WATER PERMEABILITY OF RECYCLED AGGREGATE CONCRETE CONTAINING NEW POZZOLAN MICRONISED BIOMASS SILICA MATERIAL

PM. DR. ISMAIL BIN ABDUL RAHMAN
SURAYA HANI BT ADNAN
MIA WIMALA SOEJOSO
DR. AHMAD MUJAHID BIN AHMAD ZAIDI

FUNDAMENTAL RESEARCH GRANT SCHEME
NO. VOT: 0385

UNIVERSITI TUN HUSSEIN ONN MALAYSIA
ABSTRACT

Natural Aggregate (NA) is an essential ingredient for producing concrete. However, NA is a depleting resource and the quarrying and mining process are not environmental-friendly. Thus, Recycled Aggregate (RA) is introduced as an alternative material to replace NA. Such an approach has been widely accepted in developed countries like United Kingdom, United States, Netherland, Denmark and Hong Kong. Nevertheless, concrete containing RA or known as Recycled Aggregate Concrete (RAC) has certain weakness in terms of permeability. This study is conducted in depth to explore ways to overcome these problems. Micronised Biomass Silica (MBS) has been recognised as a material with a good potential for such application. MBS is derived from controlled incineration of rice husk which is amorphous and with silicon dioxide (SiO₂) content for about 87.67%. The reduction of MBS particle size to 25.77 μm was by means of jar mill. The grade of 25 MPa concrete was produced with cement content 450 kg/m³ and w/c 0.5. MBS are used as cement replacement material for up to 12% by weight and RA was used for up to 100%. Comparative study was conducted with three different conditions namely; concrete with RA, concrete with MBS and MBS-RA concrete was carried out. It was found that the incorporation of 12% MBS and 100% RA has produced concrete with water permeability coefficient 7.94 x 10⁻¹² m/s and water penetration depth 64.5 mm for 28 days age of concrete and its compressive strength is 35.40 MPa. Furthermore, Scanning Electron Microscopy (SEM) was used to examine the microstructure of RAC and Natural Aggregate Concrete (NAC). It was observed that the quality of RAC significantly influences by ITZ. Regression analysis was also conducted to establish the relationship among different parameters (compressive strength, water permeability coefficient and water penetration) for RAC, NAC, MBS concrete and MBS-RA concrete. It was discovered that compressive strength has strong relationship with water permeability coefficient and water penetration. Two equations were proposed for predicting the compressive strength and water penetration for RAC and MBS-RA.
concrete. For proposing these equations, SPSS 14 was used. A nomograph chart as a guideline to designing RAC (with or without MBS) was also developed as the outcome of this study. This chart named as Nomograph Chart MBS-RA Concrete which comprises four axes represent cement content, compressive strength at 28 days or 365 days, percentage of RA and water penetration. Nomograph Chart MBS-RA Concrete is proposed to be used for designing MBS-RA concrete at 28 and up to 365 days.
'Natural Aggregate' (NA) adalah satu bahan yang penting untuk menghasilkan konkrit. Bagaimanapun, NA adalah satu sumb yang semakin menyusut dan proses kuari dan perlombongan adalah satu proses yang tidak mesra alam. Lantas, 'Recycled Aggregate' (RA) diperkenalkan sebagai bahan alternatif untuk menggantikan NA. Pendekatan ini telah diterima pakai secara meluas di negara maju seperti United Kingdom, United States, Netherland, Denmark dan Hong Kong. Namun, konkrit yang mengandungi RA atau dikenali sebagai 'Recycled Aggregate Concrete' (RAC) mempunyai beberapa kelemahan dari segi kebolehtelapan. Kajian ini dijalankan secara khususnya untuk mencari kaedah untuk mengatasi masalah ini. Micronised Biomass Silica (MBS) telah dikenalpasti sebagai satu bahan yang berpotensi digunakan sebagai jalan penyelesaian. MBS yang berasal dari pembakaran terkawal sekam padi adalah bersifat amorfus dan mempunyai kandungan silikon dioksida (SiO₂) sebanyak 87.67%. Pengurangan saiz partikel MBS kepada 25.77 μm telah dijalankan dengan menggunakan 'jar mill'. Gred konkrit 25 MPa telah dihasilkan dengan kandungan simen 450 kg/m³ dan nisbah air/simen yang digunakan adalah 0.5. MBS digunakan sebagai bahan pengganti simen sehingga 12% dan RA digunakan sebagai bahan pengganti NA sehingga 100%. Kajian perbandingan dijalankan dengan tiga keadaan berbeza iaitu konkrit dengan RA, konkrit dengan MBS dan konkrit MBS-RA. Didapti penggunaan 12% MBS dan 100% RA telah menghasilkan konkrit dengan pekali kebolehtelapan air 7.94 \times 10^{-12} \text{m/s} dan kedalaman penetrasi air adalah 64.5 mm untuk umur konkrit 28 hari dengan kekuatan mampatannya adalah 35.40 Mpa. Selanjutnya, 'Scanning Electron Microscopy' (SEM) telah digunakan untuk memeriksa mikrostruktur RAC dan 'Natural Aggregate Concrete' (NAC). Dari pemerhatian yang telah dijalankan di dapatk kualiti RAC dipengaruhi oleh ITZ. Persamaan regresi juga telah dijalankan untuk mengukuhkan hubungan antara parameter berbeza (kekuatan mampatan, pekali kebolehtelapan air dan penetrasi air)
untuk RAC, NAC, konkrit MBS dan konkrit MBS-RA. Didapati bahawa kekuatan mampatan mempunyai hubungan yang kuat dengan kebolehtelapab air dan penetrasi air. Dua persamaan telah dicadangkan untuk meramalkan kekuatan mampatan dan penetrasi air untuk RAC dan konkrit MBS-RA. Untuk mencadangkan persamaan ini, SPSS 14 telah digunakan. Carta nomograf sebagai panduan untuk merekabentuk RAC (dengan MBS atau tanpa MBS) juga telah dicipta sebagai hasil kajian ini. Carta ini dinamakan sebagai ‘Nomograph Chart MBS-RA Concrete’ dan ia mengandungi empat paksi yang mewakili kandungan simen, kekuatan mampatan pada 28 hari atau 365 hari, peratusan RA dan penetrasi air. ‘Nomograph Chart MBS-RA Concrete’ boleh digunakan untuk merekabentuk konkrit pada 28 dan sehingga 365 hari.
CHAPTER 1

INTRODUCTION

1.1 Background of study

Construction industry plays an important role in Malaysia in becoming a developed country in year 2020. For Gross Domestic Products (GDP) in year 2007, the construction industry activity has contributed about 2.5% (Construction Industry Master Plan Malaysia, 2007). According to Construction Industry Master Plan Malaysia (2007), the construction industry in Malaysia has created the job for about 800,000 people. Thus, from this number, it is clearly shown that how construction industry having a great effect for job sector in Malaysia.

