

DURABILITY AND LEACHABILITY OF CONCRETE CONTAINING COAL
BOTTOM ASH AND FLY ASH

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To My Lovely Parents
Safar Rafieizonooz and Batool Rafeghi

And

My Beloved Wife
Elnaz Khankhaje

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ABSTRACT

Concrete is one of the main construction materials, though its application in construction has negative environmental impact such as carbon dioxide (CO₂) emission and depletion of natural resources. In order to reduce the use of river sand as natural fine aggregate, the utilization of waste materials such as coal bottom ash (CBA), recycle concrete aggregate and recycle glass is quite effective. Moreover, in terms of reducing the amount of CO₂ emission from cement industry, the utilization of supplementary cementitious materials (SCMs) such as coal fly ash (CFA), silica fume, blast-furnace slag and biomass ash is quite common and beneficial. In this study, the effect of using CBA as sand replacement and CFA as partial replacement of cement on various mix designs, was examined. The performance was investigated based on physical and mechanical properties, durability and leaching performance. The resistance to sulfuric acid and sulfate solutions and elevated temperature was also investigated. Two different leaching methods to obtain leaching performance of coal ash concrete performed were batch and tank leaching tests. Results revealed that concrete workability reduced with increasing percentage of CBA content replacing sand. At the early age of 28 days, no significant effect was observed in compressive, flexural and tensile strengths of all concrete samples. After curing ages of 91 and 180 days, compressive strength of both the experimental and control concrete samples increased significantly but remained almost similar. However, flexural and splitting tensile strengths of the experimental mix containing 75% CBA and 20% CFA exceeded more than the control sample. Moreover, drying-shrinkage of experimental concrete mixtures containing 50%, 75% and 100% CBA and 20% CFA was lower than the control mix. In general, the study revealed that coal ash concrete exhibited good influence in terms of resistance to chemical attacks than the control specimen. On the other hand, coal ash concrete mixtures showed higher loss in weight when exposed to higher temperature. Finally, from the results of leaching tests, it is observed that there is no leaching of any heavy metals. It is concluded that the experimental concrete mixes can be used which will minimize the use of natural resources, reducing energy and environmental problems to a great extent.

ABSTRAK

Konkrit merupakan salah satu daripada bahan binaan utama, walaupun penggunaannya dalam pembinaan memberi kesan negatif terhadap alam sekitar seperti pelepasan karbon dioksida (CO_2) dan pengurangan sumber asli. Dalam usaha untuk mengurangkan penggunaan pasir sungai sebagai agregat halus semula jadi, penggunaan bahan buangan seperti abu dasar arang batu (CBA), agregat konkrit kitar semula dan kaca kitar semula adalah agak berkesan. Selain itu, untuk mengurangkan jumlah pelepasan CO_2 daripada industri simen, penggunaan bahan bersimen tambahan (SCM_s) seperti abu terbang arang batu (CFA), wasap silika, sanga relau bagas dan abu biojisim biasa diguna dan bermanfaat. Dalam kajian ini, kesan penggunaan CBA sebagai gantian pasir dan CFA sebagai gantian separa simen dalam pelbagai reka bentuk campuran, telah dikaji. Prestasi yang diselidiki adalah berdasarkan ciri-ciri fizikal dan mekanikal, keboleh tahanan dan prestasi larut lesap. Kajian juga dijalankan ke atas kerintangan asid sulfurik dan larutan sulfat serta peningkatan suhu. Dua kaedah larut lesap berbeza yang dijalankan untuk memperolehi prestasi larut lesap konkrit abu arang batu merupakan ujian larut lesapan berkelompok dan tangki. Keputusan menunjukkan bahawa kebolehkerjaan konkrit berkurangan dengan peningkatan peratusan kandungan CBA menggantikan pasir. Pada usia awal 28 hari, tiada kesan yang ketara diperhatikan dalam kekuatan mampatan, lenturan dan tegangan semua sampel konkrit. Selepas usia pengawetan 91 dan 180 hari, kekuatan mampatan bagi kedua-dua sampel konkrit bagi eksperimen dan kawalan meningkat dengan ketara tetapi kekal hampir sama. Walau bagaimanapun, kekuatan lenturan dan tegangan terbelah campuran eksperimen yang mengandungi 75% CBA dan 20% CFA didapati melebihi daripada sampel kawalan. Selain itu, pengeringan-pengecutan campuran konkrit eksperimen dengan kandungan 50%, 75% dan 100% CBA dan 20% CFA adalah lebih rendah berbanding campuran kawalan. Secara umum, kajian ini mendedahkan bahawa konkrit abu arang batu menunjukkan pengaruh yang baik dari segi rintangan kepada serangan kimia berbanding spesimen kawalan. Sebaliknya, campuran konkrit abu arang batu menunjukkan kehilangan berat yang lebih tinggi apabila terdedah kepada suhu yang tinggi. Akhir sekali, dari keputusan ujian larut lesap, diperhatikan tiada kesan larut lesapan sebarang logam berat. Dapat disimpulkan bahawa campuran konkrit eksperimen boleh digunakan untuk meminimumkan penggunaan sumber asli, mengurangkan tenaga dan masalah alam sekitar ke tahap yang lebih hebat.

