PAPER SLUDGE BLENDED CEMENT MORTAR: A STUDY ON THE MECHANICAL PROPERTIES

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A project report submitted in partial fulfilment of the requirements for the award of Bachelor of Engineering (Honours) Civil Engineering

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DECLARATION

I hereby declare that this project report is based on my original work except for citations and quotations which have been duly acknowledged. I also declare that it has not been previously and concurrently submitted for any other degree or award at UTAR or other institutions.

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APPROVAL FOR SUBMISSION

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ABSTRACT

With the expanding of industrialization, factory by product such as paper sludge started to accumulate and causing the raise in the concern of environmental and economical effect. Paper sludge like others solid waste, it can be either disposed by landfill or through incineration process. In fact, landfill is not environment friendly while incineration process is very costly; therefore incorporate it into concrete mortar is one of the great ways to reduce it. The main purpose of this study is to determine the mechanical properties of concrete mortar incorporated with paper sludge, fly ash and ground granulated blastfurnace sludge. In order to determine the best proportions of the lightweight mortar incorporated with fly ash, ground granulated blastfurnace slag and paper sludge in term of mechanical properties; few tests have been carried out namely: water absorption, compressive test, scanning electron microscope, oven dry density and thermal conductivity test. All the specimens were aged for 7 and 28 days before being tested. It is found that increasing substitution of paper sludge causes rapid decline in the compressive strength, thermal conductivity and oven dry density but expansion in water absorption. However, substitution of paper sludge into concrete mortar is only viable at such circumference that it able to achieve all the minimum requirements as stated in ASTM C129 (2017).

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LIST OF SYMBOLS / ABBREVIATIONS

Al_2O_3	Alumina
C_2S	Dicalcium silicate
C_3A	Tricalcium aluminate
C_3S	Tricalcium silicate
C_4AF	Ferrite
CaO	Calcium oxide
CO_2	Carbon Dioxide
K_2O	Potassium oxide
MgO	Magnesia
Na_2O	Sodium oxide
SiO_2	Silica
$^{\circ}C$	Celsius
$^{\circ}F$	Fahrenheit
kg	Mass
kg/m^3	Density
min	Minutes
MPa	Mega Pascal, Pressure
s	Seconds
ASTM	American Society for Testing and Materials
BS	British Standard
GGBS	Ground Granulated Blastfurnace Slag
LOI	Loss of Ignition
OPC	Ordinary Portland Cement

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Around 3247 tons of paper wastes produce daily in Malaysia according to a statement published by Solid Waste and Public Cleansing Management Corporation (SWCORP) in 2016 and 82.5% of it goes into landfill for decomposition; primarily gas that releases from decomposition of organic waste by landfill is methane, a greenhouse gas that has 25 times more potent than carbon dioxide in term of its global warming potential shown in the Table 1.1 (IPCC/TEAP, 2005).

Table 1.1: Lifetimes, radioactive efficiencies and direct (except for CH_4) GWPs relative to CO_2 (IPCC/TEAP, 2005)

Industrial Designation or Common Name (years)	Chemical Formula	Lifetime (years)	Radiative Efficiency (W m^{-2} ppb^{-1})	Global Warming Potential for Given Time Horizon			
				SAR[‡] (100-yr)	20-yr	100-yr	500-yr
Carbon dioxide	CO_2	See below[a]	[b] $1.4x10^{-5}$	1	1	1	1
Methane[c]	CH_4	12[c]	$3.7x10^{-4}$	21	72	25	7.6
Nitrous oxide	N_2O	114	$3.03x10^{-3}$	310	289	298	153
Substances controlled by the Montreal Protocol							
CFC-11	CCl_3F	45	0.25	3,800	6,730	4,750	1,620
CFC-12	CCl_2F_2	100	0.32	8,100	11,000	10,900	5,200
CFC-13	$CClF_3$	640	0.25		10,800	14,400	16,400
CFC-113	CCl_2FCClF_2	85	0.3	4,800	6,540	6,130	2,700
CFC-114	$CClF_2CClF_2$	300	0.31		8,040	10,000	8,730
CFC-115	$CClF_2CF_3$	1,700	0.18		5,310	7,370	9,990
Halon-1301	$CBrF_3$	65	0.32	5,400	8,480	7,140	2,760
Halon-1211	$CBrClF_2$	16	0.3		4,750	1,890	575
Halon-2402	$CBrF_2CBrF_2$	20	0.33		3,680	1,640	503
Carbon tetrachloride	CCl_4	26	0.13	1,400	2,700	1,400	435
Methyl bromide	CH_3Br	0.7	0.01		17	5	1
Methyl chloroform	CH_3CCl_3	5	0.06		506	146	45
HCFC-22	$CHClF_2$	12	0.2	1,500	5,160	1,810	549
HCFC-123	$CHCl_2CF_3$	1.3	0.14	90	273	77	24
HCFC-124	$CHClFCF_3$	5.8	0.22	470	2,070	609	185
HCFC-141b	CH_3CCl_2F	9.3	0.14		2,250	725	220
HCFC-142b	CH_3CClF_2	17.9	0.2	1,800	5,490	2,310	705
HCFC-225ca	$CHCl_2CF_2CF_3$	1.9	0.2		429	122	37
HCFC-225cb	$CHClFCF_2CClF_2$	5.8	0.32		2,030	595	181

Therefore, lightweight concrete block with blended cement of fly ash, ground granulated blastfurnace slag (GGBS) and mainly paper sludge waste are introduced to mitigate the overwhelming amount of paper sludge waste in Malaysia

Ordinary masonry unit such as clay brick start to lose its popularity as a lightweight concrete block introduces in the market due to the benefit it possesses. Lightweight concrete block like other ordinary masonry units, normally used for the masonry construction such as non-load bearing wall, but it possesses a much lower density ranging between 650 kg/m^3 – 1500 kg/m^3 as compared to dense aggregate block that fall in between 1800 kg/m^3 – 2100 kg/m^3(Collins, 2018). Besides that, lightness of the block help greatly in reducing the load that applied on the beam and column; hence, only a small beam or column is needed to handle the death load that imposed on the building and subsequently reduce the overall construction cost. Furthermore, the lightweight concrete block possesses the ability to resist fire and act as a thermal insulator (Gupta, Singh and Sakale, 2018).

As masonry unit is widely used in construction, a lot of engineer and researcher put a lot of effort in finding a solution to develop an environmentally sustainable material that aims to reduce the wastes produced and decrease the carbon dioxide that generated from the production of cement. Common agriculture and industry by-product used for researching are rich hush, wood ash, fly ash and palm oil fuel ash while for this experiment paper sludge is selected as the main study material to partially replace the proportion of cement in the production of the lightweight concrete block.

Paper sludge is one of the top waste that's generated in Malaysia aside from food waste and plastic waste, it is said that Malaysian are able to generate 3247 tons of paper waste daily. Reusing of unrecyclable paper not only help in lower down the paper sludge waste in Malaysia but also reducing the landfill area and thus minimize the pollution of it to the environment. One of the main concerns of International Relation is that the growth of natural resources is unable to cope with the demand; as an example, the net loss of the global forest area (deforestation plus reforestation) in the last decade of the 20th century was about 94millon hectares which equivalent to 2.4 percent of total world forest” (International Relations, 2018). By using paper sludge waste in the production of the lightweight concrete block, it able to conserve natural resources by reducing the demand for rare material and thus lower down the deforestation rate due to mining purpose.

There are several studies done previously by the researcher regarding the application of paper sludge waste on concrete block or also known as papercrete. For instance, a study done by a group of researchers shows that paper sludge waste is viable in the production of concrete block and the compressive strength of it able to fulfil the requirement of ASTM C129 with the minimum compressive strength of 3.45MPa (Gupta, Singh and Sakale, 2018). Several sets of the specimen were cast with various proportions of cement, paper sludge and sand and it is found that as the paper sludge proportion increases, there will be a slight decrease in the compressive strength of the concrete block (Gupta, Singh and Sakale, 2018). Generally, paper sludge possess a little or none cementitious properties but it contain Silica(SiO_2), Alumina(AI_2O_3) that able to react with calcium hydroxide in the presence of water to form calcium silicate hydrate and calcium aluminate hydrate that possess cementitious properties but most importantly the present of kaolinite and calcite that under temperature of 700˚C for 2 hours will undergoes calations and form metakaolinite, a highly effective pozzolan (Garcı´a et al., 2008); thus it is suitable to partially replace cement in the casting of concrete block.

1.2 Problem Statement

Refer to a statement published by YBHG. DR.MOHD Pauze Bin Mohamad Taha (2016), 38,200 tonne/day of solid waste was generated in the year of 2016 and is estimated to grow further to 45,900 tonnes/day by the year 2020; from all the waste that's generated, 8.5% of it is paper waste and only 17.5% of it goes to recycle. Furthermore, paper made products are often labelled as environmentally friendly due to its ability to be recycled and degradable but people do not know that according to expert, this may not be totally correct and is misleading. Environment and waste management expert Dr Theng Lee Chong mention that it is true that paper is recyclable and bio-degradable but paper made product that with plastic film coating on it are not recyclable due to contamination and high cost. Therefore, concrete block with blended cement of paper sludge may be one of the solutions to this massive paper sludge waste.

As urbanization takes place, the usage of cement increase drastically as it is one of the primary materials for construction. According to the Intergovernmental Panel on Climate Change (IPCC), for every tonnes of cement produced there will be one and a quarter tones of equivalent carbon dioxide (CO2) released. So it is important to search for the partial replacement of cement in the production of concrete brick before the Global warming becomes more severe. Waste paper sludge like another pozzolan, possess siliceous and aluminous properties which possess little or no cementitious value but in the presence of water it will able to react with calcium hydroxide to form compound possessing cementitious properties; therefore it can be used to partially replace cement in the production of concrete brick which indirectly can lower down the paper sludge waste in Malaysia.

1.3 Aim and Objectives of the Study

1.3.1 Aim

1. To study the mechanical properties of lightweight mortar incorporate with paper sludge, fly ash and ground granulated blastfurnace slag.

1.3.2 Objective

1. To achieve a lightweight concrete mortar with density of 1300±50 kg/m³ using blended cement with paper sludge waste, fly ash and Ground granulated blastfurnace slag (GGBS).
2. To obtain the optimal percentage of paper sludge waste to replace the ordinary Portland cement in the production of lightweight concrete mortar in the presence of fly ash and Ground granulated blastfurnace slag (GGBS) without compromising the compressive strength as stated in ASTM C129 (2007).
3. To study the effect of paper sludge waste on the thermal conductivity of lightweight mortar.

1.4 Scope of Study

This study is to investigate the effect of paper sludge waste on the engineering properties of lightweight concrete block in term of compressive strength, absorption and linear shrinkage in the presence of fly ash and Ground granulated blastfurnace slag (GGBS). Different proportion of paper sludge waste is introduced in this study to obtain the optimal proportion of it without compromising the strength and consistency of lightweight concrete block compare to ordinary lightweight concrete block (100% OPC) which is 10%, 20% and 30% replacement of cement while fly ash and ground granulated blastfurnace slag (GGBS) is capped at 5% each for the replacement of cement. The cement to sand ratio chosen is 1:1 because the result obtained by Yun, Jung and Choi (2007) showed that the mechanical properties of this ratio are the best among all the ratio considered. Ling, Nor and Mudiyono(2006) conduct an experiment on the effect of the water cement ratio to achieve the highest quality of concrete block in term of its strength. These researchers found out that, in order to achieve the highest quality of concrete block, a water-cement ratio of 0.55 is used.

Standard cube of 50mm was used in this experiment and cured for 7 and 28 days in order to determine the chronological compressive strength. For thermal insulation test, 50mm cube test will be selected due to insufficiency raw material supplied. The targeted density of lightweight concrete block for this experiment is 1600kg/m^3 with a tolerance of ±50 kg/m^3. Each designation factors will have 3 specimens and the average result of it is calculated. The result obtains from concrete block tested in 7 and 28 days were studied and discussed to select the highest quality of the concrete block cast.

1.5 Significance of the Study

1. Incorporating paper sludge waste as part of cement replacement material in the casting of lightweight concrete mortar to construct a sustainable environment and as an innovative method to reduce the solid waste in Malaysia.
2. Develop a mix proportion of lightweight concrete block that ably replaces ordinary concrete block as a concrete masonry unit which used for building construction without compromising the original properties in term of compressive strength, absorption and linear shrinkage.

1.6 Layout of Report

This report has a total of five chapters: introduction, literature review, methodology, discussion and conclusion.

In chapter 1, this chapter mainly discusses the introduction of the study, problem planned to solve, aim and objective of the study, the scope of the study, benefits of this study and layout of the report.

Chapter 2 discusses the review of another profession on the properties of paper sludge, lightweight concrete block, fly ash, ground granulated blastfurnace slagand ordinary Portland cement. On the other hand, it also discusses the advantages of lightweight concrete block and the effect of paper sludge waste on the engineering properties of lightweight concrete block.

Chapter 3 discussed about the procedure and method that necessary to conduct the experimental study. This includes the fresh mortar mixing procedure, and also compression strength test as complied with ASTM or BS code.

Chapter 4, discusses the experimental results of lightweight concrete masonry unit with blended of paper sludge waste, fly ash and ground granulated blastfurnace slag (GGBS) as partial cement replacement materials in terms of fresh density, dry density, compressive, absorption and linear shrinkage

The conclusion of this experimental study will be done in chapter 5. This chapter summarizes the important, benefit and result of this study, according to the aim and objective of this experimental study. Recommendation and modification will be given for future development and improvement of this study.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The lightweight concrete block also knows as concrete masonry unit is made up of fine aggregate, water, Ordinary Portland cement and other raw material such as biomass clinker, fly ash, and woody ash while this report will mainly focus on the effect of paper sludge waste on lightweight concrete blocks in the presence of fly ash and ground granulated blastfurnace slag (GGBS). In comparison with ordinary concrete block, lightweight concrete mortar possesses a better lightness, lower thermal conductivity, good sound absorption ability but the strength of it must comply with ASTM C129 (Gupta, Singh and Sakale, 2018).

Lightweight concrete block with densities ranged from 650kg/m³ to 1500kg/m³ have found its value in the market and had been used for masonry structure and construction purpose for many years. The water-cement-sand ratio is the vital element in producing a good quality of lightweight concrete block; for instance, a higher proportion of sand in the production of lightweight concrete block help in producing a higher strength concrete block but subsequently will result in a higher density (Shermale and Varma, 2016).

Incorporation of paper sludge waste in the field of civil engineering had shown significant in building up a sustainable environment. For instance, “fast firing of tiles containing paper mil sludge, glass cuellet and clay” (Maschio et al., 2009), “application of paper waste in cement concrete” (Singh and Saleem, 2015), “Properties of waste paper sludge ash (WPSA) as a cement replacement in mortar to support green technology material” (bin Mohd Sani et al., 2011) and “Papercrete: A lightweight concrete” (Shermale and Varma, 2016).

2.2 Advantages of the Lightweight Concrete Block with Paper Sudge Waste

As urbanization takes place, people start to put more time and effort in searching a replacement for the ordinary concrete block. The research puts on concrete block include, the feasibility and economic value of solid and hollow concrete block by Building Materials & Technology Promotion council and papercrete as a sustainable building material for building construction by Gupta, Singh and Sakale (2018); the ultimate aim of all these researches is to find a concrete block that is sustainable, durable, consistent and also has a great economic value. Therefore, lightweight concrete block with paper sludge waste able to meet all these criteria because it is sustained by reducing the paper sludge waste, low production cost (using waste material) and in engineering view, its properties only have slightly different compared to an ordinary concrete block in term of compressive (Gupta, Singh and Sakale, 2018).

Even though lightweight concrete block possesses a relatively low compressive strength compare to dense concrete block, but its performance as the non-load bearing structure has decreased the structural dead load and eventually minimizing the dimensions of load bearing structure such as column, beam and slab which lead to lower construction cost. Besides that, according to research done by Gupta, Singh and Sakale(2018), papercrete (concrete block with blended of paper sludge waste) has a much lower thermal conductivity than normal concrete block; therefore, its insulation value is much higher. As we know, paper is a flammable material which leads to people concern on the flammability of the lightweight concrete block with blended of paper sludge waste but according to a research done by Gupta, Singh and Sakale(2018), it does not glow upon contact with fire which means it is not flammable. Furthermore, in term of thermal conductivity, paper blended lightweight concrete block has much lower thermal conductivity compare to ordinary concrete, thus is possess a higher insulation value (Shermale and Varma, 2015). Moreover, the present of paper sludge able to increase the acoustic effect of a product for example the blended of paper sludge in the wood-wool composite board at 20% able to increase the acoustic effect of it by a factor of 2 (Doudart de la Grée, Yu and Brouwers, 2018).

2.2.1 Compressive Strength

Compressive strength is one of the most common engineering properties that used to determine the quality of the concrete block. According to research done by Shermale and Varma (2016), the compressive strength of the concrete block decreased with the increase of paper sludge proportion. Aside from paper sludge proportion in the concrete block, sand and cement also take an important role in building up the compressive strength of a concrete block; as shown in Table 2.1as the proportion of cement increase with the fixed amount of paper ratio, the average strength of the papercrete raise from 1.9MPa (1-1,Paper-Cement) to 2.52MPa (1-3,Paper-Cement). On the other hand, when the proportion of cement and paper was fixed, the decreasing in the proportion of sand in concrete block showed a slight decrease in the average strength. Additionally, for non load bearing concrete masonry units, the minimum net area compressive strength requirements are 3.45MPa for an individual unit and 4.14MPa for an average of three units as refer to ASTM C129.

Table 2.1: Strength of concrete block with different proportion of Paper-Cement-Sand ratio (Shermale and Varma,2016)

Mix No	Materials	Proportion	Weight of sample(gm)		Average mass density	Average Strength (MPa)
			1	2		
1	**Paper/Cement**	1-1	372	495	0.433	1.9
2	**Paper/Cement**	1-1	613	615	0.614	2.34
3	**Paper/Cement**	1-3	772	814	0.793	2.52
4	**Paper/Cement /Sand**	1-1-5	1108	1127	1.117	3.53
5	**Paper/Cement /Sand**	1-1-3	910	918	0.914	3.3
6	**Paper/Cement /Sand**	1-1-2	770	787	0.778	2.5

2.2.2 Thermal Insulation

When talking about a strategy to improve energy efficiency, the most critical part is how we ensure that the energy loss is at its minimum; therefore, thermal insulation is a great solution to mitigate this problem by reducing the heat loss or gain through the building envelope. Thermal insulation can be incorporated into some of these building elements like: walls, roofs and floors to further increase the overall thermal insulation of a building. For example in Malaysia, during the hot days, people like to open the air conditional so that the indoor temperature can be maintained at a comfortable level but without a good thermal insulation for the building envelope, rapid heat gain into the building can result in a higher amount of air-conditional to be install or the indoor temperature cannot be maintained at a comfortable level.

According to a paper publish by Gorgis, Zaki and Salih(2006)on properties of papercrete, incorporate 5% of paper by cement weight into concrete has the highest value of thermal conductivity at 1.21W follow by reference sample(0% paper sludge) at 1.13W and accordingly for 10%, 15% and 20% at 1.08W, 0.92W and 0.79W as refer to Figure 2.1. In a nutshell, we can say that as the percentages of paper sludge increase, the thermal conductivity of the paper sludge blended concrete will decrease.