On the other hand, government and private sectors play a main role in Malaysia’s construction industry. For example, government has responsibility to build the social and economic infrastructure like hospitals, schools; highways; dams and airport for ensure the society’s comfortable. Meanwhile, private sector has to play their role in building the factories, office buildings and housing as for their business interest. So, it can be seen how important the construction industry role for ensure these necessity is fulfilled.

Although construction industry activity is conducting actively, the environment protection must also be in parallel progress. Realizing of this situation, Construction Industry Development Board (CIDB) has introduced some policies which one of them is adopting waste reduction methods (Construction Industry Master Plan Malaysia, 2007). Additionally “Green Building Materials” concept also has been promoted for ensuring the effectiveness of environment conservation in construction industry activities. This concept is focusing on application of recycle material as construction material and less
consumption of energy for producing concrete. For supporting this concept, Recycled Aggregate (RA) has been introduced as a construction material.

In developed countries such as United Kingdom, United States and Denmark, the application of RA in their construction industry has been practiced for quite some time. The source of RA is from demolition of old building which lead into landfill problem. Hansen (1992) has estimated that from 1992 until 2000, three times of demolished waste concrete would be generated yearly. Thus, to overcome this matter the demolition waste has been turned into RA.

Although RA has widely been used in some developed countries, its utilization in Malaysia is assumed as new material in construction industry. Less interest in RA application is may due to some factors such as lack of review of RA performance in concrete and there is still sufficient supply in natural resources. The landfill area for construction waste has not been so critical in Malaysia. However, as a responsibility society, the application of RA in the construction industry to protect the natural resources is much important.

In this study, RA was used to produce concrete. RA which is produced from demolished or crushes concrete is being partially or fully replace the natural aggregate (NA) for producing concrete. According to Exteberria et al. (2007) and Kong et al. (2010), the concrete producing by using RA is known as Recycled Aggregate Concrete (RAC). However, RAC generate lower quality of concrete compared to Natural Aggregate Concrete (Ridzuan et al., 2001; Fraaij et al., 2002; Zaharieva et al., 2003a; Topcu & Sengel, 2004). This is the major issue as far as use of RA in concrete is concerned.

Other equally indicators to determine the quality of concrete made of RA are its workability and durability (Neville & Brooks, 2004). Therefore, the durability of RAC, in terms of its water permeability was emphasized in the present study. Moreover, RAC is recognised to have a lower durability compared to Natural Aggregate Concrete (NAC) and it was revealed by Olorunsogo & Padayachee (2002) and Zaharieva et al. (2003a). Based on their study it showed that RAC possess lower durability characteristic.

Therefore, it is foreseen that an application of pozzolans would increase the performance of RAC. Hence, this study was initiated. In the present study, Micronised Biomass Silica
(MBS) will be introduced as a new pozzolanic material to increase the performance of RAC especially in durability and it was measured in terms of water permeability. The permeability of MBS-RA concrete specimens in the present study was measured using the modified DIN 1048 equipment which was developed.Conventionally, 150 mm and 200 mm cube size is used as specified according to the DIN 1048. However, for this study, 100 mm cube was used instead of 150 mm and 200 mm for economic reason. In addition, the smaller size could be more feasible for determining the water permeability in laboratory and also at site.

MBS is derived from controlled incineration of any biomass waste. In the present study, rice husk has been chosen as a raw material for producing high silica content of MBS. Rotary furnace was set up to fixed temperature of 500 °C as to obtain a white amorphous silica within one (1) hour. However, in previous studies such as Nehdi et al. (2003), Coutinho et al. (2003) and Ganesan et al. (2008) normally rice husk ash is produced by using temperature in range 650 °C- 750 °C. Moreover, study by Ismail & Waljuddin (1996) burned the rice husk at temperature between 400 °C -700 °C to produce rice husk ash which the temperature is not fixed. Thus, it can be seen that MBS is dissimilar with rice husk ash in terms of its process in burning rice husk by using controlled temperature at 500 °C. Gambhir (2004) stated that rice husk ash contained about 80-90 percent of amorphous SiO₂ thus higher percent of SiO₂ was expected for MBS. It is hypothesised that with addition of MBS, very high content of amorphous SiO₂, is intended to improve the lower permeability of RAC and it was experimented and to be proven in the present work.

1.2 Objectives of Study

The objectives for this study are listed as follows:

i) To identify the characteristics of MBS as pozzolanic reactive partially cement replacement material.
ii) To determine the optimum percentage of MBS and RA for producing lowest water permeability of RAC.

iii) To establish a relationship in terms of mathematical model between compressive strength, water permeability and water penetration of RAC incorporated MBS.

iv) To develop a guideline chart for producing RAC with incorporation of MBS.

