THE PROPERTIES OF HIGH PERFORMANCE CONCRETE CONTAINING GRANITE QUARRY DUST (GQD) AND ELECTRIC ARC FURNACE SLAG (EAFS) AS AGGREGATES

LIM JAY SERN

UNIVERSITI SAINS MALAYSIA

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by

LIM JAY SERN

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LIST OF ABBREVIATIONS

CO_2	Carbon dioxide
OPC	Ordinary Portland cement
NRS	Natural river sand
GQD	Granite quarry dust
NGR	Natural granite rock
HPC	High performance concrete
SCMs	Supplementary cementitious materials
PFA	Pulverized fly ash
GGBS	Ground granulated blast-furnace slag
RCA	Recycled coarse aggregate
EAFS	Electric arc furnace slag
EU	European Union
XRD	X-Ray Diffraction
XRF	X-Ray Fluorescence
SEM	Scanning electron microscopy
SAI	Slag activity index
NCA	Natural coarse aggregate
UPV	Ultrasonic pulse velocity
ACI	American concrete institute
HSC	High strength concrete
RHA	Rice husk ash
SF	Silica fume
w/b	Water/binder
SP	Superplasticizers/superplasticizer
SiO_2	Silicon dioxide/free silica/soluble silica
Al_2O_3	Alumina/aluminum oxide
MgO	Magnesium oxide/periclase/dolomite
Na_2O	Sodium oxide
K_2O	Potassium oxide
LOI	Loss on ignition
ITZ	Interfacial transition zone

$AgNO_3$	Silver nitrate
RCPT	Rapid chloride penetration test
$MgSO_4$	Magnesium sulfate
SSA	Specific surface area
DRI	Direct reduced iron
CaO	Lime
NA	Natural aggregate
LA	Los Angeles loss
ER	Expansion rate
BD	Bulk density
SG	Specific gravity
WA	Water absorption
FM	Fineness modulus
AIV	Aggregate impact value
ACV	Aggregate crushing value
FeO	Ferric (II) oxide
Cr_2O_3	Chromium (III) oxide
MnO	Manganese (II) oxide
ZnO	Zinc oxide
CrO_3	Chromium oxide
NiO	Nickel oxide
CuO	Copper (II) oxide
K_2O	Potassium oxide
P_2O_5	Phosphorus pentoxide
TiO_2	Titanium dioxide
SO_3	Sulfur trioxide
AASC	Alkali activated slag concrete
AASFC	Alkali activated slag fly ash concrete
SSD	Saturated surface dry
LVDT	Linear variable displacement transducer
C-S-H	Calcium silicate hydrates
C-A-S-H	Calcium aluminate silicate hydrates
ASR	Alkali silica reaction
ACR	Alkali carbonate reaction

CIRI-CIRI KONKRIT BERKEKUATAN TINGGI MENGANDUNGI ABU BATU KUARI (GQD) DAN ABU RELAU ARKA ELEKTRIK (EAFS) SEBAGAI BAHAN PENGANTI AGREGAT

ABSTRAK

Penggunaan produk sampingan industri sebagai bahan pengganti pukal mentah menekankan untuk mengurangkan kesan karbon yang disumbangkan daripada industri konkrit. Kajian ini bertujuan untuk memeriksa optimum komposisi pasir sungai semulajadi-sisa kuari granit (NRS-GQD) dalam mortar campuran pertigaan dengan abu sanga relau bagas yang digiling-abu terbang (GGBS-PFA). Di samping itu, pengaruh abu relau arka elektrik (EAFS) sebagai bahan gantian granit semulajadi (NGR) terhadap sifat-sifat konkrit dan struktur panel papak konkrit tertakluk kepada beban lenturan empat mata dalam sistem pengikat campuran pengikat GGBS-PFA dan optimum NRS-GQD komposisi dalam agregat halus. Hasil kajian menunjukkan bahawa kemasukan GQD sebagai bahan pengganti NRS pada 60% dalam mortar campuran pertigaan GGBS-PFA menghasilkan sifat kekuatan optimum. Tambahan pula, penggunaan EAFS sebagai bahan gantian NGR telah meningkatkan kekuatan mampatan konkrit campuran pertigaan GGBS-PFA daripada 1.9% sehingga 18.7% pada hari ke-28 dan seterusnya. Keputusan juga menunjukkan bahawa terdapat peningkatan yang ketara dalam ketahanan konkrit campuran pertigaan GGBS-PFA terhadap udara, klorida dan sulfat dengan kemasukan EAFS sebagai gantian NGR. Namun, kemasukan EAFS sebagai bahan gantian NGR telah menjejaskan sifat penyerapan air, kapilari dan pori konkrit campuran pertigaan GGBS-PFA. Pengunaan EAFS juga dilaporkan meningkatkan beban retak pertama dan muktamad juga kekuatan penel papak konkrit.

