ENHANCING THE PERFORMANCE OF RECYCLED AGGREGATE CONCRETE FOR CONSTRUCTION

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ENHANCING THE PERFORMANCE OF RECYCLED AGGREGATE CONCRETE FOR CONSTRUCTION

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BF	Modified recycled aggregate concrete specimen consisting of treated recycled concrete aggregate and single barchip fiber
CH	Calcium hydroxide
CM	Calcium metasilicate
CO	Control specimen or natural aggregate concrete
CSH	Calcium silicate hydrate
E_d	Dynamic modulus of elasticity
E_s	Static modulus of elasticity
EDX	Energy dispersion X-ray
FRP	Fiber reinforced polymer
GFRP	Glass fiber reinforced polymer
HB1	Modified recycled aggregate concrete specimen consisting of treated recycled concrete aggregate and hybrid fiber (0.96% barchip fiber + 0.24% polypropylene fiber)
HB2	Modified recycled aggregate concrete specimen consisting of treated recycled concrete aggregate and hybrid fiber (0.72% barchip fiber + 0.48% polypropylene fiber)
HB3	Modified recycled aggregate concrete specimen consisting of treated recycled concrete aggregate and hybrid fiber (0.48% barchip fiber + 0.72% polypropylene fiber)
HB4	Modified recycled aggregate concrete specimen consisting of treated recycled concrete aggregate and hybrid fiber (0.24% barchip fiber + 0.96% polypropylene fiber)

HCl	Hydrochloric
ITZ	Interfacial transition zone
LVDT	Linear variable displacement transducer
NCA	Natural coarse aggregate
NW	Normal water
OA	Open air
PF	Modified recycled aggregate concrete specimen consisting of treated recycled concrete aggregate and single polypropylene fiber
RA	Recycled aggregate
RAC	Recycled aggregate concrete
RCA	Recycled concrete aggregate
RO	Unmodified recycled aggregate concrete specimen
SEM	Scanning electron microscope
SW	Sea water
UPV	Ultrasonic pulse velocity
XRD	X-ray diffraction
XRF	X-ray fluorescence

MENINGKATKAN PRESTASI KONKRIT AGREGAT KITAR SEMULA UNTUK PEMBINAAN

ABSTRAK

Kajian ini bertujuan untuk membangunkan satu kaedah pengubahsuaian yang dapat meningkatkan prestasi konkrit agregat kitar semula (RAC) untuk menggalakkan penggunaan meluas bahan ini oleh industri pembinaan, khususnya untuk aplikasi struktur. Oleh itu, eksperimen penyelidikan ini memberikan pandangan tentang keperluan meningkatkan pelbagai tahap struktur pada sifat RAC melalui proses penambahbaikan pelbagai fasa. Fasa pertama memberi tumpuan kepada rawatan untuk meningkatkan sifat agregat konkrit kitar semula (RCA) sebelum ia digabungkan ke dalam campuran RAC dengan permulaanya merendam RCA kasar ke dalam asid hidroklorik pada kepekatan 0.5 mol dan kemudian mengisitepuan agregat ini ke dalam larutan kalsium metasilicate. Fasa kedua melibatkan peningkatan campuran RAC melalui tetulang dengan sistem gentian yang berbeza. Gentian diskrit pendek barchip dan polipropilena digunakan dalam pelbagai jumlah pecahan dan dimasukkan dalam bentuk tunggal dan hibrid. Kesan kedua-dua rawatan permukaan pada sifat RCA sebelum dan selepas rawatan ditentukan. Kajian ini juga menyiasat keberkesanan pengubahsuaian multi-fasa berkenaan ke atas prestasi kejuruteraan dan ketahanan RAC yang terhasil apabila terdedah kepada pelbagai keadaan pengawetan, iaitu, air biasa (NW), terbuka (OA) dan air laut (SW). Selain itu, tingkah laku lenturan rasuk RAC diubahsuai diperiksa. Hasil kajian menunjukkan bahawa sifat fizikal dan mekanikal RCA ketara bertambah baik selepas rawatan permukaan. Kesan kemasukan RCA kasar yang dirawat adalah didapati penting dalam meningkatkan sifat kejuruteraan dan ketahanan RAC. Walau bagaimanapun, penambahan gentian selanjutnya, terutamanya dalam bentuk hibrid, boleh mengoptimumkan keputusan. Seperti yang ditunjukkan dalam keputusan, kekuatan mampatan yang optimum diperolehi oleh RAC diubahsuai jenis HB4 (0.96% polipropilena + 0.24% barchip), di mana kekuatan mampatan ia pada 300 hari dalam pengawetan yang berkaitan, boleh dipertingkatkan sebanyak 11% hingga 21% lebih tinggi daripada konkrit biasa. Selain itu, ciri-ciri kekuatan mekanikal RAC diubahsuai dari segi kekuatan lenturan, modulus keanjalan dan rintangan hentaman juga boleh mengatasi ke atas konkrit biasa dan RAC yang tidak diubahsuai. Kesan pengubahsuaian juga didapati bermanfaat dalam meningkatkan prestasi ketahanan RAC apabila terdedah kepada persekitaran yang agresif. Keputusan menunjukkan bahawa penyerapan air dan kebolehtelapan udara RAC diubahsuai yang terdiri daripada gentian hibrid masing-masing boleh dikurangkan sehingga 9% dan 37%, selepas terdedah dalam jangka masa panjang dalam pengawetan air laut. Ciri-ciri ketahanan lain, seperti penyerapan kapilari, penembusan klorida, pengkarbonan dan pengecutan kering, juga didapati berkurangan. Kajian ke atas kelakuan lenturan mendedahkan bahawa beban retak pertama, kapasiti beban muktamad dan kemuluran rasuk RAC yang diubah suai yang terdiri daripada gentian hibrid masing-masing boleh dipertingkatkan dengan kira-kira 4%, 21% dan 60%, lebih tinggi daripada rasuk RAC yang tidak diubahsuai .

