Abstract: Ultra-high-performance concrete (UHPC) is a new type of concrete with improved features such as high strength, long service life, ductility, and toughness. UHPC’s energy-intensive cement and quartz sand may make it unsustainable despite its engineering expertise. Thus, a UHPC that is energy efficient and environmentally benign should use less energy-intensive components and industrial wastes. This review consolidates and critically reviews the latest global research on coal bottom ash (CBA) as a fine aggregate replacement material and nano-calcium silicate hydrate (C–S–H) as concrete additives. Based on the critical evaluation, replacing aggregate with CBA up to 60% improves strength by 23%. Since high-quality natural sand is depleting and CBA output is increasing due to coal power plants, the concrete industry can use CBA as an aggregate. However, CBA as an aggregate substitute in UHPC has scarcely been reported. Besides, nanomaterial technologies like nano-C–S–H have also been proven to increase traditional concrete’s strength by 33%. But, their impact on UHPC has yet to be fully explored. Thus, to develop UHPC with a lower carbon footprint and comparable or better performance to market-available UHPC, further research on CBA as aggregate replacement in UHPC with nano-C–S–H as an additive on mechanical durability and microstructure is needed.

Keywords: ultra-high-performance concrete, coal bottom ash, nano-C–S–H

1 Introduction

Construction has been crucial to the expansion of cities and manufacturing in recent decades [1]. From the time of Romans, when it was first utilised, concrete has been a core part of the construction field [2,3]. Concrete has been a core component of the construction industry since its introduction in the nineteenth century [2]. Gravel sand is combined with cement and water to make concrete [4]. Concrete’s status as the world’s second most widely employed material, after water, has increased rapidly due to the rapid infrastructure development [5]. The world’s demand for concrete is forecast to reach about 7.5 billion m$^3$ by 2.050 (approximately 18 billion tons) [6]. 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 [7]. Various engineering structures have extensively used concrete [6,8,9]. Concrete technology has advanced to build bigger buildings, longer bridges, and more earthquake-resistant constructions due to unforeseen demands [4,10]. Because of the improved strength-to-weight ratio, smaller section sizes will be feasible and hugely beneficial for developing long-lasting constructions [11]. Due to its high intrinsic density, concrete has various downsides, including a large footprint and hefty finished components [12]. In view of these restrictions, scientists have applied packing theory to design new concretes with improved qualities like high strength, long service life, ductility, and toughness [12,13]. Furthermore, the widespread shortage of essential materials was exacerbated by the extensive use of crushed rock and cement as binding agents in concrete production [4,14]. The building sector’s massive concrete demand will increase the rate at which
carbon dioxide (CO2) is released into the atmosphere [15–17]. The use of environmentally friendly concrete has been the focus of numerous strategies [16,18]. Green concrete fits the criteria of being made from one or more alternative or recycled waste materials, having an ecologically friendly production process, or having excellent performance and outstanding durability [14,16,19]. Because of this, it is essential to develop advanced cementitious products [13,20], namely high-performance concrete (HPC) and ultra-high-performance concrete (UHPC). These types of concrete can last longer and withstand a higher structural load than conventional concrete (CC) [3,21–26].

It was in the early 1990s that the initial concept of UHPC was first developed in France [27–30]. UHPC denotes a relatively novel group of advanced cementitious composite materials with significantly superior mechanical and durability capabilities compared to CC materials [21–23]. The four theoretical ideas commonly followed in the development of UHPC are reducing the overall pore structure, improving the microstructure, enhancing mixing homogeneity, and increasing deformation toughness [31–33]. The material offers compressive and flexural strengths of up to 200 and 48 MPa, respectively [11,34,35]. Besides, UHPC is also a very dense material with exceptional durability. These attributes are achieved by 1) improving the particle packing, 2) lowering the water/binder ratio to below 0.3, and 3) using a high water reducer dosage [36–38]. According to ASTM C1856, UHPC is a concrete that meets a stipulated durability level, ductility behaviour, toughness standards, and compressive strength of at least 120 MPa [39]. The EN 206:2013 standard specifies that UHPC’s compressive strength must be greater than 100 MPa [40], making it a reliable and durable material for the innovative architecture of modern buildings and bridges. UHPC has a wide range of potential applications due to its high performance in long-span bridge engineering, defensive military engineering, peculiar-shaped structure, maritime construction engineering, and many others [41–43].

It is difficult for concrete structures and infrastructure to create sustainably since cement and concrete are greenhouse gas emitters [19,36]. UHPC contains 600–1,300 kg m\(^{-3}\) carbon emissions from its three times more cement than CC [16,44,45]. Sustainable development requires energy-efficient building designs due to the global energy crisis and environmental destruction [42]. 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 [46]. UHPC may be a viable material in the building sector due to its better engineering features [46]. Still, it may not be sustainable due to the high dosage of energy-intensive constituents such as cement and river sand [36,47,48]. Thus, developing energy-efficient and environmentally friendly UHPC utilizing less energy-intensive components and industrial by-products would help expand the material’s use [36,49,50]. UHPC must maximise its use of a low-carbon, low-energy-consumption alternative material [17,44,46,51–54]. Sustainable UHPC can be made by replacing cement, aggregate, and reinforcing components with agricultural and industrial byproducts [55–57].

On the other hand, energy requirements are increasing rapidly due to the rapid growth of the global economy and urbanisation rate [58]. As with many other countries, Malaysia has long relied on coal as a low-cost energy option [59]. Coal supplies 30% of global primary energy and will likely be the leading power source for the foreseeable future [60]. As Malaysia’s electricity demand increases, so will the ash residue produced by the country’s coal-fired power plants [61]. Fly ash (FA), coal bottom ash (CBA), and boiler slag result from power plant coal burning. These materials pollute and cause disposal concerns [62–64]. 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 a supplemental cementing material [14,65,66]. CBA’s particle size distribution is close to natural sand. Thus, it can replace sand in the construction and architecture of buildings and infrastructure [67–69]. Therefore, using both in concrete production is a reliable way to lessen the waste disposal issue and help preserve the environment [14,70,71]. Ecological sustainability of coal-fired power plant byproducts is essential to achieving the sustainable development goals (SDGs), especially SDG 12, which seeks to “ensure sustainable consumption and production patterns” [72]. SDG 12 aspires to sustainably manage and efficiently utilise natural resources and considerably reduce environmental pollution through prevention, reduction, and recycling by 2030 [72]. Thus, coal ash recycling became popular as a green alternative to non-renewable aggregates [73–75]. Fine concrete aggregates have primarily come from river banks [68,76,77]. Global concrete production has caused various concerns about natural aggregate depletion [57,60]. Over 230 million cubic metres of river sand are mined annually [78]. UHPC’s highly fine aggregate concentration (1,000 kg m\(^{-3}\)) threatens its sustainability and embodied energy [29]. Overmining sand can harm the ecology, economy, and society [78]. Sand mining depletes natural resources, lowers subsurface water levels, and destroys microorganism habitats, which could have long-term environmental effects. Concrete aggregates are popular. Therefore, more sustainable materials are needed [7,79]. Global sustainable development can be achieved by converting coal thermal electricity generating waste into an eco-friendly byproduct for
concrete manufacturing [70]. Over 85% of CBA is stored in open impoundments and landfills worldwide because current waste management systems cannot handle the growing amounts [58,60,80]. Thus, using this material to make concrete products would save landfill space, time, resources, and energy [81,82]. The Malaysian Construction Industry Development Board pioneered using this byproduct to augment recycled resources in concrete [19]. This approach would lower manufacturing costs without compromising waste landfill’s environmental and health dangers [6].