THE PROPERTIES OF HIGH PERFORMANCE CONCRETE CONTAINING GRANITE QUARRY DUST (GQD) AND ELECTRIC ARC FURNACE SLAG (EAFS) AS AGGREGATES

ABSTACT

The utilization of industry by-product as the raw bulk replacement material has been emphasized to reduce the carbon footprint contributed from the concrete industry. This study was aimed to examine the optimum natural river sand-granite quarry dust (NRS-GQD) composition in ground granulated blast-furnace slag-pulverized fly ash (GGBS-PFA) ternary blended mortar. In addition, the influence of electric arc furnace slag (EAFS) as natural granite rock (NGR) replacement material towards the concrete properties and strutural responses in the manner of concrete slab panel subjected to four-points bending load in GGBS-PFA ternary blended binder system and optimum NRS-GQD composition as fine aggregate. The results showed that the inclusion of GQD as NRS replacement material at 60% in GGBS-PFA ternary blended mortar yielded the optimum mechanical strength. Moreover, the inclusion of EAFS tends to enhance the compressive strength of GGBS-PFA ternary blended concrete from 1.9% to 18.7% at 28 days onwards. The results also showed that there is a significant improvement in air, chloride and sulfate impermeability properties of the GGBS-PFA ternary blended concrete with the inclusion of EAFS as NGR replacement material. However, the inclusion of EAFS as NGR replacement material tends to impair the water absorption, capillary absorptivity and total porosity properties of the GGBS-PFA ternary blended concrete. The utilization of EAFS also reported enhanced the first and ultimate crack load also the stiffness of the concrete slab panel.

CHAPTER 1

INTRODUCTION

1.1 Background

Habert et al. (2012) reported that the building materials sector is one of the largest carbon dioxide (CO_2) emission contributor in the world. The carbon emissions contributed by building materials have included the extraction of raw materials, transportation, manufacturing, installation, loading and unloading of materials as well as deconstruction and disposed (Syngros et al., 2017). Hence, construction or building materials have become the main concern towards the effort on reducing the carbon dioxide emissions from the construction industry.

Concrete is a composite made of the combination of ordinary Portland cement (OPC), natural river sand (NRS), natural granite rock (NGR), and water which is majorly used in the construction industry due to its wide application and unique characteristics. In addition, it is an engineered material which meet almost any desired specification (Aprianti et al., 2015) to fit several kind of application such as buildings, water supply plants, industrial, residential and agricultural drainage units, also highway infrastructure (Palankar et al., 2016), depending on the need (Ingrao et al., 2014). Today, the current yearly consumption of concrete has surpassed $1m^3$ per person (Cembureau, 2015) and the demand of the concrete has been forecasted to increase by up to approximately 18 billion tons by 2050 (Monteiro, 2006). Therefore, the production of environmentally friendly concrete technology has become the current agenda in worldwide (Ingrao et al., 2014).

Dinakar et al. (2008) concluded that the fundamental elements to support an environmentally friendly concrete technology for sustainable development was through conservation of primary raw materials. Conservation of primary materials can be achieved through reductions in the consumption of cement, aggregates and water with the use of waste materials and industrial by-products. Such approach tends to utilize the renewable resources in concrete production, while, reducing the usage and the carbon footprint generated during extraction and manufacturing of the primary materials. Recycling of the industrial by-product is an effective way to reduce the use of natural resources and landfill areas, thus realizing cost savings and environmental friendly towards a more sustainable construction (Tam, 2008).

High performance concrete (HPC) is defined as a concrete with improved performances in terms of workability, strength and durability properties, which cannot be obtained with ordinary materials through conventional mixing, placing and curing operations (ACI, 2014). HPC has led to important advances in high-rise buildings and long-span bridges which allow engineer to increase the available space and reducing the costs of formwork, reinforcement steel and concrete demand. However, rapid development of concrete industry has induced a series of drawbacks mainly related to environmental carbon footprint. This becomes more apparent with an increasing trend associated to the actual and future growth of developing economies, demanding increasing quantities of natural raw bulk materials (Faleschini et al., 2015). Therefore, it has raised the attention of the researchers in finding the alternative materials to reduce the environmental impacts related to concrete production industry.

Supplementary cementitious materials (SCMs) is defined as a substantial quantity of waste materials produced globally as by-products from different sectors

with cementitious or pozzolanic properties to be used as binder in cementitious composites production. Such waste materials may be hazardous to the environment and human activities if not deposited safely. Hence, the conversion of these wastes into a more valuable products has become an alternative to conventional disposed method (Aprianti et al., 2015). Conventionally, silica fume, pulverized fly ash (PFA) and ground granulated blast-furnace slag (GGBS) were used as the SCMs to reduce the carbon footprint of the concrete through the reduction of the OPC consumption (Can et al., 2018) in HPC concrete production.

The carbon footprint contributed by the concrete production can be reduced further through reduction in the consumption of natural aggregates (Can et al., 2018) which are non-renewable (Wigum, 2015). The CO_2 emission from the aggregate production were from process of mining, blasting, transporting, including the electricity which contributed to the indirect emissions from crushing and screening operations (Moray et al., 2006; Sanal, 2018). A total of 48.3 billion tons of aggregates were forecasted to be used in the global construction industry per annum. With such demand, uncontrolled and abusive behavior on mining the natural aggregates would potentially lead to agricultural losses, rainforest destruction (Can et al., 2018), environmental pollutions (Ismail et al., 2013) and even depletion of natural aggregates in the future (Yong and Teo, 2009).

