CHARACTERISTICS OF BINARY BLENDED MORTAR AND CONCRETE WITH COAL BOTTOM ASH AGGREGATE AND PRECIPITATED CALCIUM CARBONATE ADDITIVE

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LIST OF ABBREVIATIONS

Al_2O_3	Alumina
$CaCO_3$	Limestone
CaO	Lime
CBA	Coal bottom ash
CFA	Coal fly ash
C-S-H	Calcium silicate hydrates
CO_2	Carbon dioxide
FeO_3	Iron oxide
GGBS	Ground granulated blast furnace slag
ITZ	Interfacial transition zone
K_2O	Potassium oxide
LOI	Loss on ignition
MgO	Magnesium oxide
$MgSO_4$	Magnesium sulfate
MnO	Manganese (II) oxide
Na_2O	Sodium oxide
NRS	Natural river sand
OPC	Ordinary portland cement
PCC	Precipitated calcium carbonate
RCA	Recycled concrete aggregate
SEM	Scanning electron microscopy
SiO_2	Silicon dioxide
SF	Silica fume
SO_3	Sulfur trioxide
SP	Superplasticizer
SSD	Saturated surface dry
TiO_2	Titanium dioxide
UPV	Ultrasonic pulse velocity
W/B	Water to binder ratio
XRF	X-ray fluorescence
XRD	X-ray diffraction

CIRI-CIRI CAMPURAN BINARI MORTAR DAN KONKRIT MENGANDUNGI ABU BAWAH ARANG BATU AGREGAT DAN MENDAKAN KALSIUM KARBONAT SEBAGAI BAHAN TAMBAHAN

ABSTRAK

Terdapat kajian yang bercanggah mengenai penggunaan abu bawah arang batu (CBA) sebagai penggantian agregat halus, yang dianggap disebabkan oleh perbezaan dalam penggredan CBA mentah. Matlatmat kajian ini adalah untuk memperhalusi penggredan CBA bagi mendapatkan penggredan CBA yang paling optimum, yang boleh digunakan sebagai bahan pengganti agregat halus dalam campuran binary mortar dan konkrit yang mengandungi OPC dan GGBS. Tambahan pula, pengaruh mendakan kasium karbonat (PCC) yang digunakan sebagai bahan tambahan dalam mortar/konkrit campuran binary yang mengandungi CBA sebagai penggatian agregat halus telah dikaji. Tiga penggredan CBA yang berbeza digunakan, iaitu diayak melalui 10mm, diayak melalui 4.75mm, dan penggredan tersintesis CBA. Penggredan tersintesis CBA dicapai dengan mengasingkan CBA dalam saiz ayak yang berbeza dan kemudiannya digabungkan menjadi CBA penggredan tersintesis yang konsisten. PCC yang digunakan adalah dalam bentuk ampaian dengan menambahkan air dan superplasticizer(SP) untuk membolehkan kebolehaliran yang lebih baik apabila dicampur dengan mortar dan konkrit. Menurut penemuan, agregat CBA penggredan tersintesis adalah penggredan CBA terbaik kerana ia menghasilkan kekuatan mekanikal dan sifat pengangkutan bendalir yang optimum. Selain itu, kandaungan aggregate CBA sehingga 60% menunjukkan prestasi yang lebih baik berbanding campuran-campuran binary kawalan. Apabila membandingkan antara kandungan CBA yang berbeza dalam campuran binari, 40% kandungan CBA dalam campuran binary menunjukkan prestasi optimum dari segi kekuatan mekanikal dan sifat pengangkutan bendalir. Di samping itu, penggunaan PCC sehingga 4% dalam campuran-campuran binari yang mengandungi agregat CBA menunjukkan prestasi yang lebih baik dari segi kekuatan mekanikal dan prestasi pengangkutan bendalir berbanding dengan campuran tanpa menggunakan PCC sebagai bahan tambahan. Penggunaan agregat CBA yang sudah digredkan meningkatkan struktur mikro konkrit disebabkan oleh zarah bentuk yang tidak sekata, yang saling mengunci lebih baik dengan OPC dan GGBS berbanding pasir sungai semula jadi. Penggunaan PCC sebagai bahan tambahan mampu mempercepatkan proses penghidratan konkrit campuran binary dan bertindak sebagai pengisi untuk mengurangkan liang di dalam campuran-campuran binary.

CHARACTERISTICS OF BINARY BLENDED MORTAR AND CONCRETE WITH COAL BOTTOM ASH AGGREGATE AND PRECIPITATED CALCIUM CARBONATE ADDITIVE

ABSTRACT

There have been conflicting studies on using coal bottom ash (CBA) as a fine aggregate replacement, which is due to differences in raw CBA grading. The goal of this study is to refine the grading of CBA to obtain the most optimum grading of CBA that can be use as fine aggregate replacement material in a binary blended mix containing OPC and GGBS. Furthermore, additional study on the influence of precipitated calcium carbonate (PCC) as an additive in binary blended mortar/concrete containing graded CBA as a fine aggregate replacement will be investigated. Three different grading of CBA were used, namely sieved through 10mm, sieved through 4.75mm, and synthesised grading CBA. The synthesised grading CBA was achieved by separating the CBA particles in different sieve size (4.75mm – 0.0075mm) and later combined into a consistent grading CBA. The PCC used were in suspension form by adding water and superplasticizer (SP) to allow a better flowability when mixing with mortar and concrete. According to the findings, synthesised grading CBA aggregate is the best grading because it yields the optimum mechanical strength and fluid transport performance. Moreover, the CBA aggregate content of up to 60% showed better performance compared to the control binary blended mix. When comparing the different CBA content in the mix, 40% of CBA content in the binary blended mix showed optimum performance in terms of mechanical strength and fluid transport properties. In addition, the use of PCC up to 4% in a binary blended mix containing graded CBA aggregate was able to perform better in terms of mechanical strength and fluid transport performance compared to mixes without the use of PCC as an additive. The use of graded CBA aggregate enhances the concrete’s microstructure due to the irregular shape particle, which interlocks better with the binder than natural river sand. The use of PCC as an additive accelerates the hydration process of the binary blended concrete and acted as a filler to reduce pores inside the binary blended mix.

