PERFORMANCE OF SINTERED GEOPOLYMERISED PALM OIL FUEL ASH AND WATER TREATMENT SLUDGE LIGHTWEIGHT AGGREGATE

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LIST OF ABBREVIATIONS

ACV	Aggregate Crushing Value
AIV	Aggregate Impact Value
ASR	Alkali-Silica Reaction
BA	Bottom Ash
BI	Bloating Index
C-A-S-H	Calcium Aluminiusilicate Hydrate
CBR	California Bearing Ratio
C-S-H	Calcium Silicate Hydrate
CSW	Concrete Slurry Waste
EDX	Energy Dispersive X-Ray
FA	Fly ash
FTIR	Fourier Transform Infrared Spectroscopy
GBFS	Granulated Blast Furnace Slag
ITZ	Interfacial Transition Zone
LECA	Light Expanded Clay Aggregate
LL	Liquid Limit
LOI	Loss On Ignition
L/S	Liquid To Solid
LWA	Lightweight Aggregate
LWAC	Lightweight Aggregate Concrete
LWC	Lightweight Concrete
M	Molarity
MIBA	Municipal Incinerated Bottom Ash
Ms	Modulus Ratio
MSWI	Municipal Solid Waste Incinerator
N-A-S-H	Sodium Aluminosilicate Hydrate
NP	Non-Plastic
OD	Oven Dried
OPBC	Oil Palm Boiler Clinker
OPC	Ordinary Portland Cement
OPS	Oil Palm Shell

PFA	Pulverized Fuel Ash
PI	Plasticity Index
PL	Plastic Limit
POC	Palm Oil Clinker
POFA	Palm Oil Fuel Ash
RHA	Rice Husk Ash
SEM	Scanning Electron Microscopy
SS	Sewage Sludge
SSD	Saturated Surface Dry
UPV	Ultrasonic Pulse Velocity
WTP	Water Treatment Plant
WTS	Water Treatment Sludge
XRD	X-Ray Diffraction
XRF	X-Ray Fluorescence

PRESTASI AGREGAT RINGAN GEOPOLIMER TERSINTER ABU KELAPA SAWIT DAN ENAP CEMAR RAWATAN AIR

ABSTRAK

Konkrit telah diakui sebagai produk pembinaan yang paling popular terutamanya digunakan dalam industri pembinaan dan agregat adalah antara unsur penting dalam campuran konkrit. Penggunaan agregat semula jadi yang berlebihan untuk pembangunan industri pembinaan telah menyebabkan masalah kekurangan sumber semula jadi dan kesan buruk terhadap alam sekitar. Penggunaan sisa industri sebagai bahan binaan akan menyelesaikan masalah pembuangan dan mengurangkan kesan negatif terhadap alam sekitar. Antara sisa, sifat bersimen abu kelapa sawit (POFA) sebagai sisa industri menyumbang kepada geopolimer perlu dieksploitasi sepenuhnya untuk dijadikan bahan binaan alternatif. Penggabungan POFA dengan enap cemar rawatan air untuk agregat pembuatan masih belum diterokai. Kajian ini memfokuskan pada penggunaan bahan buangan yang terdapat di tempatan iaitu POFA dan kelodak sebagai bahan mentah, dengan 8 kumpulan L/S, diaktifkan oleh 6 kumpulan cecair alkali sebagai pengeluaran agregat kasar untuk aplikasi konkrit. Agregat tiruan disinter dan dinilai dengan ujian yang sesuai, seperti fizikal, mekanikal, struktur mikro dan kimia untuk mencirikan bahagian campuran bahan mentah yang optimum. Hasil kajian menunjukkan bahawa nisbah cecair/pepejal dan pengaktif alkali adalah 0.6 dan 2.5 dioptimumkan untuk dicampurkan dengan kelodak bagi pembuatan agregat tiruan. Gabungan campuran 40% POFA dan 60% kelodak agregat tiruan telah menunjukkan kekuatan tertinggi sehingga 5.43 MPa dengan prestasi penyerapan air yang baik. Ujian makmal dilakukan untuk menentukan sifat kejuruteraan dan ketahanan konkrit. Hasil eksperimen menunjukkan bahawa agregat buatan POFA-

kelodak berpotensi dalam pengeluaran konkrit agregat ringan gred 25 kerana ia memberikan ciri-ciri yang diinginkan untuk mencapai kekuatan sasaran. Selain itu, memanfaatkan produk buangan dalam pengeluaran konkrit tidak hanya akan menguntungkan proses rantaian kitar semula tetapi juga menggalakkan penghasilan produk hijau.

