Tensile Behaviour of Concrete with Polyvinyl Alcohol (PVA) Fiber

By,

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Dissertation submitted in partial fulfilment of
the requirements for the
Bachelor of Engineering (Hons)
(Civil Engineering)

JULY 2007

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CERTIFICATION OF APPROVAL

Tensile Behaviour of Concrete with Polyvinyl Alcohol (PVA) Fiber

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A project dissertation submitted to the
Civil Engineering Programme
Universiti Teknologi PETRONAS
in partial fulfilment of the requirement for the
BACHELOR OF ENGINEERING (Hons)
(CIVIL ENGINEERING)

Approved by,

(Dr. Victor R Macam Jr)

UNIVERSITI TEKNOLOGI PETRONAS
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JULY 2007

CERTIFICATION OF ORIGINALITY

This is 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.

MOHD ZULIEZAMRI MOHD

ABSTRACT

The purpose of the report is to summarize and brief the final year project. The topic of the project is "The Tensile Behaviour of Concrete with Polyvinyl Alcohol Fiber". The main objective of this project is to study about the tensile behaviour of concrete when being added with another mixture which is polyvinyl alcohol (PVA) fiber. This study includes to investigate the effects of PVA fiber content to concrete's strength through experiments, and to determine whether PVA fiber is ideal in enhancing the properties of concrete. Concrete is very strong material when it is placed in compression. However, unreinforced or plain concrete are characterized by low tensile strengths; which is they are brittle materials. Therefore, regular concrete is normally reinforced with high tensile strength steel to correct for the lack of tension in concrete. For many applications, it is becoming increasingly popular to reinforce the concrete with small, randomly distributed fibers. PVA fiber has some suitable characteristics as reinforcing materials for cementatious composites such as strong bonding strength with concrete, high tensile strength and others. Nowadays, PVA fiber is considered as one of the most suitable polymeric fibers to be used as the reinforcement of cements. The used of concrete with PVA fiber in engineering applications has furthered the need for the study of its behaviour under tensile loading. Tensile strength is the basis for its ability to resist bending, or its flexural strength. The scope of study would include research through journals and reading materials in relation to concrete strength, PVA fibers and fiber reinforced concrete. The concretes with PVA fibers are mixed according to the mix proportioning that had been calculated. Several numbers of lab experiments such as compressive strength and splitting tensile test are carried out to determine the effects of infusing PVA fiber in concrete mix. The tests were being carried through with ages of 1, 3, 7, 19, 28, and 60 days, with curing in humid chamber. From the research, it can be concluded that the addition of fibers will increase the strength of concrete, thus making it a much more attractive material than plain concrete, which appears to have no such limit. Based on the results, it observed that the highest strength is produced from concrete infused with 1% PVA fibers. Besides, the fresh concrete seems to become drier when more PVA fibers added in the mix.

ACKNOWLEDGEMENT

First and foremost, the Author would like to thank God, for giving His precious time to complete this Final Year Project (FYP).

An utmost gratitude to Dr. Victor Rivera Macam Jr. for allowing the Author to do a Final Year Project under his supervisions. Even with a tight time schedule, support and good advices were always given which is the key factor of finishing the project in time. Without his relentless effort to guide and supervise, the project will not have been successful.

Special thanks to Ms. Haslina Tukiman for the references of her project as a guideline for the Author to understand and meet this project requirement. She has given numerous inspirations for the Author to carry on the project and been very helpful in assisting the Author in a lot of difficult time especially on the experimental activities.

Last but not least, an utmost gratitude to father and mother which has brought the Author up and be good role models throughout these years.

Also the Author would like to thank all lecturers, technician especially Mr. Johan Ariff Mohamed and Mr. Meor Asniwan Meor Ghazali for helping in performing laboratory experimental. Lastly, the Author is very grateful to friends especially Mr. Mohd Aizat Kamarudin, Mr. Amril Hadri Jamaludin, Ms. Nazifa Mohd Asri, Mr. Mohamed Ali Abdullah, and Mr. Wan Ahmed Nabil Wan Mohamed who have been supportive during the period of this project were held. Not to forget to all others who have help in the project directly and indirectly and might not be mentioned here.

Thank you for all the supports given and only god may repay them

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CHAPTER 1

1.0 INTRODUCTION

1.1 Background of Study

Concrete for twenty first century can be much stronger, more durable and at the same time cost and energy efficient. However, this will not possible unless people understand this material better. Concrete is a structural material which consists of cements, sands, aggregates, and water. The strength and other properties of concrete are dependent on how these four ingredients are proportioned and mixed. Sometimes, concrete can contain other substances such as fly ash or others, which can also change its properties.

Unlike steel, concrete is a material that adequate in strength in only one direction. Concrete is very good in compression but useless in tension. Engineering design is based on concrete's compressive strength. Compressive strength refers to what concrete is capable to resist loads when they are being pushed. However, any appreciable tension will break the microscopic rigid lattice resulting in cracking and separation of the concrete. The compressive strengths for concrete are usually in the range of 3000 to 5000 psi, while the tensile strength is only about one tenths of its compressive strength.

Therefore, regular concrete is normally reinforced with high tensile strength steel to correct for the lack of tension in concrete. The steel bars usually placed in the tension side of the concrete. It is becoming increasingly popular to reinforce the concrete with small, randomly distributed fibers. In the 1900's, asbestos fiber were being used. By 1960 steel, glass and synthetic fiber such as polypropylene fibers were used in concrete.

A wide variety of different types of fibers have been proposed for use in concrete. For each application, it needs to be determined which type of fiber is optimal in satisfying the product specifications. This selection process has to consider whether the fibers are chemically and mechanically compatible with the cement matrix. The general types of fiber reinforcement materials are:

- Steel - including high-tensile strength and stainless steel.
- Glass - either 'E' or alkali-resistant.
- Synthetic - including polypropylene, polyethylene, polyester, acrylic, and Kevlar.
- Carbon - either high-modulus or high-strength.
- Natural - including wood, sisal, coconut, bamboo, jute, and elephant grass.

Their main purpose is to increase the energy absorption capacity and toughness of the material. However, the increase in tensile and flexural strength is often the primary objective. Polyvinyl alcohol (PVA) fiber is considered as one of the most suitable polymeric fibers to be used as reinforcement of concrete. The type of PVA fiber that used in this study is KURALON (RF4000) which manufactured by Kuraray. Co. Ltd. PVA fiber has been used globally in a wide range of cement applications, owing to some suitable characteristics as reinforcing materials for concrete. At the first, PVA fiber displays high tenacity and modulus of elasticity compare with other general organic fibers. Second, bonding strength between fiber and cement is stronger. It is possible to control bonding strength by surface treatment. At last, PVA fiber has got wide acceptance because of it good durability, weather resistance, alkali resistance, less hazardous and reasonable cost alternative.

This study would be looking into the tensile behavior of concrete when being added with PVA fibers. Tensile strength is the basis for its ability to resist bending, or its flexural strength. Compressive strength, which is easier to measure than tensile strength, can be used as an index of tensile strength, once the empirical relationship between them has been established for the materials to be used in the mix and the size of the element involved. For this study, compressive and tensile splitting test are conducted to investigate the concrete tensile behavior when infused with PVA fibers

1.2 Problem Statement

Concrete is very strong material when it is placed in compression. However, unreinforced or plain concrete are characterized by low tensile strengths; which is they are brittle materials. For that reason, reinforcements are used in concrete structures. Historically, the reinforcement has been in the form of continuous reinforcing bars, which could be placed in the structure at appropriate locations to withstand the imposed tensile and shear stress. Nowadays, fibers such as polyvinyl alcohol (PVA) fiber can also be used as the reinforcement of concrete.