CHAPTER 1

INTRODUCTION

1.1 Consumption of Ordinary Portland Cement in the construction industry

Development in the country has never stopped amidst of Covid-19 Pandemic. This statement has been proven by the increasing trend of cement production in Malaysia. During 2019, cement production increased 20% from 16.1 million Metric Tonnes in 2019 to 19.48 million Metric Tonnes in 2020. The increasing cement production also meant demand in the construction industry (J.Muller, 2021).

The production of cement naturally produces carbon dioxide (CO_2) as a by-product. This was due to the usage of clinker, one of the components needed to produce cement. When limestone ($CaCO_3$) was processed into lime (CaO) during combustion, CO_2 was the by-product. Moreover, the combustion of fossil fuels also contributed to the emission of CO_2 (Gibbs *et al.*, 2001).

Apart from cement production, the construction industry used up to 40% of global energy annually, contributing to a significant amount of Carbon dioxide (CO_2) emissions harmful to the environment. Since CO_2 was produced when there was any energy released during construction, various life cycles of the building phases, including production, construction, operational, and demolition, contribute to CO_2 emissions (Subrata, 2018). From the statistic shown by the Emission Data Base for Global Atmospheric Research (E.D.G.A.R), between the year 2000 to 2019, CO_2 emission in Malaysia increased dramatically from 132.6 Million Tonnes to 248.8 Million Tonnes (EDGAR, 2019).

To counter the problem of cement consumption, the use of cement replacement material in concrete had become the mainstream, which was called blended cement. Blended cement is the use of supplementary cementitious material (SCM) to produce concrete with similar or better performance compared to full cement concrete. Most common SCM in the market now is fly ash (FA), ground granulated blast furnace slag (GGBS), silica fume (SF) etc. The use of SCM as cement replacement were able to enhance the concrete's performance mainly due to the pozzolanic reaction between the binder and calcium hydroxide (CaOH) produced of the cement.

1.2 Coal thermal plant waste and uses of coal bottom ash in concrete

For ages, coal has been one of the cheapest sources to generate power for many countries, including Malaysia. The increase in electricity consumption in Malaysia, one of Southeast Asia's greatest economies, has increased the number of coal-fired power plants required to maintain the required energy output. Coal energy emits twice as much carbon emissions as natural gas, which causes twice the environmental damage(Ahmad and Zainol, 2020; Bartan *et al.*, 2017; Jamora *et al.*, 2020; Nguyen Thi *et al.*, 2019; Sebi, 2019). With the increased energy consumption in Malaysia, the coal-fired power plant's by-product will also increase correspondingly. Coal combustion produces two types of ash: coal fly ash (CFA) and coal bottom ash (CBA). CFA was already widely utilized in the construction sector to replace OPC without compromising its performance. It was due to CFA containing high silicon dioxide (SiO_2) and aluminum oxide (Al_2O_3) that promotes additional hydration products, enhancing the microstructure of the concrete. According to a recent study, CBA can provide value-added properties to the current construction industry, which will benefit both the economy and the environment(Zhou *et al.*, 2022). The majority of previous studies on CBA as aggregate replacement for their research showed weaker mechanical properties at an early age compared to the control mix(Hashemi *et al.*, 2018; Rafieizonooz *et al.*, 2016; Singh and Siddique, 2015). However, as curing ages increase, the strength of concrete containing CBA as aggregate showed similar results to control concrete with natural aggregate(Ahmad Maliki *et al.*, 2017; Singh and Siddique, 2016). The inclusion of CBA aggregates on the concrete mix reduced the early age strength due to greater porosity, water absorption, and permeability. The primary factor in the decrease in early strength was the uneven and angular shape of CBA aggregates. However, as curing age increases, CBA aggregate mix had less permeable pore space, which improved the microstructure and durability of the mix(Hamzah *et al.*, 2016; K Muthusamy *et al.*, 2018; Singh and Siddique, 2014; Wyrzykowski *et al.*, 2016). There are concerns regarding the toxicity of CBA aggregates that have been raised over the world about its use in construction materials. Toxicity Characteristic Leaching Procedure (TCLP) investigation by Rafieizonooz *et al.* (2017) demonstrated that the toxic components leached were below the maximum quantity to designate them as material with toxicity characteristics. This suggests that using CBA in construction materials is safe and can help to lessen the construction industry's negative environmental impact.

1.3 The use of precipitated calcium carbonate in concrete

Precipitated calcium carbonate (PCC) is obtained from lime with numerous industrial applications. PCC was formed by hydration of high-calcium quicklime. After the process of hydrating high-calcium quicklime, the slurry will be mixed with carbon dioxide. The result is a pure white powder with a uniformly narrow particle size distribution. PCC was widely used in other industries such as the paper industry, polymer industry and healthcare applications. Previous research showed a reduction in water absorption when PCC was used as cement replacement at a low replacement level ranging from 1-6%(Evangelia and Maria, 2021; Khalaf *et al.*, 2021; Shaikh and Supit, 2014; Shaikh and Supit, 2015; Vanitha *et al.*, 2021). The binder replacement of PCC in concrete mixes also resulted in similar or better strength when compared to normal concrete. The reduction in water absorption and the improved mechanical performance was due to the higher amount of C-S-H gel formation due to the presence of excellent particle PCC, which enhanced the microstructure of the concrete. From the previous, there is still a lack of knowledge on the usage of PCC as an additive in concrete material.