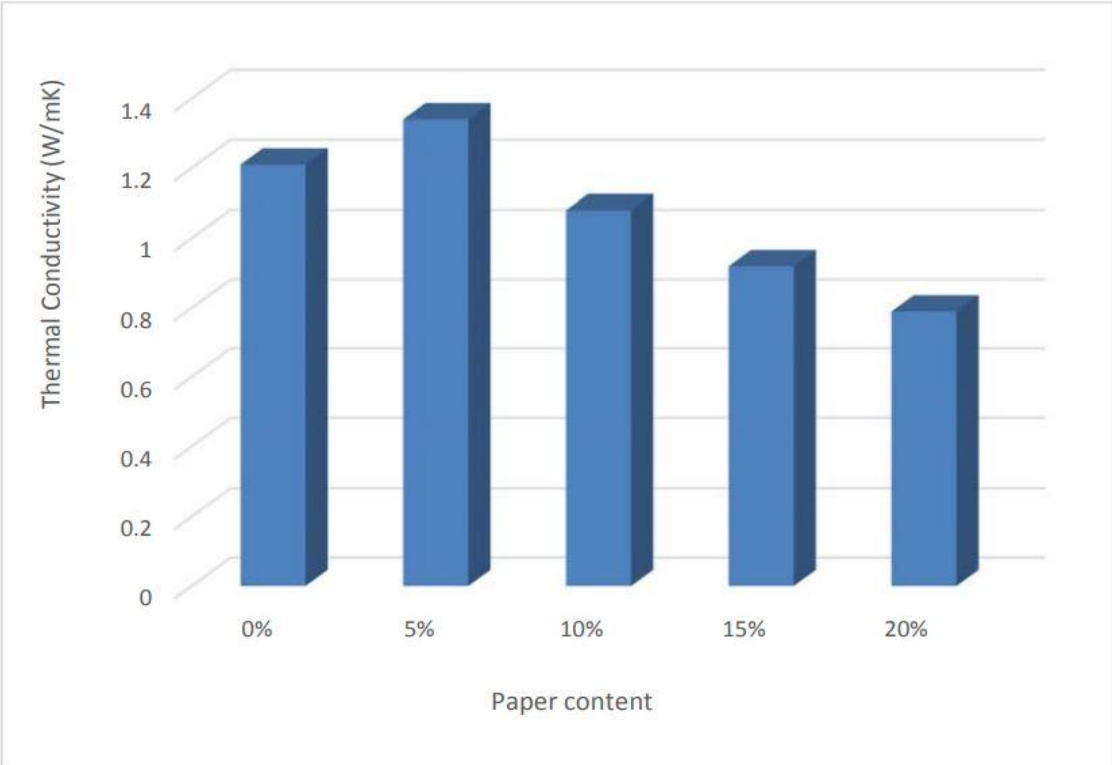

Figure 2.1: Result of thermal conductivity of concrete(Gorgis, Zaki and Salih, 2006)

2.3 Cement

Hydraulic cement in other term know as Portland cement is one the common, but most important civil engineering material; in accordance with ASTM C150 (2005), it is classified as Type 1 cement. Properties of cement vary in the different type of cements because every and each company or factory have their own recipe in cement production. To fully utilize each type of cement, it is essential to know the properties of it.

Cement properties generally categorized into two categories, “Chemical properties” and Physical properties”. Chemical properties refer to the chemical composition of cement and the chemical reaction between each compound in the cement. For quality controlling purpose of concrete or cementing materials, chemical properties are normally ignored and physical properties are taken into consideration” (Biswas, 2018). Figure 2.2 shows the examine criteria for both physical properties and chemical properties of cement.

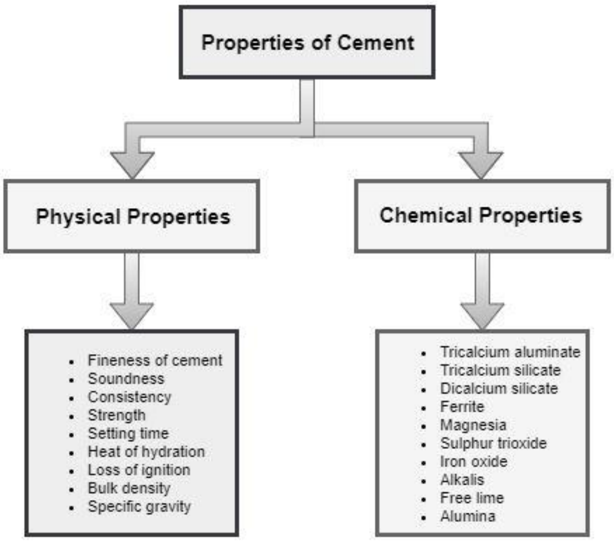

Figure 2.2: Criteria to determine cement quality (Civil Engineering, 2018)

2.3.1 Physical Properties

To achieve a good quality of cement, the key parameters we need to take into consideration are:

- The fineness of cement – the fineness of cement is depending on the size of particles. The fineness of cement is achieved through the grinding process that takes place at the end of the cement production process. The fineness of cement is important because it is directly linked to the hydration rate of cement.
- Soundness – soundness of cement is referring to the ability of cement to not to shrink upon hardening. Quality cement is able to retain its volume after setting without delaying its expansion, which contributed by excessive free lime and magnesia. Two common tests can be used to determine cement soundness, “Le Chatelier” test and “Autoclave” test. Autoclave test can refer to ASTM C151 for standard procedures and guideline.
- Consistency – is the ability of raw cement paste to flow. Normally tested using “Vicat” test.
- Strength – generally, three types of parameter are used to determine the strength of a concrete, “Compressive strength”, “Flexural strength” and “Splitting tensile strength”; “while the factors affect the these

parameters include: water cement ratio, cement-fine aggregate ratio, curing conditions, size and shape of a specimen, the manner of molding and mixing, loading conditions and age" (Civil Engineering, 2018).

- Setting Time – Setting time start to count once the cement reacts with water, this also terms as the hydration process. Cement has two types of setting time, "initial-setting" time and "final-setting" time. During the construction phase, initial setting time should not be too early and is optimal if it falls between 30min to 45min; on the other hand, final setting time should fall below 10 hours to consider as a good quality concrete. Standard testing methods can refer to ASTM C191 for Vicat Needle and ASTM C266 for Gillmore Needles.
- The heat of hydration – Hydration process takes place when water is added to the cement. A hydration process will generate heat and the amount of heat generated is vital when constructing a massive structure. When the amount of heat generated is too high, the natural cooling process may not able to remove all the heat in time, which may lead to a serious structural problem, thermal cracking. The present of C_3S and C_3A are the major contributing factor to high heat of hydration, follow by water-cement ratio, fineness and curing temperature of cement. "The heat of hydration of cement can be calculated by determining the difference between the dry and the partially hydrated cement (obtained by comparing these at 7th and 28th days)" (Civil Engineering, 2018). On the other hand, the heat of hydration is beneficial when construction takes place in cold weather country. Calculation of heat of hydration can refer to ASTM C186 for the standard testing method.
- Loss of ignition – when a cement sample is heated to 900 – 1000˚C, weight might lose and the amount of weight lost is calculated as loss of ignition. High loss of ignition may lead to pre-hydration and carbonation when improper and prolonged storage during transportation or transfer (Pavement Interactive, 2018).

- Specific gravity (Relative density) – specific gravity normally used as data for mixture proportioning of cement. Generally, Portland cement has a specific gravity of 3.15 and varies in another type of cements such as Portland-blast-furnace-slag and rapid hardening cement" (Civil Engineering, 2018).

2.3.2 Chemical Properties

Generally, four main raw ingredients are used for the manufacturing of cement: limestone (calcium), sand or clay (silicon), bauxite (aluminium) and iron ore (iron oxide). Chemical analysis of cement can provide us with an insight into the function, properties and even the quality of the cement. Keys chemical compositions are:

- Tricalcium aluminate (C_3A) – Proportion of C_3A in cement can control the ability of cement to resist sulfate attack; low amount of C_3A helps in building up the cement sulfate resistance. C_3A do not contribute to the strength of concrete.
- Tricalcium silicate (C_3S) - C_3S responsible for the early strength development of concrete because of it able to cause rapid hydration and hardening.
- Dicalcium silicate (C_2S) – a function of C_2S is directly opposed to C_3S, it helps develop later strength of concrete.
- Ferrite (C_4AF) – Ferrite in cement does not contribute much to the strength of concrete, even though it hydrates rapidly, but it acts as an agent to lower down the melting point of the raw material from 3000˚F to around 2600˚F in the kiln.
- Magnesia (MgO) – Manufacturing of Portland cement uses magnesia as raw materials in a dry process (Civil Engineering, 2018). An excessive amount of magnesia may cause the cement to be unsound and expensive, but a small amount of it can add strength to the cement. Generally, cement is limited to 6% of MgO.
- Sulphur Trioxide – excessive sulphur trioxide contribute to unsound cement.

- Iron oxide / Ferric oxide – aside from the strength of concrete on concrete, iron oxide and ferric oxide give the colour and outlook of the cement.
- Alkalis – Alkali of the cement determine by the amount of potassium oxide (K_2O) and sodium oxide (Na_2O); excessive amount may cause difficulty in regulating the setting time while lacking amount of it can cause discoloration. The optimal amount of alkali can be determined by using $Na_2O + 0.658K_2O$ (Civil Engineering, 2018).
- Silica fume – Silica fume is one of the major components in cement that regulate the compressive strength, abrasion resistance and bonding strength of the concrete but excessive may result in longer setting time.
- Alumina – alumina help in lower down the setting time of concrete, but cause the concrete to be weaker. The high amount of alumina adds the ability of concrete to withstand the frigid temperatures since it is chemical-resistant.

2.4 Paper Sludge

As mentioned in chapter one, Malaysian are able to generate 38,200 tons of solid waste per day, and it is estimated to grow further to 45,900 ton per day by the year 2020; among all these solid waste, 8.5% of it is paper waste and only 17.5% of it goes for recycling. Eventually, these unrecycled paper waste will go to land fill which lead to the environment issue.

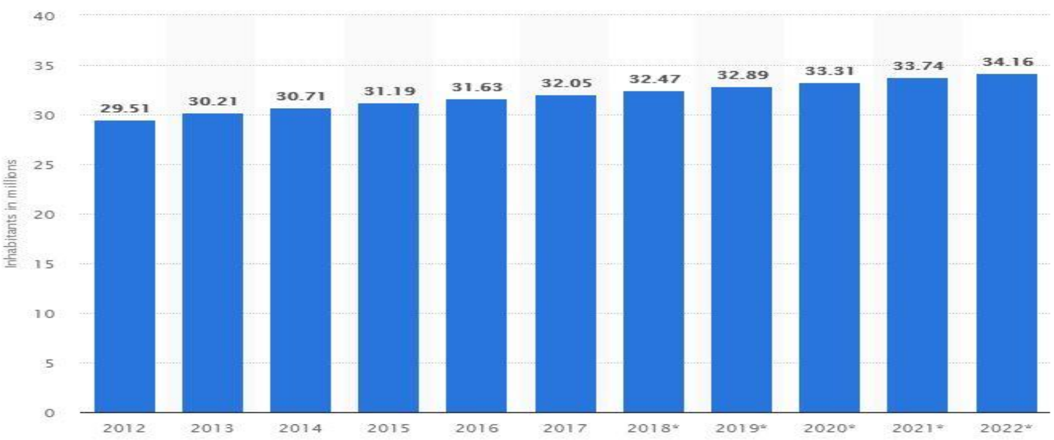

Figure 2.3: Malaysia current and forecasted population (Statista, 2018)

As the Malaysia population increasing year after year as referring to Figure 2.3, more paper waste will be generated and existing landfill area might no longer a practical way to handle the overwhelming amount of waste. A lot of researcher and business man take up this opportunity to search for the solution for it or allocating this waste into another field. Researches done by Kumar and Gupta (2016) and Abishek (2017) revealed that adequate amounts of paper sludge waste are viable in the production of concrete and it able to provide the same amount of strength compared to normal concrete. Amit and Islam (2016) revealed that "convention of paper sludge as a raw material in the construction industry is clearly reasonable without co-operating the material requirements according to available standard. Considering the huge cost, complexity involved in the treatment and environmental factors, it can be demonstrated that the potential use of paper sludge in the construction industry is a substitute to the treatment, disposal of paper sludge and it would provide ample solution to the waste problem and stimulate eco-friendly environment with a condensed or low-cost raw material". Additionally, Kumar and Gupta (2016) found that, mixing of paper sludge waste in soil able to increase the unconfined compression strength, increase the moisture content and decrease the maximum dry density with optimum mixing percentage of 6%.

2.4.1 Chemical Properties of Paper Sludge Waste

According to research conducted by Garcı´a et al. (2008) revealed that, the main composition of raw paper sludge contains a high amount of loss on ignition (LOI) at 47.62 percent follow by calcium oxide (CaO) 19.82%, silica (SiO_2) 18.01%, alumina (Al_2O_3) 10.14% as shown in Table 2.2.

Table 2.2: Chemical composition of raw paper sludge (Garcı´a et al., 2008)

Items	**Chemical composition of raw sludge (% by mass)**										
Oxide (%)	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	TiO_2	K_2O	P_2O_5	SO_3	Na_2O	LOI
Raw sludge	18.01	10.14	0.55	19.82	2.58	0.26	0.21	0.1	0.33	0.25	47.62

Pozzolan is defined as "a siliceous or silico-aluminous material that will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds having cementitiousproperties” (Collins, 2018). “The presence of clayey materials such as muscovite, kaolinite and also high purity of calcium carbonate and cellulose can act as accelerators in the activation of the metakaolinite, as well as in the pozzolanic reaction, resulting in different hydrated phases from those that are normally produced with a commercial metakaolinite” (Garcı´a et al., 2008). Therefore, raw paper sludge has to undergo an optimal calculation process in order for it to become a good pozzolan. So, according to the research done by Garcı´a et al. (2008), the optimal condition found is when paper sludge is heated at temperature of 700˚C for duration of 2 hours. Table 2.3 shown the chemical composition of paper sludge when it is heated to 700˚C for duration of 2 hours.

Table 2.3: Chemical composition of paper sludge (Garcı´a et al., 2008)

Chemical analysis by EDAX in samples heated to 700 °C/for 2 h

Oxides (%)	Metakaolinite	Calcite	Talc
MgO	–	0.17 ± 0.05	2.45 ± 0.12
Al_2O_3	6.39	0.80 ± 0.14	1.04 ± 0.11
SiO_2	48.56	7.28 ± 1.67	77.09 ± 0.75
K_2O	0.52	–	–
CaO	43.76	91.75 ± 1.88	18.03 ± 1.11
TiO_2	–	–	–
Fe_2O_3	0.77	–	1.39 ± 0.60
Total	100	100	100

2.5 Scanning Electron Microscope (SEM)

Aside from data that we collect from the compression test, scanning electron microscope is another great tool to determine the strength of the specimen. Under SEM, it able to observe the bonding of each particle, type of crystal form during the curing of concrete and the compact matrix of each specimen which help us to further identify the characteristic and mechanical properties of our samples. As refer to a paper published by Gorgis, Zaki and Salih in 2017, reference sample R and M5 as listed in table able to demonstrate a good bonding between particles and cement paste as shown in figure and figure. While on the other hand, sample M10, M15 and M20 show poor bonding between paper fibre, particles and cement paste which lead to lower mechanical strength as compare to reference sample R and sample M 5. Figures 2.5, 2.6, 2.7 and 2.8 clearly show the characteristic of weak bonding as the particles, paper fibre and cement paste have being de-bonded due to lower

$CaCO_3$content compare to reference sample. In addition, the presence of pores in the specimen increases as the percentage of paper sludge blended into the concrete increase.

Table 2.4: Percentage of paper sludge by weight of cement with their Mix ID (Gorgis, Zaki and Salih, 2017)

Mix ID	Percentages of pulp paper mass by weight of cement
R	0
M5	5
M10	10
M15	15
M20	20

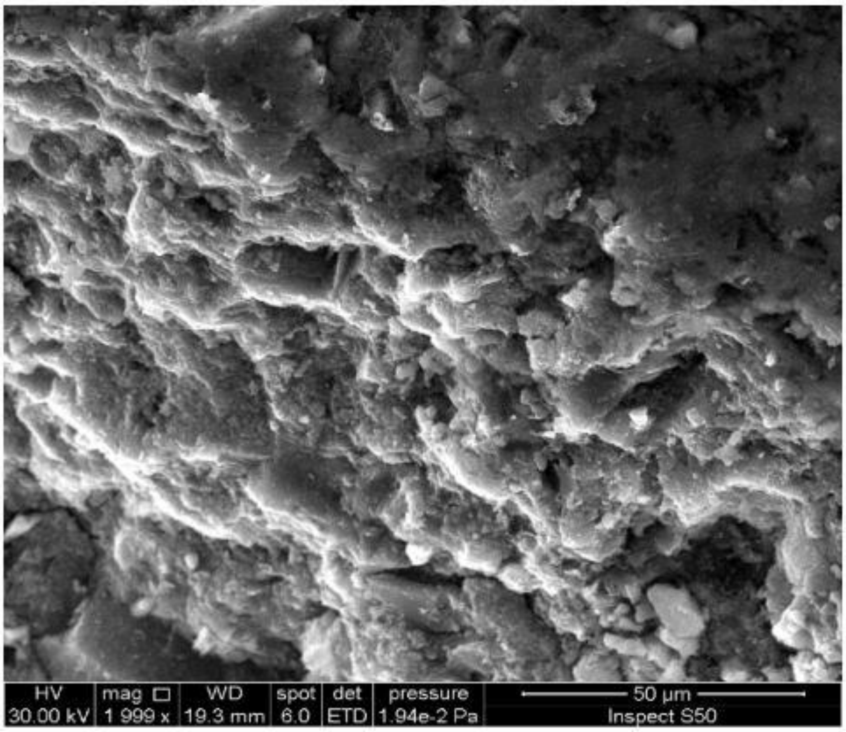

Figure 2.4: Sample R(0% paper sludge) under scanning electron microscope (Gorgis, Zaki and Salih, 2017)

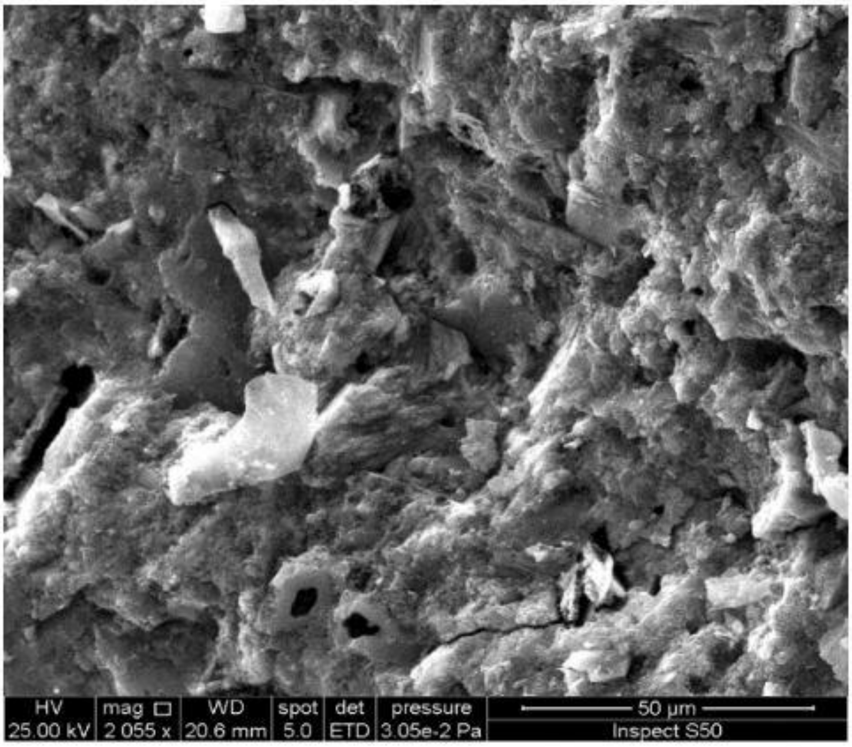

Figure 2.5: Sample M5(5% paper sludge) under scanning electron microscope (Gorgis, Zaki and Salih, 2017)