PERFORMANCE OF SINTERED GEOPOLYMERISED PALM OIL FUEL ASH AND WATER TREATMENT SLUDGE LIGHTWEIGHT AGGREGATE

ABSTRACT

Concrete has been acknowledged as the most preferred construction product mainly used in construction industry and aggregate is one of the essential constituents in concrete mixture. Huge consumption on natural aggregate for the development of construction industry have caused an issue on natural resource depletion and adverse impact on the environment. The utilization of industrial waste as building material will solve disposal problem and reduce the negative impact on the environment. Among the wastes, the cementitious property of palm oil fuel ash (POFA) as industrial waste contributes to the geopolymer based binder which needs to be fully exploited to be used as alternative building material. Incorporation of POFA with water treatment sludge to perform manufacture aggregate is scarcely explored. This study focuses on utilizing locally available waste materials namely POFA and silt as the raw materials, with 8 range of L/S ratio, activated by 6 range of alkaline ratio as coarse aggregate production for concrete application. The artificial aggregate is sintered and evaluated by using relevant tests, such as physical, mechanical, microstructure and chemical analysis to characterize the optimum raw materials mix proportion. The results revealed that liquid/solid ratio and alkaline activator ratio of 0.6 and 2.5 respectively were optimized to mix with silt for manufacturing artificial aggregate. The combination of 40% activated POFA and 60% silt mixture of artificial aggregate showed highest crushing strength of 5.43MPa with acceptable performance in water absorption. Laboratory tests are done to determine engineering and durability properties of concrete. The experimental result shows that there is a potential in using artificial POFA-silt aggregate in the production of lightweight aggregate concrete (LWAC) grade 25 as it gives desirable properties to achieve the target strength. Besides, capitalizing waste materials in manufacturing concrete will benefit the process of recycle chain besides encouraging the production of green product.

CHAPTER 1

INTRODUCTION

1.1 Introduction

Rapid industrialization in developing country has parallel effect to the growth in construction industry since new construction is needed to support the urbanization. Concrete is one of the important building products since the early centuries. It is estimated that approximately 1.35 billion tonnes are being used for construction works annually (Hardjito et al., 2004). Among the composite material, aggregate occupies the large volume (60 to 75 %) to the total concrete volume (Kosmatka et al., 2002). Accordingly, it causes huge demands on consumption of aggregate. Therefore, sufficient and continuously supply of natural sources should be assured to support the construction's need and the economic development. According to a statement from Institution of Engineers Malaysia (2007), the supply of natural aggregate is forecasted to be sufficient for the development in the next few years. Meanwhile, control measures should be taken and implemented to prevent depletion of non-renewable natural aggregate resources which resulted from overconsumption (Hamid et al., 2006; Ismail et al., 2018). Moreover, the excavation activity will also exert negative effect on the environment, which includes depletion of natural resources and degradation of soil quality (Dangodara and Modi, 2018). As a result, it brings to the issue of sustainability and the challenge of overconsumption of the natural source. Due to the depletion of natural aggregate and its impact on the environment, transforming concrete in construction industry into sustainable technology is known as the needed adjustment to balance the needs on natural resources and for environment preservation. Thus, the concern about environmental issues has become significant and ignoring is not a choice anymore.

The activities of recycling and reusing of industrial wastes have raised attentions in most of the research area. The utilization of industrial waste materials for construction products has been deeply studied to determine suitable modification for construction use. Different techniques have been applied to process diverse materials, such as clay, shale, slate, slag, pulverized fuel ash (PFA), fly ash (FA) and others into usable products with remarkably similar chemical compositions and structures.

Palm oil industry plays an essential role in the development of economic and agricultural field as Malaysia is one of the largest palm oil producers and top exporter in which Malaysia is expected to produce millions of tons of waste annually (Abdullah and Sulaiman, 2013). Based on Malaysian Palm Oil Board (2012), Malaysia palm oil plantation sector had increased from 5.74 million (2016) to 5.81 million hectares (2017). Therefore, it clearly shows that the productivity of palm oil industry is increasing year by year. Since the productivity is high, therefore, palm oil waste disposal has become a problem that requires prompt solution, which calls for more places for landfill, funds allocation for the purpose of transportation and maintenance and others. There are studies on utilizing palm oil waste to produce building materials in exhibiting requirement for the use of green building (Chiang et al., 2009; Shakir et al., 2013). Thus, study on the usage of residue waste from palm oil production is needed.

Moreover, the residue from water treatment plant (WTP) is useless if there is no modification for other purposes. Sludge from WTP has the potential to be investigated and used for building materials production. Huang et al. (2005) examined that the results for the properties of bricks and artificial aggregate made from water treatment residue and excavated soil have their own feasibility usage in construction materials. Among the studies, reuse of this material as contributor in building products is an environmental-friendly strategy, since desirable performance can be achieved. Application of sludge to be used as construction materials have been investigated by researchers and shows that the end products have fulfilled the standards required. Wie et al. (2020) defined that the chemical composition that exists in sludge is a factor to support its production as construction products which will have to undergo sintering process. The new usage of sludge is environmental friendly and also will sustain the limited natural resources.

Since there are on-going issues on the depletion of natural resources and also a huge amount of unwanted wastes from different industries, it is the right time to come up with a possible solution to produce new materials which will benefit the construction industry. Innovative work on the study of artificial aggregate is important to prevent natural resources depletion. It is a possible solution which needs to be investigated further to prevent a serious problem in the future. Thus, the replacement of artificial aggregate for natural aggregate in construction is studied.

