EFFECT OF POLYVINYL ALCOHOL (PVA) ON TENSILE STRENGTS OF MORTAR

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CERTIFICATION OF APPROVAL

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by

Noor Amalina Hidayu Binti Fuaddin

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CERTIFICATION OF ORIGINALITY

This to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

NOOR AMALINA HIDAYU BINTI FUADDIN

ABSTRACT

The paper is focused on the results experimental of Polyvinyl Alcohol (PVA) action into tensile strength of mortar. The main objective of the project is to study the effects of PVA in mortar mixing in increasing the bond between aggregate and cement paste. PVA acts as an adhesive material between cement and aggregate of mortar especially for finishing works. PVA is being incorporated in the mixing as it is an environmental-friendly product and less expensive. Besides that, the research is to prove that finer aggregates will result in higher tensile strength of mortar. Another objective is to determine the influence of PVA into Interfacial Transition Zone (ITZ) of mortar. ITZ is one of the factors that influence the strength of mortar. This zone is the weakest link in the mortar matrix because it has the highest porosity. Further properties of ITZ are discussed in this report. In order to complete the project in time and to achieve the objectives of the project, several methods need to be implemented. They are project plan, literature review (properties of mortar, PVA and ITZ), calculations and laboratory works. During laboratory works, the application of PVA is varied to determine the optimum mix design. The tests for mortar samples are tensile test and compressive test. Testing onto mortar is done for 3rd day, 7th day and 28th day. Based on the results obtained from experiments, it can be concluded that PVA increases tensile strength but reduces the compressive strength of mortar. The recommendation from this project is that further studies of behavior of PVA into shrinkage of mortar can be done. This research might lead to a stage where PVA will replace other materials in order to increase tensile strength of mortar.

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CHAPTER 1

INTRODUCTION

1.1. Background Studies

Mortar has been widely used since ancient civilization. It is a building compound composed of sand, cement and a specified amount of water. The composition solidifies and hardens after mixing and placement due to a chemical process of cement hydration. The amount of water required for mixing will vary according to the proportion and condition of the sand. Sometimes mortar is also referred to sand cement.

Mortar is used for plastering over bricks or other masonry. It acts as an excellent binder between bricks in walls, fences and walkways. Mortar is also used for quick repair in slabs or retaining wall. The children's recreational equipment such as swing sometimes sets firmly in the ground by using mortar. Homeowners always do this to minimize the chances of the equipment shifting or toppling in use.

Due to its many applications, researchers in many countries have made modification towards mortar. The reason for this is to improve the mechanical behavior such as workability, durability and various strength of mortar. Some applications of mortar require them to have high tensile strength so that they can reduce chances of having any cracking or shrinkage. Such applications are for cement rendering and plastering of non-loadbearing wall.

Nowadays, mortar mixes are often incorporated with different grades of polymer to create a polymer cement mortar. Cement mortar which has been added with polymer is chemically active towards its hardening. Polymer is used as an additive material in mortar as it improves the properties of mortar. Polyvinyl Alcohol (PVA) is one of the polymers used in the mortar mixing. The use of PVA as a cement additive has been escalated due to its economic price and environmental friendly.

1.2 Problem Statement

In 1996, the walls of one of a brick building in New York City were pushed outward by barrels of flour piled against the walls. The walls suddenly fell into the street. An examination showed that the problem was caused by the poor quality of mortar. The mortar used has little adhesion and low tensile strength.

Based on the evidence, the tensile and adhesive strength of mortar are two important parameters in mortar. Usually, whenever a building has fallen due to poor mortar, it has been generally account of tensile strength failure of the mortar. It is generally known that concrete has high compressive strength but extremely weak in tensile strength. This is the same case for mortar. However, the strength of mortar to resist compression is not of the great importance as it seldom fails this way.

There are many disadvantages of low tensile strength in mortar. The tensile strength is defined as the resistance of a material to a force tending to tear it apart, measured as the maximum tension the material can withstand without tearing. The extreme weak in tensile strength will lead to low ductility. Mortar with low ductility has the tendency to break easily. The causes of tensile stress are tensile or flexural loads, temperature changes, shrinkage, and moisture changes.

The adhesion of mortar to brick or stones varies greatly with the different materials and the number of porosity. The adhesion of mortar depends on the quality of cement, character of the sand and the amount of sufficient water. Adhesion strength is influenced by area known as Interfacial Transition Zone (ITZ). ITZ is the highest porosity zone in normal mortar matrix. The higher the porosity, the lower the adhesion strength of mortar will be. Micro cracks are always present here, failure will normally occur from this zone. The presence of interfaces between cement paste and aggregates will lead to increase of cracks in the mortar.

1.3 Objectives of Research & Scope of Study

The objectives of the research are:

i. To study the effects of PVA in mortar mixing in increasing the bond strength between aggregate and cement paste.
ii. To determine the influence of ITZ to tensile strength.
iii. To prove the hypothesis made in the early stage which is finer aggregates will result in higher tensile strength compared to coarser aggregates.
iv. To determine the optimum mix design of mortar by incorporating PVA.

The study for this project mainly focuses on increasing the tensile strength of mortar. Therefore, the scope of study is constrained to as follows.

i. Conduct laboratory experimental assessment towards mortar instead of using concrete.
ii. Assessment of laboratory experiments with different concentration of PVA to obtain optimum mix design. The tests for samples are tensile test and compression test with static load.
iii. Comparison between the results obtained from FYP II student (concrete incorporated PVA) and the results obtained from the laboratory experiments by FYP I student (mortar incorporated PVA).

CHAPTER 2
LITERATURE REVIEW

This chapter explains the fundamental of mortar and its properties. Mortar properties can vary significantly depending on the choice of materials and proportions for an application.

2.1. Mortar Constituents

Mortar is defined as a material used in a plastic state, becomes hard in place due to chemical reaction and hydration of cement. The word "mortar" is used without regard to the composition of the material but simply defining its use as a bonding material (A. D Cowper, 1927).

Mortar is a mixture of two components, namely fine aggregates and paste. The paste, comprised of cement and water, binds fine aggregates (sand) as the paste hardens because of the chemical reaction of the cement and water. The strength of mortar depends upon the properties of the mix, the properties of its ingredients, and other controls during placing, vibrating and curing. Mortar with high quality of cement governs the high performance of the mechanical behavior. The ASTM standard for cement in mortar is listed in Table 2.1

Table 2.1.ASTM Standard for Cement Mortar

ASTM Std No.	Name of the Standard
C91	Specification for masonry cement
C150	Specification for Portland Cement
C595	Specification for Blended Hydraulic Cement
C1157	Performance Specification for Hydraulic Cement
C1329	Specification for Mortar

Cement can be described as a material with adhesive and cohesive properties which make it capable of bonding mineral fragments into a compact whole. The cement hardens and sets under water by virtue of chemical reaction with it and therefore, called hydraulic cements. (A.M Neville, 2002). Four compounds are usually regarded as the major constituents of cement: They are listed in Table 2.2.

Table 2.2. Main Components of Portland Cement

Name of Compound	Oxide Composition	Abbreviation
Tricalcium silicate	3 $CaO.SiO_2$	C_3S
Dicalcium silicate	$2CaO.SiO_2$	C_2S
Tricalcium silicate	$3CaO.Al_2O_3$	C_3A
Tetracalcium aluminoferrite	$4CaO.Al_2 O_3. Fe_2 O_3$	C_4AF

Sand is another component in mortar mixing. Based on the research by A.D Cowper (1927), the important parameters of the sand in mortar are its type and shapes. Besides that, the cleanliness and a uniform distribution of particle size of sand also appear to be of great importance. Sand also has to be free from chemical and clay in order to obtain good mortar mixing and to avoid deterioration.

Dibdin (1912) in his series tests has emphasized that the mortar containing the right proportion of sand in a fine state division can tolerate serious loss of ultimate strength. This is more obvious when the sand itself contains a large proportion of the finer sizes.

Water is one of the components in the concrete. The presence of water is to allow occurring of hydration process of Portland cement. The quality of hardened concrete is greatly influenced by the amount of water used in relation to the amount of cement. Higher water contents dilute the cement paste. Besides, the impurities of water affect the setting of cement and eventually affect the concrete strength adversely or cause staining of its surface and also lead to corrosion to reinforcement. (A. M. Neville, 2005).

By hydration process- reaction with water- Portland cement mix with sand and water produces mortar. Cement gel with high compressive strength when it hardens is being produced from this chemical process as recrystallization occurs. The higher the percentage of C_3S, the higher early strength of Portland cement will be obtained. The strength level is continuously increasing with higher percentage of C_2S if moist curing continues. Therefore, the most important compound in Portland cement is C_3S where it contributes early strength development because it is earliest to hydrate (E.G. Nawy, 2001).

2.2 Selection of Mortar

The selection of mortar is important as it balances the construction requirements and the performance of the finished element with the properties of the available mortar materials and type. The mortar must be durable and must help to resist moisture penetration. The property of mortar often been overemphasized is its compressive strength.

However, making a selection based on compressive strength alone ignores other important properties. The type of mortar to be selected is mostly dependent on its applications. The selection of mortar requires careful evaluation of the properties for each type of mortar. The selection of mortar material and type determine the performance requirements for the project.

The basic rules of mortar selection are:

- Do not use a mortar stronger in compression than is structurally required by the project.
- No single type of mortar is best for all purposes.

Mortars are divided into four Types: M, S, N and O. These mortars have basic characteristics and can be used in a variety of applications. The basic mortar selection is shown table 2.3

Table 2.3. Basic Mortar Selection Guide

Locations	Building Segment	Mortar Type	
		Recommended	**Alternate**
Exterior, above grade	Reinforced or Loadbearing walls,	N	N
	Non-loadbearing walls, Parapets	S	S
	Chimneys	N	S
Exterior, at or below grade	Foundation walls, Retaining walls, Sewers Manhole, Paving	M	S
Interior	Partitions	N	S

The basic characteristics for each types of mortar are as below:

Type N mortar: General all-purpose mortar with good bonding capabilities and workability.

Type S mortar: High tensile and flexural bond strength.

Type M mortar: High compressive strength mortar but not very workable.

Type O mortar: Low Strength mortar.

Based on the applications stated, mortar for non-load bearing wall and for rendering cement, high tensile strength in order to reduce shrinkage which causes cracks in the plaster. Crack occurs in the angles at the ceiling of corners of the room. It happens due to rapid drying of mortar in its first coat. In the perpendicular angles, they may extend to the depth of the finishing coats.