1.4 Problem Statement

Although there was a substantial body of knowledge on the reuse of CBA as fine aggregate replacement in concrete formulation, there is a scarce amount of study on graded CBA for useful application as a concrete constituent material.

Moreover, contradicting conclusions were reported on the influence of CBA as aggregate or binder replacement materials on the properties of concrete in various past studies. This is predominantly due to large fluctuation in the grading and chemical composition of the CBA material from one sampling point on the same source to the other and from one source to another. Therefore, there is a need to derive a suitable approach for reuse of CBA material as constituent aggregate for concrete production without compromising the fresh and hardened properties of the resultant concrete. Finally, the use of PCC as an additive in structural concrete containing alternative aggregate system was scarcely explored in present literatures. In specific, there is no research published in the current body of knowledge on the influence of PCC as an additive on the properties of concrete containing CBA as fine aggregate.

1.5 Research Objectives

1. To develop an approach of refinement to the grading of CBA to ensure consistent quality of concrete produced with large-volume CBA as an aggregate phase for mortar and concrete production.
2. To evaluate the influence of the graded CBA as natural aggregate replacement material on the fresh and hardened properties of mortar and concrete.
3. To evaluate the influence of PCC as an additive on structural concrete's fresh and hardened properties.

1.6 Scope of Works

A few phases of work were done prior to determining the suitable grading of CBA as fine aggregate in concrete containing coal bottom ash and the optimal amount of precipitated calcium carbonate as additive. To find the suitable grading and optimal percentage of CBA as fine aggregate replacement in concrete, a few gradings of CBA were sieved accordingly and used as fine aggregate replacement to determine the mechanical and fluid transport properties of the binary blended mortar containing GGBS and OPC. After finding out the optimal grading and suitable CBA replacement level, the next phase of work focuses on a more thorough study on the influence of PCC as an additive in binary blended mortar containing graded CBA as fine aggregate replacement. After finding the optimal amount of PCC used in the mortar containing graded CBA, the last phase of work will focus on the various characteristics of binary blended concrete containing CBA and PCC additives.

1.7 Significance of Research

The research aimed to reduce the usage of natural resources such as cement and river sand in concrete production. By integrating GGBS in the concrete mix, the amount of cement used is significantly reduced and can reduce CO_2 emissions, which can harm the environment. The usage of CBA as a fine aggregate replacement also significantly reduced the amount of natural fine aggregate such as river sand needed in the concrete mix. Reducing the use of river sand also helped preserve natural resources and not harm the habitat and ecosystem of the existing area. Moreover, the usage of PCC in concrete as an additive is to enhance further the microstructure of concrete containing CBA aggregates. PCC was used in this study due to the filler properties and the ability to accelerate the hydration process, which can enhance the performance of the binary blended concrete. Hence, using GGBS+OPC binary blended concrete with CBA as fine aggregate replacement and PCC as an additive has vast potential to reduce the carbon emission and negative impact of the construction industry towards the environment while maintaining the environment or improving the concrete quality.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

Coal bottom ash (CBA) was a by-product material produced by the coal combustion. In recent years there had been several studies related to CBA being used as fine aggregate replacement material which will be discussed in this chapter of the thesis. Several properties of mortar/concrete using CBA as fine aggregate such as chemical properties, fresh properties, and engineering properties were discussed in this chapter. Each individual properties of mortar/concrete were consolidated into a table for a clearer comparison. The use of CBA in different type of mix such as pure OPC blend, binary blend or ternary blend were also discussed to show what was the current body of knowledge regarding the use of CBA as fine aggregate.

Precipitated calcium carbonate (PCC) was a pure white powder which was processed from high-calcium quicklime through several process. The PCC used in mortar/concrete up to certain amount were able to show better performance (Khalaf *et al.*, 2021). The fresh properties, hardened properties and the fluid transport properties of the existing studies with PCC were discussed in this chapter to understand more on how PCC affects the mortar/concrete mixes when used as additive.

2.2 Chemical composition of CBA and its suitability as concrete aggregate

The chemical composition of CBA reported by numerous studies was presented in **Table 2.1**. From **Table 2.1**, the major composition of CBA consisted of silica, alumina and ferrite. Most studies showed CBA having less than 4% MgO, while the L.O.I ranged from 0.1 – 2.68%. Most of the prior studies showed CBA having silica, alumina, and iron with more than 70% by weight and having less than

5% of SO_3 and 6% of L.O.I. The composition fulfilled the exact fly ash Class F chemical requirement as stated in ASTM C618 (ASTM, 2019). There are a few classes of fly ash which were stated in the standard, class N, F, and C. As for the chemical requirement for Class F fly ash, the $SiO_2 + Al_2O_3 + Fe_2O_3$ (silica dioxide, aluminium oxide and iron oxide) must be at least 50%. The standard also prescribed that CaO (calcium oxide) must be less than 18%, SO_3 (sulphur trioxide) must be less than 5% and loss on ignition less than 6%. Similar chemical compositions results were shown when comparing the chemical composition of Class F fly ash requirement with CBA. However, the current review and research aimed at CBA as fine aggregate replacement. The explanation of CBA having properties similar to fly ash was to prove that CBA have similar pozzolanic properties that could influence the performance of the concrete or mortar when used as fine aggregate replacement.

The studies from Kim and Lee (2018) proven the statement above by using BSE and EDX images to observe the interaction between bottom ash aggregate and cement concrete. Based on micrograph evidence as shown in **Figure 2.1**, there was interaction and bonding between bottom ash and cement, improving the interfacial bond of both elements. Their study also stated that the cement paste was able to penetrate the surface pores of CBA aggregate, with the free water pre-absorbed by the CBA. With that, an internal curing phenomenon might occur, further strengthening the concrete or mortar.

