DEVELOPMENT OF ON-SITE MIXED MORTAR WITH HYDRATED LIME FOR PLASTERING

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A project report submitted in partial fulfilment of the requirements for the award of the degree of Bachelor of Science (Hons) Construction Management

Faculty of Engineering and Green Technology

Universiti Tunku Abdul Rahman

May 2019

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

I certify that this project report entitled "**DEVELOPMENT OF ON SITE-MIXED MORTAR WITH HYDRATED LIME FOR PLASTERING**" was prepared by **LEONG JIA YIN** has met the required standard for submission in partial fulfilment of the requirements for the award of Bachelor of Science (Hons) Construction Management at Universiti Tunku Abdul Rahman.

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Specially dedicated to my supervisor, Dr Kwan Wai Hoe for his inspiration, guidance and supervision. Besides, dedicated to my beloved family and friends for supporting me in completing this thesis report.

ACKNOWLEDGEMENTS

I am here to express my gratitude to the parties who assist and guide me to complete this thesis report. First and foremost, I would like to extend my thanks to my project supervisor Dr. Kwan Wai Hoe for guiding me and providing precious and priceless advice, supervision, information and instruction throughout this research.

Besides, I would like to express my gratitude to my loving family and friends for supporting me physically and mentally and their encouragement along the development of this project. Lastly, special thanks to all the lab staffs that had helped and guided me throughout this research. I really appreciate all of their contributions for me in order to get this project done successfully and on time.

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ABSTRACT

Hydrated lime is a lime powder which contain mainly calcium hydroxide $Ca(OH)_2$ which produced from the limestone. As the calcium hydroxide will undergoes carbonation and will absorb carbon dioxide in the air, therefore, it may reduce the usage of cement if replacement of cement with hydrated lime is suitable to achieve particular purpose. Recently, there are many defects arising from cement-based mortar and lime-based mortar in construction industry, including the insufficient knowledge on producing an optimum ratio of cement-lime mortar has led to several issues in the industry, therefore, a research on cement-lime mortar has to be well-investigated. In the research and in order to fully utilize the hydrated lime, an optimum cement lime ratio has been determined and a deep understanding of its mechanical properties, durability performance and early-age behaviour on the replacement of cement with hydrated lime have to be studied. In current research, a series of engineering properties tests were carried out, including compressive strength test and density test. Water absorption test, capillary absorption test were carried out to study the properties of the mortar in term of durability. Results showed that the replacement of the cement with hydrated lime decreased the compressive strength of the examined specimens and also undermine the mechanical properties and durability properties of the structure. However, the mortar with hydrated lime provided a better surface and sense of touch when the optimum level of mortar was applied to the prototype. The mortar had greater adhesiveness and provided a smoother and aesthetic surface.

Keywords: Hydrated Lime, Replacement, Engineering Properties, Durability Properties, Porosity

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LIST OF SYMBOLS AND ABBREVIATIONS

%	Percentage
℃	Degree Celsius
g	Gram
kg	Kilogram
m	Metre
mm	Millimetre
mm^2	Millimetre Square
μm	Micrometre
nm	Nanometre
min	Minute
MPa	Megapascal
N	Newton
kg/m^3	Density
kN	Kilo Newton
cm^2/g	Square Centimetre per Gram
g/cm	Gram per Cubic Centimetre
N/mm^2	Newton per Millimetre Square
Al_2O_3	Aluminium Oxide
CaO	Calcium Oxide
$Ca(OH)_2$	Calcium Hydroxide
$CaCO_3$	Calcium Carbonate
CO_2	Carbon Dioxide
Fe_2O_3	Iron Oxide
H_2O	Water
MgO	Magnesium Oxide
SiO_2	Silica / Silicon Dioxide
C_3S	Tricalcium Silicate

BS	British Standard
BET	Brunauer–Emmett–Teller
CEM	Cement
C-S-H	Calcium Silicate Hydrate
EDX	Energy Dispersive X-ray
OPC	Ordinary Portland Cement
PC	Portland Cement
SEM	Scanning Electron Microscopy
SCT	Standard Consistency Test
STT	Setting Time Test
XRF	X-ray Fluorescence

CHAPTER1

INTRODUCTION

1.1 Research Background

Construction industry is a large sector of industry which affected the development and growth of the country's economy. According to Construction Industry Review and Prospect 2016/2017 report, it stated that construction sector contributed 4.5% of national GDP in Malaysia. Under the Eleventh Malaysia Plan(11MP) , the construction industry is expected to expand by 10.3% and to contribute about 5.5% to the economy yearly until 2020. Not only that, it is irrefutable that construction industry with high expenditure has become one of the important factors which contributed to the positive development in manufacturing sectors. (Construction Industries Review 2016/2017, 2016)

Although construction industry is one of the main factors which enhances the growth of economy in every country, but there are actually a lot of controversial issues arising within this industry. The examples are the delay in handover of projects, the defects of the building after work done, the disputes among parties and etc. According to the data in Malaysia, the construction materials are one of the contribution factors to building failures and defects with highest index of 0.982. Construction material is vital because the materials being used in this industry will determine the behaviour of the structure and resulted in any types of negative impacts in few years' time. Maybe the defects and failure will not be seen in a year or two, but it may slowly begin to spread like a cancer in the concrete.(Ahzahar, Karim, Hassan, & Eman, 2011)

The resource that used for building materials is a crucial issue that affecting the performance, value and also life span of the building. For example, the uses of different materials as binder in the formation of mortar for plastering will have different strength and weakness in term of physical properties and durability. In this case, it may directly lead to deterioration of mortar and further increase the maintenance costs of the building. Hence, choosing a suitable material for plastering mortar is the potential topic for research.

Generally, mortar is a bonding agent which is formed by mixing binding material or cement with fine aggregate (surki, sand, saw dust etc.) and water. Cement is the necessary material for mortar which acts as binder and gives the bonding strength. But there are some defects arising in the use of conventional cement based mortar and the demand of cement keeps increasing all over the time so that, some researchers had found out that some materials which available in local that could be a replacement material for cement in formation of mortar.

Lime is one of the cement replacement materials in the formation of mortar (Holland, Nichols, & Nichols, 2014). According to Looney and Pavia (2015) , they stated that hydrated lime enhances the water retention and workability of Portland cement mortar(Looney & Pav, 2015). Not only that, it enables the construction industry to make full use of resources, leading to enhance project's efficiency and productivity and saving material cost. This research elucidating the use of hydrated lime will enhance the performance and the knowledge on cement-lime mortar.

1.2 Problem Statement

Construction industry acts as an emblem and economic status of the particular country. According to the report of Edwards, he stated that there are approximate 2.49 Billion tonnes of cement produced annually all around the world. It has showed that the construction industry is totally influenced by the supply chain of cement.

In fact, conventional mortar (cement based mortar) has greater water resistance, and it is also suitable to use in outdoor construction. However, due to its higher sand:cement (S/C) ratio and water:cement (W/C) ratio, there are several disadvantages in the use of cement mortar, such as greater bleeding and poorer water retention(Wang, He, & He, 2018). According to Sandin(2005), lime mortar is more easier to work than cement mortar. Due to this reason, more water is added to compensate more cement. This resulting in the mortar has high shrinkage and too strong which increase the risk of cracking and flaking of the plaster. Besides the increasing of the cement also increases the impermeability of the plaster which lead to the plaster need longer time to dry. However, lime mortar has high water retention value, but it has poorer water resistance, lower strength and easier weathering compared to cement based mortar; it also has poorer durability as it is easy to deteriorate under freeze–thaw cycles and dry wet cycles, (Wang et al., 2018).

Lastly, although most of the contractor or sub-contractor knew that partially substitute hydrated lime as cement replacement material will enhance the performance of the mortar for plastering, but they have insufficient knowledge on cement-lime mortar, for instance, the optimum cement-lime ratio which gives the better performance on plastering. This will lead to wastage of materials and cause defects on the plaster if the cement-lime ratio is not properly mixed. Therefore, substitution of hydrated lime in cement mortar is a better alternative way for the advantage of longer initial setting time, greater mechanical properties and durability performance.

1.3 Aim and Objectives

The aim of this research is to develop a ready mixed mortar by adding hydrated lime which enhances the mechanical properties and durability. In order to achieve the aim, measurable and related objectives expressed as follows:

i.) To develop an optimum cement-lime ratio mortar for plastering on prototype.

ii.) To determine the durability performance and mechanical properties of cement mortar with hydrated lime.

1.4 Scope of Study and Limitation

The scope of study for this research is to develop an optimum cement-lime ratio ready-mixed mortar by adding hydrated lime as partial cement replacement materials compare to conventional cement mortar. The dosage of hydrated lime is the independent variable for this research to study the effect of partially substitute hydrated lime in cement mortar in term of mechanical properties and durability performance. The setting time and properties, mechanical properties and durability performance of cement mortar with hydrated lime will be determined in this research by carrying out several laboratory tests.

A trial mix will be carried out to determine the optimum mix proportion in order to produce the mortar which will give the better performance. The plastic state of mortar will be tested by using flow table test. Meanwhile, compressive strength test, water absorption test, density test, porosity and gas permeability test will be carried out for testing the performance of hardened state of mortar. The density test, compressive strength test, porosity test, and permeability test and will be carried out at 3, 7, 14 and 28 days of curing age while the water absorption test and capillary absorption test are carried out only at 28days of curing age. Last but not least, the standard consistency, initial and final setting time for all mortars must be determined by using Vicat apparatus.

The major limitation of this research is material specification and compositions are not verified by any testing. The real chemical composition and specification of hydrated lime are not tested and verified due to lack of equipment and time, so that the information given by the supplier may not as accurate as what the hydrated lime contains. Besides, the curing of mortar cube is a time constraint. The process of mortar cube curing is not suggested to speed up in order to eliminate all the other factors which may lead to inaccurate results. Although the curing process of mortar cube can be accelerated by increasing the curing temperature, but it may leads to plastic cracks not only on the surface of concrete, it will also affect deeper inside of the mortar mass. This will directly affect the strength of the concrete. Due to lack of time, the tests for all the specimens are carried until the curing age of 28 days only. The result will be more reliable and accurate if the curing age of concrete has been extended until 56days. Lastly, the specimens' stability is also one of the limitations of this research. As the heating element in the oven had broken, the maximum temperature can be used is 70°C instead of 105°C. Therefore, the water or moisture in the specimens may not completely dry until they reach the specimens' stability.

1.5 Significant of Study

Deterioration of concrete or mortar has caused a lot of negative impacts to building structure and also the users. Cracking, shrinkage and shedding of plaster are the examples of mortar deterioration. All of these deteriorations may lead to unpleasant appearance and it may fail to perform its primary function that to prevent the penetration of chemical substances which may attack the wall. Due to the negative impacts of the deterioration of mortar, it is a must to enhance the performance and mechanical properties of mortar.

According to Holland et al. (2014), there is a potential of future research on the study of physical changes in durability of reinforced concrete made with lime rich mixes when compared to normal Portland cement based concrete, such as permeability and crack propagation. In this research, hydrated lime will be added into mortar as cement replacement material to discover the mechanical properties, durability and performance when react with the cement paste. A better quality and performance of cement-lime mortar is expected in this research. Ultimately, the building structure has a longer life span, reduces the defects and gives an artistic appearance. Apart from producing a good quality of mortar, use of hydrated lime as cement replacement material can directly increase the productivity of the labour and reduce the cost that used to maintain or replace the wall finishes in the future.

Therefore, the significant of this research is to develop an optimum cement-lime ratio of ready mixed mortar with hydrated lime in the market which enhances the mortar’s durability, mechanical properties and performance. Furthermore, current research is to investigate how the hydrated lime affects the mortar on both exterior wall and interior wall. Not only that, although hydrated lime is one of the common material in construction industry, but there is still not much research on adding hydrated lime as cement replacement material in mortar.

1.6 Organisation of Study

This research includes five chapters which are introduction, literature review, research methodology, result and discussion and conclusion and recommendation.