2.3 Tensile Strength of Mortar

Tensile strength is defined as the amount of tensile stress subjected to material before failure. Tensile strength in mortar gives practical significance of mortar fracture occurs through cracking. In another words, mortar fracture is essentially a tensile failure regardless of whether the fracture is caused by compression, freezing or by other factors.

Tensile stresses in structures are caused by more-or-less uniform shrinkage or drying and by temperature changes. The tensile strength, f_t, increases as the compressive strength, f_c, increases but in decreasing rate. A number of empirical formulae connecting f_t and f_c have been suggested and in general, the equation goes to be:

$$f_t = k(f_c)^n$$

where k and n are coefficients. Normally, n value is 0.7 meanwhile k value could be 0.3, 0.2 or 0.12, depending on the loading conditions but this is not very important since the differences between the various expressions are not large (Popovics, 1998).

The distribution of horizontal stresses in the internal surface between the loaded generatrices of a cylinder is under splitting test. The load P is transmitted over a strip of width D/12 (Popovics, 1998). This is shown in the figure as follow:

In mortar, tensile strength is more sensitive to the increase in the strength of the paste-aggregate link than compressive strength. Tensile strength is significant to mortar as it holds the mortar together. Mortar with low tensile strength will crack easily and has the tendency to fall apart when the cracks are bigger.

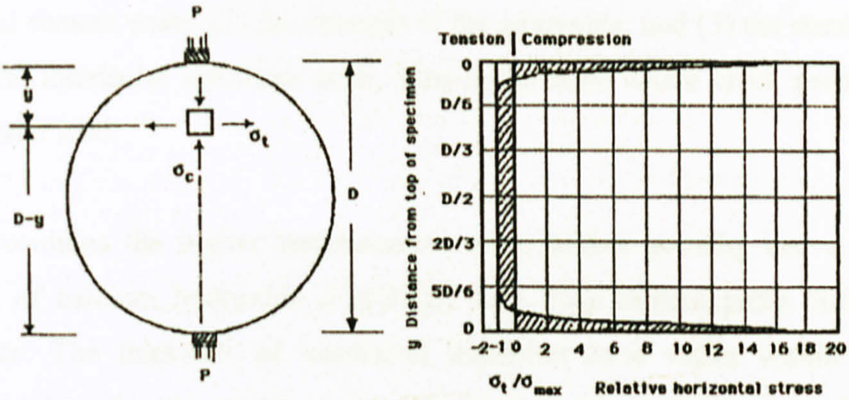

Figure 2.2. The distribution of horizontal stresses in the internal surface between load and cylinder under splitting test

The tensile strength can also be determined by equation below:

$$T = 2P / \pi LD$$

Where; T = tensile strength
P = failure load
L = length of specimen
D = diameter of specimen

(A. M. Neville, 2005)

2.4 Interfacial Transition Zone

Mortar strength may be influenced by three factors: (1) the strength of the matrix, mostly hardened cement paste; (2) the strength of the aggregate; and (3) the strength of the bond called the interfacial transition zone. This is the zone where crack propagation usually starts under load.

It also contains the higher water-cement ratio, higher porosity and a higher volume fraction of calcium hydroxide ($Ca(OH)_2$) than does cement paste farther away from aggregate. The thickness of interfacial transition zone varies within 10 to 50 µm. Therefore, lowering the water-cement ratio increases the concrete strength and makes the matrix stronger. The material in the transitional ring becomes denser and stronger. The presence of ITZ in the aggregate is shown in the Figure 2.3.

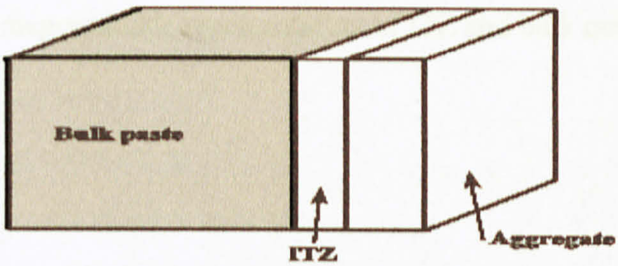

Figure 2.4. The presence of ITZ around aggregate particles in mortar

In their experiments by E.J Garboczi and D.P. Bentz (1978), they found that ITZ exists around aggregate (rock,sand) particles in mortar and concrete. This is due to flocculation of cement paste matrix. Microcracks is a major factor which contributes to poor strength of ITZ. On first upon loading, ITZ will fail first which eventually initiates fracture of the mortar or concrete.

P.K Mehta and P.J.M Monteiro (2006) discovered that there are several factors influencing the amount of microcracks in ITZ. They are aggregate size and grading, water-cement ratio, cement content, curing conditions, consolidation degree of fresh concrete and thermal history of mortar or concrete.

The tensile stresses induced by differential movement of aggregate and cement paste can also produce cracks in ITZ even before a structure is loaded. Therefore, cracks propagate rapidly at much lower level under tensile loading compared to compressive loading. The diagrammatic of ITZ and bulk cement paste is as shown in Figure 2.5.

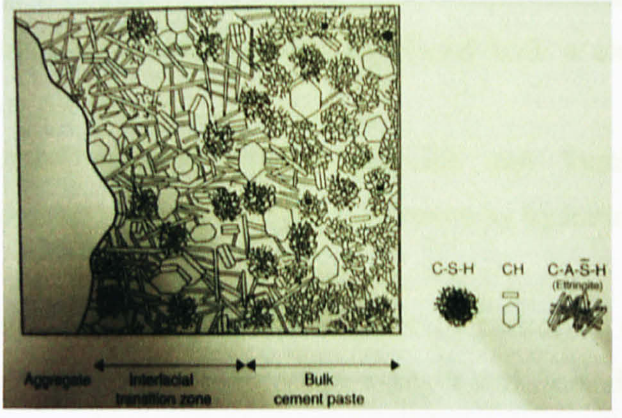

Figure 2.5. The diagrammatic representation of ITZ and bulk cement paste.

2.5 Polyvinyl Alcohol (PVA)

Polymer modification of cement paste increases its tensile and flexural strength by increasing the toughness of mortar and concrete. In the research by Ivan Razl (2004), he described the mechanism of polymer modification of Portland cement paste in three separate steps which are:

1. Cement paste particles start to hydrate after mixing with water. Cement gel begins to form on the surface of the cement particles.
2. The mixture of cement gel is enveloped with a close-packed layer of polymer particles.
3. The closely packed polymer particles start forming polymer films (membranes) when water is being removed by hydration and evaporation.

Polyvinyl Alcohol is a water-soluble polymer made by hydrolysis of a polyvinyl ester (such as polyvinyl acetate). It has high tensile strength and flexibility, as well as high oxygen and aroma barrier properties. However these properties are dependent on humidity, in other words, with higher humidity more water is absorbed. PVA exists in white solid color with excellent tensile stress, mouldability, impact strength, wear resistance and excellent electrical insulation. The molecular structure of PVA is as shown in the equation of Figure 2.6;

$$-(-CH_2-\underset{\displaystyle OH}{\overset{|}{CH}}-)_n-$$

Figure 2.6. Molecular structure of PVA

Water, which acts as a plasticizer, will then reduce its tensile strength, but increase its elongation and tear strength. PVA is fully degradable and is a quick dissolver. PVA has a melting point of 230°C and 180–190°C for the fully hydrolyzed and partially hydrolyzed grades. It decomposes rapidly above 200°C as it can undergo pyrolysis at high temperatures. PVA is mixed with water to obtain different concentration of PVA, namely 2%, 3% and 4%.

This project is to implement PVA into mortar. The results for tensile strength and compressive strength will be observed. Based on the studies by Fernando Antonio et al. (2008), tests performed on mortar incorporated polymer have the beneficial action on tensile strength of mortar but smaller contribution on the compressive strength. These mechanical behaviors result from the polymer action on the atrophy of hydrated $Ca(OH)_2$ crystals and the reduction in the density of microcracks in the paste-aggregate interface.

The strength of paste-aggregate link increases due to the action of polymer. Polymer acts as an adhesive material which binds the link together. The higher the concentration of polymer incorporated in mortar, the higher the tensile strength is. Simultaneously, Polymer in the mortar reduces the density of microcracks of the paste.

In 2008, Fernando Antonia discovered that cement paste with lower microcracks density has more effect on tensile strength than compressive strength. This is due to propagation of microcracks occurring easily in lower level load under tensile forces than under compressive forces.

However, the performance of each type of polymer differs depending on the molecular structures. In this project, PVA has been chosen to be tested in mortar as the use of PVA is more economical compared to other polymer and it is environmental friendly. In addition, PVA improves the resistance from segregation of aggregates due to increase of viscosity when mixing with water. The increase of viscosity results in retarding flocculation of cement grains.

2.5.1 BF17W (Fully- Hydrolyzed Polyvinyl Alcohol)

Fully hydrolyzed grade in PVA is known as BF17W. BF17W comes in powder form and heated with water to form a solution which looks like an adhesive or glue in certain concentration desired. Table 2.4 shows the properties of BF17W (Fully-hydrolyzed Polyvinyl Alcohol).

Table 2.4. Typical properties of BF17W

Items	Unit	Results
pH	None	6.00
Viscosity	Cps	28.9
Hydrolysis	Mole %	96.93
Volatile	Wt %	2.62
Ash	Wt %	0.31
Colour	None	White to Ivory

CHAPTER 3
METHODOLOGY

Several methodologies need to be done in order to achieve the objectives of this project. This chapter includes the procedure identification and brief description for procedures.