1.3 Scope of Study

The scopes for this study can be divided and described in the following stages:

i) Preparation of materials
The RA was obtained from the crushed waste cube specimens. The crushed waste cube was grind and crushed using the jaw crusher. The age of waste cube was not accounted. For MBS, it was produced by burning the rice husk in furnace with control temperature at 500 °C. Jar mill was used to produce a particle size of MBS at 25 μm. Another raw material used for present study are Ordinary Portland Cement (OPC), fine aggregate, Natural Aggregate (NA) as coarse aggregate, superplasticizer and water.

ii) Characterisation of materials
For RA and NA the tests that were conducted are sieve analysis, specific gravity, Aggregate Crushing Value, Aggregate Impact Value, Water Absorption and Flakiness and Elongation Index. For MBS, the test that conducted includes fineness using particle size analyzer, microscopic examination using Scanning Electron Method (SEM), Pozzolanic Activity Index, X-Ray Fluorescence (XRF) and X-Ray Diffraction (XRD).
iii) Optimisation of MBS and RA content to be incorporated in the concrete

The optimisation of MBS and RA content was assessed by determining the MBS-RA concrete compressive strength and water permeability. The percentage replacement of MBS used in present study is 0%, 4%, 8% and 12% and the various percentages replacement of RA used in present study are 0%, 25%, 50%, 75% and 100%.

iv) Statistical Analysis

The statistical analysis was conducted to ascertain the correlation between different parameters such as compressive strength, water permeability coefficient and water penetration with the replacement level of RA and also MBS,

v) Establishment of Mathematical Model

The mathematical model was developed to predict the compressive strength and water permeability for concrete incorporating different content of RA and MBS.

vi) Establishment of Nomograph Chart

The nomograph chart was produced as a guideline to formulate MBS-RA concrete.

1.4 Significance of Study

The depletion of natural aggregate becomes an issue as far as construction industry is concerned. Thus, one alternative material which is RA has been suggested its application as to reduce this problem. However RA has lower performance while be utilize as aggregate in concrete compared to NA. Hence, MBS is used as pozzolanic material for increasing the performance of RA. The MBS-RA concrete is determining its performance in terms of compressive strength and water permeability. Thus it is hope that the outcome of present study will contribute a knowledge which can be used to produce a good durability of RAC in terms of water permeability and the findings from present study will contribute in promoting and attracting the use of RA as alternative materials for construction industry in Malaysia. Moreover, with the employment of RA
iii) Optimisation of MBS and RA content to be incorporated in the concrete

The optimisation of MBS and RA content was assessed by determining the MBS-RA concrete compressive strength and water permeability. The percentage replacement of MBS used in present study is 0%, 4%, 8% and 12% and the various percentages replacement of RA used in present study are 0%, 25%, 50%, 75% and 100%.

iv) Statistical Analysis

The statistical analysis was conducted to ascertain the correlation between different parameters such as compressive strength, water permeability coefficient and water penetration with the replacement level of RA and also MBS,

v) Establishment of Mathematical Model

The mathematical model was developed to predict the compressive strength and water permeability for concrete incorporating different content of RA and MBS.

vi) Establishment of Nomograph Chart

The nomograph chart was produced as a guideline to formulate MBS-RA concrete.

1.4 Significance of Study

The depletion of natural aggregate becomes an issue as far as construction industry is concerned. Thus, one alternative material which is RA has been suggested its application as to reduce this problem. However RA has lower performance while be utilize as aggregate in concrete compared to NA. Hence, MBS is used as pozzolanic material for increasing the performance of RA. The MBS-RA concrete is determining its performance in terms of compressive strength and water permeability. Thus it is hope that the outcome of present study will contribute a knowledge which can be used to produce a good durability of RAC in terms of water permeability and the findings from present study will contribute in promoting and attracting the use of RA as alternative materials for construction industry in Malaysia. Moreover, with the employment of RA
and MBS in this study is hopefully can decrease the waste problem (concrete waste disposal and rice husk disposal) in Malaysia.

1.5 Organisation of Thesis

Chapter 1 presents the background of study, objectives of study, scope of work and significance of study.

Chapter 2 entails the literature review on the factors that influence the properties of pozzolans and the findings from previous studies on RA and RAC. Studies on using different types of pozzolans are also included.

Chapter 3 provides the information on methodology adopted in this study.

Chapter 4 presents the information about MBS as cement replacement material. Results obtained from physical properties testing (particle size analyzer, surface area, microscopy image and amorphous properties), chemical properties testing (chemical composition) and consistency testing (standard consistency) for concrete containing MBS is presented in this chapter.

Chapter 5 provides the methodology and results of testing conducted on RAC and RAC with and without MBS. The methodology encompasses compressive strength test and water permeability test. The results are presented in terms of compressive strength, water permeability coefficient and water permeability penetration for series of concrete (RA replacement 0%, 25%, 50%, 75%, 100% and MBS replacement 0%, 4%, 8%, 12%). A model for compressive strength and water penetration of MBS-RA is presented in this chapter. A guideline for producing RAC with incorporation MBS in terms of nomograph chart is also included.

Chapter 6 presents the conclusion and recommendation for further works.
CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Concrete is a solid material which widely been used nowadays in construction industry. This solid material is produced when cement, coarse aggregate, fine aggregate, water and admixture are mixed thoroughly. Concrete is becoming a favourite choice because its basic ingredients are easily found, require little maintenance service, easy to handle, most economical material, good in compression, durable and good fire resistance.

Since concrete is preferred option as construction material, the reducing in source of natural material i.e. aggregate is concerned. If the application of natural aggregate is not well organized, the depletion of natural aggregate will resulted. Thus, in the present study, the natural aggregate was replaced with alternative material which is known as RA.

However, concrete which is produced by RA is reported does not have equivalent quality as concrete produced by NA thus; reduce the attraction for RA application in concrete. From the literature search, it was recognised that mortar attached to RA has lead into this drawback. Hence, studies to find way to improve the performance of RAC are worth explored.

According to Kou et al. (2007); Ann et al. (2008); Corinaldesi & Moriconi (2009), utilisation of pozzolanic material could enhance the performance of RAC. In the present study, MBS is pointed out as a potential pozzolanic material to improve the properties of RAC. With the employment of MBS, the inferior performance as a result
of using RA expected to be compensated, and will support the RA application in construction industry.

2.2 Aggregate

Aggregate is an inert material used in producing concrete. Generally three-quarters or 75 per cent place by volume of concrete is filling-up by aggregate (Neville, 2004 and Gambhir, 2004). This granular material plays an important role in strength and durability of concrete performance.