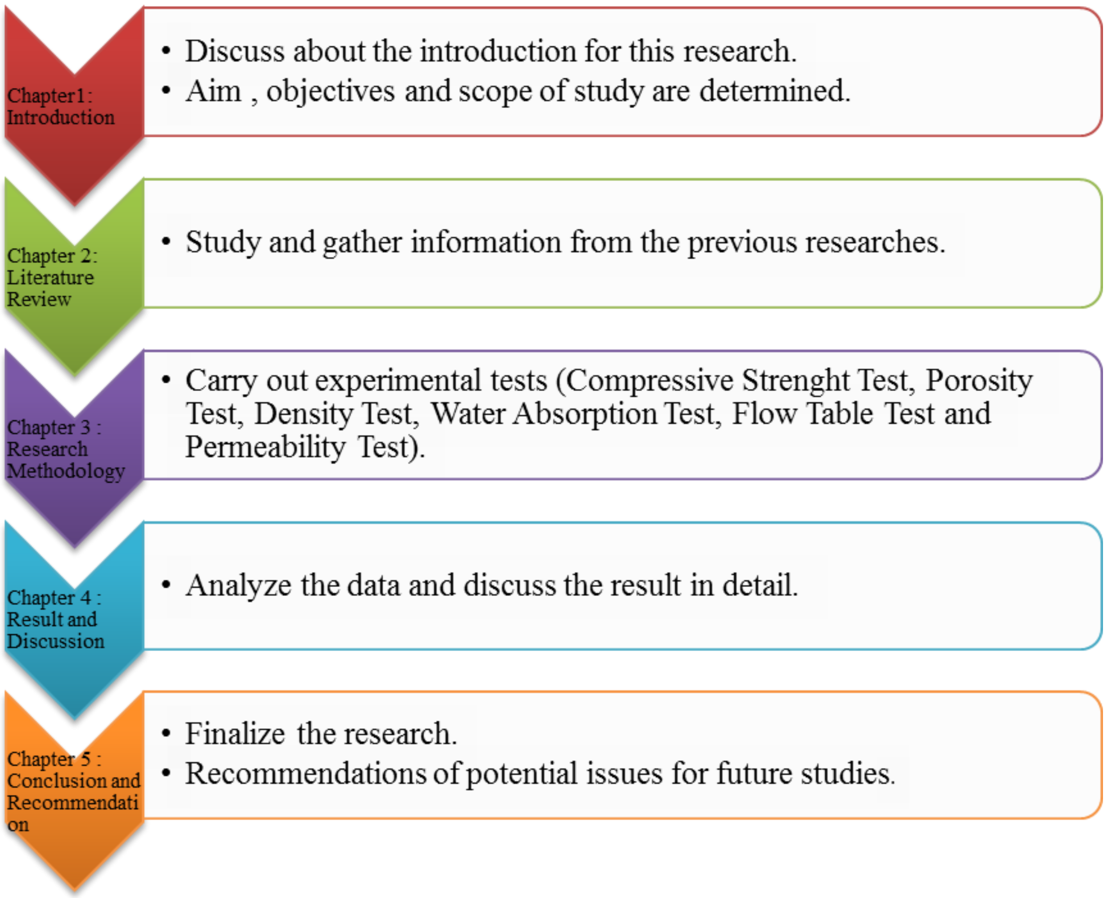

Figure 1.1: Organisation of Study

1.7 Research Framework

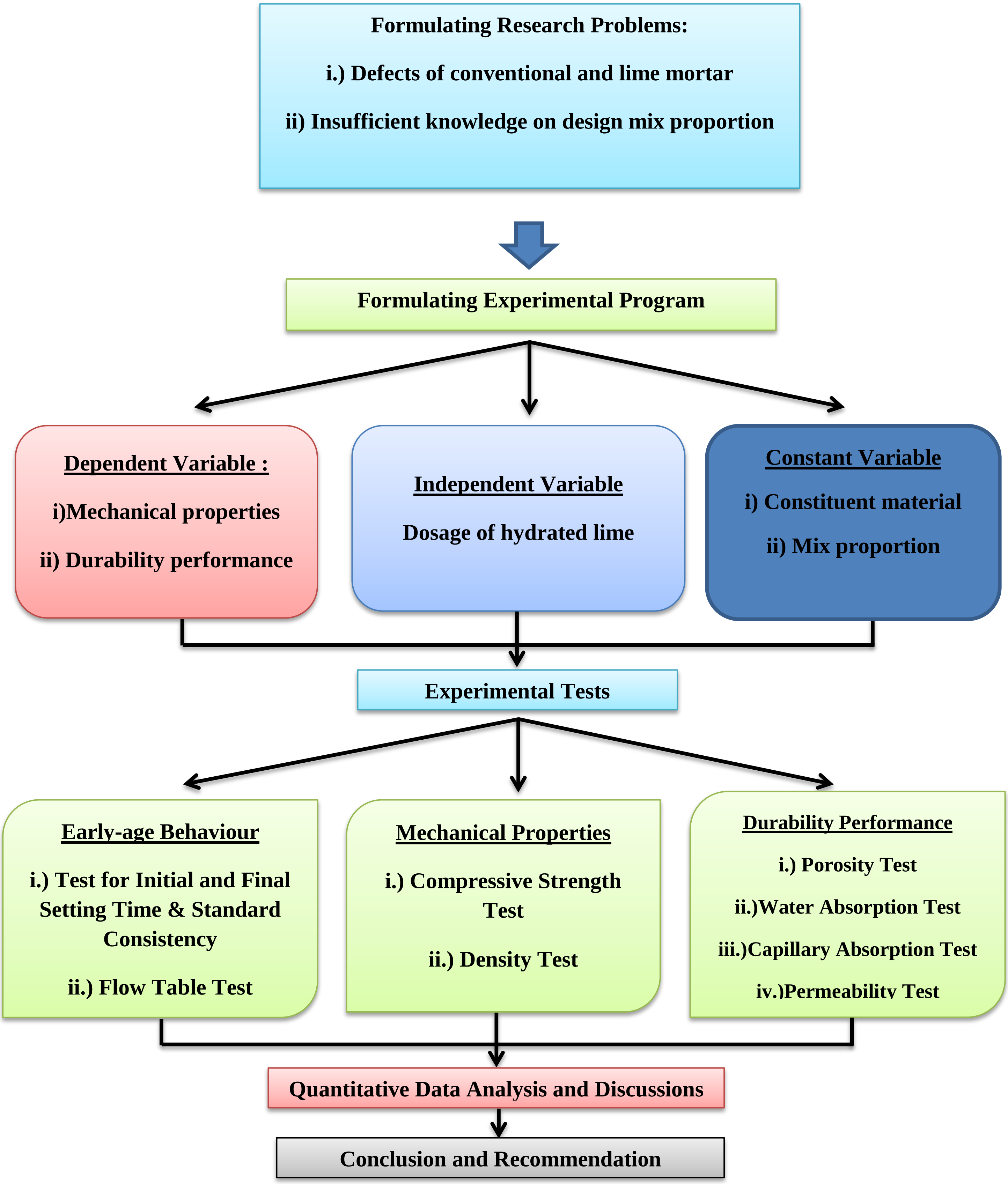

Figure 1.2 : Research Framework

CHAPTER2

LITERATURE REVIEW

2.1 Introduction

Cement is indispensable to construction industry. However, there are some defects if cement is used as the only binder in concrete and mortar and also the price of the cement keep increasing with the demand in the construction industry. In the past few years, there are some researchers tried to look for suitable materials as part of substitute of cement in the concrete and mortar in order to reduce the use of cement which will enhance the performance of the mixed concrete and mortar and also directly affect the profitability of certain project.

This chapter mainly review the study of hydraulic lime and its properties. Composition and properties of concrete and mortar after adding the hydraulic lime are to be discussed and explained in this chapter. Moreover, the previous researches on how the different cement-lime ratio affects the performance of mortar are studied.

2.2 Mortar

2.2.1 Background

The oldest mortar that still survives is that found in Galilee, Israel, near Yiftah'el, which is said to be 10000 years old. The Egyptians are said to construct the pyramid by using the gypsum mortar and lime mortar (Newman & Choo, 2003)

Nowadays, the term of "mortar" is used to describe a paste produced by adding a essential amount of water to a mixture of binding material like lime or cement and fine aggregate (Gopi, 2009). Mortar is made by mixing lime paste, cement, water and sand proportionally. Building mortar is categorized into cement-lime mortar, cement mortar, gypsum mortar, lime mortar and so on according to the different materials adopted in it(Li & Ren, 2011).

Finishing mortar which known as plastering mortar which is used to plaster the surface of structures of building and structural components. It also aims to protect the satisfying operational requirements, substrate and improving aesthetic appearance. However, in terms of improve the workability of mortar and reduce the cement consumption, certain amount of lime, clay or gypsums is added during the mixing of mortar(Li & Ren, 2011).

2.2.2 Components of Mortar

In plastic state of fresh mortar, it must have good workability, water retention ability and sufficient stiffness. The properly designated components should provide high workability and adhesiveness, workability and ease of application as well as spasmodic resistance(Spychał, 2015).

2.2.3 Workability

Workability is defined as the nature that concrete mixtures, where in certain constructional conditions, it is easier to operate to produce a good quality concrete, which is more even and dense(Li & Ren, 2011). The reduction of workability can potentially lead to more voids in mortar joint which in turn allows more water to penetrate through itself (Newman & Choo, 2003). A poor workability mortar will lead to a risky job which can results the dropping off of plaster(Sandin, 1995).

2.2.4 Adhesion

Good adhesion is always necessary for the rendering to function, and this is established at the moment of application. The mortar must make complete contact with the background. If this is not achieved, there is no prospect for satisfactory adhesion. For rendering the strength of the mortar is usually not important, but good adhesion is an essential requirement. Adhesiveness depends on the qualities of the fresh mortar. High internal tension during curing leads to great stress in the contact area.

2.2.5 Fluidity

The fluidity of mortar, also called “consistency”, is defined as the performance of flowing motion created by external force or its self-weight. Mortar consistency differs along with these factors: the amount and the types of the adopted cementing material, the amount of water consumption and the amount of mortar itself. The consistency of masonry mortar mainly depends on the type of block, condition of construction and weather condition.(Li & Ren, 2011)

2.2.6 Water Retention

The water retention or water retentivity is a role of the ability of plastic state of mortar to resist the suction of an absorptive substrate. It is inversely proportional to the amount of water removed or the ease with which water is removed by substrate suction (Newman&Choo,2003). According to Li & Ren (2011) , they stated that "water retention" is referring to the ability of newly-mixed mortar to retain its internal water from leakage loss(Li & Ren, 2011). This property avoids the bleeding or "water loss" to the substrate by suction. If not, as the substrate absorb excessive water from the mortar, it will induce insufficient hydration of cement and make the mortar loss of mechanical performance(Patural et al., 2011). At last, a good mortar must have long broad life and greater water retention in plastic state to allow the mason has sufficient time to spread the mortar before initial set occurs (Nawy, 2008).

The requirements for a hardened mortar may be shortened and expressed in the form of strength and stability, durability and appearance. Strength and Strength Level Mortar takes compressive strength as its strength index. Sufficient compressive strength is needed by a mortar to resist the applied load (Newman & Choo, 2003). To a water absorbing substrate, mortar strength mainly depends on the strength and amount of its cement content. Different from masonry mortar, the main technique requirement of plastering mortar is not strength, but workability and the binding force with the base material. (Li & Ren, 2011) Besides, the long-term durability to meet the exposure condition in which it will be used is one of the important criteria for a good mortar. According to Hossain et al (2016), they stated that there are many properties are included in the term of durability. For instance, weather resistance, acid resistance , corrosion resistance and so on(Hossain et al., 2016).

2.3 Plaster

Plastering is one of the most ancient building techniques in the world. One of the building that build up using this technique was the Pyramids of Egypt, which contain plasterwork executed at least 4,000 years ago that is still hard and durable. The principal tools of the plasterer of that time were in design and purpose like those used today. For their finest work the Egyptians used a plaster made from calcined gypsum that is identical with plaster of Paris (Emma,2015).

Plaster is a composite, not homogeneous material (a mortar) applied in thin layers (often few millimetres) to cover the masonry(Toniolo, Paradisi, Goidanich, & Pennati, 2011). After the mortar mixture which composed of filler, binder and some special additives become harden. It classified as a medium of artistic expression waned by the 19th century, when imitation and mechanical reproduction displaced this creative art. As a surface material for interior walls and ceilings and to a lesser degree for exterior walls, plaster remains in common use. It facilitates cleanliness and sanitation in building and is a retardant to the spread of fire.(The Editors of Encyclopeadia Britannica,2008)

Table 2.1 : Various Mortar Compositions for Different Plastering Work (Gopi, 2009)

Plasters	Mortar composition recommended
i) External plasters below damp proof course	1 cement : 1 lime : 6 sand
ii) External plasters on all walls	1 cement : 2 lime : 9 sand
iii) Internal plasters on all walls	All mixes are suitable

Table 2.1 shows that the various mortar compositions for different plastering work. Different plastering work has to use different composition of mortar in order to meet the requirements of certain work. For a normal and good plaster, it should meet some essential requirements in order to performance its functions as an important part of a building.

According to Gopi (2009), there are few major requirements of plaster to be achieved to produce a high quality of plaster, which are adhesiveness, durability, workability (Gopi, 2009). A good plaster should adheres to the background and remain adhered during all climatic changes. The adhesiveness will directly affect the durability of the plaster. Due to this reason, the plaster must has reasonable weather resistance, wear resistance and others ability to ensure the adhesiveness of the plaster can be maintained. Not only that, the workability of plaster is important in increasing task efficiency and productivity.

However, the construction industry are not aware of the required layers that applied on the wall and usually do not understand that continuing to render layer over layer is not a great choice as all this activities will lead to cracking of the plaster. Although a layer of render is not heavy, but it is different story that if there are up to three or more coats. This will lead to the cracking of plaster as the result of the plaster cannot sustain itself when the weight increases. This phenomena occurs deep inside the internal plaster itself and it is different from the cracked external render. (Emma, 2015) If the water get into the crack and reach the wall, it will lead to the plaster flaking off from the wall.

2.4 Hydrated Lime

Centuries ago, lime has been used as a construction material in mortars and plastering since ancient times. Limestone was calcined using furnaces adapted to the characteristics of each region. In the same way, lime slaking was diverse and led to lime putties with different properties. In the past few years, the implementation of cement has reduced the usage of lime in construction work. However, lime is still the major materials to be considered in restoration works because mortar mixed from lime provide better compability with the tradition materials, like stone and masonry compare to polymeric material and cement. The lime quality has been traditionally related with factors such as the origin and method of calcination of the limestone, the nature of the process of slaking or the lime putties' age.(Rosell, Haurie, Navarro, & Cantalapiedra, 2014). Figure 2.1 shows the general lime cycle.

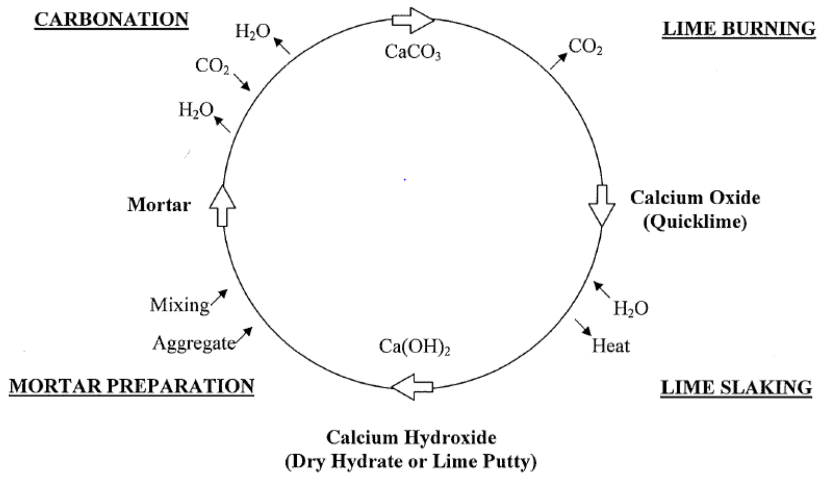

Figure 2.1 : Lime Cycle (Edwards, 2005)

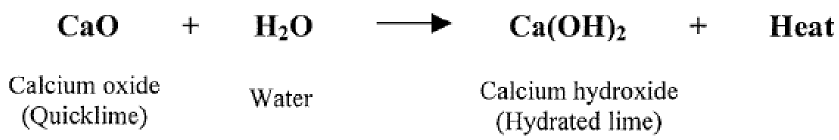

Figure 2.2 : Slaking reaction to form hydrated lime(Edwards, 2005)

Hydrated lime traditionally known as slaked lime, it has the chemical formula of $Ca(OH)_2$, it is the value added downstream product of quicklime. According to Lyons(2010), the process of production of hydrated lime is through the addition of water to quicklime in dry powder state which the process is named as “slaking of lime’(Figure 2.2). It is a highly exothermic reaction as it releases high amount of heat. Generally, it is suitable for use within mortars or in manufacturing of certain aerated concrete blocks.

Table 2.2 : Chemical Composition of Hydrated Lime

Chemical composition , %	(BORAL CEMENT, 2012)	(Zumrawi, 2014)	(Sébaïbi, Dheilly, Beaudoin, & Quéneudec, 2006)	(Sengul, Aksoy, Iskender, & Ozen, 2012)
$Ca(OH)_2$	>88	65	97.4	82.04
CaO	>70	48	74.2	85.78
$CaCO_3$	-	3.5	-	-
Fe_2O_3	<0.3	0.7with Al2O3	0.06	-
MgO	<0.8	1.5	0.70	3.52
SiO_2	<1.3	5.2	0.10	-
Al_2O_3	0.4-0.8%	-	0.08	-
Loss of ignition	26	-	28.8(1000c)	22.51
Others	3	-	<0.01	7.24
Density, kg/m³	450-500	-	-	472

According to Oliveira et al, hydrated lime is mainly composed of calcium oxides (CaO) or calcium hydroxides [$Ca(OH)_2$]and smaller fractions of magnesium oxides. But the hydrated lime may have a different chemical composition compare to other due to different raw materials where the original limestone form. This kind of lime confers water retention and workability properties to the mortars when in the plastic state. Although water retention is related to the reaction times of mortar hardening and the degree of hydration of the cement, maintaining the plastic state of the mass, workability is related to the consistency and plasticity of the mortar.(Oliveira et al., 2015) Hydrated lime particles have a large specific surface area, and the surface of the particles can absorb a thick layer of water film, so that the particles of the fresh mortar mixture are liable to slip, thereby increasing the water-holding capacity and plasticity of the mortar, and the mechanisms were done(Wang et al., 2018).

The mechanical strength of hydrated lime immediately after it is applied to a wall is not very high. However, hydrated lime has several highly desirable properties as a construction and building material, such as aesthetic appearance, antimicrobial capability (inactivation of avian influenza virus), and high humidity control. So far, since calcium hydroxide (slaked lime) is thermodynamically unstable phase in air, fabrication of the hardened body of pure phase of slaked lime has not been employed. However the carbonization of slaked lime takes a long time, therefore the dense body of slaked lime is expected to be used as not only tiles but also daily use construction ceramic materials such as furniture(Hashimoto et al., 2016).

2.5 Effect of lime as partial cement replacement material in concrete or mortar

The addition of lime to cement sand mixtures results in an overall improvement in almost all properties; these are manifested in the increase in bond strength as well as water retention and enhancement of compressive strength. In these types of mixtures, cement provides early strength, consistency of hardening rate, while the presence of lime improves water retention, plasticity and workability.

2.5.1 Workability

The workability is one of the physical parameters of concrete and mortar in plastic state which will affects the strength and durability and the appearance of the finished surface. The workability of concrete depends on the water cement ratio and the water absorption capacity. If the water added is more, it will lead to bleeding or segregation of aggregates. In the cement-lime mortar, lime is the primary contributor to workability of cement-lime mortars. According to the study of Looney and Pavia (2015), the results indicated that the use of lime delivered PC mortars with superior workability and surface finish and a lack of segregation and bleeding. However, the lime content must be added in a suitable portion instead of excessive of lime content which will lead to degradation of the mortar.