As an alternative solution, several environmental policies and regulations were set up by the Federal and State Governments in Malaysia to control and tighten the operational conditions of quarry activities. However, such regulations tend to increase the difficulty in obtaining a license and/or restrict the operation of a new quarry, consequently, reduced the production output of aggregates. In fact, the solution

provided tends to reduce the environmental issues, however, it will be a restriction towards the production of concrete aggregates to fulfill the aggregate demand in Malaysia. Therefore, the concrete industry is urged to shift towards the reproduction and the reuse of alternative aggregates by searching and fully utilizing the existing potential sources of aggregate (Ismail et al., 2013).

Granite quarry dust (GQD) is a waste produced from granite aggregate extraction process (Chouhan et al., 2017) in the form of fine particles with the size less than 5.0 mm (Ilangovana et al., 2008). Generally, granite has been used as coarse aggregate in concrete production with the sizes ranging from 40.0 mm to 5.0 mm which complied to the requirement in MS EN12620 (MSD, 2010a) for concrete application. The GQD which is a material with fine gradation (75μm to 5mm) was normally being rejected and disposed at the mining site or at the granite processing units (Almeida et al., 2007). Chouhan et al (2017) reported that disposal of GQD have degraded the environment in the manners of land degradation, visual effect, flooding of water and air pollution (Singh et al., 2015). Besides, random disposal of the dust especially for the size which is less than 75μm led to respiratory and allergy problems to the human (Chouhan et al., 2017) and also become a source of air pollution (Prakash and Rao, 2016). As aforementioned, a total of 48.3 billion tons of granite aggregates were forcasted to be used in the global construction industry per annum, and, about 25% of GQD was produced throughout the granite extraction process. Therefore, utilization of GQD as fine aggregates in concrete production was deemed to be an alternative to improve the sustainability credential (Can et al., 2018).

In addition, utilization of recycled coarse aggregate (RCA) from construction demolition has been popularly introduced as an alternative solution to reduce

environmental impacts as coarse aggregate replacement material in Malaysia (Yong and Teo, 2009; Kwan et al., 2012; Ismail and Ramli, 2014). However, Faleschini et al. (2015) summarized that fully utilization of RCA as natural coarse aggregate (NCA) replacement material through direct volume or weight replacement have led to a reduction of 20-25% in compressive strength in comparison to conventional mixtures. Additionally, the durability of RCA concrete decreases due to the higher porosity of RCA. In general terms, full utilization of RCA is advisable for the concretes application with low-medium compressive strength concrete with 20-40MPa but not for high strength or high performance concrete. The authors also summarized that the inclusion of RCA as coarse aggregate replacement material in HPC application does not yielded desirable results at high replacement level. Beyond 30% of total aggregate mass, the inclusion of RCA as NCA replacement material tends to reduce the mechanical and durability performance of the concrete. Therefore, the use of recycled aggregates derived from metallurgical industry have seems to be an alternative solution as coarse aggregate replacement material in concrete production to achieve sustainability goals of the concrete industry.

Electric arc furnace slag (EAFS) is a waste product from steel production process through EAF process which was being disposed and landfilled within the factory grounds (Sofili et al., 2010). Although such wastes have been classified as non-hazardous waste which can be disposed-off to appropriate landfills, however, disposal of such wastes requires large landfill area which is rather unfavourable in economical and long term (Tezara et al., 2016). In conjunction with the world steel production which was estimated to exceed 1781 million tons in 2020, and 250 million tons of EAFS was expected to be produced. It will be a huge amount of such waste to be managed (Yellishetty et al., 2010). Therefore, it has raised the attention of the

government, manufacturers and researchers, globally, in finding alternative way to reduce and adding value to the waste produced.

Utilization of EAFS from iron and steel manufacturing sector as a raw material in another industry has a great environmental aspect since the reuse or recovery of this material provides environmentally related benefits (Yuksel, 2017). Meanwhile, it also allows for a reduction of the amount of waste to dispose in landfill (Rondi et al., 2016). Currently, EAFS has been gaining ground among the European Union (EU) member as a useful "by-product" over the past few years (Liapis and Papayianni, 2015). In Malaysia, researchers have utilize EAFS in agricultural fertilizer (Sharif and Rezan, 2011), heavy-duty green ceramic tile (Teo et al., 2014) and aggregates of pavement (Oluwasola et al., 2014) application. With such application, reuse of EAFS in civil engineering application especially in as NCA replacement material in concrete production could positively alleviates the need for their disposal, reduce the use of natural resources (Yildirim and Prezzi, 2011) and contribution towards a more sustainable concrete development agenda.

1.2 Statement of problem

Overall, the concrete production has generated tons of carbon gaseous emission to the environment during the extraction, transportation and manufacturing process. It was believed the carbon gaseous emision should responsible to the green house effect. The extraction process of natural aggregates included NRS and NGR have raised the problems such as rainforest destruction, agricultural losess, environmental pollution and potentially caused to the depletion of such resources due to uncontrol mining activities. The disposal of the wastes from granite quarry and steel manufacturing

industry have caused to the environmental and human health related problem. Such process is unfavourable in terms of economical and long term to the manufacturers and environment.