There are studies which make use of the waste product to manufacture artificial or sintered aggregate, for instance FA, ground granulated blast furnace slag (GBFS) and others (Gesoğlu et al., 2012, Majhi and Nayak, 2020). Utilisation of POFA is generally for geopolymer or cement replacement which gives desirable performances (Husseien er al., 2018). However, there is a need to investigate fully apply of POFA for other construction purposes. A study on the lime treated POFA and sewage sludge to form aggregate is established and will be the reference sources for this study. This is due to the further parameters (type of activator, production process, sintering consitions) is required as guidance for limited standards and knowledge on artificial aggregate (Lau et al., 2018). By utilizing such waste, it will be a feasible way to overcome some issues, for instance, landfill shortage and environmental problems.

Since the aggregate will occupy 70% of the concrete mixture which is mentioned earlier so it plays an essential role for engineering and durability properties of concrete. So, artificial aggregate properties will directly affect the performance and toughness of concrete which need to be considered. Further evaluation on the possible raw materials for artificial aggregate production should be studied. Therefore, POFA and silt are predicted to have high potential as artificial aggregate for construction material due to the chemical contents within both of them.

1.2 Statement of problem

The high demand and uncontrolled use of natural aggregate has caused adverse impact towards the environment since the process of exclusion of aggregate will contribute to pollution and depletion of natural resources (Nasr et al., 2020; Zeyad et al., 2019). The aggregate manufactured from industrial waste is essential to prevent the natural aggregate shortage and delivery issues that may affect the supply chain for future development.

There are studies in view of determining types of waste that can be modified as construction materials. Investigation on the use of palm oil residue (palm oil kernel shell showed 20% replacement for coarse aggregate n concrete could enhance impact and blast resistance of concrete (Fanjio et al., 2020). Soltan et al (2016) reported artificial aggregate production from waste granite and clay performed good thermal insulation and improved permeability. Incorporating of LECA and BA contributed effective mechanical performances, included reducing autogenous shrinkage, density and thermal conductivity of concrete (Zhang et al., 2017). The study on palm oil waste as a component to produce artificial aggregate had been conducted by Lau et al. (2017) and Lau et al. (2018). They had established that the lime treated POFA with sewerage sludge to form resilient aggregate. The knowledge of these studies has served as a source of reference to stabilize the combination of materials. However, due to the different characteristics of artificial aggregate compared to natural aggregate, there is still a need for further research. Thus, investigation on the characteristics performance of the aggregate is required to define the possibility outcomes that can be achieved according to the existing research study.

Rapid development of palm oil industry leads to residue wastage issue which brings adverse impact towards the environment and human health in general. The improper disposal of the wastes from palm oil industries has caused various environmental and human health-related problems. Therefore, utilization of POFA as additive for FA and ground blast furnace slag geopolymer was studied (Islam et al., 2014; Huseien et al., 2016; Huseien et al., 2018). The potential in utilizing POFA incorporated with aluminosilicate source showed better performance due to the high amount of $SiO_{2,}$ which is a good pozzolanic material. Research conducted by Salih et al. (2014) encouraged further investigation to assess the application of single source of POFA for geopolymer technology. Studies on fully utilized sole treated activated POFA as geopolymer are limited and more experimental works on factors affecting its performance are required. Studies done by Lau et al., (2018) on the POFA and sewage sludge aggregate production can be the reference for this study. This can be extended to generate artificial aggregate with geopolymer technology, since POFA can be the binder reagent to support the aggregate formation.

Huge amount of sludge generated due to the rapid population growth and increasing demand for water supply have caused issue for insufficient landfill area (Ahmad et al., 2016). Thus, sludge is also listed to be modified for construction use. High silica oxide (SiO_2) content that exists in sludge has been investigated for brick production and produced satisfying results which showed that it can alternatively replace conventional bricks (Huang and Wang, 2013; Hassanpour, 2018; Liu et al., 2020; Gomes et al., 2020). Based on the previous studies, mostly single type water treatment sludge (WTS) is stimulated by chemical activator or sintering process to achieve the target properties (Gomes et al., 2019). The use of sludge as raw material for construction material has a good potential, since it has high mechanical performance after undergoing appropriate treatment. According to Wei (2015), solidifying sludge derived aggregate was strongly enhanced by crystallization and chemical incorporations within the aluminosilicate or silicate framework. Huang and awing (2013) showed aggregate made with treatment sludge was viable for structural and non-structural LWA production. However, review of the previous studies showed that there is a gap of knowledge on the use of high silica sludge content with POFA in the production of building materials specifically aggregate (Gomes et al., 2019).