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ABSTRACT

This study aims to develop a modification method that can enhance the performance of recycled aggregate concrete (RAC) to encourage the widespread use of this material by the construction industry, particularly for structural applications. Hence, this experimental research provides insight into improving the various structures levels of RAC properties through multi-phase improvement processes. The first phase focuses on the treatment to improve the recycled concrete aggregate (RCA) properties before they are incorporated into the RAC mix by initially soaking coarse RCA in hydrochloric acid (HCl) at concentration of 0.5 mole and then impregnating these aggregates with a calcium metasilicate (CM) solution. The second phase involves the modification of the RAC mix through reinforcement with a different fibre system. Short discrete barchip and polypropylene fibres are used at various volume fractions and are added in single and hybrid forms. The effects of both surface treatments on the RCA properties before and after treatment are determined. This study also investigates the effectiveness of multi-phase modification with respect to the engineering and durability performance of the resultant RAC when exposed to various curing conditions, namely, normal water, open air and seawater. Moreover, the flexural behaviour of modified RAC beam is examined. Findings show that the physical and mechanical RCA properties significantly improve after surface treatment. The effect inclusion of the treated coarse RCA is significant in enhancing the engineering and durability properties of RAC. However, the further addition of fibre, particularly in hybrid form, can optimise the results. As shown in the results, the optimum compressive strength obtained by modified RAC in types HB4 (0.96% polypropylene + 0.24% barchip), where their compressive strength at 300 days in the corresponding curing conditions, can be significantly improved by 11% upto 21% higher than normal concrete. Moreover, other mechanical strength properties of modified RAC in terms of flexural strength, modulus of elasticity and impact resistance can also surpass to those of normal concrete and unmodified RAC. The effect modification is also found beneficial in improving the durability of RAC performance when exposed to an aggressive environment. Results indicate that the water absorption and intrinsic air permeability of modified RAC consisting of hybrid fibre can be reduced by up to 9% and 37%, respectively, after being exposed in the long term to seawater curing condition. Other durability properties, such as capillary absorption, chloride penetration, carbonation and dry shrinkage, are also found to be significantly reduced. The study on flexural behaviour reveals that the first crack load, ultimate load capacity and ductility of the modified RAC beam consisting of hybrid fibre can be remarkably enhanced by approximately 4%, 21% and 60%, respectively, higher than that of the unmodified RAC beam.

CHAPTER 1

INTRODUCTION

1.1 General

Concrete is the most widely used construction material in the world because of its versatile properties and economical value compared with other materials. It has long been in use as a major material for providing a stable and reliable of engineering structure. Most types of construction work use concrete, for example, foundations, architectural structure, dams, houses, towers, highways, and pavements. However, the use of conventional concrete has some limitations depending on the engineering properties required by certain structural designs that demand greater strength, workability, and durability. Conventional concrete sometimes poses quality problems such as "bleeding," and it also tends to "honeycomb," which causes segregation. The growing demand for more sophisticated architectural and structural forms that can withstand extreme conditions in different types of environment has accelerated research in the development of a new concrete design. Therefore, engineers and scientists in the construction industry have proposed the use of high-performance concrete (HPC), an upgraded and enhanced version of traditional concrete.

The recent construction boom has brought with it a rising demand to develop concrete structures in extreme environments, making HPC a popular choice to replace conventional concrete. For example, in areas with severe heat and humidity, concrete usually experiences some type of premature deterioration. Concrete exposed in areas with a high concentration of carbon, sulphate, and chloride can absorb these chemicals into the structure through ground water or wind, which also accelerates the corrosion of steel in the concrete structure. Thus, HPC was generally designed to deal with such concerns. HPC has significantly high strength, workability, and durability to ensure long life in severe environments and resistance to any chemical attack. Structures built with HPC may be expected to last 100 years and with less maintenance than those built with normal concrete. Moreover, HPC's characteristics allow greater flexibility in design as well as better economy—less volume of HPC and less reinforcement bars are required, resulting in overall construction-cost savings.

