# PROPERTIES OF ULTRA-HIGH PERFORMANCE CONCRETE (UHPC) CONTAINING MODIFIED AGGREGATE SYSTEM AND CHEMICAL ADDITIVES

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# PROPERTIES OF ULTRA-HIGH PERFORMANCE CONCRETE (UHPC) CONTAINING MODIFIED AGGREGATE SYSTEM AND CHEMICAL ADDITIVES

by

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# TABLE OF CONTENTS

## LIST OF TABLES

**Page**

## LIST OF FIGURES

**Page**

## LIST OF ABBREVIATIONS AND SYMBOLS

| | |
|---|---|
| $Al_2O_3$ | Aluminium Oxide |
| ASTM | American Society for Testing and Material |
| BS | British Standard |
| °C | Degree Celsius |
| $C_3A$ | Tricalcium Aluminate |
| $CaCO_3$ | Calcium Carbonate |
| CaO | Calcium Oxide |
| CBA | Coal Bottom Ash |
| Cl | Chloride |
| C-S-H | Calcium Silicate Hydrate |
| FA | Fly Ash |
| $Fe_2O_3$ | Ferric Oxide |
| FM | Fineness Modulus |
| GGBS | Ground Granulated Blast-Furnace Slag |
| HBP | Housing Building and Planning |
| ITZ | Interfacial transition zone |
| $K_2O$ | Potassium Oxide |
| LOI | Loss on Ignition |
| MgO | Magnesium Oxide |
| MnO | Manganese Oxide |
| MS | Malaysian Standard |
| $Na_2O$ | Sodium Oxide |
| OPC | Ordinary Portland Cement |
| $P_2O_5$ | Phosphorus Pentoxide |
| PCE | Polycarboxylate Ether |
| S/B | Sand to binder ratio |
| SCM | Supplementary Cementitious Material |
| SEM | Scanning Electron Microscopy |
| SF | Silica Fume |
| $SiO_2$ | Silicon Dioxide |
| $SO_3$ | Sulphur Trioxide |
| SP | Superplasticiser |

| | |
|---|---|
| TEM | Transmission Electron Microscopy |
| $TiO_2$ | Titanium Dioxide |
| UHPC | Ultra-High Performance Concrete |
| UPV | Ultrasonic Pulse Velocity |
| W/B | Water to binder ratio |

**SIFAT KONKRIT BERPRESTASI TERAMAT TINGGI (UHPC) BERKANDUNGAN SISTEM AGREGAT YANG TERUBAHSUAI DAN BAHAN TAMBAH KIMIA**

## ABSTRAK

Kekuatan, ketahanan, dan prestasi kemuluran yang lebih tinggi Konkrit Berprestasi Teramat Tinggi (UHPC) menjadikannya bahan pembinaan serba boleh. Walau bagaimanapun, ia juga menimbulkan masalah kemampanan kerana kandungan simen yang tinggi dan penggunaan intensif pasir kuarza semasa fasa pembuatan UHPC. Abu bawah arang batu (CBA) adalah alternatif yang mungkin untuk agregat kerana peningkatan pengeluaran dari stesen janakuasa arang batu dan kekurangan pasir semulajadi berkualiti tinggi. Tujuan kajian ini adalah untuk menentukan pendekatan yang cekap untuk menggabungkan CBA sebagai pengganti agregat dalam komposit UHPC. Teknologi nanomaterial, seperti nano kalsium silikat hidrat (C-S-H), telah digunakan sebagai bahan tambahan untuk meningkatkan parameter mekanikal, ketahanan dan mikrostruktur UHPC yang mengandungi agregat CBA. Fasa pengikat semua campuran UHPC adalah campuran ternari yang dioptimumkan dengan gabungan OPC, sanga relau letupan berbutir tanah (GGBS) dan abu silika (SF) pada nisbah 15:4:1. Tetulang gentian keluli didapati optimum pada 2% kepada isipadu pengikat. Menurut penemuan, campuran UHPC dengan CBA gred sebagai penggantian agregat mencapai pembangunan kekuatan dan ketahanan yang lebih baik kerana struktur mikro yang lebih padat. Semua campuran UHPC mempunyai pengurangan prestasi mekanikal dan ketahanan apabila CBA digunakan sebagai pengganti agregat. Di antara semua campuran UHPC dengan tahap CBA yang berbeza sebagai pengganti agregat, campuran CBA 40% mencapai prestasi terbaik. Dengan penambahan nano C-S-H pada dos optimum 0.25%, UHPC bercampur dengan 40%

kandungan CBA mencapai kekuatan dan ketahanan yang setanding dengan campuran UHPC kawalan dengan pasir sungai sepenuhnya dan tanpa nano C-S-H. Walaupun hasil pengimejan struktur mikro membuktikan bahawa semua campuran UHPC dengan agregat CBA mempunyai struktur mikro yang lebih berliang, pada tahap penggantian 40%, matriks adalah yang paling padat. Penyertaan C-S-H nano telah terbukti menghasilkan gel C-S-H yang lebih terdispersi dalam matriks, yang menyumbang kepada prestasi kekuatan dan ketahanan yang lebih baik. Semua UHPC yang mengandungi nano C-S-H mempamerkan gel C-S-H yang tersebar dengan baik dalam matriks, menyumbang kepada kekuatan dan ketahanan yang lebih baik.