Despite the limited standards and knowledge regarding artificial aggregate, relevant experimental works need to be carried out to investigate its characteristics and performances. More experiments investigation done is able to improve the precision result for artificial aggregate formation. In addition, the effect of geopolymer addition, raw combination, curing method and manufacturer approaches for the production of artificial aggregate also leads to the need for further study in this field. The use of waste materials as alternative aggregate is among the initiatives that not only can reduce the issues of waste disposal but it is also capable of reducing the continuous need for natural aggregate. This is due to the existence chemical oxide within waste materials may contribute for crystalline formation and enhance mixture's bonding. A thorough search of the existing literature showed that there is no research on the combination of WTS and POFA derived on the properties of aggregate has been done. Therefore, study on the probability of waste materials utilization as building materials and the output of manufacturer aggregate implemented in concrete application is necessary. For this study, parameters effect on the production of artificial aggregate from combination activated POFA and silt for concrete application will be observed.

Based on the state problems, there are several questions have been outlined for this study:

1. What is the influence of liquid to solid (L/S) ratio and alkaline activator ratio on the performance of POFA paste?
2. How is the performance of sintered artificial aggregate derived from POFA and silt?
3. What is the optimum proportion of POFA to silt for sintered artificial aggregate production as coarse aggregate?

4. How is the performance of concrete incorporated with sintered lightweight artificial aggregate?

1.3 Objectives of research

This study main objective is to investigate the feasibility of industrial waste POFA, incorporated with water treatment waste for manufacturing artificial aggregate with the admixture of alkaline activator in the form of combination of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3). The properties of each raw material are discussed in this study which includes the physical, mechanical and microstructure of the sintered artificial aggregate based on the optimization of the mix proportion for the mixture of POFA and silt. Furthermore, the application of sintered artificial aggregate in lightweight concrete (LWC) in terms of mechanical properties is also studied.

The aims of this research are as follows:

1. To examine the effects of L/S and alkaline activator at different ratio on the performance of POFA paste.
2. To investigate the physical, mechanical and microstructure properties of POFA-silt sintered artificial aggregate.
3. To define the optimum proportion of POFA to silt for sintered artificial aggregate production.
4. To investigate the engineering and durability performance of lightweight artificial aggregate concrete comprising optimized sintered artificial aggregate.

1.4 Scope of work and limitation

This research study is to define the artificial aggregate performance through the production of geopolymer binder with silt. POFA is utilised as a binder together with alkaline activator and with the presence of CaO to react with base material with silt in manufacturing artificial aggregate. There are mainly three phases involved, which include optimization, production and application.

The optimization of POFA geopolymer paste was obtained from several parameters, which are the 0.6 L/S ratio, 2.5 alkaline activator ratio and 10% percentage of CaO based on the strength results acquired from laboratory tests. The concentration of alkaline NaOH of 12 M was applied on the optimization assessment for activated POFA paste based on the previous studies. The proportion of liquid alkaline activator to POFA is important in order to have better workability for the paste. The ratio of Na_2SiO_3 to NaOH was investigated to prevent the fast set of paste. Thus, alkaline activator ratio of 2.5 was adopted. The addition of CaO was to determine its contribution on the performance of POFA paste. Rheological evaluations were investigated from the initial stage until the final stage which included setting of time, flow test and compressive strength for POFA paste.

Production of artificial aggregate involves three different processes namely mixing, extruding, and pelletizing. Assessments on the different ratio of optimized POFA to silt activator were done to investigate the properties of artificial aggregate. Sintering condition for the artificial aggregate was determined from the preliminary laboratory works to obtain the desirable sintering temperature and duration. Artificial aggregate products were sintered at high temperature which is about 1150^{o}C. Laboratory tests included physical property, mechanical property, chemical soundness and microstructure tests were conducted up to 28 days to determine the optimum sintered artificial aggregate. This is due to the curing period of artificial aggregate which will affect its suitability for commercial use.

The optimum artificial aggregate with high strength was then selected as fully coarse aggregate replacement for lightweight aggregate concrete (LWAC) production. Concrete grade 25 was set for the concrete mix. The performance and properties of the LWAC are defined based on the engineering and durability properties which described in Chapter 3. The application of LWAC can be studied according to the results gathered from the properties determination.

1.5 Significance of study

Waste materials have always been an issue related to waste management, which involves scarcity of landfill area or efficient waste disposal approaches. From the agro-waste produced from the combustion of oil palm plants, POFA is one of the industrial by-products resulting from the burning process. The residues produced from the production of palm oil will be dumped at landfill area. Moreover, unwanted sludge generated from WTP is also wastage. There are immediate benefits which can be gained from waste materials stated above, for instance by recycling the unwanted waste materials generated by the palm oil industry and also the water treatment industry in a large volume. To reuse these industrial waste materials is an efficient way to manage the unwanted materials which will also lessen the impacts on the environment. Thus, transforming these waste materials into useful products is essential to increase their value. POFA has the potential to be modified as recycled construction materials. This is due to its chemical contents, which is rich in SiO_2. It will react with the presence of CaOH during hydration process to produce Calcium Silicate Hydrate (C-S-H) gel. As result, it meets the pozzolanic properties which contribute to the strength of concrete. Besides, the availability of sludge from WTP can also be investigated, since it contains high amount of SiO_2. Sludge has the properties as clay materials which will perform better after undergoing proper heat treatment process.