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LIST OF ABBREVIATIONS

ACAA	-	American Coal Ash Association
ACI	-	American Concrete Institute
ASTM	-	American Society for Testing and Materials
BS	-	British Standards
CAC	-	Coal Ash Concrete
CFA	-	Coal Fly Ash
CBA	-	Coal Bottom Ash
C-H	-	Calcium Hydrate
C-S-H	-	Calcium Silicate Hydrate
E	-	Ettringite
ELT	-	Equilibrium Leach Test
FESEM	-	Field Emission Scanning Electron Microscopy
HDPE	-	High Density Polyethylene
ICP-MS	-	Inductively Coupled Plasma - Mass Spectrometry
LOI	-	Loss On Ignition
L/S	-	Liquid to Solid ratio
MSWI	-	Municipal Solid Waste Incineration
MWLP	-	Mine Water Leaching Procedure
NETL	-	National Energy Technology Laboratory
OPC	-	Ordinary Portland Cement
rpm	-	Revolutions Per Minute
SBLP	-	Serial Batch Leaching Procedure
SDTLP	-	Semi-Dynamic Tank Leaching Procedure
SEM	-	Scanning Electron Micrograph
SSD	-	Saturated Surface Dry
TCLP	-	Toxicity Characteristics Leaching Procedure
UPV	-	Ultrasonic Pulse Velocity

US EPA	-	United State Environmental Protection Agency
UTM	-	Universiti Teknologi Malaysia
WVWRI	-	West Virginia Water Research Institute
W/C	-	Water to Cement ratio
XRF	-	X-Ray Fluorescence Spectrometry

LIST OF SYMBOLS

V	-	pulse velocity (km/s)
L	-	length of the specimen
T	-	transit time
W	-	percentage mass loss (%)
W_{initial}	-	mass of the samples before submersion in sulfuric acid solution
W_t	-	mass of the samples at (t) days after submersion in sulfuric acid solution
f_c	-	compressive strength reduction
$f_c (28 \text{ d})$	-	28 days compressive strength of the concrete specimens
$f_c (t \text{ d})$	-	compressive strength at (t) days after submersion in sulfuric acid solution.
$M_{t i}$	-	mass released during the current leaching interval, i (mg/m^2)
C_i	-	constituent concentration in the eluate for interval i (mg/L)
V_i	-	eluate volume in interval i (L)
A	-	specimen external geometric surface area exposed to the eluent (m^2)
F_i	-	flux for interval, i ($\text{mg}/\text{m}^2 \cdot \text{s}$)
M_i	-	mass released during the current leaching interval, i (mg/m^2)
T_i	-	cumulative time at the end of the current leaching interval, i (s)
T_{i-1}	-	cumulative time at the end of the previous leaching interval, i-1 (s)
C_i	-	constituent concentration in the eluate for interval i (mg/L)
f_{cu}	-	Compressive strength of cube in MPa
R^2	-	coefficient of determination
f_f	-	Flexural strength of concrete in MPa

- f_t - Tensile strength of concrete in MPa
- of - the percentage of compressive strength loss
- om - the percentage of loss in weight

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CHAPTER 1

INTRODUCTION

1.1 Background

Concrete is one of the most important materials in building construction and other infrastructure works. About 2.7 billion m³ of concrete was generated in 2002 worldwide, which is more than 0.4 m³ of concrete generated per person annually (Naik 2008). It is anticipated that the need for concrete will increase further to almost 7.5 billion m³ (about 18 billion tons) a year by 2050 (Monteiro 2015) . Such an enormous utilization of concrete calls for higher use of natural aggregates and cement, thus taking toll on the environment. At least three-quarters of the total volume of concrete consists of coarse and fine aggregates. Obviously, natural resources such as river sand are getting depleted (Mardani-Aghabaglou et al. 2014). The prohibition on mining in some areas and the growing needs for natural environment conservation further exacerbate the problem of river sand availability.