Much progress has been made in the development of concrete such as HPC to fulfill the need for specific performance characteristics required by various construction purposes. However, several issues still confront the concrete industry today. First, one the greatest challenges facing the concrete industry has to do with natural raw-materials consumption, with concrete having been identified as a non-environment-friendly material (Tu et al., 2006). For instance, natural aggregate, besides cement and water, forms one of the main ingredients of concrete and takes up about 70–80% of concrete volume (Alexander & Mindess, 2005). The growth of the construction industry and, consequently, the increasing demand for concrete, mean the greater use of natural aggregate and a significant impact on the environment (Marinkovic et al., 2010). The consumption of natural aggregates implies environmental impact on quarrying and mining. Meanwhile, the construction industry's excessive use of natural aggregates yearly has depleted their sources in some parts of the world (Safiuddin et al., 2007). As a result, the cost of aggregate has substantially increased, which in turn contributed to soaring construction costs.

Second, concrete production has been identified as a significant contributor to CO_2 gas emissions (Naik, 2008) besides being a high-energy consumer (Chindaprasirt et al., 2007). These have in turn contributed to pollution and environment degradation. For example, the use of kilns in the process of limestone decarbonation in the Portland cement industry represents high-energy consumption as it releases nearly pure carbon dioxide into the atmosphere and it has been estimated to contribute about 74%–81% in CO_2 emissions in total concrete production (Flower & Sanjayan, 2007). In overall this industry is estimated to be responsible for approximately 7% of the worldwide CO_2 emission generated annually (Chindaprasirt, et al., 2007).

Third and last is the issue on the end-use of concrete arising from construction and demolition (C&D) waste, which constitutes a large amount of total solid-waste generation in the world (Rao et al., 2007) and creates problems of waste disposal. Many concrete structures today are either reaching the end of their structural life or are exhibiting premature deterioration, paving the way for reconstruction work, which will inevitably result in large amounts of concrete rubble. Managing such a huge quantity of waste requires a large land area for landfills which would pollute the environment (Yuan & Shen, 2011) and increase operation costs in waste management.

The conservation of natural resources, reduction of greenhouse gas emissions, and environmental protection have become the heart of modern development. Therefore, the concrete and construction industries need to shift their production methods toward models of sustainability. The Earth Summit in Rio de Janeiro in 1992 defined sustainable development as that which “meets the needs of the present without compromising the ability of future generations to meet their own needs”

(Brundtland, 1987). In other words, sustainable development seeks to guarantee the balance of environmental protection and economic and social development.

Toward sustainable development, Meyer (2009) and Poon (2007) suggested that the concrete industry implement the recycling concept. The shortage of natural aggregate in urban areas due to depletion and the increasing quantities of C&D waste have compelled manufacturers of concrete to consider replacing natural aggregate with recycled C&D waste as an alternative material. Many researchers (Grdic et al., 2010; Limbachiya et al., 2000; Rao, et al., 2007) have reported on the potential of recycled aggregate produced from C&D waste for concrete applications. Meanwhile, recycling industrial by-products such as fly ash (from burning coal), ground granulated blast furnace slag (GGBFS) (from the steel industry), and rice husk ash (from rice mills) can yield types of pozzolanic substances that can be used as supplementary cementitious materials to replace Portland cement. These mineral additions will not only reduce the amount of cement but also improve the strength and durability of concrete (Berndt, 2009; Papayianni & Anastasiou, 2010; Van Tuan et al., 2011) without negative environmental impact. Clearly, the construction industry must engage in recycling activities to adapt to the mandate of a sustainable system. As Tam (2008) noted, recycling is an effective way to reduce the use of natural resources and landfill areas, thus realizing cost savings toward sustainable construction.

Sustainability can also be achieved through the efficient use of resources in the concrete industry. As suggested by Meyer (2009) and Berndt (2009), the design for concrete structures must be sustainable, with a view to durability and long life. A sustainable structure will go a long way in cutting the use of material, cost, and energy precisely because it requires less maintenance and avoids waste from premature deterioration. In addition, the current trend in construction industry was changed very fasting growth toward more complicated and challenging than before. A lot of issues will arise and facing in many directions which requires all parties involved in this field should have creative thinking to seek for better solution. The enhancement in production of construction material such concrete either in production or their performance is highly requisite in way future construction challenge situation.

Therefore, this present study seeks to explore ways in which the quality of concrete products can be improved with given the considerations for sustainability. The focus in the development of concrete products is not just on issues of mechanical strength and durability but also on the adoption of sustainable practices and processes. This is necessary to ensure that the concrete industry moves toward greater creativity and innovation in optimizing the use of limited resources through recycling and other sustainable means of production. This way, the industry can reduce its dependence on natural resources and thus preserve the environment which becomes important issues discussed today.

1.2 Present Scenario in Malaysia

The construction sector in Malaysia is predicted to boom and grow rapidly in the coming years after having been affected by the global economic slowdown in 2008. This liveliness with new incentives were introduced by the Malaysian government in the 10th Malaysia Plan, which covers the period from 2011 to 2015, a major national structural transformation plan aimed towards achieving a high-income economy (Economic Planning Unit, 2010). To achieve this target, the Minister of Works in

Malaysia (2010) stated that the government is allowed to spend RM230 billion development allocations and RM20 billion facilitation funds for the 10th Malaysia Plan. Out of the RM230 billion for development expenditure, around 60% (RM138 billion) is estimated for physical developments to be undertaken by the construction sector. Around 52 high-impact projects worth RM63 billion have also been identified for implementation under Public–Private Partnership initiatives, which include seven tolled highway projects, two coal electricity-generating plants, a land development for the Malaysian Rubber Board, the Petronas LNG Melaka plant, and two aluminium smelters in the Sarawak Corridor of Renewable Energy (SCORE), Sarawak (MIDF Research, 2010; Minister of Works Malaysia, 2010). Overall, this Plan is showing a potential positive impact to the drastic surge in growth of the construction industry and other related sectors, as well as further enhancing the national economy.