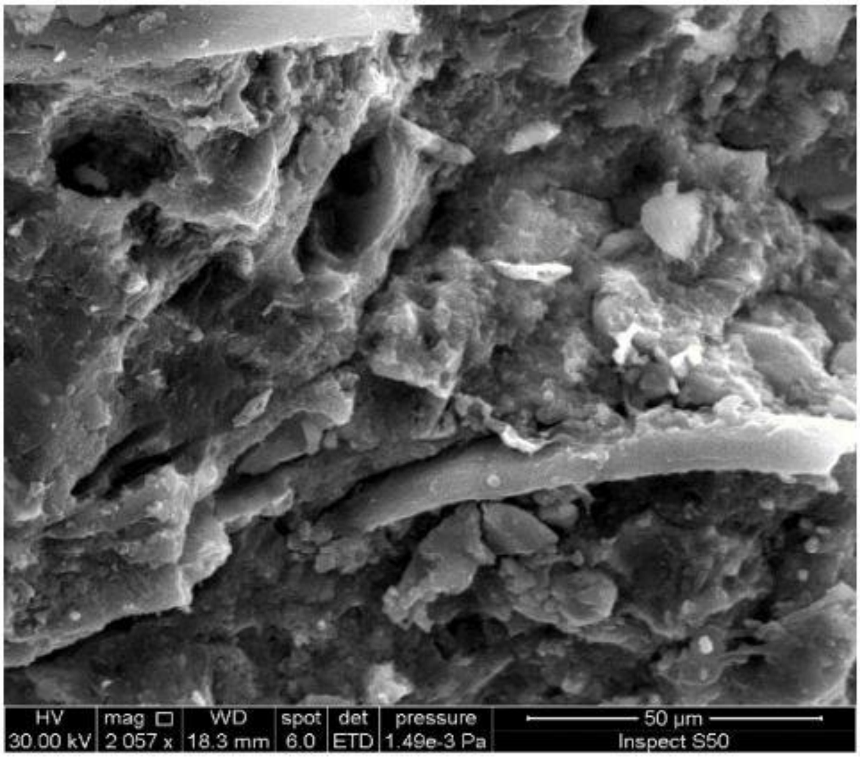

Figure 2.6: Sample M10(10% paper sludge) under scanning electron microscope (Gorgis, Zaki and Salih, 2017)

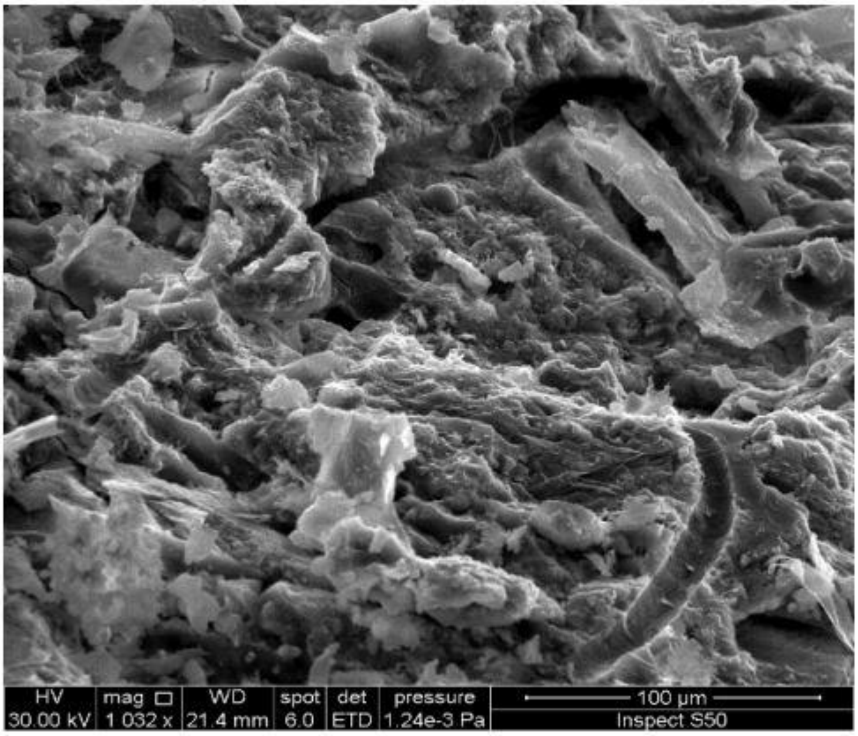

Figure 2.7: Sample M15(15% paper sludge) under scanning electron microscope (Gorgis, Zaki and Salih, 2017)

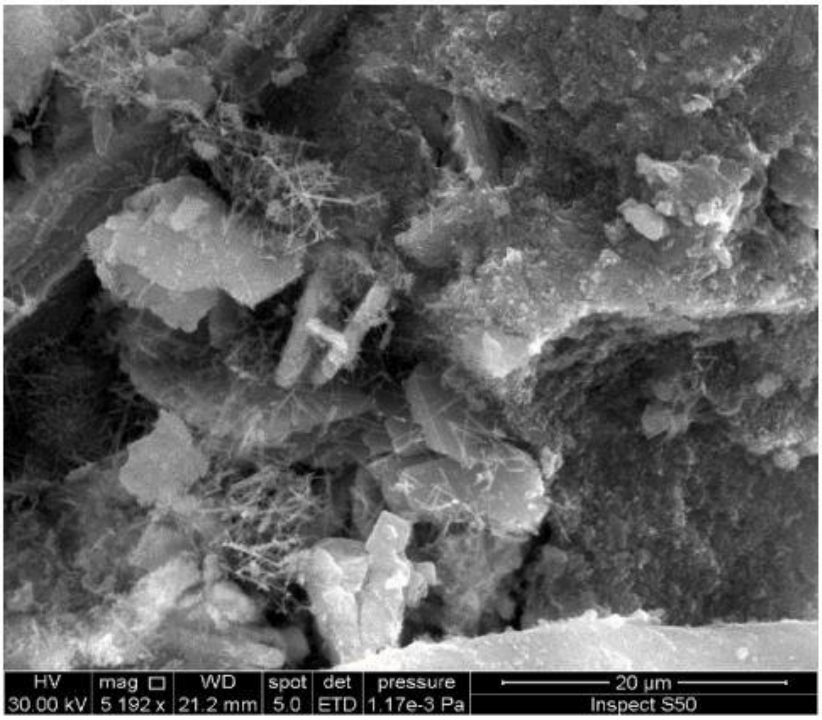

Figure 2.8: Sample M20(20% paper sludge) under scanning electron microscope (Gorgis, Zaki and Salih, 2017)

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter mainly discusses the materials needed, test procedure and also test methods (comply with ASTM or BS code) that will be conducted to meet the objectives of the study. The gathering and preparation of raw materials, testing method and procedure for the lightweight concrete block will be presented in detail in this chapter.

3.2 Raw Material

Materials used in this experiment for the production of lightweight concrete block include: ordinary Portland cement, paper sludge, fly ash, granulated ground furnace blast, water and sand (coarse and fine).

3.2.1 Ordinary Portland Cement

Ordinary Portland cement, selected for the production of our lightweight concrete block is manufactured by YTL Cement Sdn. Bhd. as shown in Figure 3.1. Ordinary Portland cement is classified as Type I cement in accordance with ASTM C150 (2005). Ordinary Portland cement used had been sieved through 300μm sieve to retain any pre-hydrated cement particle. Sieved ordinary Portland cement is then stored in an airtight container to prevent it reacts with moisture in the air so that it would not affect the formation of Calcium Silicate Hydrate gel as shown in Figure 3.2. Chemical and physical properties of ordinary Portland cement manufactured by YTL Cement Sdn. Bhd is shown in Table 3.1.

Figure 3.1:Ordinary Portland cementin sealed container

Figure 3.2:“ORANG KUAT” Branded OPC

Table 3.1: Chemical and Physical properties of Ordinary Portland cement (YTL Cement Marketing SdnBhd, 2016)

Tests		Units	Specification MS EN 197-1 : 2014 CEM I 42.5N	Test Results
			Chemical Composition	
Lime Saturation Factor (LSF)		%	0.66 - 1.02	0.94
Insoluble Residue (IR)		%	5.0 max.	0.4
Magnesium Oxide (MgO)		%	5.0 max.	1.5
Sulfate Content (SO_3)		%	3.5 max.	2.8
Loss On Ignition (LOI)		%	5.0 max.	3.4
Chloride (Cl^-)		%	0.1 max.	0.01
			Physical Properties	
Specific Surface Area		m^2/kg	-	347
Soundness		mm	10 max.	1.0
Setting Time	- Initial	mins	60 min.	160
Compressive Strength Mortar prism (1:3:0.5)	: 2 days	N/mm^2	Not less than 10.0	21.3
	: 28 days	N/mm^2	Not less than 42.5	53.5

3.2.2 Paper Sludge

The paper sludge collected was then dry with the oven to remove the excess moisture content. After the paper sludge was fully dried, the paper sludge was cut into smaller pieces and ground to powder form with a blender. The powder was then sieved through No 4 mesh size (4.75 mm size) so that its particle size will be the same as fine aggregate.

Figure 3.3: Raw paper sludge

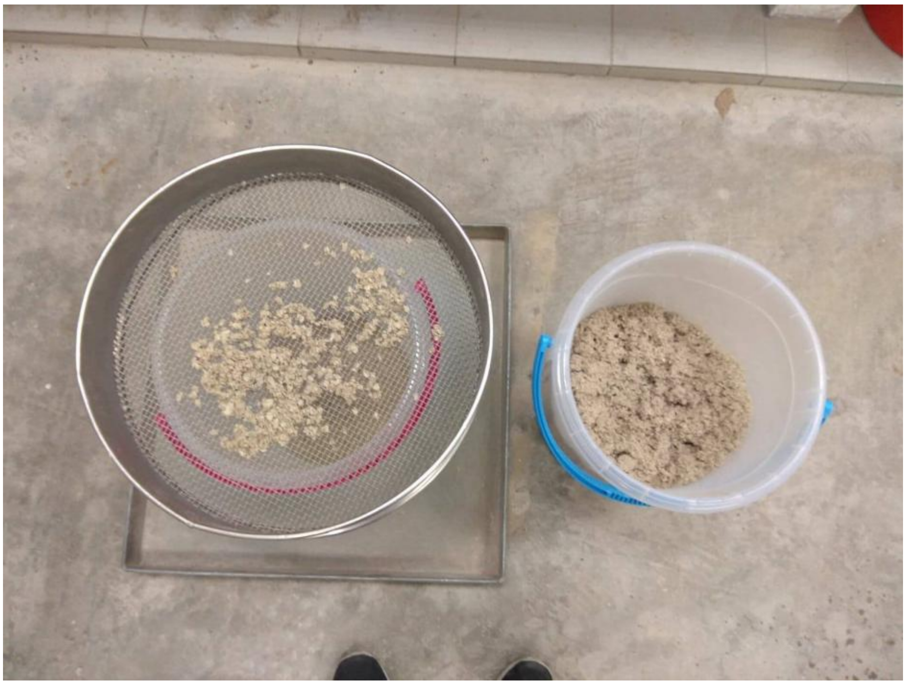

Figure 3.4: Paper sludge sieved through No 4 mesh size and store into a sealed container

3.2.3 Fine Aggregate

For this experiment, the only fine aggregate was used to produce the lightweight concrete block. Fine aggregate used for concrete block mixing was dried in an oven at the temperature of 105 °C ± 5 °C for at least 24 hours to remove the excess moisture content. The sieved fine aggregate was kept in an airtight container to prevent moisture in the air to contacts with the fine aggregate as it will affect the water cement ratio of concrete block casting.

Figure 3.5: Fine aggregates in oven for drying process

3.2.4 Water

Water is one of the major raw materials needed for the concrete block casting. Water used in concrete block casting in this experiment complied with ASTM C1602; sources of raw water can come from a combined water, non-potable water, mixing water and potable water that do not contain any pernicious contaminant that will affect the hydration process of the cement in both short and long term. In this experimental study, tap water was selected as mixing water to cast concrete block in this experimental study.

3.2.5 Fly Ash

Fly ash, normally generated during the combustion of coal; in this experiment, the fly ash was brought from LIELEE NDT STRUCARE ENTREPRISE. Fly ash was sieved through No.325 mesh sizes and the maximum retained percentage should not exceed 34% as comply with ASTM C618 (2007) for class F and Class C fly ash.

3.2.6 Ground Granulated Blastfurnace Slag (GGBS)

Ground granulated blastfurnace slag, normally obtained by quenching molten iron slag which is a by product of iron making. The maximum fineness requirements for ground granulated blastfurnace slag as complying to ASTM C989 (1999) was at least 20% of the material retained on No 325 mesh sizes. Therefore, before mixing the cement paste, the granulated ground blastfurnace slag was sieved through a No 325 mesh sizes sieve to make sure it complies with ASTM C989 (1999).

3.3 Mould

In this study, the chosen dimension of our lightweight concrete block is 400mm x 100mm x 100mm as suggested by Archtoolbox (2018). The dimension chosen is due to the concern of market convenient and market availability. The dimension chosen will be used as a standard reference for concrete masonry unit. Nominal dimension of our block is 400mm x 100mm x 100mm but the actual dimension is 390mm x 90mm x 90mm because industry recommendation mortar thickness is 10mm. But for this study, 50mm sizes steel mould would be choose to cast the concrete mortar specimens for the study on thermal conductivity, water absorption, compressive strength and also oven dry density.

3.4 Mixing Procedures

In this study, ordinary Portland cement, fine aggregates, paper sludge, fly ash and granulated ground blastfurnace slag was weighted and pour into a stainless steel mixing pot to secure the dry mixture is evenly mixed. Next, water was weighted and pours into the dry mix according to the water cement ratio decided. Wet mixture was then mixed until the water was evenly distributed to every part of the paste. After the mixture was evenly mixed, fresh density test of the concrete was carried out. Lastly, the mixture was pouring into the steel mould prepared earlier.

3.5 Water Curing

The water curing process is vital for the lightweight concrete block to gain the desired strength. After the concrete block air dried was 24hours, the hardened concrete block was then removed from the mould and submerged in the water for 7 and 28 days until the testing age. The average water temperature used for water curing was ranging between 25 – 30˚C. To make sure each concrete block was cured evenly; all the concrete blocks had to be fully immersed into the water as shown in Figure 3.5.

Figure 3.6: Water curing process in water tank

3.6 Compressive Strength Test (ASTM C 140 – 07a, 2007)

As comply with ASTM C 140 – 07a (2007), the compressive strength test was conducted with INSTON 5582 Testing Machine. A constant compression loading rate of 0.02mm/s was applied to the specimen until failure occurred. The compressive strength test was carried out three times and the average result of it was taken to study.

The concrete block specimens were oven-dried for 24 hours before the compressive strength test was carried out. According to ASTM C 140 – 07a (2007) 7.4.1, the chosen face should be the horizontal direction and in the same direction as in service. The centroid of the specimen should be aligned with the centroid of the loading plate. The dimension of the concrete block was measured using a digital vernier calliper before the test was carried out. Next, the test specimen was compressed until it cracks. The maximum compressive load was recorded and the test was repeated twice to get an average reading of three specimens. The net area compressive strength and gross area compressive strength of each specimen were then calculated using Equation 3.1 and Equation 3.2.

Net area of the specimen can be calculated as follow:

$$NetVolume(V_n), mm^3 = (W_s - W_i) \times 10^6 \quad (3.1)$$

$$AverageNetArea(A_n), mm^2 = \frac{V_n}{H} \quad (3.2)$$

where:

W_s = saturated weight of specimen, kg

W_i = immersed weight of specimen, kg

H = average height of the specimen, mm

Gross area of the specimen can be calculated as follow:

$$GrossArea(A_g), mm^2 = L \times W \quad (3.3)$$

where:

L = average length of the specimen, mm

W = average width of the specimen, mm

Net area compressive strength can be calculated as follow:

$$\frac{P_{max}}{A_n} \quad (3.4)$$

where:

Pmax = maximum compressive load, Newton (N)

An = average net area of specimen, mm²

Gross area compressive strength can be calculated as follow:

$$\frac{P_{max}}{A_g} \quad (3.5)$$

where:

Pmax = maximum compressive load, Newton (N)

An = gross area of specimen, mm²

3.7 Absorption Test (ASTM C 140 – 07a, 2007)

Three specimens were prepared to test for absorption as complying with ASTM C 140 – 07a (2007). Firstly, the hardened specimens had to be immersed in water at a temperature of 15.6 to 26.7˚C for 24 hours and the immersed weight of the specimens was recorded as immersed weight, W_i. After 24 hours of immersing, the specimens were removed from the water and allowed to air dry for 1min ± 5seconds. Surface water of the specimens can be removed by using a damp cloth and the weight of the specimens was weighted using a weighing machine and the reading obtained was recorded as saturated weight, W_s. After the saturated weight of the specimens was recorded, the specimens were then placed into an oven at 105˚C for at least 24 hours and the weight of the specimens was then recorded as oven-dry weight, W_d. The absorption of the specimens was calculated using Equations 3.3 and 3.4. Additionally, the moisture content and the oven dry density of the specimens can also be determined in this test using Equations 3.5 and 3.6.

Absorption of the specimen can be calculated as follow:

$$Absorption, \frac{kg}{m^3} = \frac{W_s - W_d}{W_s - W_d} \times 1000 (3.6)$$

$$Absorption, \% = \frac{W_s - W_d}{W_d} \times 100 (3.7)$$

where:

W_s = saturated weight of specimen, kg

W_i = immersed weight of specimen, kg

W_d= oven-dry weight of specimen, kg

Moisture content of the specimen can be calculated as follow:

$$Moisturecontent, \% = \frac{W_r - W_d}{W_s - W_d} \times 100 (3.8)$$

where:

W_s = saturated weight of specimen, kg

W_r = received weight of specimen, kg

W_d = oven-dry weight of specimen, kg

Oven-dry density of the concrete block can be calculated as follow:

$$Density, kg/m^3 = \frac{W_d}{W_s - W_i} \times 1000 (3.9)$$

where:

W_s = saturated weight of specimen, kg

W_i = immersed weight of specimen, kg

W_d = oven-dry weight of specimen, kg

3.8 Microstructure Analysis (ASTM C1723, 2010)

There are many techniques have been used to study microstructure; for instance, it broadly divided into two main categories, “Indirect method” and “Direct method”. In this experimental study, we will be focused on just indirect method of microstructure study, which is Scanning Electron Microscope (SEM). Hitachi VP-SEM S – 3400N will be the only machine used for Scanning Electron Microscope test and the test conducted was complied with ASTM C 1723 (2010). The 28thdays curing period of lightweight concrete block with blended of paper sludge, fly ash and ground granulated blastfurnace slag was taken to conduct the SEM for this experimental study. Crushed pieces of the specimen were prepared and coated with a gold layer before the test was conducted. 15kV accelerating voltage of SEM was selected and magnification of the SEM images was set to ×500, ×1000 and ×2000 for microstructure analysis.