Finding new alternative materials for sustainable development so as to substantially decrease the consumption of natural resources became imperative to safeguard the interests of future generations. Moreover, high consumption of natural resources led to greater amount of industrial wastes and environmental degradation (Khankhaje et al. 2015). Therefore, the interest of researchers increased to utilize industrial waste materials as replacement of natural resources in construction industry.

Coal is one of the most significant sources of energy with fuelling almost 40 percent of electricity in the world. In many countries this figure is much more: Poland relies on coal for over 97 percent of its electricity; South Africa for 92 percent; China for 77 percent; and Australia for 76 percent. Coal was introduced as a raw material for power generation since 1988 in Malaysia (International Energy Agency 2012).

The projected forecast for electricity usage in peninsular Malaysia produced from coal and gas by the year 2024, are 58% and 25%, respectively. Even though, some difference exists between these figures and those of 2014, it appears that dependence on fossil fuels may be reduced but won't be eliminated altogether. In fact coal consumption will likely mount from 43% to 58% (Tenaga 2014).

Two types of ash, coal fly ash (CFA) of 80 percent and coal bottom ash (CBA) of 20 percent are produced at coal power plant. Most of them are being dumped at the waste disposal site near the factory. This will pollute the environment and creating a disposal problem because a large dumping space is required. Electricity production in Malaysia leads to a whopping amount of CFA some 6.8 million tonnes and CBA roughly 1.7 million tonnes. While CFA is being used to manufacture pozzolanic Portland cement, CBA is not commonly used at all.

The coal ash content depends upon the non-combustible matter present in coal. Rock detritus filled in the fissures of coal becomes separated from the coal during pulverization. In the furnace, carbon and other combustible matter are burnt, whereas the non-combustible matter results in coal ash. Swirling air carries ash particles out of hot zone where it cools down and CFA is produced through this process. CBA is displaced from under the furnace which is directed to suspension ponds that take over several acres of countryside land.

Previously, most of the available researches had been focusing on the properties of CFA since CFA accounts for a larger portion (approximately two-third) of the total coal ash produced as compared to bottom ash (American Coal Ash Association (ACAA), 1998). There have been a substantial number of studies on concrete production incorporating coal ash either as cement replacements, fine and coarse aggregates. Cheriaf et al. (1999) studied the property of CBA concrete and found that CBA has pozzolanic property as sand replacement and is suitable for using in concrete manufacturing. It was also reported by Kim and Lee (2011) that CBA can be used as aggregates (fine and coarse) in high-strength concrete. Singh and Siddique (2013) in their review reported that CBA is a potential substitute material for sand in concrete. Singh and Siddique (2015) also investigated the properties of concrete incorporating high volume of CBA as sand replacement. Aggarwal and Siddique (2014) investigated the microstructure and properties of concrete containing CBA and waste foundry sand as replacement of natural sand in concrete.

Concrete made with low calcium CBA as a replacement of river sand displayed strength properties comparable to that of conventional concrete (Singh and Siddique 2014b). The major advantages of using CBA as fine aggregate in concrete production is that reduction in dead weight of structure as well as alleviation of environmental hazards. Concrete made with using CBA has low density as compared to control concrete, since CBA has low specific gravity. Sua-iam and Makul (2014) have reported that the use of waste materials either as cement supplementary material or as sand replacement in concrete can result in cost savings and help in reducing the environmental problems.

However, from literature search, no study on durability and stability properties of concrete incorporating CBA as fine aggregate and CFA as replacement of Ordinary Portland Cement (OPC) has been published. Hence, detailed studies about durability of concrete incorporating CFA as cement replacement and CBA as fine aggregate are required before the CFA and CBA as construction material are accepted in manufacturing of concrete.

One of the most important factor in anticipated life of the structure is durability and stability of concrete made utilizing industrial by-products. Concrete made utilizing industrial waste materials can be considered as durable concrete if it preserves its initial quality, serviceability and form when subjected to chemical attacks, elevated temperature, weathering process and other activities of deterioration for the anticipated life time.