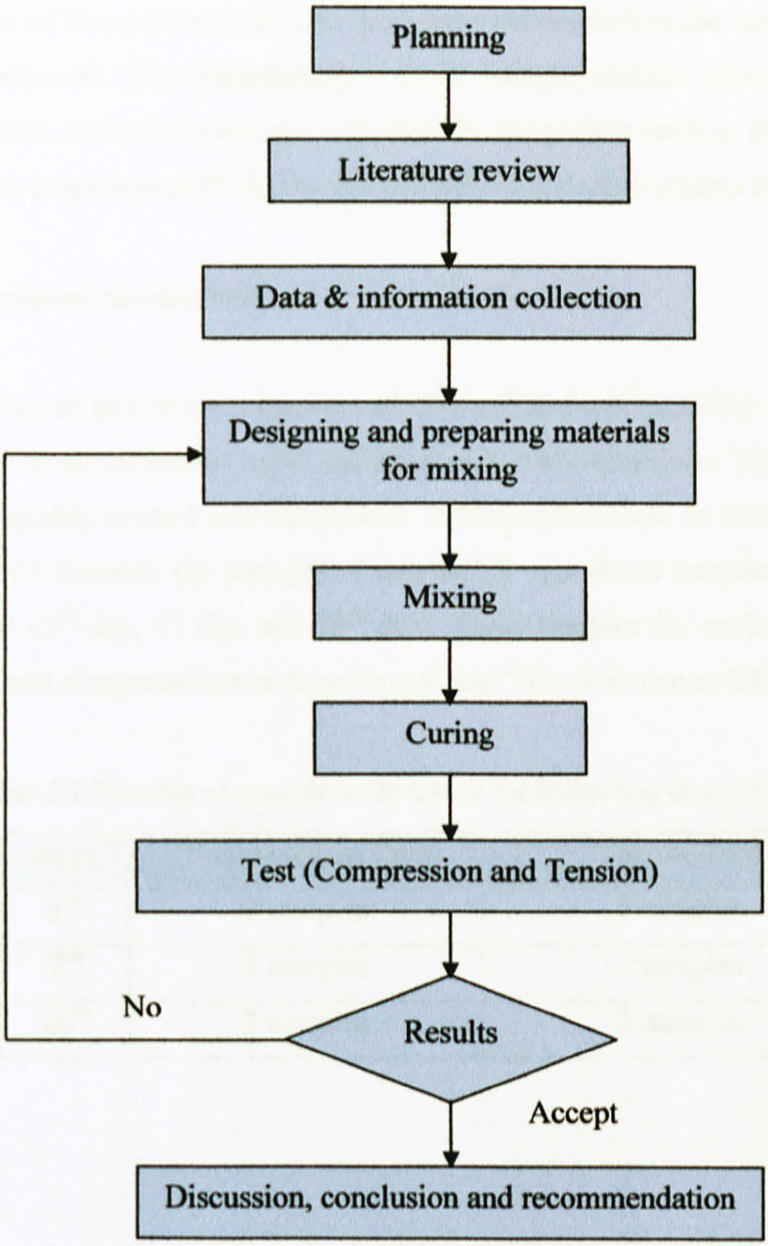

Figure 3.1 Flow Chart of Research of Methodology

3.1 Project Planning & Literature Review

Planning is a compulsory methodology in any project. Planning is done by establishing milestones and making decisions. Project planning and literature review are the crucial methodologies at the early stage of this project (refer appendix A-1,A-2,A-3).

The purpose of literature review is to have deep understanding and basic fundamental of the topic proposed. This methodology is done through journals, articles, books and also websites. Data and information are collected for the project such as the properties of the concrete, the properties of PVA, the test procedures and other related theories.

3.2 Hardened mortar tests

The properties of mortar are a function of time and ambient humidity. Therefore, tests on mortar have to be performed under specified or known conditions. The two objectives of testing are quality control and compliance with specifications. In order to determine the effect of PVA towards the strength of mortar, 18 cylindrical samples are cast for three days of test (3^{rd} day, 7^{th} day and 28^{th} day). Three samples for each tests namely, split tensile test and compression test for each test day. This is shown as table below:

Table 3.1 Number of sample to be tested for following days (3^{rd}, 7^{th} and 28^{th})

Days	Compression Test	Tensile Test
3^{rd}	3 samples	3 samples
7^{th}	3 samples	3 samples
28^{th}	3 samples	3 samples

For mortar tests, the total of 126 samples of 6cm diameter x 12cm length is cast. The reason for this amount of samples is that 6 samples of hardened mortar are required for tests (compression test and tensile test) in a day. Therefore, for every day of strength, 18 samples needed for testing. The tests are done for 7 times for control, saturated surface dry aggregate (SSD) and dry aggregate (Dry). Different concentration of PVA is incorporated for SSD aggregate and dry aggregate. This has made up the total of 126 of mortar samples required for the laboratory work. To make it clearer, the determinant of amount samples is represented in the table attached in appendix B-1.

3.3 Tensile Test

In the split tensile test machine, vertical compressive load is applied on the cylindrical specimen that creates compressive and tensile stresses in the specimen. The maximum stresses are located on the elements in the internal vertical surface. These vertical stresses are compressive.

The horizontal stresses are also compressive near the loaded generatrices. However, they become tensile stress as they move away from an external surface. This will form almost uniform tensile stress field exist over about 80% of the vertical plane. A cylindrical specimen is usually recommended for the split tensile test machine.

The mortar is positioned horizontally in order to measure the tensile strength of the mortar. This is shown in the Figure 3.2.

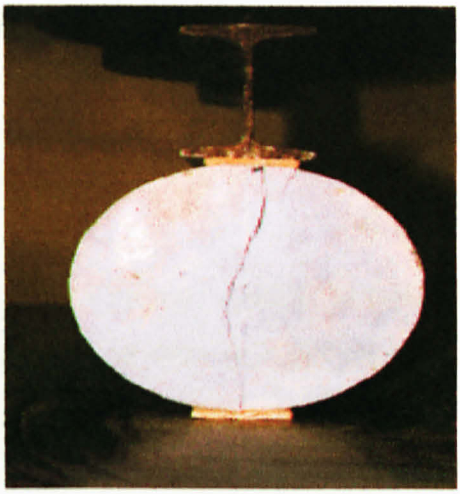

Figure 3.2. Compressive load applied on mortar which is positioned horizontally.

In this project, the mortar samples are also been tested for its compressive strength. This is to determine whether PVA also has effects towards compressive strength of mortar. The mortar is positioned vertically in order to measure the compressive strength of the mortar as shown in Figure 3.3.

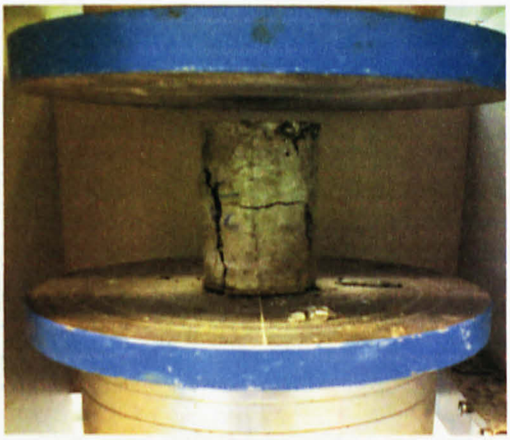

Figure 3.3. Compressive load is applied on mortar which is positioned vertically.

3.4 Hazard Analysis

A hazard is described as potential harmfully situation which poses level threat to life, health, property or environment. Hazard has many causes which are; (1) natural, (2) manmade and (3) activity related. Natural hazards include anything which is caused by natural process such as volcanoes. Manmade hazards are created by humans, which includes a huge array of possibilities.

Since this project is regarding with concrete, working in concrete lab exposes a person with a lot of hazards. Hence, good practice in handling material is important while conducting the laboratory works.

In order to prevent the accident and illnesses, the prevention method should be applied. In concrete lab, we can reduce the risk of unsafe conditions and acts by:

- Practice good housekeeping
- Follow the procedures and instruction by lab technician
- Use proper lifting method
- Use appropriate personal protective equipment (PPE)
- Follow all the rules provided by laboratory

When working with fresh concrete, care should be taken to avoid skin irritation or chemical burns. Prolonged contact between fresh concrete and skin surfaces, eyes, and clothing may result in burns that are quite severe, including third-degree burns. If irritation persists consult a physician. For deep burns or large affected skin areas, seek medical attention immediately.

Other chemical hazard that possibly happens during this project is PVA. PVA can cause irritation to eyes and skin. Therefore, to avoid these physical hazards, it is required to use appropriate personal protective equipment (PPE) such as gloves and goggle as shown in Figure 3.4.

Figure 3.4. Gloves need to be worn during mixing to avoid hazards

It is a must to wear earmuff when working with vibration table. The vibration table causes extremely loud noise. The sound made by vibration table is very high in decibels which can affect hearings. Therefore, besides wearing glove while fill in fresh mortar in the mould; earmuff needs to be worn too as shown in Figure 3.5 below:

Figure 3.4. Wearing earmuff is a must during vibration of samples

3.5 Tools and Materials

The tools and materials needed to prepare PVA solution are as per listed below:

1. Distilled water
2. BF17W Polyvinyl Alcohol
3. A hot plate with a magnetic stirrer
4. 1 liter beaker
5. thermometer
6. steel stirrer

The materials that have to be prepared before conducting a mixing are as per listed below:

1. Ordinary Portland Cement
2. Water
3. Fine aggregate (sand with size of 70μm)
4. Sieving machine
5. Cylinder mould
6. Pail and tray
7. Concrete Mixer
8. Vibrating Table
9. Scrapper

3.6 Experimental work

The experimental work is done in order to prove that smaller size aggregate (70μm) will result in higher tensile strength. The results obtained are compared with previous experimental work with the aggregate size of 0.15mm to 5 mm.

The variables for mixing design are as below:

i. Two types of aggregate conditions which are saturated surface dry (SSD) and dry aggregate.
ii. Three different concentrations of PVA solution which are 1%, 2% and 3%.

3.6.1 Mixing Procedure

The mix is designed based on fraction of aggregate to cement to water. The water to cement ratio is 0.35 and aggregate cement ratio is 2:1. Different concentration of PVA is used. PVA is diluted by three different mix ratios (PVA: Water) namely, (1:2),(1:3),(1:4).

i. Prepare all materials for mixing and weigh them according to mix design.
ii. Clean the drum mixer thoroughly with water.

    Note: Drum mixer has to be cleaned with water so that the mixing water will not be absorbed by drum.
iii. Pour all fine aggregates and cement into mixer and mix for two minutes.
iv. Pour half of the water with PVA solution and mix for two minutes. Make sure that PVA solution is completely dissolved in water.
v. Pour another half of water with PVA solution and mix for two minutes.
vi. Perform a hand mixing and mix again for two minutes.

3.6.2 Aggregate Preparation

Preparation of aggregate has to be done in a correct way as it is one of important factor of strength in mortar. For this experiment, fine aggregate is being used for mixing. The procedure of preparation is as follows:

i. Arrange the sieve according to its sizes and carry out the sieving for about 15 minutes.
ii. Wash the aggregate to remove the grass and unnecessary things.
iii. Soak for one day in order to achieve the saturated surface dry (SSD) aggregate.
iv. Remove the water. Let them dry.

3.6.3 PVA Solution Preparation

PVA comes in powder form. Here, we are desired to prepare a 20% aqueous solution of PVA as shown in Figure 3.5. Hence, conventional heating method is used. The procedure is as below:

i. Heat one liter of distilled water up to 88 – 90°C on the hot plate with magnetic stirrer.
ii. Once the water is heated, added lightly the PVA into the water while stirring continuously.

   Note: This is very important to avoid the gooey mass of wet polymer that sticks together, settle out and clings to the wall of the beaker. Avoid overheating the solution.
iii. Allow the solution to cool once it is completely dissolved.

