TERNARY BLENDED CEMENT CONCRETE UTILIZING RICE HUSK ASH AND GROUND GRANULATED BLAST-FURNACE SLAG AS CEMENT REPLACEMENT

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by

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LIST OF ABBREVIATIONS

$Ca(OH)_2$	Calcium Hydroxide
CH	Calcium Hydroxide
CO_2	Carbon Dioxide
C-S-H	Calcium Silicate Hydrate
C_2S	Dicalcium Silicate / Belite
C_3S	Tricalcium Silicate / Alite
DMT	Dynamic Modulus Test
GGBS	Ground Granulated Blast-furnace Slag
ITZ	Interfacial Zone
OPC	Ordinary Portland Cement
PC	Portland Cement
PFA	Pulverized Fuel Ash
RHA	Rice Husk Ash
RCPT	Rapid Chloride Penetration Test
SiO_2	Silica
SEM	Scanning Electron Microscopy
SF	Silica Fume

SP	Superplasticizer
UPV	Ultrasonic Pulse Velocity
XRD	X-Ray Diffractometry
XRF	X-Ray Fluorescence

PENGGUNAAN ABU SEKAM PADI DAN SANGA KISAR RELAU-LETUPAN SEBAGAI GANTIAN SIMEN UNTUK PENGHASILAN KONKRIT SIMEN TIGA CAMPURAN

ABSTRAK

Konkrit adalah bahan yang terbanyak digunakan di dunia. Setiap tahun, pertumbuhan penduduk meningkat dan penggunan konkrit akan bertambah sejajar dengan keperluan tempat tinggal. Simen adalah bahan penting dalam konkrit, ia merupakan pengikat utama dalam konkrit. Seperti yang dilaporkan oleh banyak sumber, industri pembuatan simen menyumbang 6-8% daripada pelepasan karbon dioksida global serta proses intensif tenaga, dan mengurangkan sumber asli kita, terutamanya batu kapur. Pengeluaran simen memberi kesan berbahaya kepada persekitaran kita, oleh itu pengurangan penggunaan simen adalah penting. Dalam kajian ini, abu sekam padi (RHA) dan sanga kisar relau-letupan (GGBS) digunakan dalam konkrit sebagai gantian simen. Hibridisasi bahan-bahan telah dilakukan dalam nisbah optimum untuk memastikan prestasi yang optimum. Aspek seperti kekuatan mekanikal dan sifat ketahanan dinilai, dan semua spesimen dibuat dalam 3 unit untuk mendapatkan purata. Untuk mendapat pemahaman mendalam tentang sifat bahan, kajian seperti pemeriksaan mikroskop elektron (SEM) juga dijalankan. Gabungan RHA dan GGBS dalam konkrit sebagai pengganti simen meningkatkan sifat kekuatan dan ketahanan spesimen pada usia pegawetan jangka lama. Pada usia pengawetan awal, prestasi keseluruhan sebanding dengan spesimen kontrol. Cadangan nilai gantian adalah antara 10% hingga 40%, penggantian lebih dari nilai ini akan membuatkan prestasi spesimen menurun. Kebanyakan spesimen ditambah baik dari segi struktur liang roma yang dilakukan oleh RHA, dan juga tindak balas pozzolanik yang menghasilkan kalsium silikat hidrat sekunder (C-S-H).

TERNARY BLENDED CEMENT CONCRETE UTILIZING RICE HUSK ASH AND GROUND GRANULATED BLAST-FURNACE SLAG AS CEMENT REPLACEMENT

ABSTRACT

Concrete is the most used materials in the world, in most part of the world, shelters are made of concrete. As the population growth increases every year, the need for shelter will consequently increase with the demand of concrete. Cement is an important material in concrete, it acts as the main binder. Cement manufacturing industries contributes up to 6-8% of the global carbon dioxide emission as well as energy intensive process and depletes our natural resources. Due to the harmful effects to our environment, hence the need to reduce the usage of cement is crucial. In this research, the materials, rice husk ash (RHA) and ground granulated blast-furnace slag (GGBS) were used in concrete as a cement replacement. The hybridization of the materials was done in an optimum ratio to ensure proper replacement value of the materials. Important aspects such as the mechanical strength and durability properties are assessed, and all specimens were fabricated in 3 units to get the average. To gain further understandings on the properties of the binder, a study of microstructural level, such as scanning electron microscopy (SEM) was also conducted. The incorporation of RHA and GGBS in concrete as cement replacement enhances the strength and durability properties of specimens especially at the later curing age, at the early curing age, the overall performance was comparable to the control. It is suggested that the replacement range value shall fall between 10% to 40% to get the optimum performance. Most specimens are refined in terms of pore structure due to the pore fillings effect of RHA, and also the pozzolanic reaction that produces secondary calcium silicate hydrate (C-S-H).