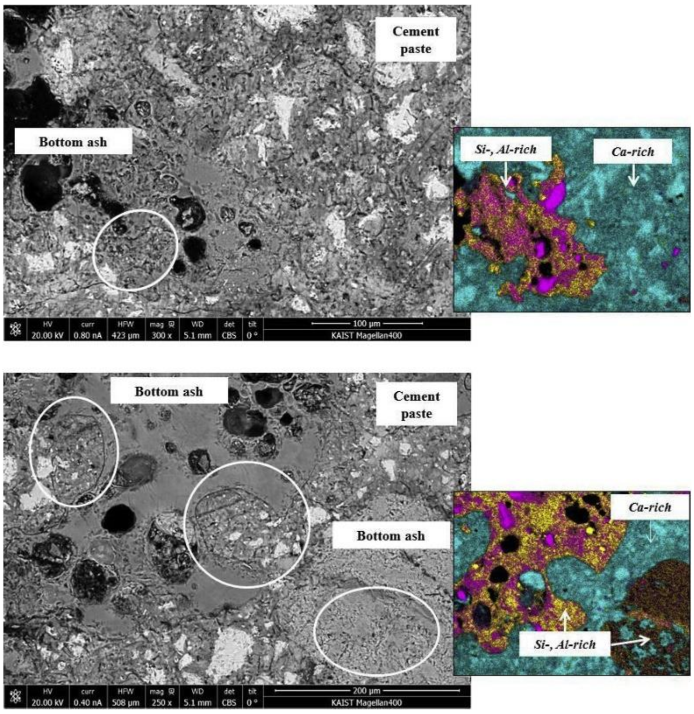

Figure 2.1 BSE images of concrete with CBA (left) and element spatial distribution (right).

Table 2.1 Chemical Composition of Coal Bottom Ash

Author	**Compound (% of the total mass)**											
	SiO_2	Al_2O_3	Fe_2O_3	CaO	SO_3	K_2O	MgO	TiO_2	MnO	P_2O_5	Na_2O	L.O.I
(Kim *et al.*, 2012)	34	36	16.8	2.4	-	5.90	-	3.90	-	-	-	-
(Abubakar *et al.*, 2013)	42.7	23.0	17.0	9.80	1.22	0.96	1.54	1.64	-	1.04	0.29	1.99
(Singh and Siddique, 2015)	56.44	29.24	8.44	0.75	0.24	1.29	0.40	3.36	-	-	0.09	0.89
(Jamaluddin *et al.*, 2016)	68.9	18.7	6.5	1.61	-	1.52	0.53	1.33	-	-	0.24	2.68
(Rafieizonooz *et al.*, 2016)	45.3	18.1	19.84	8.7	0.352	2.48	0.969	3.27	0.248	-	-	-
(Baite *et al.*, 2016)	62.32	27.21	3.57	0.5	-	2.58	0.95	2.15	0.01	-	0.7	-
(Singh and Siddique, 2016)	56.44	29.24	8.44	0.75	0.24	1.24	0.40	-	-	-	0.09	0.89
(Wyrzykowski *et al.*, 2016)	57.64	22.59	7.89	4.90	0.39	2.24	1.53	0.55	0.09	-	0.46	1.13
(Rafieizonooz *et al.*, 2017)	45.3	18.1	19.84	8.7	-	2.48	0.69	3.27	0.248	0.351	-	0.1
(Ghosh *et al.*, 2018)	60.71	25.86	1.97	0.89	-	1.28	0.63	6.81	-	-	0.38	0.92
(Hashemi *et al.*, 2018)	50.49	27.56	10.93	4.19	0.10	0.82	1.24	2.23	0.08	-	0.57	1.11
(Kumar and Singh, 2020)	66.9	17.7	6.5	1.56	-	-	0.51	-	-	-	-	-

2.3 The Formulation of mix design incorporating CBA as fine aggregate

The difference of mix design studied by various researchers regarding the use of coal bottom ash as aggregate replacement material is shown in **Table 2.2**. All the researchers used pure OPC mortar for their studies (Baite *et al.*, 2016; Hashemi *et al.*, 2018; Wyrzykowski *et al.*, 2016). Meanwhile, Kim *et al.* (2012) used pure OPC mix with silica fume (SF) as an additive. The fine aggregates that were used were CBA as a partial replacement of natural sand.

For the application of CBA as aggregate in concrete, most of the related studies were also done with pure OPC concrete mix (Abhishek Sachdeva and Khurana, 2015; K Muthusamy *et al.*, 2018; Kim and Lee, 2018; Singh and Siddique, 2015; Singh and Siddique, 2016). Researchers also designed binary blended concrete containing CBA aggregate, where fly ash was used as supplementary cementitious material (Chitharth Kannappan, 2018; Rafieizonooz *et al.*, 2016; Rafieizonooz *et al.*, 2017). In most studies, the coarse aggregate used in most of the concrete mix was crushed stone aggregate. In an isolated investigation, K Muthusamy *et al.* (2018) used oil palm shells as coarse aggregate in combination with CBA fine aggregate. As for fine aggregate in the concrete mix, all the studies used CBA and river sand except for Singh and Siddique (2016), who used river sand or quarry dust and CBA as fine aggregate replacement.

As for the formulation of Self-compacting concrete mix (SCC), there were pure OPC mix, binary blended mix, and ternary blended mix used by numerous reported studies. For those which involved binary or ternary blended cement concrete, fly ash and metakaolin were used as cement replacements for the concrete mix. The coarse aggregate used in the mix proportion were natural coarse aggregate by Hamzah *et al.* (2016) and Jamaluddin *et al.* (2016). On the other hand, Singh *et al.*

(2019) and Kumar and Singh (2020) used natural coarse aggregate and recycled concrete aggregate in their studies on the subject matter. As for fine aggregate, all reported studies on the subject matter used CBA as a full or partial replacement of natural fine aggregate.