**PROPERTIES OF ULTRA-HIGH PERFORMANCE CONCRETE (UHPC) CONTAINING MODIFIED AGGREGATE SYSTEM AND CHEMICAL ADDITIVES**

## ABSTRACT

Ultra-High Performance Concrete's (UHPC) higher strength, durability, and high ductility performance make it a versatile construction material. However, it also poses sustainability problems due to its high cement content and quartz sand-intensive consumption during the manufacturing phase of UHPC. Coal bottom ash (CBA) is a possible alternative to aggregate due to its increasing output from coal power stations and the scarcity of high-quality natural sand. The purpose of this study is to determine an efficient approach to incorporate CBA as an aggregate replacement in UHPC composites. Nanomaterial technologies, such as nano calcium silicate hydrate (C-S-H), were used as an additive to improve the mechanical, durability, and microstructure parameters of UHPC containing CBA aggregate. The binder phase of all UHPC mixes was ternary blended mix optimised with a combination of OPC, ground granulated blast furnace slag (GGBS) and silica fume (SF) at the ratio of 15:4:1. Steel fibre reinforcement is found to be optimum at 2% to the binder volume. According to findings, UHPC mix with graded CBA as the aggregate replacement achieved better strength and durability development due to a denser microstructure. All UHPC mixes had a reduction in mechanical and durability performance when CBA was used as the aggregate replacement. Among all UHPC mixes with different levels of CBA as an aggregate replacement, the 40% CBA mix achieved the best performance. With the addition of nano C-S-H at the optimum dosage of 0.25%, UHPC mixes with 40% CBA content achieved comparable strength and durability results as the control UHPC mix with fully river sand and without nano C-S-H. Although microstructure imaging

results proven that all UHPC mixes with CBA aggregate have more porous microstructure, at 40% replacement level, the matrix was the most densified. All the UHPC containing nano C-S-H exhibited a well-dispersed C-S-H gel within the matrix, contributing to better strength and durability.

# CHAPTER 1

# INTRODUCTION

## 1.1 Background

Construction has been crucial to the expansion of cities and manufacturing in recent decades (Ganesh et al., 2019). Since ancient Romans, when it was first utilised, concrete has been a core part of the construction field. Aggregates like rocks, bricks, or ceramic tiles were used to make Roman concrete, mixed with gypsum and quicklime and pozzolana, a type of volcanic dust. After then, fewer Roman elements were incorporated into the construction, and stone and mortar became the norm. After its introduction in the 19$^{th}$ century and subsequent development throughout the 20$^{th}$, modern concrete became an integral part of the global construction industries (Bajaber and Hakeem, 2021; Shaikh et al., 2020). Gravel sand is combined with cement and water to make concrete. Concrete's status as the world's second most widely employed material, after water, has risen rapidly due to rapid infrastructure development (Bheel et al., 2022; Y. H. Kim et al., 2021; Kota and Kalyana Rama, 2020; Majhi and Nayak, 2019). An estimated 6 billion cubic metres of concrete are produced annually worldwide, with China producing almost 40% of this total (Akeed, Qaidi, Ahmed, Faraj, et al., 2022; Azmee and Shafiq, 2018; Rodríguez-Álvaro, Seara-Paz, González-Fonteboa, Ferrándiz-Mas, et al., 2021). The world's demand for concrete is forecast to reach about 7.5 billion m$^3$ by 2050 (approximately 18 billion tons) (Ali et al., 2022). Since its invention, concrete has become the most widely used construction material due to its inexpensive cost, versatility in design, and ability to withstand heavy loads (Azmee and Shafiq, 2018; Hamada et al., 2022; Kumar and Singh, 2020; N. Singh, Kumar, et al., 2019). Various engineering structures have extensively used concrete (Ali et al., 2022; Ponraj Sankar et al., 2021; Xue et al., 2020). Significant concrete technology advancements have occurred during the past two decades (Xue et al., 2020). There has been a lot of progress in concrete engineering during the past few decades. Researchers have actively attempted to increase concrete compressive strength since the 1930s (Akeed, Qaidi, Ahmed, Faraj, et al., 2022). Demands from unexpected sectors of society have led to advancements in concrete technology, allowing for the construction of taller skyscrapers, wider bridges, and more vital structures that can withstand natural disasters like earthquakes (Akeed, Qaidi, Ahmed, Emad, et al., 2022; Bheel et al., 2022). Because of the improved strength-to-weight ratio, lower section sizes will be feasible, which is hugely beneficial for developing long-lasting constructions (Nodehi and Nodehi, 2022).