CHAPTER 1

INTRODUCTION

1.1 Background of Research

The production of Portland cement (PC) is well known as one of the main contributors in emissions of greenhouse gases, specifically carbon dioxide (CO_2). As reported by one of the sources, 6% of the world's CO_2 emissions is accounted by the cement and aggregates production industries. Since PC is the most widely used construction material today, it has been intensively manufactured to sustain its demands. The production of 1 tonne of cement will yield 1 tone of CO_2. In 1994, Davidovits (1994), estimated about a total of 3500 million ton of world cement CO_2 emissions will be produced within 25 years. The figure increases by around 5% every year. Due to the aforementioned issues, intensive research in pursuing the reduction of global carbon footprint from utilizing supplementary cementitious materials (SCMs) as partial cement replacement materials to develop a whole new binder phase (Cheah & Ramli, 2012). In this particular research, the author uses rice husk ash (RHA) and ground granulated blast furnace slag (GGBS) as a supplementary binder in concrete. Many researchers draw their attentions experimenting on RHA to resolve the problems in conservation of energy and resources, especially in the rice growing countries (Methta, 1992). Since rice husk ash is high in silica (SiO_2) content, therefore the exploitation and utilization of the SiO_2 has recently become a major research subject in the recent years (Agarwal, 2006; Asavapisit & Ruengrit, 2005; Bui, Hu, & Stroeven, 2005; De Sensale, 2006; De Sensale, 2010; Vayghan, Khaloo, & Rajabipour, 2013). When rice husk ash is subjected to combustion under the temperature of 500°C-700°C, the resultant silica content of RHA will be present in an amorphous state (Ganesan *et al.*, 2008) which led to its high reactivity as a pozzolanic material. There are many advantages reported in incorporating RHA as a supplementary cementitious material, few of it are increased durability (Coutinho, 2003) and reduced effects of alkali silica reaction (ASR). Sugita *et al.* (1997) suggested that:

i. the average pore size of rice husk ash concrete is reduced, compared with that of control concrete;
ii. the effective water to binder (w/b) ratio of rice husk ash concrete is less than the used one because a portion of free water has been absorbed in the abundant number of mesopores present on surface of rice husk ash particles and having an average pore diameter of about 80Å;
iii. hydration of cement is improved; and more C-S-H gel may be formed in rice husk ash concrete due to the reaction that probably occurs between the silica in rice husk ash and the Ca^{2+}, OH^- ions or $Ca(OH)_2$ in cement hydration (Justnes, 1997; Sugita *et al.*,1997)

Rice husk ash is considered as a natural pozzolan. Most natural pozzolans when included into concrete mix will tend to increase water requirements to achieve desired flow because of their microporous character and high surface area (Barger et al., 2001; Malhotra & Mehta, 1996).

In last decade, the use of supplementary cementing materials has become an integral part of high strength and high performance concrete mix design. The materials used can be natural occurring, by-products or industrial wastes. The use of these supplementary cementitious materials has posed many challenges to the researchers on the mean to implement the supplementary cementitious material technology into industrial use to reduce the deleterious effects of process incurred in production of cement, hence the carbon footprint. Generally, some commonly used supplementary cementitious materials are pulverized fuel ash (PFA) or commonly known as fly ash, ground granulated blast-furnace slag (GGBS), silica fume (SF) and rice husk ash (RHA). RHA is known to have a high pozzolanic activity, which is mainly attributed to high amorphous silica content and the very large surface area governed by the porous structure of the particles (Jamil *et al.*, 2013). When RHA is burnt under controlled condition, highly reactive RHA will be produced, where the silica contents can be as high as 90% or even 100%. The reactivity is also favored by increasing its fineness (Givi *et al.*, 2010; Rukzon *et al.*, 2009). Another widely used binder that are being used in this research is the GGBS. The usage of GGBS in concreting is commonly known for its ability in enhancing the properties of concrete in terms of durability and strength. GGBS are basically a by-product of steel making industries which are being utilized into good use in the present time. GGBS has been used widely in Europe for its known enhancements to concrete, and nowadays it is increasingly used across Asia and United States. GGBS is known for its sulfate resisting properties and also mitigating alkali-silica reaction (Cervantes *et al.*, 2017). GGBS also behave like cement (hydraulic). The usage GGBS are quite popular in self-consolidating concrete (SCC), SCC is also making an impact on the construction world as it needs no additional vibrations of any means to consolidate as it can consolidate itself with just the help of gravity. Besides having many advantages in terms of concrete enhancements, the usage of GGBS is also economical, as reported by the American Concrete Institute committee, ACI 233R-03 (ACI, 2003) Since RHA and GGBS are considerably abundant, therefore the research significance of this work is to see which strength level can be presently achieved by using the combination of these two materials in replacing cement for concrete production. Optimization of all the 3 materials (RHA, GGBS and OPC) is carried out with the help of simple mathematical proportioning model known as the Absolute Volumetric Method as defined in the technical report of American Concrete Institute ACI 211.1R.