Figure 3.7: Coating process

Figure 3.8: Hitachi VP-SEM S – 3400N

3.9 Thermal Conductivity Test

For cement based materials like mortar, the k-value, thermal conductivity is the most crucial element to determine the amount of heat transferred through conduction. In accordance with BS EN 12664 (BSI, 2001), thermal conductivity test was conducted to determine the thermal resistance of the building materials. There are four methods that frequently adopted by the researcher to determine the k-value of the cement based materials: “Steady state boxes method”, Steady state hot plate method”, Transient plane source (TPS) method” and “Transient hot wire method”; due to university machine availability, only “Steady hot plate method” will be adopted for thermal conductivity test.

Guarded hot – plate method setup compromised of hot plate, cold plate, data logger, insulation plate and a system of guard heaters. The hot plate was powered by an electrical heater, which was fixed to 40˚C while the cold plate was cooled with liquid-cooled heat sinks through a chillers’ and to be maintained at 18˚C. This experiment was conducted through fixing the specimen between hot and cold plates for 24 hours so that the specimen able to achieve thermal equilibrium as shown in Figure 3.9. After a steady state was achieved, the thermal conductivity can be determined based on the temperature difference between the specimen. The temperature difference of the specimen can be measured by a thermocouple placed on the surface of the specimen throughout the test.

After all the data had been collected, the thermal conductivity can be calculated based on heat power Q, the specimen thickness (Δx), the temperature differential across the specimen ($T_{hot} - T_{cold}$), and the heat transfer area (A) shown in the Equation 3.10

$$k = \frac{Q}{2} \cdot \frac{\Delta x}{A \cdot \Delta T} \quad (3.10)$$

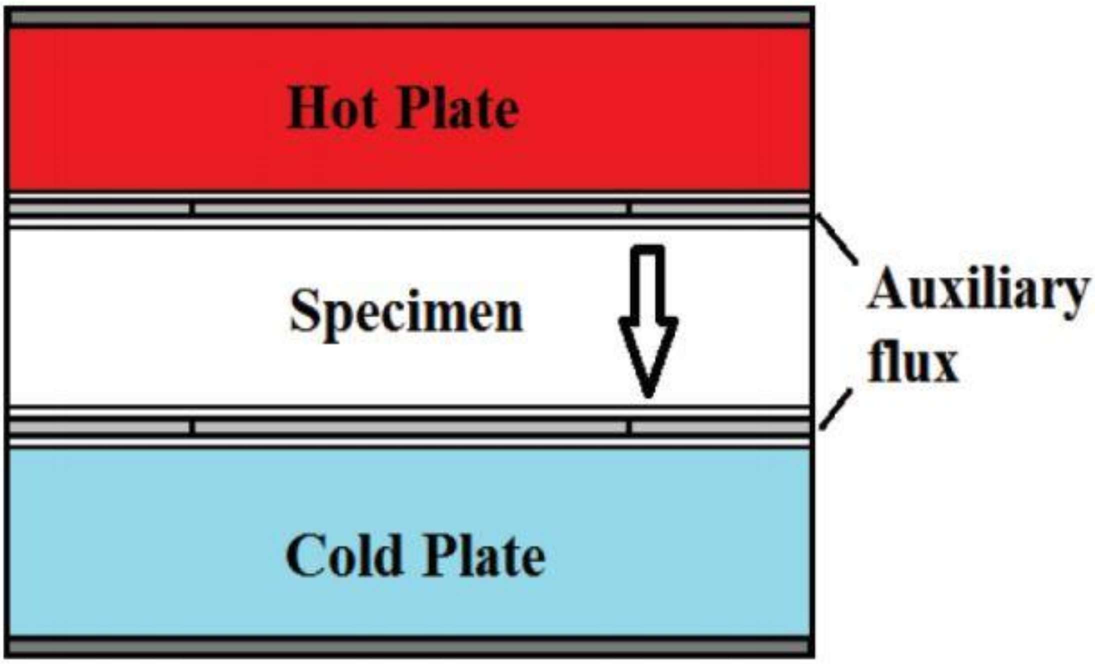

Figure 3.9: Setup of guarded hot plate test

CHAPTER 4

RESULT AND DISCUSSION

4.1 Introduction

Several tests have been carried out on the lightweight mortar blended with fly ash, granulated blastfurnace slag and paper sludge, namely LM-GGBS-FA-PS (lightweight mortar blended with paper sludge, ground granulated blastfurnace slag and fly ash). This chapter will mainly discuss and compare the result collected from those tests. Four proportions were chosen for this experiment, 0%, 10%, 15% and 20% of paper sludge as partial cement replacement material while the partial cement replacement of granulated blastfurnace slag and fly ash remained the same throughout the test at 5% each. The entire specimens were water cured for 7 and 28 days age before testing. Even though granulated blastfurnace slag and fly ash were added into the specimen but this paper will mainly focus on the effect of paper sludge as cement replacement materials on its engineering properties in terms of compressive strength, water absorption ability, thermal conductivity and overall microstructure characteristic.

4.2 Mix Proportions

In an investigation on the effect of paper sludge on cement mortar, four proportions as shown in Tables 4.1 and 4.2 were chosen as the primary investigation target to achieve the standard physical properties according to ASTM C 140 – 07a, 2007.

Table 4.1: Mix proportions for this study

Specimen	**w/c ratio**	**Proportion**				
		Cement	**Fine Aggregate**	**GGBS**	**Fly Ash**	**Paper sludge**
LM-GGBS5-FA5-PS0	0.55	0.90	1.00	0.05	0.05	0.00
LM-GGBS5-FA5-PS10	0.55	0.80	1.00	0.05	0.05	0.10
LM-GGBS5-FA5-PS15	0.55	0.75	1.00	0.05	0.05	0.15
LM-GGBS5-FA5-PS20	0.55	0.70	1.00	0.05	0.05	0.20

Table 4.2: Mix proportions for this study in term of kg per meter cube

Specimen	Materials (kg/m³)						EW (kg/kg)
	Water (kg/m³)	Cement (kg/m³)	Fine Aggregate (kg/m³)	GGBS (kg/m³)	Fly Ash (kg/m³)	Paper sludge (kg/m³)	
LM-GGBS5-FA5-PS0	396.00	720.00	800.00	40.00	40.00	0.00	2.80
LM-GGBS5-FA5-PS10	352.00	640.00	800.00	40.00	40.00	80.00	2.80
LM-GGBS5-FA5-PS15	330.00	600.00	800.00	40.00	40.00	120.00	2.80
LM-GGBS5-FA5-PS20	308.00	560.00	800.00	40.00	40.00	160.00	2.80

Note:

LM-GGBS5-FA5-PS0 = lightweight mortar blended with 5% of ground granulated blastfurnace slag and 5% of fly ash

LM-GGBS5-FA5-PS10 = lightweight mortar blended with 10% of paper sludge along with 5% of ground granulated blastfurnace slag and 5% of fly ash

LM-GGBS5-FA5-PS15 = lightweight mortar blended with 15% of paper sludge along with 5% of ground granulated blastfurnace slag and 5% of fly ash

LM-GGBS5-FA5-PS20 = lightweight mortar blended with 20% of paper sludge along with 5% of ground granulated blastfurnace slag and 5% of fly ash

EW = Extra water for paper sludge due to its absorption ability to avoid insufficient water for cement hydration process

4.3 Compressive Strength

Table 4.3 and Figure 4.1 show the compressive strength of each specimen while Figure 4.2 show the compressive strength development trend after 7 and 28 days water curing period. As shown in Table 4.3 and Figure 4.1, the compressive strength of LM-GGBS-FA-PS (lightweight mortar blended with paper sludge, ground granulated blastfurnace slag and fly ash) is pretty consistent as the percentages different of each specimens is very small. In the following figures, samples that aged for 28 days show a relatively higher compressive strength as compare to sample aged for 7 days. Generally, the promotion of mortar strength is due to the hydration process that take place during water curing period. Therefore, as the water curing period increase, the strength of the mortar will increase as more C-S-H gel had been formed.

According to Figure 4.2, the substitution of paper sludge does not accelerate nor increase the strength of the mortar as compared to the control sample (LM-GGBS5-FA5-PS0). For 10% of substitution, the strength of the mortar drop by 74.58% on the 7th day of water curing period and 70.70% on the 28th day of water curing period. In addition, for every 5% substitution of paper sludge into cement, its compressive strength will be reduced by around half as shown in Figure 4.1. According to Zaki, Gorgis and Salih (2018), cellulosic materials like paper sludge have very poor binding ability with calcium-silicate-hydrate, C-S-H gel hence low compressive strength was generated as more the substitution level of paper sludge increase as shown in Figure 4.2.

Even though the substitution of paper sludge cause a rapid declined in the compressive strength of the mortar specimen; however, it still able to achieve the minimum requirement of 3.45MPa according to ASTM C129, 2017 for single unit of concrete masonry unit at 15% substitution of paper sludge. On the other hand, the amount of paper sludge used in the production of concrete masonry unit can decrease the total amounts of paper sludge that had been generated; for example, every 1000 kg of cement used for the production of concrete masonry unit, 150 kg of waste paper sludge will be reuse while according to Statista, (2019), around 4,100 million metric tons of cement was produced in the year 2018 and if we assume one quarter of the cement produced was used for the production of concrete masonry unit, 153.75 million metric tons of waste paper sludge will be consume annually.

Table 4.3: Compressive strength of the specimens

Specimen	7 days curing period strength (MPa)				28 days curing period strength (MPa)			
	sample 1	sample 2	sample 3	Average	sample 1	sample 2	sample 3	Average
LM-GGBS5-FA5-PS0	24.84	22.05	24.13	23.67	36.53	34.18	35.78	35.50
LM-GGBS5-FA5-PS10	5.79	6.26	6.00	6.02	9.79	11.05	10.36	10.40
LM-GGBS5-FA5-PS15	3.07	2.89	2.94	2.97	5.10	4.73	5.05	4.96
LM-GGBS5-FA5-PS20	1.60	1.52	1.63	1.58	2.73	2.52	2.84	2.70

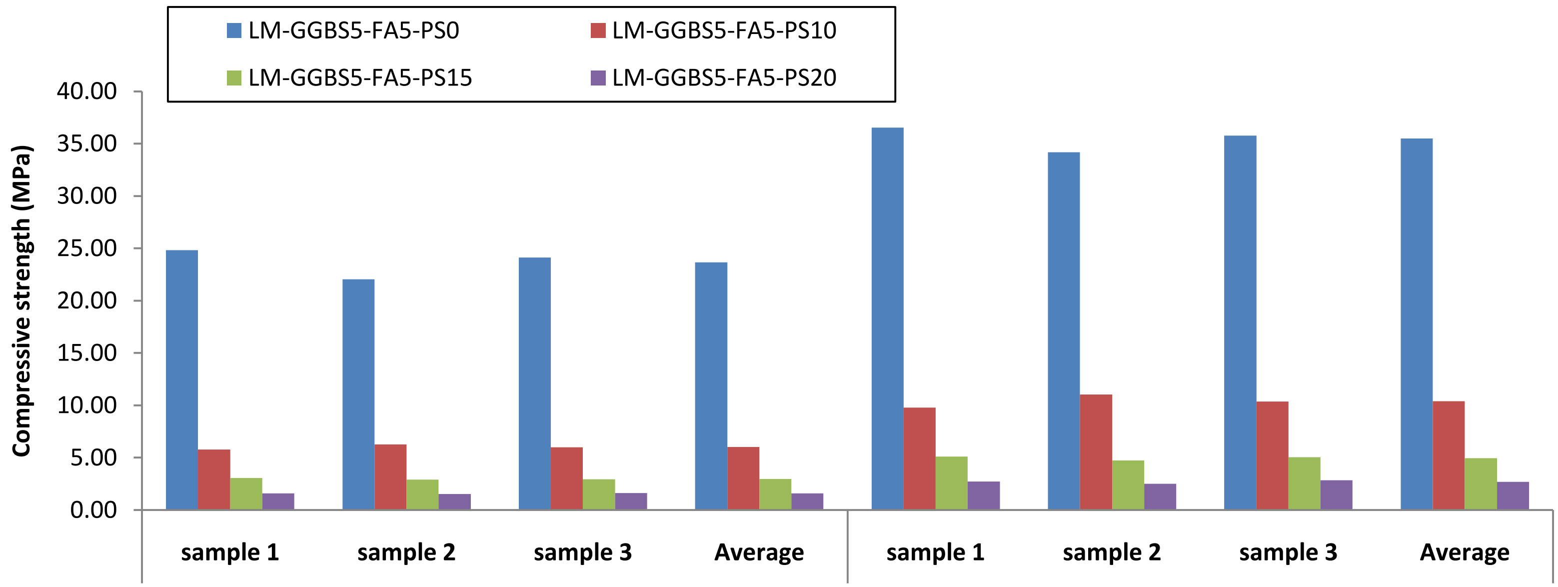

Figure 4.1: Compressive strength development until 28 days of water curing periods for all the specimens

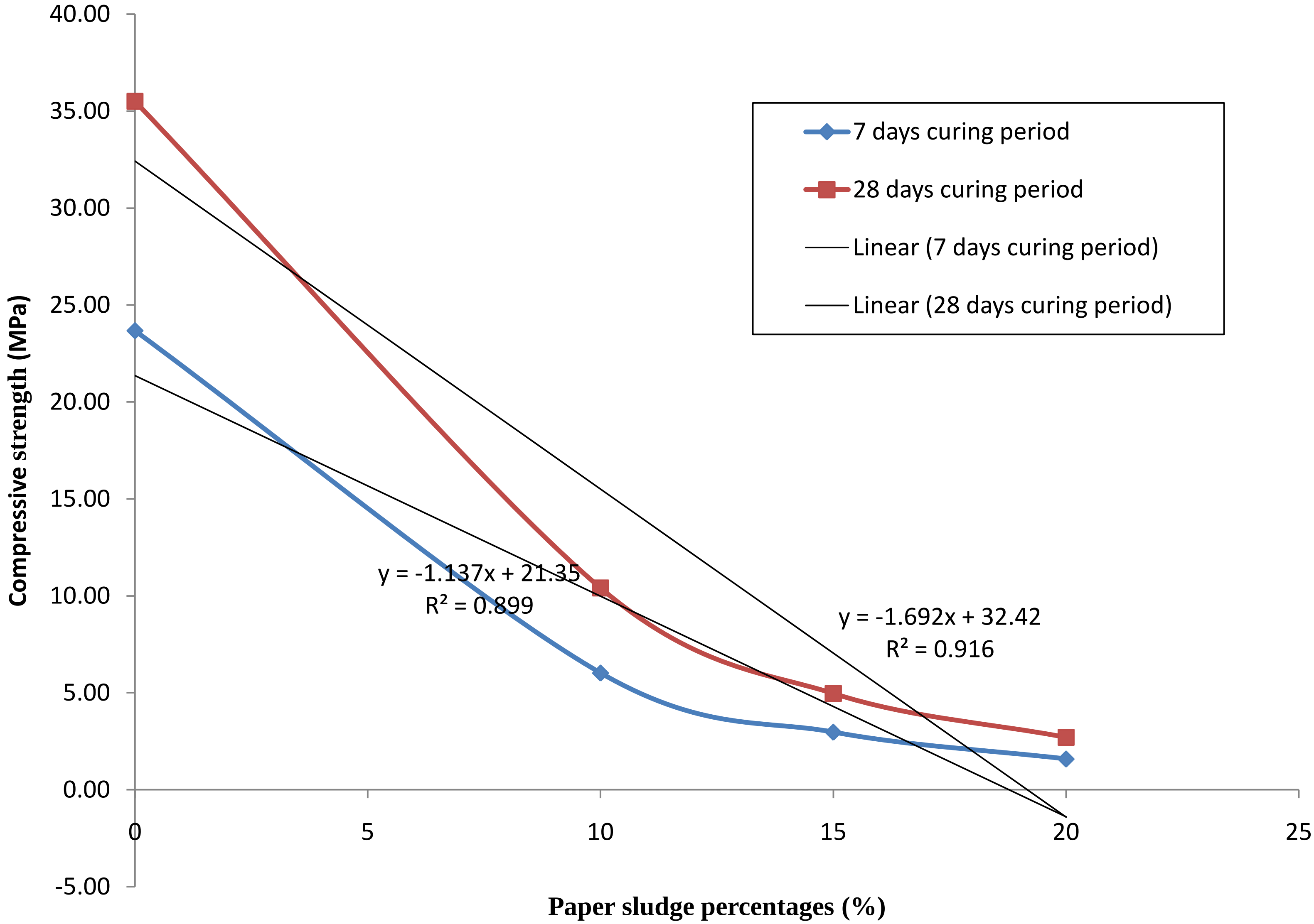

Figure 4.2: Average compressive strength of the specimens on 7 and 28 days of water curing period

4.4 Water Absorption

It is noted that higher water absorption was observed as the substitution level goes up as shown in Figure 4.3 and Table 4.4. For instances, 10% substitution of paper sludge shows a minimal increase in the water absorption as compared to reference sample. On the other hand, as the substitution level goes up, the growth rate of water absorption decrease, one can see the water absorption growth rate of samples LM-GGBS5-FA5-PS20 is the lowest among all the proportion as shown in Table 4.4. Overall, 28 days samples show a relatively lower water absorption ability as compared with 7 days samples. On the other hand, the substitution level of paper sludge has a high positive correlation on the specimen water absorption ability, this may happened due to the hydrophilic properties of paper sludge and the loss in cohesion and poor binding of the C-S-H gel on the cellulosic materials (Zakiet al., 2018).