The rapid growth of the construction sector indirectly increases production and consumption in the building material manufacturing sector, particularly in concrete production. In turn, the increasing demand for construction materials has led to higher profits for the building-material manufacturing industry. The downside of rising demand as far as the industry is concerned, however, is the various issues related to its production. The concrete industry is expected to face issues of scarcity, rising prices, and declining quality of raw materials amid heightened demand for its products and vibrancy of the sector. Besides cement and water, aggregate is another major component of concrete. It actually accounts for the largest proportion, at 70% to 80%, of concrete and has a significant influence on concrete properties. However, the production of granular aggregates in concrete not only requires massive natural stone materials, but also destroys the ecological environment (Safiuddin et al., 2011).

The increasing awareness of environmental issues in recent years has contributed to the reduction of production factors from new quarry areas. Production is becoming more limited and controlled due to pollution and related environmental conservation issues, especially in rapidly developing areas. Findings from a research conducted by Pereira (2007) on long-term security for the supply of aggregates in Selangor, in view of the impending implementation of the Selangor Policy on Environmentally Sensitive Areas (ESAs), highlight that six quarries and 66% of new aggregate resources in the state are located in highly sensitive ESAs categorised as 'no-go areas' for quarrying. In addition, results indicate that at least 10 medium- and low-sensitivity quarries and another 26% of new resources located in ESAs are categorised as areas under 'controlled development', with high precaution and very strict conditions for quarrying. Meanwhile, only 8% of the newly identified resources are actually available for operation in the future.

As suggested above, in the future, the land areas used for mining or quarrying to produce aggregates will no longer be available and will be restricted due to the accelerating growth in population as well as to the urbanisation and industrialisation processes. In addition, the sustained use of aggregate will soon deplete the aggregate reserves (Abdul Rahman et al., 2009). Accordingly, if aggregate consumption is not controlled and properly planned, Malaysia will face a decline in its supply, a challenge to the future of the industry, particularly to industry members that depend on the use of natural aggregate, which is the main raw construction material. Although importing aggregates can overcome this problem, it is a short-term solution and is inefficient because of the high transportation costs arising from the uncertainty in global fuel prices. Aggregate consumption issues must be addressed before a major crisis occurs. Therefore, it is important for the needs of the concrete industry to shift towards the reproduction and use of alternative aggregate by searching and fully utilising existing potential sources.

Concurrently, the waste generated from construction and demolition activities is identified as one of the main contributors to solid waste in Malaysia. The sustained growth of the construction industry simultaneously generates substantial construction waste in Malaysia, thus significantly affecting the environment and causing social problems in local communities (Begum et al., 2009; Mahayuddin et al., 2008). Nowadays, a huge amount of waste is generated in construction sites. The estimated total construction waste generated from a project site during the construction of a new building is around 27,068.40 tonnes (Begum et al., 2006). The increasing renovation and demolition works for the upgrade of existing construction, which have become necessary because of the growing number of old buildings that have deteriorated over the years, outdated building designs, and so on also have significantly contributed to the increase in solid waste (Safiuddin, et al., 2011). The more specific composition of waste generated was determined in the research conducted by Begum et al. (2006), who showed that concrete and aggregate are the largest components of waste materials generated by construction sites. Their amounts and composition are tabulated in Table 1.1 and shown in Figure 1.1.

Table 1.1 Estimated amount and composition of construction waste generated at construction sites (Begum, et al., 2006).

Construction waste materials	Amount of waste generated (tonnes)
Soil and sand	7290
Brick and blocks	315
Concrete and aggregate	17820
Wood	1350
Metal products	225
Roofing materials	54
Plastic materials	13.5
Packaging products	0.90
Total	27068.40

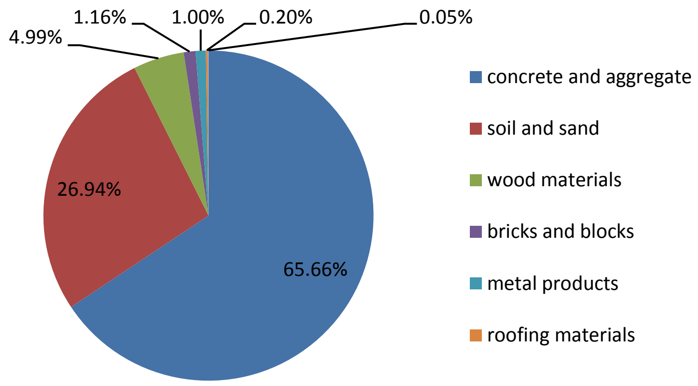

Figure 1.1 Composition of construction waste material generated at construction sites (Begum, et al., 2006).

The same results were observed by Mahayuddin et al. (2008) when they conducted a survey at illegal dumpsites. They found that aggregate and concrete composed a large proportion of the waste (see Figure 1.2).