1.2 Problem Statement

There are several obstacles that are being faced in research field currently, which are:

i. The use of cement as the main binder in the construction industry posed many deleterious effect on the environment as its' process of production requires a lot of energy intensive steps, and also involve the process of acquiring the raw materials to make cement requires explosives to break down the limestone into smaller attainable size, which will constantly change the land contour of the limestone hill.

ii. The requirement of a type of measurements for managing the industrial wastes from the rice manufacturing and steel production sector should be established through a proper and efficient ways of planning, especially in terms of disposal.

iii. In the present knowledge, the use of rice husk ash in concrete production may require pre-treatment process on the ash. This in turn raises the embodied energy and cost of the material, hence confining its use for the purpose of academic studies rather than practical implementation in the concrete manufacturing sector.

iv. Very limited current knowledge has been established on the mechanical strength, durability performance, rheology, and microstructures development of ternary blended low embodied carbon concrete containing raw RHA and GGBS.

1.3 Research Question

There are several research questions that can be derived from the problem statement. The questions are as the follows:

i. Based on the various aspects of parameters covering mechanical performance, durability performance, rheological properties and microstructural development, is the incorporation of RHA and GGBS as cement replacement in concrete production feasible?

ii. What is the most efficient method to incorporate the industry by-products namely RHA and GGBS as a measure for recycling the material for use in concrete production sector?

iii. As compared to conventional concrete, does the ternary mix comprises of RHA, GGBS and PC performs better or worse in terms of mechanical, durability, rheological properties and microstructural development?

1.4 Research Objectives

This study has few objectives which all are concentrated on the sustainability of the construction industry. In the construction industry, there are 4 main constraints that are taken into consideration, which are; time, cost, environmental impact and energy consumption. These constraints are mainly about the efficiency of delivering the idea of sustainability. The industrial wastes have been increasing yearly in terms of its production, therefore intensive moves have been established to incorporate the industrial waste into the production of environmental friendly materials. RHA is one of the industrial wastes that are being utilized presently in research and development of eco-friendly concrete material.

RHA is known for its high content of silica. In this study the potential of RHA when mixed with GGBS and cement was comprehensively studied. This involves a proper characterization of the physical and chemical properties of RHA and GGBS, followed by studies on the mechanical properties, dimensional stability, impermeability characteristic, microstructure of concrete, water absorption properties and atmospheric carbonation of ternary blended concrete containing RHA-GGBS as supplementary binder material at various degree of cement replacement. All these parameters will provide a more in depth understanding on the ternary blended concrete containing RHA and GGBS

The overall objectives of this research are:

1. To study the possibility of reducing the use of Ordinary Portland cement in the formulation of industrial grade concrete with the incorporation of GGBS and RHA.
2. To determine the optimum combination of RHA and GGBS for use as cement replacement materials in concrete production.
3. To assess the mechanical strength, durability performance, rheological properties and microstructures development of RHA-GGBS ternary blended low embodied carbon concrete material.

1.5 Significance of Research

A thorough characterisation on the chemical and physical properties of industrial ash for hybridization towards self-sustained solidification and stabilization of the wastes will be achieved from the study. The production of cement lead to the depletion of natural resources of the main raw materials used, limestone. Therefore this study also promote the alternative sustainable ways of producing alternative binder phase to partially replace the usage of cement at high volume of replacement.

Novel theory on the reaction kinetics of the hydration reaction between GGBS and high amorphous silica RHA materials to form solidified products will be developed from the study. The ground granulated blast-furnace slag contain high amount of calcium, which when mixed in proper proportion with rice husk ash which are high in amorphous silica, will trigger a pozzolanic reaction. The reaction involves the role of the amorphous silica, calcium (in presence of water) and the hydration products, calcium hydroxide to form the gel that give rise to the strength development of concrete, which is calcium silicate hydrates.

Knowledge on the method for large volume stabilization of biomass energy waste ash for use as construction materials will be formulated at the end of the study. A specified fractions of RHA-GGBS and cement are established at the end of the investigation. A high strength concrete (M50) comprises of three different materials (OPC,GGBS and RHA) are to be fabricated at its optimum mix design and performance. M50 concrete are used to construct a structure that have to withstand dynamic loading or high rise building above 40 floors. M50 concrete are going to be used widely in the future due to the rapid development of cities with skyscrappers. With more understanding of the utilization of RHA ang GGBS, a greener concrete with strength of M50 can be fabricated to suits the need in the future to produce green building.