There are several obstacles to be addressed in the effort towards producing a high performance ternary blended concrete with the utilization of GQD as NRS replacement material in fine aggregate fraction and EAFS as NGR replacement material in coarse aggregate fraction. The specific problem statements are presented as follows.

i. There is scattered literature on the cementitious composite made with the use of ternary blended binder system containing GGBS and PFA as cement replacement material and GQD as NRS replacement material. The intrinsic physical properties of the GQD potentially influence the concrete's mechanical strength and durability properties. Therefore, a proper GQD combination with NRS should be established for suitable use in the ternary blended binder system.

ii. The present literature is scatter with the knowledge on the influence of the properties of fresh concrete, mechanical strength, durability and dimensional stability properties of the ternary blended binder system incorporated high level of GGBS and PFA as cement replacement material with the inclusion of EAFS as NGR replacement material in the coarse aggregate fraction. The current literatures majorly focused on the high level inclusion of EAFS as NGR replacement material in the blended binder system. There is limited study the effect of the inclusion of EAFS as NGR replacement material at various content from 0% to 100% on the properties

of ternary blended cementitious composite with GGBS and PFA as cement replacement material.

iii. There is very limited reported literature on the structural responses of the concrete slab panel subjected to flexural load with the inclusion of EAFS as NGR replacement material in the ternary blended concrete.

1.3 Research aims and objectives

The detailed aims and objectives of the study are presented as follows:

1) To investigate the feasibility of the inclusion of GQD as NRS replacment material and the optimum replacement level of GQD in ternary blended mortar through mechanical properties.

2) To assess the influence of EAFS as the NGR replacement material with established optimum NRS-GQD composition in fine aggregate fraction in terms of the properties of fresh concrete, mechanical and durability performance, dimensional stability and microstructure of the hardened concrete.

3) To study the structural responses of concrete slab panel made with various EAFS as the NGR replacement material with ternary blended binder system.

1.4 Significance of research

This study aims to derive the experimental data on the use of waste materials such as GQD and EAFS to substitute NRS and NGR in fine and coarse aggregates

fraction, respectively, with the use of ternary blended binder system incorporated with GGBS and PFA as cement replacement material. The performance of cementitious composites with aforementioned materials included fresh cementitious composites properties, mechanical and durability performance, dimensional stability and microstructure of hardened cementitious composites were evaluated respectively to the objectives of the study.

The usage of the aforementioned waste materials such as GGBS, PFA GQD, and EAFS tends to reduce the carbon footprint from the concrete industry along with the modernization era. Besides, disposal of such wastes has become a serious environmental agenda which has threaten the human being in the future and concurrently influencing the environmental aesthetic. In fact, scientist nowadays still could not estimate the negative impact of the disposal of the aforementioned waste to that particular area in future development. Such commonly waste will no longer be treated as a waste material but as valuable materials for the production of high-performance concrete through recycling process. Hence, the possibility of such a recycling approach will promote a worldwide scale use of GGBS, PFA, GQD and EAFS as a sustainable source in high performance concrete production in the long term.

Furthermore, recycling of the aforementioned waste materials enables the cementitious composites manufacturer to produce a high-performance cementitious composites with higher profit margin. Through such an approach in the cementitious composites production, the cost of construction in terms of concrete will be reduced resulting in reduced cost in high rise building or infrastructure development. This is an essential outcome for the government currently to reduce the infrastructure

development cost without burden to the current national financial status which also beneficial to the government, the manufacturers, the developers and the end-users.

At the end of this study, several concrete slab panels with optimum NRS-GQD composition and various NGR replacement level through the use of EAFS ranging 0% to 100% in 20% of step increment by volume are fabricated for four-point bending load assessment to monitor the structural responses included the load-deflection response, service load capacity, the ultimate load capacity and failure mode of the concrete slab panels. These data can be used as a model to predict the structural behavior of high-performance ternary blended concrete with large volume GQD and EAFS as aggregates in structural application. This produced a knowledge framework for future design of reinforced concrete structures built using the GGBS-PFA ternary blended concrete with GQD and EAFS as fine and coarse aggregate fraction, respectively.

1.5 Scope of work

The major scopes of the research work are given as follows.

- Assessment on the chemical and physical properties of the materials included binder, fine and coarse aggregates.
- Establishing the optimum binder hybridization ratio incorporated GGBS and PFA as cement replacement material.
- Optimization on the superplasticizer dosage used in the optimum ternary blended binder hybridization ratio.

- Investigate the influence of the inclusion of GQD as NRS replacement material in fine aggregate fraction in the ternary blended binder system in terms of workability and engineering properties of the mortar and obtain the optimum NRS-GQD through the mechanical strength properties with the reference of durability and dimensional stability properties.

- Study the effects on the inclusion of various EAFS as NGR replacement material in coarse aggregate fraction on fresh concrete properties, mechanical and durability performance, dimensional stability behavior and microstructure development of the concrete with the use of established optimum ternary blended binder hybridization ratio, superplasticizer dosage and NRS-GQD composition.

- Investigation on the structural performance of the concrete slab panels made with the use of various EAFS as NGR replacement material in coarse aggregate fraction, established the optimum ternary blended binder hybridization ratio, superplasticizer dosage and NRS-GQD composition in fine aggregate fraction subjected to a four-point flexural load.