PCE-based SP was used in the formulation of concrete mix in various studies as a high range-water reducing additive. It reduced the amount of water needed for the concrete mix to achieve the targeted slump or flow diameter (Zhang *et al.*, 2019). It can be seen from **Table 2.2** that all SCC concrete mixed with CBA as a fine aggregate replacement had used a PCE-based SP. The PCE-based SP used made the SCC flow better even though the water content was low in the mix (Hamzah *et al.*, 2016; Jamaluddin *et al.*, 2016; Kumar and Singh, 2020; Singh *et al.*, 2019). From the mix designs of various studies on the use of CBA as constituent aggregate shown in **Table 2.2**, we concluded that CBA as sand replacement in GGBS-OPC binary blended concrete/mortar had not been explored or reported by any prior studies.

Table 2.2 Types of mix design

		Types of material			
Reference	Types of concrete mix	Cementitious material	Coarse Aggregates	Fine Aggregates	Admixture
Mortar					
(Kim *et al.*, 2012)	Pure OPC mortar mix with SF as an additive	OPC and SF	-	CBA and crashed sand	Use of SPin mortar mix
(Baite *et al.*, 2016)	Pure OPC mortar mix	OPC	-	CBA and natural sand	-
(Wyrzykowski *et al.*, 2016)	Pure OPC mortar mix	OPC	-	24h soaked CBA and dry CBA and normal-weight aggregate sand.	SIKA VISCOCRETE 1S
(Hashemi *et al.*, 2018)	Pure OPC mortar mix	OPC	-	CBA and silica sand	PCE -based SP
Concrete					
(Abubakar *et al.*, 2013)	Binary blended concrete mix	OPC and fly ash	Crushed stone Aggregate	CBA and river sand	-
(Singh and Siddique, 2015)	Pure OPC mix	OPC	Crushed stone Aggregate	CBA and river sand	
(Abhishek Sachdeva and Khurana, 2015)	Pure OPC concrete mix	OPC	Crushed Stone Aggregate	CBA and river sand	Glenium – 51 PCE-SP
(Rafieizonooz *et al.*, 2016)	Binary blended concrete mix	Fly ash and OPC	Crushed Stone Aggregate	CBA and river sand	-
(Singh and Siddique, 2016)	Pure OPC concrete mix	OPC	Crushed Stone Aggregate	CBA and river sand (two difference fineness)	Use of SP in a batch of mix.
(Rafieizonooz *et al.*, 2017)	Binary blended concrete mix	Fly ash and OPC	Crushed limestone	CBA and river sand	-
(Kim and Lee, 2018)	Pure OPC concrete mix	OPC	Crushed Gravel	Crushed Gravel	PCE-based SP
(Chitharth Kannappan, 2018)	Binary blended concrete mix	Fly ash and OPC	Crushed angular aggregate	CBA and river sand	Conplast SP430 (G) SP
(K Muthusamy *et al.*, 2018)	Pure OPC concrete mix	OPC	Oil palm shell aggregate	CBA and river sand	-
SCC					
(Hamzah *et al.*, 2016)	Pure OPC concrete mix	OPC	Natural Coarse Aggregate	CBA and river sand	PCE-based SP
(Jamaluddin *et al.*, 2016)	Pure OPC concrete mix	OPC	Natural Coarse Aggregate	Natural sand and CBA	PCE-based SP
(Singh *et al.*, 2019)	Binary/Ternary blended concrete	Fly ash and OPC Fly ash, metakaolin and OPC	Natural Coarse Aggregate and Recycled Concrete Aggregate	Natural sand and CBA	PCE-based SP
(Kumar and Singh, 2020)	Binary blended concrete mix	Fly ash and OPC	Natural Coarse Aggregate and Recycled Concrete Aggregate	Natural sand and CBA	SP Glenium 51

2.4 Workability of CBA mortar and concrete

The workability of different studies on CBA as fine aggregates were studied as shown in **Table 2.3**. **Table 2.3** presented the studies in two different categories, mortar and concrete phase. The replacement level of CBA in each study, the sieve size used to sieve the aggregate, and the w/b ratio of the mix were shown. The range of flow/slump value and the trend were also shown in the **Table 2.3**.

2.4.1 Mortar

The difference in workability was studied by various researchers regarding coal bottom ash as aggregate replacement material was shown in **Table 2.3**. According to **Table 2.3**, the workability of mortar reported by different studies was reasonably diverse. According to Kim *et al.* (2012), when the mortar was replaced with 100% CBA, workability increased for all different w/b ratios except for 0.5 w/b ratio. The flow diameter for CBA mortar was 150mm compared to control (flow diameter of 155mm) at w/b ratio of 0.5, which was the only mortar that showed a decrease in flow characteristic. As the w/b ratio decreased from 0.38 to 0.20, the workability of the CBA mortar showed a marked improvement compared to the control mix. The increase in workability of mortar was due to the release of water absorbed by the CBA aggregates into the mix during mixing. Hence, the CBA mortar mix showed higher slump value than the natural fine aggregate mortar mix except for w/b of 0.5. At the high w/b ratio, the rough surface of the CBA compared to natural aggregate imposed a predominant influence on the workability of the mortar. The use of SP in this study might contribute to the high flow value for all the mixtures at the range of 150mm- 220mm.

According to **Table 2.3**, Baite *et al.* (2016) study showed that the mortar flow increased from 17mm to 35mm as the CBA was used to replace sand up to 50%.