In current construction materials science and technology advances, synthetic calcium silicate hydrate (C–S–H) seed is being investigated extensively as a possible hydration accelerator in cement-based products [83,84]. This nanoscale material is around 10 nm across. It shares chemical features with the main cement hydration product (C–S–H gel) [83,85]. The C–S–H gel primarily provides cement-based products with their binding effect [83]. UHPC with microfibres exhibits strain-hardening and ductile failure modes under tension and flexural load [86]. Fibres may not delay microcracks due to their considerable separation distance and less interlocking with the binder phase [86]. Thus, humidity and other detrimental chemicals infiltrate concrete faster, accelerating its deterioration [86]. Therefore, it is essential to optimise UHPC performance using nanoparticle modification at the nanoscale [85]. Nanoparticles prevent microcracks from developing and spreading due to their nanometre-scale spacing and high specific surface areas [86–88]. The first working mechanism is the “filler effect,” in which pores are filled to increase packing density due to the particles’ small particle size [85,89,90]. The second effect, the seeding or nucleation effect [90], helps produce primary C–S–H gels by providing nucleation sites [88]. In addition, the modern building sector has prioritised the research and development of low-carbon concrete [83,89,90]. One method of doing so is using SCMs instead of cement [83]. Synergistic effects between supplemental materials and nano-C–S–H may enhance aggregate substitution levels with CBA, decreasing the conventional aggregate and cement content [84,90].

2 Significance and aim

Existing studies have reported numerous mix designs of UHPC, including different kinds of supplementary material to reduce carbon footprint [8,55]. However, there is a lack of elaboration on using CBA in the UHPC mix and utilising nano-C–S–H as the nanomaterials. Besides, previous literature of the main author has extensively discussed the utilisation of CBA as a cement and fine aggregate replacement [59]. However, the available data mainly discuss the treatment method of CBA, the chemical and physical properties of CBA, and the influence of CBA incorporation in conventional high-strength concrete towards the fresh and hardened properties of concrete. Besides, review articles from the previous works [68,91,92] also focused mainly on the fresh and hardened properties of different kinds of mortar and CC with CBA as an aggregate replacement, but none of the scopes is related to UHPC application. Besides, the existing studies of nano-C–S–H applications [84,90] are limited to CC only. Therefore, their influence on UHPC concrete in terms of mechanical and durability parameters is yet to be further investigated. Previous research literature prompted ongoing findings on CBA as an aggregate replacement and nano-C–S–H as an additive in UHPC.

The present work aims to comprehensively review various studies and research investigations on the properties of UHPC and CC with CBA as the aggregate replacement and nanoadditives. The findings of related articles published in key scientific databases such as Web of Science, Scopus, ScienceDirect, and Google Scholar were reviewed and consolidated into suitable tables or figures to derive a critical review. The review is intended to increase the readers’ awareness and knowledge regarding the application and usability of CBA in UHPC and conventional mortar/concrete with suitable nanoadditives. With the increasing understanding of the material’s properties, CBA will be made viable for broader application in the construction industry in the near future to reduce the negative impact the construction industry imposes on the environment. The work presented also provides consolidated information and critical analysis of the existing literature on UHPC and CC made with CBA as an aggregate replacement and nanoadditives. This review covered various topics, including the mix design and particle size grading of aggregate in UHPC. Besides, the physical and chemical properties of CBA material were also reviewed. In terms of concrete behaviour, the workability, mechanical, and durability properties of CBA concrete are elucidated in the present work. Moreover, the microstructure of CBA UHPC, ordinary concrete and mortar, and the effect of nano-C–S–H as additives in cementitious products were also elaborated. Therefore, the present review thoroughly explains CBA material properties and potential uses in UHPC and traditional mortar/concrete. As more is learned about the material’s qualities, CBA will be in a better position to be advocated for its widespread use in the construction industry, helping to mitigate the industry’s detrimental environmental impact.
3 UHPC – Material design and aggregate grading

Portland cement, fine aggregates, coarse aggregates, water, and optional admixtures make up the base ingredients for CC. 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 (SPs) to get low water-to-cement ratios. 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 [34]. As a result, UHPC would likely have much lower w/c ratios than regular concrete, which is ordinarily around 0.40 [22,43]. Furthermore, without dispersed fibre reinforcement, UHPC would be rather weak in tension and prone to cracking because of plastic and drying shrinkage, despite being exceptionally resilient under compression. Fibrous reinforcement is added to concrete to avoid cracking by transferring tensile stresses within the material [86]. Fibers' inability to prevent the onset of microcracks is likely due to the greater spacing and the reduced degree of interlocking between them [86]. 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.

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 [93]. Therefore, they concluded that the quality of the concrete might be enhanced by using aggregates with a continuous geometric grading. Theoretically, as indicated in the following Eq. (1) based on the research of Fuller and Thompson, a minimal porosity might be attained by employing an ideal particle size distribution across all of the used particle components in the mix [93,44]:

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

where \(D\) is the particle size (\(\mu m\)), \(P(D)\) is a fraction of the total solids being smaller than size \(D\), \(D_{\text{max}}\) is the maximum particle size (\(\mu m\)), 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 Eq. (2) [95]. 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 \(D_{\text{min}}\) is denoted in \(\mu m\) [95]:

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

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 mixes tend to have moduli that are above 0.5 [96]. The value of \(q\) to be applied for UHPC is usually lower than 0.23 [97].

The mix designation of UHPC from previous researchers is tabulated in Table 1. Based on all the different mix proportions of UHPC, cement and silica fume were the most used materials as the binder. Some studies describe using fillers like quartz sand in place of cement. Besides, some other SCMs also being utilised to replace cement, such as FA and ground granulated blast furnace slag (GGBS). However, some researchers have successfully replaced silica fume with an equivalent quantity of metakaolin and natural zeolite [8]. 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 1, the sand-to-binder ratio of UHPC is relatively low (0.50–1.60) compared to CC, 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 SP dosage was needed to achieve the desired workability compared to the CC 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, e.g., nanosilica (12.2 kg m\(^{-3}\)), nanocotton straw ash (25.0 kg m\(^{-3}\)), and nanorice 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 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...
Table 1: UHPC mix designation from previous studies