2.5.2 Water Retention

Water retention is essential so that the mortar remains workable and retains enough water for proper curing and bonding. Some previous studies have proven that increase of lime-cement ratio will enhance the water retention of mortar.

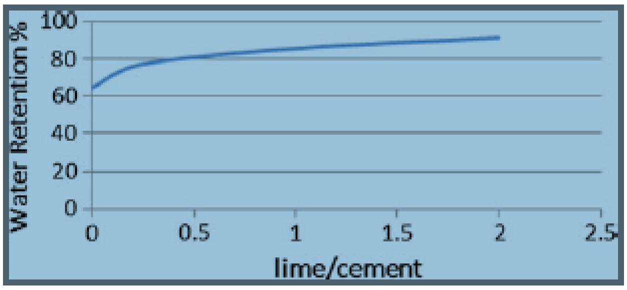

Figure 2.3 : Water retention against lime content (Pavia & Brennan, 2019)

Figure 2.3 indicated the effect of different lime-cement ratio on the water retention of the mortar in plastic state. The increase of lime content will enhance the water retention ability of the mortar. This result agreeing with the previous study (Looney&Pavia,2015). According to Looney & Pavia (2015), it reported that mortars containing lime showed the highest water retention. Not only that, the greater the lime content, the greater the water retention within the mortar. This is because the water retention is a function of the amount of free lime.

2.5.3 Air content

In the year of 2013, Lenart came out with the result on the same aspect of the mortar. The result showed that fresh mortar with the increase of lime content in cement-lime mortar will reduce the percentage of air. Pavia and Brennan (2019) had investigated that the Portland Cement mortar without lime had highest level of air content. Lime addition up to a 1/1 ratio (Portland Cement/lime) reduced air content. The increasing of lime/cement ratio will directly increase the air content. This supports by previous studies that noted the addition of hydrated lime reduces the air content (Schuller et al. 1999; Sugo et al. 2001). However, research has shown the bond strength will be significantly reduced as the increasing of air entrainment.

Tate(2005) has found that if mortar air content is increased from 5% to 20%, a 79% decline in mortar bond strength results(Tate, 2005).

2.5.4 Flexural and Compressive Strength

Flexural and compressive strength are the essential requirements for a mortar, but both of them are not as important for a plastering/finishing mortar as the plaster is not required to withstand the main loads. Although they are unimportant, but they still need to achieve the minimum requirement for the flexural and compressive strength after the partial replacement of cement by hydrated lime. In the past few researches, some of the researchers stated that the addition of lime in cement mortar will reduces the compressive and flexural strength while some stated that it will enhances both strength of mortar.

Table 2.3 : Compressive Strength and Flexural Strength of different cement-lime ratio mortar(Lenart, 2013)

Type(Cement:Lime:Sand ratio)	Average Flexural Strength(MPa)	Average Compressive Strength(MPa)
D(1:0.25:3)	3.8	16.5
E(1:0.5:4)	3.2	12.7
F(1:1:6)	1.7	5.3
G(1:2:9)	0.7	2.0

In the year of 2013, Lenart stated that the increase of the lime content in the cement mortar will reduces both compressive and flexural strength. This statement is later agreed by the study of Pavia and Brennan in year of 2015 and 2019(Lenart, 2013).

Table 2.4 : Compressive Strength and Flexural Strength of different cement-lime ratio mortar(Pavia & Brennan, 2019)

Cement:Lime:Sand Mix Proportion	Compressive Strength, (N/mm2)	Flexural Strength, (N/mm2)
1:0:6	9.82	3.48
1:0.25:6	12.67	4.39
1:1:6	5.98	2.14
1:2:6	2.65	0.88

According to Pavia and Brennan,(2019), they reported that the effect of added lime on the strength of cement mortar is deeply dependent on the quality added. From their research, the low lime content mix(1:0.25:6) is the strongest in both flexural and compressive strength while the high lime content(1:2:6) is the weakest. Besides, the increase of lime added to the cement mortar will decrease the compressive and flexural strength of mortar.

2.5.5 Hardened Surface Finish

The appearance surface of the mortar should be smooth and artistic to the user especially for the finishing mortar for plastering which provide a platform for paint coating. In the studies of Looney and Pavia (2015), the Portland Cement mortar(right) showed an acceptable surface finish with dark colour and minimal cavitation while the mortar containing lime show a smooth surface with no cavitation and it is light in colour.

Figure 2.4 : Surface finish (from left to right) PC-lime;plasticised;PC mortars (Looney&Pavia,2015)

2.5.6 Bond Strength

According to Tate (2005), bond strength between mortars and masonry units is the most significant physical property of the masonry. Tensile bond strength is the capability of the mortar to hold the masonry units together and to withstand the force that tries to pull them apart. There are few plastic mortar characteristics which can enhance the tensile bond strength:

- High water retention in cement-lime mortar, which enables the early curing of the cementitious materials. The binder combines with water chemically to produce the crystals that make mortars become hardened. Water promotes the reaction between lime and carbon dioxide(CO_2), which results in formation of calcium carbonate.
- High initial flow and workability, which enables easy complete coverage of masonry units
- Cement-lime mortar with low air content has higher bond strength. This is because the air bubbles trapped at the interface between the mortar and masonry unit will inhibit the formation of good mechanical keys between the two materials. The amount of air-entrainment needed is minimal since the lime is water retentive.

There are a lot of studies that proved the superior bond strength of cement-lime mortars. Most of the studies concluded with cement-lime mortars were substantially higher than that in similar prisms constructed with mortar of other cementitious materials.
Besides, testing performed by the Brick Industry Association on assemblages made of bricks of low, medium and high rates of absorption also demonstrated that cement-lime mortars were able to provide outstanding bond. For masonry units having higher rates of absorption, cement-lime mortars can be performed well without pre-wetting the brick(Tate, 2005).

In the studies of Pavia and Brennan, the results suggested that low lime addition enhances bond strength of Portland Cement mortar: the 1/0.25/6 mortar bond is 16% greater than the 1/0/6 bond and approximately 30% and 70% larger than the 1/1/6 and 1/2/6 bonds respectively. This agrees with previous studies which show that addition of lime enhances bond strength of Portland Cement mortars(Pavia & Brennan, 2019).

2.5.7 Porosity

Pore structure and surface fractal dimension which acts as an indicator of pore structure are also evaluated. The moisture transport and capillary absorption are influenced by the pore structure within the mortar and they are the factor which will affect the degradation, durability and service lifespan of building materials.

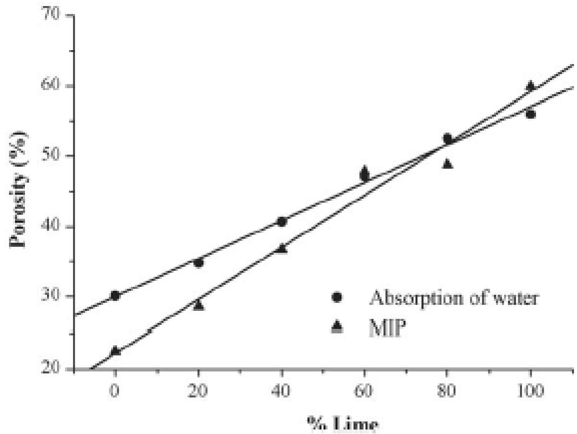

Figure 2.5 : Porosity against Percentage of Lime Content(Arandigoyen & Alvarez, 2006)

According to Arandigoyen & Alvarez (2006), they found that the porosity of the mortar will increase with the increasing of lime in the paste. This is due to the completion of hydration of calcium silicate with the presence of lime which leads to decrease of the dense particle resulting with a more homogenous porosity. This is proven in their next study in year of 2007.

In the previous research, they stated that the size of calcite crystal and the W/B ratio influenced the microstructure with good homogeneity. The formation of amorphous calcium silicate hydrate gel (C-S-H) of cement creates irregular morphology within the structure.
As the hydrated lime mixes with the cement, the amorphous of irregular morphology of C-S-H and calcite crystals mixed together with variety of shapes. A clear difference in morphology between the lime pastes and the hydrated calcium silicates has been established. Therefore, the mixed pastes have a combination of both morphologies, which will be a function of the proportion between cement and lime. A more complete hydration takes place within the structure.

As the increase of hydrated lime, the dense particles (C-S-H) gel decreases accordingly. From the research, this is supported by that the amount of hydrated silicates decreases and vanishes almost completely in the 80% lime paste. The amount of these dense particles reduces with the increase of the hydrated lime, resulting in materials with a more homogeneous porosity. The low lime content mortar is heterogeneous with dense C-S-H while the high content lime paste is homogenous with higher porosity. (Arandigoyen & Alvarez, 2006) The statement is further supported by their study in the later year.

Porosity (%)		Cement/lime						
		0–1	1–8	1–4	1–2	1–1	2–1	1–0
B/Ag	1:2	23.06	22.14	22.44	22.59	22.39	21.86	20.91
	1:3	20.87	20.57	21.41	21.37	21.62	21.45	20.62
	1:4	20.41	19.16	21.03	21.46	21.47	21.17	20.49

Figure 2.6 : Porosity of Different Mortar(Arandigoyen & Alvarez, 2006)

2.5.8 Capillary Absorption Coefficient

The ability of capillary absorption of a structure is mainly due to the pores within the structure are well-interconnected. The difference of pressure inversely proportional to its radius when liquid is in contact with the capillary and then forcing the liquid get into the capillary. According to Arandigoyen & Alvarez(2006), they concluded that the higher the percentage of hydrated lime the greater the capillary in the mortar paste.

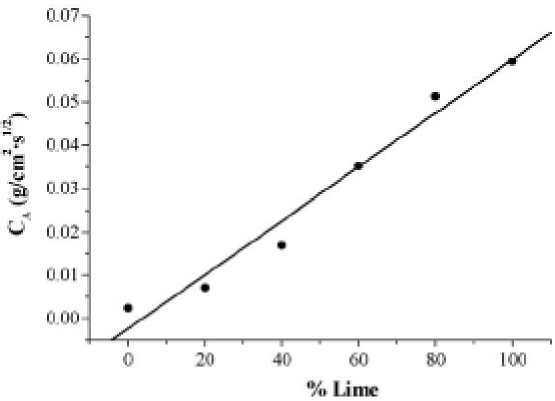

Figure 2.7 : Capillary Coefficient against Percentage of Lime in Mortar Paste (Arandigoyen & Alvarez, 2006)

The increasing of capillary coefficient as the increase of hydrated lime can be explained by considering the microstructure: pore size distribution and morphology. In high hydrated lime content cement mortar, a homogenous, high porosity and unique pore size are exist within the mortar and the pores has a good connectivity between themselves. Besides, high cement paste showed the problems for diffusion of liquids through the structure due to the pore size distribution is complex and contains pores with wider range. They concluded due to the gel nature of cement, the connectivity between pores of rich cement paste is not as good as in rich lime paste and the heterogeneous porosity along the material with dense particles owing to the cement that have to be surrounded by the fluid in its diffusion route, travelling a longer distance than the straight line.(Arandigoyen & Alvarez, 2006) Not only that, as the decrease of hydrated lime content in the mortar the decrease in pores size between 0.3 and 0.8 mircomm in a high degree accordingly while the new pores below 0.05 mircomm are discovered as the increment of cement in the paste.

2.5.9 Setting Time

There are two types of setting time of concrete must be measured which are initial setting time and final setting time. The concrete's initial setting time refers to the starting of hardening of the mixture while the concrete's final setting time refers to concrete mixture which gains sufficient hardness(Dave, Misra, Srivastava, & Kaushik, 2017). From the previous study, it shows that the addition of lime water will delay the initial setting time by about 28.57% in the cement paste. For the final setting time of the cement paste, it was delayed by14% from 245minutes to 215minutes. (Elaty & Ghazy, 2014) However, the setting time in cement-lime mortar with little amount of cement content is remarkably shortened as the carbonation predominates as the hardening process in the lime-rich mortar.

2.6 Summary and Conclusion of Literature Review

From the previous studies, a lot of researcher had found out that the hydrated lime is suitable to become a partial replacement material of cement in concrete and mortar. They have examined performance of concrete or mortar after adding hydrated lime by conducting few of experimental tests. Moreover, some of the researchers found that replacement with appropriate amount of cement by hydrated lime will significantly enhance the performance of the concrete or mortar in both plastic and hardened state. The mortar with 1:0.25 cement lime ratio will provides the greatest bond strength, flexural and compressive strength. Not only that, it has highest adhesive strength and lowest water absorption coefficient among other mortar with different cement lime ratio.

CHAPTER3

RESEARCH METHODOLOGY

3.1 Introduction

This research methodology is to design the experiment programs and the program flow for this research. All the materials used for the specimens will be discussed in this section as well as the experimental tests. Standard Consistency Test(SCT), Setting Time Test (STT), Compressive Strength Test, Flow Table Test, Density Test, Water Absorption Test, Gas Permeability Test, Porosity test and Capillary Absorption Test are to examine the early-age behaviour, mechanical strength and durability properties of the specimens. The experimental specimens will be casted after the conducting of trial mix.

3.2 Materials

The materials such as Portland cement, mining sand (fine aggregates), and water are essential materials used to produce conventional concrete and mortar. Moreover, hydrated lime is used as partial replacement material in the production of cement-lime mortar. The physical properties of the materials will be clarified in this chapter.

3.2.1 Ordinary Portland Cement (OPC)

Portland cement generally is grey fine powder which produced by calcining limestone and clay. It is used as binder which reacts with water in order to bind the ingredients together to form a hardened concrete and mortar. In this research, HUME Ordinary Portland Cement is used. This cement is certified to MS EN 197-1:2014 and CEM | 52.5N. It is manufactured by grinding Portland cement clinker and especially selected high quality limestone. Besides it is general purpose cement which is aimed to accomplish the designated strength with enhanced workability for concreting, bricklaying and plastering. This type high performance cement has higher fineness particles, thus resulting in better cohesiveness, water retention and other properties in mortar and concrete. The better workability will improve the execution of work which lead to less wastage of mortar and concrete and produce smoother finishing.

Figure 3.1 : Hume Ordinary Portland Cement

3.2.2 Fine Aggregate (Mining Sand)

In this research, size of the aggregate for mortar is determined by using sieve analysis. Mining sand can be known as fine aggregate which satisfying the standard of BS EN 13139: 2002 where particle size of sand is under 4.75 mm standard. The mining sand which used for this research was obtained from the workshop of UTAR. The mining sand will be cleaned to remove the impurities material like clay, dust and others in order to minimize the external factors which may influence the result in the future. After cleaned, the sand was also heated in order to eliminate the moisture in it.