Table 4.4: Water absorption of the specimens

Specimen	7 days curing period (%)				28 days curing period (%)			
	sample 1	sample 2	sample 3	Average	sample 1	sample 2	sample 3	Average
LM-GGBS5-FA5-PS0	12.94	13.41	13.64	13.33	10.55	11.00	11.79	11.11
LM-GGBS5-FA5-PS10	25.77	24.72	24.48	24.99	23.75	24.08	21.52	23.12
LM-GGBS5-FA5-PS15	34.28	34.06	35.83	34.72	34.90	35.21	36.32	35.47
LM-GGBS5-FA5-PS20	41.89	43.62	43.15	42.89	40.34	41.18	41.46	40.99

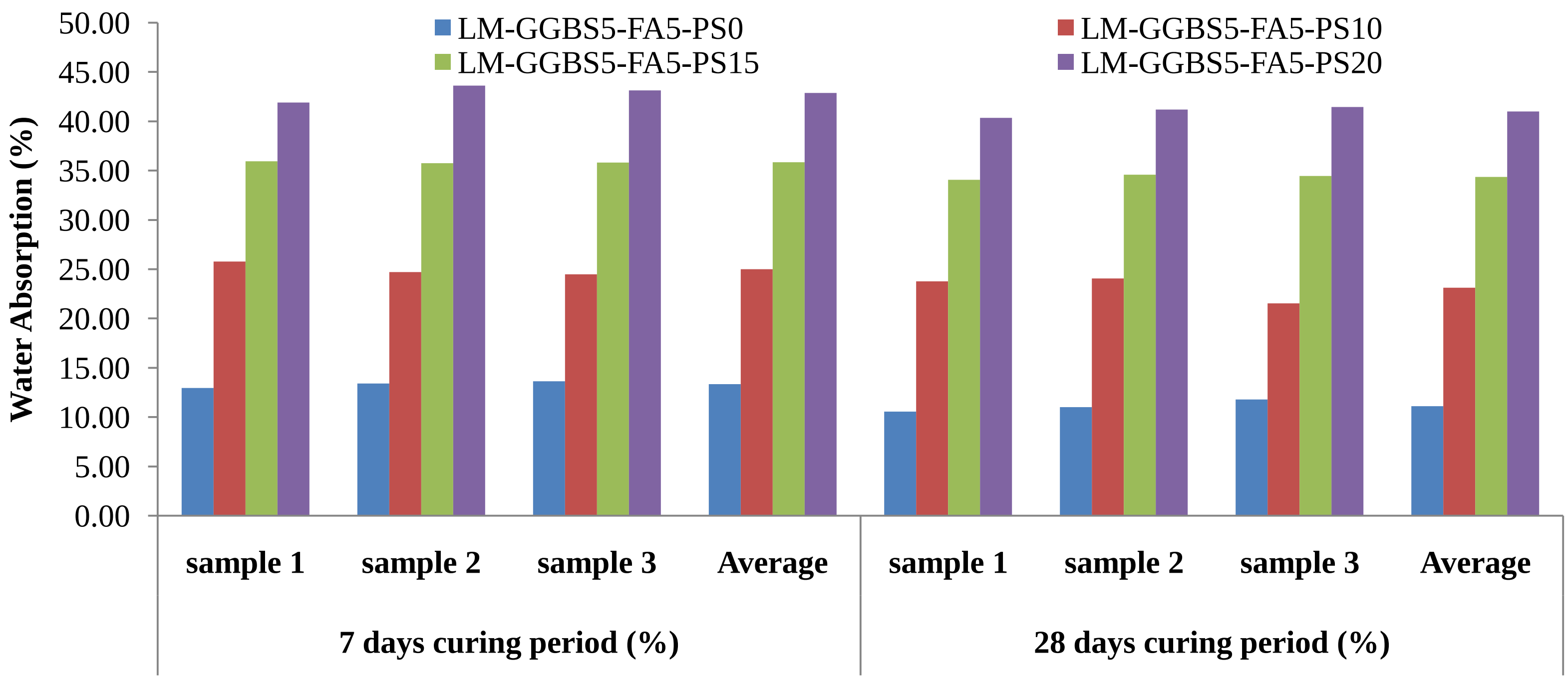

Figure 4.3: Water absorption development until 28 days of water curing periods

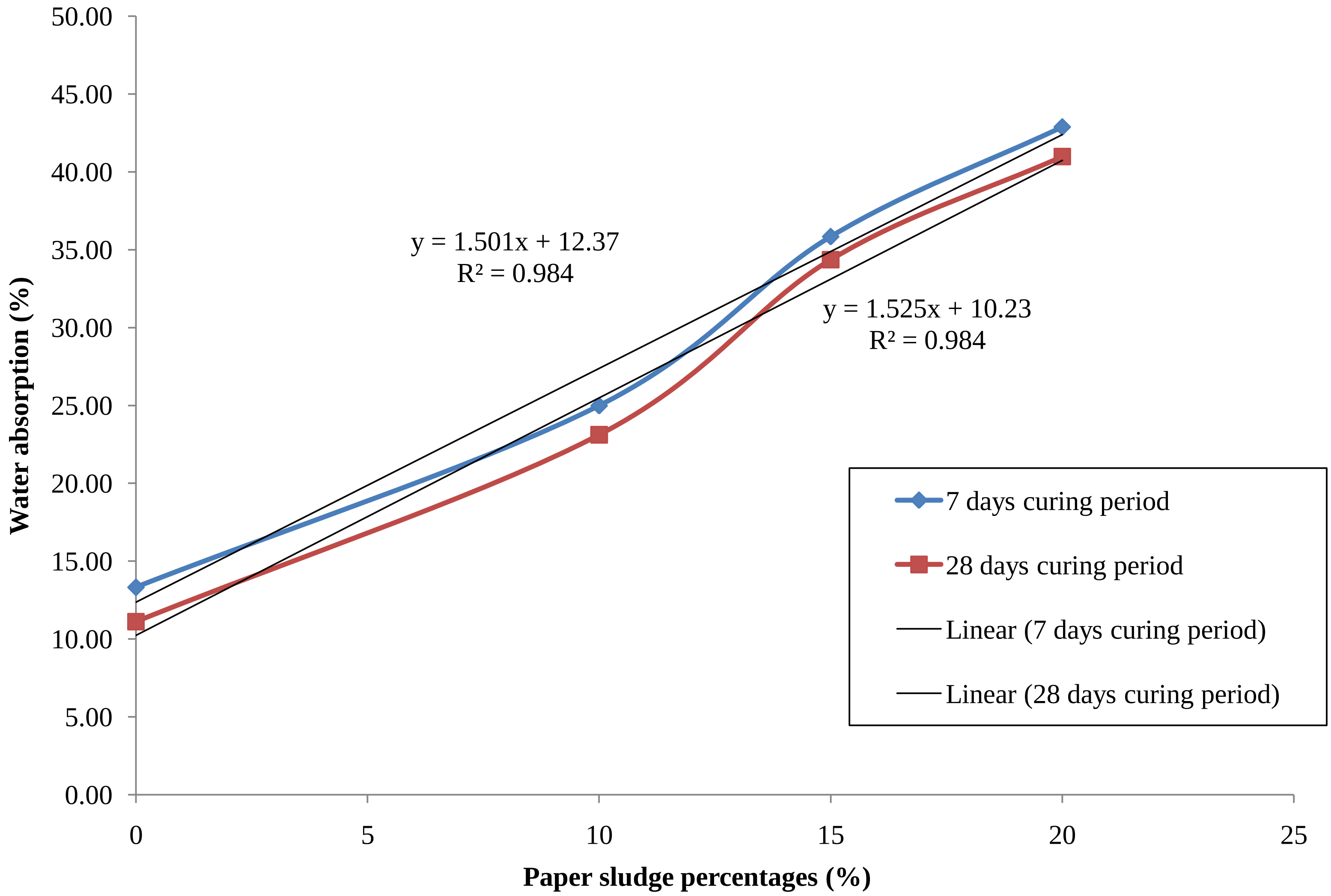

Figure 4.4: Average water absorption of the specimens on 7 and 28 days of water curing periods

4.5 Oven Dry Density

In considering the data presented in Figure 4.5 and Table 4.5, the over dry density decrease as the substitution level of paper sludge increase while 15% of paper sludge substitution best suit the object of this research which ranged at 1300 ± 50 kg/m^3. In fact, if in term of lightness, samples LM-GGBS5-FA5-PS20 is the best but its performance is slightly lower than standard requirement as stated in ASTM C129 (2007). According to Figure 4.6, the substitution level of paper sludge has high negative correlation on the oven dry density of the specimens; as substitution of paper sludge increase, the oven dry density of the samples will decrease. Indeed, the lightness of the samples substituted with paper sludge happened due to low dry density of the paper sludge at 830kg/m^3 which is far lower than dry density of cement at 3150 kg/m^3 (Chen et al., 2016).

Table 4.5: Oven dry density for the specimens

Specimen	7 days curing period (kg/m³)				28 days curing period (kg/m³)			
	sample 1	sample 2	sample 3	Average	sample 1	sample 2	sample 3	Average
LM-GGBS5-FA5-PS0	1934.80	1932.16	1916.80	1927.92	1919.44	1977.92	1937.28	1944.88
LM-GGBS5-FA5-PS10	1515.04	1524.64	1523.36	1521.01	1551.52	1535.44	1596.56	1561.17
LM-GGBS5-FA5-PS15	1282.40	1268.64	1278.96	1276.67	1293.20	1294.80	1284.88	1290.96
LM-GGBS5-FA5-PS20	1174.32	1160.08	1180.64	1171.68	1228.64	1242.40	1222.72	1231.25

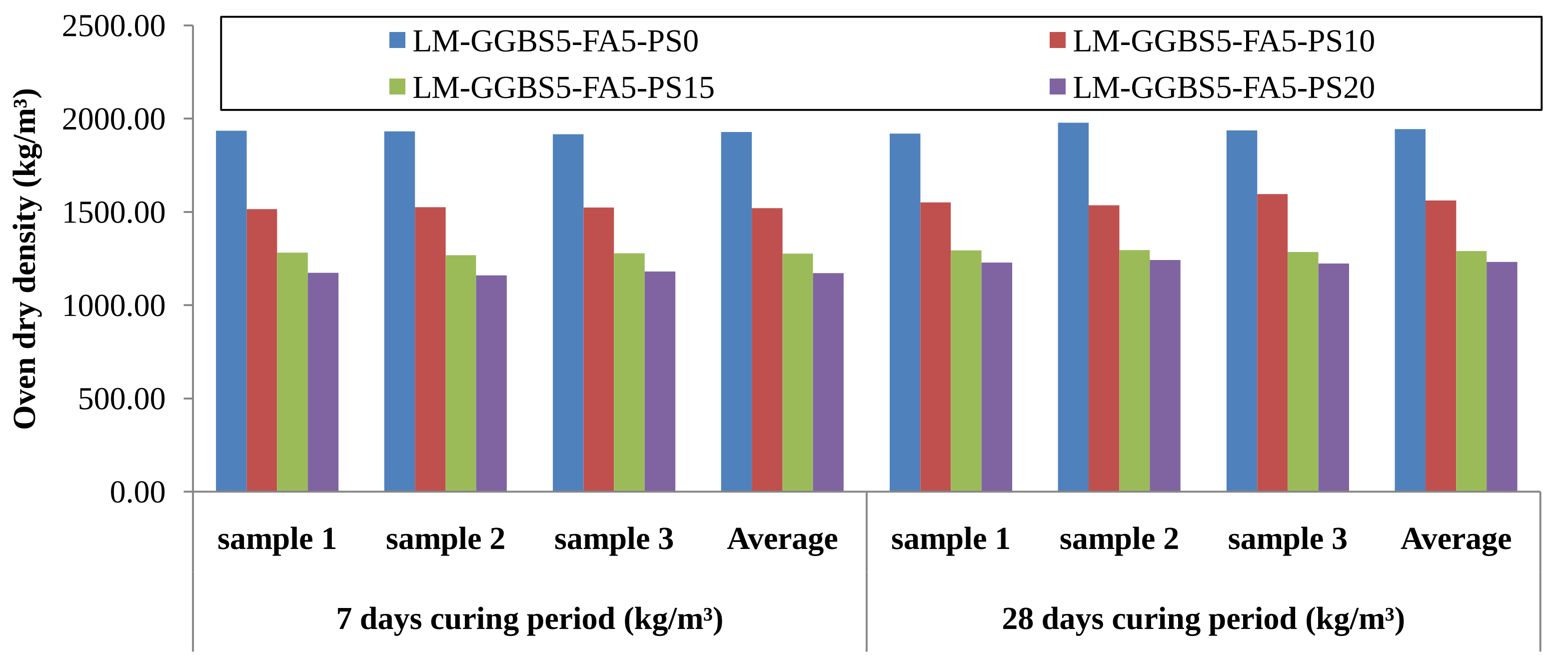

Figure 4.5: Oven dry density development until 28 days of water curing periods

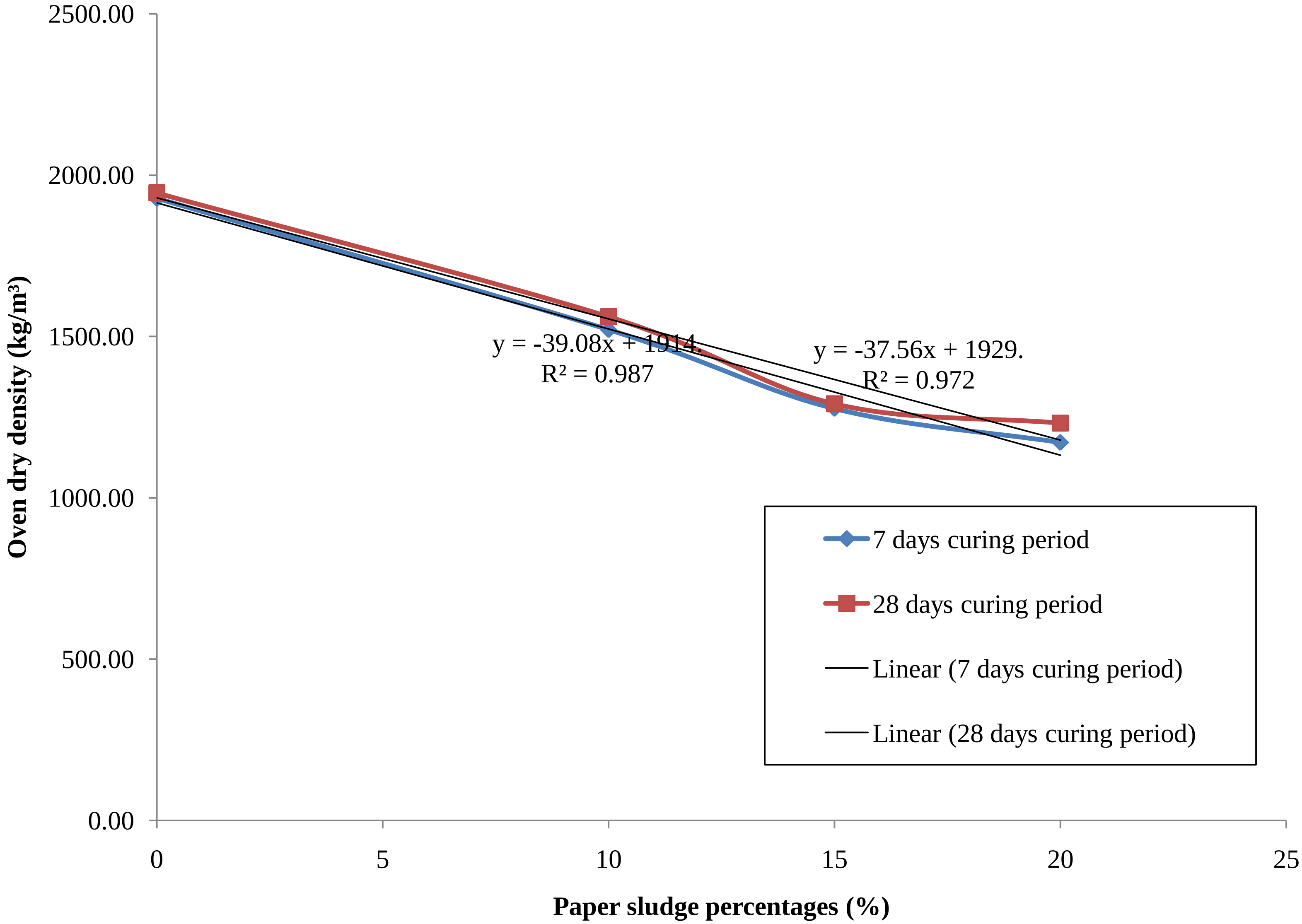

Figure 4.6: Average oven dry density of the specimens on 7 and 28 days of water curing periods

4.6 Scanning Electron Microscope

SEM or known as scanning electron microscope is a technique used to study the microstructure characteristic of a product. Its help us to understand the behaviours and characteristics of a concrete based product. Besides that, by collecting enough evidence through this test, we able to determine the main factor contributing to a high performance concrete based products. Generally in order to distinguish between fully hydrated cement and partially hydrated cement, one of the most common properties is the amount C-S-H gel present which according to Diamond (1976), "about 70 per cent of fully hydrated cement consists of C-S-H gel, 20 per cent calcium hydroxide, and the rest ettringite, calcium aluminate mono sulphate hydrate, unhydrated clinker residues and other minor constituents".

4.6.1 Microstructure of Raw Material

As shown in Figure 4.7, paper sludge was found to be fiber like shape under magnification of 160. This shows that the raw paper sludge is in its natural state and did not undergo high temperature treatment. Although according to Garcı´a et al. (2008), paper sludge under 700˚C for 2 hours able to maximizes its pozzolane characteristic but this process requires additional time, money and specify equipment which might not be practical for long term supply and mass production therefore, raw paper sludge was used in this experiment. Furthermore, additional processing of paper sludge waste might indirectly generate more waste which does not suit the objectives.

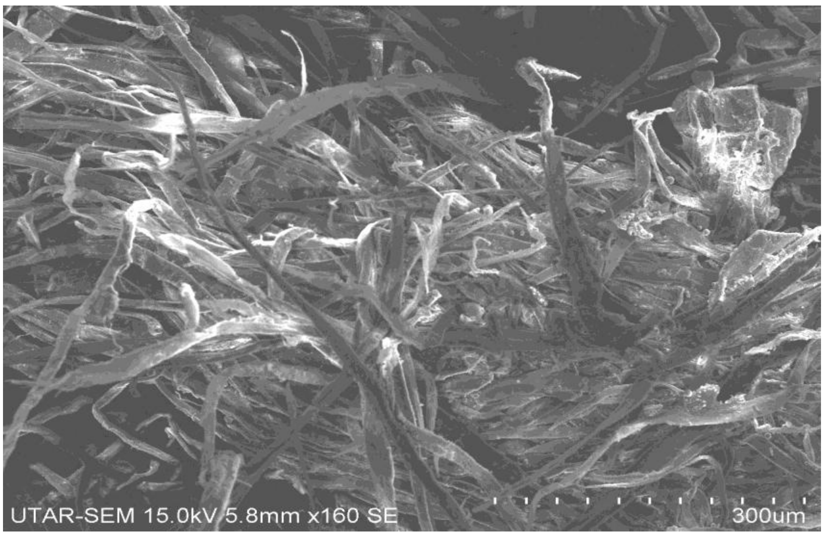

Figure 4.7: Raw paper sludge

Based on Figure 4.8, the granulated ground blastfurnace slags show uneven particles size distribution but overall passed though No 4 mesh size which is 4.75mm. In addition, granulated ground blastfurnace slags are irregular in shape. As compare to other raw materials granulated ground blastfurnace slag is slightly bigger which good in building up the strength of the mortar.