1.6 Layout of the thesis

There are total seven chapters covered in this thesis aimed to cover the major aspects of the engineering, durability and structural behavior of the high-performance ternary blended cementitious composites with a large volume of GQD and EAFS as natural aggregates replacement material in fine and coarse aggregate fraction, respectively. Chapter 1 has covered the brief background studies regarding the current

contemporary problems encountered in the cementitious composites production sector and the impact on the sustainability of the aforementioned industry. Meanwhile, the statement of the problem, research aims and objectives, significance of research and scope of work are also discussed in depth.

Chapter 2 has mainly covered the related literature review on the use GQD and EAFS in the concrete as NRS and NCA replacement in fine and coarse aggregate fraction, respectively. Besides, the physical properties and chemical composition of the GQD and EAFS used by the previous studies as NRS and NCA replacement material, respectively, have also covered. This chapter also covered the subsequent characteristics of the aforementioned material in the production of concrete production in terms of fresh properties, mechanical, durability and microstructural properties. The critical summary of all the reviewed literature and the research gap are summarized and presented at the end of Chapter 2.

Chapter 3 has covered the details of the experimental program and relevant test methodology which employed in the study to investigate the objectives of the study with the relevant international or national standards. Besides, the important parameters of the investigation and characteristics of materials used in the experimental program are also established in this chapter. The method to develop the optimum binder hybridization and superplasticizer (SP) dosage are also covered in this section. The details of the mix proportioning and the materials information are presented before the end of the chapter.

Chapter 4 encompassed the detail results on the optimization of NRS-GQD composition in the ternary blended binder system with the optimum SP dosage developed earlier. The results of the inclusion of the GQD as NRS replacement

material in the fine aggregate fraction of the ternary blended mortar included the workability, bulk density, ultrasonic pulse velocity (UPV), compressive and flexural strength properties are covered. The optimum NRS-GQD composition is then developed based on the mechanical strength performance with the reference of durability and dimensional stability properties of the ternary blended mortar as attached in Appendix IV.

Chapter 5 covers the discussion on the concrete properties with the inclusion of EAFS as NGR replacement material in coarse aggregate fraction of the ternary blended concrete with the optimum NRS-GQD composition which established at the earlier chapter. The assessed parameters included the setting times and workability of the fresh concrete, mechanical, durability and dimensional stability properties of the hardened concrete. Besides, the microstructure of the concrete is also covered with the selected test samples.

Chapter 6 covered the structural behavior of the concrete slab panels. The structural assessment includes load-deflection responses, service load capacity, the ultimate load capacity and mode of failure. An analytical method for predicting the serviceability moment capacity, ultimate moment capacity, crack width and crack spacing is also described in depth in this chapter.

The major findings and conclusion from the experimental works are summarized in the last chapter, Chapter 7. In addition, the recommendations for further research purposes are also discussed in depth at the end of this chapter.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview of High Performance Concrete (HPC)

American Concrete Institute (ACI) defined the high performance concrete (HPC) as a concrete which meets the special combinations of performance and uniformity requirements that are usually cannot be achieved routinely using conventional constituents and normal mixing, placing and curing practice. The ACI has summarized the HPC with regards characteristics including the ease of placement and compaction without segregation, lower heat released at the early stage, early age strength, development of long-term mechanical properties, volume stability and long life in severe environments (ACI, 2014).

For the past 15 years, the HPC evolved gradually and mainly by the production of concrete with higher strength ranging from 80 to 140MPa. Although HPC possessed high strength, however, it was not the same as high strength concrete (HSC), which HPC required other special characteristics including high modulus of elasticity, high density, low permeability and resistance to some forms of attack. Generally, the supplementary cementitious composites (SCMs) included pulverized fly ash (PFA), ground granulated blast-furnace slag (GGBS), silica fume (SF) or metakaoline (MK) was incorporated which potentially contributed to the enhancement in both mechanical and durability properties, also reduce the heat of hydration and slump lost at the early stage of placement of the HPC. In addition, in HPC, the coarse aggregate was well chosen which was typically smaller than the ordinary concrete with 10 to 14mm of nominal size of the aggregate was chosen as compared to the ordinary concrete which incorporated the nominal size of aggregate in the range of 20 to 45mm. The reason of using smaller aggregate size was to reduce the differential stresses at the aggregate-

cement paste interface which would potentially led to micro-cracking. Besides, the smaller aggregate particles were stronger as compared to the larger ones due to the fact that comminution of rock removes the largest flaw planes in aggregate, which control strength of aggregate. The coarse aggregates also have to be strong enough and clean which was free from adhering to any clay or dust, and also away from reactive silica. The shape must be equidimensional which was neither flaky nor elongated. Meanwhile, the fine aggregates was more preferably coarser with a fineness modulus of 2.7 to 3.0. In addition, the HPC should have low water/binder (w/b) ratio ranging 0.22 to 0.35. Therefore, the use of superplasticizers and SCMs were substantial to achieve the criteria while maintaining the desired workability. Theoretically, the lower w/b ratio tends to reduce the volume of the space originally occupied by water, and therefore enhanced the properties of concrete especially in mechanical strength performance (Aitcin, 1998).