The uses of concrete with PVA fiber in many engineering applications have furthered the need for the study of its behavior under tensile loading. Common applications for fiber reinforced concrete include paving applications such as in airports, highways, bridge decks and industrial floors, which endure significant cyclic loading during their service life. Within these areas of application, the tensile strengths of the concrete are important performance and design parameters.

1.3 Objectives and Scope of Study

The main objectives of this project are to;

- investigate on the tensile behavior of concrete with PVA fiber,
- study on the characteristics of PVA fiber and the advantages it would bring to concrete,
- investigate about the effects of fiber contents in concrete,
- study about the other types of fiber reinforced concrete (FRC),
- determine whether PVA fiber is ideal to increase the tensile strength of concrete.

The scope of study would include research through journals and reading materials in relation to PVA fiber and concrete's strength. Besides, lab experiments are carried out to investigate the effects of infusing PVA fiber in concrete mix.

CHAPTER 2

2.0 LITERATURE REVIEW

2.1 Polyvinyl Alcohol (PVA) Fiber

Among many other uses, polyvinyl alcohol (PVA) is an organic material that used to make concrete reinforcement fibers. It is made from carbon, hydrogen, and oxygen (*Figure 2.1a*). Polyvinyl alcohol has excellent film forming, emulsifying, and adhesive properties. It is also resistant to oil, grease and solvent. It has high tensile strength and flexibility. However, these properties are dependent on humidity; in other words, with higher humidity more water is absorbed. The water which acts as a plasticizer will then reduce its tensile strength, but increase its elongation and tear strength.

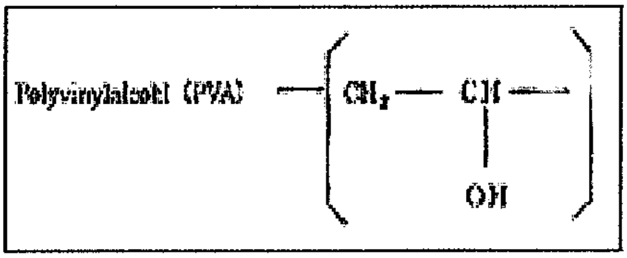


Figure 2.1a: Chemical structure of polyvinyl alcohol (PVA).

Cement-based materials are characterized by low tensile strengths, and low tensile strain capacities. The tensile strain capacity of cement-based materials can be improved by addition of fibers. PVA fiber emerged during a search of low cost high performance fibers for concrete. The hydrophilic nature of PVA fiber imposed great challenge in the composite design, as the fibers are apt to rupture of being pulled out because of the tendency of fiber to bond strongly to cementitious matrix as state by V. C. Li in [1].

PVA fibers are true structural concrete reinforcement fibers, like steel fibers and glass fibers. Common plastic fibers perform one task in concrete which is they restrain plastic shrinkage. But after the first 24 hours, they are largely ineffective in restraining drying shrinkage or other cracking because their modulus of elasticity is less than that of concrete. That's another way of saying they are more stretcher than concrete. To be a true structural fiber, the fiber should be stiffer than the concrete it is reinforcing.

Polyvinyl alcohol fibers are very high-performance reinforcement fibers for concrete. PVA fibers have excellent characteristics for a concrete repair product. Today, there is a new technology invented on PVA fiber which is PVA-ECC. ECC is an abbreviation for Engineered Cementitious Composites. PVA-ECC is a unique implementation of PVA fibers in a micromechanically designed matrix invented by Dr. Victor C. Li, professor of Civil and Environmental Engineering at the University of Michigan.

Physically and mechanically, ECC behaves like normal concrete. Under tension, however, ECC behaves more like a ductile metal. The strain capacity during strain-hardening (after first crack) is about 5%, or roughly 500 times more than typical fiber-reinforced concrete. During strain-hardening, multiple microcracks limited to about 60 mm in crack-width form along the length of the tensile specimen. If the specimen is unloaded before final failure, the microcracks are often small enough to prevent the intrusion of water. In *Figure 2.1b*, the plot shows that PVA-ECC is stronger in tension than any fiber-reinforced mortar.

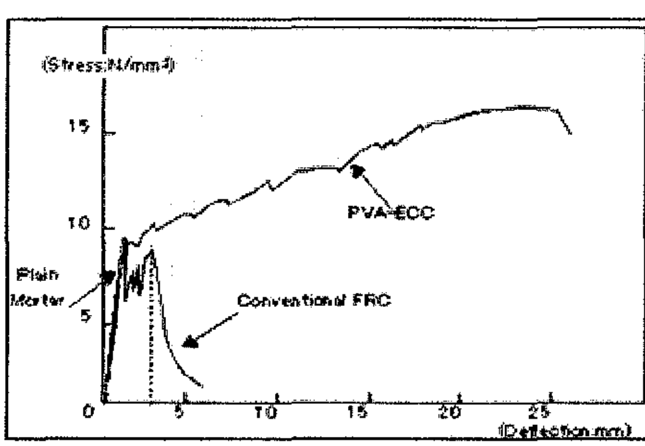


Figure 2.1b: Strain-hardening curve for PVA-ECC.

PVA fibers are superior in several ways:

1. High bond strength with concrete help to keep the patch together even it is damaged
2. PVA Fibers will not cut the user or equipment
3. PVA fibers will never rust
4. High modulus of elasticity and tensile strength help keep the concrete intact
5. PVA fibers have a very high abrasion resistance
6. PVA fibers produce concrete and mortar with very high fatigue resistance
7. PVA fibers have superior crack fighting properties
8. PVA fibers are resistant to UV rays, alkali, abrasion and most chemicals

PVA fibers are also unique in their ability to create a molecular bond with mortar and concrete that is 300% greater than other fibers. PVA fibers tend to develop very strong chemical bonding with cement due to presence of hydroxyl group in its molecular chains. This tends to limit the multiple cracking effects. Bond strength between fiber and concrete is an important consideration. Steel has very high tensile strength, but steel fibers have low bond strength with concrete or mortar. When you put the concrete under load, it cracks and the steel fibers tend to slip out without providing significant benefit from their high tensile strength. PVA fibers, on the other hand, form a molecular bond with the concrete during hydration, so it is not easy to pull them out.

Reducing the chemical debonding energy enhances the complementary energy by minimizing premature fiber breakage during the fiber/matrix interface debonding process, prior to fiber slippage. Lowering within certain limits the interfacial frictional bond strength at the onset of fiber slippage can also facilitate fiber pullout. A simple way to reduce overly strong interfacial bonding would be to adjust the bond properties by coating the fiber with an oiling agent. It is evident that increasing oiling agent leads to an increase in tensile strain capacity, accompanied by a larger crack width and reduced crack spacing. Furthermore, it may be expected that the optimal oiling content could be different for composites manufactured with different processing routes, as studied by Li et al [2]. This can improve strain hardening at the composite level as showed by Li et al [3].

PVA fibers are also used to reduce many types of concrete cracks. Cracking may initiate the process that reduces durability. If the crack opens, the reinforcing fiber are exposed to the environmental deterioration process. Crack width is strongly influenced by the stiffness, volume fraction and bond properties of the fibers. To restrain shrinkage cracking, the fiber should be stiffer than the concrete it is reinforcing. PVA fibers reduce normal cracks to micro-cracks that restrict water penetration and protect steel reinforcement. Because they are less "stretchy" with a higher modulus of elasticity, PVA fibers are more effective than other fibers in reducing long-term drying cracking. Relatively low dosages of PVA fibers can effectively reduce many types of cracking, including drying shrinkage, settlement and fatigue-related cracks. Through fracture roughness tests, it was revealed that PVA fibers were able to efficiently postpone microcrack formation, thereby delaying the localization of the failure crack.