Table 3.1: Sieve Analysis of Mining Sand

Sieve Size Range	Sieve Fraction		Nominal Aperture Size	Cumulative Undersize
mm	gram	% by mass	mm	% by mass
>4.75	0	0	4.75	100
4.75-2.36	86	8.6	2.36	91.4
2.36-1.18	214	21.4	1.18	70.0
1.18-0.600	204	20.4	0.600	49.6
0.600-0.300	390	39.0	0.300	10.6
0.300-0.150	82	8.2	0.150	2.4
0.150-0.075	14	1.4	0.075	1.0
<0.075	10	1	0	0
Total	1000	100		

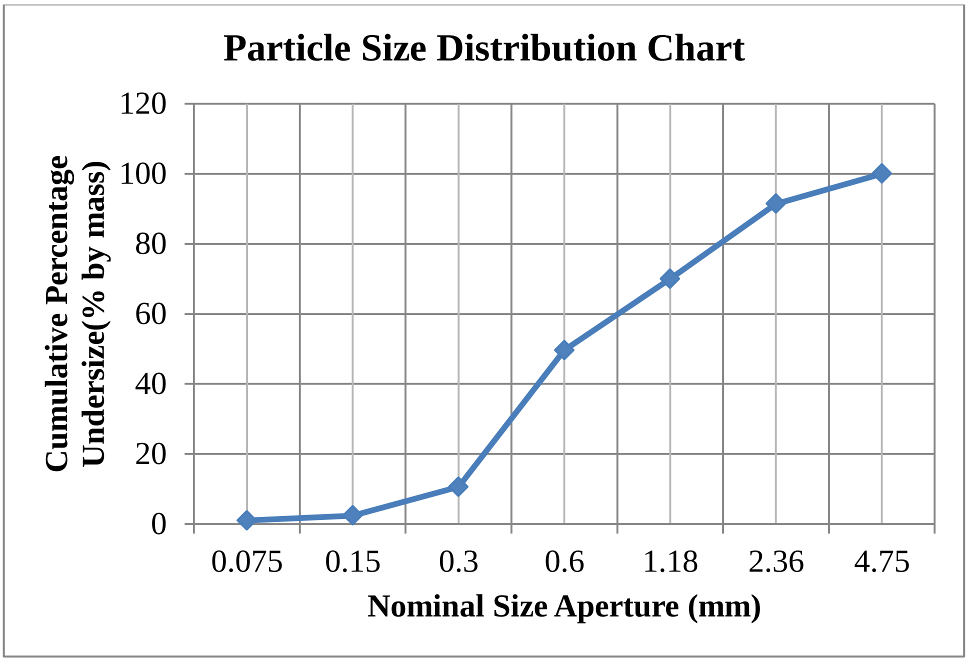

Figure 3.2 : Particle Size Distribution Chart of Mining Sand

3.2.3 Water

Water is one of the essential materials in mortar mixing process since it reacts with the cement to bond all the materials together within the mortar. So, the quality of water may affect the hydration of cement and the ultimate strength and properties of the mortar. In this research, all water that used in this research is the tap water. The water is observed in order to ensure the water is free of oil, polluted substance and impurities.

Figure 3.3 : Source of Water

3.2.4 Hydrated Lime

The hydrated lime was obtained from the MCB Industries in Taiping. It traditionally known as slaked lime with the formula of $Ca(OH)_2$. It is produced by introducing quicklime with sufficient water to convert the available oxides to hydroxides. The chemical compositions vary in the literature due to the raw materials for production of hydrated lime is different. According to the MCB Industries, hydrated lime contains minimum 91.0% of calcium hydroxide [$Ca(OH)_2$] , minimum 69.0% of calcium oxide [CaO] , maximum 3.0% of calcium carbonate [$CaCO_3$] , magnesium oxide [MgO] with maximum 3.0% and silicon dioxide with maximum 0.5%. Besides, it stated that 92.0% of the hydrated lime can be size through #200 Mesh (BS mesh).

Table 3.2 : Chemical Compositions of Hydrated Lime(MCB Industries Sdn Bhd)

Chemical Compositions	Weight (%)
Available $Ca(OH)_2$	Min. 92.0%
Magnesium Oxide (MgO)	Max. 2.0%
Calcium Carbonate ($CaCO_3$)	Max. 5.0%
Acid Insoluble Matter	Max. 5.0%
Fineness passing through 75microns (BS 200 mesh)	Min. 90.0%

Figure 3.4 : Hydrated Lime from MCB Industries Sdn Bhd

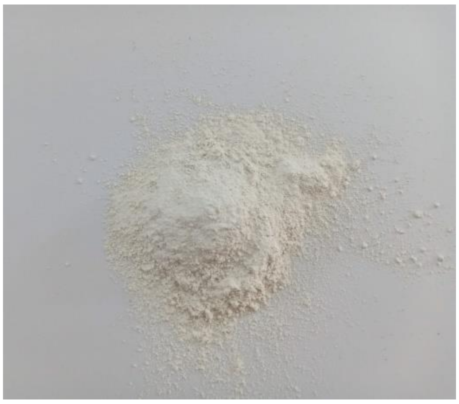

Figure 3.5 : Sample of Hydrated Lime Powder

3.3 Design Mix Proportion of Mortar

This research is to study the amount of hydrated lime as cement replacement material on the mortar for plastering. In order to determine and obtain an optimum cement-lime ratio which provides better mechanical strength and durability performance, a trial mix is conducted before casting of the specimens for this research. The cement sand ratio and the water binder ratio are remain unchanged which considered as the constant variable while the manipulate variable is the percentage of hydrated lime as cement replacement material in mortar. The cement sand ratio and water binder ratio are set as 1:3 and 0.6 respectively. There are total 6 mortar samples will be casted with increasing hydrated lime content of 0%,5%,10%,15%,20% and 25%. A few sets of trial mix were carried out to look for the optimum water binder ratio for mortar before 0.6 of water binder ratio was set as the constant variable for this research study. A few sets of trial mix with 0.5, 0.55 and 0.6 of water binder ratio were conducted and 0.6 of water binder ratio was found as the optimum water binder ratio which provided ideal workability and flexibility for the mortar in order to mix with hydrated lime.

Table 3.3 : Mix Proportion of Cement-Lime Mortar

Mix Code	**Cement (kg/m^3)**	**Water**	**Sand (kg/m^3)**	**Hydrated Lime (kg/m^3)**	**Hydrated Lime Replacement (%)**
L_0	**500**	**250**	**1500**	**0**	**0**
L_5	**475**	**250**	**1500**	**25**	**5**
L_{10}	**450**	**250**	**1500**	**50**	**10**
L_{15}	**425**	**250**	**1500**	**75**	**15**
L_{20}	**400**	**250**	**1500**	**100**	**20**
L_{25}	**375**	**250**	**1500**	**125**	**25**

3.4 Preparation, Casting and Demoulding of Specimens

All the ingredients like cement, sand, hydrated lime and water are weighted precisely by following the proposed plan. After that, all the ingredients are poured into the mixing machine and make sure that the mixture is uniformly and well mixed.

The steel moulds are fixed correctly and cleaned to ensure the moulds free from unwanted substances. A layer of demoulding oil is then applied on each steal mould to ensure the ease of demoulding with the intention to avoid the specimens from any damages. Next, the steel mould with fresh mortar is placed on the vibrating table to ensure the fresh mortar is well compacted in order to minimize the formation of air voids. After compaction, the specimen is then leave for hardening and setting at the room temperature for one day. Lastly, all the specimens are demoulded carefully and immersed into water for curing until the proposed curing age in order to carry out specific tests.

Figure 3.6 : Experimental Specimens with Different Level of Replacement of Hydrated Lime

3.5 Experimental Tests

3.5.1 Flow Table Test

The consistency and workability of fresh cement-lime mortar are determined by using flow table test in accordance to BS EN 1015-3:1999. The readily mixed fresh cement-lime mortar is repeatedly tapped for 25 times on a levelled surface, in order to observe the spreading level of plastic state of fresh mortar. The diameter of the fresh mortar is measured and recorded in both directions. The greater the diameter indicates the higher the flow ability of fresh mortar, so giving a better performance in term of workability**.**

Figure 3.7 : Equipment for Flow Table Test

3.5.2 Compressive Strength Test

The compressive test is conducted conforming to BS EN 12390-3:2009 at 3, 7, 14 and 28 days to determine the compressive strength of the specimens. It is performed by using the compressive testing machine conforming to BS EN 12390-4:2009 until the failure occurred. Three specimens are to be tested in order to obtain the average compressive strength of the specimens. Ensure that the testing machine bearing surfaces are clean and wipe the excess water or moisture from the surface of specimens. The specimens are centred on the plate of the testing machine. Run the test and record the force applied to the specimens until failure occurred.

Figure 3.8 : Compressive Strength Machine

3.5.3 Water Absorption Test

The water absorption test for this research was conducted conforming to BS 1881-122 : 1983. In this test, 3 specimens with dimension of 100mm x 100mm x 100mm are used. The specimens are dried under 105°C for 24 hours by using oven. The dry weights of the specimens are measured. Next, the specimens are immersed into the water for 30 minutes and the weights after immersion are measured. The surface of specimens must free from water by using a clean cloth to wipe off. Lastly, the water absorption rate is calculated by using the formula given.

Formula :

$$\text{Water absorption} = \frac{Ww - Wd}{Wd}\ x\ 100\%\ x\ correction\ factor$$

Where :

Ww = The wet weight of the specimen

Wd = The dry weight of the cylinder

$$\text{Correction factor} = \frac{volume}{surface\ area\ x\ 12.5}$$

Where :

$Volume = length\ x\ width\ x\ height\ (mm^2)$

$Surface\ area = 6(length\ x\ width)$

Figure 3.9 : Specimens Immersed in Water after Oven-Dried

3.5.4 Porosity Test

Porosity as a measure of the proportion of total volume occupied by pores within the hardened concrete or mortar was measured in accordance to the standard of RILEM 1984. This test is known as vacuum saturation method which developed by RILEM. According to RILEM (1984), 3 cylinder specimens with dimension of 45mm diameter and 40mm height are used in this test. There are three variables required in order to determine the porosity of the hardened mortar, including the weight of saturated specimen in air (W*a*), the weight of oven-dried specimen (W*d*) and the weight of saturated specimen submerged in water(W*w*). Next, the specimens are immersed into the water inside the apparatus and the apparatus is connected to a compressor through vacuum-pressure vessel. The compressor is switched on after all staff are well prepared for about 15minutes. Repeat the vacuuming process after two hours intermission. Lastly, the specimens are leave for 24 hours to enable the full saturation and absorption of specimens. The porosity(%) is calculated by using the formula as shown below.

Calculation :

$$P = \frac{Wa - Wd}{Wa - Ww}\ x\ 100$$

Where :

P = Porosity (%)

Wa = The weight of saturated specimen in air

Wd = The weight of oven-dried specimen

Ww = The weight of saturated specimen submerged in water

Figure 3.10 : Vacuum-Pressure Vessel to Obtain Saturated Weight

3.5.5 Capillary Absorption Test

Capillary absorption test is used to study the absorption rate of water through capillary suction of mortar. 3 prism specimens are used in this test which is in accordance to BS EN 1015-18 : 2002. This test is carried out at the 28 days of curing age of the specimens. The prism specimens are wrapped by the cling film in order to ensure there is the only surface where contacted to the water. The specimens are then immersed with standing position into 5mm depth of water level with sand in order to measure the water's capillary action. The sand is used to enable the only surface of specimens directly contact with the water to get more accurate result. The capillary absorption coefficient is determined by using formula.

Calculation :

$$\text{Capillary Absorption} = \frac{Weight\ gain(g)}{Area\ (\sqrt{time})}$$

Where,

Area = Base Surface Area of Specimen (m^2)

Figure 3.11 : Capillary Absorption Test with Prism Specimens

3.5.6 Gas Permeability Test

Gas permeability is one of the parameters in determining the durability of concrete. Permeability determines the ease with which gases, dissolved deleterious materials and liquids can penetrate the concrete (Lynsdale&Cabrera,1984). 3 specimens with dimension of 45mm and 45mm height are used to carry out this test by using the Leeds cell permeameter which is proposed by Lynsdale and Cabrera. According to Lynsdale and Cabrera(1984), the specimens are placed into the oven and dried under 105°C for 24 hours. The dried specimens are then removed from the oven and leave them until the specimens drop to the room temperature. Next, the specimens are fitted into the silicon rubber and put into a steel ring cylinder. The nitrogen gas is allowed to flow through the specimens in the gas pressure of 2 bars. The flow of nitrogen gas is then leave for 15 minutes to accomplish a steady state of flow. The time taken for the bubble meter to move upward is measured and recorded. The intrinsic permeability is calculated by using the formula given.

Calculation:

$$\mathrm{K} = \frac{(2P^2VL\ x\ 1.76\ x\ 10^{-16})}{A\ (P_1{}^2 - P_2{}^2)}$$

Where,

K = Intrinsic Permeability (m^2)

V = Flow Rate (cm^3/sec)

L = Specimen’s Thickness (m)

A = Specimen’s Cross Section Area (m^2)

P_1 = Usually 2 bars, Absolute Applied Pressure Bars [atmosphere pressure + pressure used]

P_2 = Usually 1 bars, Pressure at Which the Flow Rate is Measured [atmosphere pressure]

Calculation of Specimen’s Cross Section Area (A) :

$$A = \pi r^2$$

Where,

A = Cross section area of specimen (m^2)

r = radius of specimen (m)

Calculation of Flow Rate :

$$V = \frac{\pi r^2 H}{T}$$

Where,

V = Flow Rate (cm^3/s)

r = Radius of Flow Meter (m)

T = Average time (s)

H = Length Read on Flow Meter (cm)

Figure 3.12 : Leeds Cell Permeameter

3.5.7 Density Test

Density test is used to determine the degree of compactness and internal void of the hardened mortar. This test was carried out by following the standard of BS EN 12390-7:2009. In order to determine the density of the mortar, volume of the specimen, mass of the specimen in air and mass of the immersed specimen are being measured and calculated. Three concrete cubes with dimension 100mm x 100mm x 100mm are used. Next, the mass of the specimens are measured before and after the specimen being immersed into the water respectively. The volume of the specimens are measured by using vernier calliper. After all the required data has been collected, the density of the specimen is calculated by using formula as shown below.

Calculation:

$$\rho = \frac{m}{v}$$

Where:

ρ = Density of mortar

m = Mass of mortar

v = volume of mortar

$$V = \frac{m_a - m_w}{\rho_w}$$

Where:

ρ_w = Density of water

V = Volume of mortar

m_w = Mass of mortar immersed in water

m_a = Mass of mortar in air

$$\rho_m = \frac{m_a \times p_w}{m_a - m_w}$$

Where:

ρ_m = Density of mortar

ρ_w = Density of water

m_w = Mass of mortar immersed in water

m_a = Mass of mortar in air

Figure 3.13 : Equipment to Measure Mass of Specimens in Air and Submerged In Water

3.5.8 Early-age Behaviours of Cement-Lime Mortar

In order to determine the standard consistency, initial and final setting time of the mortar, Vicat apparatus is used. These tests are carried out in accordance with the standard of BS 4550-3-3.5:1978 for Standard Consistency Test (STT) and BS EN 196-3:1995 for Setting Time Test (STT). To determine the initial setting time, a 1mm square needle is used to penetrate through the mortar paste with 10 minutes interval till the scale shows 5+0.5mm from the bottom of plate. The needle is replaced with an annular attachment for determining the final setting time. The needle is released at every 30 minutes intervals until an impression has been made on the mortar by needle. The initial and final setting time were measured and recorded.

Figure 3.14 : Vicat Apparatus

3.6 Structural Application

After all the tests are completed, the optimum cement-lime ratio mortar which gives the better performance in both mechanical properties and durability properties is selected to apply on a brick wall with dimension 1m x 1m. A 19mm thick layer of plaster is applied on the brick wall for the purpose of determine the practicability of the specific mortar. The conditions of the mortar before, during and after the application are observed and the appearance of the hardened plaster after curing are observed and recorded.

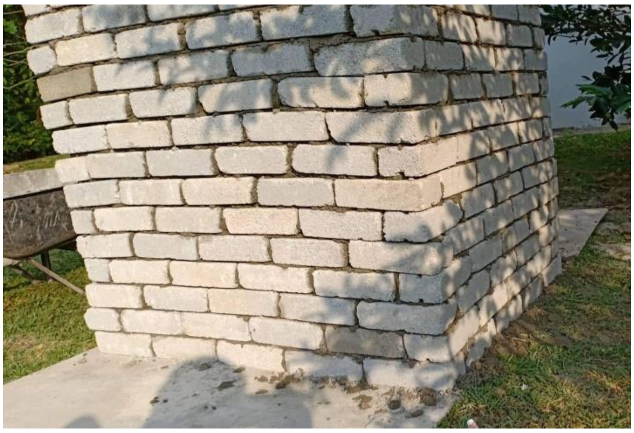

Figure 3.15 : Self-constructed Brick Wall

Table 3.4 : Test Program Schedule

Properties	**Type of Test**	**Test Age**	**Type and Size of Specimen**
Setting Time and Workability	Setting Time Test (STT) (BS EN 196-3:1995)	Plastic State of Fresh Mortar	-
	Standard Consistency Test (SCT) (BS 4550-3-3.5:1978)	Plastic State of Fresh Mortar	-
	Flow Table Test (BS EN 1015-3:1999)	Plastic State of Fresh Mortar	-
Mechanical Properties	Compressive Strength Test (BS EN 12390-3:2009)	3,7,14,28 days	50mm x 50mm x 50mm (Cube)
	Density Test (BS EN 12390-7:2009)	3,7,14,28 days	100mm x 100 mm x 100mm (Cube)
Durability Properties	Water Absorption Test (BS 1881-122:2011)	3,7,21,28 days	100mm x 100 mm x 100mm (Cube)
	Capillary Absorption Test (BS EN 1015-18:2002)	28 days	40mm x 40mm x 160mm (Prism)
	Porosity Test (RILEM 1984)	3,7,14,28 days	45mm diameter with 40mm height (Cylinder)
	Permeability Test (Lynsdale&Cabrera 1984)	3,7,14,28 days	45mm diameter with 40mm height (Cylinder)

CHAPTER4

RESULT AND DISCUSSION

4.1 Introduction

In this current chapter, quantified data obtained from the experimental tests were discussed and analysed on the influences of the manipulated variable (different ratio of replacement of cement with hydrated lime) towards the performance and properties of fresh and hardened mortar. Dependant variables for this research: Workability, Compressive Strength, Density, Water Absorption Rate, Gas Permeability Rate, Capillary Absorption Coefficient and Porosity have been studied based on the laboratory test which stated in the Chapter 3. The correlation between the variables and the variances were studied in order to get strong findings with reliable proof.