1.6 Scope of Work

The major scopes of works in the research are given as follows:

i. Establishing stable hybridization matrix of ternary blended concrete consisting RHA, GGBS and cement from the optimization process of mixing.
ii. Evaluation on properties of ternary blended concrete.
iii. Study the effect of variance of dosage hybridization ratio of RHA-GGBS as cement replacement in concrete inclusion on rheological, durability and mechanical properties of concrete.
iv. Study the different effects of various RHA-GGBS inclusion dosage in concrete as partial cement replacement on durability properties of concrete.
v. Assessment on dimensional stability of ternary blended concrete with the inclusion of different dosage of RHA-GGBS.

To establish a stable hybridization matrix, various combination ratio of ternary blended concrete consisting of RHA-GGBS and cement is experimented. The parameters for this investigation are the mechanical properties, which includes; compressive strength and flexural strength, durability tests, which consists of water absorption test, porosity test, carbonation test, capillary absorption test, permeability test, and chloride permeability test. The study also highlights on the rheological properties of the fresh mortar mix, which includes the setting time test, standard consistency test, and soundness of the specimen.

CHAPTER 2

LITERATURE REVIEW

2.1 Ordinary Portland Cement (OPC)

Ordinary Portland cement, which are largely used in the construction are produced from the calcination of limestone and clay according to the reaction:

$5CaCO_3 + 2SiO_2 \longrightarrow (3CaO,SiO_2)(2CaO,SiO_2) + 5CO_2$ (Davidovits, 1994)

Under the heat of approximately 1450°C during the calcination process in the kiln, it causes the calcium from the limestone to combine with the silicon in the clays. This forms mainly calcium silicates (C_2S and C_3S) and also some calcium aluminates (C_3A + C_4AF). The process also releases some carbon dioxide as described in the reaction above.

Cement is a binder, a material that sets and hardens and can bind other materials together. Cement can be categorized in 2 different characters, hydraulic or non-hydraulic, depending on the ability of cement to set in the presence of water. OPC is a hydraulic cement s it can set and harden in the water. OPC become adhesive due to chemical reaction between the dry ingredients and water. The chemical reactions yield minerals hydrates that are not so water soluble and so are quite durable in water and safe from chemical attack.

The hardening of cement is rather a chemical reaction in the presence of water particles. As the cement grains dissolve in the water, it releases the calcium ions and silicon ions into the water, which will then form the Calcium Silicate Hydrate matrix (C-S-H). The C-S-H matrix will fill up the spaces between the cement grain and water, using up free pore water, and become solid. Strength will develop quickly at first, and slows down over time. In fact, the formation of C-S-H matrix slows down very rapidly over time; this could be correlated with when all the surfaces of cement grains are completely covered with the C-S-H matrix. The hydration of cement can be varying by factors such as: temperature, amount of water presence, and presence of other supplementary cementitious materials (SCM)

2.2 Supplementary Cementing Materials (SCM)

Currently, supplementary cementing materials (SCM) have been making its way to the construction field. SCM are materials that possess the characteristic of the widely known binder material, cement, it contributes to the properties of hardened concrete or mortars through hydraulic or pozzolanic activity. Most commonly known SCMs are, fly ashes, slag cement (Ground, granulated blast-furnace slag, GGBS), and silica fume. These materials are often added into concrete to make concrete mixtures more economical, increase the durability, enhance strength or influence other properties of concrete. SCM can be used as partial replacement in cement for concrete or mortars production. Most SCMs that are used in the present time are the by-product of the industrial activities, for example, fly ash is a by-product of thermal power generating stations. It is a finely divided residue that is results from the combustion of pulverized coal and is carried from the combustion chamber of the furnace by exhaust gases. GGBS is a glassy granular material formed when molten iron blast-furnace slag is quenched rapidly, specifically by using water sprays or immersion in water and subsequently ground to a fineness similar to that of cement. Silica fume is a finely divided residue resulting from the production of elemental silicon or ferro-silicon alloys that is carried from the furnace by the exhaust gases, it is well known for its advantage in producing high-strength concrete.

2.3 Calcium Silicate Hydrates (C-S-H)

Calcium silicate hydrates are the most abundant reaction products in the cement paste during the process of hydration, it is in the form of gel in layers that attributed to the binding properties of cement. The C-S-H gel occupies about 50% of the paste volume, it also responsible for most of the engineering properties of cement paste. During the hydration period of cement, the belite (C_2S) and alite (C_3S) will react with water to form C-S-H and calcium hydroxide. C-S-H can be identified as low-density C-S-H and high-density C-S-H. The less dense gel is more porous and forms rapidly during the early hydration period, while the denser gel, which is less porous, forms slowly over days and weeks. Generally, the rate of formation of C-S-H gel is rapid at the early period of hydration process and decreases over time. Beside the process of hydration, C-S-H could also be formed from the process called pozzolanic reaction, the difference between pozzolanic reaction and hydration is pozzolanic reaction requires lime or calcium hydroxide ($Ca(OH)_2$), which is produced during the hydration process. Pozzolanic reaction involves siliceous or aluminous materials to react with calcium hydroxide to produce secondary C-S-H. Usually the pozzolanic reaction only occurs at the later curing age of concrete as not all the calcium hydroxide produced during the hydration process will also react with cement alumina and sulfates to form components such as ettringite (Dunstan, 2011).