The type of fiber that is used in this project is RF 4000 manufactured by Kuraray Co. Ltd, a Japanese company. The properties of the fibers are indicated by the table below:

Table 1: Properties of PVA fiber (RF 4000)

Fiber type	Diameter (mm)	Thickness (dtex)	Cut length (mm)*	Tensile Strength (N/mm^2)	Elongation (%)	Young's Modulus (kN/mm^2)	Specific Gravity	Primary Applications
RF4000	0.66	4444	30	900 (0.9GPa)	7	23	1.3	Aggregate above 3/4" (20mm) and shotcrete

**Other properties of PVA concrete are summarized in tables in *Appendix 1*

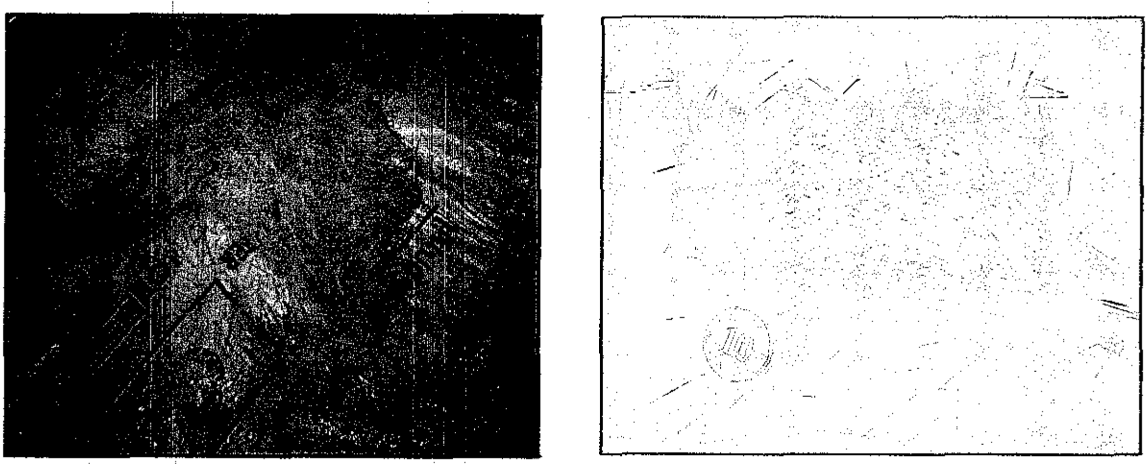


Figure 2.1c: Polyvinyl alcohol (PVA) fiber (RF 4000).

2.2 Behaviour of Concrete

In its simplest form, concrete is a mixture of paste and aggregates. The paste, composed of Portland cement and water, coats the surface of the fine and coarse aggregates. Through a chemical reaction called hydration, the paste hardens and gains strength to form the rock-like mass known as concrete. The remarkable trait of concrete within this process is its' plastic and malleable when newly mixed, strong and durable when hardened. These qualities explain why one material, concrete, can build skyscrapers, bridges, sidewalks and superhighways, houses and dams.

The key to achieving a strong, durable concrete rests in the careful proportioning and mixing of the ingredients. A concrete mixture that does not have enough paste to fill all the voids between the aggregates will be difficult to place and will produce rough, honeycombed surfaces and porous concrete. A mixture with an excess of cement paste will be easy to place and will produce a smooth surface; however, the resulting concrete is likely to shrink more and be uneconomical.

A properly designed concrete mixture will possess the desired workability for the fresh concrete and the required durability and strength for the hardened concrete. Typically, a mix is about 10 to 15 percent cement, 60 to 75 percent aggregate and 15 to 20 percent water. Entrained air in many concrete mixes may also take up another 5 to 8 percent.

Portland cement's chemistry comes to life in the presence of water. Cement and water form a paste that coats each particle of stone and sand. Through a chemical reaction called hydration, the cement paste hardens and gains strength. The character of the concrete is determined by quality of the paste. The strength of the paste, in turn, depends on the ratio of water to cement. The water-cement ratio is the weight of the mixing water divided by the weight of the cement. High-quality concrete is produced by lowering the water-cement ratio as much as possible without sacrificing the workability of fresh concrete.

Generally, using less water produces a higher quality concrete provided the concrete is properly placed, consolidated, and cured. Almost any natural water that is drinkable and has no pronounced taste or odor may be used as mixing water for concrete. Excessive impurities in mixing water not only may affect setting time and concrete strength, but also may cause efflorescence, staining, corrosion of reinforcement, volume instability, and reduced durability. Specifications usually set limits on chlorides, sulfates, alkalis, and solids in mixing water unless tests can be performed to determine the effect the impurity has on various properties.

Aggregates comprise 60 to 75 percent of the total volume of concrete. The type and size of the aggregate mixture depends on the thickness and purpose of the final concrete product. Relatively thin building sections call for small coarse aggregate, though aggregates up to six inches (150 mm) in diameter have been used in large dams. A continuous gradation of particle sizes is desirable for efficient use of the paste. In addition, aggregates should be clean and free from any matter that might affect the quality of the concrete.

Soon after the aggregates, water, and the cement are combined, the mixture starts to harden. All Portland cements are hydraulic cements that set and harden through a chemical reaction with water. During this reaction, a node forms on the surface of each cement particle. The node grows and expands until it links up with nodes from other cement particles or adheres to adjacent aggregates.

Concrete is a heterogeneous material which is inherently full of flaws such as pores, air voids, and shrinkage cracks. The mechanism of failure in concrete can be divided into three stages. The first stage involves the weak regions within the concrete and is termed flaw initiation (crack initiation). The second stage is characterized by slow and progressive growth (crack propagation) of the inherent flaws to a critical size and is known as microcracking. In the final stage, when a sufficient number of unstable cracks have formed, a continuous or macrocrack will develop, eventually leading to failure.

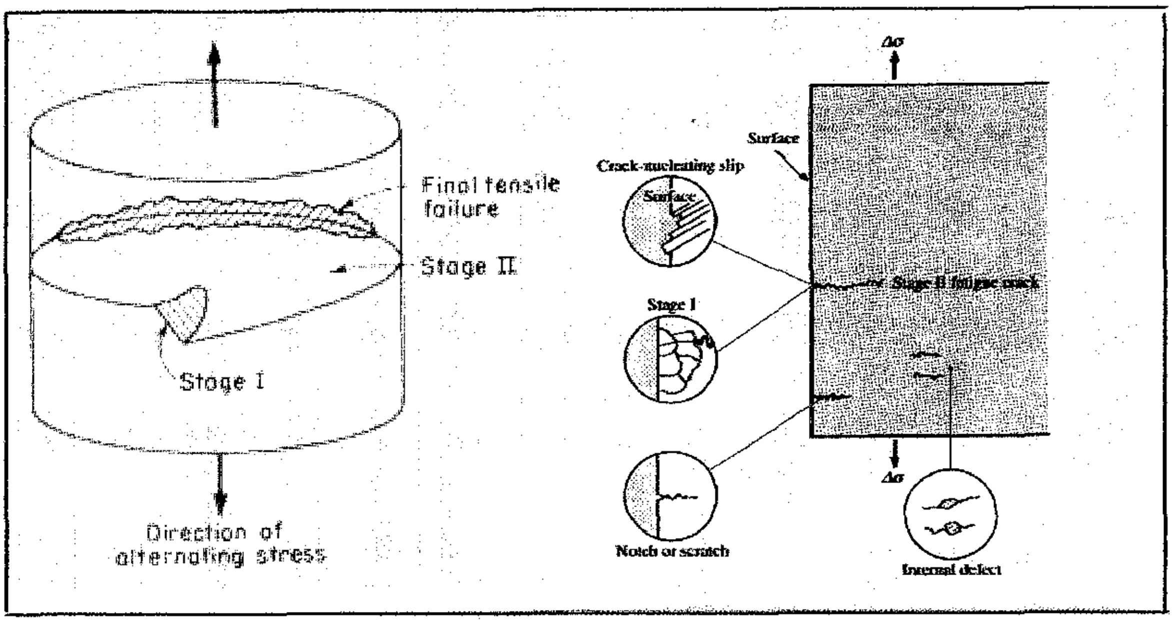


Figure 2.2a: A diagram showing location of the 3 steps in a fatigue fracture under axial stress.