Figure 3.5.20% PVA aqueous solution

Based on studies by J.H Kim and E.Robertson (1998), polymer needs to be used at the rate of 10-20% to be effective. This rate is considerably to the cost since small of PVA have been shown to significantly increase aggregate-paste bond strength and reduce the thickness of ITZ. Therefore, PVA at a rate of 20% aqueous solution has been chosen.

3.6.4 Mould Preparation

The mould used for this experiment is in cylindrical shape with diameter of 6 cm and 12 cm length as shown in Figure 3.6. The small size of mould is chosen as it requires fewer constituents for mortar mixing. Furthermore, this is to standardize the shape of mould since experiment for aggregate size of 0.15mm to 5 mm use the same shape and size.

Figure 3.6. Cylindrical shape of mould

Before conducting a mixing, the moulds have to be prepared first. One mixing will require about 21 moulds. The amount of mould required is according to calculation. The procedure for mortar preparation is shown as below:

i. Clean the cylinder mould from dust or any unwanted items.
ii. Apply the grease inside the end cap.
iii. Place the cap and one end of cylinder mould.

3.7 Mixing Proportion

Since different concentration of PVA is being implemented for every mixing, the calculation for mixing design is varied too. The design mix for this experiment is based on aggregate to cement ratio of 2:1 and water to cement ratio of 0.35. The procedures conducted based on British Standard (BS) Codes and Practices which is BS 1881. The calculation for every mix proportion is shown in Appendix C. The mix proportion for every concentration is designed for 21 mortar samples as shown in table 3.1.

Table 3.2. Mix proportion for mortar mixing with different PVA concentrations

Mixing Components	1% PVA Weight(Kg)	2% PVA Weight(Kg)	3% PVA Weight(Kg)
Water	1.784	1.784	1.784
Cement	5.105	5.105	5.105
Sand	10.21	10.21	10.21
PVA solution	0.01784	0.036	0.054
Total	17.12	17.14	17.154

CHAPTER 4

RESULTS AND DISCUSSION

The results obtained after mortar samples have been tested for tensile strength and compressive strength. Three mortar samples were utilized for each test. In this research, different conditions of aggregates were used which are saturated surface dry (SSD) and dry aggregate. For each case, different concentrations of PVA were applied which is 1%, 2% and 3%.

The results are then compared with results of mortar with bigger size of aggregate (0.15mm- 10mm). This comparison is done to prove hypothesis that finer aggregate results in higher tensile strength. Therefore, the results for mortar with aggregate of 70 μm are expected to be higher than results for mortar of aggregate 0.15 mm to 5 mm.

To obtain percentage increase or decrease, the formula used is as below:

$$\textbf{Percentage} = \frac{\textbf{PVA strength value} - \textbf{Control Strength value}}{\textbf{Control strength value}} \times 100$$

4.1. Comparison between Control for Tensile and Compressive Strength

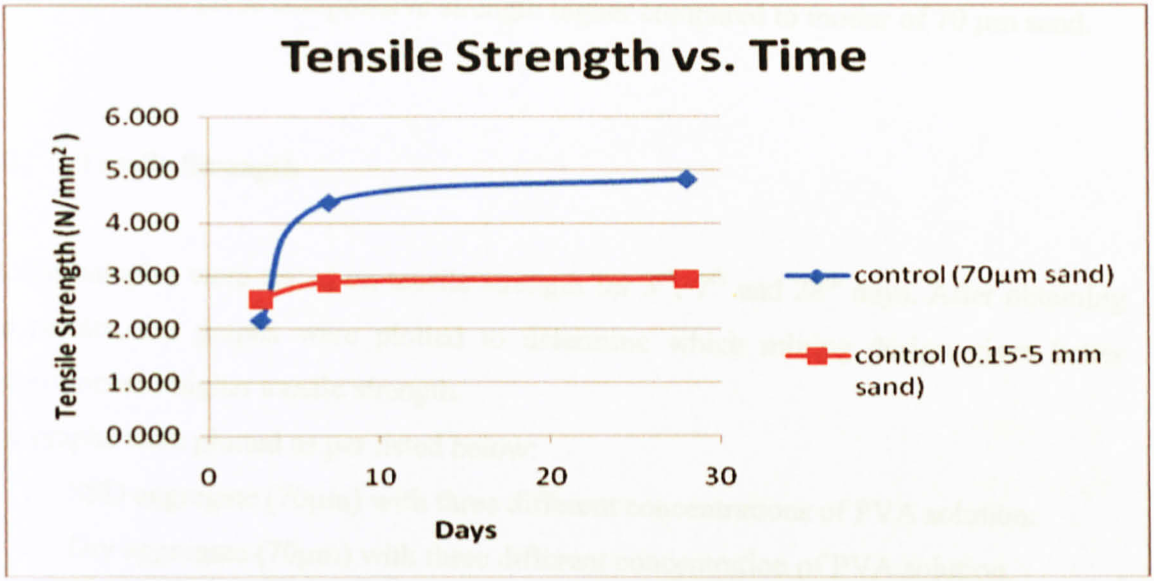

Figure 4.1. Graph of Tensile Strength vs. Time for control

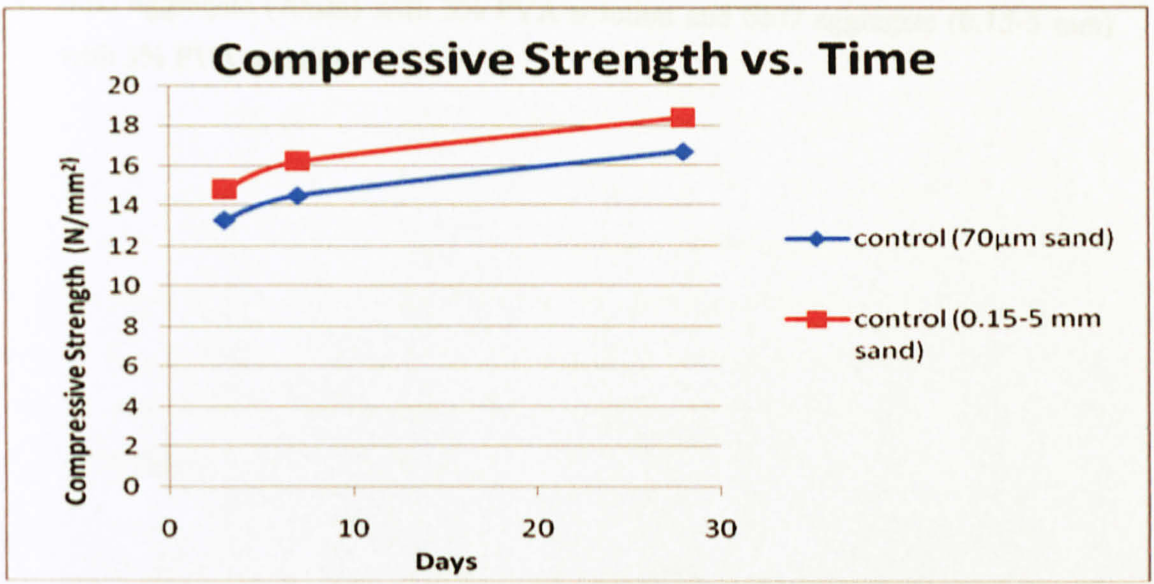

Figure 4.2. Graph of Compressive Strength vs. Time for control

Based on both graphs shown in Figure 4.1 and 4.2, it can be concluded that mortar with finer sand yields higher tensile strength than mortar with larger sand. However, mortar with larger sand gives compressive strength higher compared to mortar of 70 μm sand.

4.2. Tensile Strength

Mortar samples were tested on tensile strength for 3rd, 7th and 28th days. After obtaining the results, the graphs were plotted to determine which mixing design gives better proportion and higher tensile strength.

The graphs were plotted as per listed below:

1. SSD aggregate (70μm) with three different concentrations of PVA solution.
2. Dry aggregate (70μm) with three different concentration of PVA solution.
3. SSD aggregate (70μm) with 3% PVA solution and Dry aggregate (70μm) with 3% PVA solution.
4. SSD aggregate (70μm) with 3% PVA solution and SSD aggregate (0.15-5 mm) with 3% PVA solution.

4.2.1 SSD aggregate (70µm) with three different concentrations of PVA solution

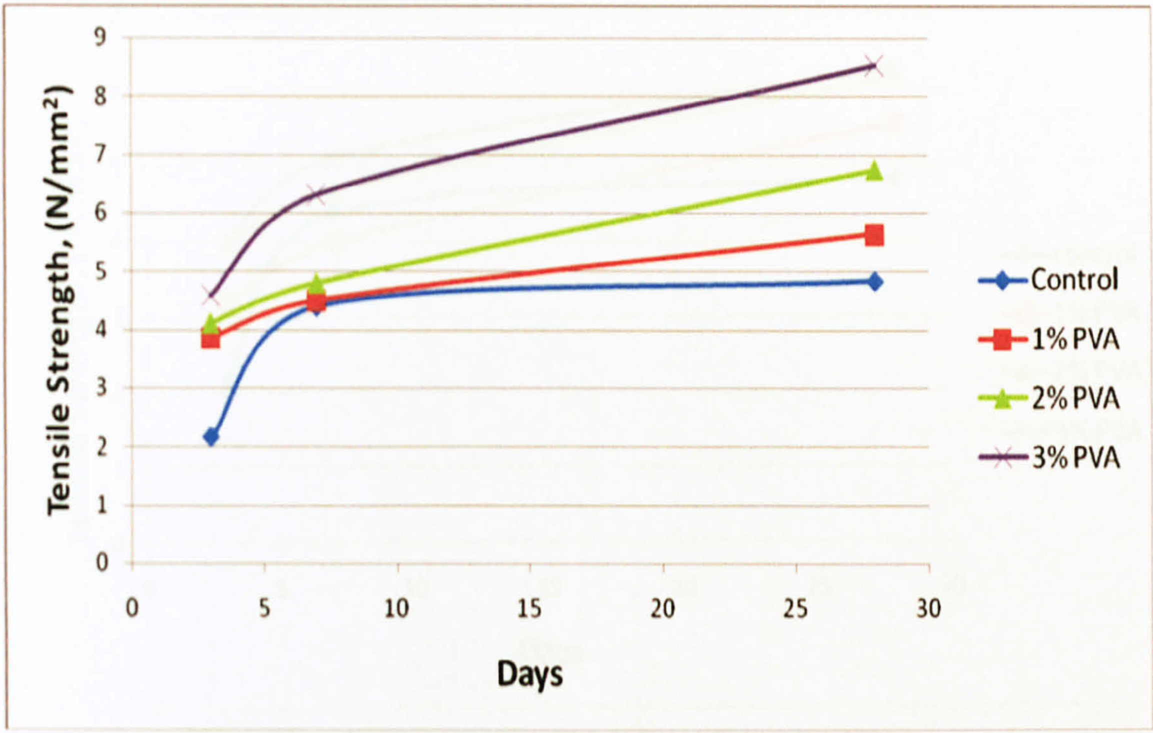

Figure 4.3. Graph of tensile stress vs. Time for SSD

Based on Figure 4.3, mortar samples with addition of PVA solution yield higher tensile strength compared to control (without PVA). For each day of testing, 3% PVA gives the highest results compared to 2% and 3%.Comparing with control samples, the value for 1% PVA at 28 days increases about 16.77%. For 2% and 3% samples, the value increases about 39.54% and 76.60%, respectively.