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Mix designation (kg·m$^{-3}$)</th>
<th>S/B</th>
<th>W/C</th>
<th>SP</th>
<th>28-days compressive strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[98]</td>
<td>1,114 — — 1,072 — — — — 169 — — 234 —</td>
<td>0.96</td>
<td>0.19</td>
<td>40 —</td>
<td></td>
</tr>
<tr>
<td>[99]</td>
<td>700 — — 1,055 219 — — 175 — — 44 — —</td>
<td>1.50</td>
<td>0.29</td>
<td>46 149</td>
<td></td>
</tr>
<tr>
<td>[100]</td>
<td>832 — — — — — — — — — — — — —</td>
<td>1.17</td>
<td>0.20</td>
<td>30 174</td>
<td></td>
</tr>
<tr>
<td>[101]</td>
<td>900 — — 1,125 — — — — — — — — — — —</td>
<td>1.25</td>
<td>0.23</td>
<td>54 194</td>
<td></td>
</tr>
<tr>
<td>[102]</td>
<td>691 — — 759 — — — — — — — — — — —</td>
<td>1.10</td>
<td>0.27</td>
<td>22 146</td>
<td></td>
</tr>
<tr>
<td>[103]</td>
<td>486 556 — — — — — — — — — — — — —</td>
<td>0.98</td>
<td>0.20</td>
<td>5.5 125</td>
<td></td>
</tr>
<tr>
<td>[104]</td>
<td>896 — — — — — — — — — — — — —</td>
<td>1.14</td>
<td>0.21</td>
<td>20.1 152</td>
<td></td>
</tr>
<tr>
<td>[105]</td>
<td>— — 44670 — — — — — — — — — — —</td>
<td>1.60</td>
<td>0.23</td>
<td>50.1 110</td>
<td></td>
</tr>
<tr>
<td>[106]</td>
<td>955 — — 1,051 — — — — — — — — — — —</td>
<td>1.10</td>
<td>0.17</td>
<td>15 170</td>
<td></td>
</tr>
<tr>
<td>[107]</td>
<td>— — 170 690 900 — — — — 1,170 — — — — —</td>
<td>1.05</td>
<td>0.30</td>
<td>— 156</td>
<td></td>
</tr>
<tr>
<td>[108]</td>
<td>890 — — 1,050 — — — — — — — — — — —</td>
<td>1.18</td>
<td>0.18</td>
<td>1.60 117</td>
<td></td>
</tr>
<tr>
<td>[109]</td>
<td>1133.1 — — 953.2 — — — — — — — — — —</td>
<td>0.84</td>
<td>0.23</td>
<td>7.60 104.7</td>
<td></td>
</tr>
<tr>
<td>[110]</td>
<td>884 — — 1,040 — — — — — — — — — — —</td>
<td>1.18</td>
<td>0.24</td>
<td>20.8 115</td>
<td></td>
</tr>
<tr>
<td>[37]</td>
<td>640 160 — — — — — — — — — — — — —</td>
<td>1.02</td>
<td>0.18</td>
<td>32 165</td>
<td></td>
</tr>
<tr>
<td>[111]</td>
<td>1,050 — — 514 — — — — — — — — — — —</td>
<td>0.50</td>
<td>0.17</td>
<td>44 205</td>
<td></td>
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<tr>
<td>[112]</td>
<td>758 — — 733 — — — — — — — — — — —</td>
<td>1.35</td>
<td>0.20</td>
<td>13 200</td>
<td></td>
</tr>
<tr>
<td>[113]</td>
<td>712 — — 1,020 — — — — — — — — — — —</td>
<td>1.43</td>
<td>0.25</td>
<td>31 149</td>
<td></td>
</tr>
<tr>
<td>[114]</td>
<td>800 — — 880 — — — — — — — — — — —</td>
<td>1.10</td>
<td>0.15</td>
<td>9.6 140</td>
<td></td>
</tr>
<tr>
<td>[103]</td>
<td>712 221 — — 1,020 — — — — — — — — — —</td>
<td>1.43</td>
<td>0.23</td>
<td>6.5 135</td>
<td></td>
</tr>
<tr>
<td>[1]</td>
<td>960 — — 1,017 — — — — — — — — — — —</td>
<td>1.05</td>
<td>0.17</td>
<td>34 116</td>
<td></td>
</tr>
<tr>
<td>[115]</td>
<td>710 71 106 1,000 — — — — — — — — — —</td>
<td>1.15</td>
<td>0.25</td>
<td>25.7 117.61</td>
<td></td>
</tr>
<tr>
<td>[116]</td>
<td>856.5 — — 1,177.5 — — — — — — — — —</td>
<td>1.10</td>
<td>0.17</td>
<td>19.7 155</td>
<td></td>
</tr>
<tr>
<td>[96]</td>
<td>600.2 — — 843.8 218.7 — — — — — — — —</td>
<td>1.20</td>
<td>0.22</td>
<td>45.9 67.8</td>
<td></td>
</tr>
<tr>
<td>[38]</td>
<td>720 80 — — — — — — — — — — — —</td>
<td>1.30</td>
<td>0.18</td>
<td>9.6 166</td>
<td></td>
</tr>
<tr>
<td>[117]</td>
<td>775 — — 610.2 — — 610.2 — — — — — — —</td>
<td>1.28</td>
<td>0.18</td>
<td>22 144.8</td>
<td></td>
</tr>
<tr>
<td>[118]</td>
<td>700 — — 682.4 904.6 — — — — 105 — — —</td>
<td>0.97</td>
<td>0.18</td>
<td>17.5 140</td>
<td></td>
</tr>
</tbody>
</table>

Properties of UHPC and CC with CBA and nanoadditives: A review
between 2.36 and 4.75 mm. Most of the aggregates used in UHPC have 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 for UHPC was well graded to ensure optimal packing and resulting in a denser microstructure.

4 Physical and chemical properties of CBA

In this section, the physical and chemical properties of CBA are discussed. Comparisons are also made with reference to the technical guidelines of concrete aggregate to demonstrate the material's suitability for use as a concrete constituent.

4.1 Physical properties of CBA

FA and CBA are the two types of coal ash gathered in the furnace. The coarser and denser ash that settles to the bottom of the furnace is referred to as CBA [119]. Given the global scale of CBA production, it is recommended that CBA be reused as a secondary building material ingredient to significantly reduce the use of scarce natural aggregates and the accumulation of waste in landfills [96]. CBA might have different physical characteristics depending on when and where it was collected, even from the same source [65,120]. Moreover, the particle size distribution of CBA varies with the different combustion technology, combustible sources, and the rate of combustion, which in turn affects the overall performance of CBA [63]. Furthermore, the combustion temperature and the level of pulverisation have a significant influence on its physical properties, particularly the size distributions of CBA [121–123].

CBA concrete's huge potential in the building industry can be attributed to the high demand for aggregate materials in this market [124]. CBA can be used as a fine aggregate replacement in concrete due to its appearance and particle size distribution, comparable to river sand [70,96,125]. CBA particles are often angular, highly irregular in shape, and visibly porous, having a rough, gritty surface texture and interlocking properties [65,66,123]. Additionally, research shows that the most consistent growth of concrete strength and pore structure features occurs when CBA is employed as a fine aggregate in place of sand [126]. Constant hydration and refining pores with the C–S–H gel created by pozzolanic action increased the compressive strength in concrete containing CBA over an extended curing time [127]. Furthermore, it was determined that the concrete with a pozzolanic material had a higher resilience than the projected life when subjected to harsh exposure settings [4]. As a result, there is a need to incorporate novel pozzolanic elements into

![Figure 1: Particle size grading of the aggregate in UHPC from previous studies.](image-url)
concrete that are safer for the environment [4]. The use of CBA in concrete is largely responsible for lowering emissions of greenhouse gases from coal-fired thermal power plants and the production of solid waste [4].

Based on results from various researchers, the specific gravity \(G_s\) of CBA ranged from 1.11 to 3.05 g·cm\(^{-3}\). The different fineness modulus (FM) of CBA could explain the discrepancy in \(G_s\) values. Previous researchers’ results showed that CBA’s FM ranges from 1.15 to 5.63. On the other hand, river sand had a specific gravity of 2.60 and a FM of 1.97, [125]. Therefore, the reduced density in bottom ash concrete can be attributed to CBA’s lower specific gravity than river sand. In addition, CBA’s porous internal structure makes it lighter and more fragile than natural sand [91]. Therefore, when CBA is used to replace river sand to make concrete, the resulting mix will be lighter since a lighter material (CBA) has replaced the heavier particles (river sand). Besides, the decreasing concrete density was also because of the increased void space [125]. Previous studies also reported that the water absorption, \(\omega\), of CBA particles varies widely between 1.00 and 37.20% of total weight. 