A large volume of concrete is produced when aggregate is dispersed out in cement paste and normally aggregate’s source is from natural rock and gravel. Aggregate has some advantages like it is a cheap material, high volume in stability and good in durability than that of concrete with fully cement mix.

Parent rock or source of aggregate plays an important role for determining the properties of aggregate itself. Properties of aggregate like specific gravity, crushing value, impact strength and water absorption will give an effect to the performance of fresh and hardened concrete. The factors that lead into aggregate properties are like weathering, abrasion method and crushing of parent rock. Some descriptions about aggregate properties such physical properties, mechanical properties and grading of aggregate were explained at following section.

2.2.1 Physical Properties

The performance of concrete was actually influenced by physical property of aggregate. Physical properties of aggregate are such as specific gravity, bulk density, porosity, water absorption and moisture content and water absorption. In this sub-section, physical property of aggregate was reported.
Specific gravity of aggregate is important physical property to determine as to indicate aggregate’s density. The density is required to fulfilled the mix proportioning for ascertain the quantity of aggregate obligatory for specified concrete volume (Mindess, Young & Darwin, 2003). ASTM C 127-93 has defined that specific gravity is the ratio of mass or weight in air of a unit volume of material to the mass of the same volume of water at the stated temperature. Specific gravity can also be expressed as density which:

\[
\text{Specific Gravity} = \frac{\text{density of solid}}{\text{density of water}}
\]

Aggregate containing some porosity and specific gravity is depending either the pores in including in measurement. It is important to identify the type of pores either it is permeable or impermeable pores (Neville & Brooks, 2004). Permeable pores are pores that link to the surface of the aggregate particles and impermeable pores are pores that are preserved within the particles. Absolute specific gravity is refers to volume of solid material excluding all pores and apparent specific gravity is refers to solid material including impermeable pores but not the capillary pores. Between these two types of specific gravity, apparent specific gravity is generally been used in concrete practice. Gambhir (2004) stated that specific gravity of aggregate could become as an indicator of concrete strength i.e. the higher specific gravity of aggregate, the higher strength of concrete.

The second physical properties of aggregate are bulk density. Bulk density of aggregate is mass of material in either compacted or in incompact condition in a given volume and expressed in kg/m³ (Neville & Brooks, 2004). It is also known as unit weight. Bulk density is calculated from the mass of compacted and incompact aggregate that fills a measure of known volume. According to Gambhir (2004), this property is significant to verify the consistent in aggregate grading.

Porosity of aggregate which is the third physical properties of aggregate is much related to its bonding characteristic with cement paste. Pores of aggregate are in various sizes. According to Neville (2004), the smallest pore of aggregate is larger than gel
pores in cement paste. Generally the porosity in aggregate is in range from 0 to 50%. It is estimated that three-quarter of aggregate is in concrete volume. Hence, the porosity of aggregate contributes to overall porosity performance in concrete (Gambhir, 2004).

Another physical property of aggregate is water absorption. Water absorption is referred in percentage which it is the ratio of increasing in mass to mass of dry sample and conducted according to BS EN 1097-3:1998. In order to measure the water absorption of aggregate, weight of water which has been absorbed by aggregate in saturated surface dry (SSD) condition within 24 hours is determined. Hence, water absorption can become as an indicator for water contained in aggregate in SSD condition (Neville & Brooks, 2004). According to Mindness et al. (2003), aggregate with high water absorption illustrates the aggregate has high porosity and will lead into high permeability of concrete produced. On the other hand, water absorption data is significant as for determining the required water in mix proportion of concrete (Mehta & Monteiro, 1993, and Gambhir, 2004).

The performance of fresh and hardened concrete for RAC is influenced by water absorption of RA (Khalaf & DeVenny, 2004; Etxeberria et al., 2007; Li et al., 2009). Thus, it can be concluded that these physical properties are among factors that will influence the performance of Recycled Aggregate Concrete containing Micronised Biomass Silica.

2.2.2 Mechanical Properties

Mechanical properties of aggregate that are important include its crushing strength, hardness and toughness of aggregate. These properties are much influenced the concrete performance.

Two tests can be applied for determining the strength of aggregate. The tests are Aggregate Crushing Value (ACV) and ten percent fine value (TFV) (Mindness et al., 2003). ACV is an indirect test which its main objective is to determine the resistance of an aggregate to crushing (Neville, 2004). An average value of crushing strength of aggregate is 200 MPa. Generally, aggregate achieves its crushing value at 70 MPa to
350 MPa which is much higher than that of concrete strength. ACV test can be conducted according to BS 812-110 (1990). In this test, the specimens must be able to pass 14.0 mm test sieve and retain at 10.0 mm sieve. If this size is not available, other sizes of specimens can also be used for this test. Nevertheless, aggregate crushing value and compressive strength of concrete do not have a clear relationship. It is expected that compressive strength of concrete is lower when its crushing value is higher (Mindness et al., 2003; Neville & Brooks, 2004 and Gambhir, 2004). ACV is insensitive to variation of strength in weaker aggregate with crushing value more than 25 to 30. This is occurred because before the load 400 kN is applied, this aggregate has been crushed and compacted. Thus, at the end of the test, total of crushing aggregate has been decreased. In order to overcome this situation, TFV test is conducted according to BS 812-111 (1990). This test use same equipment as ACV test. The required load is measured to produce ten percent (10%) of fines for 14 mm to 10 mm size of aggregate.

The other mechanical property of aggregate is hardness. Hardness can be defined as resistance to wear. It is important for concrete which being used in road and surfaces that subjected to heavy traffic. The hardness test is conducted according to BS 812-112 (1990). This test has been identified that for abrasion value less than 30% and 50%, the aggregate is suitable for wearing and non-wearing surfaces respectively.

Toughness is also one of mechanical property of aggregate. Toughness is defined as resistance of aggregate to failure impact (Neville et al., 2004). The toughness test is conducted according to BS 812-112 (1990) as to determine the Aggregate Impact Value (AIV) of bulk aggregate. Besides, toughness test can become as an alternative to crushing value test.