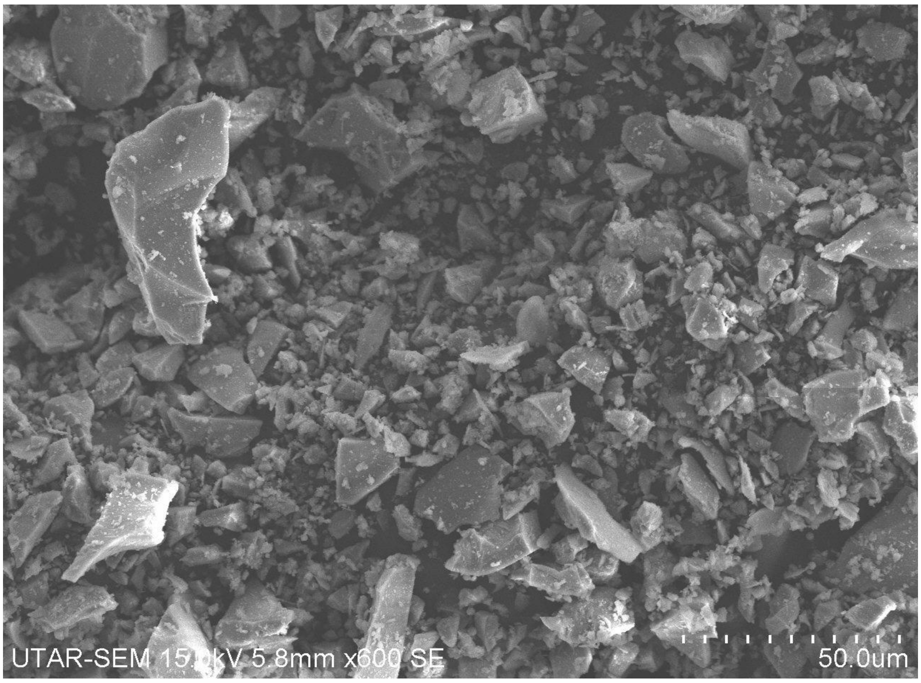

Figure 4.8: Granulated ground blastfurnace slag

Like granulated ground blastfurnace slag, fly ash was found to have scattered particle shape and sizes as shown in Figure 4.9. Fly ash is generally formed under high temperature which causes it to be circular in shape as shown in Figure 4.9. Morphology of ordinary Portland cement and granulated ground blastfurnace slag show some similarity as in Figures 4.10 and 4.9, both of them are irregular in shape but with regard of their morphological identity, the latter clearly show smaller in particles shape. On the other hand, a large number of impurities were found based on the metallographic observations on the ordinary Portland cement used in this experiment. These impurities mainly consist of inert ash which largely attributed to the low mechanical strength of the mortar.

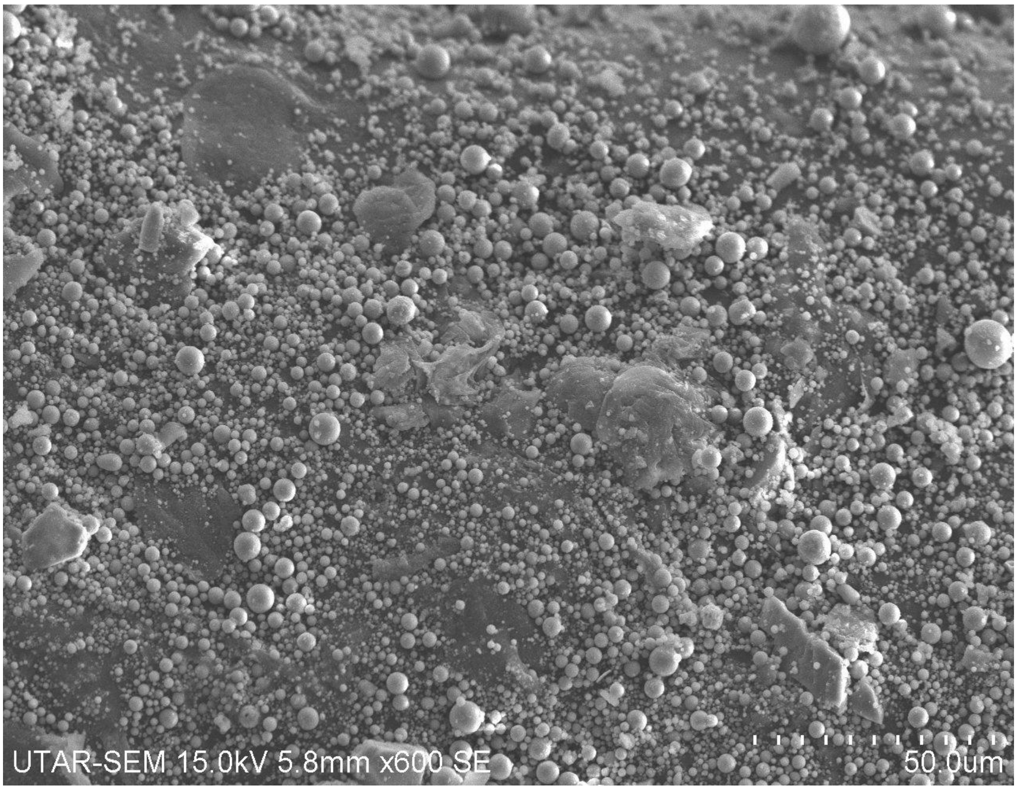

Figure 4.9: Fly ash

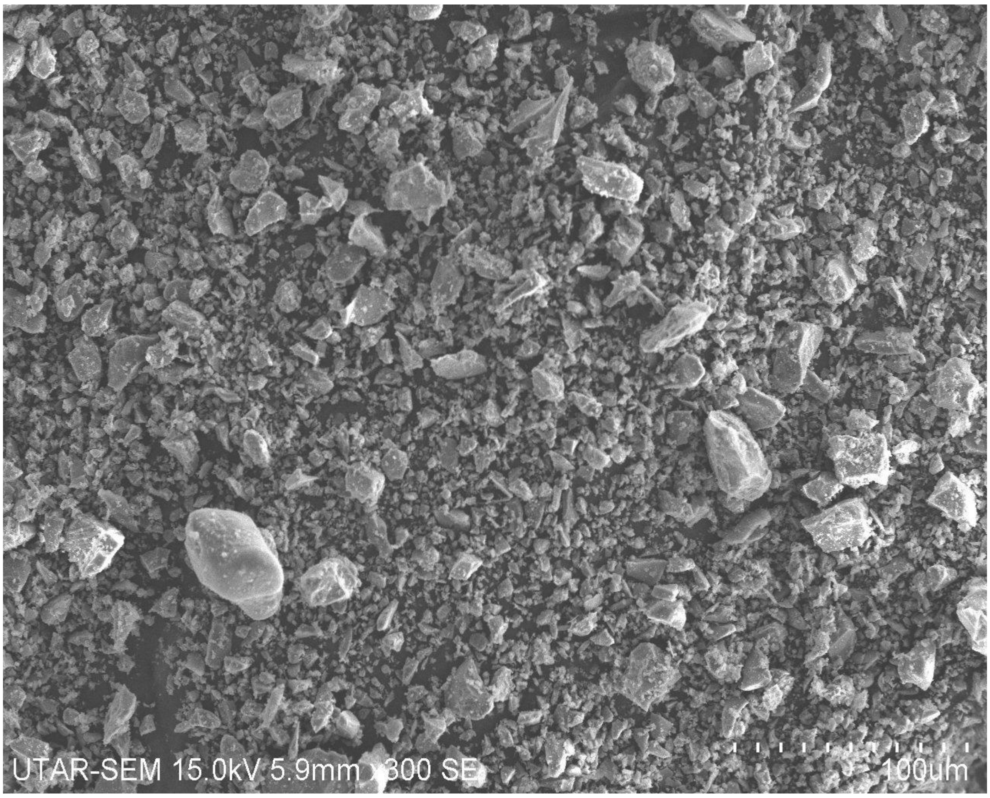

Figure 4.10: Ordinary Portland cement

4.6.2 Microstructure of the Specimen

Structure such as that illustrated in Figure 4.11, clearly show both granulated ground blastfurnace slag and fly ash were binded tightly into the matrix. Furthermore, there is a change in the fly ash shape which shows that the fly ash had partially reacted with the cement paste. The absent of fiber like shape in Figure 4.11 further proof the absent of paper sludge in sample LM-GGBS5-FA5-PS0.Although sample LM-GGBS5-FA5-PS0 generally shows a tight connection between each particles but few micro-crack can be seen in Figure 4.11 which will affect the strength of the mortar. As compare to Figure 4.11, the substitution of paper sludge show a much more loosen matrix as illustrated in Figures 4.12, 4.13 and 4.14. This might cause by the natural properties of paper sludge which is fiber like shape and soft that can cause a large amount of void existed during the mixing process. Unlike ground granulated blastfurnace slag and fly ash, raw paper sludge is a much more stable element that hardly will react with cement, therefore, additional of paper sludge cause the decreasing in the physical properties of the concrete mortar. Figure 4.12, 4.13 and 4.14 show the fiber like shape which is paper sludge does not react with the cement paste during hydration process.

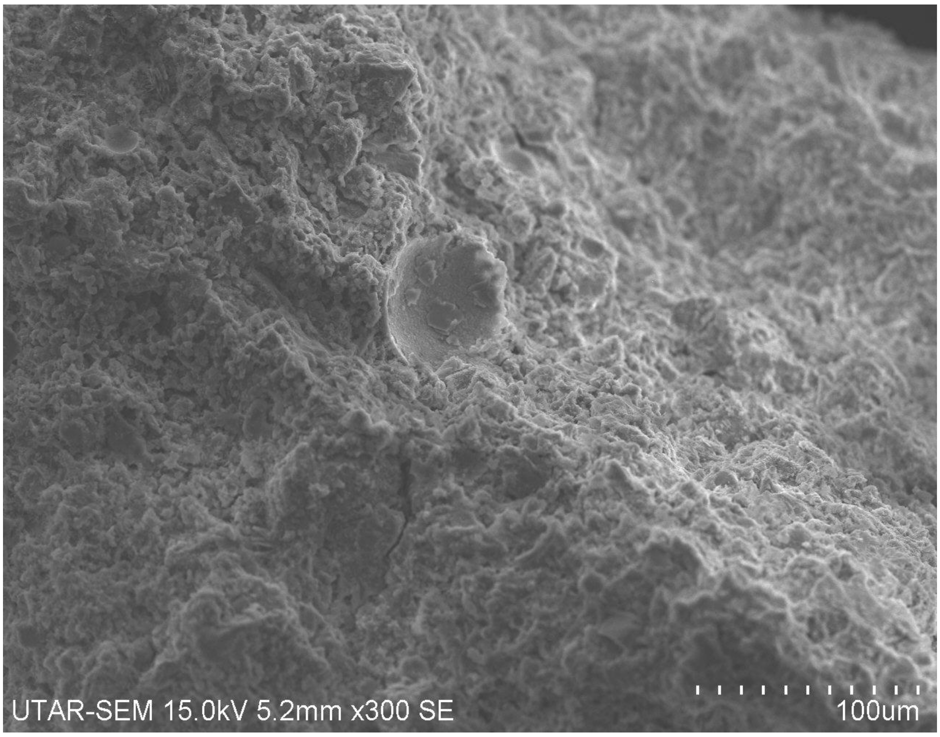

Figure 4.11: General view of sample LM-GGBS5-FA5-PS0 under magnification of 300

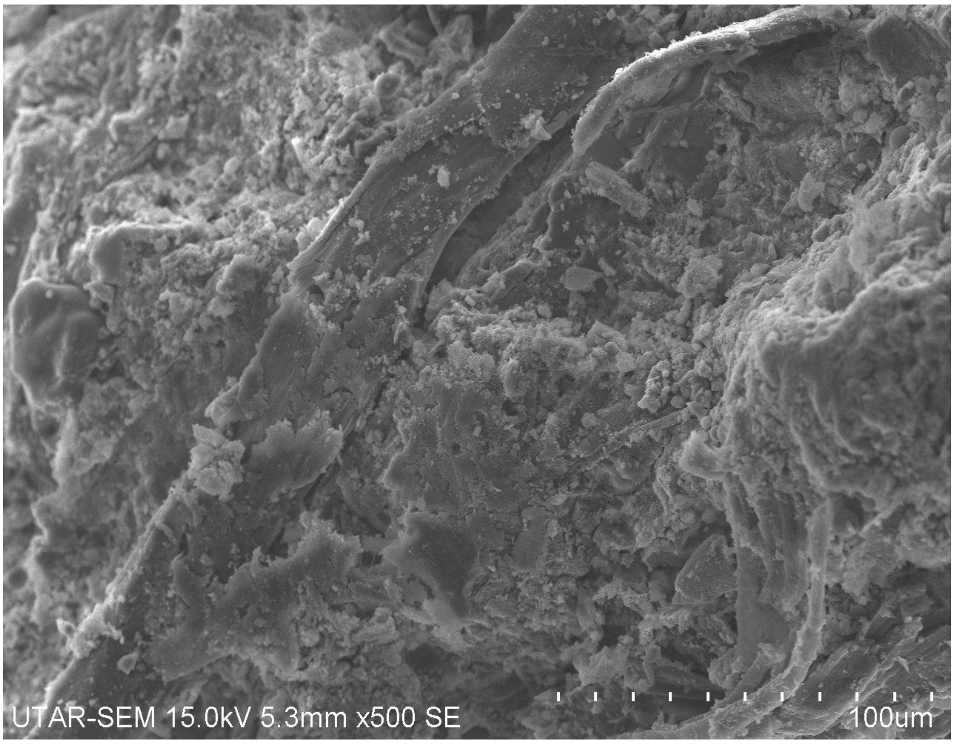

Figure 4.12: General view of sample LM-GGBS5-FA5-PS10 under magnification of 500

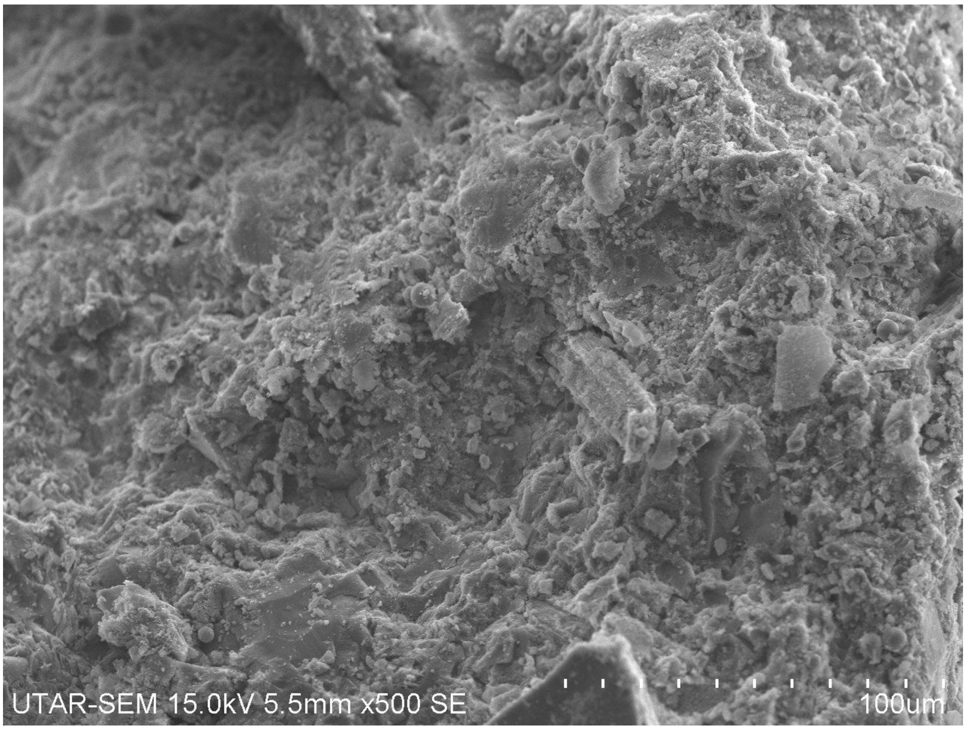

Figure 4.13: General view of sample LM-GGBS5-FA5-PS15 under magnification of 500

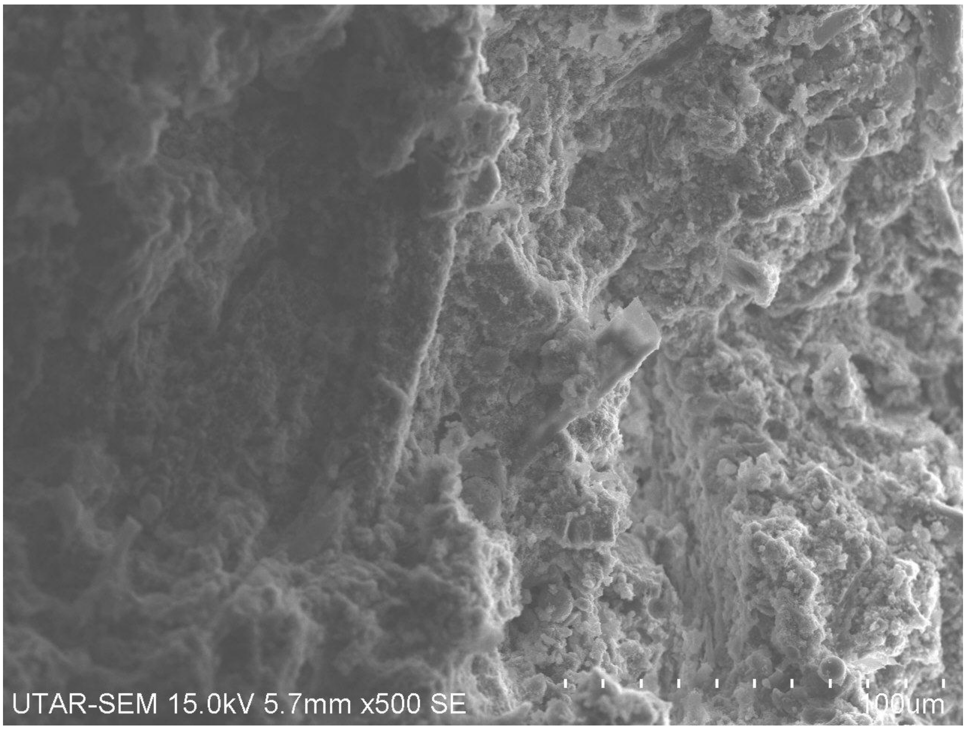

Figure 4.14: General view of sample LM-GGBS5-FA5-PS20 under magnification of 500

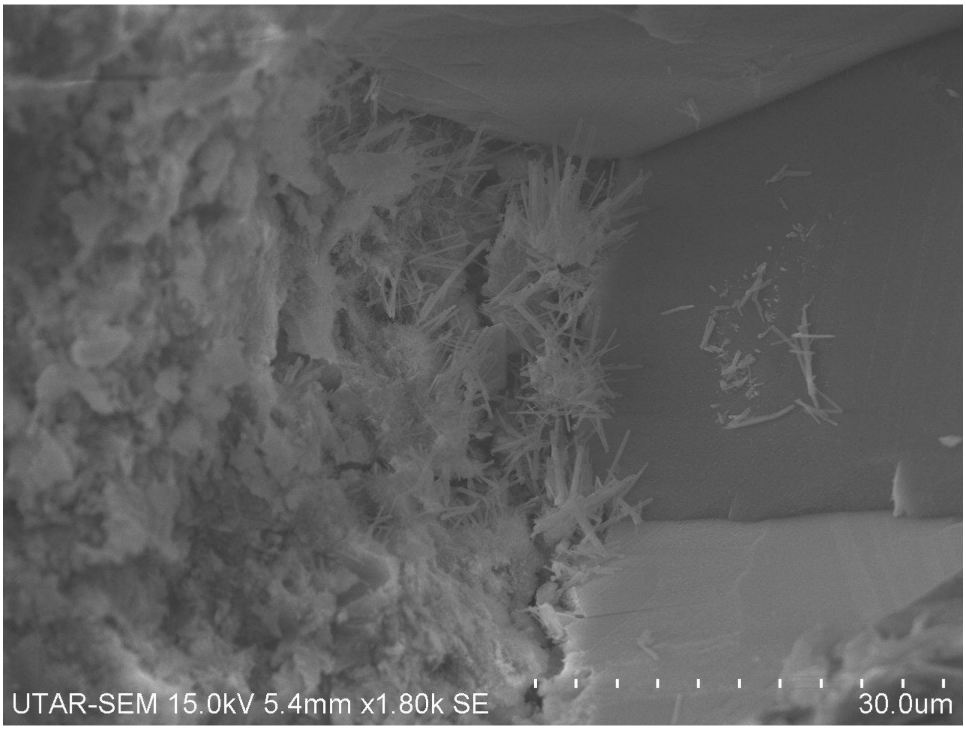

Figure 4.15: Detail view of sample LM-GGBS5-FA5-PS0 under 1800 magnification

A large amount of crystal was found deposited on the joint of each particles and according to a study done by Gemelli, Lourenci, Folgueras and Camargo (2004), the crystals that found are ettringite crystal also know as anhydrite crystal which formed during the hydration process of the cement paste. In detail, in order for the anhydrite crystal to form, crucial aqueous ions such as aluminium, sulphur and calcium have to be present and to be precipitated to form hydrated calcium aluminumsulfate hydroxide, $C_6AS_2H_{32}$. On the other hand, the comparison between the research done by Gemelli, Lourenci,Folgueras, and Camargo(2004) in Figure 4.13 with Figure 4.14 which conducted in this experiment had further proof the existing of anhydrite crystal in sample LM-GGBS5-FA5-PS0. Ettringite is mostly formed at the early stages of cement hydration process and later leaves its original location to fill up the void or crack formed; this result in building up the early strength of the concrete mortar.