However, as the sand replacement level with CBA increased further from 75% to 100%, the workability decreased slightly from 30mm to 29mm. Despite this, the overall workability of mortar with CBA as sand replacement showed a higher slump value than the control mortar. The trend of workability was explained that the CBA aggregate only partially absorbed the water that was supposed to be used in lubrication of the mortar mix. The remaining water was utilised to improve the workability of the CBA mortar. However, the decreased workability of mortar after 50% of CBA replacement was due to the lightweight characteristic of CBA. At a predefined viscosity of the mix, it enabled the mortar to sustain the mortar's self-weight better than river sand. Hence, lower flow diameter values were recorded for the mortar mix.

According to **Table 2.3**, Hashemi et al. (2018) study showed CBA mortar mixes were designed at w/b ratio of 0.3 and 0.4 while using SP to achieve a given level of workability. Compared to other mortar mixes without SP, the workability of mortar mix with 40% CBA and w/b ratio of 0.2 – 0.5 was improved with the use of SP. Hence, the use of SP increased the flowability of the CBA mortar at various w/b ratios.

2.4.2 Concrete

According to **Table 2.3**, research by Abubakar *et al.* (2013) shows that the increase of CBA content reduced the slump of concrete incorporating fly ash as cement replacement from 25mm to 15mm as CBA content increases from 5% to 20% by volume of aggregate. It was stated in the study that the use of fly ash increased the workability of the concrete to a certain extent due to the fine spherical shape of FA, which provided the ball-bearing effect. It reduced the water demand of the blended cement while increasing the workability of the fresh concrete mix. The loss of workability with the inclusion of CBA as fine aggregate replacement material was compensated with the increase in fly ash content. A point was reached whereby a further increase of FA content could no longer compensate for the workability of the concrete as CBA content was increased up to 20% by mass of aggregate. Hence, a drop in the workability of the concrete was noticed at the CBA content. In another study by Rafieizonooz *et al.* (2016), the workability of the mortar and concrete increases with increasing content of CBA as aggregate replacement material up to a certain aggregate replacement level (25% - 75%). A decline in workability from the optimum level was observed with a further increase of CBA content beyond the level. For instance, when CBA content increased to 25% by volume, the workability increased to 92mm compared to control at 73mm. However, as the CBA replacement increased from 50% to 100%, the workability decreased from 76mm to 37mm. The use of CBA as fine aggregate enhanced the concrete strength due to the irregular and rough particles. However, due to the rough and porous particles of CBA, the water demand of the CBA concrete or mortar was increased, causing a decrease in workability with higher content of CBA.

According to **Table 2.3**, a study conducted by Singh and Siddique (2016) and Muthusamy et al. (2018) shows a decrease in concrete's workability in the presence of CBA as aggregate replacement material. The finding of the study differs from the studies mentioned above, which observed an increase in workability to a certain extent when CBA was used as sand replacement. Singh and Siddique (2016) used two types of sand in their mix, river sand and quarry dust. Concrete that used river sand showed lower slump value compared to quarry dust as CBA content increases.

The authors explained that the decreased workability as CBA content increases was due to the dry and porous particle of CBA. CBA absorbed the water internally, which reduces free water available for the lubrication of the fresh mix. The irregular and rough morphology of CBA particles increased the frictional force between particles during the mixing of the concrete. It was concluded that numerous factors influence the workability of concrete containing CBA as sand replacement such as the aggregate size, the porous structure and the moisture content of the concrete. Hence, a proper grading and controlled moisture content of the CBA is required to achieve consistent CBA concrete's workability.

According to **Table 2.3**, Abhishek Sachdeva and Khurana (2015) presented the effect of replacing fine aggregate with CBA in terms of workability. The results showed workability of the CBA concrete had a decreasing trend as the CBA content increased from 0% - 40% by mass of aggregate with a fixed content of SP (1.2% by binder's mass). However, the amount of SP was increased up to 2.5% for 40% CBA replacement concrete to achieve 100mm slump. Similarly to earlier studies, the decrease of CBA concrete's workability with higher CBA content was attributed to the irregular shape and coarser particle of CBA. Moreover, compared to normal sand, the porous structure of CBA also hindered the workability of concrete as it absorbed the water used in the mixing process.

According to **Table 2.3**, research by Jamaluddin *et al.* (2016) regarding the incorporation of CBA as fine aggregate in SCC concrete showed a decreasing trend in workability as replacement of CBA increases from 10% to 30% at a fixed water/binder ratio. However, for different w/b ratios, the results showed that the increase in w/b ratio increased the workability of SCC concrete with CBA as fine aggregate replacement at the same replacement level. Although the increase in CBA replacement decreased the workability of the SCC concrete, the increase in w/b ratio compensated the reduction of the workability. For example, at BA15, where 15% CBA was replaced, it was shown in the result that the workability was 650mm flow diameter at w/b ratio of 0.35 compared to control mix, which is 700mm. However, when the w/b ratio of BA15 (15% CBA replacement) increases to 0.40, the slump flow increases from 650mm to 688mm. The observation confirmed that the increase in w/b ratio increase the slump flow of the SCC mix at the same replacement level. The study showed two critical factors, first was the use of CBA would decrease the workability of SCC concrete due to the coarser aggregate used to compare to sand. The second was the increase of w/b ratio would increase the slump flow of the SCC concrete even at the same CBA replacement.