Unfortunately, concrete has several drawbacks because of its inherently high density. For instance, its development phase necessitates an enormous footprint, and its finished components have correspondingly massive dimensions and weight (Faried et al., 2021a). In light of these limitations, scientists have turned their attention to developing new varieties of concrete with enhanced properties such as high strength, long service life, high ductility, and toughness by applying the principles of packing theory (Faried et al., 2021a; Marvila et al., 2021). Concrete demonstrates brittle behaviour since it has limited tensile strength and strain capacity (Chun and Yoo, 2019; Wu, Khayat, et al., 2018; Wu, Shi, et al., 2019; K. Yu et al., 2018). Tensile strength of concrete is normally between 8 and 15% of its compressive strength (Wu, Shi, et al., 2019). Concrete's low tensile and flexural strengths and lack of durability make it a fragile material (Rodríguez-Álvaro et al., 2020; Shaikh et al., 2020; Tolga Cogurcu, 2022). The mechanical, thermal, and chemical stress leading to conventional concrete cracking makes it unsuitable for use in hostile environments (Dimov et al., 2018; J. Li et al., 2020). These include but are not limited to reinforcing corrosion, alkali-silica reaction, sulphate assault, and freeze-thaw action. It can speed up the deterioration of concrete structures, reduce their service life, and increase the life cycle cost due to continual monitoring, repair, and rehabilitation (Hamada et al., 2022; J. Li et al., 2020; N. Singh et al., 2018; Vieira et al., 2022). Furthermore, the widespread shortage of essential materials was exacerbated by the extensive use of crushed rock and cement as binding agents in the production of concrete (Bheel et al., 2022; Majhi and Nayak, 2019). The building sector's massive concrete demand will increase the rate at which carbon dioxide ($CO_2$) is released into the atmosphere (Ali et al., 2022; Irshidat and Al-Nuaimi, 2020; Lin et al., 2018; Shi et al., 2019). The increased global temperature that arises from this $CO_2$ emission is the root cause of climate change and other adverse effects (Ali et al., 2022; D. Zhang et al., 2022). The use of environmentally friendly concrete has been the focus of numerous strategies (Shi et al., 2019). Concrete that meets the criteria of being made from one or more alternative or recycled waste materials, having an environmentally friendly production process, or having high performance and outstanding durability is considered green concrete (Keerio et al., 2021; Majhi and Nayak, 2019; Shi et al., 2019). Because of this, it is essential to develop advanced cementitious products (Marvila et al., 2021; Vieira et al., 2022), namely High-Performance Concrete (HPC) and Ultra-High Performance Concrete (UHPC), that can last longer and withstand more loading (Dimov et al., 2018; Elsayed et al., 2022; Larsen and Thorstensen, 2020; Marvila et al., 2021). In addition, as bridge engineering has advanced, many researchers have rigorously investigated the use of UHPC in bridge structures (Graybeal et al., 2020; Nodehi and Nodehi, 2022; Shaikh et al., 2020; Xue et al., 2020). In areas with new road connections, UHPC can span wider distances with robust superstructures and fewer substructures. Prefabricated UHPC pieces are easier to deliver and build, improving urban and rural efficiency. In regions where traffic overburdens the existing system, UHPC can replace bridges with unique solutions that meet clearance, capacity, and longevity specifications while reducing cost and construction time (Azmee and Shafiq, 2018; Graybeal et al., 2020; Rajasekar et al., 2018; J. Wang et al., 2019). When ageing and failing structures require minimal service disturbance, UHPC supplies new reconstruction and retrofit solutions that extend structure service life (Farzad et al., 2019; Graybeal et al., 2020; Hou et al., 2021; Rajasekar et al., 2018). This is accomplished by modulating the concrete's composition to boost its mechanical attributes and endurance (Elsayed et al., 2022; Liang et al., 2018; J. Wang et al., 2019). Great flowability with self-consolidation, high strength and toughness, exceptional durability, and self-healing ability can all be achieved with well-designed UHPC (Farzad et al., 2019; Wu, Khayat, et al., 2019; Wu, Shi, et al., 2018). Due to UHPC's greater tensile strength, the thickness can be substantially lowered, resulting in weight reductions of 35% compared to conventional concrete decks (Abellán García et al., 2020; Fang et al., 2022; Said et al., 2022; Shi et al., 2019; You et al., 2022). As a result, fewer resources are spent on building and more space is delivered because precast UHPC elements are used (Abellán García et al., 2020; Zeng et al., 2020). Using UHPC, the road bridge in Bourg-les-Valence, France, was completed in 2005 at a 66% weight reduction compared to typical concrete. The amount of reinforcements was cut by 90% as well. Another example, in 2006, the Mars Hill Bridge in the US was built with UHPC, which allowed the use of far less costly shear reinforcement (Faried et al., 2021a). Sustainable bridge construction initiatives in Malaysia have used UHPC for bridge structures. Since 2010, another 113 UHPC bridges have been built or are currently under development in Malaysia (Azmee and Shafiq, 2018). The Kampung Linsum Canyon Bridge over the Sungai Linggi River was the first UHPC highway composite bridge built in Malaysia in 2010 (M. Zhou et al., 2018).

It was in the early 1990s that the concept of UHPC was first developed in France (Kamal et al., 2014; J. Liu et al., 2020; T. Liu et al., 2020; Shen, Lu, He, et al., 2020). UHPC denotes a relatively novel group of advanced cementitious composite materials with significantly superior mechanical and durability capabilities compared to conventional concrete (CC) materials (Guo et al., 2018; Larsen and Thorstensen, 2020; Marvila et al., 2021; Nodehi and Nodehi, 2022). UHPC has a compressive strength that is 3-16 times greater than that of regular concrete, between 150 MPa and 800 MPa (Arunothayan et al., 2021; Liao et al., 2021; Shen, Lu, Wang, et al., 2020; Zeng et al., 2022). This material excels in compressive strength, tensile strength, flexural strength, modulus of elasticity, and resistance to abrasion (Amin, Zeyad, et al., 2022; Liao et al., 2022; Shen, Zheng, et al., 2020; Vieira et al., 2022). UHPC also comes with exceptional durability in the context of carbonation, water absorption, water permeability, drying shrinkage, freeze and thaw temperature extremes, chloride penetration, and chemical attack (Amin, Hakeem, et al., 2022; Fang et al., 2022; K. Liu et al., 2022; Nodehi and Nodehi, 2022). Reducing pore structure, improving microstructure, boosting homogeneity, and increasing toughness are four theoretical ideas commonly followed in the development of UHPC (Shi et al., 2019; Siwiński et al., 2020; Teng et al., 2019; L. Yang et al., 2019). According to the Portland Cement Association (PCA), UHPC is "a high-strength, ductile construction material produced by blending Portland cement, supplemental cementitious ingredients, quartz flour, fine silica sand, high-range water reducer, water, and steel or organic fibres" (Portland Cement Association, n.d.). The material offers compressive and flexural strengths of up to 200 and 48 MPa (Mansour et al., 2022; Nodehi and Nodehi, 2022;

Portland Cement Association, n.d.). It is estimated that UHPC is four times as strong as standard concrete due to its enhanced qualities (Bahedh and Jaafar, 2018; M. Ren et al., 2021). UHPC has proven to have a wide range of potential construction applications due to its high performance in fields such as long-span bridge engineering, defensive military engineering, peculiar shape structure, maritime construction engineering, and many others (Huang et al., 2021; Mansour et al., 2022; Pyo et al., 2017; X. Wang et al., 2021). Erected in 1997, the Sherbrooke footbridge in Sherbrooke, Quebec, was the first construction structure in the world to be constructed using UHPC (Kamal et al., 2014). UHPC also has been used in various high-profile projects, such as the Museum of European and Mediterranean Civilisations in France, the Olympic Museum in Lausanne, Switzerland, the Qatar National Museum, the Footbridge of Peace in South Korea, etc. (Gu et al., 2022).