The movements of moisture in concrete cause deterioration because of sulfuric acid and sulfate attack. Concrete made with CBA as replacement of fine aggregate shows a notable performance when subjected to chemical attacks. Singh and Siddique (2014a) studied the performance of concrete incorporating CBA as sand replacement when exposed to sulfate and sulfuric acid attack.

Elevated temperature is another kind of process that can effects the performance of concrete in its intended life. The main factors which influence the heat resistance of concrete are temperature and duration of fire, the type of cement and aggregates used in its structure, moisture content of concrete and size of structural members. CBA is porous material and its presence as sand replacement in concrete causes in porous structure in the concrete. The higher porosity of concrete can be believed positive when concrete is exposed to high temperature up to 200 °C. This might be due to the evaporation of internal water is not complete. Yuksel et al. (2011) evaluated the effect of high temperature on properties of CBA concrete.

1.2 Problem Statement

The growing demand for electricity resulted in the construction of many coal fired power plants. As the consumption of coal by power plants increases, so does the production of coal by product such as CBA and CFA. While the use of coal

increases, waste issues associated with coal production are tempted more and more thoughtfulness. Malaysia is very serious about environmental issues resulting in the introduction of stringent control about the emission standards on the new projects for coal power (Joseph, 2005). Even though there is no report about the production of coal ash annually in Malaysia, but theoretically, there is about 10% of total weight of the coal burned produces ash (Huang, 1990).

By the year 2024, it is predicted that Malaysia will have to rely on coal and gas (58% and 25% respectively) to generate electricity (Tenaga 2014). Although there are some disparities between the aforementioned figures and those of 2014 (43% coal), it is likely that the requirement for fossil fuels could increase. This increase in utilization of coal will lead to generate of more coal ash that could eventually result in more environmental problems.

Disposal of unused coal ash is costly and places a considerable burden on the power industry, and finally transferred to the electricity consumer. In addition, the disposing of ash in landfills contributes to the ongoing problem of diminishing landfill space in Malaysia, and as a result of that, ash disposal may pose an environmental hazard.

There are several researches documenting heavy metal concentrations and leaching in coal ash from different countries such as Australia (Jankowski et al. 2006), USA (Heidrich et al. 2013), India (Prasad and Mondal 2008), South Africa (Musyoka et al. 2013) and Zimbabwe (Gwenzi and Mupatsi 2016). The majority of these researches concentrate on leaching behaviour of heavy metals from unbound coal ash. The findings of these literatures are in contrast with each other: Some researchers (Jianmin Wang et al. 2004; Sushil and Batra 2006) stated that some heavy metals could be leached out from coal ash; whereas others (Drakonaki et al. 1998a; Beard 2002; Gwenzi and Mupatsi 2016) reported that the leaching of mentioned elements from coal ash was unimportant. These conflicting findings might be due to differences in leaching method and procedures, variability in type

and origin of coal burned, types of boiler, degree of coal pulverization, firing conditions in the furnace, ash handling practice and processing technologies used in thermal power stations.

There is a requirement for a methodical approach to assess locally existing of CBA and CFA for potential construction utilization because as mentioned earlier even coal ash produced from the same source of fuel can be completely difference depending on the procedures and operating conditions.

The using of CBA as alternative replacement of the natural sand and CFA as cement substitute in concrete production are going to solve the problem of these kind of waste. Therefore, Malaysia has a great potential to turn its profuse source of electrical by coal industry by-products into worth added products especially in construction material. However, looking on the brighter side of things, extensive research has provided an alternative way of optimizing the usage of coal residues based into value added product in construction industry.

1.3 Aim and Objectives

The aim of this research is to use CBA as partial and total replacement of fine aggregate (sand) and CFA as partial replacement of OPC in production of concrete. Moreover, this research aimed to analyse the leachability of CBA, CFA and coal ash concrete. To achieve the aim of this research, following objectives are prepared:

1. To characterise the physical and chemical properties of CBA and CFA
2. To develop a mixture proportioning to prepare coal ash concrete (CAC)
3. To evaluate the mechanical properties of concrete containing CBA and CFA

4. To determine the durability of coal ash concrete when exposed to aggressive condition: sulfate attack, acid attack and elevated temperature
5. To evaluate the leachability of CBA, CFA and coal ash concrete (CAC)

1.4 Significant of Study

Since construction is inevitable in many areas of the world and Malaysia is not an exception, which has the environmental problem such as leaching hazardous material, air pollution and disposal of wastes. One of the most common wastes which can be used in construction industry is coal fired fuel ash. Thus basic knowledge and understanding of concrete, CFA and CBA properties are of great importance to produce coal ash concrete. Using this mixture, could increase the use of disposal wastes which can reduce the environmental problems as mentioned earlier.