The purpose of this study focuses on the manufacturing of artificial aggregate as essential components of construction material, which will promote sustainable development. The development of construction industry increases the needs on the consumption of construction products, concrete is one of the products that has a high demand. High volume of aggregate is required as it is the constituent element for concrete production. This situation causes depletion of natural resources. Thus, the introduction of POFA and silt which come from unwanted waste. Furthermore, they are also categorized as green products. Besides reducing waste disposal and scarcity of landfill area, the artificial aggregate produced can be used alternatively as replacement for natural aggregate, thus reducing the demand for natural resources. This includes the properties and characterization of the industrial by-products and also the performance of artificial aggregate itself within concrete. Therefore, this will allow a large volume of waste to be recycled into useful purpose which originated from industrial waste.

Generally, artificial or synthetic aggregate is light in weight, which can reduce the structural load and construction handling cost, besides confirming the performance as building materials for construction application. Hence, the application of artificial aggregate in concrete will also serve as insulation products or for structural use based on its properties. However, there are some aspects which affected the properties of the artificial aggregate, such as manufacturing protocols, pelettization method and curing approaches. Knowledge on the artificial aggregate production is studied from previous studies to improve the performance of artificial aggregate used in this study.

Therefore, identifying the potential and feasibility of artificial aggregate production by incorporating silt (grinded from sludge) and POFA is significant to be investigated.

1.6 Outline of thesis

Research thesis is divided into six chapters to clearly show the research structure in order to organize the information systematically.

Chapter One explains briefly about background of research, current scenario and problems which require further attention, aims of the study, scope of work, research limitation and significance of the research to provide a clear direction of the study.

Chapter Two presents the literature reviews on general information related to natural and artificial aggregate. The recycling of waste materials as sustainable construction materials includes industrial waste products, recycled and demolition materials based on the previous studies. In this chapter, the common or existing methods of artificial aggregate production are also illustrated. The mechanism reaction of geopolymer, types of raw material which has the potential to be used as alkaline activated binder and the properties of waste materials used as construction materials are presented. The usage of artificial aggregate to make LWC is also briefly illustrated.

Chapter Three outlines the flow of methodology for laboratory works. The laboratory tests that have been carried out on physical, mechanical and chemical properties involved several different types and standard of tests, details on the procedures and analytic results are also presented. The proportion of materials used for the production of artificial aggregate and the curing condition are also mentioned in this chapter along with the schedule of lab experiments.

Chapter Four focuses on data collection. The results gathered from each test are tabulated in table or graph form for analysis. All the results are mainly from laboratory experiment tests. It explores the feasibility of planned materials as a binder to bond with silt which is then modified as artificial aggregate.

Discussion and findings are discussed in Chapter Five. There are relationships between the results gathered from the lab tests as mentioned in the chapter 4. It also analysed the preliminary results which studied the strength developed by the geopolymer. The influence of different proportions of materials is determined. The interpretation of reasons which affected the final product in terms of strength, water adsorption, specific gravity and others are also discussed. Deep analysis and examination conducted on the behaviour of the products according to X-Ray Fluorescence (XRF), X-Ray Diffraction (XRD) and Scanning Electron Microscopy (SEM) or Energy Dispersive X-Ray (EDX). In addition, discussion on the microstructure and its relationship with the mechanical properties are reported. The performance of optimum sintered artificial aggregate as coarse aggregate in concrete application is discussed in this chapter.

Chapter Six presents the overall findings and conclusion along with recommendations for future study. Lastly, this chapter also provides the summary of the study to conclude all the results.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In this chapter, literature review on current scenarios and solutions for sustainable construction materials are presented. Possible usages of waste materials and their contributions to construction industry are discussed. The use of industrial waste materials as pozzolanic or main raw with the addition of activators and admixture has the potential to give better performance as construction products. The effect of different manufacturing methods to produce final product and the properties of raw materials used are described in this chapter. It also covers the application of artificial aggregate for concrete use.

2.2 Issues extend from construction development and future perspective

In recent years, construction activities had brought impact towards the environment, for example, scarcity of natural resources, pollution, waste disposal and other issues. These problems have become the concern of the public as they may cause imbalance in the biodiversity. Due to the increasing number of populations in the world annually, it also directly increases the demand for building development. This is the reason construction industry is one of the contributors for natural sources depletion. It is estimated that 40% resources are being consumed and approximately 40% wastes are produced which also includes the impact of greenhouse from the construction activities (Hu et al., 2019). Meanwhile, among the structural construction materials, concrete is majorly used for the construction of most of the buildings.