4.2 Workability

The workability of the mortars is identified after the mortars are freshly casted. The flow table test is carried out to test for the workability of the mortars. Workability is easier to feel than to describe. So that, another test of structural application will be discussed in below part. The ability of a mortar or a plaster to remain smooth and mouldable even against the suction it may experience from other porous building materials. The table below shows the workability of the mortar with different replacement of cement with hydrated lime.

Table 4.1 : Results of Flow Table Test with Different Types of Mortar

Specimen (Mix Code)	Water/cement ratio	Flow (mm)
L_0	0.6	207
L_5	0.6	210
L_{10}	0.6	205
L_{15}	0.6	195
L_{20}	0.6	183
L_{25}	0.6	170

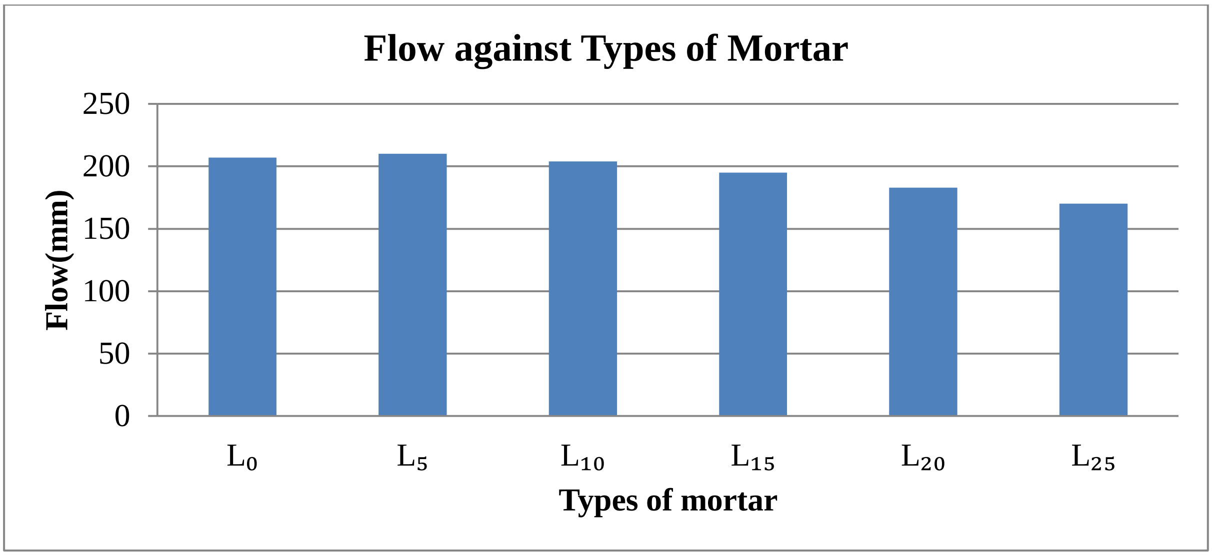

Figure 4.1 : Bar Chart of Flow against Types of Mortar

Figure 4.1 showed the results of the workability of 6 types of fresh mortar. From the results, there is no significant difference of the flow of mortar after 5% replacement of cement with hydrated lime. However, a decreasing of workability of mortar for the follow$_{o}$ing types of mortar with different replacement ratio of hydrated lime which are 210mm (L_5), 205mm (L_{10}) 195mm (L_{15}), 183mm (L_{20}) and lastly 170mm (L_{25}). The mortar with highest workability among these 6 types of mortar is L_5 whereas the L_{25} has the lowest workability.

However, the decreasing trend of the workability of hydrated lime mixes in this study agreed by the study of the Looney and Pavia (2019). The study stated the increase of hydrated lime will enhance the water retention and water demand of the mortar and the higher water demand is required to achieve specified initial flow with increasing of lime content.

In this study, with the same amount of water being added into different lime content mixture, the workability of mortar has slightly increase and then decreasing gradually as the amount of lime content increase. The decreasing trend of the workability of mortar is due to the particles of hydrated lime powder are far away smaller than the particles of cement. If the lime content of the mixture is increase then more water is required to wet the surface of the particles for the hydration. In this research, as same water/cement ratio is being used for few types of mortar, so that a decreasing of the workability of mortar is obtained due to the higher lime content mortar requires greater amount of water to get a reasonable workability.

4.3 Density

Studies proved that the density of the specimens increased with the increasing of curing age. This is due to the increasing of reacted products (C-S-H gel) over the curing age of the specimens. Not only that, the previous studies also proved that the porosity of the specimens influenced the density of the structure due to the higher the porosity, the greater amount of voids which reduced the density of specimens. The effects of the replacement level of hydrated lime on the specimens are showed in the Table 4.2.

Table 4.2 : Results of Average Density with Different Types of Mortar

	Average Density (kg/m^3)			
Specimens (Mix Code)	**3 days**	**7 days**	**14 days**	**28 days**
L_0	2057	2156	2181	2202
L_5	2080	2176	2186	2202
L_{10}	2062	2152	2181	2184
L_{15}	2046	2139	2169	2176
L_{20}	2045	2137	2165	2175
L_{25}	2025	2117	2146	2155

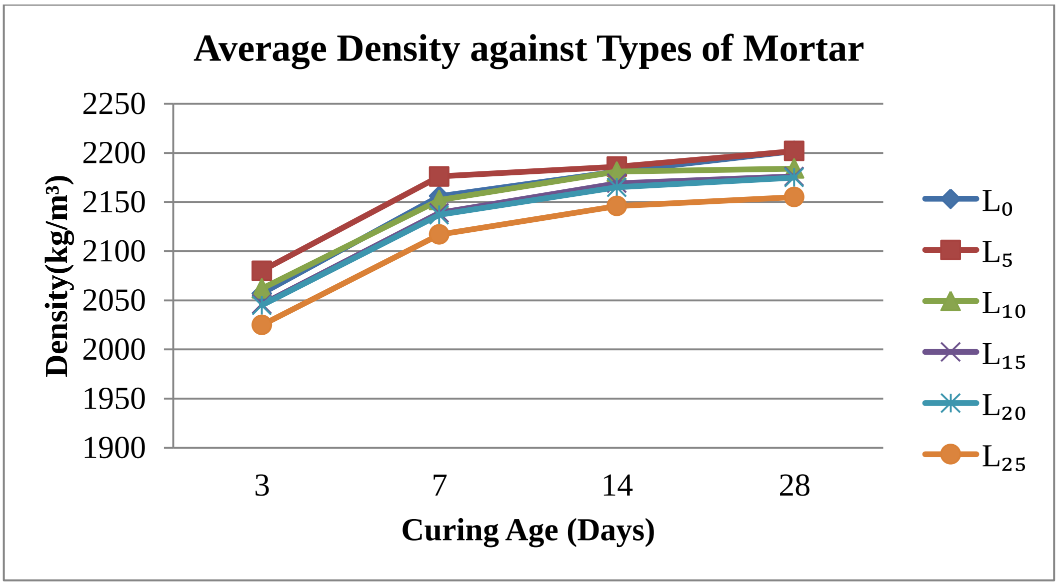

Figure 4.2 : Graph of Average Density against Types of Mortar

From Figure 4.2, it indicated an increasing trend at which the density of all different content of hydrated lime increase with the 28 days curing period. The density of all the specimens with different level of replacement hydrated lime was increased dramatically from the 3rd to 7th day in the 28 days curing period, before climbing more slowly along the curing period. In the graph, we can concluded that the 5% content of replacement hydrated lime sample have provide the optimum result in density among others 5 with different content of replacement hydrated lime, at which it gives a highest density, 2080kg/m3 to 2202.20kg/m3 in the 28 days of curing period, followed by 0% and 10%, which the density was 0.5kg/m3 to 24kg/m3 and 4.5kg/m3 to 24kg/m3 smaller compared to sample with 5% content of hydrated lime. The 25% content of hydrated lime sample give the weak result in density compared to other samples, it have a density from 2024.78kg/m3 to 2154.66kg/m3 in 28days curing time. However, the result shows the decreasing of density as the content of the hydrated lime increase at 3,7,14 and 28 days.

With increasing of content of hydrated lime in the mortar composition, less amorphous calcium silicate hydrate gel (C-S-H) is formed and more calcium hydroxide crystals, plate-like crystals and needle-like crystals lead to the microstructure becomes more porous. The bulk density decreases and the total porosity increases with the increasing of hydrated lime content in the mortars compositions. Cement-lime mortars show a higher volume of pores with increasing hydrated lime content in the mortar composition(Cizer, Balen, & Gemert, 2008). This statement is further proven in the porosity test which showed the greater the replacement level of hydrated lime, the greater the porosity of the specimens.

One-way ANOVA: Density versus Replacement Level of HL (%)

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Replacement Level of HL (%)	5	18052	3610	1.25	0.298
Error	66	191243	2898		
Total	71	209294			

S	R-sq	R-sq(adj)	R-sq(pred)
53.8295	8.62%	1.70%	0.00%

Replacement Level of HL (%)	N	Mean	StDev	95% CI
0	12	2149.2	58.2	(2118.1, 2180.2)
5	12	2160.9	49.9	(2129.9, 2191.9)
10	12	2144.7	52.0	(2113.6, 2175.7)
15	12	2132.1	54.4	(2101.1, 2163.1)
20	12	2130.6	53.6	(2099.6, 2161.6)
25	12	2111.2	54.4	(2080.1, 2142.2)

Figure 4.3 : One-way ANOVA for Density against Replacement Level of Hydrated Lime

Figure 4.3 illustrated that the replacement level of hydrated lime has no significant effect on the density of the cement-lime mortar. This is because the p-value which generated by the one-way ANOVA test is 0.298 which is greater than the α-level of 0.05. The hydrated lime powder is too fine which contribute no effect on the density of the mortar. The major factor which determines the density of mortar is the formation of the C-S-H gel.

4.4 Compressive Strength Test

The compressive strengths of the specimens have shown in the Table 4.2 below. The data obtained by getting the average of three numbers of 50mm x 50mm x 50mm cubes for each specimens with different level of hydrated lime replacement. Same reason with the density of the specimens, the increment of compressive strength is mainly due to the formation of C-S-H gel which contributed to strength of the structure.

Table 4.3 : Results of Average Compressive Strength with Different Types of Mortar

	Average Compressive Strength Test (N/mm²)			
Specimen (Mix Code)	**3 days**	**7 days**	**14 days**	**28 days**
L_0	12.24	17.33	28.99	33.18
L_5	17.88	20.51	29.42	28.56
L_{10}	13.35	17.62	26.03	27.03
L_{15}	12.16	16.10	23.17	24.55
L_{20}	10.83	16.10	20.14	20.86
L_{25}	11.15	12.92	18.95	18.63

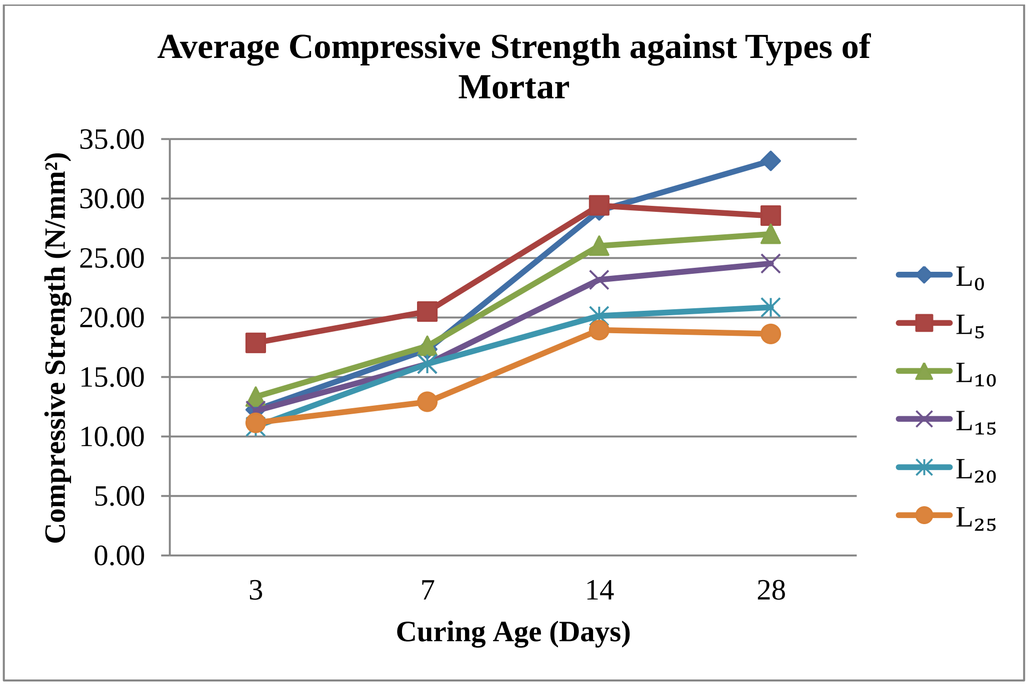

Figure 4.4 : Graph of Average Compressive Strength against Types of Mortar

From the Figure 4.4 the result showed a downward trend in compressive strength with the increment of replacement of cement with hydrated lime. The results showed that the L_0

had the highest compressive strength at 28days curing age followed by the specimen with hydrated lime replacement at every 5% interval which were L_5 (28.56 N/mm²), L_{10} (27.03 N/mm²), L_{15} (24.55 N/mm²), L_{20} (20.86 N/mm²) and L_{25} (18.63 N/mm²). The increasing of hydrated lime content in cement mixture reduces the content of calcium silicate C_2S and C_3S. The calcium silicate reacts with water molecules to form calcium silicate hydrate gel (C-S-H). As the content of calcium silicate decrease, the hydration process will also decrease and finally reduce the formation of calcium silicate hydrate gel as the increase of hydrated lime. Therefore, the decreasing trend of compressive strength is obtained as the increase of lime content. This statement can be supported by the research of Pavia and Brennan (2019). Besides the compressive strengths are superior in mortar with higher cement content due to their greater hydrate content(Looney & Pavia, 2015).The higher porosity of the mortar will reduce the compressive strength of the mortar as explained in the research of Looney and Pavia.

However, the result showed that the compressive strength of the L_5 and L_{10} specimens were slightly higher than the control of the study (L_0) at the early age of mortar. This can be explained by due to the higher water retention ability with low hydrated lime replacement enhanced the hydration of Tricalcium Silicate (C_3S) which contributes to the early strength of the mortar. The research of Pavia & Brennan(2019) stated that the increase of strength and stiffness triggered by low lime addition can be due to the high water retention of lime enhancing the hydration of PC (Pavia & Brennan, 2019).