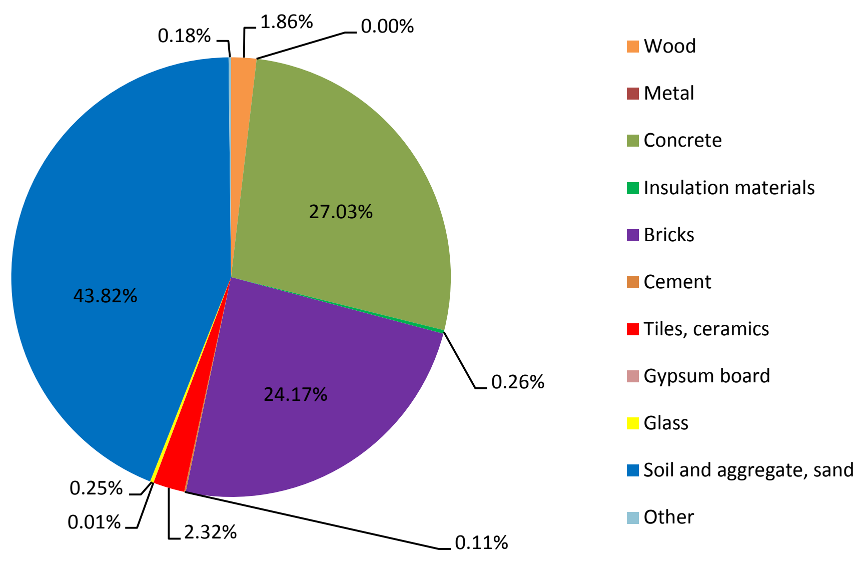

Figure 1.2 Composition of construction waste materials disposed of at illegal dumpsites (Mahayuddin, et al., 2008).

Both findings indicate that the waste levels are high and that a large portion of potentially useful demolition waste, such as concrete waste, is directly disposed of in landfill sites without being fully utilised. The increasing construction waste causes environmental problems due to unplanned disposal and the scarcity of landfill sites (Safiuddin, et al., 2011). Recycle and reuse of concrete and aggregate waste as new aggregates, which serve as substitutes for natural aggregates, seem the best solution to this problem. The use of recycled aggregates generated from construction waste can reduce problems in solid waste disposal in Malaysia (Begum & Pereira, 2007). In addition the application of recycled concrete aggregates (RCAs) in construction can maintain aggregate security and ensure sustainable development (Pereira, 2007). This is in line with the effort and commitment of the Malaysian government to realise sustainable development by launching the Green Building Index in 2009 (Aun & Ming, 2009), and to initiate more green townships across the country via the implementation of the green building technology and the onset of the energy efficiency program under the 10th Malaysia Plan (Minister of Works Malaysia, 2010). Both initiatives emphasise adaptation of sustainable elements in various construction aspects, including material use.

Therefore, based on the current scenario of the Malaysian construction sector, the present study will focus more on issues related to the use of aggregate as key ingredients in concrete production to cope with the rapid developments in the future. Aggregate produced from concrete waste, or RCA, is potentially seen as a renewable material that will serve as an alternative solution to replace existing natural aggregate. However, further research needs to be done to understand how the characteristic properties of RCA affect the performance of concrete.

1.3 Problem Statement

Efforts to encourage the use of RCA in large-scale concrete production have become particularly interesting after the discovery of the various economic and environmental benefits of RCA. However, the construction industry continues to have misgivings about the use of RCA in the commercial production of concrete, especially for structural applications. This condition may be attributed to certain unfavourable qualities of RCA compared with those of natural aggregates.

RCA is produced by crushing concrete lumps into smaller particles, which are then separated using a sieve of a specific size. This conventional crushing technique, such as the use of a jaw crusher, leaves old mortar particles (cement paste) in the original aggregate particles of RCA. The amount of old mortar incorporated in RCA varies across different reports, but it can reach as high as 56% (Butler et al., 2011). The presence of old mortar particles, which are characterized by relatively high porosity (Kou & Poon, 2010; López-Gayarre et al., 2009; Padmini et al., 2009; Tam et al., 2005; Tam & Le, 2007), results in RCA characterised by lower density, higher water absorption and lower mechanical strength than natural aggregates (Chakradhara Rao et al., 2011; Katz, 2003; Padmini, et al., 2009; Tabsh & Abdelfatah, 2009; Tam & Tam, 2007). Moreover, the impact stress caused by the crushing process makes the surface layer of RCA weak, porous and brittle (Ogawa & Nawa, 2012). The process also leaves numerous microcracks in RCA (Tam, et al., 2005). Consequently, the incorporation of RCA in concrete mixes can crucially affect the behaviour and performance of the resulting concrete in terms of freshness as well as mechanical and long-term properties. The presence of small cracks and pores of old mortar adhered on RCA forms a weak link in the microstructure of concrete. This change affects the ultimate strength of recycled aggregate concrete (RAC) (Tam, et al., 2005). Moreover, the presence of cracks and the porous nature of old mortar allow the absorption of more water. As a result, the effective water content for the hydration process is decreased. Consequently, a loose interfacial transition zone (ITZ) forms between the RCA and the new cement paste in the hardened concrete (Poon et al., 2004). Moreover, the looseness and pores at the interfacial bond provides an easier path for moisture and aggressive ions such as carbon, sulphate and chloride to diffuse into concrete. These characteristics are detrimental to the durability of the concrete in terms of long-term performance. Most researchers agree that the adverse behaviour of RCA is the key factor behind the poor performance of RAC.