Figure 2 summarises the physical parameters of CBA, including specific gravity, FM, and water absorption (\(\omega\)), as reported by various researchers.

### 4.2 Chemical properties of CBA

Silica, iron, and alumina form the bulk of CBA, with other chemical compounds and gradings added for convenience in concrete production [65,136]. According to BS EN 12620: 2013 requirements, the primary chemical composition intended for concrete application is the total sulphur (S) content of the aggregates, and filler aggregates must be less than 1% by mass [179]. As reported by various researchers, the chemical components of CBA are consolidated from the listed literature and summarised in Figure 3 as a whisker plot diagram. Based on the whisker plot, the main compositions of CBA are silicon dioxide (SiO\(_2\)), which weighed about 45–58%, aluminium oxide (Al\(_2\)O\(_3\)) at 18–26%, and iron(II) oxide (Fe\(_2\)O\(_3\)) at 6–11% of the total weight. Magnesium oxide (MgO) and sulphur trioxide (SO\(_3\)) are the minor components of CBA, which are less than 1 and 0.75%, respectively. Only 18 out of 58 sources of CBA reported a total content of oxide of sulphur (SO\(_3\)) higher than 1% from the overall mass, based on chemical composition data from several investigations illustrated in Figure 4. As a result, according to European Standards, most CBA from various studies is suitable for aggregate replacement in concrete. The highest content of SO\(_3\) was 8.76% [128]. Conversely, the lowest content of SO\(_3\) was less than 0.01% [164].

![Figure 3: Whisker diagram summarising the chemical properties of CBA from previous studies.](image-url)

Discolouration, poor air entrainment, segregation, and low compressive strength of the concrete were all prevalent impacts of more significant loss of ignition (LOI) of the pozzolanic material [92]. In CBA, higher LOI values indicate more carbon that was not burned [92]. Furthermore, as the unburned carbon formed in larger porous particles
would absorb water, the high LOI resulted in higher water demand for fresh concrete [92,146]. As a result, CBA with a high LOI is unqualified for use in construction materials like mortar and concrete [65]. In that case, ASTM C618-22 limits the LOI of Class F and C ash to be less than 6% [180]. However, only 13 of 64 sources from different researchers presented CBA with an LOI value greater than 6%, as displayed in Figure 5. The highest LOI value reported is 27.1% [120], while the lowest is less than 0.01% [159].

5 Properties of cementitious composites containing CBA as aggregate replacement material

In this section, the properties of UHPC and CC containing CBA as an aggregate replacement material are elucidated in terms of fresh properties, mechanical strength, fluid transport properties, length change behaviour, and microstructure morphology.
5.1 Workability

The physical properties of CBA particles are critical in determining the design concrete mix’s workability. The increased inter-particle friction caused by the CBA’s uneven form and rough surface reduces mortar fluidity and workability.

The workability test results from the slump test or flow table test of CC obtained from previous researchers are summarised in Figure 6. The results showed that when the content of CBA aggregates increases, fresh mortar’s workability will decrease regardless of their source and concrete categories. Therefore, more SP is needed to increase the workability when the slump flow is fixed as constant for increasing the CBA aggregate content.

The mix workability is affected by the physical properties of CBA, which are finer and have a porous texture than the river sand [81,96,154]. The use of CBA as aggregate improves the texture of the concrete by adding more irregular and fine-shaped porous particles to the mix, which are often highly rough surfaced [136]. However, due to the CBA’s irregular shape and constant water absorption, its workability deteriorates [4,120,183]. As a result, during the mixing process, the porous CBA particles absorbed more water internally than natural river sand particles [122,125], reducing the amount of free water available for particle lubrication [168]. The trend was confirmed by a consistent decrease in the free water content as the CBA sand content increased [139]. Furthermore, replacing river sand with CBA also increased the specific surface area of fine aggregate in concrete [53]. CBA particles’ rough surface texture and intricate shape also increased inter-particle friction [53,125,170]. The portion of cement paste used to coat the CBA particles reduced as the percentage of CBA incorporated increased, increasing the friction between the CBA particles [160]. It is worth noting that while the W/B ratio remained constant, the amount of SP continued to increase, achieving a constant slump range due to the presence of CBA particles, which have higher water absorption rates [19,77,130].

As a result, it can be concluded that the increased specific surface area, irregular particle shape, and surface texture of CBA particles cause a decrease in the workability of concrete containing CBA aggregate. Besides, partial internal absorption of the mixing water by the dry and porous CBA particles also led to the same observation. Consequently, when the W/B ratio is kept constant, more SP content is needed to improve the workability of fresh mortar in achieving the desired slump flow for both UHPC and CC.

5.2 Compressive strength

The previous findings on the compressive strength of CBA aggregate UHPC and CC have been summarised. Most of the results illustrated that the compressive strength of the CBA aggregate concrete decreases when the aggregate replacement level of CBA increases.
A related study reported that due to the CBA particles’ fragility and the greater pore volume constituted while they are utilised, the compressive strength drops as the CBA concentration increases, as shown in Figure 7 [187]. A reduction in the compressive strength of all CBA aggregate concrete is reported at all curing ages [188,189]. The decrease in the compressive strength is more significant when the content of CBA as an aggregate is at a higher rate [190]. This observation could be due to the mixes’ high initial free water content [65], which resulted in bleeding and poor interfacial bonding between the aggregates and the cement pastes [65,153,160]. In comparison to dense river sand particles, CBA particles have a higher water absorption tendency due to their porous nature. The attribute reduces concrete mix workability and hinders adequate compaction of concrete containing CBA aggregate, resulting in a lower strength value [77]. Furthermore, as water enters the CBA’s pores, the evacuation of air bubbles may induce voids between the cement paste and aggregate interfaces, resulting in a decreased bond strength [160]. The trend also showed that improved compressive strength over time is better for using CBA at a lower level of aggregate replacement. Numerous previous studies also reported similar results on the subject matter [172]. However, the compressive strength of CBA concrete increased more substantially compared to the control concrete without CBA on extended curing duration beyond 28 days [126]. The early-compressive strength was negatively affected as the amount of sand substituted by CBA increased [152]. CBA concrete mixtures’ compressive strength may have been influenced by the emergence of an inadequate C–S–H gel and a more significant percentage of voids at an incipient
curing age [136]. The delay in hydration and stalled pozzolanic activity of CBA during the early curing period caused the concrete strength to be reduced when CBA is used as an aggregate replacement [119,121]. Additionally, while the water binder ratio is fixed, the free water trapped in the pores of CBA aggregate concrete affects the hydration process due to water deficiency in the binder phase. Therefore, it causes the binder to perform poorly due to the incomplete hydration of cement [132]. Due to the porous characteristics of CBA aggregates, moisture transfers from the aggregate to the cement paste via porous networks and stimulates hydration reaction at a later age [132].

A different finding reported that the compressive strength of specimens increases when more CBA is incorporated as a sand replacement, as shown in Figure 8 [126]. A similar trend was also reported by other researchers [4,123]. The observation was reported due to the pore refinement effect of the CBA pozzolanic reaction with the surrounding binder phase [6,163]. It might also be due to the more significant development of C–S–H resulting from the higher silica content of CBA that aid in strength development [14]. However, the situation is limited to using CBA aggregate below 30% [183]; beyond that aggregate replacement level, the strength deteriorates because the increase in the porosity of concrete became more dominant over the effect of pore refinement, as aforementioned. Similar strength behaviour was displayed for 7- and 28-day periods.