Fatigue may be defined as a process of progressive, permanent internal structural changes in a material subjected to repeated loading. There are three common ways in which stresses may be applied which are axial, torsional, and flexural (Kelly, 1997). Examples of these are seen in *Figure 2.1b*. In concrete, these changes are mainly associated with the progressive growth of internal microcracks, which results in a significant increase of irrecoverable strain. At the macrolevel, this will manifest itself as changes in the material's mechanical properties.

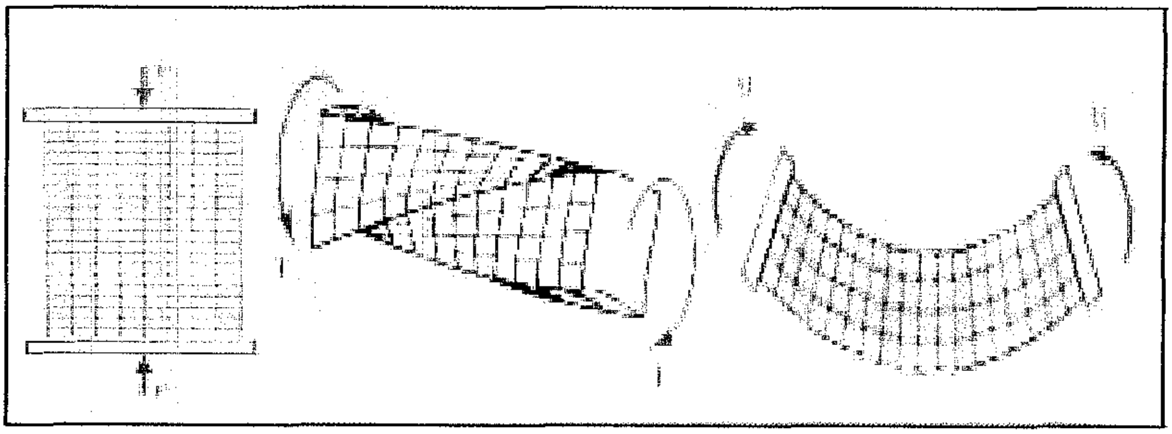


Figure 2.2b: Visual examples of axial stress, torsional stress, and flexural stress.

2.2.1 Concrete strength

Engineering design is based on concrete's compressive strength. Compressive strength may be defined as the measured maximum resistance of a concrete specimen to axial loading. Compressive strength of concrete is a primary physical property and frequently used in design calculations for bridges, buildings, and other structures. Most general-use concrete has a compressive strength between 20 and 35 MPa. High-strength concrete by definition has a compressive strength of at least 70 MPa. Compressive strengths up to 140 MPa have been used in special bridge and high-rise building applications.

The flexural strength or modulus of rupture of concrete is used to design pavements and other slabs on ground. Compressive strength, which is easier to measure than flexural strength, can be used as an index of flexural strength, once the empirical relationship between them has been established for the materials to be used in the mix and the size of the element involved. The flexural strength or modulus of rupture of normal-density concrete is often approximated as 0.6 to 0.8 times the square root of the compressive strength in Mega Pascal. Wood (1992) illustrates the relationship between flexural strength and compressive strength for concretes exposed to moist curing, air curing, and outdoor exposure.

The direct tensile strength of concrete is about 8% to 12% of the compressive strength and is often estimated as 0.4 to 0.7 times the square root of the compressive strength in Mega Pascal. Splitting tensile strength is 8% to 14% of the compressive strength as stated by Hanson (1968) [7]. Splitting tensile strength versus time is presented by Lange (1994) [5].

The torsional strength for concrete is related to the modulus of rupture and the dimensions of the concrete element. Hsu (1968) in [11] presents about this torsional strength correlations.

The shear strength of concrete is about 5% of the compressive strength. The correlation between compressive strength and flexural, tensile, torsional, and shear strength varies with concrete ingredients and environment.

Modulus of elasticity, denoted by the symbol E, may be defined as the ratio of normal stress to corresponding strain for tensile or compressive stresses below the proportional limit of a material. For normal-density concrete, E ranges from 14,000 to 41,000 MPa. For concrete strengths between 20 MPa and 40 MPa, E can be approximated as 5,000 times the square root of the compressive strength. Like other strength relationships, the modulus of elasticity to compressive strength relationship is mix-ingredient specific and relationships should be verified in a laboratory (Wood 1992).

There are many factors that can affect the strength of concrete. Some of them are concrete porosity, water/cement ratio, aggregate-paste bond and cement-related parameters. Voids in concrete can be filled with air or with water. Air voids are an obvious and easily-visible example of pores in concrete. The less porous the concrete, the stronger it will be as measured by compressive strength.

Water/cement ratio is defined as the mass of water divided by the mass of cement in a mix. In mixes where the w/c is greater than approximately 0.4, all the cement can, in theory, react with water to form cement hydration products. At higher w/c ratios it follows that the space occupied by the additional water above w/c=0.4 will remain as pore space filled with water, or with air if the concrete dries out. Consequently, as the w/c ratio increases, the porosity of the cement paste in the concrete also increases. As the porosity increases, the compressive strength of the concrete will decrease.

It will be obvious that if the aggregate in concrete is weak, the concrete will also be weak. Rocks with low intrinsic strength, such as chalk, are clearly unsuitable for use as aggregate. Besides, the strength of the bond between the paste and the aggregate is also critical. If there is no bond, the aggregate effectively represents a void that will reduce the strength of concrete.

2.2.2 Strength Development in Concrete

The building up process of concrete results in progressive stiffening, hardening, and strength development. Many factors influence the rate at which the strength of concrete increases after mixing. The process of strength growth is called 'hardening' which is may continue for weeks or months after the concrete has been mixed and placed.

Curing is one of the factors influence the strength development in concrete. Common curing times are 2, 7, 28 and 90 days. The curing temperature is typically 20 degrees Centigrade. After reaching the required age for testing, the cubes are crushed in a large press to obtain their compressive strength.

Compressive strength is generally expressed in Mega Pascal (MPa) at an age of 28 days. Other test ages are also used. There is a relationship between the 28-day strength and other test ages. Seven-day strengths are often estimated to be about 75% of the 28-day strength and 56-day and 90-day strengths are about 10% to 15% greater than 28-day strengths as shown in *Figure 2.2.2*. The specified compressive strength is designated by the symbol f'_c, and ideally is exceeded by the actual compressive strength f_c.

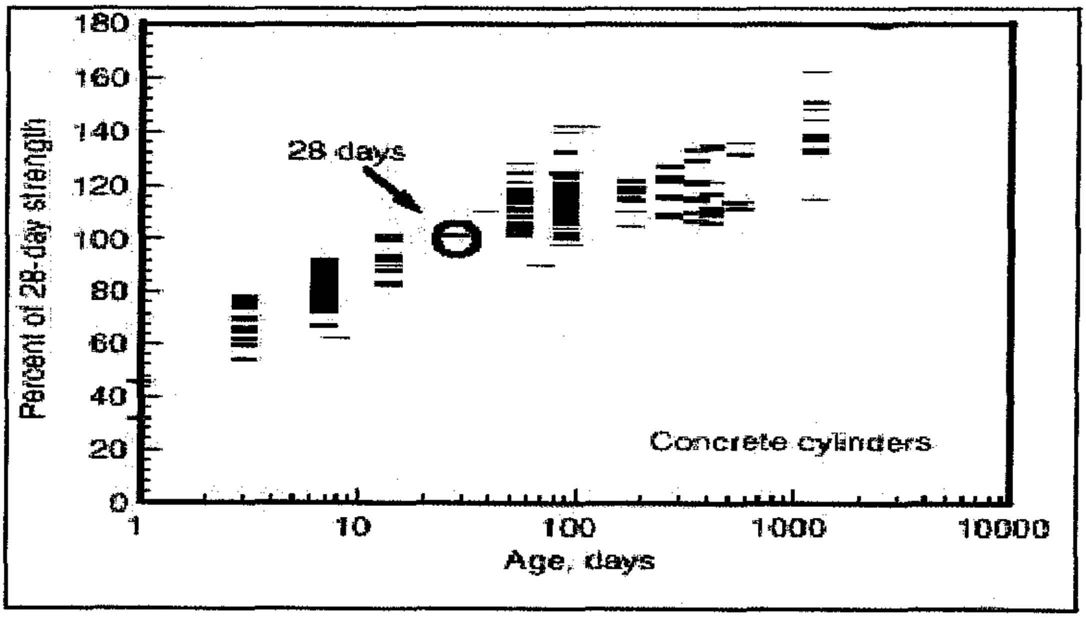


Figure 2.2.2: Compressive strength development of various concrete illustrate as a percentage of the 28-day strength (Lange 1994).