4.2.2 Dry aggregate (70µm) with three different concentrations of PVA solution

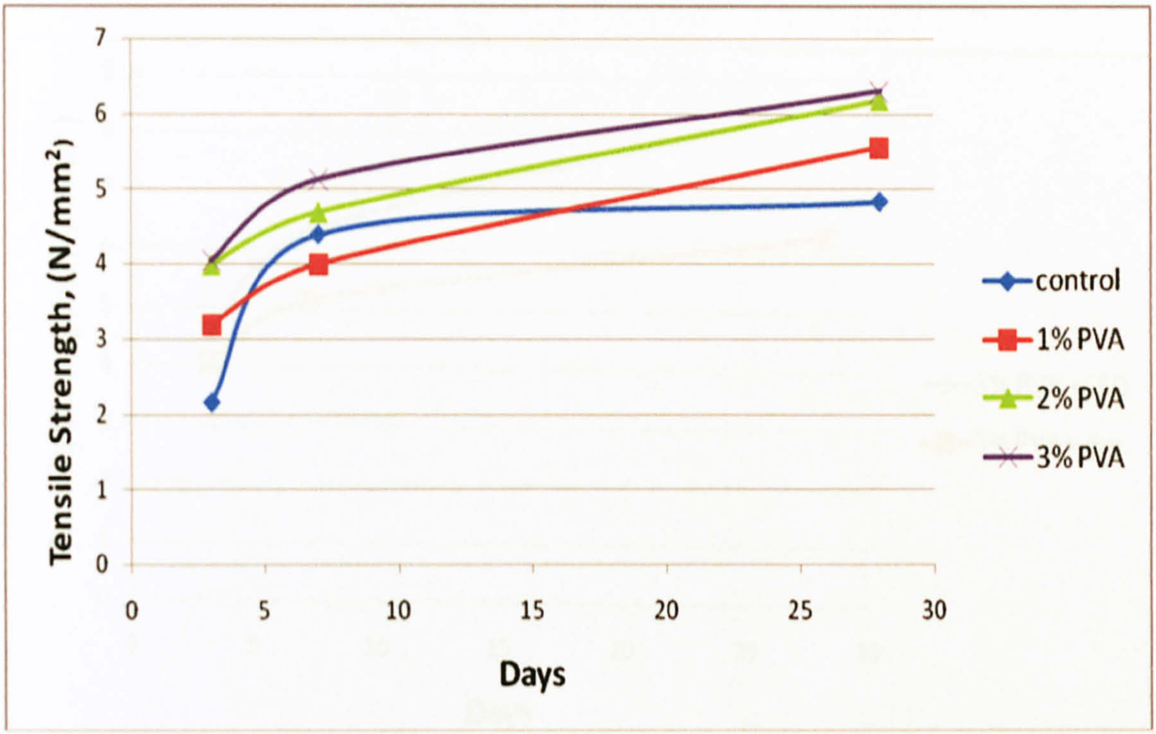

Figure 4.4. Graph of tensile stress vs. Time for Dry aggregate

Based on Figure 4.4, mortar samples with addition of PVA solution also yield higher tensile strength compared to control (without PVA). For every day testing, 3% PVA gives the highest results compared to 2% and 3%.

The difference between Figure 4.3 and 4.4 is only the condition of sand. The result obtained for dry aggregate is expected to be lower than SSD aggregate. At 28 days, the increment for 1%, 2% and 3% are 14.91%, 27.95% and 30.43%, respectively. From Figure 4.3 and 4.4, it can be seen that control gives rapid hardening at day 7 compared to samples with PVA concentrations.

4.2.3 SSD aggregate (70μm) with 3% PVA solution and Dry aggregate (70μm) with 3% PVA solution

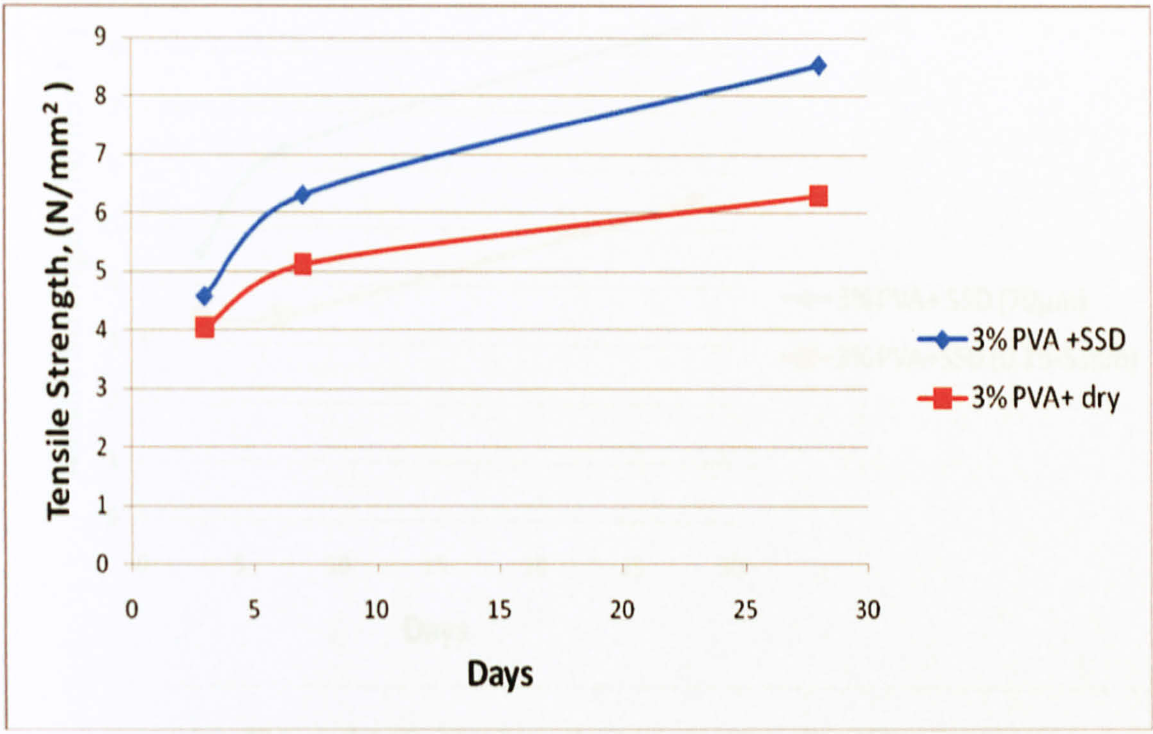

Figure 4.5. Graph of tensile stress vs. Time for 3% of both conditions

As shown in Figure 4.5, using SSD aggregate yield higher tensile strength compared to dry aggregate and control. There is a huge difference of values between SSD aggregate and dry aggregate at 28 days which is 26.14%.

Based on the previous results, it can be concluded that different conditions of aggregate affects the results. Besides PVA modification into mortar samples, the usage of different condition of aggregate influences the strength obtained. The quality of mortar depends on the type of sand which are either saturated surface dry (SSD) or dry sand. SSD is the correct proportion to use in mortar.

4.2.4 SSD aggregate (70µm) with 3% PVA solution and SSD aggregate (0.15mm- 5 mm) with 3% PVA solution

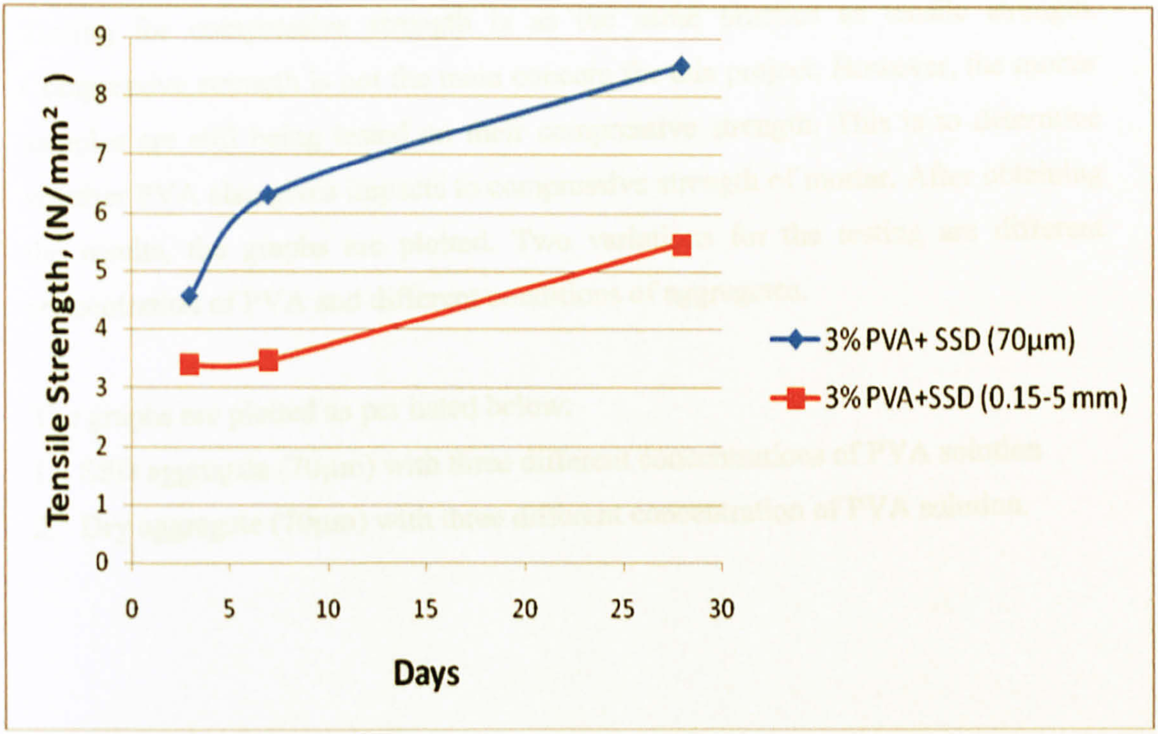

Figure 4.6. Graph of tensile stress vs. Time for different size aggregate

Comparison is being made between SSD aggregate of 70µm (finer) with SSD aggregate of 0.15mm to 5 mm in Figure 4.5. The early hypothesis made can be proven since finer aggregate (70µm) results in higher tensile strength. The percentage difference of SSD (70µm) and SSD (0.15mm to 5mm) at 28 day is 35.87%. Therefore, to obtain high tensile strength mortar for certain applications, finer aggregate is recommended. Finer aggregate means higher surface area of aggregate, therefore more contacts with the paste. It becomes compact and tendency for it to be pull apart is lower which means high tensile strength.