2.4 Superplasticizers

Superplasticizers are basically a high-range water reducer; it’s a type of chemical admixture that are widely used in the construction world currently to boost the quality of concrete, specifically in term of rheology of the concrete. In concrete, when cements are mixed with water, the cement particles tend to be drawn towards each other due to its’ forces of attraction, it is a natural chemical phenomenon in concrete called flocculation. Superplasticizers molecules will temporarily suppress the forces of attraction between the cement particles by attaching itself to the cement particles, which the phenomenon is called the dispersion effect. The new generation of superplasticizers is represented by polycarboxylate ether-based superplasticizer (PCE), with a relatively low dosage (0.15-0.3% by cement weight) they allow a water reduction up to 40%, due to their chemical structure which enables good particle dispersion. Since in most cases concrete's strength performance are influenced by the water to cement ratio (by weight), therefore superplasticizer is invented to enable the production of concrete with lower water to cement ratio. The addition of superplasticizers in concrete leads to the production of self-consolidating concrete and high-performance concrete. The invention of superplasticizers opens up greater opportunities for the designer and engineer to play with their designs. Figure 2.1 shows the effect of superplasticizers on cement particles.

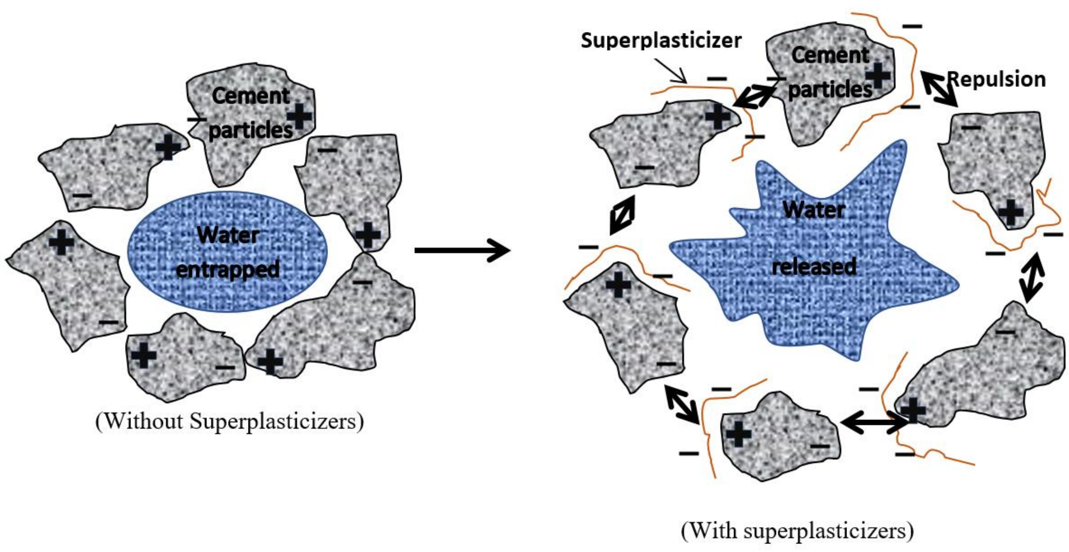

Figure 2.1 The effect of superplasticizers on cement particles. Adapted from Kong *et al.* (2013)

2.5 Rice Husk Ash (RHA)

RHA is basically rice husk which has been burned and converted into ashes. On the other hand, rice husk is an agricultural residue obtained from the covering of rice grains during the milling process. From 600 million tons of paddy produced in the world, 20% of it are the rice husk produced (Bhanumathidas & Mehta, 2001; Ramezanianpour, Mahdikhani, & Ahmadibeni, 2009; Kishore, Bhikshma, & Prakash, 2011; Jamil, Kaish, Raman, & Zain, 2013). Rice husk were converted to ashes from the uncontrolled burning about temperature of below 500°C, rice husk ash that are produced in this way are expected to have adverse effect towards its pozzolanic reactivity, the ignition was not complete and considerable amount of unburnt carbon was found in the resulting ash. In order to produce a reactive RHA in terms of pozzolanic reactivity, it has to be burnt under a temperature of up to 700°C (Ramezanianpour et al., 2009; Habeeb & Mahmud, 2010). Before RHA was found to be useful as a mineral admixture in concrete and also a pozzolanic material, they were usually dumped into water streams and leads to the pollution and contamination of springs (De Sensale, 2006; De Sensale et al., 2008).