For RAC to be commercially utilise in construction application, particularly for structural parts, it must possess appropriate physical, mechanical and durability performance. Thus, various approaches and methods have been developed to improve the RCA as a qualified aggregate material for concrete and to minimize its disadvantages. Such approaches and methods have been a subject of interest for many researchers. Surface treatment is an innovative and beneficial method that modifies and enhances the physical properties of RCA before its use in concrete mixes. Primarily, the literature indicates two techniques for implementing surface treatment on RCA. For instance, Tam, Tam and Le (2007) proposed the use of a low concentration of acid to minimize weak or loose mortars attached to the surface of RCA particles, thereby improving the surface contact between the aggregate and cement mortar. Another RCA surface treatment procedure is modifying or improving the RCA surface by refilling pores and cracks using suitable mineral admixtures such as microfillers. Katz (2004) introduced the surface treatment technique by filling RCA with a silica fume (SF) solution. In this method, the dried RCA is soaked in the silica fume solution to coat the surface of RCA with the silica fume particles. This treatment strengthens the structure of the aggregate, particularly the ITZ between the RCA surface and cement paste, thereby improving the mechanical strength of the concrete. Other alternative methods include soaking with various types of admixtures or solutions, such as nanosilica solution (Kutcharlapati et al., 2011), polymer solution (Kou & Poon, 2010) and silane-based water repellent (Zhu et al., 2013).

Although each method uses a different approach, both treatment methods have their own novelty and benefit for the improvement of the physical properties of RCA and for the minimization of the adverse effects of RCA on concrete. Therefore, these surface treatment methods are proposed to be suitable for consolidation. In doing so, an optimal result may be achieved more efficiently. The outcome derives benefits from the two treatment methods, which can also complement each other and subsequently reduce the weaknesses of RCA properties beyond the existing approach. Additionally, the effects of combining these methods on the properties of RCA, as well as on the performance of the resulting concrete, have not been studied previously. Merging both treatment methods is necessary to develop a comprehensive and systematic approach. Such an approach may eventually lead to a standardized treatment method for RCA before being used in concrete production.

Focusing only on improving RCA properties through surface treatments without considering any existing residual mortar when producing new concrete is insufficient. The residual mortar attached to the RCA has been identified as the key factor responsible for poor RAC performance. In addition, the quality of RCA fluctuates when collected from different sources. The presence of adhered mortar on RCA can cause the RAC to become a heterogeneous composite and that consist of multiple structure phases which differ from that of normal concrete. The presence of adhered mortar on the surface of RCA provides RAC with two different ITZs (instead of one as in normal concrete): a new ITZ between the RCA and the new cement paste as well as an old ITZ formed between the original aggregate and the old adhered mortar attached. The surface treatment method may affect the improvement of RAC properties up to a certain level only. As shown from the previous literature, the effect from surface treatment improves the strength of the interface bond between aggregate-new mortar compared with that of the aggregate-old adhered mortar bond, thereby making the latter components the weakest point in the composite system. As a result, the concrete can fail in this region. In fact, similar cases have happened where the quality of the new cement paste was superior to that of the old cement paste. One important criterion for selecting concrete is structural parts with high strength. Thus, the use of RCA in influence to increase the strength of concrete becomes questionable. A consideration is that high strength concrete fails during loading in a different manner than normal concrete; cracks can go through the aggregate rather than at the interface between the aggregate matrix (Li, 2011). This phenomenon was observed by Etxeberria, Vázquez, Marí and Barra (2007) in earlier research. Additionally, in current practice, a mix design procedure specifically for RCA use on structural-grade concrete is lacking.

A specific mix proportion for RAC must be developed to enable RAC to meet certain criteria for structural applications. Thus, specific improvements to the different properties of the RAC composite at various structures and dimensional levels are required. Combining the different beneficial methods that have been developed recently in advanced concrete technology can optimize the mechanical and durability properties of RAC. As proposed in this research, apart from steps that improve the quality of RCA through the surface treatment, the inclusion of fibre also has the potential to overcome this problem. Previous studies show that when randomly dispersed, short, discrete fibre either in single or hybrid form is added to the concrete matrix, the texture is strengthened and the brittleness of the concrete is decreased. Moreover, the efficient transfer of stress between the matrix and the fibres enables the propagation or coalescence of cracks to be controlled, thereby improving the mechanical properties and durability of concrete. Thus, this study is necessary to understand the potential of this new approach in detail. The characteristics or parameters that can enhance RAC performance are examined.