HPC has led to important advances in civil engineering, especially in the high-rise buildings and long-span bridges application. With the use of HPC, the engineers were allowed to reduce the columns and beams size which increased the available floor space while reducing the costs in terms of formwork and reinforcing steel. Meanwhile, implementation of HPC in structural members also prolonged the structures' service life (Faleschini et al., 2015). Generally, HPC required high quantity of binders ranging from 400kg/m^3 to 550kg/m^3 as aforementioned (Aitcin, 1998). Such characteristic has become a setback towards the environmental footprint on our planet. However, the inclusion of SCMs as cement replacement was popularly discovered and widely in use in HPC application, therefore, the current research approach should be shifted to finding the alternatives to reduce the consumption on the natural bulk materials. It would be more beneficial towards the environmental friendly approach with the implementation of recycled material as the natural bulk materials in HPC application (Faleschini et al.,

2015). Besides, Aitcin (1998) claimed that there was limitation on mechanical strength performance of the HPC which was attributed to the limited mechanical strength of the natural aggregates.

2.2 The properties of GGBS-PFA ternary blended concrete

Ground granulated blast-furnace slag (GGBS) and pulverized fly ash (PFA) were popularly being used as supplmentary cementitious composites (SCMs) in ternary blended binder system. Such an approach tends to reduce the cement consumption from the concrete production, while, improving the concrete performances. However, the high cement replacement level with GGBS-PFA hybrid was reported tends to infleunce the setting performance and early ages strength of the concrete. The authors claimed that such result was due to the cement dilution effect. Besides, the latent hydraulic properties of GGBS and late pozzolanic reaction of PFA does not contribute in the formation of hydration products at the early ages resulting in less hydration products produced at the early ages. The authors also claimed that the presence of GGBS-PFA hybrid tends to increase the workability properties of the fresh concrete. The authors established that the finer particle size of GGBS tends to increase the paste volume, while, sperical particle shape of PFA have enhanced the movement of the neighbouring particles through ball bearing effect. (Zhou et al., 2012).

Cheah et al. (2016) have conducted an experimental program to investigate the bulk density of the ternary blended mortar which consist of GGBS-PFA hybrid in the ratio of 4 to 1 to replace the cement content with the step increment of 10% by binder volume. Similar bulk density results of the ternary blended mortar were observed along various replacement level. Meanwhile, there was increment in bulk density from 7 days

curing age to 28 days curing age. The authors established that the continuous hydration within the specimen have promoted a denser microstructure of the specimens. However, the bulk density of 60% to 100% of GGBS-PFA hybrid mortar were observed reduced. This was largely due to the continuous moisture loss due to the high porosity at the early ages of the ternary blended mortar. However, for the specimens with high content of cement, continuous shrinkage happens to the specimen causes reduction in volume and result maintain or increase in bulk density. The authors claimed that the inclusion of GGBS-PFA hybrid as cement replacement material tends to improve the 7 days strength as compared to the control mix. However, the results showed that beyond 60% cement replacement level, the compressive strength of the ternary blended mortar reduced. The authors attributed such improved performances to the presence of cement acted as an activator for GGBS-PFA hybrid to form aluminosilicate monomers and geopolymeric framework at the early age which have strengthen the primary calcium silicate hydrates (C-S-H) framework. However, the authors also reported that beyond 60% cement replacement level, the compressive strength of the ternary blended concrete was observed reduced at 7 days. Beyond 60% cement replacement level, the GGBS-PFA hybrid tends to retard the hardening process of the ternary blended mortar. Beyond 28 days, the authors reported that the presence of GGBS-PFA hybrid further improved the compressive strength of the ternary blended mortar, while, 50% of cement replacement level with GGBS-PFA hybrid exhibited the optimum mechanical strength performance. The presence of GGBS-PFA hybrid tends to further refine the micro-pores presence in the cementitious matrix resulting in enhanced the mechanical strength properties of the ternary blended mortar.

Güneyisi and Gesoglu (2010) have studied the mechanical strength properties GGBS-PFA ternary blended concrete as compared to coventional concrete. The GGBS

to PFA ratio was kept in 1 to 1 with the cement replacement level of 0%, 20%, 40% and 60%. From the results, the GGBS-PFA ternary blended concrete with 20% cement replacement level exhibited the highest mechanical strength performance among all of the concrete mixes at 90 days of testing ages, while the 28 days mechanical strength was lower than conventional concrete. The authors attributed to the presence of PFA have promoted the later age strength of the ternary blended concrete due to the late pozzolanic reaction. However, the results showed that the mechanical strength of the ternary blended concrete mixes was lower as compared to conventional concrete at 28 and 90 days of testing age. low mechanical strength as compared to the conventional concrete. As the cement replacement level increases, reduction in strength was observed more significant. The authors did not further explain on such observation. The authors also established that the presence of GGBS-PFA hybrid tends to reduce the drying shrinkage magnitude.