2.3 Fiber Reinforced Concrete (FRC)

Concrete made with Portland cement has certain characteristics; it is strong in compression but weak in tension and tends to brittle. The weakness in tension can be overcome by the use of conventional rod reinforcement and to some extent by the inclusion of a sufficient volume of certain fibers. Since mid 1800's steel reinforcing has been used to overcome this problem. As a composite system, the reinforcing steel is assumed to carry all tensile loads. The problem with employing steel in concrete is that over time steel corrodes due to the ingress of chloride ions. More recently, micro fibers such as those used in traditional composite materials, have been introduced into the concrete mixture to increase its toughness, or ability to resist crack growth.

Fiber reinforced concrete (FRC) is a Portland cement concrete reinforced with short discrete fibers that are uniformly distributed and randomly oriented. In FRC, thousands of small fibers are dispersed and distributed randomly in the concrete during mixing, and thus improve concrete properties in all directions. Fibers help to improve the post peak ductility performance, pre-crack tensile strength, fatigue strength, impact strength and eliminate temperature and shrinkage cracks.

Several different types of fibers, both natural and manmade, have been incorporated into concrete. Manmade fibers include steel fibers, glass fibers, and synthetic fibers. Use of natural fibers in concrete precedes the advent of conventional reinforced concrete in historical context. However, the technical aspects of FRC systems remained essentially undeveloped. Since the advent of fiber reinforcing of concrete in the 1940's, a great deal of testing has been conducted on the various fibrous materials to determine the actual characteristics and advantages for each product. These different types of fibers have been used to reinforce the cement-based matrices. The choice of fibers varies from synthetic organic materials such as polypropylene or carbon, synthetic inorganic such as steel or glass, natural organic such as cellulose or sisal to natural inorganic like asbestos.

Currently the commercial products are reinforced with steel, glass, polyester and polypropylene fibers. Within these different fibers, the character of fiber reinforced concrete changes with varying concrete's, fiber materials, geometries, distribution, orientation and densities. The selection of the type of fibers is guided by the properties of the fibers such as diameter, specific gravity, Young's modulus, tensile strength and the extent these fibers affect the properties of the cement matrix. The use of fibers also alters the behavior of the fiber-matrix composite after it has cracked, thereby improving its toughness.

The primary use of fibers in concrete is to enhance the properties of concrete containing conventional reinforcement. The enhancements of concrete properties include:

- Resistance to crack propagation due to plastic and drying shrinkage.
- Resistance to thermal and moisture stresses.
- Increased ductility.
- Increased impact and abrasion resistance.
- Increased tensile, flexural, and fatigue strength.
- Decreased permeability.
- Decreased mix-water bleed rate.

Fibers are generally short discontinuous and randomly distributed throughout the cementatious matrix. Since fibers, such as PVA fiber tend to be more closely spaces than conventional reinforcing bars, they are better at controlling cracks. Besides, PVA fiber can improve the fatigue properties, ductility of material, impact resistance, and abrasion resistance.

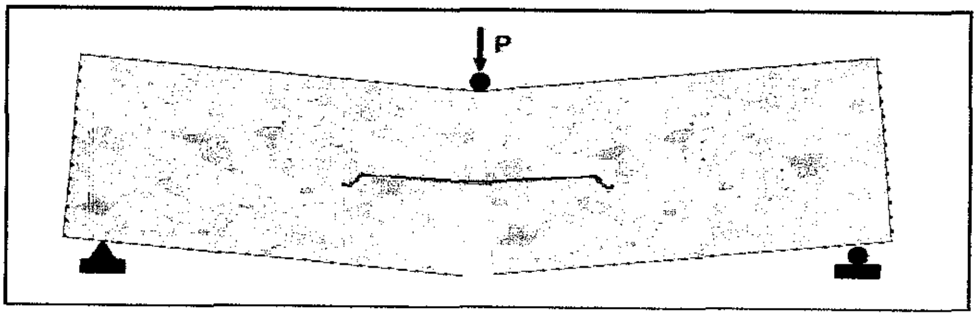


Figure 2.3a: Principle of fiber reinforcement.

After matrix crack initiation, the stresses are absorbed by bridging fibers, and the bending moments are redistributed. The concrete element does not fail spontaneously when the matrix is cracked; the deformation energy is absorbed and the material becomes pseudo-ductile.

Toughness is defined as the area under a load-deflection (or stress-strain) curve. As can be seen from *Figure 2.3b*, adding fibers to concrete greatly increases the toughness of the material. That is, fiber-reinforced concrete is able to sustain load at deflections or strains much greater than those at which cracking first appears in the matrix.

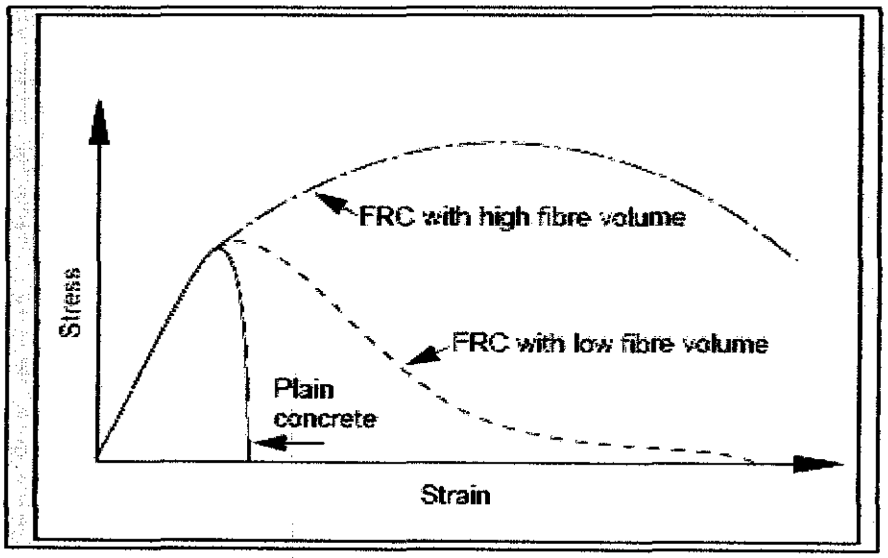


Figure 2.3b: Stress strain curve of fiber reinforced concrete.