Besides the physical properties, the mechanical properties of aggregate can significantly influence the performance of the RAC containing MBS. Khalaf & DeVenny (2004) reported that the aggregate strength i.e. RA does influence the produced concrete strength. Tam & Tam (2007) does agree with Khalaf & DeVenny (2004). Therefore it is important to determine the physical and mechanical properties to assume the suitability of using RA in concrete for specified application.
2.2.3 Size, Shape and Surface Texture

Aggregate can be classified into two groups which are coarse and fine aggregate. Coarse aggregate is identified when it is retained at 4.75 mm sieve and consisting a small amount of finer materials. Gambhir (2004) has revealed that coarse aggregate can be described as uncrushed gravel, crushed gravel and partially crushed gravel. Uncrushed gravel is refers to natural disintegration of rock. While, crushed gravel is refers to crushing hard gravel. Furthermore, partially crushed gravel refers to product which is produced from mixing of uncrushed and crushed gravel. On the other hand, aggregate is recognised as fine aggregate when it passes 4.75 mm sieve. Gambhir (2004) further pointed out that fine aggregate can be described as natural sand and crushing gravel sand. Natural sand is natural disintegration of rock. While crushing gravel sand is crushing natural gravel. The grading of aggregate is normally being used in determination the required paste for producing workable fresh concrete. Normally, for producing concrete, the range of aggregate sizes that have been used in between 10 mm to 50 mm and favourable size is 20 mm.

On the other hand, the particle shape and surface texture of aggregate are the indicators to the properties of fresh and hardened concrete (Mindness et al., 2003). The aggregate shape can be classified using geometrical characteristics. BS 812- Part 1 (1975) have classifies the aggregate shape into six categories which are rounded, irregular, flaky, angular, elongated and flaky and elongated.

In United States (US) there is no specific ASTM that has been used for aggregate classification (Neville & Brooks, 2004). But the aggregate is generally classified as well rounded, rounded, subrounded, subangular and angular.

The other characteristic of aggregate is its surface texture. The surface texture of aggregate is identified by smoothness or roughness of the aggregate. It depends on hardness, grain size and pore characteristics of parent material of aggregate. BS 812: Part 1 (1975) classifies the surface texture of aggregate in six (6) categories which are glassy, smooth, granular, rough, crystalline and honeycombed.

Performance in workability of concrete mixes is much related to shape and texture of aggregate (Gambhir, 2004 and Mindness et al., 2003). It is due to cement
paste is required to coat the aggregate. Cement paste also give the lubrication in the mean to decrease interaction between the aggregate particles in mixing process. For producing workable concrete, the most suitable aggregate is in spherical shape and smooth in surface which natural sand and gravel is much similar to this shape (Mindness et al., 2003). However, crushed aggregate i.e. RA has more angular shape and will lead into rougher surface texture. On the other hand, Gambhir (2004) has pointed out that aggregate with flaky and elongated particle shape will contribute into poor performance in durability of concrete.

According to Etxeberria et al. (2007), the shape and surface texture of RA does influence the fresh concrete performance of RAC. For RA, the crushing process could influence the shape and performance of RA (Tam & Tam, 2007a). As a consequence, this test is significant to carry out as for presume the appropriate application of RA in concrete.

2.3 Recycled Aggregate

RA can be defined as an aggregate that has been produced from used material as coarse or fine aggregate. RA can be produced from different sources like broken precast elements and cubes after testing, and demolished concrete buildings (Rao et al., 2007). Olorunsogo & Padayachee (2002) revealed that RA consisting materials like dust, mortar, brick, stone and mortar. In RA, the lowest percentage of proportion is dust which accounted 1.90% and the highest proportion is stone and mortar which is 84.60% (Olorunsogo & Padayachee, 2002). RA can be produced from large amount of waste material from construction industry which this waste material can lead into environmental problem. Thus, Ravindrarajah (1987) expressed his opinions that using RA would reduce the use of natural aggregate and landfill for disposal.

Mannan & Ganapathy (2004) added that waste material has an ability to meet design requirement as construction material if it is properly processed. When waste material is used as an aggregate, there are three principal areas which must be considered (Mindess et al., 2003). The factors are economy, compatibility and concrete
properties. In economy factor, the utilisation of waste material can be economic and cost effective depending on quantity available, amount of transportation required and mix design requirements. In compatibility point, waste materials must not react adversely with other constituents in the concrete mix. Lastly, the properties of waste material itself will improve the concrete properties in terms of its mechanical properties and durability.

Ravi et al. (2006) also revealed that RA gave an advantage in aspects of environmental and economic. He stated that in environmental aspect, RA is becoming as important resources, as an inert material, durable and recyclable. In economic side, the government is able to organise the opening of new source aggregate by encouraging the use of RA. Furthermore, disposal cost, the transport distance cost for natural aggregate and hauling can be reduced when RA is used as an option material in construction industry.

It can be observed that although RA has inferiority performance of its physical and mechanical properties as compared to NA, it still has advantages as an alternative aggregate for producing concrete. Thus, to develop the reputation of RA as an alternative aggregate, the present study using the RA as coarse aggregate replacement in concrete containing MBS was explored. In order to recognise the characteristics of RA, the following sections will describe the physical and mechanical properties of RA.

### 2.3.1 Physical Properties of RA

The physical properties of RA depend on its source. These properties are very much related to the performance of origin concrete. Many studies have been conducted by previous researchers such as Sagoe (2001), Olorunsogo & Padayachee (2002), Topcu & Sengel (2004) and Xiao et al. (2005). They determined the physical properties of RA like specific gravity and water absorption.

Previous studies found that specific gravity for RA is lower than NA (Sagoe, 2001; Olorunsogo & Padayachee, 2002; Topcu & Sengel, 2004; Xiao et al., 2004; Rahal, 2007; Kong et al., 2010). Lower specific gravity of RA is always associated with high porosity and high capacity to absorb water. Adhered cohesive mortar in RA which
is porous and weak in strength, lead into lower in specific gravity. Moreover, NA which comes from natural sources like gravel and stone lead into higher specific gravity compared to RA.