On extended curing duration, the compressive strength of CBA concrete mixes increases correspondingly. The compressive strength of CBA aggregate concrete mixtures improved faster than the control concrete mixture as time progressed [158,161,164]. Beyond 28 days of the curing period, CBA’s pozzolanic effect may have consumed the portlandite in the concrete mixtures to yield additional C–S–H gel, thus improving the gain in the compressive strength [119,136,158]. The improved compressive strength of CBA aggregate concrete mixtures was also aided by the decreased free water binder ratio caused by the absorption of some water by porous CBA particles [125]. As the curing time progresses, the reactive silica in the CBA reacts with the alkali calcium hydroxide produced by cement hydration to form calcium silicate and aluminite hydrates [53]. As a result, the ITZ’s pores are filled and compressive strength increases [125]. Due to the generation of extra C–S–H gel by the consumption of portlandite by the secondary hydration of CBA, the compressive strength was increased [54,122,136]. The cumulative effect of all these parameters is the reason for CBA aggregate concrete mixtures having analogous compressive strength to the control concrete mixture with only natural aggregates.

In conclusion, when CBA is used as aggregate replacement above the optimal content, the compressive strength of CBA aggregate concrete deteriorates. The behaviour of the compressive strength development of CBA aggregate concrete with curing time is almost identical to that of control concrete. There was a significant drop in the compressive strength at an early curing age when compared to control concrete. However, CBA aggregate concrete mixtures’ compressive strength increased substantially as the curing period progressed. Therefore, it can be stated with considerable assurance that the pozzolanic activity of CBA was responsible for the significant increase in the compressive strength of CBA aggregate concrete mixtures over time.

5.3 Flexural strength

Modulus of fracture, or the ability to resist bending forces, is another term for flexural strength [122]. The flexural strength test findings of CBA aggregate UHPC and CC by previous researchers are summarised. General trends showed that the flexural strength of the CBA aggregate concrete decreased while more CBA was utilised as aggregate.

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**Figure 7:** Reduction in the compressive strength of CBA CC with increasing CBA content [187].

**Figure 8:** Improvement in the compressive strength of CBA CC with increasing CBA content [126].
replacement. However, on a positive note, the flexural strength of CBA aggregate concrete improves with extended curing age.

It is shown in Figure 9 that replacing the natural aggregate with 30% of CBA in CC without fibre reinforcement improved the strength [191]. In addition, the pozzolanic attribute of CBA particles helps to consume portlandite by generating additional secondary C–S–H gel at the paste aggregate interfacial transition zone (ITZ) due to the particles’ secondary hydration [119,136,158].

The results from Abbas et al. [54] show that the porous properties of CBA have diminished flexural strength value as the aggregate replacement levels have increased over 30%, as shown in Figure 10. A similar trend was also reported by numerous studies [19,122]. This trend is due to the presence of numerous pores in CBA particles, which weaken the strength of the resultant concrete [136]. Furthermore, because the flexure strength depends on aggregate performance, the nature of CBA aggregate, which is relatively soft, porous, and brittle, produces concretes with a poorer elasticity, allowing cracks to propagate through it quickly [71,141]. In addition, the CBA’s high porosity increased in the ITZ, which hindered the full hydration of cement particles, increasing the likelihood of micro-crack propagation and interface fracture under stress and lowering the flexural strength [71,160]. It was reported that concrete using CBA as a sand replacement loses some of its flexural strength at an early age because of an increase in the number and volume of all pores and an expansion of the ITZ [14,65].

Additionally, the flexural strength of CBA aggregate concrete increased with age [53]. The deterioration in the flexural strength of CBA aggregate concrete at earlier ages could be due to a delay in hydration and delayed pozzolanic activity of CBA during the early curing period [53,172]. The uniform dispersion of the C–S–H gel and the presence of secondary C–S–H gel due to the consumption of portlandite by secondary hydration of CBA resulted in greater flexural strength of CBA aggregate concrete mixtures. It is especially apparent for mixes with a high proportion of CBA as a fine aggregate over 91 days and beyond.

Previous findings on the load deflection test of CBA aggregate CC are presented in Table 2. The results illustrate that the deflection of CBA aggregate concrete increases when the aggregate replacement level of CBA increases. In the present literature, there has not been enough research on the bending deflection of concrete made with CBA as an aggregate replacement for UHPC. For CC, it has been shown that structural beams integrating with 100% CBA aggregate have better load–deflection behaviour [124]. The beam with concrete containing higher CBA aggregate content can withstand a higher imposed load. The deflection improvement is proportional to the beam’s strength capacity. Due to the high CBA concrete beam stiffness, the deflection capacity has increased. Increased CBA quantity led to a stronger pozzolanic reaction of CBA with calcium hydroxide, resulting in the formation of additional C–S–H gel in the paste aggregate interface. These C–S–H gel fill the gaps between cement paste components and aggregates in the ITZ and improve its strength [108,158].

![Figure 9: Improvement in the flexural strength of CBA CC with increasing CBA content [191].](image)

![Figure 10: Reduction in the flexural strength of CBA CC with increasing CBA content [54].](image)

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Replacement ratio (%)</th>
<th>Load–deflection of CBA aggregate concrete</th>
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<tr>
<td></td>
<td></td>
<td>Max deflection (mm)</td>
</tr>
<tr>
<td>CC</td>
<td>0</td>
<td>17.654</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>18.760</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>18.871</td>
</tr>
</tbody>
</table>
To summarise, a small sample of findings showed that an increase in the CBA content as aggregate replacement in the concrete mix at a low level might increase the flexural strength of concrete containing the CBA aggregate. However, most research findings showed that increasing the CBA content beyond 60% as an aggregate would decrease flexural strength. However, the flexural strength of CBA aggregate concrete mixes increased faster than control concrete as the curing time increased.

5.4 CBA concrete quality

Previous research on the UPV of CBA aggregate CC is summarised in Figure 11. When using a higher percentage of CBA as aggregate, all the data showed that the UPV results of the resultant CBA concrete decreased. However, no existing study reporting the UPV results of UHPC incorporates CBA as an aggregate replacement.

The UPV technique is based on the propagation of a high-frequency sound wave through the specimen. It is used to test the consistency and quality of concrete [65]. The UPV test is a non-destructive method of identifying defects, including void space, honeycombing, and other fractures in a material’s continuity [173]. Ultrasonic wave velocity is proportional to the concrete’s density [65]. The concrete with CBA as a sand replacement results in a linear decrease in the UPV value, as reported by previous findings [53,65,171]. In addition, the porosity of concrete and the time required for a high-frequency sound wave to penetrate the concrete at an early stage increased with the CBA content as a sand replacement [65,143]. Therefore, using CBA as a sand replacement causes a reduction in the UPV values through the concrete. However, at a later age, the concrete micro-structure becomes dense due to the filling of pores with more C–S–H gel generated by the pozzolanic action of CBA with the surrounding paste, and the UPV value increases correspondingly [53,65]. Positive results for density, homogeneity, and uniformity in the bottom ash concrete mixtures tested herein were indicated by the study’s higher values for UPV [119]. Based on the standard BS 1881: Part 203 (Table 3), most of the concrete made with CBA as sand replacement at an optimal level (up to 40%) can achieved an UPV value of higher than 3,500 m·s\(^{-1}\), which put the concrete quality at a good grading [192].