Table 2.3 Workability of different studies

Reference	Replacement ratio (%)	Sieve Size	w/b ratio	Slump value (mm)	Trends
Mortar					
(Kim *et al.*, 2012)	100	-	0.5 – 0.2	Mix with Normal Aggregate = 150 – 210mm Other Mix =150-220mm	Increase in workability for all mix with CBA except for w/b 0.5.
(Baite *et al.*, 2016)	0,10,20,30, 40,50,75,100	5mm	0.5	16-35	Increases workability up to 50% replacement then decrease
(Hashemi *et al.*, 2018)	0,40%	4.75mm	0.5 – 0.2	Control 120mm Other mixes workability with 40% CBA replacement < 40mm	Decrease workability as CBA replacement increases When SP is used, mix with 40% CBA replacement and 0.4- 0.3 w/b ratio shows an increase in workability compared to 40% CBA replacement without SP.
Concrete					
(Abubakar *et al.*, 2013)	0,5,10,15,20	4.75mm	0.48	55-15	Increase in workability up to 15% replacement then decreases.
(Abhishek Sachdeva and Khurana, 2015)	0,10,20,30, 40		0.38	100mm fixed	Increase in usage of SP as CBA replacement increases to achieve 100mm slump
(Rafieizonooz *et al.*, 2016)	0, 25, 50, 75 ,100	4.75mm	0.55	73,92,76.53.37	Increase workability up to 25% replacement then decrease
(Singh and Siddique, 2016)	0,20,30,50, 75,100	4.75mm	0.45 and 0.5	River Sand = 70,61,41,30,15, 11 Quarry Dust = 125,112,103,64, 38,25	Decreases workability as CBA replacement increases.
(Chitharth Kannappan, 2018)	0,10,20,30, 40,50	-	0.38	100mm for control.	
(K Muthusamy *et al.*, 2018)	0,5,10,15,20			100,85,75,60,5	Decrease workability as CBA replacement increases.
SCC					
(Jamaluddin *et al.*, 2016)	0,10,15,20, 25,30%	20mm – 0.075mm	0.35-0.45	545- 720mm	Increase workability for all individual mix as w/c ratio increases Decreases in workability as replacement of CBA increases.
(Singh *et al.*, 2019)	10%	4.75mm	Fixed ratio	675- 695	Decrease in workability as RCA increases.

2.5 Engineering properties of concrete with CBA aggregate

2.5.1 Compressive strength

The compressive strength trend results for mortar/concrete with CBA aggregate was shown in **Table 2.4** below. The replacement ratio ranging from 0 – 100% were shown for each of the studies, while the testing age was ranged between 7 days to 180 days. There compressive strength of the mortar/concrete will be compared between the control mix and the CBA mix for each individual studies.

2.5.1(a) Mortar

The difference in compressive strength of concrete with CBA as aggregate for different research is shown in **Table 2.4**. For mortar mix, Kim *et al.* (2012) mentioned that the decrease in w/b ratio in CBA mortar increased the compressive strength. The compressive strength of CBA mortar was relatively lower than mortar that used natural aggregate. When the w/b ratio was fixed at 0.5, the mortar with normal sand was 44MPa, while mortar with CBA replacement was 36MPa. When the w/b ratio decreases from 0.5 to 0.24, the compressive strength of normal sand mortar ranges from 44MPa to 92MPa, while CBA mortar ranges from 36MPa to 88MPa. The compressive strength and density of the mortars showed that CBA mortar had similar compressive strength compared to normal aggregate by 5% to 11%, except for w/b ratio of 0.5. When w/b ratio decreases, the density of mortar increases. The concentration of calcium hydroxide in mortar was greater at a lower w/b ratio. Moreover, the pozzolanic reactivity of cement paste and CBA increases as the w/b ratio reduces. The author explains that the rougher surface area of CBA also contributes to a better bond with cement paste than normal fine aggregates with smoother surfaces.

According to **Table 2.4**, Wyrzykowski *et al.* (2016) showed that a fixed w/c ratio of 0.35 for all the mortar incorporated 40% CBA had higher 28 days compressive strength than the reference mortar. On the 28th day of curing, dry CBA and soaked CBA mortar showed compressive strength ranging from 75 MPa to 78 MPa. The compressive strength values were higher compared to reference mortar with compressive strength of 65 MPa. In separate work, Hashemi *et al.* (2018) reported a different outcome. At all curing ages, CBA mortar which replaced 40% mass of sand with CBA, exhibited a lower compressive strength of 5 MPa to 45 MPa compared to control mortar which was 32 MPa – 48 MPa. The compressive strength of CBA mortar decreased when w/b ratio decreased from 0.5 to 0.2. However, when SP was incorporated in the same CBA mix, the strength significantly increased from 8 MPa to 49 MPa.

According to **Table 2.4**, comparison between all the research on mortars showed that the use of CBA as fine aggregate had a mixed influence on the compressive strength of the mortar. Some studies showed positive results, while others showed negative results. However, although the results shown by Kim *et al.* (2012) and Hashemi *et al.* (2018) were negative, the difference of compressive strength between the CBA mortar and control mortar was only marginal. As for Wyrzykowski *et al.* (2016), the improved compressive strength of CBA mortar was mainly due to the use of finer fraction 300micron bottom ash in the study. It is the major difference of the study compared to other studies that used raw CBA without pre-sieving.

2.5.1(b) Concrete

According to **Table 2.4**, at 7d of curing, Abubakar *et al.* (2013)'s study showed the compressive strength of CBA concrete decreased in strength compared to control concrete (23.5 MPa) except for 10% CBA replacement concrete which was 26MPa. The difference between the control and the CBA mix was less than 10%. It is indicative that the CBA concrete mix was following the trend of control concrete in terms of strength gain. For curing ages of 28 and 90 days, the strength gained for CBA concrete were higher (32.6 – 42 MPa) compared to control concrete (32.1 – 35.3 MPa). The study concluded that at a long-term curing age, the concrete produced incorporating CBA up to 20% was able to achieve higher compressive strength than normal concrete. This was due to the pozzolanic reactivity between the binder and surface of CBA aggregate, increasing secondary hydration product which enhanced the concrete.