Although UHPC has superior performance, it is typically produced using a massive amount of cement, which results in many $CO_2$ emissions and causes direct environmental issues (Amin, Zeyad, et al., 2022; Lao et al., 2022; Liao et al., 2022; Mangi et al., 2020). Approximately 40% of all energy is used in the construction industry, and 30% of all natural resources are used in the process. Also, these construction activities are responsible for generating 40% of $CO_2$ and the contamination related to construction waste by almost 30% (Ganesh et al., 2019). Expanding the usage of UHPC in the building industry will lead to higher energy consumption and severe environmental repercussions from cement production because UHPC is typically generated with a high content of cement (Arunothayan et al., 2022; Yirui Li et al., 2021; You et al., 2022). UHPC has three times as much cement as conventional concrete, which generates carbon emissions of 600-1300 kg/m$^3$ incorporated in the material (Y. Liu et al., 2020; Shi et al., 2019). Compared to typical concrete, UHPC uses significantly more cement in its composition (typically 750–1200 kg/m$^3$), and cement production consumes a significant amount of natural resources, a tremendous amount of energy, and releases a vast amount of $CO_2$ (Aisheh et al., 2022b; Arunothayan et al., 2022; Gu et al., 2022; Karimipour and de Brito, 2021; X. Wang et al., 2021). Cement manufacturing is the third greatest source of $CO_2$ emissions from industry, liable for around 10% of all human-caused emissions into the atmosphere (Abbas et al., 2020; Arunothayan et al., 2022; Ganesh et al., 2019). It is estimated that one tonne of clinker produced will release about 0.83 tonnes of $CO_2$ and use 6.7 MJ of energy (Aisheh et al., 2022b; Gooi et al., 2020; Gupta et al., 2021; Karimipour and de Brito, 2021). Meanwhile, projections from the International Energy Agency put the rise of $CO_2$ emissions in 2050 at around 4% (Amin et al., 2021).

Sustainability is a big challenge in buildings, as cement and concrete are major greenhouse gas emitters (Keerio et al., 2021; Pyo and Kim, 2017). In light of the ongoing worldwide energy crisis and environmental devastation, energy-efficient building design is essential for a sustainable future of construction (M. Ren et al., 2021). Carbon neutrality, carbon peak, and carbon trading have all risen to prominence as pressing concerns in the international community as nations work to meet the growing demand to cut back on $CO_2$ emissions and energy use (You et al., 2022). Recent years have seen a shift away from conventional methods of energy generation due to growing concerns for the global environment and the adoption of renewable energy sources (Mangi et al., 2020). Environmental protection is garnering thriving prominence. It is a goal of every sector to reduce their environmental effect and increase their energy conservation (Shi et al., 2019). Regarding material aspects, two main approaches to dealing with environmental issues have been proposed. The first step is using high-performance construction materials in buildings and infrastructure to improve serviceability duration (Pyo and Kim, 2017). Second, develop less environmentally detrimental construction materials by employing industrial by-products or demolition debris (Hou et al., 2021; Miraldo et al., 2021; Nakararoj et al., 2022; Ngohpok et al., 2018). Therefore, despite UHPC's high performance, its further use and advancement are hampered because it does not meet the present policy of lowering carbon emissions. UHPC may be a viable material in the building sector due to its better engineering features (X. Y. Zhang et al., 2022). Still, it may not be sustainable due to the high dosage of energy-intensive constituents such as cement and river sand (Khongpermgoson et al., 2019; Pyo and Kim, 2017). Therefore, efficient and ecologically friendly UHPC using less energy-intensive materials and industrial by-products would be beneficial (Kumar and Singh, 2020; Pyo and Kim, 2017). Hence, the only path forward for UHPC is to produce a low-carbon, low-energy-consumption alternative supplemental material (He et al., 2018; Y. Liu et al., 2020; J. H. Park et al., 2021; X. Y. Zhang et al., 2022). One effective method is to replace cement, aggregate, and reinforcing materials in creating sustainable UHPC using agricultural and industrial waste (Amin, Zeyad, et al., 2022; Karimipour and de Brito, 2021; Pushkar, 2019a; Rajasekar et al., 2018).

Energy demand is rising rapidly due to the rising global economy and urbanization (H. Zhou et al., 2022). Renewable energy sources have been expanding internationally in response to rising global issues about climate change and other environmental threats (Carević et al., 2019; Rodríguez-Álvaro, González-Fonteboa, et al., 2021). Coal, though, remains a significant energy source, particularly for producing energy (Rodríguez-Álvaro, González-Fonteboa, et al., 2021). As with many other countries, Malaysia has historically used coal as a low-cost energy source (Khaw et al., 2022). Coal is the second largest energy source, supplying approximately 30%