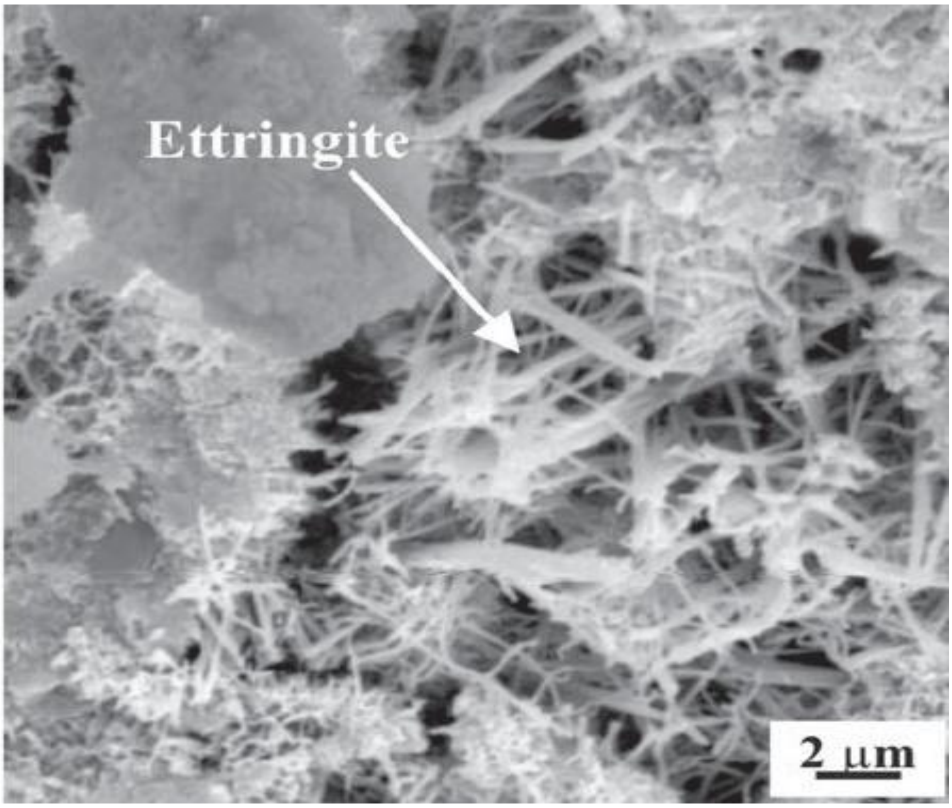

Figure 4.16: SEM micrograph done by Gemelli et al. (2004)

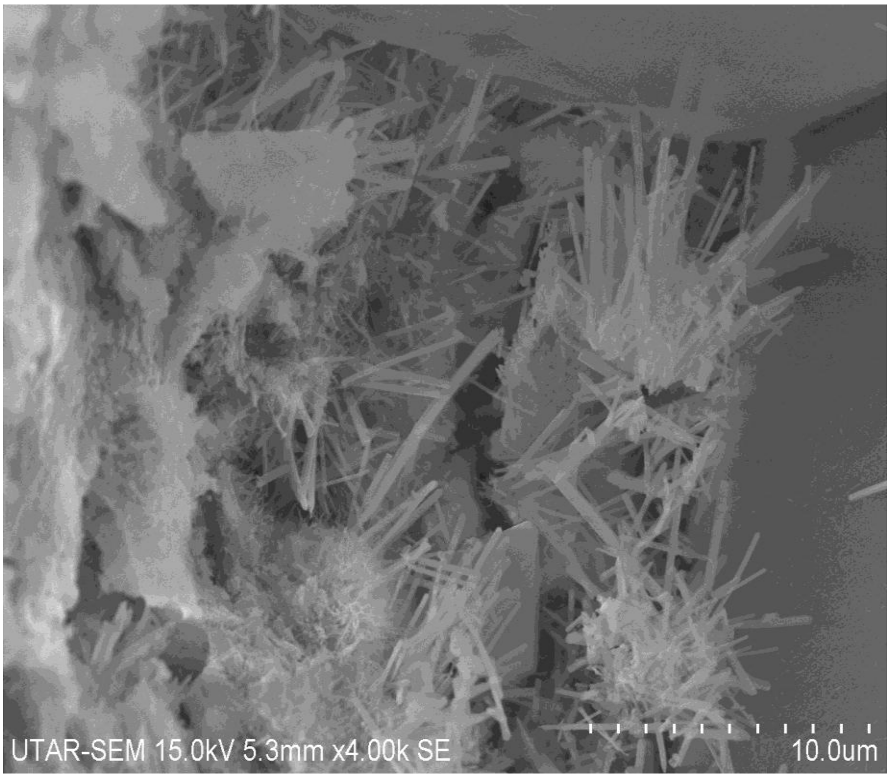

Figure 4.17: Detail view of sample LM-GGBS5-FA5-PS0 under magnification of 4000

In contrast, the substitution of paper sludge result in a lower amount of anhydrite crystal formed as illustrated in Figures 4.18, 4.19 and 4.20. As the level of paper sludge substitution increase, the lower the amount of anhydrite crystal found. This may happen due to the lower amount of ordinary Portland cement used for the sample. Furthermore, a low amount of anhydrite crystal cause the void formed unable to be filled and result in lower strength achieved which can be proof by the compression test result mentioned in chapter 4.3. Besides that, all samples with regard to their substitution levels, show few particles of unreacted fly ash.

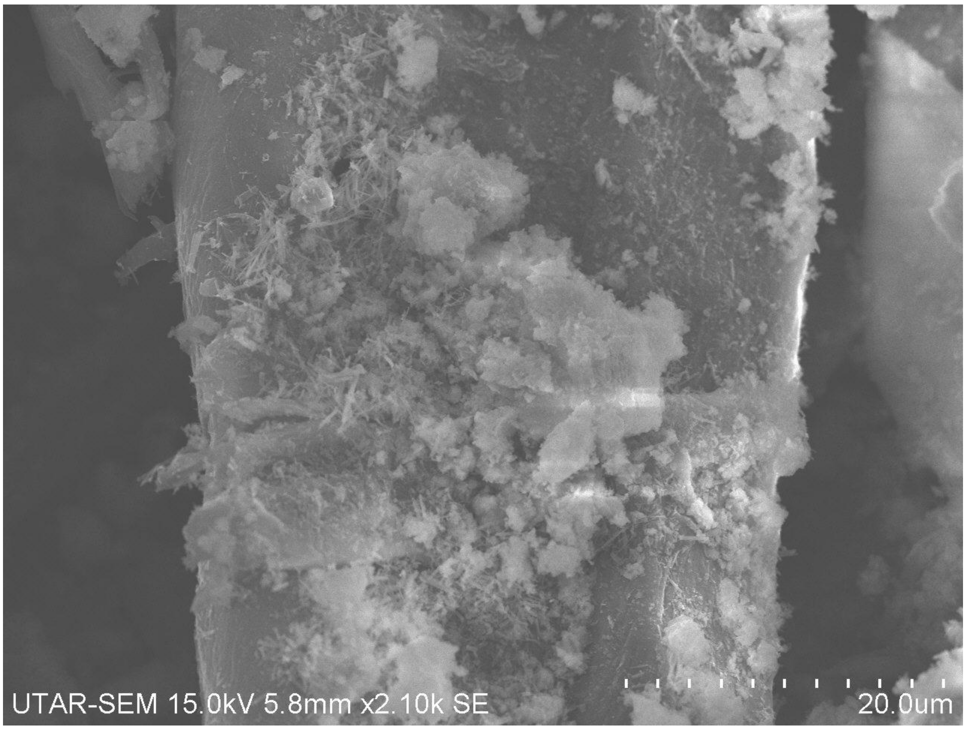

Figure 4.18: Detail view of sample LM-GGBS5-FA5-PS10 under magnification of 2100

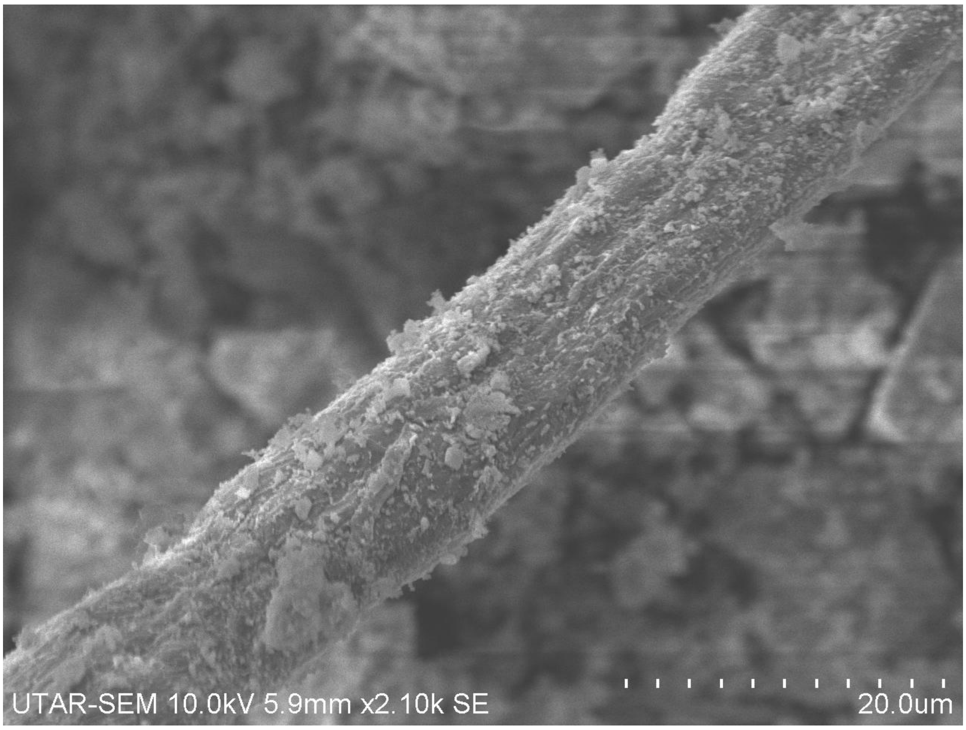

Figure 4.19: Detail view of sample LM-GGBS5-FA5-PS15 under magnification of 2100

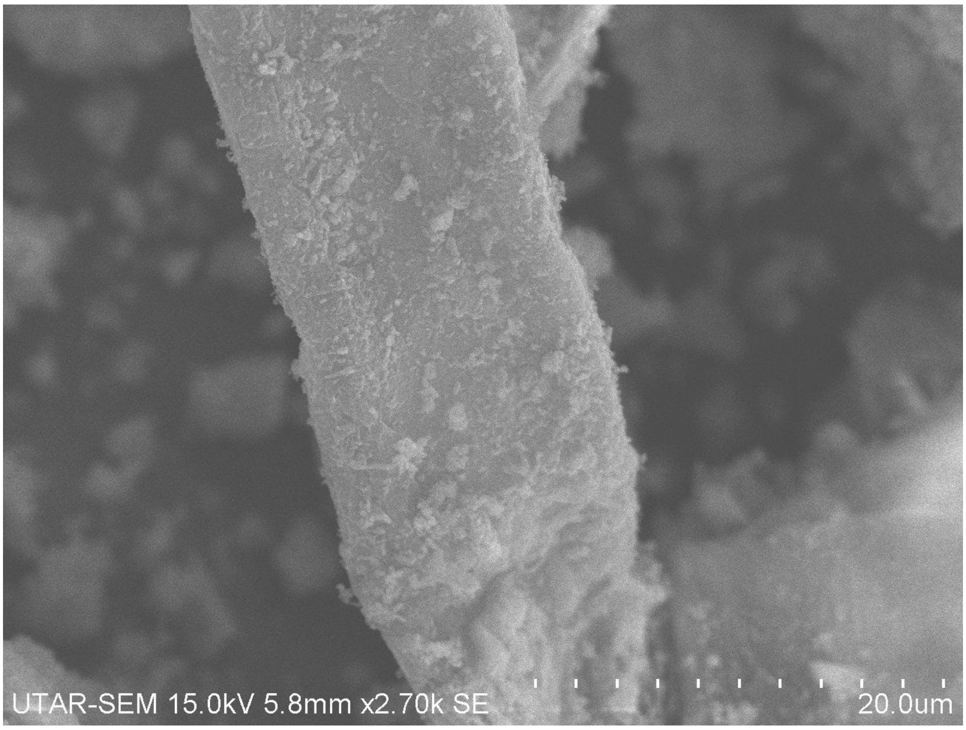

Figure 4.20: Detail view of sample LM-GGBS5-FA5-PS20 under magnification of 2700

4.7 Thermal Conductivity

Based on Table 4.6, substitutions of paper sludge clearly show some improvement in the thermal conductivity of the mortar. Sample LM-GGBS5-FA5-PS20 show the lowest thermal conductivity value. All samples were aged for 28 days before goes for thermal conductivity test. An increment of roughly 0.05W/(m·k) per 5% substitution can be observed as indicated in Figure 4.6. Besides that, paper sludge is highly correlated with the thermal conductivity of the concrete mortar in a negative manner as indicated in Figure 4.11

Table 4.6: Thermal conductivity of all the samples

Specimen	**28 days curing period thermal conductivity (W/(m·k))**		
	sample 1	**sample 2**	**Average**
LM-GGBS5-FA5-PS0	0.5985	0.5930	0.5958
LM-GGBS5-FA5-PS10	0.5074	0.5101	0.5088
LM-GGBS5-FA5-PS15	0.4517	0.4523	0.4520
LM-GGBS5-FA5-PS20	0.4055	0.4020	0.4038

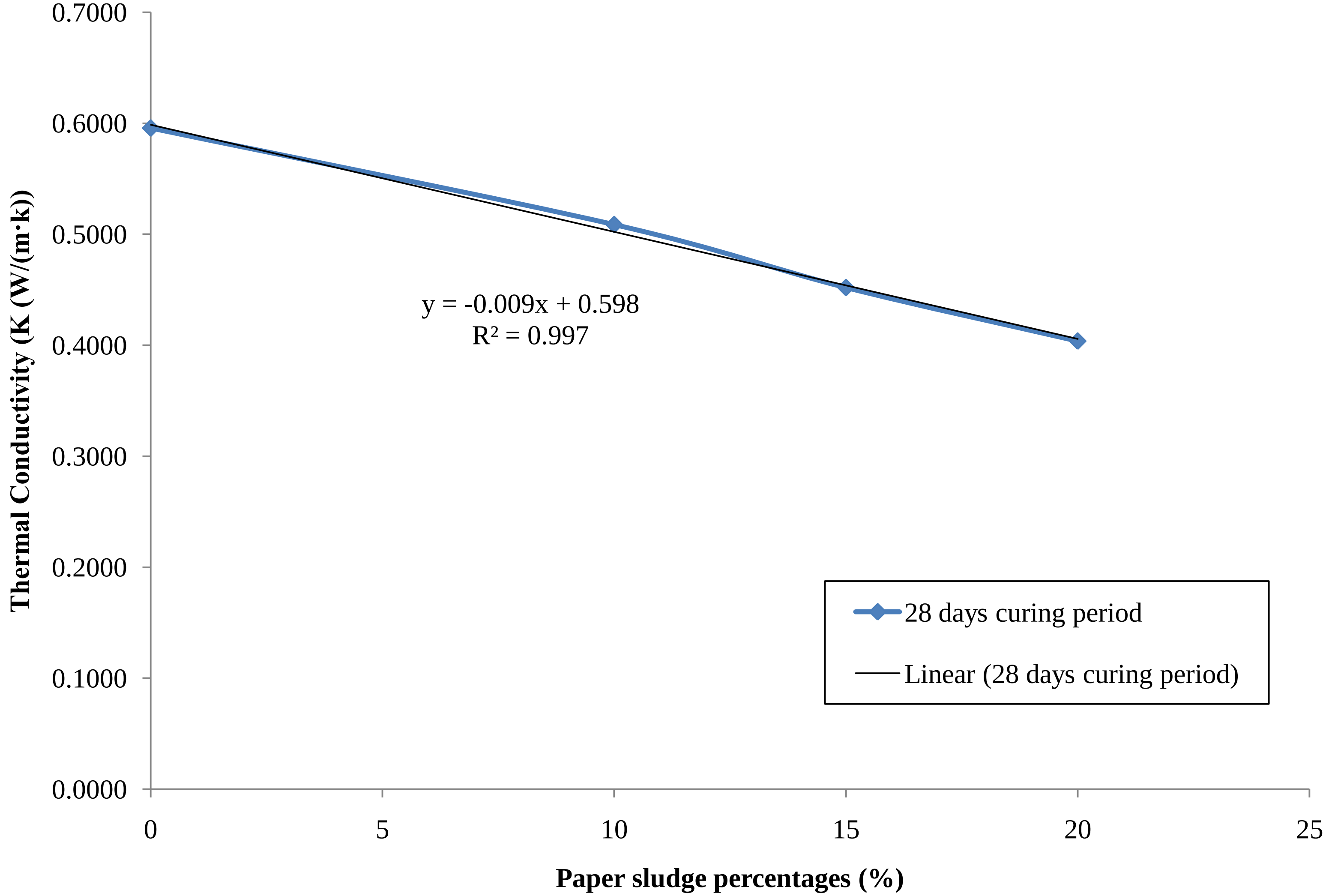

Figure 4.21: Relationship between substitutions of paper sludge and thermal conductivity

CHAPTER 5

CONCLUSION

5.1 Conclusion

Based on the research that had been done earlier, few conclusions can be made based on the objectives listed earlier in chapter 1. The first objective of this study is to produce a lightweight concrete mortar with density of 1300 ± 50 kg/m^3 using blended cement with paper sludge waste, fly ash and ground granulated blastfurnace slag (GGBS). This objective was achieved when the substitution level of paper sludge reach 15% which named as LM-GGBS5-FA5-PS15 as shown in Table 4.5. The main purpose of this objective is to produce a lightweight masonry unit that able to reduce the death loads that impose on the building which help in reducing the building construction cost.