Limbachiya, Leelawat & Dhir (2000) reported that bulk density of RA is lower compared to NA. Xiao, Sun & Falkner (2006) agree with Limbachiya et al. (2000). Yong & Teo (2009) presumably that remain mortar has attributed to these results.

Gomez (2002) and Poon et al. (2004a) also found that total porosity of RA is much higher than that of NA. Porosity is also another physical property of aggregate that contributes to lower specific gravity of RA. Zaharieva et al. (2003a) also agreed with Gomez (2002) and Poon (2004) that higher porosity of mortar that coating on RA leads into this characteristic. Limbachiya (2004) also reported that RA is more porous, rougher and coarser compared to NA.

In term of water absorption property, the percentage of water absorption for RA is much higher than that of NA (Gomez, 2002; Kenai et al., 2002; Zaharieva et al., 2003a; Xiao et al., 2005). According to Xiao et al. (2005), the water absorption for RA and NA are 9.25% and 0.4% respectively. The high water absorption was also mentioned as resulted from the attached mortar to aggregate. Topcu (1997) also reported that these adhered mortars altered aggregate absorption and density properties. The high water absorption of RA contributes to adverse effects on concrete. Because of high water absorption in RA, RA should be pre-soaked before mixing process to maintain the workability of fresh concrete (Zaharieva et al., 2003a). Zaharieva et al. (2003a) also pointed out that the presence of cracked surface in RA could increase the water requirement and allow air to flow into aggregate and also the Interfacial Transition Zone (ITZ). Poon et al. (2004a) also identified that RA that taken from demolition activity of reinforced buildings and concrete runway is prone to cracking. Gambhir (2004) recognised the low density mortar that attached to RA will lead to 5 per cent higher of water absorption compared to NA. Barra & Vazquez (1998) also stated the mortar of original concrete that attached to RA cause the increase in water absorption of the RA.

Thus, from the previous findings, it is appeared that RA possesses characteristic of low specific gravity, high porosity and higher water absorption. Adhesive mortar
which is coated on RA surface leads into these properties and might influence the fresh
and hardened performance of RAC.

2.3.2 Mechanical Properties of RA

It has been recognised that ACV of RA is much higher compared to NA (Limbachiya et
al., 2000; Sagoe, 2001 and Kong et al., 2010). Experimental work conducted by Xiao et
al. (2006) also showed that RA exhibited higher in ACV than those of NA. This finding
indicates that RA is a weaker aggregate compared to NA. Mortar which attached to RA
particles contributed to this inferiority. However, the adhered mortar could make RA
particle size much bigger that would result higher ACV. The bigger size of aggregate
would increase the resistance to crushing when the load is imposed.

TFV test has been carry out by Poon, Kou & Lam, (2006). In the test it was
recognised that RA attained lower value of TFV (126 kN) compared to NA (159 kN).
Limbachiya et al. (2000) and Kou, Poon & Chan (2007) also obtained lower value of
RA compared to NA in TFV test. On the other hand, Limbachiya et al. (2000) and Poon,
Kou & Lam (2002) have conducted AIV test in their study and acquired of higher AIV
value for RA compared to NA.

Although the mechanical properties are important to conduct as an expected
result for hardened RAC performance, there is still lack of data on this. Thus, in present
study these tests (ACV and AIV) have been conducted on RA as to characterize the RA
used.

2.3.3 Surface and Shape of RA

It was recognised that RA has a grainy surface compared to NA (Sagoe, 2001). It was
identified that surface structure for RA particles is covered with some crumbs (Katz,
2004). The crumb size is about few microns to several hundreds microns and loosely
connected to bulk aggregate.
In other studies by Zaharieva et al. (2003a) and Gambhir (2004), it was stated that RA is normally in an angular shape and has coarser surface than that of NA. Zaharieva et al. (2003a) highlighted that these characteristics be able to affect the fresh performance of RAC. On the other hand, Gambhir (2004) pointed out that RA has similar particle size distribution as NA. He stated that crushing process of RA influences the RA properties. Mamlouk & Zaniewski (2006) have declared that crushing activity of waste concrete leads into angular and rough surface texture of RA. So, RA possesses a larger surface area than that of rounded NA which on the other hand lead to better interlocking and adhesion of cement paste.

It can be concluded that generally RA possesses inferior properties compared to NA. However, RA is still becoming as an attractive material to be exploited as an alternative material in construction industry. The brief properties of RA are presented in Table 2.3 and the detail explanation has been elaborated in previous sub-section.

2.4 Recycled Aggregate Concrete (RAC)

Concrete which is produced from RA is familiarly known as RAC. RA normally replaces partially or fully as coarse or fine aggregate in RAC. RA has attracted many researchers to study and improve its quality for RAC production. Continuous research for improving quality of RAC to make it equivalent to Natural Aggregate Concrete (NAC) performance have been conducted and it was published in the Third State of the Art Report 1945-1989 by Hansen (1992). The report is a compilation of reports on RAC from year 1945 to year 1989. On the other hand, some of RAC performance on fresh and hardened properties are summarised in the following section.

2.5 The effect of RA inclusion to the workability

Many studies have been conducted to identify the workability performance of fresh RAC. Mostly, the findings indicated that RA content in RAC influence the fresh
concrete performance. As RA replacement in concrete increases, its workability decreases (Topcu & Sengel, 2004). According to Topcu (1997), slump value of RAC was around 75 mm corresponding to 100 mm of NAC. Lower workability of RAC is due to the mortar coating of RA that led to higher capacity in absorbing water. Limbachiya (2004) also found that concrete mix containing more than 30% replacement of RA, is harsher and less cohesive compared to NAC mix. Hence, the homogeneity and flowability of concrete made of RA would be affected.

Texture and the angular shape of RA have been recognised as a factor for lower workability of RAC (Ridzuan et al., 2001). Bataineh et al. (2007) has identified that irregularity of RA surface also contributed to lower workability of RAC.

On the other hand, Olorunsogo (1999) and Gambhir (2004) have recognised the method for improving the workability performance of RAC. Olorunsogo (1999) has identified that the application of round shape of RA can improved the workability of RAC. Gambhir (2004) also recognised that an additional of 5% to 10% of water is required for RAC mix to achieve the same workability as NAC mix. However, the high quantity of water needed to maintain the workability cause reduction in the compressive strength and increase the permeability of resulted RAC (Gomez, 2002; Poon et al., 2004a).