of primary energy worldwide, and will likely remain the leading fuel for the forthcoming years (Abbas et al., 2020; Hashemi et al., 2018; N. Singh, Kumar, et al., 2019; H. Zhou et al., 2022). Coal is generally accepted as the most common fuel used in thermal power plants (M. Singh, 2018). Countries like China and Pakistan rely heavily on coal as their primary energy source (Danish and Mosaberpanah, 2021). In addition to recently being Southeast Asia's largest power plant leader (Khaw et al., 2022), recent statistics show that Malaysia's reliance on coal as a fossil fuel for electricity generation would increase from 43% in 2014 to 58% in 2024 (Rafieizonooz et al., 2022). Coal is essential in many industrial processes that generate power and produce cement, bricks, and steel (Danish and Mosaberpanah, 2021; Sanjuán and Argiz, 2021). As of 2019, one-third of the world's energy comes from coal, which is also crucial in producing iron and steel (Sanjuán and Argiz, 2021). As Malaysia's electricity demand rises, so will the amount of waste produced by the country's coal-fired power plants (Hasim et al., 2022a; Khaw et al., 2022). However, burning coal results in waste products such as fly ash (FA), coal bottom ash (CBA), and boiler slag, each of which contributes to its own set of environmental pollution and disposal issues (Danish and Mosaberpanah, 2021; Gooi et al., 2020; Hasim et al., 2022a; Kasina et al., 2021). CBA and FA are two significant by-products of coal electricity production and are consistently produced in large quantities (Ali et al., 2022; Gupta et al., 2021; Khongpermgoson et al., 2019; Sanjuán and Argiz, 2021). When pulverised coal is burned in a furnace, the flue gases remove the lighter ash (M. Singh, 2018; H. Zhou et al., 2022). In electrostatic precipitators, flue gas ash is removed before it is discharged into the air (M. Singh, 2018). FA is the coal ash collected by electrostatic precipitators, which makes up 80% of the total amount of flue gas ash (Gupta et al., 2021; Nguyen Thi et al., 2021; Rafieizonooz et al., 2022; Sanjuán and Argiz, 2021). Clinkers are too heavy and sink to the furnace bottom (M. Singh, 2018; H. Zhou et al., 2022). CBA is the ash that settles at the bottom of the furnace and makes up 20% of all coal ash (Ankur and Singh, 2021; Hashemi et al., 2018; Nakararoj et al., 2022; Nguyen Thi et al., 2021).

FA is widely used as a cement alternative in mortar and concrete and has proven to enhance concrete's performance and toughness when used as supplemental cementing material (Gupta et al., 2021; Majhi and Nayak, 2019; M. Singh, 2018). Whereas CBA has a particle size distribution similar to sand, it can be utilised as a sand substitution in construction and architecture (Balapour et al., 2020; Keerio et al., 2021; Kota and Kalyana Rama, 2020; Majhi and Nayak, 2019). Using both FA and CBA in concrete production is a reliable way to lessen the waste disposal issue and help preserve the world (Ali et al., 2022; Irshidat and Al-Nuaimi, 2020; Ngohpok et al., 2018; N. Singh, Kumar, et al., 2019). The thermal plants utilise approximately 20 tonnes of coal to produce 1 MW of energy, and they produce about 15-20% CBA as a by-product (Hamada et al., 2022; N. Singh, Kumar, et al., 2019; N. Singh et al., 2018; Z. Zhao et al., 2020). Waste products like ash are dumped in landfills or water treatment facilities (Ali et al., 2022; Gooi et al., 2020; M. Ibrahim et al., 2022; Rodríguez-Álvaro, Seara-Paz, González-Fonteboa, and Martínez-Abella, 2021). Improper disposal of CBA poses severe risks to human health and the environment (Abbas et al., 2020; Albiajawi et al., 2021; Ali et al., 2022; Hamada et al., 2022). For instance, dumping CBA into landfills or free-floating in the environment could lead to the loss of fertile land and the contamination of water supplies and air quality (Hamada et al., 2022; Schafer, Clavier, Townsend, Kari, et al., 2019; N. Singh, Kumar, et al., 2019). Cancers of the skin, lungs, and bladder are some diseases linked to CBA exposure (Ali et al., 2022; N. Singh, Kumar, et al., 2019). Thus CBA has been listed as a Group I human carcinogen (Hasim et al., 2022a). Residents of areas close to uncontrolled coal-ash disposal sites were given a 1 in 50 probability of developing cancer due to arsenic pollution, according to an Environmental Protection Agency (EPA) report (U.S. Environmental Protection Agency (USEPA)., 2014). For this reason, the EPA has issued new rules that promote developing novel approaches to recycling these by-products (Balapour et al., 2021). To achieve the Sustainable Development Goals (SDGs), especially SDG 12, which aims to "ensure sustainable consumption and production patterns," an effort toward ecological sustainability of coal-fired power plants by-products is crucial (United Nations, 2015). SDG 12 aims to achieve sustainable management and efficient use of natural re-sources and significantly decrease environmental pollution through prevention, reduction, and recycling by the year 2030 (United Nations, 2015). Hence, coal ash recycling became popular as a means of replacing non-renewable aggregates in an environment-friendly way (Hasim et al., 2022a; Nguyen Thi et al., 2021; Pushkar, 2019a; Yating Zhu et al., 2020).

Synthetic calcium silicate hydrate (C-S-H) seed is being investigated more frequently as a possible accelerator in cement-based products (Alzaza et al., 2022; Kanchanason and Plank, 2019; H. Li et al., 2021; Morales-Cantero et al., 2022). This typical nano-scale substance has a diameter of around 10 nanometres and can be significantly enhanced by the addition of nanoparticles; it is the major by-product of concrete hydration (Wu et al., 2021; D. Zhao and Khoshnazar, 2021), whose primary function is to provide cement-based products with their binding effect (D. Zhao and Khoshnazar, 2021). The first is the "filler effect," in which pores are filled to increase packing density due to the particles' incredibly small size (Morales-Cantero et al., 2022; Wu et al., 2021; Z. Zhou et al., 2021). The second effect is known as the seeding or nucleation effect, and it entails aiding the formation of C-S-H by providing sites for nucleation (H. Li et al., 2021; Wu et al., 2021; D. Zhao and Khoshnazar, 2021; Z. Zhou et al., 2021). The amount of chemicals produced during hydration increases because of a secondary chemical reaction (Wu et al., 2021).