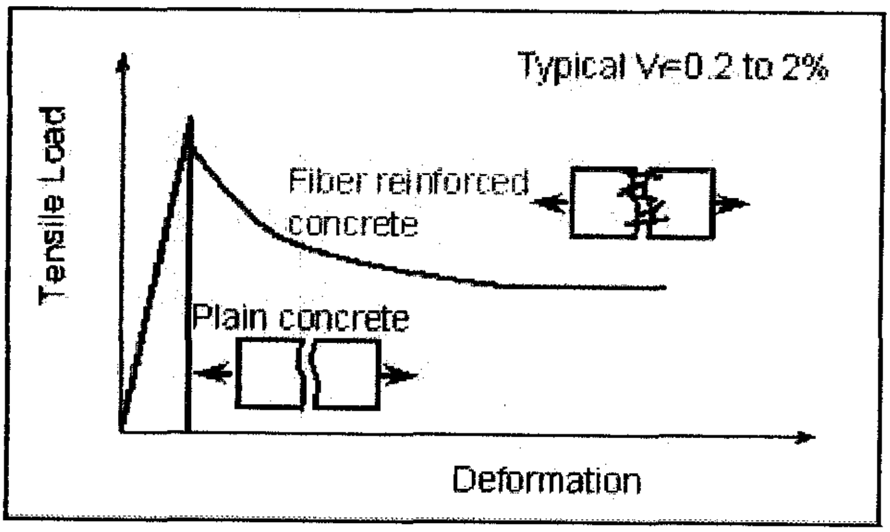


Figure 2.3c: Tensile Load versus Deformation for Plain and FRC.

For the effective use of fibers in hardened concrete:-

- Fibers should be significantly stiffer than the matrix (a higher modulus of elasticity).
- Fiber content by volume must be adequate.
- There must be a good fiber-matrix bond.
- Fiber length must be sufficient.
- Fibers must have a high aspect ratio, i.e. they must be long relative to their diameter.

The percent of fiber in the concrete mix is based on volume and is expressed as a percent of the mix. Tests ranging from 1.7% to 2.7% are common. When volumes greater than 2% are used, the concrete can be difficult to mix. When concrete is placed by processes other than from a ready mix truck, the fiber volume may be higher. One such example is when shot concrete is employed. Volumes of 2.3% have been successfully used. In some pre-casting operations using fiber reinforced concrete volume percentages have been used as high as 5%. Generally, if all other properties are equal, concrete strength increases linearly with volume of fiber.

Aspect ratio is simply the length of a fiber divided by its diameter. This property is used to represent the amount of surface area of the fiber against the concrete mix. This aspect ratio is important for another reason. It has been determined that balling of fibers in the mix increases as the aspect ratio increases. An aspect ratio of 100 for steel fibers was found to be optimum.

Orientation of the fibers is generally random, simply because they are not placed one at a time in a straight line. Fibers are either added to the dry cement or sprayed onto a form and covered with the wet concrete mix. Both of these procedures will produce a random pattern of fiber reinforcing. Tests with steel fibers, however, have shown that they can be aligned by using magnets and that the resulting concrete will have an improved ultimate strength. This process is used in fabricating precast beams and columns.

It should be noted that published information tends to deal with high volume concentrations of fiber. However, for economic reasons, the current trend in practice is to minimize fiber volume, in which case improvements in properties can be marginal. For the quantities of fibers typically used (less than 1% by volume for steel and about 0.1% by volume for polypropylene) the fibers will not have significant effect on the strength or modulus of elasticity of the composite. It must also be noted that high volume concentrations of certain fibers may make the plastic concrete unworkable.

2.3.1 Steel Fibers

Steel fibers have been used in concrete since the early 1900s. The early fibers were round, smooth and the wire was cut to the required lengths. Modern commercially available steel fibers are manufactured from drawn steel wire, slit sheet steel or by the melt extraction process which produces fibers that have a crescent-shaped cross section. Typically steel fibers have equivalent diameters from 0.15mm to 2mm and lengths from 7mm to 75mm. Stainless steel fibers have been used for high-temperature applications.

Steel fibers have been used in conventional concrete mixes, shotcrete and slurry-infiltrated fiber concrete. Typically, content of steel fiber ranges from 0.25% to 2.0% by volume. Fiber contents in excess of 2% by volume generally result in poor workability and fiber distribution, but can be used successfully where the paste content of the mix is increased and the size of coarse aggregate is not larger than about 10 mm. Concretes containing steel fiber have been shown to have substantially improved resistance to impact and greater ductility of failure in compression, flexure and torsion.

Research and design of steel fiber reinforced concrete began to increase in importance in the 1970s, and since those days various types of steel fibers have been developed. They differ in material as well as in size, shape and surface structure, as shown in *Figure 2.3.1*. Due to different manufacturing processes and different materials, there are differences in the mechanical properties such as tensile strength, grade of mechanical anchorage and capability of stress distribution and absorption.

By adding steel fibers while mixing the concrete, a so-called homogeneous reinforcement is created. This does not notably increase the mechanical properties before failure, but governs the post failure behavior. Thus, plain concrete, which is a quasi-brittle material, is turned to the pseudo-ductile steel fiber reinforced concrete.

Bond strength between steel fibers and concrete is another important consideration. Steel fibers, however, have relatively low bond strength with concrete and mortar, causing the fibers to pull out under strain before reaching their tensile strength. When you put the concrete under load, it cracks and the steel fibers tend to slip out without providing significant benefit from their high tensile strength. PVA fibers, on the other hand, form a molecular bond with the concrete during hydration, so it is not easy to pull them out.

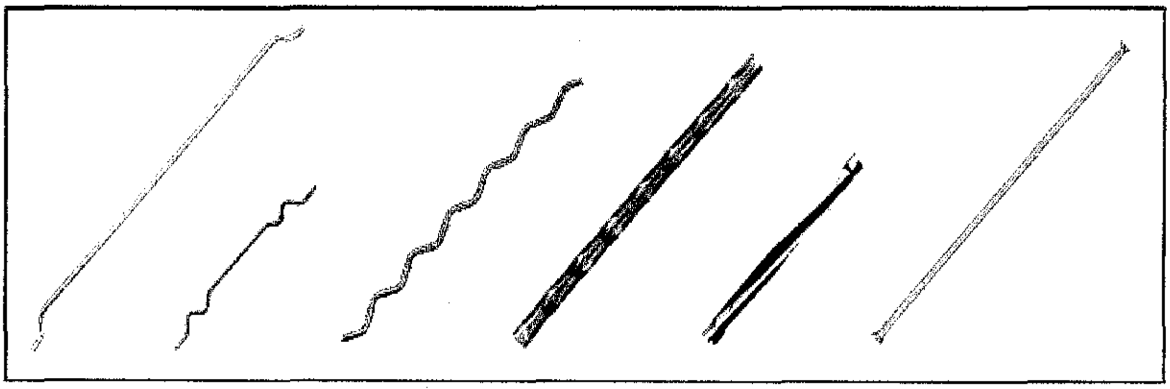


Figure 2.3.1: Different types of steel fibers.

2.3.2 Glass Fibers

Glass fiber is available in continuous or chopped lengths. Early conventional borosilicate glass caused reduction in strength due to alkali reactivity with the cement paste. Alkali resistant glass fibers were then produced resulting in long term durability, but other strength loss trends were observed. Better durability result was observed when AR glass is used with developed low alkaline cement. Glass fiber concretes are mainly used in exterior building panels and as architectural precast concrete. This material is very good in making the front shapes of any building and it is less dense than steel. However, glass fibers are fragile and can be easily damaged.

Glass fiber has high tensile strength and elastic modulus but has brittle stress-strain characteristic and low creep at room temperature. Claims have been made that a 5% glass fiber by volume has been used successfully in sand-cement mortar without balling. Glass-fiber products exposed to outdoor environment have shown loss of strength and ductility.

Because of the lack of data on long-term durability, GRC has been confined to nonstructural uses where it has wide applications. It is suitable for use in direct spray techniques and premix processes and has been used as a replacement for asbestos fiber in flat sheet, pipes and a variety of precast products. GRC products are used extensively in agriculture; for architectural cladding and components; and for small containers.