1.4 Research Objectives

This study is designed to enhance the performance of RAC and make this material suitable for structural applications. After identifying the main factors that contribute to the inferior properties of RCA, this study propose a method for enhancing RAC performance that involves a multi-phase process. The proposed method involves the following steps to improve the RAC mix: (i) The first phase involves enhancing the properties of coarse RCA before incorporating into the RAC mix. In this process, the surface structure of RCA is modified through a combination of two different surface treatment methods. This study initially treats RCA with a low-concentration hydrochloric acid and then impregnated with calcium metasilicate (CM) solution. (ii) The second phase involves modifying the RAC mix by inclusion of fibres. In this study, short discrete barchip fibre and polypropylene fibre were used at various volume fractions and added in single and hybrid combination forms to help modify and improve the properties of RAC in the plastic and hardened states. Moreover, this study employs a suitable experimental programme to characterise the behaviour that leads to RAC production as well as to fully understand the feasibility and effectiveness of the modification in enhancing RAC performance. This study emphasises short- and long-term effects of the modification on RAC performance, including their engineering and durability properties, when subjected to different curing conditions. The objectives of this study are as follows:

1. To study the effect of combining two different surface treatment methods on the properties of coarse RCA,

2. To investigate the effect of different curing conditions on the engineering properties of modified RAC,
3. To examine the durability performance of modified RAC when subjected to different curing conditions, and
4. To analyse the flexural behaviour of composite beams consisting of modified RAC and reinforced by a glass fibre reinforced polymer (GFRP).

1.5 Scope of the Research

The major scope of this research work is developing a method that can enhance the performance of RAC. This study discusses the use of coarse RCA with a maximum size of 20 mm. The RCA was produced from concrete waste collected from the debris collection area of the Laboratory School of Housing, Building and Planning (HBP), Universiti Sains Malaysia, Penang. This material is processed through various crushing stages and then sorted using a vibratory sieve to obtain the required particle size. The first approach involves improving the properties of RCA by combining two different surface treatment methods before incorporating it into the RAC mix. In this study, the RCA is first treated by soaking it in hydrochloric acid at 0.5 mole concentration. Subsequently, it is impregnated with a calcium metasilicate (CM) solution in order to coat the surface of RCA with CM particles. The effects of both surface treatments on the properties of RCA before and after treatment are determined. This phase also involves comprehensive testing to evaluate the basic mechanical strength as well as the physical and chemical properties of the treated RCA; these properties were compared with those of untreated RCA and natural coarse aggregate. Several tests were conducted to investigate these properties, such as tests for particle size distribution, porosity and absorption, particle density, particle shape, aggregate crushing value, aggregate impact value, Los Angeles abrasion value, chloride and sulphate content.

The second stage involves modifying the RAC mix. Aside from the inclusion of treated RCA, the RAC mix was also modified by inclusion of fibre. In this study, short discrete barchip fibre and polypropylene fibre were added in single and hybrid forms with the appropriate volume fractions to help modify and improve the properties of RAC in the plastic and hardened states. The mix proportion of concrete was designed according to the method by the Department of Environment (Teychenné et al., 1997). Accordingly, a series of concrete mixes was designed and prepared for this study depending on the type of RCA and type of fibre as well as the varying volume fractions of the fibre content used.

Specific experimental testing was set up and performed based on appropriate standard procedures. The testing was conducted to assess the influence of various related research parameters to gain an in-depth understanding of the engineering properties and durability of modified RAC exposed to various curing conditions: normal water (NW), open air (OA) and seawater (SW). All concrete specimens were initially cured using standard moist or water curing at an atmospheric temperature of 25 ± 2 °C for 28 days before further exposure to different curing regimes. The assessment of the engineering properties of modified RAC included determining the slump of fresh concrete mix and the mechanical strength of hardened concrete, namely, compressive strength, flexural strength, static modulus of elasticity, dynamic modulus of elasticity and impact load resistance. Moreover, an ultrasonic pulse velocity test was also conducted to assess the quality of hardened concrete. The experimental program determined the durability properties of the modified RAC in short- and long-term performances through various tests. The durability properties of concrete are closely related to permeability and porosity. Thus, the appropriate tests used in this study included water absorption, intrinsic air permeability, capillary absorption, carbonation and chloride resistance. Mercury intrusion porosimetry has been commonly used to examine the pore structure of cement-based materials, however this equipment was unavailable during the study so the porosity of concrete was determined using the total porosity test (based on water-accessible porosities) as recommended by RILEM (1984). Moreover, scanning electron microscopy (SEM) analysis was performed to visualise the micro-pore structures of the related concrete mixes produced. The investigation on the long-term performance of modified RAC also involved determining their dimension stability. This test was carried out by measuring the length change of the corresponding specimens against exposure time.

The final aspect of the study involved the method used to prepare and produce RAC in a structural beam form reinforced by glass fibre reinforced polymer (GFRP) which in an I-beam forms. The behaviours such as the ultimate load, load deflection, stress strains, ductility and fracture cracks of the modified RAC structure beam when subjected to flexural loading were studied. The failure mechanism of the modified RAC structure beam was also investigated.