RHA can act as a pozzolan varies in pozzolanic activity index, depending on the degree of grinding and the burning temperature. Characteristic of RHA can be varies depending on type or origin of paddy used, method of productions, or the temperature of burning; a controlled temperature will keep the silica in amorphous state. Moreover, the micro porosity and the high surface area of the product also contribute to very high pozzolanic activity even when the material is not grounded to a fine particle size yet, for instance silica fume and metakaolin. The globalization era has given rise to new technologies that open doors to many ways of utilizing RHA. RHA has been widely used in the world as a source of biomass energy production, mainly to reduce the environmental impact due to improper disposal (Fernandes et al., 2016). Besides being used as a source of biomass energy production, rice husk ash also finds it uses in the productions of waterproofing materials, flame retardant, insecticides, oil spill absorbent, specialty paints etc.

2.5.1 Physical Properties of RHA

RHA particles have a porous structure with high surface area. When RHA is observed under scanning electron microscope, it was found that it possess a microporous nature, similar to that of diatomaceous earth and volcanic ash (Malhotra & Mehta, 1996). The high surface area and microporous nature of RHA caused it to demand more in water consumption. The fine particles of RHA operates as a refinement on the pore structure of cementitious system, and act as nucleation point for hydration products, and restrict development of deleterious crystals formed during the hydration process (De Sensale *et al.,* 2008). In terms of visual observation, the as-received rice husk ash are coarse and grainy, they are usually prior ground to a certain fineness before used as binder in concrete productions. Some rice husk ash are even chemically treated before it is suitable for concrete use, such as the RHA used by Salas *et al*. (2009)

2.5.2 Chemical Properties of RHA

RHA are mainly constituted of silica. Silica is one of the main minerals in RHA that will react with calcium hydroxides to form the binder matrix that give strength to the concrete, which is secondary the Calcium Silicate Hydrate (C-S-H). Based on the past studies done by several researchers, the X-Ray Fluorescence (XRF) results indicate that, RHA's major mineral is SiO_2, which make up to 90.1% of the minerals content in RHA. Table 2.1 shows the chemical properties of RHA studied in terms of its' oxides.

Table 2. 1 Typical oxides analyses of rice husk ash.

Source	Chemical Composition (%)								
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	MnO	Na_2O	K_2O	SO_3
Uruguay RHA (De Sensale, 2006)	87.2	0.15	0.16	0.55	0.35	-	1.12	3.6	0.32
USA RHA (De Sensale, 2006)	88.0	0	0.1	0.8	0.2	0.2	0.7	2.2	-
India RHA (Ganesan et al., 2008)	87.32	0.22	0.28	0.48	0.28	-	1.02	3.14	-
China RHA (Bie et al., 2015)	92.09	0.1	0.07	0.97	0.53	-	0.11	4.04	0.55
Thailand RHA (Chatveera & Lertwattanaruk, 2011)	78.12	0.31	0.23	0.08	0.34	-	0.17	0.82	0.09
Pakistan RHA(Rapid Cooled) (Khan et al., 2012)	89.5	0.40	2.86	0.30	0.25	-	-	0.25	-
Pakistan RHA (Slow Cooled) (Khan et al., 2012)	84.0	2.01	1.39	0.6	0.85	-	-	0.85	-
Greece RHA (Antiohos, Papadakis, & Tsimas, 2014)	93.15	0.13	0.18	0.89	0.4	-	0.16	1.63	0.10

2.6 Mechanical Strength Development of Concrete with Rice husk ash

The effect of RHA as a partial cement replacement indicates some good improvement on mechanical properties. As reported by Givi *et al*. (2010b), the inclusion of RHA as partial cement replacement enhances the compressive strength of concrete, but the optimum replacement level of OPC by RHA to yield maximum long term strength enhancement, the replacement level is in range of 10% up to 30%. On the other hand, a recent study by Mandandoust (Madandoust *et al*., 2011) also stated that the inclusion of 20% RHA in concrete as cement replacement yields lower strength at early age, but in the long term the results indicate a pozzolanic activity in

RHA contained concrete and the strength development is comparable to normal concrete at the age of 270 days.

2.6.1 Mechanical Properties

In terms of mechanical properties, most of the past studies reported a lower early strength, and higher or equal to the control in terms of long term strength. This is due to slow reaction of RHA, compared to ordinary Portland cement. The reaction mechanism of RHA when incorporated in concrete is mostly by pozzolanic reaction. A pozzolanic reaction occurs when a siliceous or aluminous material get in contact with calcium hydroxide (CH) or Portlandite in the presence of humidity to form compounds exhibiting properties similar to that hydrates of cement (Papadakis & Tsimas, 2002; Snellings *et al*., 2010). In the case of RHA in concrete, the pozzolanic reaction occurs between the amorphous silica in RHA and CH from the hydration product of cement paste, this reaction will produce a kind of gel similar in the hydration of cement, which is called the calcium silicate hydrate (C-S-H).