Jia (2012) have studied the carbonation of the concrete comprising of GGBS-PFA hybrid as cement replacement material. The GGBS to PFA ratio was kept at 60 to 40 and the cement replacement level was 50% to compare with conventional concrete using accelerated carbonation assessment. The result showed that the carbonation depth of ternary blended concrete was relatively higher than conventional concrete at all testing ages. The authors attributed such observation to the presence of GGBS-PFA hybrid tends to reduce the alkalinity of the concrete resulting in higher carbonation depth observed. The presence of GGBS-PFA hybrid tends to cunsumpt the portlandite contributed from the cement hydration process for secondary hydration and pozzolanic reaction resulted in reduced the alkalinity of the concrete. Besides, the presence of GGBS-PFA hybrid tends to reduce the cement content in the concrete which will also

reduce the alkalinity of the concrete. Therefore, the presence of GGBS-PFA hybrid have increased the carbonation depth of the concrete.

Cheah et al. (2019a) have investigated the properties of GGBS-PFA ternary blended concrete and control mix. The GGBS-PFA hybirdization ratio was kept at 4 to 1 and the cement replacement level using GGBS-PFA hybrid was ranging from 50% to 90% at 10% increment by binder volume. The results showed that the lower water demand was required by the ternary blended mortar. As the cement replacement level increases, the water demand was observed reduces. The authors attributed such performance to the smooth surface texture of GGBS particles and spherical shaped of PFA have increased the workability of the mortar mixes. Besides, the authors also reported that the ternary blended mortar mixes with 50% and 60% cement replacement level exhibited higher compressive strength as compared to the control mix. However, beyond 70% cement replacement level, the compressive strength reduces and comparatively lower than control mix. The authors attributed such observation to the cement dilution effect. As the cement replacement level increases, the cement content reduces. The secondary hydration and pozzolanic reaction from GGBS-PFA hybrid was highly dependent on the calcium hydroxide produced during cement hydration process. Hence, the amount of cement was insufficient when GGBS-PFA was used at high cement replacement level beyond 70% resulting in reduction in compressive strength.

2.3 Overview of the extraction process of granite quarry dust (GQD)

The natural granite rock (NGR) is a felsic intrusive igneous rock which is granular and phaneritic in texture (Rana et al., 2016). It is popularly used as the coarse aggregate in Malaysia due to its high availability (Khor, 2006) with the particle size

ranging from 5mm to 45mm which compliance to the coarse aggregate category of concrete as prescribed in BS EN12620 (BSI, 2008) according to the application.

Granite was extracted from granite quarrying process which consists of multi-stage of process. The granite extraction was started with the blasting of the quarry face. Subsequently, the blast granite rock was transported for primary crushing using a jaw crusher. The subsequent step aimed to crush the granite rock into smaller particles. Meanwhile, the fine material, dust or any remaining subsoil and weathered rock was screened via a vibrating feeder and drop into a separated conveyor belt. The screened material is called scalpings and is used as rock fill. The output from primary crusher was then conveyed onto the secondary crusher. The stone dust and small size crushed stone during the process was then screened again onto the blinding stockpiles. The larger sized stones produced from the secondary crusher was lastly conveyed to final crushing stages through a series of cone crushers and screens into the required aggregate sizes. During the granite quarrying process, there were a numbers of quarry products produced with various range of sizes for the various engineering application. Therefore, the screening process was important to differentiate the produced granite rock according to the sizes (NorthStone (NI) Ltd., 2018).

From the aforementioned granite quarrying process, the quarry fines or dust being produced with the particle sizes less than 4.75mm (Ilangovana et al., 2008). According to BS EN12620 (BSI, 2008), the coarse aggregate was categorized as the aggregate with the size which retained on a 5.0mm square hole test sieve. Therefore, the GQD produced does not fulfil to the coarse aggregate requirement prescribed in BS EN12620 (BSI, 2008). It was considered as a waste produced from the granite quarrying process due to its high availability and disposal rate on site. The physical properties,

chemical and mineralogical composition of the GQD established in the past findings in the application as the natural river sand (NRS) replacement were reviewed in the following sub-section.

2.3.1 Physical properties of GQD

This section aimed to discuss the physical properties of the GQD which was adopted as natural river sand (NRS) replacement in the past findings. According to the past findings, the GQD was subjected to sieving process to obtain the fine aggregate grading which comply to the international standard. Singh et al. (2016a) and Hunger and Brouwers (2008) reported that the GQD was angular and rough in texture which was observed from the scanning electron microscopy (SEM) image as shown in Figure 2.1 and 2.2. A similar observation was reported by Donza et al. (2002) who claimed that the GQD was angular in shape and crystalline in surface texture as showed in Figure 2.3. The GQD was observed angular in shape as compared to the natural sand which was relatively rounded in shape.

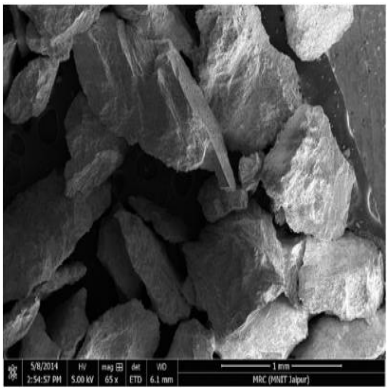


Figure 2.1 SEM image of GQD (Singh et al., 2016a).