2.6 The effect of RA inclusion to the strength

Generally, strength of RAC is lower than that of NAC. The compressive strength of RAC decreases when percentage of RA increases (Fraaij et al., 2002; Kenai et al., 2002; Topcu & Sengel, 2004; Poon et al., 2004a and Xiao et al., 2005). It has been recognised that an average compressive strength of RAC is about 80-95% of NAC (Topcu & Guncan, 1995). If more than 50% RA is used as replacement material, the compressive strength of concrete was found to decrease (Topcu, 1997). According to Olorunsogo (1999), the factors like smoother texture and rounder shape of RA were the reasons for lower compressive strength of RAC.
However, contrary results were obtained by Diah & Majid (1998), Ridzuan et al. (2001) and Hawairi & Otaibi (2006). From their studies, they obtained higher compressive strength compared to those of NAC when fully replacement of RA was adopted for producing concrete. In Ridzuan et al. (2001) study, it is found that the compressive strength of RAC is higher for about 12.1 % corresponding to NAC. While in Diah & Majid (1998) and Hawairi & Otaibi (2006) increase in compressive strength for about 24.5% and 27.7% as compared to NAC respectively was recorded. Ridzuan et al. (2001) recognised that higher compressive strength in RAC due to angular shape and rough texture of RA. The angular shape and rough texture of RA lead to better bonding force, therefore improve strength of concrete. Ridzuan et al. (2001) also believed that type of crushers also plays a main role for creating RA shape.

Poon et al. (2004b) had conducted study on compressive strength of series of RAC. It was revealed that RAC obtained lower in compressive strength than that of NAC. Poon et al. (2004b) also in their opinion feel that the higher porosity of RAC is due to the attached mortar paste on RA. In addition, their study also revealed that RA obtained from High Performance Concrete produced dense ITZ of concrete. RA that obtained from Normal Performance Concrete (NPC) or lower grade of concrete was found to produce loose and porous ITZ. Poon et al. (2004b) believed that different types of ITZ in concrete do influence its strength development. Dense ITZ will ensure the strong bond between aggregate and cement which lead into high strength concrete. However, loose and porous ITZ does create weak bond between aggregate and cement which lead into low strength concrete.

RAC can also have higher compressive strength when RA was in oven dried condition prior to pouring into the concrete mix. The dry state enhances the interfacial bond between cement paste and aggregate particles (Poon et al., 2004b). It was reported that in oven dried condition, water may enter the RA particles from bulk of cement paste and the cement particles may accumulate around the RA particles. So, stronger bond is resulted from cement paste and aggregate particles.

ITZ which existed between aggregate and cement paste has effect on the performance of hardened RAC. It is the weakest link in concrete. According to Ryu (2002a), Vickers Hardness test can be used to determine the ITZ characteristics. He
revealed that the RAC’s Vickers Hardness increases as water-cement ratio decreases. He also found that two types of ITZ existed in RA. Tam & Tam (2008), Kong et al. (2010) and Exteberria et al. (2006) also have similar experience as Ryu (2002a). First ITZ (old ITZ from origin concrete) is between RA and old mortar attached. Second ITZ (new ITZ) is between RA and new mortar. Ryu (2002b) stated that as water-cement (w/c) ratio of concrete mix is low, the strength of concrete is contributed by old ITZ. For higher w/c ratio of concrete mix, the new ITZ has an influence the concrete performance. Exteberria et al. (2006) does agree with Ryu (2002b).

For improving the quality of RAC, Two-Stage Mixing Approach (TSMA) was introduced by Tam, Gao & Tam (2006a). This method has two parts which the required water is divided into two with same quantity but added at different time. Firstly, fine and coarse aggregates are mixed for 1 minute. Then, half of the water is added and mixed with another 1 minute. After that, cement is added and mixed for 30 seconds before the remaining half of water is added and mixed for another 2 minutes (Tam et al., 2006a). Tam et al. (2006a) has proven that strength increased up to 21.19% for 20% replacement of RA in concrete. Tam et al. (2006a) also revealed that at first stage of concrete mixing when half of the required water is used for mixing, it led to the formation of a thin layer of cement slurry on the surface of RA. This layer will absorb into old cement mortar which has porous properties and leads into filling of old cracks and voids. At second stage, the remaining water is added to complete the process of concrete mixing.

Tangchirapat et al. (2007) had conducted study on application of Rice Husk-Bark Ash (RHBA) as cement replacement material for producing RAC. RHBA is produced when 65% of rice husk and 35% of eucalyptus bark were burnt together as a fuel at controlled temperature about 800-900 °C. It was found when 20% of RHBA is used as cement replacement material for 100% RAC, its compressive strength is higher compared to control concrete at 28 days. The increase is about 108% of control concrete. The increase of compressive strength is contributed by pozzolanic reaction of RHBA in RAC. It is proven as RAC without RHBA attained compressive strength of 94% of the control concrete. So, RHBA has an ability to improve the compressive strength of RAC.

Ravindrarajah (1987) also suggested that the application of pozzolans material like fly ash and silica fume would improve the strength of RAC. Similarly, Kou, Poon &
Chan (2007) also found that the utilisation of fly ash can increase the performance of RAC at later ages. For fully RA application in concrete, 25% and 35% of fly ash has ability to increase about 4.2% and 1.4% of compressive strength at 90 days of those of control concrete. The higher compressive strength in RAC is contributed by the pozzolanic activity of fly ash in concrete.

It is also agreed by Ann et al. (2008). In their study, pozzolans material like Pulverised Fuel Ash (PFA) and Ground Granulated Blastfurnace Slag (GGBS) were used as cement replacement material in RAC at 30% and 65% of cement (by weight) respectively. It is evident that 30% PFA and 65% GGBS in RAC, can increase the strength at later age (90 and 180 days). At early ages (7 and 28 days), RAC with these cement replacement material obtained lower in compressive strength than that of control concrete.