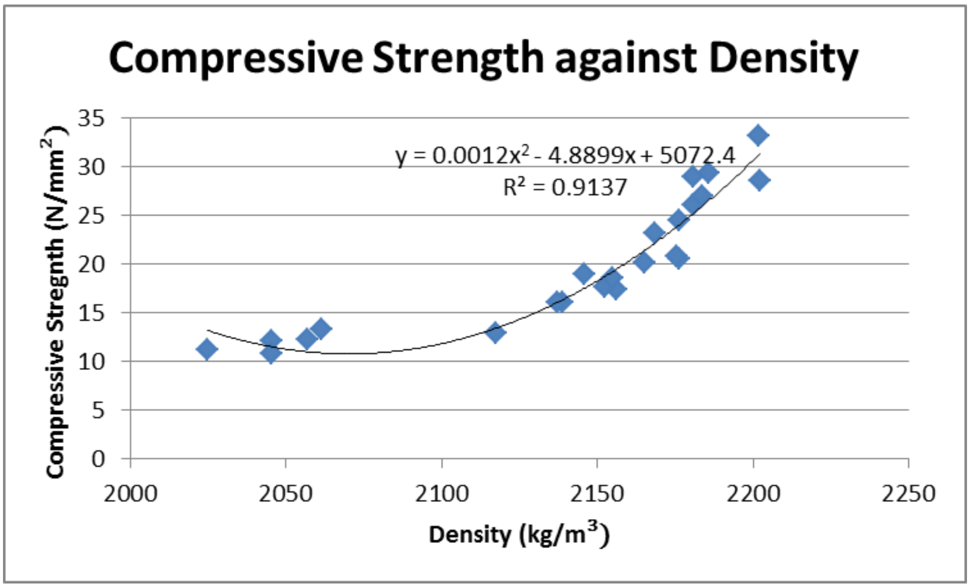

Figure 4.5 : Correlation between Compressive Strength and Density

From the Figure 4.5, it showed that there was a strong positive relationship between the density and the compressive strength of specimens. The R^2 value of the correlation between compressive strength and density is 0.9137 which indicated that they have strong relationship among them. This is because the increase of formation of calcium hydrate silicate gel and lesser open porosity of specimens provided higher compressive strength for the specimen and vice versa. Therefore, the density of the mortar is strongly related with the compressive strength of the mortar as the equation given is $y=0.0012x^2-4.8899x+5072.4$ and the $R^2 = 0.9137$ which it is the evidence shows that the correlation between density and compressive strength of mortar.

One-way ANOVA: Compressive Strength versus Replacement Level of HL (%)

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Replacement Level of HL (%)	5	625.0	125.00	3.57	0.006
Error	66	2311.9	35.03		
Total	71	2936.9			

S	R-sq	R-sq(adj)	R-sq(pred)
5.91847	21.28%	15.32%	6.32%

Replacement Level of HL (%)	N	Mean	StDev	95% CI
0	12	22.94	8.90	(19.52, 26.35)
5	12	23.37	4.79	(19.96, 26.78)
10	12	18.62	7.46	(15.21, 22.04)
15	12	18.13	4.58	(14.72, 21.55)
20	12	16.98	4.21	(13.57, 20.39)
25	12	15.41	3.69	(12.00, 18.82)

Figure 4.6 : One-way ANOVA for Compressive Strength against Replacement Level of Hydrated Lime

The result of one-way ANOVA test which illustrated in the Figure 4.6 showed that the replacement level of the hydrated lime has significant influence to the compressive strength of the cement-lime mortar due to the p-value obtained in the ANOVA test is 0.006 which is smaller than the α-level (0.05).

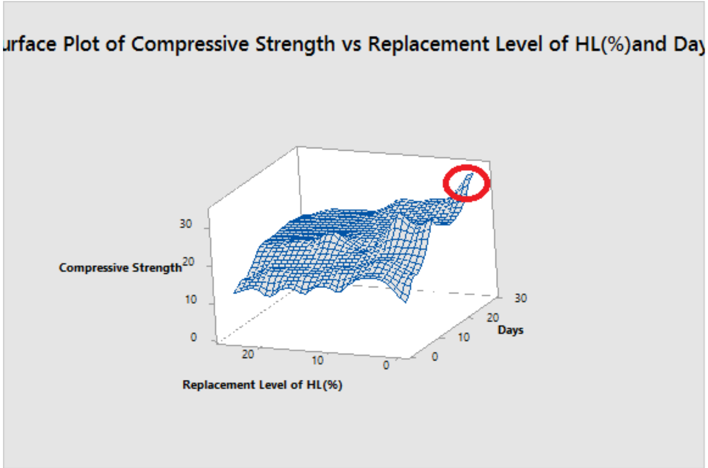

Figure 4.7 : Surface Plot of Compressive Strength agaisnt Replacement Level of Hydrated Lime and Curing Age

The 3-D surface plot of compressive strength against replacement level of hydrated lime and curing age can be observed in Figure 4.7. This surface plot demonstrated a upward tiling plot which showed the lower the replacement level of hydrated lime and the longer the curing age resulted in higher compressive strength in the specimen. The highest of the compressive strength with 33.18 N/mm^2 is obtained in the specimen with 0% replacement of hydrated lime on 28th days of curing age.

4.5 Porosity

Porosity is one of the vital factors which influence the durability of the structure. The porosity may affect the ability of resistance of structure toward the penetration of moisture and chemical attack. The previous studies showed that the higher the porosity of the structure tends to degrade of the mortar and deterioration by chemical attack and penetration of moisture.

Table 4.4 : Results of Average Porosity with Different Types of Mortar

	Average Porosity (%)			
Specimens(Mix Code)	**3 days**	**7 days**	**14 days**	**28 days**
L_0	13.55	11.05	10.05	9.00
L_5	14.07	11.92	10.55	9.45
L_{10}	15.05	12.35	10.77	9.00
L_{15}	15.87	12.88	10.98	9.20
L_{20}	17.01	13.05	12.11	9.88
L_{25}	17.81	13.85	12.95	9.95

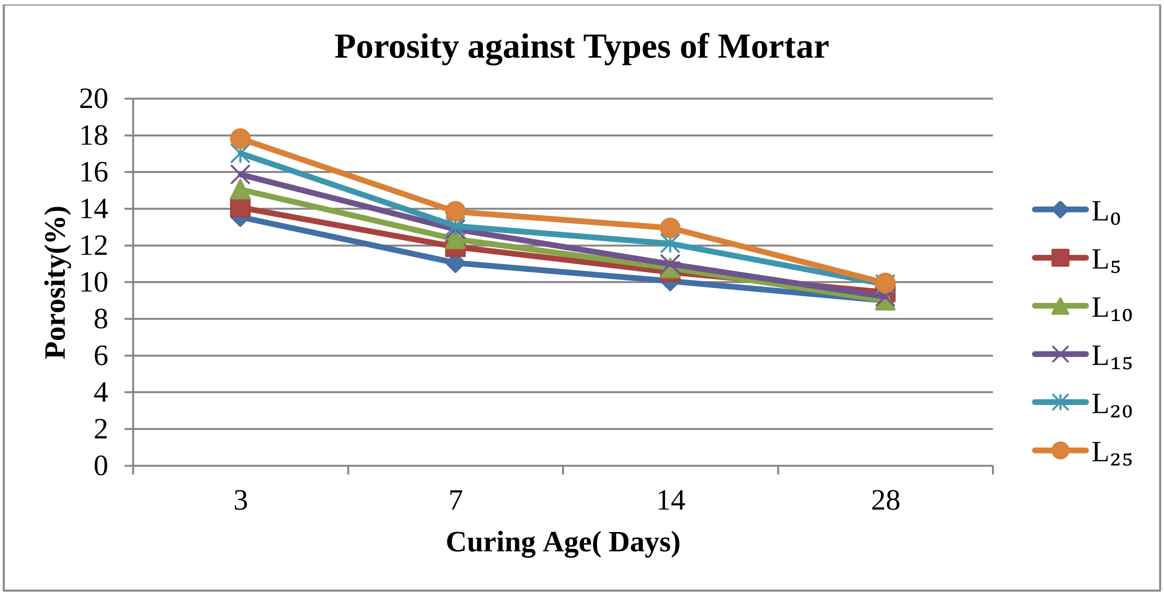

Figure 4.8 : Graph of Porosity against Types of Mortar

Table 4.4 showed the porosity percentage of each mortar specimens with different level replacement of cement with hydrated lime. From the result, it showed the L_{25} specimens has the greatest porosity along the duration of this study which are 17.81% , 13.85% , 12.95% and 9.95% within the structure whereas the control of the study L_0 has the lowest percentage of porosity which are 13.55%, 11.05%, 10.05% and 9.00%. The result generally showed that the greater the amounts of replacement of cement with hydrated lime, the greater the porosity within the structure.

From the Figure 4.8, the result showed an increasing trend in the porosity of the structure as the content of hydrated lime replacement increases. As the hydrated lime replacement increase in this research, the carbonation process occurred within the structure among the calcium hydroxide, water and carbon dioxide to form calcite crystal and calcium carbonate. According to the research of M.Arandigoyen(2006), the research showed that the porosity of the carbonated lime-paste is due to the formation of calcite crystal and the void between crystals. Their irregular polyhedral shape of calcite crystal lead to the formation of pores between the irregular structures of the calcite crystal. However the process of carbonation takes very long time to occur, so it cannot be used in this study because our period of research is not enough to clearly investigate the occurrence of carbonation.

According to the research of Arandigoyen&Alvarez(2006), they found out that the dense particle of C-S-H gels were surrounded by aggregate of small crystals which are hydrated lime. The calcium hydroxide crystals which stick onto the surface of the C-S-H gels provided an irregular surface so that the voids between the irregular shape of C-S-H gels increase and lastly lead to the increment of porosity. Not only that, as the percentage of hydrated lime increase, the dense particles of C-S-H gels decrease and the microstructure become more porous which resulted with more homogenous porosity within the structure. Besides, the formation of calcium silicate hydrate (C-S-H) gel will swell the structure and diminished the porosity of the structure. With decreasing of cement content and increasing of calcium hydroxide content, the volume of pores will increases accordingly(Cizer et al., 2008).

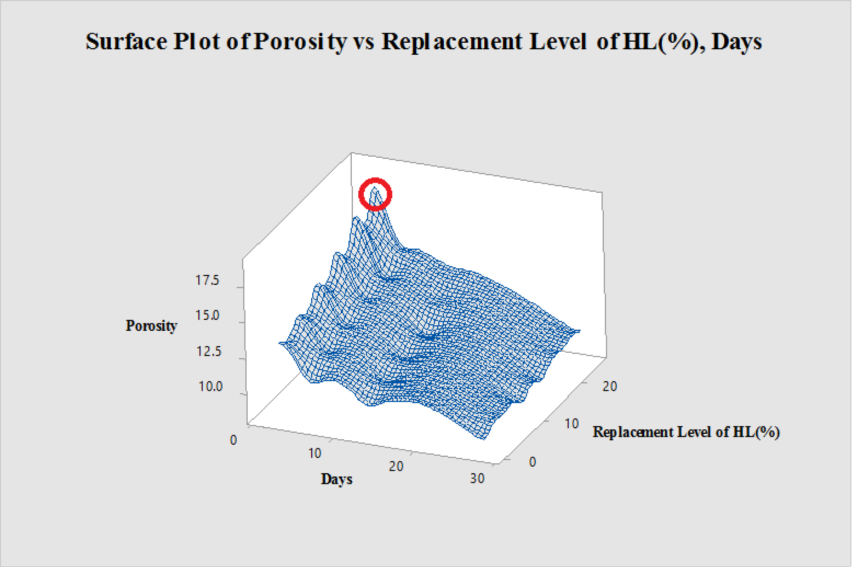

Figure 4.9 : Surface Plot of Porosity against Replacement Level of Hydrated Lime and Curing Age

The 3-D surface plot of porosity against replacement level of hydrated lime and days can be observed in Figure 4.9. This surface plot demonstrated a downward tiling plot which showed the greater the replacement level of hydrated lime and the shorter the curing age resulted in higher porosity in the specimen. The highest of the porosity with 17.81% is obtained in the specimen with highest replacement of hydrated lime on 3rd days of curing age.

4.6 Water Absorption

Water absorption rate over a certain time period can be determined by carry out the water absorption test. Table 4.5 and Figure 4.6 showed the result and the trend obtained from the test and used to study the water absorption rate of mortar with different replacement level of hydrated lime.

Table 4.5 : Results of Water Absorption Rate with Different Types of Mortar

	Average Water Absorption Rate (%)			
Specimens(Mix Code)	**3 days**	**7 days**	**14 days**	**28 days**
L_0	5.64	4.60	3.55	2.99
L_5	6.10	5.85	5.64	5.48
L_{10}	7.71	7.55	7.25	6.55
L_{15}	8.05	7.53	7.30	6.53
L_{20}	9.96	8.06	7.99	6.90
L_{25}	7.63	7.52	7.42	7.48

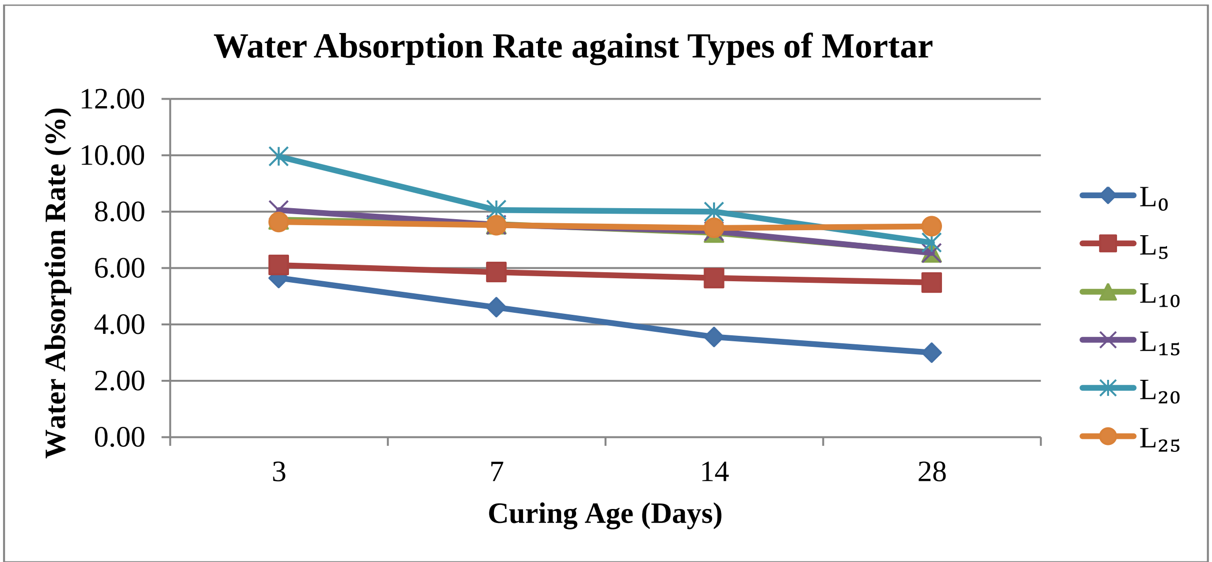

Figure 4.10 : Graph of Water Absorption Rate against Types of Mortar

The increasing trend of water absorption rate is observed with the increase of the hydrated lime content is clearly shown in the Figure 4.10. L_5 has the lowest absorptivity rate of 5.48% at 28days and yet rose to 6.55% when 5% more of hydrated lime replacement was added into the binder composition. There was no significant difference between L_{10} and L_{15} which were 6.55% and 6.53% while a consecutive increased to 6.90% and 7.48% with further replacement of hydrated lime in the binder composition at every 5% interval until L_{25}. The increasing water absorption rate as the increasing of hydrated lime replacement in binder composition can be explained by the structure's porosity and pore structure in the structure. As the statement that explained in the previous part, the porosity of the structures were increased as more hydrated lime were replaced the cement in the structure. Thus, the increasing trend of water absorption rate is supported by the increasing of the porosity of the structure in this research. In the contrary, the less dense the microstructure with more pores structure enhances the water absorption rate of the structure.