Concrete is expected to consume about 8 to 12 million tonnes of natural aggregates since aggregate occupies almost 70 % of the overall volume (Dash et al., 2016). Thus, the high demand of natural aggregates will have impact on the environment and natural aggregate resources (Durga and Indira, 2016). Hence, the construction industry is becoming more serious about addressing the environmental impacts of its operations. Besides, waste disposal is also an issue where it requires a large capacity of the land for landfills (Fei et al., 2018). Solid wastes which is generated daily have filled up the available landfill. The option to reduce the amount of waste especially industrial waste is to explore the innovative method to manage these wastes. Therefore, effective measures are needed to conserve the environment. There is a campaign ‘turn waste into wealth’ which has shifted the current issue towards a more environmentally friendly development (Witjes and Lozano, 2016).

Sustainable construction and solid waste management are important to minimise these negative effects and to protect the environment, especially for urban cities where there are limited landfills. Some of the considerations are such as to address the concept and development of sustainable construction, to figure out current construction industry practices, to explore and to propose changes in practice and others. Through a sustainable construction concept, the construction industry can contribute positively and proactively towards environmental protection (Witjes and Lozano, 2016). One of the ideal approaches is by reusing, recycling and modifying wastes as alternative for construction use. This will allow further understanding on the possibility of waste materials to be used in producing new innovative construction products.

2.3 Potential applications of major wastes reuse as construction materials

The waste generated by industry needs to be classified properly in order to apply the correct form of management. There are different classifications which will depend on the origin, composition, danger and others. Generally, construction waste (demolition waste from construction) and solid waste (mainly from industrial, commercial and domestic) are the types of wastes considered. Assessment on the potential of these primary wastes to be transformed into useful products for secondary purpose is essential to be examined.

Majority of the industrial wastes are hard to be discarded or properly disposed which will indirectly cause environmental problems (Krishna and Sabnis, 2013). Globally, it is estimated that there are 12 billion tonnes of solid waste will be generated by year 2025, which includes about 1.6 billion tonnes from municipal solid wastes and about 11 billion tonnes from industrial solid waste (Safiuddin et al., 2010).

In Malaysia, solid wastes are majorly created by the public. Different industries will generate different types of unwanted residues. It is essential to examine the different types of wastes and to transform them into useful products which can solve the landfill issue besides creating a sustainable environment. Nowadays, many types of industrial wastes can be consumed either as supplementary, substitution or replacement for components in concrete. Wastes from industrial and agricultural have been exploited in research and used extensively as conventional concrete and LWC. Agro wastes have also been used as cement replacements or fillers for concrete. The development of new construction materials from various solid wastes have been investigated by many previous significant studies. The examples of modification of waste materials as construction materials are shown in Table 2.1.

Table 2.1 Different types and sources of solid wastes and recycling and utilization potentials for construction materials (Pappu et al., 2007; Safiuddin et al., 2010)

Type of solid wastes	Detail of sources	Recycling and utilisation potentials
Agro-waste (organic)	Baggage, rice and wheat straw and husk, saw mill waste, ground nut shell, jute, sisal, cotton stalk, vegetable residues	Cement boards, particle boards, insulation boards, wall panels, roof sheets, binder, fibrous building panels, bricks, acid-proof cement, coir fiber, reinforced composites, polymer composites
Industrial waste (inorganic)	Coal combustion residue, steel slag, bausite red mud, construction debris	Bricks, blocks, cement, paint, fine and coarse aggregate, concrete, wood substitute products, ceramic products
Mining/Mineral waste	Coal washeries waste, mining waste tailing from iron, copper, zinc, gold and aluminium industries	Bricks, fine and coarse lightweight aggregates (LWA), tiles
Non-hazardous waste	Waste gypsum, lime sludge, lime stone waste, broken glass and ceramics, marble processing residues, kiln dust	Blocks, bricks, cement clinker, hydraulic binder, fibrous gypsum boards, gypsum plaster, super-sulphated cement
Hazardous	Contaminated blasting materials, galvanising waste, metallurgical residues, sludge from waste water and waste treatment plants, tannery waste	Boards, bricks, cement, ceramics, tiles

Previous studies had explored the contributions from solid waste materials, which were used for various construction applications. Industrial waste, mining and mineral waste and non-hazardous waste had proven their applicability being used as the materials for coarse aggregate production. Plant based agricultural wastes such as rice husk, palm oil residue and coconut shell are the sustainable resources to produce concrete. Rice husk ash (RHA) could be incorporated in concrete to stop concrete cracking through formation of hydration gel. For industrial waste resources, silica fume, glass wool fiber, rubber waste, plastic waste and others had been investigated. Among rubber waste, it is recommended for concrete structure used for non-load bearing and noise reduction barrier (Vishwakarma et al., 2018). The known supplementary waste materials as LWA were oil palm waste such as oil palm boiler clinker (OPBC) and shell, waste plastic, steel cutting, recycle clay brick and others. The LWA used will be accepted as long as the mechanical properties have met the requirement for field application.