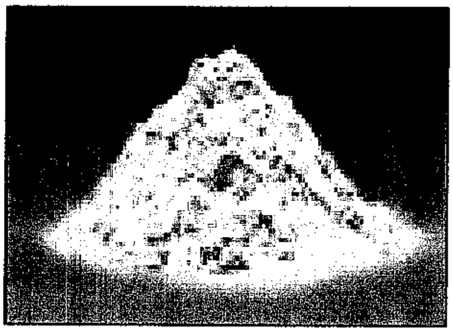


Figure 2.3.2: Glass fibers. (Typical properties of GRC are summarized in *Appendix 1b*)

2.3.3 Natural Fibers

Natural fibers include those made from plant, animal and mineral sources. It is a class of hair-like materials that are continuous filaments or are in discrete elongated pieces, similar to pieces of thread. They can be spun into filaments, thread, or rope. They can be used as a component of composite materials. They can also be matted into sheets to make products such as paper. Natural fibers can be classified according to their origin:

- Vegetable fibers (e.g. Seed fiber, Leaf fiber, Skin fiber, Fruit fiber, Stalk fiber)
- Animal fibers (e.g. Animal hair/wool, Silk fiber, Avian/bird fiber)
- Mineral fibers (e.g. Asbestos, Ceramic fibers, Metal fibers)

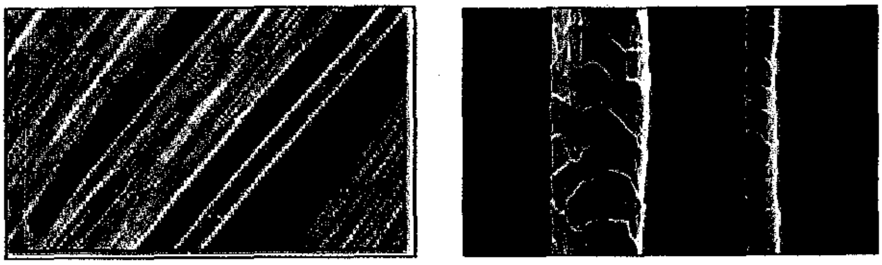


Figure 2.3.3: Natural fibers. (Typical properties of NF are summarized in *Appendix 1c*)

Natural reinforcing materials can be obtained at low cost and low levels of energy using local manpower and technology. Utilization of natural fibers as concrete reinforcement is of particular interest to less developed regions where conventional construction materials are not readily available or too expensive. Sisal-fiber reinforced concrete has been used for making roof tiles, corrugated sheets, pipes, silos and tanks. Elephant-grass-reinforced mortar has been used for low-cost housing projects. Wood-cellulose-fiber-reinforced cement has commercial applications in the manufacture of flat and non-pressure pipes. Natural fibers can be either unprocessed or processed.

2.3.4 Synthetics Fibers

Synthetic fibers are created by forcing, usually through extrusion, fiber forming materials through holes into the air, forming a thread. Synthetic fibers are man-made fibers from research and development in the petrochemical and textile industries. There are two different physical fiber forms: monofilament fiber and fibers produced from fibrillated tape. Currently there are two different synthetic fiber volumes used in application, namely low-volume percentage and high-volume percentage. Most synthetic fiber applications are at the 0.1% by volume level. At this level, the strength of the concrete is considered unaffected and crack control characteristics are sought.

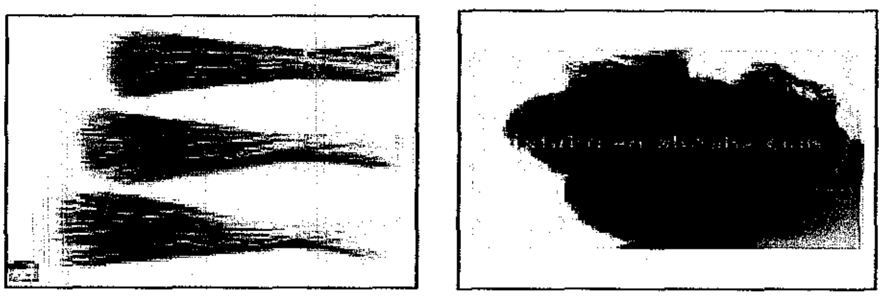


Figure 2.3.4: Synthetic fibers. (Typical properties of SF summarized in *Appendix 1d*)

2.4 Comparison of PVA fiber with other fibers

Steel fibers have greater tensile strength than PVA fibers, but this strength is rarely used. Steel fibers, like rebar, are passive reinforcement, meaning they have no reinforcing effect until the concrete cracks. The problem then is that steel fibers tend to pull out rather than hold the concrete together. Many techniques have been used to increase the mechanical bond of steel fibers (hooks and waffles are among the most popular) but even so the steel fibers still tend to pull out easily. Contrast this with PVA fibers which create a molecular bond with the cement during hydration. When PVA fiber is pulled out, it holds on firmly, taking full advantage of PVA's tensile strength.

PVA fiber is about the same price as glass, but you use 1/3 as much, so it ends up being much less expensive. It is a little more expensive than polypropylene and nylon, but it offers far greater performance. PVA does not break down in concrete. Even the best AR glass degrades in strength dramatically over time, up to 80%. Field studies have shown that PVA degrades about 1% over 20 years. PVA is extremely tough and durable. You can bend PVA fibers over a hundred times before they break. No other concrete reinforcement fiber is so tough.

They differ in many ways, but as reinforcement for concrete, these differences are especially notable. Polypropylene, nylon and the other synthetic fibers used in concrete serve only one purpose, to restrain plastic shrinkage during the first 24 hours after concrete is poured. Because of their high elongation, or "stretchiness", these fibers are essentially useless for the drying shrinkage and other sorts of cracking that all concrete suffers from. PVA is designed to handle these cracks, in addition to plastic cracking, are what PVA is designed to handle. In that regard it is a structural fiber like steel and AR glass.