According to the research, the usage of hydrated lime reduced the mechanic durability water resistance of the materials. From the previous research, the increment of cement significantly increases the amount of active silica dioxide and aluminium oxide that contributed to the water resistance of cement-lime mortar. In this research, as more hydrated lime had replaced the cement content, it has reduced the amount of active silica dioxide (SiO_2) and aluminium oxide (Al_2O_3) in the sample and thus reduced the ability of water resistance which later increase the water absorption rate. This statement is supported by the previous research of L,Gulbe in the year of 2017.

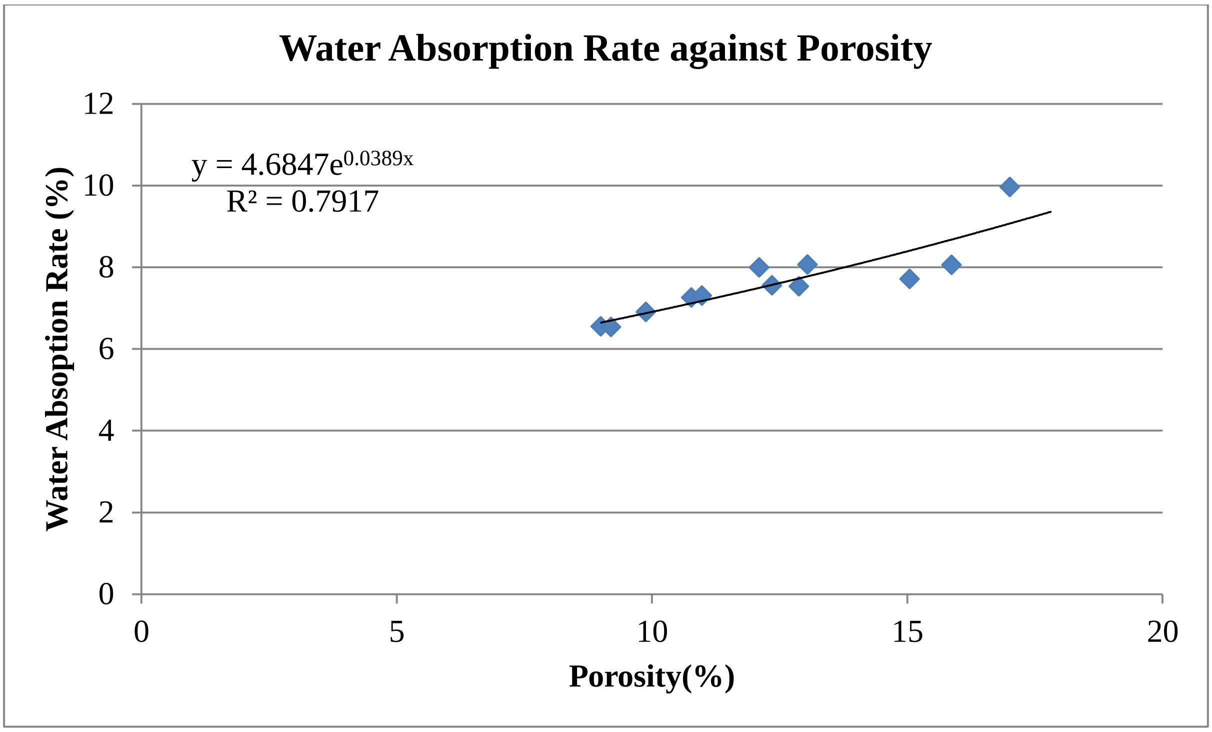

Figure 4.11 : Correlation between Water Absorption Rate and Porosity

Furthermore, Figure 4.11 indicated the scatter plot among water absorption and porosity. From the figure above, it gave the pattern of trend line is inclines ascending which proves that the relationship of these two variables is optimistic and straightforwardly corresponding. It proved that as the porosity of the structure increase, the water absorption rate of the structure also increase in the meantime. This is because the voids within the structure have a tendency to absorb the water from the surrounding. However, the ability of the water absorption of the mortar will lead to degradation of the structure as the more moisture stay within the structure as it will reduce the lifespan of mortar.

One-way ANOVA: Water Absorption versus Replacement Level of HL (%)

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Replacement Level of HL(%)	5	120.7	24.138	8.89	0.000
Error	66	179.2	2.716		
Total	71	299.9			

S	R-sq	R-sq(adj)	R-sq(pred)
1.64797	40.24%	35.71%	28.88%

Replacement Level of HL (%)	N	Mean	StDev	95% CI
0	12	4.196	1.071	(3.246, 5.146)
5	12	6.192	1.099	(5.243, 7.142)
10	12	6.869	2.117	(5.920, 7.819)
15	12	7.352	1.483	(6.403, 8.302)
20	12	8.250	2.190	(7.301, 9.200)
25	12	7.523	1.569	(6.573, 8.472)

Figure 4.12 : One-way ANOVA of Water Absorption against Replacement Level of Hydrated Lime

A similar result with the one-way ANOVA test for compressive strength, the replacement level of hydrated lime has significant effect on the water absorption which is proved by the p-value generated in the Figure 4.12. The p-value for the one-way ANOVA test for water absorption is 0.000 which is smaller than 0.05 (α-level)

4.7 Gas Permeability

Gas permeability rate is one of the factors to examine the durability of the mortar. The gas permeability rate can be determined by carrying out gas permeability test by using Leeds Cell Permeameter. In this test, nitrogen gas is allowed to pass through the specimens and the time taken for nitrogen gas to pass through the specimen are recorded and the gas permeability rate of specimens are obtained by using formula given.

Table 4.6 : Results of Average Gas Permeability Rate with Different Types of Mortar

	Average Gas Permeability Rate,K,x10^{-19} (m^2)			
Specimens (Mix Code)	**3 days**	**7 days**	**14 days**	**28 days**
L_0	2.05	1.51	1.22	0.60
L_5	2.13	1.67	1.39	0.64
L_{10}	2.20	1.84	1.45	0.70
L_{15}	2.37	1.95	1.54	0.79
L_{20}	2.40	2.03	1.58	0.77
L_{25}	2.54	2.15	1.66	1.11

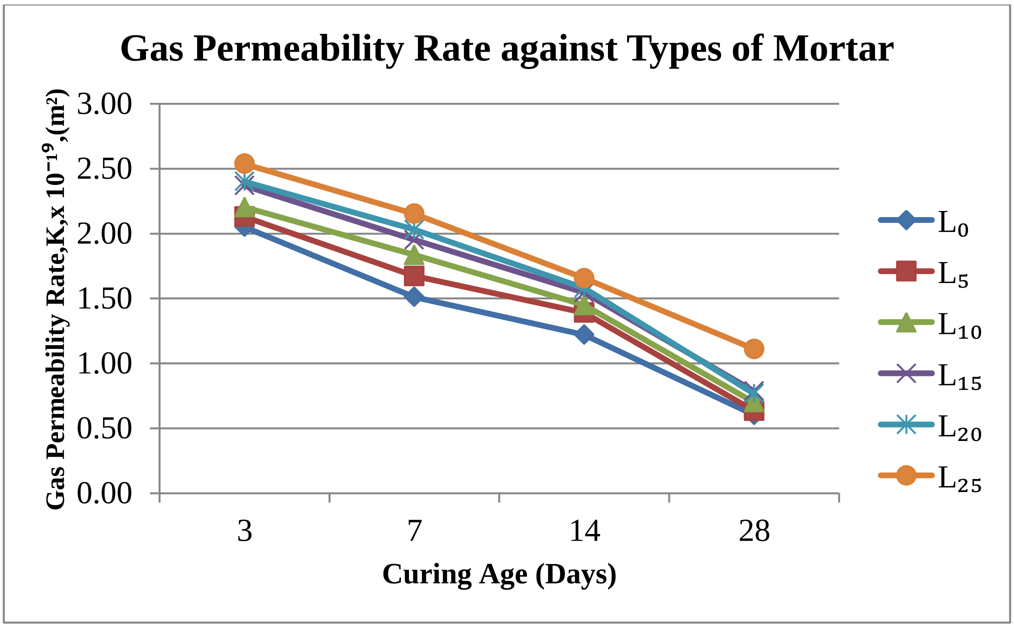

Figure 4.13 : Graph of Average Gas Permeability Rate against Types of Mortar

The gas permeability rates of mortars specimen with different level of replacement of hydrated lime are shown in the Figure 4.13. The results clearly stated that the 25% hydrated lime of replacement mortar has the highest gas permeability rate among the mortar with replacement of hydrated lime from 3,7,14 and 28days which are 2.54x10^{-19} m², 2.15x10^{-19} m², 1.66x10^{-19} m²and 1.11x10^{-19} m².However the 5% hydrated lime of replacement mortar has the lowest gas permeability rate. This can be explained by the open porosity and pore volume of the mortar structure of the 25% hydrated lime of replacement is the highest, so that the gas passed through the specimen in the fastest manner. The formation of the irregular shape of calcite crystals lead to more voids among the particles and the voids within the structure are interconnected which enable the gas flow through the structure. As more hydrated lime used to replace the cement, the greater amount of voids are formed within the structure, more gas are able to flow through the voids and thus lead to greater gas permeability rate.

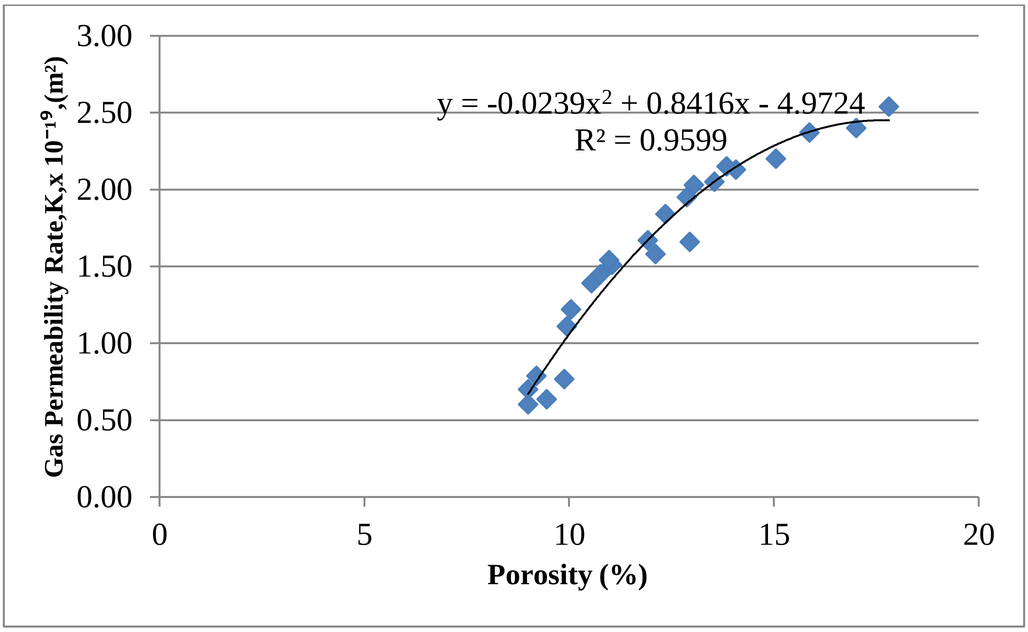

Figure 4.14 : Correlation between Gas Permeability Rate and Porosity

Figure 4.14 sketched the scatter plot among the gas permeability rate and the porosity. The scatter plot showed the pattern of the trend line is curved upward and it implied the relationship between gas permeability rate and porosity is in strong relationship. This showed that the increase of the porosity of the structure will increase the gas permeability rate of the structure too. This statement can be explained by the increasing of hydrated lime lead to more formation of irregular shape of calcite crystal therefore the more voids are formed between the crystal and lead to the voids o pores are interconnected which enable the gases or liquid can pass through the mortar effectively. The high gas permeability rate and high porosity enable the penetration of water or other chemical substances which may shorten the lifespan of the structure or mortar. The scatter plot of this correlation between gas permeability and porosity is limited to the 20% of replacement level of hydrated lime.

4.8 Capillary Absorption

Capillary absorption is closely linked to the transport of moisture within the specimens. The main influence of the capillary absorption is the porous nature of the material within the structure and the degree of the interconnected voids within the structure. Besides, capillary absorption is also influences by the capillary action which is the capability of the water flow through the capillary pores against the gravity. Previous studies had proven that there is no relationship between porosity and capillary absorption in mortar. However, the research showed the capillary absorption was influenced by the degree of the interconnected voids within structure. Therefore, capillary absorption rate of cement-lime mortar was investigated in this study. The amount of water undertaken by the prism specimens were recorded and shown in the Table 4.7, Figure 4.14 and Table 4.8.

Table 4.7 : Results of Average Mass with Different Types of Mortar

	Average Mass (gram)					
Time(hour)	L_0	L_5	L_{10}	L_{15}	L_{20}	L_{25}
Oven-dried	0.00	0.00	0.00	0.00	0.00	0.00
0.25	0.29	0.31	0.44	0.44	0.50	0.52
0.5	0.29	0.56	0.63	0.60	0.73	0.73
0.75	0.44	0.67	0.73	0.75	0.88	0.88
1	0.48	0.75	0.79	0.81	0.98	0.94
1.25	0.50	0.81	0.83	0.85	1.04	1.04
1.5	0.50	0.88	0.94	0.94	1.19	1.13
1.75	0.52	0.98	1.04	1.08	1.25	1.21
2	0.63	1.04	1.10	1.13	1.33	1.29
2.5	0.63	1.10	1.17	1.21	1.42	1.35
3	0.65	1.17	1.21	1.25	1.46	1.42
3.5	0.67	1.21	1.27	1.31	1.52	1.48
4	0.71	1.25	1.35	1.38	1.58	1.54
5	0.77	1.33	1.38	1.44	1.58	1.58
6	0.77	1.35	1.42	1.44	1.67	1.60
7	0.81	1.40	1.44	1.50	1.69	1.63
8	0.81	1.42	1.44	1.50	1.75	1.65
24	0.98	1.73	1.88	1.96	2.29	2.17
48	1.15	2.10	2.23	2.50	2.83	2.67
72	1.23	2.42	2.63	2.81	3.00	2.92
96	1.27	2.56	2.85	3.02	3.10	3.08
120	1.35	2.67	2.88	3.13	3.17	3.13

144	1.40	2.73	2.94	3.19	3.40	3.21
168	1.42	2.77	2.94	3.19	3.40	3.23
192	1.46	2.81	2.94	3.25	3.42	3.25
216	1.46	2.81	2.98	3.25	3.42	3.27
240	1.46	2.81	2.98	3.25	3.42	3.27
264	1.46	2.81	2.98	3.25	3.42	3.27
288	1.44	2.79	2.96	3.23	3.44	3.27
312	1.46	2.79	2.98	3.25	3.44	3.29
336	1.46	2.81	2.98	3.25	3.44	3.29

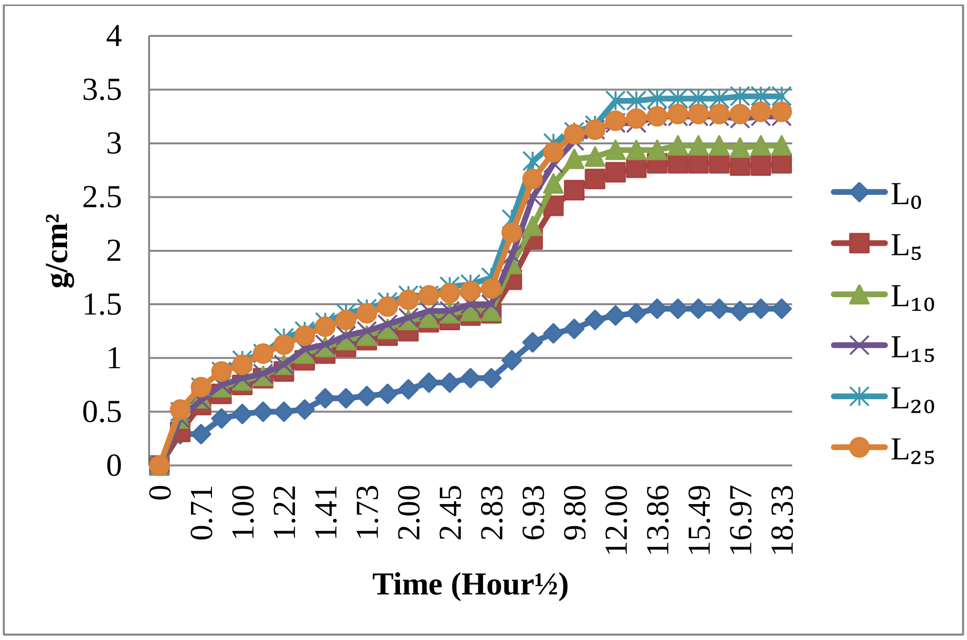

Figure 4.15 : Graph of Capillary Absorption Rate against Time

Table 4.8 : Capillary Absorption Coefficient with Different Type of Mortar

Specimens (Mix Code)	**Gradient [(g/cm²)/√time]**	
	Oven-dried to 2nd days	**Oven-dried to 14th days**
L_0	0.166	0.080
L_5	0.303	0.153
L_{10}	0.322	0.163
L_{15}	0.361	0.177
L_{20}	0.408	0.188
L_{25}	0.385	0.179

Two different gradients were taken to study ability of capillary absorption over a particular duration which are:

1.From the over-dried to 2nd days, these results indicates the fundamental ability of capillary absorption with the first turning point.