Therefore, previous studies came to a similar conclusion that the UPV value of the concrete made with CBA

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**Figure 11:** Ultrasonic pulse velocity (UPV) of CBA aggregate CC from previous studies in (a) ref. [187], (b) ref. [119], (c) ref. [143], and (d) ref. [173].
aggregate decreased when CBA substituted the natural aggregate. Compared to the control concrete, the UPV value dropped dramatically, especially at the early ages of the concrete. However, the UPV value of concrete mixtures, including the CBA aggregate, increased over extended curing duration due to the pozzolanic activity of CBA.

5.5 Water absorption

Previous findings on water absorption of CBA aggregate CC are summarised in Figures 12 and 14. Generally, the water absorption level is more significant when the replacement level of CBA aggregate increases. Therefore, compared to control mix concrete, CBA aggregate concrete with higher CBA contents had a relatively higher water absorption over a prolonged curing duration. However, no published research has yet reported the water absorption results of UHPC that uses CBA as aggregate replacement.

Concrete absorbs more water when the CBA content increases, an example is shown in Figure 12. With increasing percentages of natural sand substitution by CBA in concrete, the permeable pore space and water absorption in concrete increased [120,125]. When more CBA is added to the concrete, the quantity of water absorbed by the concrete increases gradually. It was because more empty pores are present in the concrete after the evaporation of free water, which tends to absorb more water [81,92,143]. A larger water/solid ratio produces a weaker and unconfined matrix, leading to an enhanced capillary porosity, responsible for the increased water absorption of CBA mixtures [166]. A different finding was reported by Bheel et al. [4]: the water absorption rate of specimens reduced with an increase in the CBA content. The trend persisted when CBA was used as an aggregate replacement of up to 40%, as displayed in Figure 13. Other researchers also reported similar outcomes when the replacement is up to 20% [92,163]. The pore refinement of CBA likely contributed to the concrete’s lower water absorption rate compared to control specimens. Furthermore, fine CBA particles also behaved as a filler for pores in the concrete, reducing the overall porosity and capillary pore and producing a denser microstructure [4]. Beyond the optimum replacement rate, water absorption starts to increase, which might be due to the porous structure of the concrete attributed to the presence of a large quantity of CBA in the concrete.

Table 3: Evaluation of UPV test results based on BS 1881: part 203 [192]

<table>
<thead>
<tr>
<th>Pulse velocity (m·s⁻¹)</th>
<th>Concrete quality (grading)</th>
</tr>
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<tbody>
<tr>
<td>≥4,500</td>
<td>Excellent</td>
</tr>
<tr>
<td>3,500–4,500</td>
<td>Good</td>
</tr>
<tr>
<td>3,000–3,500</td>
<td>Questionable</td>
</tr>
<tr>
<td>2,000–3,000</td>
<td>Poor</td>
</tr>
<tr>
<td>≤2,000</td>
<td>Very poor</td>
</tr>
</tbody>
</table>

Figure 12: Increase in water absorption of CBA aggregate CC from previous studies with increasing CBA content in (a) ref. [193] and (b) ref. [125].

Figure 13: Reduction in the water absorption of CBA aggregate CC from previous studies with increasing CBA content [4].
With the extended curing duration, the permeable pore spaces of CBA aggregate concrete mixtures were reduced correspondingly \[119,125,158\]. The decrease in the permeable pore space was due to the pozzolanic activity of CBA, which reduced the amount of water absorbed by the concrete \[125\]. In addition, the synthesis of ettringites and the uniform distribution of the C–S–H gel reduced voids, resulting in lower water absorption \[92,119\]. The emergence of aluminate hydration products due to a chemical reaction between cement and fine CBA aggregate particles can also be accounted for lowered water absorption \[143\].

In conclusion, the water absorption of CBA aggregate concrete increases with a higher aggregate replacement ratio with CBA. Different findings might also occur where the water absorption is reduced when more CBA is used to replace the natural aggregate. This observation could be caused by different physical properties, such as the water absorption level of the CBA from different sources \[65,120\]. The different particle grading distributions of CBA particles might also have different effects towards the performance of concrete made. Generally, with the curing period progression, the permeability of concrete will be reduced due to an internal pozzolanic reaction which reduces the available voids.

### 5.6 Pore space and permeability

The findings on the permeability properties of CBA aggregate CC based on two different testing methods are compared in Figure 14. The tests were nitrogen gas permeability and the percentage of pore spaces in the concrete. In the case of nitrogen gas, when more gas is allowed to pass through the specimens, the concrete is more porous and permeable. Similarly, a higher percentage of pore spaces in specimens indicates a more porous concrete.

According to the gas permeability test results, the apparent permeability of mortar increased as the level of sand replacement by CBA in the mortar increased \[143\]. However, with time progression, the results showed that the concrete became less permeable to nitrogen gas. The development of the pozzolanic reaction in these mixes, which reduces the permeable pore space, can explain this decrease. In addition, the reactive silica in the CBA combines with the alkali calcium hydroxide produced by cement hydration to form calcium silicate and aluminate hydrates as the curing time increases. Therefore, the voids in the matrix are filled, and the porosity and transfer characteristics of the matrix are improved \[143\].

In terms of total porosity, the degree of the voids increased with a higher level of sand replacement by CBA \[188,194\].

![Figure 14: Porosity coefficient of CBA aggregate CC from previous studies: (a) ref. \[143\], (b) ref. \[125\], (c) ref. \[170\], and (d) ref. \[195\].](image-url)
The porous structure of CBA was largely responsible for this phenomenon [54]. As free water evaporates from mortar, it leaves voids in the cement matrix, which could also be responsible for this phenomenon [143]. With time, the permeable pore space of CBA aggregate concrete mixtures shrank. The trend was more significantly observed in concrete mixes with higher CBA aggregate content. The sharp decrease of the permeable pore space is due to the pozzolanic activity of CBA at a later age, which formed additional C–S–H gel for pore refinement [125].

In conclusion, the pore space and permeability of CBA aggregate concrete increase with a higher aggregate replacement ratio with CBA. However, with the curing period progression, the permeability of concrete reduced due to an internal pozzolanic reaction which reduces the available voids.

### 5.7 Chloride diffusivity

A comprehensive finding on chloride diffusion properties of CBA aggregate UHPC and CC is presented in Figure 15. The chloride diffusion properties of UHPC using CBA as an aggregate replacement have not yet been mentioned in the literature. When more chloride ion charges pass through the specimens, the concrete is more porous and permeable, which indicates a higher degree of pore spaces in specimens resulting in more porous concrete.

The chloride diffusivity of mortar also increases with higher CBA content as an aggregate [49,92,194]. Compared to ordinary river sand, the increased pore volume of the CBA aggregate decreased the resistance of concrete to chloride-ion diffusion with an increased CBA aggregate content [142]. The substantially higher porosity of these mixes is related to the abrupt increase in chloride ion diffusivity at greater substitution levels of aggregate with CBA. The defects mentioned above and inconsistencies provide an easy conduit for chloride ions to diffuse into the concrete [49]. However, it is noticeable that CBA’s pozzolanic activity has improved chloride ion resistance on prolonged curing duration [130,135]. Another possible explanation for the reduced charge transmitted was a decrease in the alkalinity of the pores [130]. In addition, the Coulomb charge decreased over time, indicating that the microstructure of the CBA concrete became denser with an extended curing duration [138]. The pozzolanic activity and chloride

![Figure 15: Chloride diffusivity of CBA aggregate CC from previous studies: (a) ref. [130], (b) ref. [196], (c) ref. [49], and (d) ref. [188].](image-url)
binding capacity of CBA contributed to the decrease in chloride content by impeding the diffusion of chloride ions on extended curing duration [92,194].