It is observed that the C-S-H gel produced between the reaction of CH and RHA is flocs-like in morphology and has a porous structure (Chandrasekhar *et al*., 2006; Yu *et al*., 1999). The reaction of the RHA with water and CH formed during the hydration of cement that caused the formation of C-S-H (Madandoust *et al*., 2011). C-S-H gel is the main constituent that gives the cement its strength, especially in early strength development. Ordinary Portland cement usually has higher early age strength because of the abundant of C-S-H gel produced from hydration process. The reaction between these two components, amorphous silica and CH, are evidently presented by Yu *et al*. (1999), based on the data from reaction results between amorphous silica in RHA and CH, it indicates that the amount of calcium hydroxide in 30% replacement of RHA in cement paste begins to decrease after 3 days, and by 91 days it reaches nearly zero, while in the control paste it is considerably increased with hydration time. Yu *et al.* (1999) used chemically pure $Ca(OH)_2$ to study the reaction between silica in RHA and the OH^- ions by reusing the method proposed by Luxan *et al*. (1989). It was observed that the change in electrical conductivity of saturated $Ca(OH)_2$ solution at 40 ± 1°C after the addition of RHA was 3.22 mS/cm, which shows the RHA has a very good pozzolanic activity (Yu *et al*., 1999). Sivakumar and Ravibaskar (2009) reported their findings based on SEM observation, they found that after just one hour, the surface of RHA particles are covered by hydration products, after one day, most of the calcium hydroxide may have reacted with RHA.

2.6.2 Compressive Strength

In terms of compressive strength, RHA when added as a cement replacement, will react chemically and physically to contribute in strength development. RHA enhance the strength of concrete by the reaction between Silica and lime (Calcium Hydroxide) to form the C-S-H gel that contributes to the strength development. Physically, RHA has a large surface area and its fine particles act as a filler in between cement particles, therefor as a result the structure of the specimens become more packed. Compressive strength is the vital parameter of concrete that needs to be checked, it determines whether the concrete is providing sufficient strength to support the load that it will take.

The incorporation of RHA as partial replacement of cement enhances the compressive strength of concrete, but the optimum replacement level of cement by RHA to provide optimum long term strength enhancement has been reported between 10% up to 30% (Givi *et al*., 2010b). Ganesan *et al*. (2008) concluded that concrete containing 15% of RHA showed an utmost compressive strength and adverse effect at elevated content more than 15%. Zhang *et al*. (1996) suggested that 10% RHA replacement exhibited higher strength than that of control at all ages. Dakroury *et al*. (2008) reported that using 30% RHA as a replacement of cement could be considered optimum for all content of w/c ratios in an investigated mortars because of its high value of compressive strength. Mahmud *et al*. (1996) reported that 15% RHA in cement replacement as an optimal level for achieving maximum strength. Another studies reported by Ganesan et al.(2008) reported that RHA does enhance the long term strength in blended cement concrete. Similar to that of Givi's results, also shows that in the long term strength development, RHA incorporated concrete has a comparable value to that of control (Givi *et al*., 2010b). Madandoust *et al*. (2011) also reported that partial replacement of cement (specifically 20% by binder weight) indicated that at short term ages, the growth in strength is lower for RHA concrete compared to the control specimens, however in the long term, the outcome directed a pozzolanic activity in RHA concrete and the strength development is comparable to normal concrete. This proves that RHA does improve the mechanical strength of blended concrete, especially at the later ages. Another factor that contributes to the increase in strength of RHA concrete is the filler effect of fine particles properties of the material which translate into a stronger transition zone at the paste-aggregate interface. The RHA particles tend to act as filler and decreases the spacing of paste-aggregate interfacial zone. Table 2.2 – 2.3 shows the compressive strength results obtained by Ganesan *et al*. (2008) and Givi *et al*. (2010).

Table 2. 2 Compressive strength results obtained by Ganesan *et al.* (2008).

Mix	**RHA%**	**Compressive Strength (MPa)**			
		1 day	3 days	7 days	28 days
R0	0	11.6	20.9	27.2	37.0
R1	5	12.0	22.1	27.4	38.9
R2	10	12.8	24.4	27.8	42.8
R3	15	13.8	28.9	29.3	46.7
R4	20	12.2	24.8	28.3	39.8
R5	25	11.7	23.6	27.6	38.3
R6	30	11.1	20.7	27.4	37.0
R7	35	10.4	18.4	26.4	36.0

Table 2.3 Compressive strength results obtained by Givi et al. (2010a)

Mix	**RHA%**	**Compressive Strength (MPa)**		
		7 days	28 days	90 days
R0	0	27.3	36.8	42.3
R1	5	25.7	38.7	43.5
R2	10	25.1	40.6	46.1
R3	15	23.7	37.9	42.7
R4	20	21.5	36.7	41.3

Gastaldini *et al*. (2007) investigated the effect of chemical activators Which are sodium sulfate, potassium sulfate, and sodium silicate (N_2SO_4, K_2SO_4, and Na_2SiO_3) by weight of cement on RHA concrete with 20% substitution of cement by RHA using three different w/b ratios (0.35, 0.5, 0.65). Gastaldini found that chemical activators yielded a huge increase in strength at the early age of 7 days, which was the desired goal. K_2SO_4 activated mixture showed the highest increment when compared with the sample without activator. Table 2.4 below shows the results obtained.