1.6 Limitation of the Study

The major scope of this study is subjected to the following limitations:

1. This study uses only coarse RCA particles with fraction sizes from 5 mm to 20 mm.

2. The RCA used was generated from waste concrete collected from the debris collection area of the Laboratory School of Housing, Building and Planning (HBP), Universiti Sains Malaysia, Penang. The properties of the original concrete waste, particularly in terms of strength, were unknown because it originated from different grades and sources. Waste concrete used in this study mainly consisted of tested concrete cubes brought by outside contractors from different construction projects at the nearby USM area. Some also originated locally from waste concrete from experiments at the HBP Laboratory itself.
3. The dosage compositions of the coarse aggregates in this experiment were kept constant by replacing the natural coarse aggregate with untreated or treated RCA at 60% of the weight of the total coarse aggregate content in all RAC mixtures.
4. The proportion of the concrete mixture was designed using the Department of Environment method (Teychenné, et al., 1997), which was based on a constant effective water/cement ratio of 0.41 for all concrete mixtures, to achieve a target slump range of 30 mm to 60 mm and a compressive strength of 50 MPa on the 28th day.
5. The experimental tests examined the engineering and durability properties of the specimens exposed to different curing conditions were conducted for up to 300 days.
6. The tests to investigate the flexural behavior of the structural beams reinforced with glass fiber reinforced polymer (GFRP) were conducted after all the tested specimens reached at the testing age of 28 days.

1.7 Significant of Research

The significance of this study is described as follows:

1. This research work demonstrates the feasibility of using alternative construction materials, such as reprocessed concrete waste, in modern technology to manufacture commercial products that can compete with similar products generated with standard natural aggregates. Consequently, the study can contribute to diverting hundreds of tons of concrete wastes from landfill sites to recycling plants, as well as reducing raw material extraction and use. Several ways are proposed to minimise environmental impact and produce sustainable concrete.
2. The method presented in this study is a reliable alternative to a new technique that can minimise the adverse effects related to the inherent low quality of RCA products. The significant improvement in the use of treated RCA, as demonstrated in this study, enables its application in structural and non-structural concrete with fewer disadvantages in terms of performance. Moreover, the effectiveness of the proposed method encourages the application of RCA in large-scale concrete production and ensures a feasible method to achieve sustainability in the construction industry.
3. This study is significant from the perspective of concrete technology because of its innovative approach that provides an in-depth understanding of how to use RCA, which is more commonly used in a wide variety of concrete applications with improved characteristics. Specifically, this study proposes the improvement of RCA both in theory and practice. This study can

contribute to the body of knowledge on increasing RCA quality as well as on the production process for concrete.

4. From a commercial viewpoint, the superior performance of the RAC, together with the adaptation of a sustainable element, can make it a competitive commercial and alternative material for various structural or non-structural applications. In addition, the benefits gained from the application of recycled waste materials in the concrete mixture may effectively reduce production costs.

1.8 Outline of Thesis

This study is organised in eight chapters, which cover the engineering and durability properties of modified RAC at various curing conditions as well as the structural behaviour of a modified RAC composite beam.

Chapter 1 – This chapter provides an overview of the research topic and includes the introduction, current developments, relevant background, statement of the problem, research objectives, scope, significance and structure of the study.

Chapter 2 – This chapter includes the literature review, which is divided into three main parts. The first part presents the status of the use of RCA and/or RA. It also provides general information on the properties of RCA and related research on the effects of RCA on engineering and durability properties as well as the microstructure of concrete. The second part reviews various innovative improvement methods that have been conducted and reported in the literature on RCA properties, as well as the method that incorporates improvement in the mixing design and production process of RAC. This part also specifies the types and effects of fibres and admixtures on modified concrete performance. The third part examines the behaviour of several structural elements when produced using RAC.

Chapter 3 – This chapter describes the experimental procedure on conducting the surface treatment for RCA. A related testing procedure involves characterising the aggregate properties for concrete application. The relevant information on the characteristics of all material involved in the experimental work, preparing the constituent materials for the concrete, mix design, mixing procedure, curing regime, as well as the tests and standards used in conducting the investigation to determine concrete performance are discussed in detail.

Chapter 4 – This chapter explains the properties of RCA after the surface treatment process. The properties of RCA before and after the treatment process as well as their properties are investigated and compared with natural coarse aggregate. Generally, all coarse aggregates used for concrete in this study are described in terms of physical characteristics, mechanical strength and chemical properties.

Chapter 5 – This chapter discusses the influence of different curing conditions on the engineering properties of modified RAC mixtures in terms of short- and long-term performance. Effects related to the engineering properties of different RAC modifications were analysed and compared with those of normal aggregate concrete as well as with unmodified RAC specimens.

Chapter 6 – This chapter discusses the various durability properties of RAC, namely, water absorption, intrinsic air permeability, total porosity, capillary water absorption, carbonation depth, chloride resistance, drying shrinkage and SEM examination, through which the RAC microstructure is understood. The durability properties of different modifications of RAC mixed specimens are analysed and compared with those of normal aggregate concrete as well as with unmodified RAC specimens to determine their effectiveness.

Chapter 7 – This chapter further discusses the outcome of the earlier stage of the study and discusses the structural behaviour of modified RAC. In addition, the experimental methods as well as the design and installation methods of the GFRP (I-beam) element used to encase the internal reinforcement material in the design structural beam are explained in detail.

Chapter 8 – This chapter presents the conclusions based on the overall experiment results. Recommendations for future research, particularly to improve the design and method of the production process, are provided to further enhance the performance of RAC.