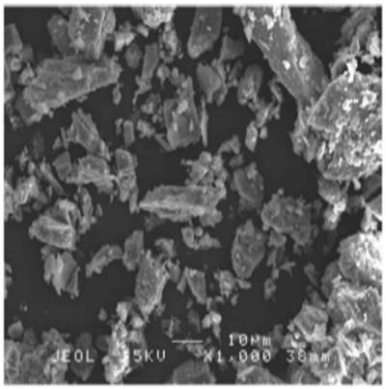


Figure 2.2 SEM image of GQD (Hunger and Brouwers, 2008).

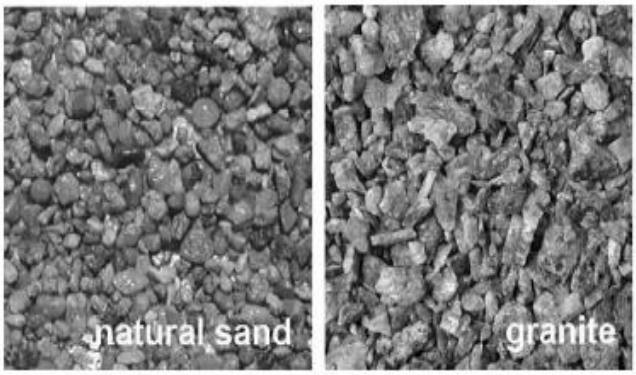


Figure 2.3 The natural sand and GQD stockpile (Donza et al., 2002).

The physical properties of the GQD established at the past findings were summarized in Table 2.1 included bulk density (BD), specific gravity (SG), water absorption (WA), fineness modulus (FM) and dust content with the sources and nominal size grading of GQD. The dust content referred to the particle size which was lesser than 75μm. The dust content of the GQD was referred as the silt and clay as stated in BS EN12620 (BSI, 2008). From Table 2.1, there was observed different in nominal size grading obtained at the past findings. The different in nominal size used in the studies was attributed to the different reference international standards. The BD of the GQD was found ranging from 1650kg/m^3 to 1850kg/m^3. The SG of the GQD was reported as ranging from 2.40 to 2.83 with the WA of 0.60% to 10.60% reported at the past studies.

The fine modulus of the GQD was reported ranging from 2.41 to 4.20. Lastly, the dust content was reported ranging from 10.45% to 13.00%.

Table 2.1 Physical properties of GQD.

References	**Sources**	**Nominal size grading (mm)**	**Physical properties**				
			BD (kg/m^3)	**SG**	**WA (%)**	**FM**	**Dust content (%)**
Donza et al. (2002)	Argentina	4.75	-	2.69	-	3.15	10.70
Raman et al. (2005)	Malaysia	4.75	-	2.63	0.60	4.20	-
Kou and Poon (2009)	China	5.00	-	2.61	0.89	3.56	-
Joel (2010)	Nigeria	No stated	-	2.54	-	2.79	-
Felixkala (2010)	India	4.75	-	2.58	-	2.43	-
Raman et al. (2011)	Malaysia	5.00	-	2.83	0.78	3.41	13.00
Balamurugan and Perumal (2013)	India	4.75	1850	2.57	-	2.41	-
Rai et al. (2014)	India	4.75	1800	2.54	1.40	-	-
Bishnoi and Bala (2015)	India	No stated	-	2.50	0.50	2.90	-
Singh et al. (2015)	India	5.00	-	2.56	4.63	2.57	-
Suman and Srivastava (2015)	India	4.75	-	2.40	-	2.85	-
Singh et al. (2016b)	India	5.00	-	2.62	4.36	2.57	-
Rai et al. (2016)	India	4.75	-	2.73	5.90	2.46	-
Kankam et al. (2017)	Ghana	2.00	1650	2.64	10.60	3.54	10.45

The particle size distribution of GQD obtained from the past findings was summarized in Table 2.2. Based on Table 2.2, the particle size distribution obtained in the past studies varies. Such varies were highly dependent on the GQD stockpile. From the results obtained by Donza et al. (2002), the particle size distribution of GQD was consists of higher fraction of coarse fraction which was larger than 1.18mm. The particles size distribution from the other authors were found consist of higher fraction which the size was smaller than 1.18mm.

Table 2.2 Particle size distribution of GQD.

References	**Cumulative percentage of passing (%)**						
	5.00mm	**4.75mm**	**2.36mm**	**1.18mm**	**600µm**	**300µm**	**150µm**
Donza et al. (2002)	-	100	72	44	31	22	16
Kou and Poon (2009)	100	-	85	73	61	40	25
Felixkala (2010)	-	100	98	93	62	47	26
Rai et al. (2014)	-	96	94	82	67	22	5

2.3.2 Chemical and mineralogical composition of GQD

Singh et al. (2015) reported the chemical composition of GQD consists of 72.57% free silica (SiO_2), 15.63% alumina (Al_2O_3), and small quantities magnesium oxide (MgO, 0.83%), sodium oxide (Na_2O, 4.21%), and potassium oxide (K_2O, 6.76%). Meanwhile, the chemical composition of NRS consists 84.73% free silica, 10.66% alumina, 1.33% MgO and 3.28% K_2O. Such results indicated the chemical composition