Table 2.4 Results of compressive strength of concrete with RHA by Gastaldini et al. (2007)

Mix	**w/b**	**Compressive Strength (MPa)**		
		7 Day	28 Day	91 Day
Ref	0.35	58.3	64.2	76.1
	0.5	36.4	47.7	53.5
	0.65	24.6	28.0	31.9
20RHA	0.35	54.2	69.7	83.4
	0.5	36.4	48.1	53.9
	0.65	17.7	27.0	33.6
20RHA, 1% Na_2SiO_3	0.35	59.2	73.3	82.8
	0.5	39.5	50.7	56.5
	0.65	25.3	36.8	42.5
20RHA, 1% K_2SO_4	0.35	65.9	77.4	91.0
	0.5	47.2	54.3	71.0
	0.65	28.9	38.9	48.3
20RHA, 1% Na_2SiO_3	0.35	54.2	74.4	77.5
	0.5	37.4	48.7	53.8
	0.65	29.1	40.3	45.1

Another study done by De Sensale *et al.* (2006) presented the development of compressive strength up to 91 days of concrete with RHA. De Sensale *et al.* (2006) used 3 different water/binder ratio (0.32, 0.4, and 0.5) with two fixed replacement level for all the different w/b ratio. He used two types of RHA from different sources, which are rice husk from USA and Uruguay (UY). Both RHA has almost the same silica content above 80%. The residual RHA used in his work was dry-milled for the duration required to achieve a mean particle size of 8 μm (Mehta, 1994). Based on X-Ray Diffraction analysis, the USA RHA is considered to be non-crystaline RHA, on the other hand, the UY RHA showed crystalline rice husk ash which were identified as cristobalite. De Sensale *et al*. (2006) used a rapid analytical method to evaluate amorphous silica in the rice husk ashes according to Paya *et al*. (2001). The percentage of reactive silica content in USA and UY RHA was 98.5% and 39.55% respectively. The reactive silica here refers to amorphous silica. Table 2.5 presents the results of the investigation.

Table 2.5 Test Results of compressive strength by De Sensale et al. (2006).

w/b	RHA	%	Compressive Strength (MPa)		
			7 Day	28 Day	91 Day
0.32		0	48.4	55.5	60.9
	UY	10	51.1	60.4	64.3
		20	44.3	54.8	62.7
	USA	10	39.5	51.4	64.5
		20	30.5	47.4	68.5
0.4		0	35.8	42.3	45.6
	UY	10	41.1	50.4	54.9
		20	27.9	40.7	51.4
	USA	10	29.7	40.8	51.5
		20	23.6	39.4	57.3
0.5		0	24.6	32.9	35.9
	UY	10	24.1	31.5	35.5
		20	24.9	34.9	37.9
	USA	10	22.7	34.5	44.4
		20	20.8	35.9	52.9

De Sensale *et al*. (2006) concluded that the increase in compressive strength of concrete with residual RHA is better justified by the filler effect (physical) than by the pozzolanic effect (chemical/physical). The increase in compressive strength of concretes with RHA produced by controlled incineration is mainly due to the pozzolanic reaction. Therefore it was concluded that RHA contributed a positive effect on the compressive strength of concrete at early ages, but in the long term, the enhancement of the concretes' compressive strength with RHA was more significant (De Sensale, 2006). Based on De Sensale's conclusion, it is clearly portrayed that RHA with lower amorphousness such as the UY RHA will contribute in terms of filler in between large particles of cement.

Ramezanianpour *et al*. (2009) studied the inclusion of RHA as a partial cement replacement. Homogenous RHA was produced at temperature of 650°C with burning duration of 60 minutes and Type 1 Portland Cement as the main binder. Cube specimens of dimension 100 x 100 x 100 mm were used to test the compressive strength. A total of 4 concrete mixtures were made; one used as a control for comparison, and the other 3 are with 7%, 10%, and 15% of RHA replacement in cement. The slump was kept constant at 70 ± 10 mm and superplasticizer was used at very low percentages according to the results obtained for the slumps. All specimens were compacted via external vibration and were kept protected after casting to avoid the loss of water through evaporation. The specimens were demolded after 24 hours and cured at 23 ± 2°C in a lime-saturated water to prevent possible leaching of $Ca(OH)_2$ from these specimens. The curing regime employed to the specimens was 3, 7, 28, and 90 days of moisture curing. The compressive strength results are presented in Table 2.6.