4.3 Compressive Strength

Testing for compressive strength is as the same practice as tensile strength. Compressive strength is not the main concern for this project. However, the mortar samples are still being tested on their compressive strength. This is to determine whether PVA also gives impacts to compressive strength of mortar. After obtaining the results, the graphs are plotted. Two variations for the testing are different concentration of PVA and different conditions of aggregates.

The graphs are plotted as per listed below:

1. SSD aggregate (70μm) with three different concentrations of PVA solution
2. Dry aggregate (70μm) with three different concentration of PVA solution.

4.3.1 SSD aggregate (70μm) with three different concentrations of PVA solution

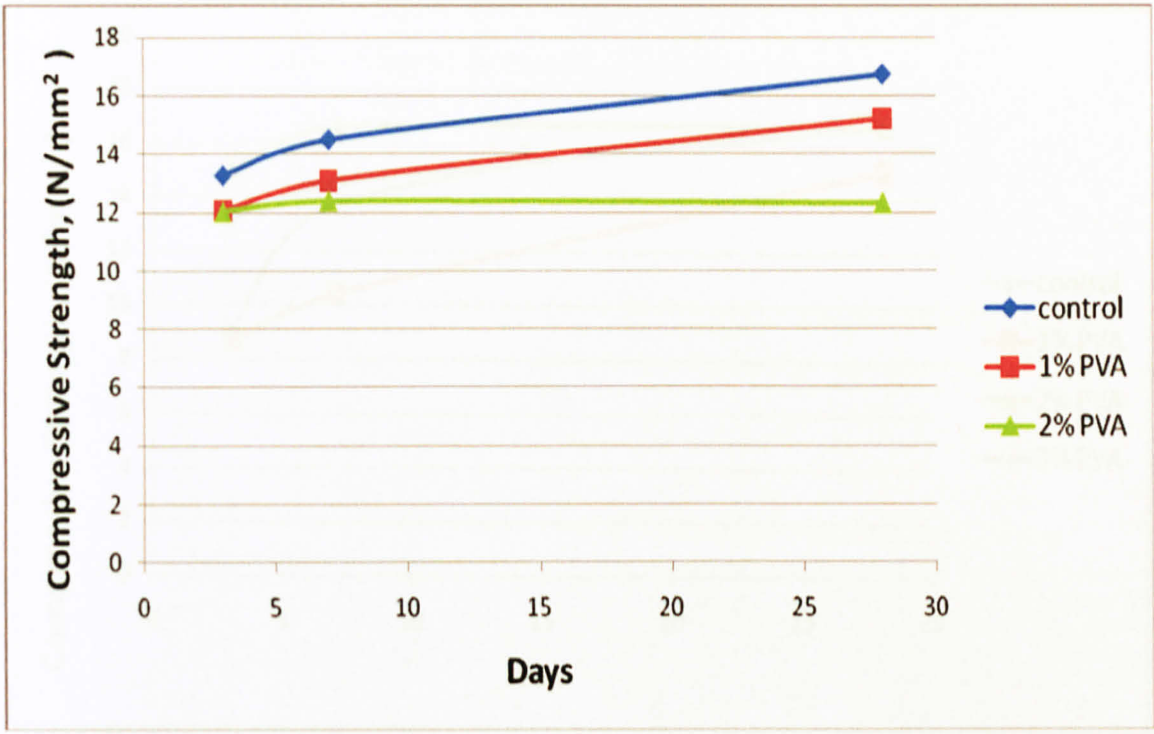

Figure 4.7. Graph of compressive stress vs. time for SSD

Based on Figure 4.7, mortar samples without PVA solution (control) have higher compressive strength for all days compared to mortar samples with PVA solution. It is also observed the lowest compressive strength is for mortar samples with 3% PVA solution. Therefore, it can be concluded that contrast to tensile strength results, the higher the PVA concentration is, the lower compressive strength for mortar samples. The percentage difference of compressive strength at 28 days between control and 1%, 2%, 3% PVA mortar sample are 8.9%, 26.35% and 20.93%, respectively.

4.3.2 Dry aggregate (70μm) with three different concentrations of PVA solution

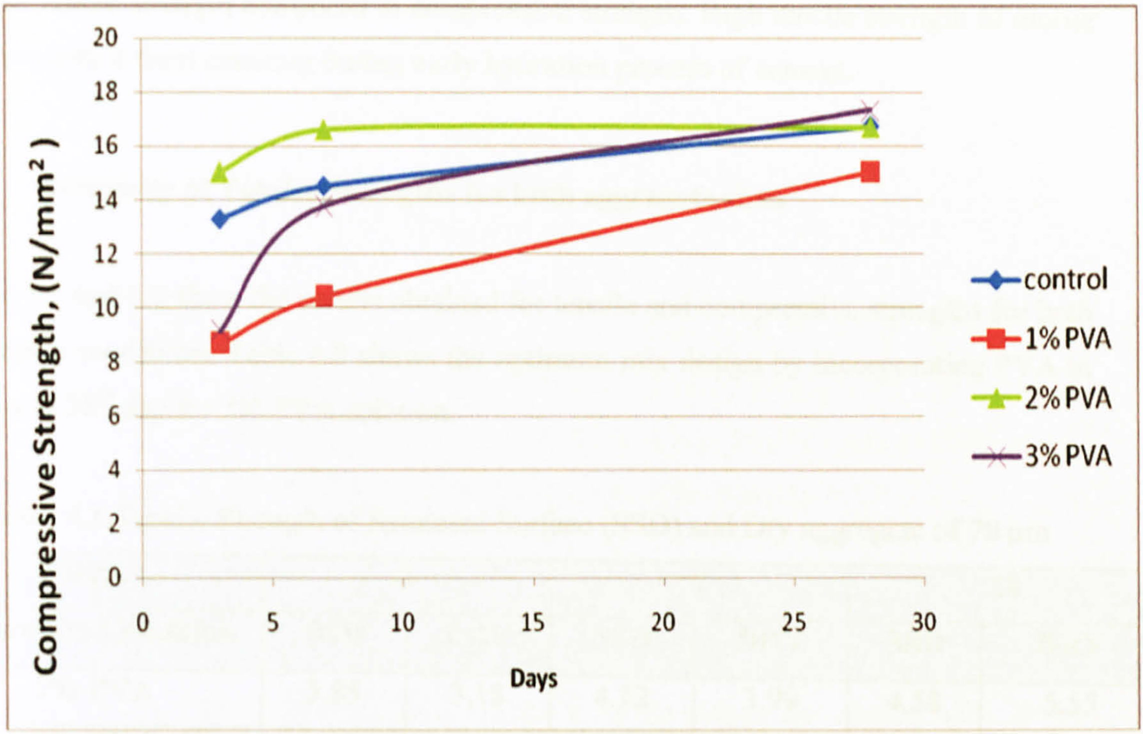

Figure 4.8. Graph of Compressive Strength vs. time for dry aggregate

Figure 4.8 shows that control samples has higher compressive strength at 28th day compared with PVA samples. However, mortar with 2% PVA yields higher compressive strength for 3rd and 7th day. This might happen due to several inaccuracies during mixing. Supposedly, the value obtained must be lower than control samples. 1% and 3% mortar samples remain lower than control samples in terms of compressive strength value.

Based on Figures 4.7 and 4.8, it shows that compressive strength decreases when PVA is being added to each mixing design. This has proved the theory we have made in the previous discussion on compressive strength. Even though compressive strength is always been overemphasized in mortar and concrete, it is not necessarily to make selection of mortar based on its compressive strength alone, as different type of mortar used for different applications.

This project is mainly to determine high tensile strength of mortar for the use of plastering wall and cement rendering. This is due to the fact that these applications needs higher tensile strength compared to compressive strength. High tensile strength of mortar will prevent it from cracking during early hydration process of cement.

4.4 Summary of Tensile Strengths for both aggregate sizes

Table 4.1 and 4.2 show the results obtained for tensile and compressive strengths for both aggregate conditions. Table 4.9 shows the optimum mix design by incorporating PVA in mortar at 28th day for 3% PVA solution.

Table 4.1. Tensile Strength of Saturated Surface (SSD) and Dry aggregate of 70 μm

Days	3		7		28	
Aggregate Condition	SSD	DRY	SSD	DRY	SSD	DRY
1% PVA	3.85	3.18	4.12	3.99	4.58	5.55
2% PVA	4.50	3.99	4.803	4.69	6.31	6.18
3% PVA	5.64	4.04	6.740	5.12	8.53	6.30

Table 4.2. Tensile Strength of Saturated Surface (SSD) and Dry aggregate of 0.15 mm to 5 mm

Days	3		7		28	
Aggregate Condition	SSD	DRY	SSD	DRY	SSD	DRY
1% PVA	2.62	2.13	2.68	3.92	5.09	4.23
2% PVA	3.44	3.12	3.45	3.22	5.26	5.09
3% PVA	3.64	3.39	4.37	3.47	5.81	5.47

Table 4.3. Optimum mix design by incorporating PVA for both aggregates of 3% PVA solution at 28th day

Aggregate Condition	Tensile Strength (N/mm^2)	
	Aggregate of 70 µm	Aggregate of 0.15 mm-5 mm
Saturated Surface Dry	76.60% increased	58.44% increased
Dry	30.43% increased	20.94% increased

From table 4.9, optimum concentration for both aggregate sizes is 3%. It also represents that higher PVA concentration used, the higher the tensile strength will be achieved. Based on the results obtained for two experimental works, it can be summarized that with the small addition of PVA can increase the tensile strength of mortar.

This effect is due to chemical interaction between cement paste and PVA and eventually enhances the bond strength between them. Therefore, the tendency of mortar to be pull apart is difficult. Comparison has been made between results for mortar with 70 µm aggregate and 0.15 mm -5 mm aggregates. It can be concluded that finer aggregate yields higher tensile strength.