Moreover, the use of abundant waste materials will not only conserve the environment, but also resolve the problems occurs on the construction products. Incorporation of silica fume can reduce bleeding, permeability and porosity due to the present of SiO_2 reacts with $Ca(OH)_2$ for hydration process (Imam et al., 2018) . Besides, waste glass with high silicon and calcium content to gives rise to tri-calcium silicate and lower the amount of di-calcium silicate and tri-calcium aluminate can be used in concrete to make it resistance to sulphate attack (Belouadah et al., 2018). Use of 20-30% of rubber materials in concrete shows good performance in sound and heat insulation. This will result good energy-saving effect with high thermal resistance (Wang et al., 2020). Thus, potential waste materials are able to perform enahmcement on different properties for construction products.

2.4 Lightweight aggregate (LWA)

Aggregates are granular material, which are commonly used for manufacturing construction products, for instance ready-mixed concrete, pre-cast products, asphalt together with lime and cement (Pacheco-Torgal & Ding, 2013). Aggregates are defined as inert materials, which are mixed with a binding material (cement) to produce concrete. There are two categories of aggregate, normal aggregate and LWA. LWA is the generic name where it has relative low density than normal aggregates. Different LWA has its own function based on the use of the concrete.

The aspect that contributes to the low bulk specific gravity and density of LWA is porosity. This is due to the cellular or high internal porous microstructure. Structural LWA with a bulk density less than 1120 kg/m³ is for fine aggregate and less than 880 kg/m³ is for coarse aggregate generally meet the requirements as per ASTM C330 (ASTM, 2007). Besides taking into account in terms of aggregate density, water absorption is also one of the essential properties. LWA has high water absorption compares to normal aggregate. It is an important aspect, which can be modified through the method of concrete proportioning. For example, the pre-wet LWA is used for concrete production to prevent the issue of slump loss. Moreover, it also acts as fillers and will affect the strength and durability performance of concrete.

There are two types of LWA namely natural aggregate (pumice, scoria or tuff) and manufactured or synthetic aggregate (GBFS, clay, FA, shale or slate). Manufactured aggregates are prepared by expanding, pelletizing, or sintering. Synthetic aggregate performs a different function based on the density and strength. According to Alexander (2019), LWA in concrete can be classified into ultra-lightweight, lightweight, structural lightweight based on the density as shown in Table 2.2

Table 2.2 Density classification of concrete aggregate (Alexander, 2019)

Category	Unit Weight of Dry-rodded aggregate (kg/m^3)	Unit Weight of Concrete (kg/m^3)	Typical Concrete Strength (MPa)	Typical Applications
Ultra Lightweight	< 500	300-1100	< 7	Non-structural
Lightweight	500-800	1100-1600	7-14	Insulating materials
Structural Lightweight	650-1100	1450-1900	17-35	Masonry units and structural

2.4.1 Natural aggregate

Natural or uncrushed aggregate is obtained from mining sources such as gravel and crushed rock which are available natural resources in the form of almost ready to use. It is generally used for manufacturing construction product. Natural aggregate can be crushed, graded or washed for the purpose of production. Normally it is in an irregular shape and has unsmooth texture. Examples of natural LWA are pumice, perlite, shale and others which have investigated for concrete application (Kumar et al., 2022; Agrawal et a., 2021; Aslam er a., 2016).

2.4.2 Artificial aggregate

Artificial aggregate is also known as secondary aggregate, sometimes it is referred to as manufactured aggregates. It can be obtained from industrial and metallurgical engineering operations of waste materials, which will retain appropriate properties for aggregate replacement. For example, cinder is obtained from the burning of coal in kilns, slag is obtained from blast furnaces as scum, and palm ash is obtained from the palm oil furnace and others (Nataraja and Rao, 2016; Yusof et al., 214; Colangelo and Cioffi, 2013).

The differences in the properties of artificial aggregate are based on their manufacturing sources and process. Most artificial aggregates have been classified as LWA because of their relative density which is approximately 50% lower than normal aggregate. It ranges from 1.12 to 1.64 depending on the material sources. Artificial aggregate with an impact value exceeding 20% is unsuitable for concrete production (Aslam et al., 2016). BS 812: Part 112 (BSI, 1990) suggested that the impact value for aggregate should not exceed more than 25% for heavy-duty usage, less than 30% to be used for concrete wearing surface and 45% for other concrete surface.

Commercial data are indicative benchmark values for synthetic aggregates because the obtained strength is related to the density and the expected application. Light Expanded Clay Aggregate (LECA) and lytag are the common benchmarks for sintered LWA used in concrete. LECA is lightweight expanded clay aggregate with a crushing strength of 4.5 MPa, and lytag is sintered PFA LWA with a crushing value of 6.9 MPa (Bogas et al., 2016). Lytag is a LWA produced commercially through the process of pelletising of PFA and fine coal with about 12-15% of water in dish pelletizer at controlled rate to form rounded green pellets (Clarke, 1993). It is then followed by sintering under high temperature to strengthen the aggregate. Basically, size and compaction degree of pellet depends on several parameters, including the feeding rate, additional added water, instrument’s inclination and rotational speed and sintering conditions (Pietsch, 2008). Studies on various possible materials to be manufactured as artificial aggregate have been done by researchers in order to define their performance (Table 2.7).