Although extensive studies have been performed on replacing CBA as a fine aggregate in conventional concrete, there seems to be a lack of investigation on replacing CBA as aggregate and incorporating nano C-S-H as hydration accelerators in UHPC. Therefore, the work presented herewith investigates the mechanical, durability and rheology properties of UHPC containing CBA as aggregates with the optimum ratio of chemical admixture and seeding additives.

## 1.2 Problem Statements

For a long time, fine aggregates for concrete have come mostly from river sand (Gooi et al., 2020; Kirthika et al., 2019; Nakararoj et al., 2022). Globally, enormous quantities of concrete are being produced, which has led to several issues related to the depletion of natural aggregate resources (Amin et al., 2020; Hashemi et al., 2018). Although the world's population has only doubled since 1970, the rate at which natural resources are being explored has increased thrice (Gomes et al., 2020). As of 2019, only China and the United States generated 300,000 metric tonnes of sand annually, a number that is expected to expand in the near future (Khaw et al., 2022). More than 230 million cubic metres of material is mined annually from rivers worldwide (Srivastava and Singh, 2020). The substantial embodied energy and sustainability of UHPC are threatened by its large fine aggregate content, usually used at the rate of 1000 kilogrammes per cubic metre (T. Liu et al., 2020). An overabundance of sand mining can have disastrous results for the environment, economy, and society (Srivastava and Singh, 2020). In specific, the massive use of sand results in a scarcity of resources, a drop in subsurface water level, and the destruction of microorganism ecosystems (Gomes et al., 2020; Gupta et al., 2021; Kirthika et al., 2019; T. Liu et al., 2020; Srivastava and Singh, 2020). The depletion of riverbed sand reserves threatens the supply of the most widely utilised fine aggregate (Y. H. Kim et al., 2021; Kota and Kalyana Rama, 2020; Pushkar, 2019b). Despite widespread awareness of the drawbacks, as mentioned earlier, natural aggregate is still widely used for various applications (Khaw et al., 2022). Concrete's common aggregates are in high demand due to heavy consumption in concrete production. Therefore, more sustainable materials are needed to meet the rising demand (Kota and Kalyana Rama, 2020; Z. Li et al., 2021). Fine natural aggregate may be used because it is less expensive. In contrast, the processing and production expense of fine aggregate replacement material may account for its slow adoption thus far. The outcome is a more rapid and severe depletion of fine natural aggregate, such as river sands (Khaw et al., 2022; Muthusamy, Jamaludin, et al., 2020). Using waste or recycled resources as a replacement for fine aggregate is crucial for ensuring the long-term viability of UHPC (T. Liu et al., 2020). Converting coal thermal electricity generating waste into an eco-friendly by-product for concrete manufacture is a solution for sustainable development on a global scale (Pushkar, 2019b). Since solutions cannot handle the ever-increasing amounts of CBA, more than 85 % of it is still being kept in open impoundments and landfills around the world (Hashemi et al., 2018; Le et al., 2018; H. Zhou et al., 2022). Therefore, it would be more efficient in terms of landfill area, time, resources, and energy used to produce concrete products that incorporate this material into the mix (Abbas et al., 2020; Ali et al., 2022; Le et al., 2018; Yoon et al., 2019). The Construction Industry Development Board (CIDB) pioneered the utilisation of this by-product to increase the proportion of recycled materials in concrete (Keerio et al., 2021). When pozzolanic material is used in concrete and the concrete is exposed to extreme weather, the concrete has a longer lifespan than expected (Bheel et al., 2022; Khongpermgoson et al., 2019). It has been determined that pozzolanic material has a major impact on a cementation system, particularly in forming a calcium silicate hydrate (C-S-H) structure (Albiajawi et al., 2021). As a result, there is a need to incorporate more environmentally sustainable pozzolanic ingredients into concrete mixes. Using CBA in concrete has been linked to significant decreases in the use of coal-fired thermal power plants and solid waste production (Bheel et al., 2022). Using this strategy would reduce manufacturing costs without sacrificing protection from the environmental and health risks posed by trash landfilling (Ali et al., 2022). There was a limited investigation on extended replacement levels of natural aggregate using coal bottom ash at a replacement level of more than 20% in UHPC in terms of mechanical, durability, and rheological properties. As the prior research done was proven that the optimal content of CBA as aggregate replacement was at 40% which displayed a better performance than the control mix with fully river sand as the aggregate (Saw, 2022), hence this research will be conducted on a more definitive lower and upper boundary based on the 40% level, which was 20%, 40% and 60%. Besides that, there was also lack of analysis of the significance of graded coal bottom ash on the quality of UHPC produced when utilised as aggregate replacement material.

When microfibres are introduced into UHPC, the material displays strain-hardening behaviour and ductile failure modes when subjected to tension and flexure. The lack of effectiveness of fibres in delaying the appearance of microcracks is likely attributable to their comparatively large separation distance and less interlocking. In this way, concrete becomes more susceptible to humidity and other damaging substances infiltration, hastening its deterioration (Meng and Khayat, 2018a). It is critical to optimize the UHPC using nanoparticles at the nanoscale to ensure its great performance (Wu et al., 2021). Incorporating nanoparticles into cement-based materials was found to have the following effect. Because of their nanometre-scale spacing and high specific surface areas, nanoparticles are very good at preventing microcracks from forming and spreading (Kanchanason and Plank, 2019; H. Li et al., 2021; Meng and Khayat, 2018a). Although it was established that nano C-S-H had been proven to increase the performance of cementitious material, however a low amount of literature reported the use of nano C-S-H in UHPC, especially those utilising coal bottom ash as aggregate.