2. From the oven-dried to 14th days, these results shows the fully absorption of the specimens throughout our study's duration.

Both gradients of the capillary coefficient show a general increasing trend as the increment of replacement of cement with hydrated lime. This can be explained as the degree of connectivity between pores is not as good as in high cement-lime paste. Not only that , as the hydrated lime increase in the structure, less formation of C-S-H gel produce homogenous porosity along the material with lesser dense C-S-H particles within the structure. Not only that, as the rise of water through a capillary, a meniscus is created on the surface of water which acts as a surface tension of the liquid. As the cement of content is higher, the meniscus of the water needs to change the orientation to look for random porosity as the structure become more complex due to the formation of calcium silicate hydrate (C-S-H) gel and vice versa(Arandigoyen & Alvarez, 2006). There is another factor which will affect the capillary absorption which is the pores volume. As the pore sizes are in smaller sizes and are well-interconnected, the capillary action occurs more easily and goes through the capillary within the structure against gravity with faster manner. However, in this study, pore size distribution is not investigated.

4.9 Standard Consistency Test (SCT) and Setting Time Test (STT)

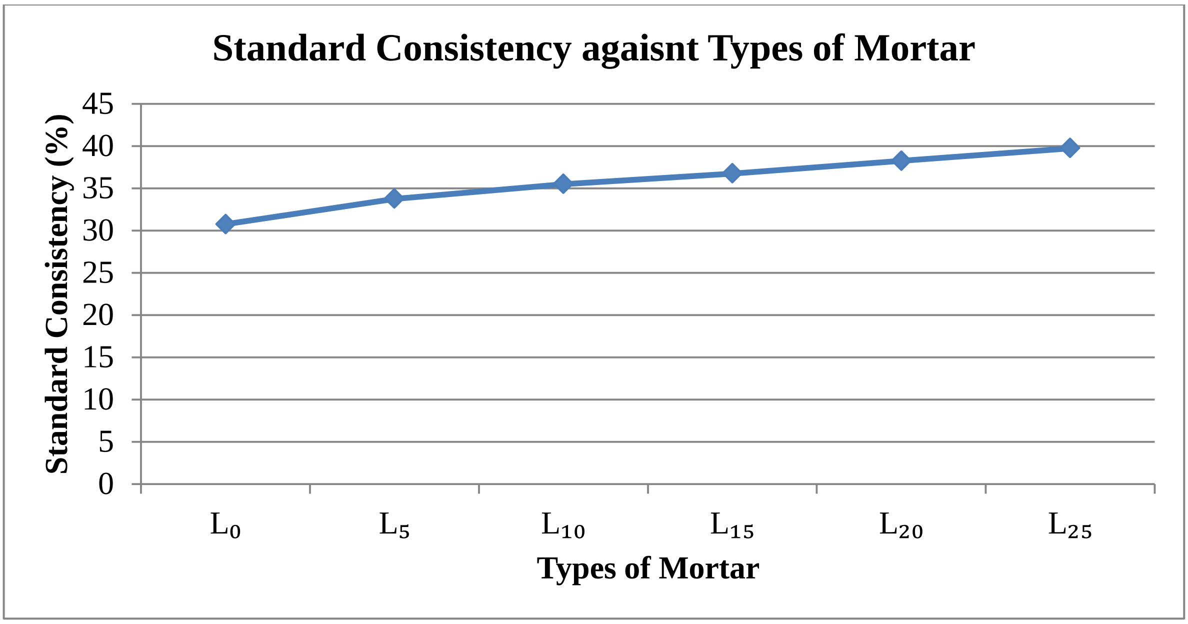

Figure 4.16 : Standard Consistency against Types of Mortar

A clear comparison between the standard consistency of Ordinary Portland Cement and different hydrated lime replacement mortar can be seen in the Figure 4.16. The Figure 4.16 showed that the results of standard consistency of 0% to 25% hydrated lime replacement of mortar. In L_0 (0% of hydrated lime replacement, the standard consistency attained is approximated 0.3125 while the standard consistency for L_{25} (25% hydrated lime replacement) is about 0.395. According to the results, an increasing trend of standard consistency is obtained as more hydrated lime are used to replacement cement content. This is because the particles size of the hydrated lime particle is far smaller than the cement particles. As more cement is replaced by hydrated lime powder, the average particles size of the mixture is decrease therefore more water are needed to wet the greater total surface areas of particles to enable the completion of hydration process. It is agreed by the research of Looney & Pavia in the year of 2015. The research came out with the result of mortar with greater amount of hydrated lime required greater amount of water demand to get a required flow.

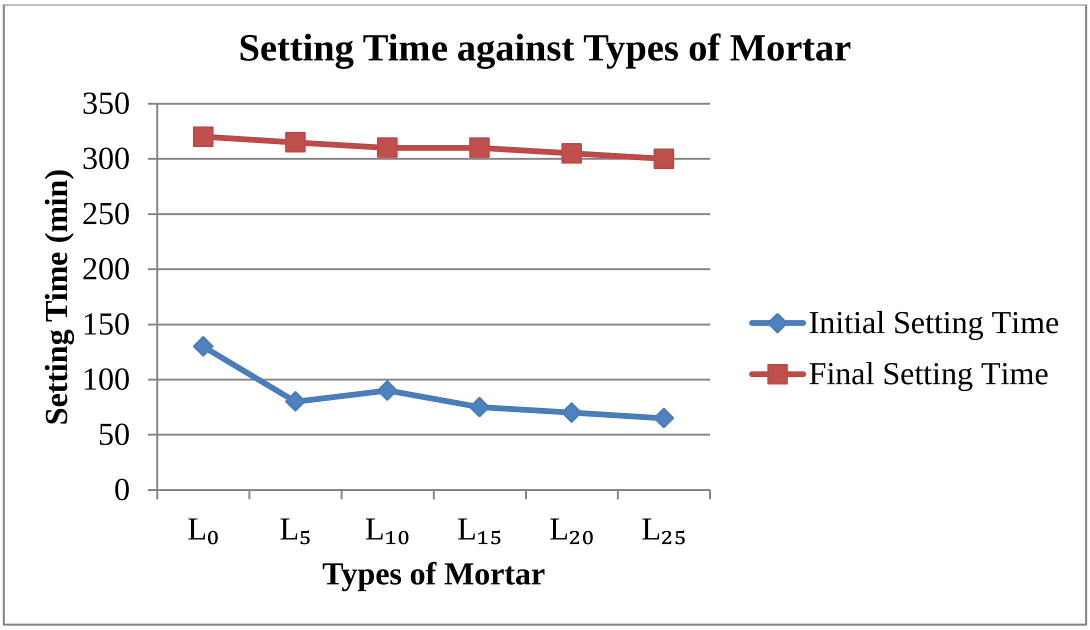

Figure 4.17 : Graph of Setting Time against Types of Mortar

On the other hand, setting times of cement-lime mortar are increasing with the increase of the replacement level of hydrated lime. Figure 4.17 showed that the faster the initial setting time as the greater the replacement level of hydrated lime, which ranges from 130 to 65 minutes. However, the result shows no significant decrease in the final setting time which decreases from 320 to 300 minutes. However the trend of both initial and final setting time in this study opposes the study of Elaty & Ghazy in the year of 2014. Their research showed that addition of hydrated lime delayed both initial and final setting time of the pastes. However, the BS 12:1996 stated that the initial setting time of Ordinary Portland Cement shall not less than 1 hour (60minutes) whereas the final setting time of OPC shall not more than 10hours (600minutes). Thus, all the mortar from L_0 to L_{25} have fulfilled those requirements.

4.10 Structural Application

Three sides of brick wall were constructed and well-prepared as a prototype to apply the control mix of mortar (L_0) and the selected cement-lime mortar. The purpose of the structural application is to test for the practicability of the selected mortar and have a comparison between selected mortar and the control mix mortar. Three stages of the processes which are during the mixing of mortar, plastering of the wall and the conditions of hardened plaster on the wall are observed and recorded. The L_{10} specimen which represented 10% of cement replaced by hydrated lime is selected as the optimum cement-lime ratio mortar among 5 types of mortar because the research showed that the L_{10} specimen provided ideal workability and properties with lowest porosity which is the most important factor to affect the durability of the mortar. The mortar with lowest porosity indicated the lowest penetration of water, moisture , water absorption, resist to chemical attack and so on.

Figure 4.18 : Well-constructed Brick Wall

As the L_{10} are selected as the optimum cement-lime ratio mortar, L_0 and L_{10} mortar are mixed and applied to the brick walls which were constructed before. During the mixing process of the mortar, the L_{10} mortar showed a higher workability than L_0 mortar. The L_{10} needed lesser force to mix and apply to the brick wall. Not only that, the L_{10} mortar showed that something like a layer of water retain on the surface of the mortar in the bucket. It was easier to use the trowel to get the L_{10} mortar than L_0 mortar.

Figure 4.19 : The Process of Plastering

During the plastering process, the L_0 was very difficult to adhere to the wall. The L_0 mortar always dropped off from the brick wall which leads to a lot of residuals of mortar dropped onto the floor and I had to take the mortar and mixed with the remaining mortar again. Not only that, a large area of plaster was flacked off from the wall while I was plastering another part of the wall. However, the L_{10} mortar was more adhesive compared to the L_0 mortar. The L_{10} was easier to stick to the brick wall. There are little residue of mortar drop onto the floor compared to the L_0. Lesser time was used to plaster the wall by using L_{10} mortar instead of L_0 mortar. Besides, the L_{10} mortar is easier to trowel up to the wall compared with the L_0 mortar. By comparing the L_0 and L_{10} mortar in fresh state, a smoother surface was easier to obtain as I troweled fewer times. However, rough surface with appearance of sand was observed on the surface of L_0 fresh mortar. After the plasters were hardened, the plaster of L_{10} gave a smoother and glossy surface instead of L_0 mortar. A sandy and coarse surface can be observed and felt with hand.

Comparison between L_0 and L_{10} Plaster		
	L_0 mortar	**L_{10} mortar**
Before	Lower workability Difficult to mix compared with L_{10} mortar	Higher workability Easier to mix compared to the control mix
During	Difficult to apply onto the wall. Took longer time to plaster the wall. Flacking off of the plaster from the wall. Lower adhesiveness.	Very easy to trowel up to the wall. Took lesser time to plaster the wall. No flacking off of the plaster and lesser amount mortar dropped off from the wall.
After	Rough and uneven surface Sandy appearance	Even, smooth and glossy surface

Comparison between L_0 plaster and L_{10} plaster.	
L_0 plaster	**L_{10} plaster**
 **Figure 4.20 : L_0 plaster with uneven surface**	 **Figure 4.21 : L_{10} plaster with more even surface**
 **Figure 4.22 : L_0 plaster with rougher surface with sandy appearance**	 **Figure 4.23 : L_{10} plaster with smoother and glossy surface**

CHAPTER5

CONCLUSION AND RECOMMENDATION

5.1 General Conclusion

The investigations of engineering properties and durability properties of mortar with different level of replacement of cement with hydrated lime have been completely and successfully conducted. Throughout this study, it can be concluded that less amount of replacement of hydrated lime is generally suitable for partial replacement of cement material as it did provide a good result as compared to the control of the study. Partially replacement of cement with 10 % of hydrated lime can help in enhancing the water retention, workability and surface of the hardened mortar in plastering. It gave the lowest porosity percentage among 5 types of cement-lime mortar as the porosity is the main factor which will directly affect the durability properties of the mortar.

5.2 Early-age Behaviour and Engineering Properties of Mortar with Replacement of Cement with Hydrated Lime

The early-age behaviour and engineering properties are examined by conducting the flow table test, setting time test, density test and compressive strength test. Throughout the investigations, conclusions can be drawn as follow:

1. The workability of mortar has a slightly increase with 5% of replacement of cement with hydrated lime whereas the decreasing trend of workability is observed as more cement was replaced with hydrated lime.

2. Both initial and final setting time of cement-lime mortar is remarkably shortened as the greater the amount of replacement of cement with hydrated lime.

3. Downward trend is obtained in density with the increment of replacement of cement with hydrated lime due to less dense of amorphous particles.

4. Higher percentage of replacement of cement with hydrated lime decreased the compressive strength of the cement-lime mortar as less formation of C-S-H gel.

5.3 Durability Properties of Mortar with Replacement of Cement with Hydrated Lime

This study is to investigate the durability properties of the mortar with hydrated lime as partial replacement material for the cement. Water absorption ability, porosity, capillary absorption coefficient and gas permeability rate were carried out to examined the durability properties of the specimens. All though the study, the following conclusions can be made:

1. The ability of water absorption is increasing as the replacement level of cement with hydrated lime is increase.

2. A general upward trend is observed in porosity of the cement-lime mortar, the lowest porosity of is obtained in the mortar with 0% of hydrated lime.

3. Capillary absorption coefficient is to be found that independent to the porosity of the structure whereas it is depend on the interconnected voids and homogenous porosity with continuous-path of the structure. However, the greater amount of replacement of cement with hydrated lime would enhance the ability of capillary absorption of the mortar.

4. A similar trending is obtained in the gas permeability rate, the L_{25} mortar has the highest gas permeability rate among all the specimens which is correlated to the porosity of the structure.

5.4 Optimum Cement-Lime Ratio for Plastering to Prototype

The L_{10} mortar which represented 10% of cement content was replaced by hydrated lime was chosen as the optimum cement-lime ration among the 5 types of the cement-lime mortar. The reason to choose L_{10} plaster as the optimum cement-lime ratio mortar is due to the L_{10} mortar provided average performance in mechanical and durability properties. Although the L_0 mortar has a higher workability which is very important for plastering, but the workability is a little bit higher which may lay to bleeding of the plaster. After the L_{10} mortar was applied to the prototype with the L_0 mortar, the L_{10} mortar showed a better performance too in the workability and provided a smoother and glossy surface rather than a sandy and rougher surface which will affect the paint work in the future.

5.5 Recommendation for Future Research

In reality, most of the construction industry is using lime as additive in mortar for plastering for the purpose of increasing the workability. However, they did not know the actual concept and the effect after hydrated lime powder being added into the mortar. After this research was carried out, there are still some recommendations for future research to be carried out in order to develop a reliable and quantified data.

1. Carry out chemical composition test such as Energy Dispersive X-ray (EDX) and X-ray Fluorescence (XRF) to exactly characterize the chemical compound within the hydrated lime in order to have a deep understanding of chemical reaction in the mortar mixture.

2. Conduct Brunauer–Emmett–Teller (BET) surface analysis to observe specimens' surface to analyse the structure of the specimens and pore size distribution in order to obtain more accurate data as support of study.

3. A comprehensive study on the Initial Setting Time and Final Setting Time of the specimens with different replacement of cement with hydrated lime.

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