For SSD aggregate, the pores are filled with water. Therefore, the water-cement ratio will not be affected much and remain at the same level. It does not affect the workability of mortar. However, it cannot be simplified that SSD aggregate is better than dry aggregate. By looking at the results, there are some values whereby dry aggregate yields higher value of strength than SSD aggregate. This is due to the fact that there are other various parameters such as shape, texture, absorption and size influence the strength of mortar. Besides that, there are few values where lower concentration of PVA gives higher value of strength. This might occur due to several inaccuracies during mixing.

SSD means that the individual sand particles have each absorbed as much moisture as they can hold, but there is no free water on the surface or between the particles. When overly wet sand is used, two factors affecting the mortar are quality and durability. This is due to decrease actual volume of sand as it is displaced by water. The worst of overly wet sand is that the excess water in the mix increases the actual water cement ratio. Conversely, if completely dry sand is used, the proportion of water to sand increases. This will eventually make the mortar water-starved.

Based on the studies on types of sand to be used in mortar, SSD sand is better than dry sand. Thus, the results for dry sand mortar are expected to be lesser than the results of SSD sand.

In other words, SSD sand will give correct proportion of water to sand in the mortar. SSD condition is also a better choice as a reference state for the following reasons.

1. The moisture content of aggregates in the field is much closer to SSD state than oven-dry (OD) state.
2. The bulk specific gravity (BSG) of aggregates is more accurately determined by the displacement method in SSD condition.
3. The moisture content can be calculated directly from measurements of apparent BSG using the displacement method.
4. It represents the optimum moisture content of aggregate in concrete or mortar.

However, the usage of SSD aggregate is not preferable. Many people prefer to use dry state as a reference point since it is not easy to obtain true SSD condition.

Based on the research and confirmation by results of experimental investigations, the action of PVA may be associated with the following phenomenon:

1. The reduction of calcium hydrated crystals $Ca(OH)_2$ in ITZ increases the paste-aggregate link by PVA. The adhesion capacity between both interfaces increases. Adhesion strength is proportional to tensile strength. Therefore, this will lead to higher tensile strength of mortar.

2. The reduction of microcrack density in the paste (either in the interface paste-aggregate or at the surface) by PVA. This will increase the tensile strength as the microcracks propagation in the paste occurs easily under the load of tensile than under compressive. It can be concluded that tensile strength is sensitive to the microcrack density in the paste. Thus, with the reduction of microcrack density, it will give significant effect to tensile strength but no improvement on compressive strength.

Since mortar or concrete has relatively high compressive strength but significantly lower tensile strength, the results expected to be higher from tensile strength. However, based on previous studies, adding PVA into mortar or concrete will decrease its compressive strength. This phenomenon is due to increase of air content of the mortar by PVA addition in mortar.

When air quantity increases, this will make it easier for mortar to be compressed. Therefore compressive strength decreases. However, air content of acceptable range plus PVA solution increases the viscosity or cohesive properties in mortar. Mortar with high cohesive properties has low tendency to be pull apart horizontally. That is why, it results in higher tensile strength in mortar with the increasing of air content.

Besides that, PVA delays the cement hydration process. The delay cement hydration also represents the reduction value of compression strength. This happened as the benefit of PVA action into tensile strength has already compensated for the delay in cement hydration.

The lower PVA contribution to compressive strength and the increase of porosity (higher air content) are the possible reasons in compressive strength reduction. Therefore, the result for mortar samples with PVA is expected to be lower than mortar samples without PVA.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

The project is to determine high tensile strength of mortar incorporating PVA. PVA modification affects the fresh properties of mortars such as higher tensile strength, adhesion, waterproofing and chemical resistance with no improvement in compressive strength.

Two variables for lab works are concentration of PVA solution and condition of aggregates. Based on the results obtained, mortar with 3% PVA solution is optimum mix concentration. The higher concentration being used, the higher tensile strength of mortar. Two findings due to this phenomenon are reduction of $Ca(OH)_2$ in ITZ and reduction of microcracks in the paste. $Ca(OH)_2$ has been possibly replaced by calcium silicate hydrate (C-S-H).

However, PVA does not increase compressive strength of mortar. This phenomenon is due to increase of air contents with the addition of PVA. PVA solution has increased the bubbles in water content of mixing which leads to increase of air contents. The increase of air content results in higher tensile strength but lower compressive strength. Besides that, this phenomenon is due to PVA action that delays the cement hydration process which decrease the value of compressive strength.

There may be other factors which contribute towards the beneficial action of PVA into mortar. To support this research and to understructure the microstructure PVA in mortar, it is recommended to observe the hydrated $Ca(OH)_2$ crystals in the paste of mortar incorporated PVA by scanning electron microscopy (SEM).

Scanning Electron Microscopy (SEM) is an electron microscope that produces high resolution images of a sample surface. Due to the manner in which the image is created. SEM images have characteristics three-dimensional appearances are useful for judging the surface structure of the sample. By using SEM, the study of ITZ can be achieved as the matrix of mortar in the presence of PVA and the transition zone between the paste and aggregates are observed.

It is also recommended to study the behavior of PVA into shrinkage of mortar for further studies. Shrinkage usually occurs during the early hydration process of cement. This process takes up water content and which leaves the mortar water-starved. Shrinkage will lead to microcraks in ITZ which propagate and eventually the mortar will fail.

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APPENDICES

APPENDIX A-1 SUGGESTION MILESTONE FOR FYP 1

DETAIL / WEEK	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Selection of Project Title											Mid-Semester Break				
Preliminary Research Work															
Submission of Preliminary and Progress Report															
Materials, Laboratory Works and Literature Review															
Submission of Interim Report															
Literature Review & Oral Presentation Preparation															
Oral Presentation															

APPENDIX A-2 SUGGESTION MILESTONE FOR FYP 2

DETAIL/ WEEK	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Laboratory works continue									Mid-Semester Break							
Submission of Combined Progress Report																
Project work continue																
Poster Exhibition																
Project work continue																
Submission of Dissertation (Soft Bound)																
Oral presentation																

APPENDIX B Mix Design Calculations

Aggregate to cement ratio= A:C= 2:1
Water to cement ratio= W:C = 0.35
Concrete density = 2400 kg/m^3

Assume W=1;

A:C:W

W/C=0.35
C=2.86

Hence, **A:C:W = 5.72 : 2.86 : 1 (Total fraction =9.58)**

For cylinder mould dimensions, taking diameter = 0.06 m and h = 0.12m

1 cylinder; V $= \pi R^2 h$
$= \pi(0.03)^2(0.12)$
=3.393 x 10^{-4} m^3

21 cylinders; V =3.393 x 10^{-4} x 21
=7.125 x 10^{-3} m^3

Mass = density x volume
= 2400 x 7.125x10^{-3}
= **17.10 kg**

Mass for each proportion;

Aggregate = (5.72/9.58) x 17.10
= **10.21kg**

Cement = (2.86/9.58) x 17.10
= **5.11 kg**

Water = (1/9.58) x 17.10
= **1.78 kg**

PVA mass (based on water mass)

1% PVA = **17.80 g**
2% PVA = **35.60 g**
3% PVA = **53.40 g**

MIX: CONTROL (0.15mm -5 mm)

SPLIT TENSILE TEST

DAY	3			7			28		
	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)
S1	674.27	44.80	0.00	694.74	29.20	2.72	693.04	10.20	0.93
S2	700.71	36.00	0.00	691.89	32.00	3.02	709.65	33.10	2.98
S3	711.79	28.10	2.56	714.79	39.90	0.00	720.35	32.10	2.91
Average	695.59	36.30	0.85	700.47	33.70	1.91	707.68	25.13	2.27

COMPRESSION TEST

DAY	3			7			28		
	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)
S1	704.10	34.30	14.76	704.53	33.00	13.97	685.08	9.10	3.95
S2	714.12	31.50	13.29	713.39	42.50	17.85	723.71	44.90	18.77
S3	705.40	38.00	16.45	710.92	39.40	16.84	712.54	42.40	18.00
Average	707.87	34.60	14.83	709.61	38.30	16.22	707.11	32.13	18.39

SUMMARY

Day	TEST	
	Tensile	Compression
3	0.85	14.83
7	1.91	16.22
28	2.27	18.39

MIX 1: 1% + SSD (0.15 mm- 5 mm)

SPLIT TENSILE TEST

DAY	3			7			28		
	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)
S1	693.13	30.10	2.76	694.70	30.30	0.00	655.64	47.70	4.61
S2	683.57	32.00	2.99	696.80	35.80	3.30	648.26	41.60	3.97
S3	695.43	49.50		678.50	46.00	4.29	640.61	54.50	5.39
Average	690.71	37.20	2.88	690.00	37.37	2.53	648.17	47.93	4.66

COMPRESSION TEST

DAY	3			7			28		
	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)
S1	693.41	36.60	15.52	695.30	23.80	10.10	633.01	56.50	23.38
S2	698.93	38.20	15.92	697.00	45.70	18.87	658.16	87.90	36.64
S3	693.77	44.60	18.62	705.00	40.80	17.19	627.16	65.20	27.88
Average	695.37	39.80	16.69	699.10	36.77	15.39	639.44	69.87	29.30

SUMMARY

Day	TEST	
	Tensile	Compression
3	2.88	16.69
7	2.53	15.39
28	4.66	29.30

MIX 2: 2% + SSD (0.15- 5 mm)

SPLIT TENSILE TEST

DAY	3			7			28		
	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)
S1	695.91	38.10	3.49	677.93	27.70	2.57	654.35	58.00	5.62
S2	688.94	20.20	1.85	686.52	28.60	2.68	692.06	32.50	0.00
S3	691.19	27.70	2.55	700.98	27.40	2.51	692.82	48.40	4.57
Average	692.01	28.67	2.63	688.48	27.90	2.59	679.74	46.30	3.40

COMPRESSION TEST

DAY	3			7			28		
	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)
S1	682.16	26.90	11.56	699.18	35.60	15.11	694.84	43.40	0.00
S2	705.10	10.30	4.29	691.54	33.80	14.30	635.70	121.20	50.70
S3	680.04	30.80	12.82	680.99	39.60	17.04	642.89	112.10	47.62
Average	689.10	22.67	9.56	690.57	36.33	15.48	657.81	92.23	32.77

SUMMARY

Day	TEST	
	Tensile	Compression
3	2.63	9.56
7	2.68	15.48
28	5.10	49.16

MIX 3: 3% + SSD (0.15 – 5mm)

