₀ calc (cm)	Diff. (%)	TVL ₈₀₀ exp (cm)	TVL ₈₀₀ calc (cm)	Diff. (%)
Sand UHPdC	19.919	19.839	-0.4	21.340	21.273	-0.3	21.950	21.521	-2.0
Barite UHPdC	17.630	17.602	-0.2	18.781	18.575	-1.1	18.827	18.894	0.4
Magnetite UHPdC	16.565	16.846	1.7	17.699	17.663	-20.2	17.685	18.006	1.8

Table 4.7 : Comparison between experimental and calculated shielding thickness required (TVL) for AmBe source

UHPdC	TVL ₂₅ exp (cm)	TVL ₂₅ calc (cm)	Diff. (%)	TVL ₄₀₀ exp (cm)	TVL ₄₀₀ calc (cm)	Diff. (%)	TVL ₈₀₀ exp (cm)	TVL ₈₀₀ calc (cm)	Diff. (%)
Sand UHPdC	85.281	85.2783	0.00	101.436	102.522	-0.01	101.436	100.206	0.01
Barite UHPdC	87.885	87.884	0.00	97.155	100.206	-0.03	103.72	102.522	0.01
Magnetite UHPdC	75.003	75.001	0.00	81.652	81.898	0.00	83.126	81.898	0.01

4.14 Summary

Replacement of the main aggregate with colemanite improves the compactness of UHPdC's matrix up to the optimum percentage. The value of the optimum percentage relies heavily on the particle size distribution of UHPdC's composition and beyond the optimum amount, colemanite presence resulted in lower strength. Compactness due to the presence of colemanite also resulted in a slight increase in gamma-ray shielding due to an increase in density. Furthermore, neutron shielding of UHPdC is also increases with the presence of colemanite. The addition of PVA fibre in the composition of UHPdC improved the thermal durability yet has an adverse effect on compressive strength and radiation shielding properties. However, PVA fibre's positive impact on the durability of UHPdC resulted in better residual shielding of UHPdC after being heated to 800°C. Overall, the thermal durability of

UHPdC depends on the aggregate that makes up its composition. A temperature of 400°C has minimal effect on UHPdC compared to 800°C. High temperature of 800°C has a more severe effect on radiation shielding properties and mechanical properties of UHPdC compared to 400°C.



CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary and Conclusion

Three objectives are outlined in this research and a total of 24 variations of UHPdC are being investigated thoroughly. This study aimed to develop three types of UHPdC which are magnetite, barite and sand UHPdC comprised of magnetite, barite and sand as aggregate respectively. These aggregates are replaced with colemanite at different percentages to find the optimum amount based on compressive strength and radiation shielding properties. The optimum mixture of these three types of UHPdC is added with an increasing percentage of PVA fibre to improve their thermal durability. The optimum percentage of PVA fibre addition in each type of UHPdC is tested for compressive strength, radiation shielding properties and thermal durability. The results indicate the optimum mixture that is developed from the study.

5.2 Effect of Colemanite Replacement on Linear Attenuation Coefficient, Macroscopic Removal Cross Section and Compressive Strength of Ultra-high Performance Dense Concrete

Replacement of aggregate with colemanite in the composition of UHPdC resulted in a lower linear attenuation coefficient but a higher value of macroscopic removal cross section. In terms of compressive strength, the replacement of aggregate with colemanite at an optimum percentage resulted in a higher value of compressive strength. Sand, barite and magnetite UHPdC recorded optimum aggregate replacement at 1, 5 and 5% respectively.

Based on the results, 5% of colemanite replacing aggregate in UHPdC produced the optimum compressive strength and radiation shielding properties.

5.3 Effect of PVA fibre addition on Ultra-high Performance dense Concretes' spalling resistance and residual compressive strength

UHPdCs with 5 % colemanite replacing aggregate show higher spalling resistance with increasing fibre addition. However, an increase in PVA fibre addition resulted in lower compressive strength, linear attenuation coefficient and macroscopic removal cross section.

In terms of thermal durability, an increase in PVA fibre addition up to the optimum percentage resulted in higher residual compressive strength of UHPdC. However, linear attenuation coefficient and macroscopic removal cross section recorded lower value with increasing percentage of PVA fibre addition.

Overall, UHPdC with 5 % colemanite replacing aggregate and 0.5 % by-volume of PVA fibre produced the optimum properties of radiation shielding, compressive strength and thermal durability.

5.4 Effect of Elevated Temperature on Linear Attenuation Coefficient, Macroscopic Removal Cross Section and Mechanical Properties of Ultra-high Performance Dense Concretes

An increase in temperature resulted in a lower linear attenuation coefficient, macroscopic removal cross section and mechanical properties of UHPdC.

However, UHPdC shows good thermal resistance up to 400°C of heat based on the small reduction recorded in linear attenuation coefficient, macroscopic removal cross section and mechanical properties.

In a comparison of three types of optimised UHPdC, magnetite UHPdC shows the highest thermal durability and this is followed by sand and barite UHPdC. In terms of linear attenuation coefficient and macroscopic removal cross section, magnetite UHPdC shows the higher value followed by barite and sand UHPdC.

Based on the experimental value, a radiation shielding structure made from magnetite UHPdC would produce the thinnest section that can attenuate 99% of gamma and neutron radiation. This is followed by barite and sand UHPdC. Eq. 4.1 – 4.9 are proposed as equations in estimating the UHPdCs' minimum required thickness to shield against gamma and neutron radiation.

5.5 Future Recommendation

Conclusions drawn from the research lead to a wider avenue of investigation to further improve the properties of UHPdC as a radiation shielding material. The optimum percentage of colemanite replacement varies according to the type of main aggregate and the particle size distribution indicates that further optimisation is viable. By improving the packing density of aggregate and fine-sized filler would lead to a more compact matrix of UHPdC hence better mechanical strength and radiation shielding efficiency. This can be

investigated by using the finer size of colemanite or a wider range of particle size distribution especially for magnetite and barite aggregate.

Doping or infusing heavyweight aggregate of UHPdC with neutron absorbing should also be investigated as this method involves finer particles which involve less alteration of UHPdC's microstructure. The efficiency of this method in providing neutron shielding property to UHPdC can be evaluated by comparing it with this study. The effect can be evaluated in terms of mechanical properties and radiation shielding value resulting from the study.

Developing a sustainable UHPdC is also important to reduce dependency on natural minerals. Many recent studies on radiation-shielding concrete have been investigating the properties of radiation-shielding concrete with waste material yet there is still a lack of studies involving UHPC. The use of waste material would not only reduce the consumption of natural minerals but also reduce wastage from the manufacturing and mining industries. These wastes would also contain heavy elements which is beneficial for gamma ray shielding property. Other waste could also contain neutron-absorbing elements which need to be explored and investigated.

This study highlights the effect of high temperatures on steel fibres in the UHPdC. Deterioration of steel fibre at high temperatures resulted in a large reduction of mechanical properties hence further investigation is required. Steel fibre that is embedded in UHPdC needs to be preserved from oxidation due to heat to prevent its decay. The method of preserving the steel fibre needs to be proposed and investigated which would lead to better thermal durability

of UHPdC. A method such as coating of steel fibre could also include neutron absorbing or heavy elements which could contribute to radiation shielding properties of UHPdC.

Overall, the utilisation of UHPdC as radiation shielding material provides many advantages for nuclear-related structures. The superior mechanical performance of UHPdC that is combined with an understanding of its radiation shielding performance allows the structure to be constructed with confidence on its structural stability. Further improving its properties would lead to optimum usage of resources and a sustainable future.

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