Although it is important to have a low density of concrete mortar but according to ASTM C129 (2007), for non-loading concrete masonry unit, it is required to have a minimum net area compressive strength of 3.45MPa for an individual unit. Therefore the second objective of this study is to identify the optimal percentages of paper sludge waste to substitute the ordinary Portland cement in the production of lightweight concrete mortar in the presence of fly ash and ground granulated blastfurnace slag without compromising the compressive strength as stated in ASTM C129. As refer to the result tabulated in chapter 4.3, the highest level of paper sludge substitution without compromising the minimum required strength as stated in ASTM C129 (2017) is 15% at average compressive strength of 4.96 MPa for 28 days water curing period and 10% at average compressive strength of 6.02MPa for 7 days water curing period.

In this energy deficit century, energy efficiency is one of the key element to determine the market value of your product while the most critical part of it is how to ensure the energy loss is at its minimum; therefore, the third objective of this study is to assess the effect of paper sludge waste on the thermal conductivity of the lightweight concrete mortar. In this study, it is found that the increasing substitution of paper sludge into the concrete mortar able to reduce the thermal conductivity of the concrete mortar at a negative correlation of 0.998. Apparently, LM-GGBS5-FA5-

PS20 possesses the lowest thermal conductivity at an average value of 0.4038 W/(m·k).

In a nut shell, sample LM-GGBS5-FA5-PS15 was selected due to it possesses the maximum substitution of paper sludge without compromising the minimum required compressive strength and has an adequate value of thermal conductivity with a low range of oven dry density.

5.2 Recommendations

The study on the lightweight concrete mortar blended with ground granulated blastfurnace slag, fly ash and paper sludge is still very virgin and finite in this field. Hence, in order to upgrade future research on this field, few facets have to be taking into attention:

1. Exploit more water to cement ratios under the same proportion to obtain the best water to cement ratios in this field.
2. Introduce varies curing method for the concrete mortar sample and study the effect on it.
3. Study the behaviours of lightweight concrete mortar blended with ground granulated blastfurnace slag by open it to more tests such as sound absorption test, drying shrinkage, sound insulation test, water permeability test, energy-dispersive X-ray microanalysis(EDX), and tensile strength etc.
4. Introduce more paper sludge substitution level to further study the relationship concrete mortar and waste paper sludge.

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APPENDICES

APPENDIX A: Saturated weight

Specimen	7 days curing period			28 days curing period		
	sample 1	sample 2	sample 3	sample 1	sample 2	sample 3
LM-GGBS5-FA5-PS0	273.14	273.90	272.29	265.24	274.43	270.72
LM-GGBS5-FA5-PS10	238.19	237.69	237.03	240.01	238.14	242.52
LM-GGBS5-FA5-PS15	217.93	215.28	217.15	216.71	217.83	215.94
LM-GGBS5-FA5-PS20	208.28	208.26	211.26	215.53	219.25	216.21

APPENDIX B: Oven-dry density

Specimen	7 days curing period			28 days curing period		
	sample 1	sample 2	sample 3	sample 1	sample 2	sample 3
LM-GGBS5-FA5-PS0	241.85	241.52	239.60	239.93	247.24	242.16
LM-GGBS5-FA5-PS10	189.38	190.58	190.42	193.94	191.93	199.57
LM-GGBS5-FA5-PS15	160.30	158.58	159.87	161.65	161.85	160.61
LM-GGBS5-FA5-PS20	146.79	145.01	147.58	153.58	155.30	152.84

APPENDIX C: Overall results

Specimen	7 days curing period			28 days curing period			
	Average dry density (kg/m³)	Average water absorption (%)	Average compressive strength (Mpa)	Average dry density (kg/m³)	Average water absorption (%)	Average compressive strength (Mpa)	Average thermal Conductivity, K
LM-GGBS5-FA5-PS0	1927.92	13.33	23.67	1944.88	11.11	35.50	0.5958
LM-GGBS5-FA5-PS10	1521.01	24.99	6.02	1561.17	23.12	10.40	0.5088
LM-GGBS5-FA5-PS15	1276.67	35.85	2.97	1290.96	34.37	4.96	0.4520
LM-GGBS5-FA5-PS20	1171.68	42.89	1.58	1231.25	40.99	2.70	0.4038

APPENDIX D: Thermal test result of LM-GGBS5-FA5-PS0 sample 1.

Hours	Heat Flow, Q (W)	Avg Hot Plate Temp	AvgCold Plate Temp	Avg Temp Different, ΔT (K)	Area, A (m2)	Thickness, L (m)	Thermal Conductivity, K (W·K−1·m−1)
1	0.52	39.20	22.19	17.01	0.0025	0.05	0.607
2	0.52	39.29	22.20	17.09	0.0025	0.05	0.604
3	0.52	39.21	22.15	17.06	0.0025	0.05	0.605
4	0.52	39.26	22.15	17.11	0.0025	0.05	0.603
5	0.52	39.24	22.08	17.16	0.0025	0.05	0.602
6	0.52	39.24	22.06	17.18	0.0025	0.05	0.601
7	0.52	39.28	22.05	17.23	0.0025	0.05	0.599
8	0.52	39.24	22.03	17.21	0.0025	0.05	0.600
9	0.52	39.30	22.00	17.30	0.0025	0.05	0.597
10	0.52	39.22	21.98	17.24	0.0025	0.05	0.599
11	0.52	39.32	21.95	17.36	0.0025	0.05	0.595
12	0.52	39.22	21.94	17.28	0.0025	0.05	0.597
13	0.52	39.32	21.93	17.38	0.0025	0.05	0.594
14	0.52	39.25	21.94	17.31	0.0025	0.05	0.596
15	0.52	39.26	21.95	17.30	0.0025	0.05	0.597
16	0.52	39.27	21.94	17.33	0.0025	0.05	0.596
17	0.52	39.20	21.94	17.25	0.0025	0.05	0.599
18	0.52	39.32	21.87	17.45	0.0025	0.05	0.592
19	0.52	39.30	21.84	17.46	0.0025	0.05	0.592
20	0.52	39.23	21.87	17.36	0.0025	0.05	0.595
AVG		39.25794167	22.00350833				0.5985

APPENDIX E: Thermal test result of LM-GGBS5-FA5-PS0 sample 2.

Hours	Heat Flow, Q (W)	Avg Hot Plate Temp	AvgCold Plate Temp	Avg Temp Different, ΔT (K)	Area, A (m2)	Thickness, L (m)	Thermal Conductivity, K (W·K−1·m−1)
1	0.52	38.76	21.40	17.36	0.0025	0.05	0.595
2	0.52	38.83	21.39	17.44	0.0025	0.05	0.592
3	0.52	38.75	21.40	17.35	0.0025	0.05	0.595
4	0.52	38.79	21.44	17.35	0.0025	0.05	0.595
5	0.52	38.77	21.42	17.35	0.0025	0.05	0.595
6	0.52	38.78	21.42	17.36	0.0025	0.05	0.595
7	0.52	38.81	21.41	17.40	0.0025	0.05	0.594
8	0.52	38.77	21.40	17.37	0.0025	0.05	0.594
9	0.52	38.83	21.40	17.43	0.0025	0.05	0.593
10	0.52	38.76	21.38	17.38	0.0025	0.05	0.594
11	0.52	38.84	21.38	17.46	0.0025	0.05	0.591
12	0.52	38.76	21.38	17.38	0.0025	0.05	0.594
13	0.52	38.85	21.37	17.48	0.0025	0.05	0.591
14	0.52	38.79	21.37	17.42	0.0025	0.05	0.593
15	0.52	38.80	21.38	17.42	0.0025	0.05	0.593
16	0.52	38.82	21.38	17.44	0.0025	0.05	0.592
17	0.52	38.75	21.37	17.38	0.0025	0.05	0.594
18	0.52	38.87	21.34	17.53	0.0025	0.05	0.589
19	0.52	38.85	21.32	17.53	0.0025	0.05	0.589
20	0.52	38.79	21.32	17.46	0.0025	0.05	0.591
AVG		38.79854167	21.38404167				0.5930

APPENDIX F: Thermal test result of LM-GGBS5-FA5-PS10 sample 1.

Hours	Heat Flow, Q (W)	Avg Hot Plate Temp	AvgCold Plate Temp	Avg Temp Different, ΔT (K)	Area, A (m2)	Thickness, L (m)	Thermal Conductivity, K (W·K−1·m−1)
1	0.45	40.16	22.36	17.80	0.0025	0.05	0.510
2	0.45	40.17	22.34	17.83	0.0025	0.05	0.510
3	0.45	40.11	22.33	17.78	0.0025	0.05	0.511
4	0.45	40.24	22.33	17.92	0.0025	0.05	0.507
5	0.45	40.17	22.32	17.85	0.0025	0.05	0.509
6	0.45	40.16	22.32	17.84	0.0025	0.05	0.509
7	0.45	40.23	22.31	17.91	0.0025	0.05	0.507
8	0.45	40.15	22.31	17.84	0.0025	0.05	0.509
9	0.45	40.19	22.31	17.89	0.0025	0.05	0.508
10	0.45	40.23	22.31	17.92	0.0025	0.05	0.507
11	0.45	40.15	22.31	17.84	0.0025	0.05	0.509
12	0.45	40.27	22.30	17.97	0.0025	0.05	0.506
13	0.45	40.20	22.30	17.90	0.0025	0.05	0.508
14	0.45	40.14	22.29	17.85	0.0025	0.05	0.509
15	0.45	40.28	22.28	18.00	0.0025	0.05	0.505
16	0.45	40.26	22.25	18.01	0.0025	0.05	0.505
17	0.45	40.21	22.23	17.98	0.0025	0.05	0.505
18	0.45	40.22	22.21	18.01	0.0025	0.05	0.505
19	0.45	40.27	22.21	18.06	0.0025	0.05	0.503
20	0.45	40.17	22.18	17.99	0.0025	0.05	0.505
AVG		40.19935833	22.28891667				0.5074

APPENDIX G: Thermal test result of LM-GGBS5-FA5-PS10 sample 2.

Hours	Heat Flow, Q (W)	Avg Hot Plate Temp	AvgCold Plate Temp	Avg Temp Different, ΔT (K)	Area, A (m2)	Thickness, L (m)	Thermal Conductivity, K (W·K−1·m−1)
1	0.45	39.81	22.16	17.65	0.0025	0.05	0.515
2	0.45	39.82	22.07	17.74	0.0025	0.05	0.512
3	0.45	39.76	22.05	17.71	0.0025	0.05	0.513
4	0.45	39.89	22.05	17.83	0.0025	0.05	0.510
5	0.45	39.81	22.06	17.75	0.0025	0.05	0.512
6	0.45	39.81	22.06	17.75	0.0025	0.05	0.512
7	0.45	39.86	22.05	17.81	0.0025	0.05	0.510
8	0.45	39.80	22.04	17.76	0.0025	0.05	0.512
9	0.45	39.83	22.03	17.80	0.0025	0.05	0.510
10	0.45	39.87	22.03	17.84	0.0025	0.05	0.509
11	0.45	39.79	22.02	17.77	0.0025	0.05	0.512
12	0.45	39.90	22.02	17.88	0.0025	0.05	0.508
13	0.45	39.83	22.02	17.81	0.0025	0.05	0.510
14	0.45	39.78	22.02	17.76	0.0025	0.05	0.512
15	0.45	39.91	22.01	17.90	0.0025	0.05	0.508
16	0.45	39.90	21.99	17.91	0.0025	0.05	0.507
17	0.45	39.85	21.97	17.88	0.0025	0.05	0.508
18	0.45	39.86	21.95	17.91	0.0025	0.05	0.507
19	0.45	39.90	21.95	17.95	0.0025	0.05	0.506
20	0.45	39.81	21.93	17.88	0.0025	0.05	0.508
AVG		39.839625	22.02355				0.5101

APPENDIX H: Thermal test result of LM-GGBS5-FA5-PS15 sample 1.

Hours	Heat Flow, Q (W)	Avg Hot Plate Temp	AvgCold Plate Temp	Avg Temp Different, ΔT (K)	Area, A (m2)	Thickness, L (m)	Thermal Conductivity, K (W·K−1·m−1)
1	0.45	41.08	21.61	19.47	0.0025	0.05	0.458
2	0.45	41.22	21.55	19.67	0.0025	0.05	0.453
3	0.45	41.13	21.54	19.60	0.0025	0.05	0.455
4	0.45	41.26	21.53	19.73	0.0025	0.05	0.452
5	0.45	41.13	21.53	19.60	0.0025	0.05	0.455
6	0.45	41.28	21.52	19.76	0.0025	0.05	0.451
7	0.45	41.15	21.52	19.63	0.0025	0.05	0.454
8	0.45	41.24	21.53	19.72	0.0025	0.05	0.452
9	0.45	41.20	21.52	19.68	0.0025	0.05	0.453
10	0.45	41.16	21.51	19.65	0.0025	0.05	0.454
11	0.45	41.23	21.51	19.72	0.0025	0.05	0.452
12	0.45	41.13	21.51	19.63	0.0025	0.05	0.454
13	0.45	41.28	21.50	19.78	0.0025	0.05	0.451
14	0.45	41.14	21.49	19.66	0.0025	0.05	0.453
15	0.45	41.32	21.42	19.89	0.0025	0.05	0.448
16	0.45	41.25	21.38	19.87	0.0025	0.05	0.448
17	0.45	41.17	21.31	19.86	0.0025	0.05	0.449
18	0.45	41.28	21.34	19.94	0.0025	0.05	0.447
19	0.45	41.19	21.36	19.83	0.0025	0.05	0.449
20	0.45	41.20	21.34	19.86	0.0025	0.05	0.449

AVG		41.20109167	21.47540417				0.4517

APPENDIX I: Thermal test result of LM-GGBS5-FA5-PS15 sample 2.

Hours	Heat Flow, Q (W)	Avg Hot Plate Temp	AvgCold Plate Temp	Avg Temp Different, ΔT (K)	Area, A (m2)	Thickness, L (m)	Thermal Conductivity, K (W·K−1·m−1)
1	0.45	40.93	21.54	19.40	0.0025	0.05	0.459
2	0.45	41.07	21.45	19.62	0.0025	0.05	0.454
3	0.45	40.99	21.56	19.43	0.0025	0.05	0.459
4	0.45	41.13	21.81	19.32	0.0025	0.05	0.461
5	0.45	40.99	21.44	19.55	0.0025	0.05	0.456
6	0.45	41.16	21.43	19.74	0.0025	0.05	0.452
7	0.45	41.04	21.43	19.61	0.0025	0.05	0.454
8	0.45	41.14	21.42	19.72	0.0025	0.05	0.452
9	0.45	41.10	21.41	19.69	0.0025	0.05	0.453
10	0.45	41.07	21.40	19.67	0.0025	0.05	0.453
11	0.45	41.15	21.40	19.75	0.0025	0.05	0.451
12	0.45	41.05	21.39	19.66	0.0025	0.05	0.453
13	0.45	41.19	21.38	19.81	0.0025	0.05	0.450
14	0.45	41.06	21.37	19.69	0.0025	0.05	0.453
15	0.45	41.23	21.31	19.92	0.0025	0.05	0.447
16	0.45	41.16	21.27	19.90	0.0025	0.05	0.448
17	0.45	41.09	21.20	19.89	0.0025	0.05	0.448
18	0.45	41.20	21.23	19.97	0.0025	0.05	0.446
19	0.45	41.11	21.25	19.86	0.0025	0.05	0.449
20	0.45	41.11	21.22	19.89	0.0025	0.05	0.448
AVG		41.09961667	21.3961625				0.4523

APPENDIX J: Thermal test result of LM-GGBS5-FA5-PS20 sample 1.

Hours	Heat Flow, Q (W)	Avg Hot Plate Temp	AvgCold Plate Temp	Avg Temp Different, ΔT (K)	Area, A (m2)	Thickness, L (m)	Thermal Conductivity, K (W·K−1·m−1)
1	0.40	41.39	21.41	19.99	0.0025	0.05	0.404
2	0.40	41.29	21.47	19.82	0.0025	0.05	0.408
3	0.40	41.32	21.51	19.82	0.0025	0.05	0.408
4	0.40	41.39	21.51	19.89	0.0025	0.05	0.406
5	0.40	41.26	21.51	19.75	0.0025	0.05	0.409
6	0.40	41.42	21.50	19.92	0.0025	0.05	0.406
7	0.40	41.32	21.50	19.82	0.0025	0.05	0.408
8	0.40	41.37	21.50	19.87	0.0025	0.05	0.407
9	0.40	41.37	21.50	19.88	0.0025	0.05	0.407
10	0.40	41.30	21.50	19.81	0.0025	0.05	0.408
11	0.40	41.43	21.48	19.95	0.0025	0.05	0.405
12	0.40	41.26	21.46	19.80	0.0025	0.05	0.408
13	0.40	41.44	21.43	20.00	0.0025	0.05	0.404
14	0.40	41.30	21.43	19.87	0.0025	0.05	0.407
15	0.40	41.53	21.42	20.11	0.0025	0.05	0.402
16	0.40	41.39	21.37	20.03	0.0025	0.05	0.404
17	0.40	41.44	21.35	20.09	0.0025	0.05	0.402
18	0.40	41.43	21.32	20.11	0.0025	0.05	0.402
19	0.40	41.36	21.30	20.06	0.0025	0.05	0.403
20	0.40	41.45	21.29	20.16	0.0025	0.05	0.401
AVG		41.37377917	21.43784167				0.4055

APPENDIX K: Thermal test result of LM-GGBS5-FA5-PS20 sample 2.

Hours	Heat Flow, Q (W)	Avg Hot Plate Temp	AvgCold Plate Temp	Avg Temp Different, ΔT (K)	Area, A (m2)	Thickness, L (m)	Thermal Conductivity, K (W·K−1·m−1)
1	0.40	41.58	21.38	20.20	0.0025	0.05	0.400
2	0.40	41.47	21.43	20.04	0.0025	0.05	0.403
3	0.40	41.51	21.45	20.06	0.0025	0.05	0.403
4	0.40	41.57	21.44	20.14	0.0025	0.05	0.401
5	0.40	41.43	21.45	19.98	0.0025	0.05	0.405
6	0.40	41.60	21.45	20.15	0.0025	0.05	0.401
7	0.40	41.49	21.46	20.04	0.0025	0.05	0.403
8	0.40	41.54	21.46	20.09	0.0025	0.05	0.402
9	0.40	41.55	21.47	20.08	0.0025	0.05	0.403
10	0.40	41.48	21.48	20.00	0.0025	0.05	0.404
11	0.40	41.60	21.47	20.14	0.0025	0.05	0.401
12	0.40	41.43	21.47	19.96	0.0025	0.05	0.405
13	0.40	41.62	21.46	20.16	0.0025	0.05	0.401
14	0.40	41.48	21.47	20.01	0.0025	0.05	0.404
15	0.40	41.70	21.47	20.23	0.0025	0.05	0.400
16	0.40	41.56	21.43	20.13	0.0025	0.05	0.402
17	0.40	41.61	21.42	20.19	0.0025	0.05	0.400
18	0.40	41.60	21.39	20.21	0.0025	0.05	0.400
19	0.40	41.53	21.38	20.14	0.0025	0.05	0.401
20	0.40	41.62	21.37	20.25	0.0025	0.05	0.399

AVG		41.54919167	21.43937				0.4020