With a higher natural aggregate replacement ratio with CBA, concrete is less resistant to chloride diffusivity due to increased porosity. However, on extended curing duration, the resistance of concrete towards chloride ions increased because of an internal pozzolanic reaction that reduced the degree of permeable voids.

5.8 Drying shrinkage

The literature on the drying shrinkage of CBA aggregate UHPC and CC is summarised. Changes in the concrete volume are due to water movement in or out of a concrete mass. In principle, concrete swells due to moisture ingress and shrinks when the moisture is lost due to drying. Drying shrinkage occurs in hardened concrete when exposed to air that is not fully humid.

The findings showed that when the content of CBA as an aggregate replacement in CC increases, the drying shrinkage of concrete increases, as shown in Figure 16 [92,120,134]. This development stems from the substitution of weaker and porous CBA for the normal fine aggregate, which provides less resistance to shrinkage between the cement paste and aggregates [157]. In addition, because of the pozzolanic reaction induced by CBA, sufficient C–S–H gel was formed to conceal the pores of the CBA mix mortars, which could be the reason for the increased shrinkage value with increasing CBA content in the mixtures [134]. Besides, it would also cause the mortar’s microscopic structures to become more compact [134]. Thus, additional C–S–H is created, filling the gaps in the CBA mix mortars and displacing the moisture during drying [134].

Previous studies have shown different findings that when CBA is used to replace natural sand in CC, it results in a material with greater dimensional stability than the control mix, as shown in Figure 17. Generally, the degree of drying shrinkage was reduced when CBA was used as an aggregate replacement material [134]. It is theorised that the CBA’s porous particles operate as water reservoirs, slowly releasing moisture during the concrete’s drying phase to aid in lowering the magnitude of drying shrinkage [65,92,136]. Similarly, drying shrinkage in CBA-based concrete mixes was lower than in control mixes when both were designed for the same slump ranges [92].

When more CBA is used as a natural aggregate replacement in concrete, the drying shrinkage reduces. Since the saturated or partially saturated pores of CBA particles would slowly release moisture while the concrete is subjected to a drying environment, the final values for drying shrinkage would be less than those of the control concrete without CBA aggregate.

Figure 16: Increase in drying shrinkage of CBA aggregate CC with increasing CBA content [134].

Figure 17: Reduction in drying shrinkage of CBA aggregate CC from previous studies with increasing CBA content in (a) ref. [136] and (b) ref. [139].
5.9 Microstructure

In general, when the content of CBA as an aggregate is at a low level (below 40%), the strength of mortar will increase due to the interlocking properties of the CBA irregular particles that have a stronger binding force between the aggregate and the binder paste. However, further increase of the CBA as an aggregate replacement will increase the pores within the microstructure, which leads to a decrease in strength.

Figure 18 shows gel products that densify the interface between the CBA aggregate and the cement paste due to a pozzolanic reaction [152]. The observation was further supported by findings in Figure 19, where the irregular-shaped CBA particles have stronger interlocking interaction with the cement mortar, and the ITZ is densified with the C–S–H gel produced [141]. Therefore, the mechanical strengths of specimens should improve when CBA is utilised as an aggregate replacement at a low content.

However, it was discovered that when the CBA content in the mortar increased (above 40%), its strength decreased [60]. Figure 20 shows scanning electron micrographs (SEMs) of concrete mixtures with 0, 50 and 100% CBA as a sand replacement.

Figure 18: Microscopic image of the interface between the CBA aggregate and cement paste on 200× magnification: The interface between (a) CBA aggregate and (b) cement paste is densified by (c) gel products due to the pozzolanic reaction [152].

Figure 19: Cross section of the hardened concrete with CBA [141].

Figure 20: SEM image of concrete mixtures with (a) 0 CBA (b) 50 CBA, and (c) 100% CBA at 28 days of curing period [119].
replacement, indicating an increase in the number and size of pores on using CBA at high content (50–100%) in concrete [119]. For CBA concrete mixtures with 50 and 100% CBA as in Figure 20(b) and (c), the C–S–H gel is not as uniform and dense as in the control concrete mixture without CBA content, as illustrated in Figure 20(a) [119]. Therefore, the strength of CBA concrete mixtures may have been impacted by creating an indistinct C–S–H gel and a greater number of empty spaces within the mixture [119]. Figure 21 displays SEM images of mortar with 0, 40, and 100% of CBA as a sand replacement [60]. The results in Figure 21(b) and (e) show that the mortar with 40% CBA was denser than the control mortars without CBA, as shown in Figure 21(a) and (d) [60]. The decrease in the pore size is believed to be caused by the pozzolanic reaction of CBA, which fill some of the pores over time [60]. In samples containing a high volume of CBA fine aggregate, the porous structure of the material is prominent [60]. As seen in Figure 21(c) and (f), the size of the pores of the matrix became relatively larger, which is due to the presence of pores within the CBA particles and the air pocket trapped between the irregularly shaped particles and the cement paste [60]. Since the number of pores significantly increased with the presence of CBA, this study corroborates the previously reported findings from the investigation into the impacts of bottom ash on permeability and mechanical strength when used at high content, i.e. above 60%.

In conclusion, replacing the natural aggregate with CBA at a controlled optimal level (20–60%) will tend to increase the performance of the specimens due to the better-interlocking properties of the CBA particles. Besides, the pozzolanic reaction of CBA aggregate with the calcium hydroxide of the surrounding cement paste also aided in densifying the ITZ. However, a further increase in the replacement level beyond the optimal level (40%) will no longer benefit the specimens’ performance. The excessive CBA content may yield more permeable void spaces, weakening the ITZ and causing deterioration of strengths and durability.

6 Nano-C–S–H and its application as an additive in cementitious composites

The main hydration product generated during the interactions between Portland cement and water is C–S–H, which is primarily accountable for the binding ability of cement-based products. Nano-C–S–H, a stable suspension of synthetically manufactured C–S–H nanoparticles, was granted a patent in 2009 [197]. Since nano-C–S–H has low interfacial energy, it can serve as a nucleation site and physically speed up calcium silicate hydration when added to cement-based materials, a phenomenon known as the filler effect [90]. It promotes the formation of hydrated phases, speeding up the hydration of the cement at an early stage [83]. Nano-C–S–H in concrete mixtures as a hydration accelerator aid in the subsequent crystallisation of C–S–H adjacent particles. The presence of nano-C–S–H shifts the gel nucleation centres and growth away from the hydrating clinker particles. It enables secondary nucleation in the capillary pores of the paste and a more uniform dispersion of C–S–H yielded from the primary hydration of cement throughout the paste [90]. When this happens, the final binder’s mechanical strength attributes improve and its permeability decreases since the porosities have been reduced [90]. Therefore, the addition of nano-C–S–H speeds up the formation of the C–S–H network of the binder phase [89]. Furthermore, including nano-C–S–H allowed primary C–S–H to develop more uniformly in the cementitious matrix. When nano-C–S–H was incorporated into concrete mixtures in previous studies [88,89], as shown in Table 4, it revealed that they contributed to expediting cement hydration and improved the heat of hydration, shortening the setting time and boosting the strength and durability of concrete. However, existing studies of nano-C–S–H application are only limited to CC. Their influence towards UHPC concrete is yet to be further investigated.