SPLIT TENSILE TEST

DAY	3			7			28		
	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)
S1	708.57	41.00	3.74	707.74	43.10	3.89	664.41	52.70	5.09
S2	704.00	32.90	3.03	695.01	35.50	3.27	678.45	41.50	0.00
S3	707.30	45.20		709.13	36.70	3.24	676.60	61.80	5.85
Average	706.62	39.70	3.39	703.96	38.43	3.47	673.15	52.00	3.64

COMPRESSION TEST

DAY	3			7			28		
	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)
S1	699.56	32.40	13.67	705.52	33.30	14.13	696.87	70.10	0.00
S2	689.56	36.00	15.56	702.12	32.00	13.36	633.09	100.10	0.00
S3	706.43	33.40	13.92	680.17	42.20	17.58	646.55	128.90	53.83
Average	698.52	33.93	14.38	695.94	35.83	15.02	658.84	99.70	17.94

SUMMARY

Day	TEST	
	Tensile	Compression
3	3.39	14.38
7	3.47	15.02
28	5.47	17.94

MIX 1: 1% + DRY (0.15 -5 mm)

SPLIT TENSILE TEST

DAY	3			7			28		
	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)
S1	697.70	13.70		692.53	36.40	3.36	652.83	51.30	5.10
S2	669.42	25.80	2.42	705.20	54.10	4.92	631.24	40.00	4.07
S3	689.46	29.40	2.73	705.78	38.60	3.50	650.59	35.80	3.55
Average	685.53	22.97	2.58	701.17	43.03	3.92	644.89	42.37	4.24

COMPRESSION TEST

DAY	3			7			28		
	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)
S1	714.98	30.60	12.67	691.20	45.30	19.19	643.92	77.90	32.77
S2	674.95	32.20	13.71	682.35	37.30	15.96	644.86	108.70	45.94
S3	673.65	35.80	14.98	694.22	41.80	17.39	672.59	68.70	28.91
Average	687.86	32.87	13.79	689.26	41.47	17.51	653.79	85.10	35.87

SUMMARY

Day	TEST	
	Tensile	Compression
3	2.58	13.79
7	3.92	17.51
28	4.24	35.87

MIX 2: 2% + DRY (0.15 - 5 mm)

SPLIT TENSILE TEST

DAY	3			7			28		
	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)
S1	679.88	35.10	3.20	692.36	9.10	0.83	629.09	54.40	5.48
S2	683.32	39.50	3.58	684.16	35.60	3.23	640.32	48.90	4.84
S3	660.83	27.30	2.59	683.98	35.10	3.20	643.34	50.10	4.95
Average	674.68	33.97	3.12	686.83	26.60	2.42	637.58	51.13	5.09

COMPRESSION TEST

DAY	3			7			28		
	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)
S1	677.04	36.20	15.33	687.82	41.50	17.15	657.60	112.40	47.63
S2	699.51	34.40	14.24	692.08	45.30	18.80	639.61	40.40	17.26
S3	641.24	38.20	16.26	685.56	46.00	19.41	651.56	56.40	23.81
Average	672.60	36.27	15.28	688.49	44.27	18.45	649.59	69.73	29.57

SUMMARY

Day	TEST	
	Tensile	Compression
3	3.12	15.28
7	2.42	18.45
28	5.09	29.57

MIX 3: 3% + DRY (0.15 – 5 mm)

SPLIT TENSILE TEST

DAY	3			7			28		
	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)
S1	662.11	52.80	5.00	652.46	52.20	5.02	648.04	65.20	6.38
S2	695.79	32.60	2.96	653.37	32.40	3.16	625.15	55.20	5.62
S3	675.65	31.60	2.97	664.97	51.90	4.94	633.26	54.30	5.45
Average	677.85	39.00	3.64	656.93	45.50	4.38	635.48	58.23	5.82

COMPRESSION TEST

DAY	3			7			28		
	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)
S1	675.33	38.20	15.97	609.43	27.50	11.63	621.68	77.40	32.24
S2	672.54	44.20	18.49	652.48	49.00	20.54	646.50	97.60	40.67
S3	669.96	37.00	15.54	682.54	52.90	22.64	648.99	117.00	49.42
Average	672.61	39.80	16.67	648.15	43.13	18.27	639.06	97.33	40.78

SUMMARY

Day	TEST	
	Tensile	Compression
3	3.64	16.67
7	4.38	18.27
28	5.82	40.78

SPLIT TENSILE TEST

DAY	3			7			28	
	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)	Weight (kg)	Stress (N/mm^2)
S1	641.05	29.50	3.76	621.69	38.30	4.87	608.34	4.71
S2	618.61	30.90	3.93	615.51	30.10	3.83	602.46	6.23
S3	621.48	0.00	0.00	604.72	37.70	4.80	612.24	5.97
Average	627.05	20.13	2.56	613.97	35.37	4.50	607.68	5.64

COMPRESSION TEST

DAY	3			7			28	
	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)	Weight (kg)	Stress (N/mm^2)
S1	609.30	26.60	13.57	609.46	37.10	15.49	603.42	12.06
S2	599.02	26.60	11.14	635.23	30.00	12.58	656.45	13.12
S3	617.53	27.50	11.48	606.38	26.90	11.28	635.24	15.23
Average	608.62	26.90	12.06	617.02	31.33	13.12	631.70	13.47

SUMMARY

Day	TEST	
	Tensile	Compression
3	3.85	12.06
7	4.50	13.12
28	5.64	15.23

SPLIT TENSILE TEST

DAY	3			7			28		
	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)
S1	634.95	32.00	4.07	619.45	34.50	4.39	654.74	51.80	6.60
S2	635.39	38.00	4.84	661.15	40.80	5.19	638.89	54.00	6.88
S3	627.67	27.00	3.44	654.81	38.00	4.83	648.51	0.00	0.00
Average	632.67	32.33	4.12	645.14	37.77	4.80	647.38	35.27	4.49

COMPRESSION TEST

DAY	3			7			28		
	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)
S1	647.10	28.00	11.70	656.81	26.10	10.92	654.74	30.40	12.80
S2	642.78	33.50	13.91	630.30	31.30	13.13	634.89	22.20	11.34
S3	644.89	24.50	10.49	639.46	26.10	13.13	648.51	30.70	12.80
Average	644.92	28.67	12.03	642.19	27.83	12.39	646.05	27.77	12.31

SUMMARY

Day	TEST	
	Tensile	Compression
3	3.85	12.06
7	4.50	13.12
28	5.64	15.23

SPLIT TENSILE TEST

DAY	3			7			28		
	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)
S1	652.52	35.60	4.53	665.41	48.48	6.17	649.10	62.30	7.93
S2	672.49	31.70	4.04	659.94	53.00	6.75	674.05	68.79	8.76
S3	647.90	40.50	5.16	675.95	47.20	6.01	657.59	69.90	8.90
Average	657.64	35.93	4.58	667.10	49.56	6.31	660.25	67.00	8.53

COMPRESSION TEST

DAY	3			7			28		
	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)
S1	648.57	26.40	11.03	656.96	23.90	9.95	660.33	24.90	10.14
S2	653.15	21.50	8.97	667.94	30.10	12.53	670.77	30.10	12.53
S3	668.82	24.90	10.42	658.61	38.50	16.28	662.61	26.10	17.00
Average	656.85	24.27	10.14	661.17	30.83	12.92	664.57	27.03	13.22

SUMMARY

Day	TEST	
	Tensile	Compression
3	4.58	10.14
7	6.31	12.92
28	8.53	13.22

SPLIT TENSILE TEST

DAY	3			7			28		
	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)
S1	648.57	23.00	2.92	621.69	37.10	4.72	631.20	43.00	5.47
S2	653.15	24.50	3.11	615.51	30.00	3.82	655.30	40.90	5.21
S3	668.82	27.50	3.50	604.72	26.90	3.43	631.20	47.00	5.98
Average	656.85	25.00	3.18	613.97	31.33	3.99	639.23	43.63	5.55

COMPRESSION TEST

DAY	3			7			28		
	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)
S1	648.57	19.27	8.78	621.69	23.00	10.14	603.42	56.00	23.59
S2	653.15	18.56	7.45	615.51	22.00	9.58	656.45	47.80	20.11
S3	668.82	19.90	9.79	604.72	25.00	11.57	635.24	35.70	15.03
Average	656.85	19.24	8.67	613.97	23.33	10.43	631.70	46.50	19.58

SUMMARY

	TEST	
Day	Tensile	Compression
3	3.18	8.67
7	3.99	10.43
28	5.55	15.03

SPLIT TENSILE TEST

DAY	3			7			28		
	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)
S1	621.69	29.00	3.69	608.34	33.00	4.20	677.04	51.00	6.49
S2	615.51	32.00	4.07	602.46	37.55	4.78	699.51	49.70	6.33
S3	604.72	33.00	4.20	612.24	40.00	5.09	641.24	45.07	5.74
Average	613.97	31.33	3.99	607.68	36.85	4.69	672.60	48.59	6.19

COMPRESSION TEST

DAY	3			7			28		
	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)
S1	641.05	38.50	16.22	609.46	39.90	16.79	621.69	47.30	24.10
S2	618.61	37.70	15.80	635.23	41.90	17.64	615.51	50.90	25.90
S3	621.48	31.00	13.04	606.38	0.00	15.35	604.72	0.00	0.00
Average	627.05	35.73	15.02	617.02	27.27	16.59	613.97	32.73	16.67

SUMMARY

Day	TEST	
	Tensile	Compression
3	3.99	15.02
7	4.69	16.59
28	6.18	16.67

SPLIT TENSILE TEST

DAY	3			7			28		
	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)
S1	634.95	44.80	5.70	654.35	45.60	5.81	682.16	44.00	5.60
S2	635.39	50.50	6.43	692.06	36.80	4.69	705.10	46.00	5.86
S3	627.67	0.00	0.00	692.82	38.20	4.86	680.04	58.34	7.43
Average	632.67	31.77	4.04	679.74	40.20	5.12	689.10	49.45	6.30

COMPRESSION TEST

DAY	3			7			28		
	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)	Weight (kg)	Max. Load (kN)	Stress (N/mm^2)
S1	609.46	36.60	15.39	641.05	37.70	15.85	665.41	45.20	23.02
S2	635.23	34.40	14.49	618.61	27.40	11.55	659.94	56.90	28.97
S3	606.38	27.20	11.46	621.48	0.00	0.00	675.95	0.00	0.00
Average	617.02	32.73	13.78	627.05	21.70	9.13	667.10	34.03	17.33

SUMMARY

Day	TEST	
	Tensile	Compression
3	4.04	9.13
7	5.12	13.78
28	6.30	17.33