As a summary, there are a few problem statements to be study further in this research:

1. Lack of analysis of the significance of graded coal bottom ash on the quality of UHPC produced when utilised as aggregate replacement material.
2. There was a limited investigation on extended replacement levels of natural aggregate using coal bottom ash at a replacement level of more than 20% in UHPC in terms of mechanical, durability, and rheological properties.
3. Although it was established that nano C-S-H had been proven to increase the performance of cementitious material, however a low amount of literature reported the use of nano C-S-H in UHPC, especially those utilising coal bottom ash as aggregate.

## **1.3** Research Questions

1. How does the graded coal bottom ash influence the quality of concrete produced when utilised as aggregate replacement material?
2. How is the behaviour of UHPC mixes, in terms of mechanical properties and durability properties, when GCBA (optimised outcome from objective 1) is used at aggregate replacement level beyond 20% by aggregate volume?
3. How does nano C-S-H influence the performance of the UHPC mix containing CBA?

## 1.4 Aim and Objectives of the Research

The study aimed to maximise the use of CBA as a fine aggregate replacement in UHPC composites while maintaining or enhancing the mechanical and durability properties of the resultant UHPC. The following are the research's precise objectives: -

1. To determine the incorporation effect of graded coal bottom ash as aggregate replacement material to produced UHPC with similar or better overall performance.
2. To study the behaviour of UHPC mixes when the graded coal bottom ash (optimised outcome from objective 1) content as the aggregate replacement for UHPC mixes is beyond 20% by aggregate volume, in terms of mechanical properties and durability properties.
3. To evaluate the influence of nano C-S-H required in a UHPC mix, including CBA, to achieve similar or better overall performance.

## 1.5 Scope of Works

The river sand aggregate content in the UHPC would be replaced by three different CBA replacement ratios and optimised binder phase comprises of OPC, GGBS and SF content, with three variable levels of nano C-S-H usage. In this investigation, a total of fourteen sets of specimens were prepared. The binder phase of the mix will be optimised by varying the proportions of OPC, GGBS and SF content. The optimal binder mix designation will then further optimized with steel fibre reinforcement at level of 1%, 2% and 3%. The optimal mix will then utilise CBA as aggregate replacement at 40% content to determine the incorporation effect of grading system to the properties of UHPC. Upon determining the necessity of graded CBA as aggregate replacement, the specimens were casted with different level of nano C-S-H for additional examination to determine the mechanical properties and optimal composition for a UHPC with CBA as a sand replacement and nano C-S-H gel as a hydration accelerator. The mechanical, durability and microstructure properties of UHPC employing CBA as a partial sand replacement and nano C-S-H gel as a hydration accelerator were studied in tests. The tests were conducted based on the American Society for Testing and Materials (ASTM) technical guidelines, British Standard (BS), or equivalent standards. The appropriate combination ratio was determined by comparing the experimental data from these thirteen distinct mix designs to the control mix.

## 1.6 Research Workflow


*Figure 1.1 Research Workflow*

## 1.7 Significance of Research

Due to humans' strong need for civilization development, concrete is increasingly used to create buildings and infrastructures worldwide. UHPC is developed to achieve higher strength and durability to construct skyscrapers and bridges with longer spans. Since UHPC requires a massive amount of resources such as cement, nanomaterials and quartz sand and fibres which increase the carbon footprint, this will put the ecosystem under severe stress. In the same way, human waste products are growing. Therefore, it is essential to effectively preserve and recycle these resources to ensure a sustainable future. CBA, for example, is a by-product collected from the bottom of the coal power plant's furnace. As a result, one of the measures to potentially reduce the environmental load is utilising by-product materials as an alternative resource. On the other hand, nanoparticles such as nano C-S-H are a good solution as filler material in UHPC in reducing the steel and synthetic fibre yet still maintaining or even enhancing the performance of UHPC.

The use of CBA as a substitute for fine aggregate in the UHPC mixture is being investigated in this study to see how it affects the concrete's mechanical, durability and microstructure properties. The addition of nano C-S-H gel as a hydration accelerator is also being investigated to determine the optimal content for even better outcomes.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Ultra-High Performance Concrete (UHPC) - Material Design

Portland cement, fine aggregates, coarse aggregates, water, and optional admixtures make up the base ingredients for conventional concrete. To fabricate UHPC, on the other hand, one must eliminate the coarse aggregate, replace some of the cement with supplementary cementitious materials (SCMs), and use superplasticisers to get low water-to-cement ratios. The use of ultra-filler techniques can achieve denser concrete, and UHPC is a well-known example of such techniques applied within these concrete microstructures (Faried et al., 2021b; Hou et al., 2021; Kang et al., 2019; Ye Li et al., 2019; Wu, Shi, et al., 2018). By improving particle packing, lowering the water/binder ratio to below 0.3, and using a high superplasticiser dosage, UHPC becomes a very dense material with exceptional durability (Gu et al., 2022; Huang et al., 2021; Said et al., 2022; Sharma et al., 2022). With minimal usage or even elimination of coarse aggregate, this optimal packing will disperse all micro-scale particles so that they fill those gaps between the bigger ones (Bajaber and Hakeem, 2021; Liao et al., 2021, 2022; Nodehi and Nodehi, 2022). Thus, concrete with excellent properties can be produced by achieving a dense matrix with limited permeability (Dingqiang et al., 2021; Sohail et al., 2021; Xie et al., 2018; Yanping Zhu et al., 2020). According to the Portland Cement Association (PCA) definition, UHPC is a high-strength, ductile construction material produced by blending Portland cement, supplemental cementitious ingredients, quartz flour, fine silica sand, and high-range water reducer, water, and steel or organic fibres (Portland Cement Association, n.d.). As a result, UHPC would likely have much lower w/c ratios than regular concrete, which is ordinarily around 0.40 (Amin, Zeyad, et al., 2022; Huang et al., 2021). Furthermore, without dispersed fibre reinforcement, UHPC would be rather weak in tension and prone to cracking because of plastic and drying shrinkage, despite exceptionally resilient under compression. Fibrous reinforcement is added to concrete to avoid cracking by transferring tensile stresses within the material. Fibers' inability to prevent the onset of microcracks is likely due to the greater spacing between them and the reduced degree of interlocking between them (Meng and Khayat, 2018a). Therefore, optimising the UHPC using nanoparticles at the nanoscale is crucial to ensure optimal mechanical strength and durability performance. The following impact was observed when nanoparticles were added to cement-based materials. According to ASTM C1856, UHPC is a cementitious mixture that meets durability, ductility, toughness standards and compressive strength of at least 120 MPa (ASTM International, 2017). The EN 206:2013 standard specifies that UHPC's compressive strength must be greater than 100 MPa (British Standard, 2021b), making it a reliable and durable material for the innovative architecture of today's modern bridges.