The application of Rice Husk Ash (RHA) as cement replacement material in RAC is found to be limited. RHA has been used as cement replacement material in Normal Aggregate Concrete (Shoaib & Waliuddin, 1996; Zhang et al., 1996; Qijun et al., 1999; Bui et al., 2005; Kartini et al., 2009; Habeeb & Fayyadh, 2009). Thus, the present research determining the performance of MBS (which the raw material is RHA) in RAC was attempted.

2.7 Durability of RAC

Besides strength, durability is also the factor for indicating a good concrete (Neville, 2004). For determining the durability, various types of test can be conducted. Most popular test is permeability, chloride ingress and carbonation test. Generally, these tests are carried out for determining the penetration of outsider fluid that enters into concrete pores. The types of fluids are water, aggressive ions, carbon dioxide and oxygen.

Many studies have been conducted to determine the durability performance of RAC. It was found that RAC showed lower performance in durability compared to NAC. Zaharieva et al. (2003a) recognised that water permeability of RAC was twice compared to NAC. RA inclusion also has doubled the air permeability in RAC. It is also
revealed that surface permeable of RAC is about 10-25 times than that of NAC (Olorunsogo & Padayachee, 2002 and Zaharieva et al., 2003a).

Few studies indicated that carbonation process in RAC happens at faster rate compared to that in NAC. According to Zaharieva et al. (2003a) and Otsuki et al. (2003), RAC attained higher in carbonation depth and chloride penetration depth compared to those of NAC indicating that RAC possesses characteristic of less resistance to carbonation and chloride attack.

Application of pozzolan materials like fly ash and silica fume also can reduce the permeability of RAC. Zaharieva et al. (2003a) and Rao et al. (2007) in their investigation indicated that the pozzolan’s utilisation can decrease the porosity in concrete and lead into lower in permeability. While Ann et al. (2008) study revealed that PFA and GGBS inclusion which is also a pozzolan material have the ability in reducing the permeability of RAC. In terms of rapid chloride ion penetration test, RAC with 30% PFA and RAC with 65% GGBS was found to be categorised as lower permeability concrete than that of control concrete when tested at age of 180 days. These pozzolans play a main role in decreasing the permeability by filling up the pores in RAC.

Tam & Tam (2007b) as mentioned in previous paragraph had proposed TSMA for enhancing the durability of RAC. In their study, it was shown that TSMA had improved about 35.41% in water permeability of concrete with fully RA replacement after 126 days curing, 51.81% in air permeability with 20% replacement of RA after 56 days curing and 29.98% on chloride permeability with fully replacement of RA after 126 days curing. From these results, it is shown that TSMA is also an effective method in enhancing the durability of RAC.

On the other hand, Padmini, Ramamurthy & Mathews (2002) have drawn a relationship between strength and water absorption of RAC. From the relationship, it shows that as strength of RAC increases, its water absorption decreases. It indicates that the strength of concrete has direct influence to the water absorption performance. Thus, it can be concluded that generally when RAC obtains good performance in strength, directly it will also indicate good performance in durability.
There is still lack of data for performance in terms of water permeability of RAC. Thus, this study was conducted as to establish a relationship between strength and water permeability of RAC incorporated with MBS.

2.8 Application of RA in world

Environment nowadays facing many challenges and as part of society, it is a responsibility to protect environment. Mehta (1999a) has listed that environmental protection, conservation of natural aggregate, shortage of disposal sites, increasing cost for waste treatment are the prime factors that enhancing the interest in using concrete waste as RA.

Although the application of RA is something new in Malaysia, but many other countries have used it widely such as in South Africa, Netherland, United Kingdom (UK), Germany, France, Russia, Canada and Japan (Olorunsogo & Padayachee, 2002). Cuperus & Boone (2003) have summarised that countries like Austria, Switzerland and Netherlands recycled more than 90% of their construction and demolition waste. In Germany over 70% of their construction and demolition waste have been recycled. These countries have fully recycled their construction and demolition waste for about more than two decades. On the other hand, France and UK also have been practising recycling practice. However, it is still at infant stage and the data on success of using RA in concrete is limited.

The following paragraph is the summary of application of RA in some developed countries like UK and United States (USA), Netherland, Denmark and Bulgaria, in Asia like Hong Kong and Taiwan.

2.8.1 United Kingdom, United States, Netherland, Denmark and Bulgaria

In United Kingdom (UK), large quantities of crushed concrete and bricks are produced annually. Increasing interest in RA application is because the increasing cost of landfill,
anxiety of decreasing in natural resources and increasing in aggregate requirement for construction work (Khatib, 2005).

In United States (USA), about 2.7 billion metric tonnes of aggregate are currently used. Natural aggregate producers, contractors and debris recycling centers are producing RA. Thus, for promoting RA, incentives for transportation of waste concrete and processed aggregates from production sites are given (Robinson et al., 2004).

In Netherland, the government has introduced the legislation to support the use of RA. The policy which selling price of RA is lower compared to NA natural aggregate has become an attractive policy. The increasing cost of landfill also supports the policy. Copenhagen as a district of Denmark has recently recycled over 80% of its demolition waste (Collins, 2003).

Since 1990s, the construction of infrastructural facilities has increased the construction waste in Bulgaria (Zaharieva et al., 2003b). Later, in 2002, 0.5% from 22% of total expenditure on environmental preservation was spent into waste management. Some efforts have been conducted by agencies like Municipality of Sofia, and the Bulgarian Academy of Sciences, besides the Ministry of Environment and Water Resources for better construction and demolition waste (C & D) utilisation. One collaboration project on research activities also has been developed by Domostroene Company, Bulgarian Company of Sciences, Universities in Northern France, Krupp Hazemag Group and RMN recycling company. This project is called as “Recycled Concrete Aggregates”. This project is purposely set up in support of NATO programme “Science for Peace”.

2.8.2 Asia

Successful of RA applications in developed countries have attracted some Asian countries for taking a challenge in using RA as their construction material. Hong Kong, Taiwan and Japan has become pioneering countries in Asia which have taken a step in utilisation to this type of aggregate.