Zhao and Khoshnazar [83] found that the compressive strength of the specimens with nano-C–S–H added demonstrated a vast increase compared to those without, especially at early curing ages. Furthermore, when nano-C–S–H was adopted, backscattered electron (BSE) micrographs revealed a greater hydration reaction degree of cement clinker. In addition, the enhancement in pore space-filling was more prominent, leading to a more homogeneous and denser microstructure in all C–S–H seeding additive specimens at every curing period. Because these engineering properties are directly related to the pore structure of cement-based materials, the alteration can be crucial for improving the mechanical performance and durability.

According to Alzaza et al. [84], the nano-C–S–H concentration of 2% to binder weight is the best dosage, considering that increasing the nano-C–S–H amount to 5% did not result in any additional strength gains independent of the curing period. Furthermore, the nano-C–S–H also enhanced the reaction rate of the binders, according to the heat of hydration measurements. Adding nano-C–S–H thus improves the amount of precipitated C–S–H and ettringite in the binder.

The findings from Zhou et al. [89] also revealed that when the nano-C–S–H level was adjusted from 0.5 to 1%,
the compressive strength increased. However, the compressive strength decreased from the optimum level when the nano-C–S–H dose increased from 1 to 1.5%. Besides, incorporating nano-C–S–H into concrete mixtures can reduce the time it takes for them to set, with the effect being more substantial on the initial setting time than the

Figure 21: SEM analysis of CBA/sand matrices based on (a and d) 0% CBA replacement, (b and e) 40% CBA replacement, and (c and f) 100% CBA replacement [60].
final setting time. Therefore, the above findings imply that adding nano-C–S–H to concrete can be a realistic strategy for increasing the hardening rate and strength gain as curing ages progress.

A similar positive impact on the application of nano-C–S–H was also explored and reported by Kanchanason and Plank [87]. The compressive strength of mortars was improved at all curing periods. It was discovered that the nano-C–S–H functions as a seeding material, initiating sooner and stronger C–S–H crystallisation from the clinker’s silicates. The C–S–H expedited cement hydration, resulting in significantly improved early strength development of mortar.

A study by Li et al. [88] also demonstrated similar benefits of incorporating nano-C–S–H in cement-based mortar. The compressive strength increased drastically when the C–S–H dosage was increased from 0.5 to 2%. The flexural strength developed in the same way as the compressive strength. The use of nano-C–S–H is advantageous to the densification of specimen microstructures. It fosters more formation of C–S–H gels, promoting the improvement of strength properties, notably at an early age. It was because the mechanical properties of cement are pertinent to the hydration of the cementing phase and microstructure development. In addition, adding nano-C–S–H from 0.5 to 2% reduces the time it takes for the cement paste to set. This observation was due to the nano-C–S–H’s ability to speed up hydration and, as a result, shorten setting times.

The findings from Morales-Cantero et al. [90] also exhibited beneficial results when nano-C–S–H was added to the cement-based mortar. The mechanical strengths were maintained or increased when 2% nano-C–S–H was added to the mortar mixes. In addition, shorter induction times, steeper slopes in the acceleration period, and higher

<table>
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<th>References</th>
<th>Nano-C–S–H content (%)</th>
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<th>Flexural strength (MPa)</th>
<th>Degree of hydration (%)</th>
<th>Setting time (min)</th>
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heat flow values at the first hydration peak may all be traced back to the increased hydration rate of cement made possible by the used admixtures.

In conclusion, using artificial nano-C–S–H or gel in cementitious-based concrete will help enhance the hydration processes and densification of the binder phase. Thus, it promotes an even distribution of the C–S–H gel and improves the concrete mix’s mechanical properties and durability. However, the optimal dosage of nano-C–S–H to be added to the concrete mixture depends on the solid concentration and their types since there are an increasing variety of similar products recently found in the market. Therefore, further experiments and findings are recommended to propose the optimal dosage for any given concrete mix design.

7 Knowledge gap analysis
1) A scarce amount of work has been reported on using CBA as a sand replacement in the formulation of UHPC.
2) Due to lack of evidence, the influence of adding nano-C–S–H to a UHPC using CBA as a sand substitute on mechanical and durability properties is not well comprehended.
3) The mechanical strength development and fluid transport properties of UHPC containing CBA aggregate are not well defined in the present literature on the subject matter.
4) Reports of durability properties, especially on bending deflection, UPV, water absorption, and chloride diffusivity on CBA aggregate UHPC, are limited.
5) Evidence on the microstructure of UHPC incorporated with CBA as an aggregate replacement and nano-C–S–H are not well defined in the prior literature.

8 Critical summary of the literature
1) UHPC is usually produced by blending Portland cement, supplemental cementing ingredients, fine aggregate, SP, a relatively low amount of water with fibre reinforcement, or nanoparticles to improve the performance further, achieving a 28-day compressive strength of at least 100 MPa.
2) CBA resembles river sand in appearance and particle size distribution, making it an ideal candidate for use as a fine aggregate replacement in concrete. According to studies, the most consistent development of concrete strength and pore structure features arises when CBA is employed as a fine aggregate in partial substitution of natural sand. Since the source of high-quality natural sand is depleting, while at the same time, production of CBA is increasing due to an increase in coal power plants, CBA is suitable to be used as an aggregate replacement in conventional and UHPC concrete.
3) The chemical composition of CBA meets the requirement of standards to produce concrete with similar or better performance when being used as a sand replacement. Therefore, it is suitable for sustainable concrete production, ensuring concrete with exceptional properties such as UHPC can be produced in a more environmentally friendly manner.
4) CBA aggregate conventional and UHPC concrete’s workability decreases when CBA aggregate’s content is increased. It was due to increased specific surface area, complicated shape and texture of CBA particles, and internal absorption of part of the mixing water by the dry and porous particles. Therefore, more SP is required to promote workability when more CBA is employed as a concrete aggregate and the slump value is fixed.
5) An increase in the CBA content as a natural aggregate replacement in the conventional and UHPC concrete mix may cause a decrease in the flexural strength, compressive strength, and UPV values at an early stage due to a delay in the hydration and pozzolanic action between the binder and the CBA aggregate to form a dense microstructure and superior ITZ. However, the flexural and compressive strength of the CBA aggregate conventional and UHPC concrete mixes will increase faster than the control concrete as the curing period increases. When the specimens’ stiffness increases, the deflection capacity will also increase.
6) Water absorption, total porosity, and chloride diffusivity increased as the replacement ratio of river sand to CBA in CC was increased due to more permeable voids. As the curing age progressed, permeable voids filled with C–S–H gel were generated by the pozzolanic action of CBA and cement, which aid in reducing fluid transport abilities. However, there is a lack of evidence on using CBA as aggregate replacement in UHPC towards water absorption, total porosity, and chloride diffusivity.
7) The drying shrinkage of conventional and UHPC concrete is reduced when more CBA is used as an aggregate replacement leading to improved dimension stability. It was due to the porous CBA particles which retained part of the mixing water and gradually released it into the hardened concrete when it was exposed to drying.
8) Due to the greater interlocking ability of CBA particles and their improved pozzolanic response, which helps to
densify the ITZ, replacing natural aggregate with CBA at a controlled level tends to boost the specimen performance. However, if the replacement rate is higher than optimal (60%), more void areas are generated, lowering the ITZ’s strength and durability.  

9) Adding nano-C–S–H into CC can be a viable technique for speeding up the hardening and hydration of the concrete and promoting improvement in mechanical strength and durability growth. However, the effect of nano-C–S–H on UHPC concrete has not been well studied.

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References