The packing fraction of various components like cement, sand, etc., and their combinations determine the mix designation of UHPC. Fuller and Thompson's seminal work established that aggregate packing had an effect on concrete's final qualities (Fuller and Thompson, 1907). Therefore, they concluded that the qualities of the concrete might be enhanced by using aggregates with a continuous geometric grading. Theoretically, as indicated in the following Equation 1 based on the research of Fuller and Thompson and Andreasen and Andersen, a minimal porosity might be attained by employing an ideal particle size distribution across all of the used particle components in the mix (Andreasen, 1930; Fuller and Thompson, 1907):

$$P(D) = \left(\frac{D}{D_{max}}\right)^q \text{ -------- } \textit{Equation 1}$$

where $D$ is the particle size (µm), $P(D)$ is a fraction of the total solids being smaller than size $D$, $Dmax$ is the maximum particle size (µm), and q is the distribution modulus. However, the equation does not consider the smallest possible particle size, despite the fact that there must be some lower bound, which can be used to refine the packing model. So, Funk and Dinger proposed an adjusted version of the Andreasen and Andersen equation, as shown in Equation 2 (Funk and Dinger, 1994). All the concrete mixtures developed for this investigation were derived using a version of the Andreasen and Andersen model with adjustments made to account for smaller aggregate sizes, where $Dmin$ is denoted in µm:

$$P(D) = \frac{D^q - D_{min}^q}{D_{max}^q - D_{min}^q} \text{ -------- } \textit{Equation 2}$$

Since the ratio of fine to coarse particles is determined by the distribution modulus q, the equation can be used to build a wide variety of concrete. Concrete mixes that are high in tiny particles tend to have distribution moduli that are below 0.25, while coarse mixtures tend to have moduli that are above 0.5 (R. Yu et al., 2014). The value of q to be applied for UHPC is usually lower than 0.23 (Hunger, 2010).

The mix designation of UHPC from previous researchers is tabulated in Table 2.1. Based on all the different mix proportions of UHPC, cement and silica fume were the most used materials as the binder. Some literature describes using fillers like quartz sand in place of cement (Shen, Lu, Wang, et al., 2020; Shen, Zheng, et al., 2020; X. Wang et al., 2021; Xue et al., 2020; You et al., 2022). Besides, some other SCMs also being utilised to replace cement, such as fly ash (FA) and Ground Granulated Blast Furnace Slag (GGBS) (Aisheh et al., 2022b; K. Liu et al., 2022; Shen, Lu, Wang, et al., 2020; Shen, Zheng, et al., 2020; X. Wang et al., 2021; Xue et al., 2020; You et al., 2022). However, some researchers have successfully replaced the silica fume with an equivalent quantity of metakaolin and natural zeolite (Xue et al., 2020). For the aggregate phase, a few types of aggregates were used in different mix designs, such as fine sand, micro sand, river sand and ground quartz, which have different particle size distributions. Based on the reported results in Table 2.1, the sand-to-binder ratio of UHPC is relatively low (0.50 to 1.60) compared to conventional concrete, which ranges from 2.00 to 8.00. At the same time, the water-to-binder ratio of UHPC ranged from 0.15 to 0.30. Therefore, a higher superplasticiser dosage was needed to achieve the desired workability compared to the conventional concrete mix. Despite having exceptional mechanical strength, UHPC tends to shrink more obviously than normal concrete mixes due to the low content of aggregate. Therefore, fibre reinforcement is introduced into UHPC as reported by different findings, ranging from 78 to 470 kg/m$^3$. To further improve the interface transition zone between the paste and aggregate or fibre, nanoparticles are added to enhance the properties of the UHPC. A few types of nanoparticles were used as the filler materials nano silica (12.2 kg/m$^3$), nano cotton straw ash (25.0 kg/m$^3$) and nano rice husk ash (7.0 kg/m$^3$). It was observed that when nanoparticles are incorporated into the UHPC mix, the quantity of fibre reinforcement required will be reduced to only about 30.0 kg/m$^3$ or possibly excluded from the mix design but still able to maintain or even improve the strength of the specimens.

As illustrated in

*Figure 2.1*, the particle size grading of the aggregate used in UHPC is relatively fine. Only a minority of the researchers have an aggregate size ranging between 2.36 to 4.75 mm. Most of the aggregate used in UHPC has a particle size smaller than 2.36 mm, with the finest particles at about 0.15 mm. It can be seen that the aggregate used