According to **Table 2.4**, the studies from Singh and Siddique (2015) showed that at early curing ages till 28 days, the strength of concrete incorporating CBA was lower than the control mix (without CBA aggregate). At 7 and 28 days of curing, the compressive strength of CBA mix was higher (21 -34 MPa) compared to control mix (25 – 33 MPa). While at 90 and 180 days, all the concrete incorporating CBA as fine aggregate showed similar strength compared to control ranging from 40 – 48 MPa. From this study, the author managed to relate both the SEM image and the compressive strength of the CBA concrete. From the SEM results shown in **Figure 2.2**, it was shown that as the CBA amount increases, the voids on the CBA concrete increase. Moreover, for the 50% and 100% CBA replacement concrete, the CSH gel is not as compact as the control concrete mix. On top of that, the SEM images were able to show a more even spread of CSH gel at 90 days of curing compared to 28 days due to the formation of extra CSH gel.

According to **Table 2.4**, Abhishek Sachdeva and Khurana (2015)'s results showed that the compressive strength tests for the 28th day of curing up to 20% of CBA as fine aggregate replacement showed a marginal decrease. The recorded compressive strength was about 2.9% lower than control, ranging from 46.52 – 47.45 MPa than control concrete at 47.92 MPa. As the CBA replacement level increased up to 30 – 40%, the compressive strength slightly decreased from 45.92 to 39.59 MPa. Therefore, the use of CBA as fine aggregate replacement can be up to 20% by mass to produce similar strength concrete as the control mix. It was explained that the decrease in compressive strength of CBA concrete was due to the usage of weaker material (CBA) to replace stronger material (Sand) in the concrete mix.

According to **Table 2.4**, Rafieizonooz *et al.* (2016)'s examined the use of CBA as fine aggregate replacement in concrete with a 25% replacement level increment until 100%. At 7 and 28 days, it was shown that all the CBA mixes had lower compressive strength compared to control concrete, where CBA mixes ranged between 15 – 26 MPa, compared to control concrete which was higher at 20-32 MPa. However, as the curing age increased to 91 days, concrete containing 50% CBA exhibited similar compressive strength performance at 35 ± 2 MPa compared to control concrete. Meanwhile, the other CBA mixes had slightly lowered compressive strength than control mix. When the curing age reached 180d, all the CBA concrete mixes showed better strength performance ranging at 36 – 37 ± 2 MPa. Except for 25% CBA replacement, it showed slightly lower strength at 35 ± 2 MPa than control concrete at 36 ±2 MPa. The increased strength performance at later curing ages of 91d and 180d was due to the C-S-H gel formation from the consumption of portlandite by pozzolanic reaction of CBA and fly ash. It resulted in forming a denser concrete microstructure, hence, improving the compressive strength performance of the CBA concrete.

According to **Table 2.4**, Singh and Siddique (2016) investigated the influence of CBA as partial replacement of sand/quarry sand on the mechanical and fresh properties of concrete. At 28d, all concrete which incorporated CBA (20%, 30%,50%,75%,100%) as sand (Concrete A) or quarry sand (Concrete B) replacement showed decreased compressive strength. For Concrete A, mix with CBA content showed slightly less compressive strength (35 – 38 MPa) than control concrete (38.21 MPa). As for Concrete B, mix with CBA content showed less compressive strength (26 – 32 MPa) than control concrete (34.04 MPa). At 91 days, Concrete A, which incorporates CBA content, showed lower compressive strength (41 – 44 MPa) compared to control concrete (40.82 MPa). A similar behaviour was exhibited by Concrete B with CBA content showed lower compressive strength (35 – 41MPa) compared to control concrete (42.32 MPa). It can be seen for 91 days that Concrete A incorporating CBA as fine replacement showed an increase in compressive strength. However, Concrete B incorporating CBA as fine aggregate replacement showed a decrease in strength due to the coarser aggregate of quarry sand. When curing age reached 180 days, the compressive strength for Concrete A showed slightly better results than control.

On the other hand, Concrete B showed slightly decreased results compared to control. The study concludes that the finer particles of normal sand concrete could achieve a slightly better result than coarser particles of the quarry sand. Both types of concrete had the same sand replacement level for CBA and yet showed results comparable to the control concrete. The pozzolanic reaction that occurred at a later curing age might also be the reason for the significant strength gain on the CBA concrete.

According to **Table 2.4**, K Muthusamy *et al.* (2018) studies show that compressive strength of CBA concrete mix increased at an early age. The main difference between the study and others was the use of oil palm shells as coarse aggregate in the concrete mix. The CBA replacement levels were 5% ,10%, 15% and 20%. The results showed that at 7d of curing, the CBA concrete showed better compressive strength, ranging from 15 – 17 ± 2 MPa compared to control concrete at 14 ± 2 MPa. A similar trend was observed as the curing age increased up to 28days. The CBA concrete had a compressive strength of 26 – 29 ± 2 MPa.

Meanwhile, control concrete only had 25 ± 2 MPa. It was shown that the CBA concrete with replacement of sand with CBA up to 20% was able to show increased compressive strength results. The increase in compressive strength of concrete incorporating CBA was due to fine CBA which acted as filler. It strengthens the concrete's internal structure, making it more compact than normal control concrete, hence, improving its strength. However, it was observed that as the replacement level increased up to 20%, the strength of the concrete slightly decreased compared to CBA concrete with 15% replacement level. The observation was attributed to the increase in CBA particles in the mix which caused excessive voids in the concrete mix. The voids render the concrete less compact than the concrete with lower CBA content, causing decreased strength.

According to **Table 2.4**, a study from A.V.Chitharth Kannappan (2018) used CBA as sand replacement in binary blended concrete with OPC and fly ash were able to show increased strength even at early age of curing. All the concrete mixes with CBA as sand replacement showed increased compressive strength ranging from 24- 27 ± 1 MPa. The exception was concrete with 50% CBA replacement level where the strength was 22 ± 1 MPa, compared to the control concrete at 24 ± 1 MPa. As curing age increased to 28days, CBA concrete mix (10%,20%,30%) showed an increase in