2.5 Properties of LWA

The main requirement of LWA is it has low density which has specification limit of 12 kN/m^3 unit weight for fine aggregate and approximately 10 kN/m^3 for coarse aggregate (Hassan, 2015). The physical properties of LWA aggregate for structural concrete, low-medium or low strength concrete are shown in Table 2.3 and will be elaborated in the following sub-section.

Table 2.3 Physical properties of different raw of LWA (Neville & Brooks, 1987)

Aggregate properties				Concrete properties	
Aggregate type	Shape and surface texture	Density (kg/m^3)	Bulk density (kg/m^3)	Unit weight (kg/m^3)	Compressive strength (MPa)
Aggregate for structural concrete (strength> 15MPa)					
-Expanded clay	Round, slightly rough	600-1600 (coarse) 1300-1800 (Fine)	300-900	1000-1700	10-60
-Expanded shale and slate	Often regular and slightly round, smooth surface	800-1400 (coarse) 1600-1900 (fine)	400-1200	1300-1600	20-50
-Fly ash (FA)	Round, slightly rough	1300-2100	600-1100	1500-1600	30-60
-Foamed-blast-furnace slag	Irregular angular, rough and open pore surface	1000-2200	400-1100	1800-2000	10-45
-Sintered-colliery waste	Angular, open pored surface	1000-1900	500-1000	1400-1600	10-40
Aggregate for low-medium strength concrete (3.5-15 MPa)					
-Pumice	Round, open texture but smooth surface	550-1650	350-650	1200-1600	5-15
Aggregate for low strength concrete (0.5-3.5 MPa)					
-Perlite	Round, angular, rough surface	100-400	40-200	400-500	1.2-3.0
-Vermiculite	Cubical	100-400	60-200	300-700	1.2-3.0

2.5.1 Density and water absorption

The structural LWA has low particle density due to the internal cellular pores system. The formation of pores occurred for raw mixtures when it is heated at high temperature. It will then retain expansion upon cooling which resulted in lightweight density. The particle density of an aggregate is defined as the ratio between the particle material mass and the volume occupied by individual particle. This volume includes the pores within the particle, but does not include voids between the particles (Yehia et al., 2020). The volume of particles can be determined through water displacement method. The less permeable LWA submerges in water will limit the water absorption, which provides more accuracy to the density of aggregate. For the pores size in LWA with the range of about 5 to 300 μm, it will contribute to high strength and durable pellet. Besides, the uniform distributions of pores within LWA will also affect the properties of LWA.

Due to the presence of cellular structure, LWA has higher water absorption than the ordinary natural aggregate. Threshold of 30% for LWA is set as per standard BS EN 13055-1 (BSI, 2002). This is due to the high water absorption is not encouraging for good concrete development. Based on a 24 hour absorption test as per standard of ASTM C 127-15 and C 128-15 (ASTM, 2007), there are a range of 5 to 25% of absorption for structural LWA. However, the natural aggregate has low moisture (less than 2%) by aggregate mass. For view on LWA, when the cellular structure within the particles reaches the fusion point, viscosity allows the LWA to be enveloped with glassy texture in high-strength vitreous phase, which limits water accessibility. Permeable pores close to LWA's surface will be exposed to moisture, where glassy inner pores will be filled slowly. Some non-interconnected pores will exist, it will be extremely slow when LWA is immersed in water. Thus, the oven dry (OD) density of LWA depends both on the density of the solid vitreous material and the exiting pores volume within the particles.

Moreover, the rate of absorption can also influence the absorption properties of LWA. There are parameters affecting the rate, such as the continuity and distribution of pores and characteristics of pore size. Besides, the cellular of LWA enables the capillary water to exit for concrete production. Capillary forces will depend on the capillary size. As the capillary size decreases, it tends to increase the capillary force. The readily moisture of LWA will contribute to the extended curing, since the saturated LWA compensates for moisture loss in concrete that is exposed to air during the curing ages. It is an advantage since it does not only encourage continuous hydration or internal curing for long term curing but will also improve the matrix zone for LWA and cement paste. In addition, the internal curing in concrete will reduce the permeability since the formation of hydration products which have denser microstructure of concrete.

Lynn et al. (2016) studied the performance of water absorption on municipal incinerated bottom ash (MIBA) aggregates. The results are illustrated in Figure 2.1. It had shown the water absorption of MIBA LWA performed almost likely of typical value as compared with lytag which was well below the standard limit which was 30% as prescribed in BS EN 13055-1 (BSI. 2002). LWA containing activated carbon, MIBA, and PFA exceeded the limit because MIBA and PFA decreased the density and considerable increased water absorption through carbon decomposition. The result provided evidence that MIBA LWA was mostly comparable with lytag (15%).