1.5 Scope of Study

In this project, CBA and CFA from Tanjung Bin power station in South Malaysia (Johor Bahru) are concerned. Tanjung Bin power station is located in south coast of Malaysia, producing 180 tons/day of CBA and 1,620 tons/day of CFA from 18,000 tons/day of coal burning. Tanjung Bin power station produces 2100 MW per year.

The study focuses on the characteristics of CBA and CFA which is collected from Tanjung Bin power plant in Malaysia. After that sustainable concrete are

produced by using CBA as fine aggregate replacement and CFA as partial replacement of OPC. Then, the engineering properties and durability performance of this concrete are carried out. Finally, the leaching test on CBA, CFA and coal ash concrete are proposed.

The engineering properties of the materials are tested using the standard method such as the British Standard (BS) or the American Society for Testing and Materials (ASTM), depending upon the suitability or the availability of the equipment in the laboratory within Universiti Teknologi Malaysia (UTM).

1.6 Research Methodology

The methodology utilized in this research can be described as follows: Information was collected through studies of the literature and study visits. Previous Malaysia experience was evaluated and foreign experiences also considered, thus identifying areas in which there was a lack of knowledge.

Moreover, experimental work was carried out by evaluating characteristics of CBA and CFA, properties of new production (concrete) in terms of workability and durability tests, leaching test, planning and evaluating new laboratory experiments.

1.7 Thesis Layout

The thesis is divided into seven chapters that consist of Chapter 1 (Introduction), chapter 2 (Literature Review), chapter 3 (Research Methodology: Program of Experimental and Characteristics of Materials), Chapter 4 (Characteristics of Ash and its Effect on Mechanical Properties of Concrete), Chapter 5 (Durability, Sulfuric Acid, Elevated Temperature and Sulfate Resistance), Chapter 6 (Leaching Test) and Chapter 7 (Conclusion and Recommendations). The explanations for each chapter are as follows:

Chapter One: Provides the general background of the research and a brief description of the statement problem. Additionally, aims and objectives, scope and limitation, significance of study and the research highlight are also described in this chapter.

Chapter Two: Explains the physical and chemical properties of CBA and CFA and description of the previous research studies on the utilization of CBA and CFA in construction industry. In next step, the leaching properties of concrete containing CBA and CFA was studied. However, there are few literatures on utilization CBA and CFA at same time in mix design of concrete, the properties of concrete containing CBA as fine aggregate replacement in concrete and CFA concrete were reviewed. The workability and mechanical properties such ash compressive, flexural and split tensile strength, Ultrasonic pulse velocity (UPV) and drying shrinkage of CBA concrete and CFA concrete were reviewed separately. The final part of chapter two, illustrated previous researches works on chemical attack (sulfuric acid attack and sulfate attack) and elevated temperature resistance of CBA concrete and CFA concrete.

Chapter Three: Describes the experimental procedure including materials characteristics, leaching tests, mix design, workability, mechanical properties and durability experiments under aggressive environmental conditions.

Chapter Four: Shows the results of characteristics of CBA and CFA. The physical and chemical properties of CBA and CFA is discussed in detail in this chapter. Moreover, this chapter Reports the mechanical properties of fresh and hardened concrete. The main properties of testing comprised compressive, split tensile and flexural strength tests; comprising UPV and drying shrinkage. In addition of that relationship between compressive, flexural and tensile strength are presented.

Chapter Five: The results and discussion of durability tests including sulfate attack, sulfuric acid attack and heat resistance conducted on normal concrete and those containing CBA and CFA are provided in this chapter. In addition of that, in this chapter microstructure involving field-emission scanning electron micrograph (FESEM), change in compressive strength and change in mass of concrete specimens under different durability tests are presented and discussed.

Chapter Six: This chapter evaluates and presents the leaching behavior of CBA, CFA and concrete particles incorporating CBA and CFA. It explains the result of Toxicity Characteristics Leaching Procedure (TCLP) and Semi-Dynamic Tank Leaching Procedure (SDTLP) methods by making relevant discussions base on the laboratory condition upon which the tests were conducted.

Chapter Seven: Concludes the findings and achievements of this study. Moreover, some recommendations are provided for future works in related areas to develop concrete application using CBA and CFA as replacement of sand and OPC.

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