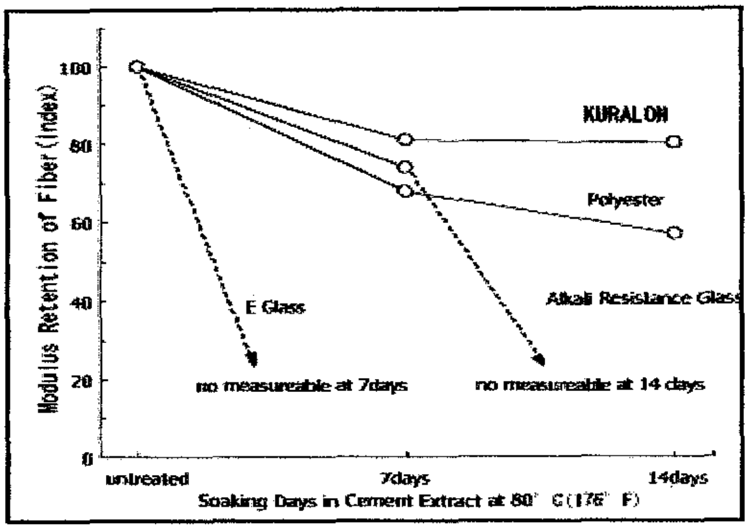


Figure 2.4a: Comparison of Modulus Retention between KURALON and other fibers

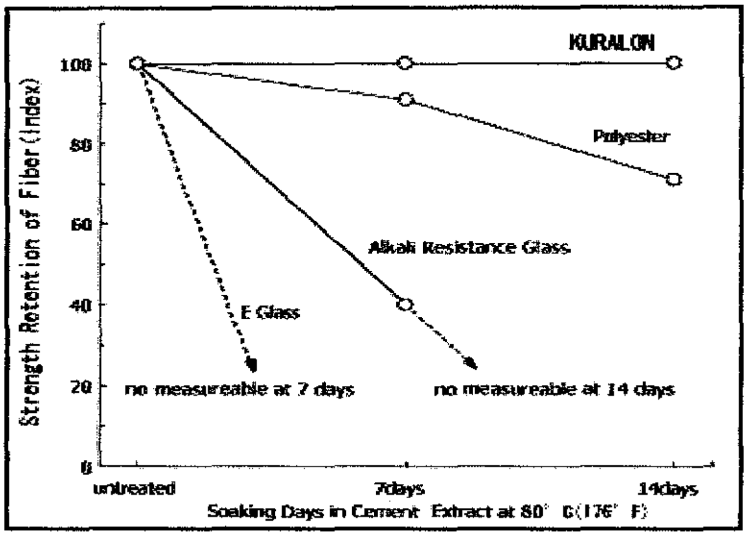


Figure 2.4b: Comparison of Strength Retention between KURALON and other fibers

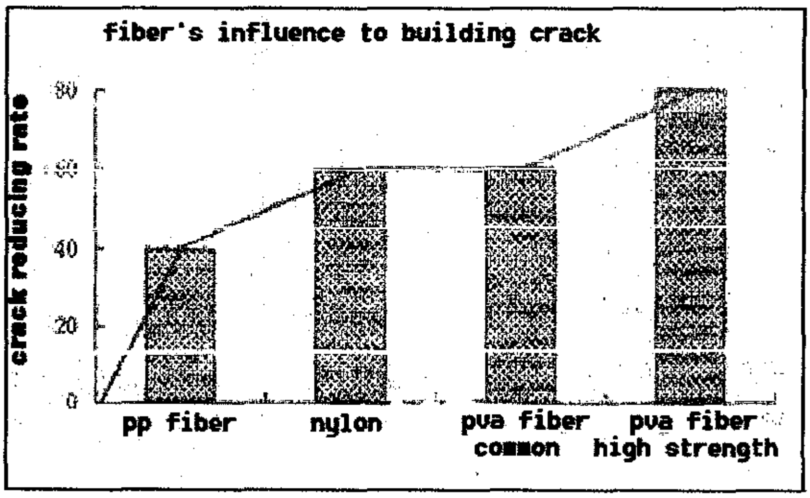


Figure 2.4c: Comparison of crack reducing rate of PVA fibers and other fibers

PVA resin, which is the raw material of PVA-fiber, is designated by the FDA (U. S. Food and Drug Administration) as a safe material. PVA's chemical structure is based solely on carbon, hydrogen and oxygen. When burned, harmful substances such as dioxin and ammonia are not created. (This structure is quite different from polyvinyl chloride.) As PVA fiber is composed of carbon, hydrogen and oxygen, only water and carbon dioxide is generated during burning.

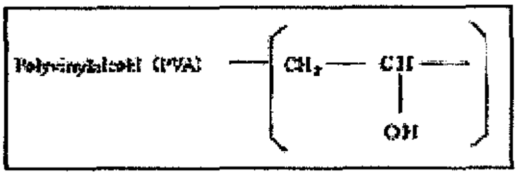


Table 2: Gases released during burning of fibers

Gas	CO		CO_2		NH_3		HCN		H_2S	
Fiber	600	400	600	400	600	400	600	400	600	40
PVA-fiber	0.45	0.13	0.59	0.13	-	-	-	-	-	-
Polyacrylonitrile-fiber	1.33	0.16	0.15	0	0.06	0.05	0.09	0.02	-	-
Polyamide-fiber	0.88	0.1	0.4	0.01	0.05	traces	0.03	0	-	-
Cotton	4.33	0.46	0.75	0.34	-	-	-	-	-	-
Wool	2	0.1	0.59	0.15	0.1	0.06	0.05	0.01	0.04	0.0

*Reference: Magazine "Fiber" No.29 (3) 1977 Suwada

Table 3: Result on toxicity test of PVA fiber and other fibers

Fiber	The number of living rats					
	5min.	10min.	15min.	20min.	30min.	24hrs.
PVA-fiber	5	5	5	5	5	5
Polyacrylonitrile-fiber	0	-	-	-	-	-
Polyamide-fiber	5	5	5	5	5	4
Metha-alamide-fiber	5	5	5	5	5	0
Wool	5	2	2	1	1	-

*as measurement done by Kuraray Co. Ltd

CHAPTER 3

3.0 METHODOLOGY

3.1 Project Implementation

The project implementations are based on timeframe for about one year. During the project's development, some techniques have been replaced and even additional techniques have been introduced in order to achieve the objectives.

3.1.1 Research and Literature Review

Literature review, a common method in any research had been crucially important in pursuing few aspects in the study. It provides the background information on the research, the related studies been done before, and the current issue takes in place in the concrete industry. It contains all relevant theories, hypotheses, facts and data which are relevant to the objective and the findings of the project. In order to collect information regarding these, primary and secondary sources are collected from library, websites and information or data from the supervisor.

The research are done through reading and understanding from literature reviews, case studies, journals, text books, websites, articles and other reading materials. It is a self study to understand more and to get as much knowledge about the project. The gathered information are digested and converted into summarization for analysis purposes.

3.1.2 Discussion

Weekly meeting with the supervisor is conducted periodically to ensure that the project is going on the right path. The main purpose is to update the progress and seek advice on project matters. The meeting resulted to a better understanding besides doing literature review. New knowledge can be discuss and exchange during the meeting. There are also some discussions done with other FYP students in order to gather more information about the mix proportioning and concrete mixing.

3.2 Mix Design and Laboratory Experiments

3.2.1 Calculations of Mix Proportioning

In order to complete this project, lab work must be conducted to experiment the strength and other properties of the concrete. The mix must be ensured that it contains sufficient PVA fiber, admixtures and super plasticizer that could increased tensile, flexural, and fatigue strength of the concrete. The mix proportion is very important because it leads to the high performance of the PVA fiber reinforced concrete characteristics. Before doing the mixing, preparation of the aggregates is very important and it must be done days before the mix to avoid error during the mix.

Before mixing, calculations need to be done for the mix proportion. To do the mix proportioning, the ratio for the element to cement must be obtained. In order to come up with the proposed mix proportion, a trial concrete mix have been done to determine the appropriate mix to be used by referring to the literature reviews and also by referring to senior's previous project.

The mixing proportions were done according to the British method. Similarly to the American Concrete Institute (ACI) approach, the British method explicitly recognizes the durability requirements in the mix selection. Below are the steps and calculations taken for the mix proportioning works.

The calculation of mix proportioning is shown below:-

*Based on Concrete Technology Book by A. M. Neville (1999) at [13]

Tables and Figures used for mix proportioning are attached in ***Appendix 2.*

A) Target design strength (28 days) = 40 MPa (40 N/mm^2)

   Target slump is about 100mm

   Maximum aggregate of 40mm (uncrushed)

B) Referring to Table 14.9 (page 763), the compressive strength for Type I OPC cement at the age of 28 days is 42 Mpa

C) From Figure 14.12 (page 764), water/cement ratio = 0.52

D) From Table 14.10 (page 765), when the slump is at the range of 60mm – 180mm, and the maximum aggregate of 40mm (uncrushed), the water content is 175 kg/m^3

   So, Cement content for the mix is given by:

   Water content / wc ratio = 175/0.52

   = 336.54 kg/mm^3

E) From Figure 14.3 (page 765), when the water content is 175 kg/m^3, the fresh density of concrete mix is 2415 kg/m^3

   So, total aggregate content = 2415 kg/m^3 – 336.54 kg/m^3 – 175 kg/m^3

   = 1903.46 kg/m^3

F) Figure 14.14 (page 766-7767), the fine aggregates proportion is 34%

   (Assume 60% fine aggregate passing)

   So, Fine aggregate = (34/100) X 1903.46

   = 647.17 kg/m^3

G) Therefore, coarse aggregate = 1903.46 – 647.17

   = 1256.28 kg/m^3

For hardened concrete test, 4 mixes need to be mixed to achieve the objectives. Each mix contains 0%, 1%, 2%, and 3% of PVA fiber. In each mix, 30 moulds of concrete cubes are being prepared, 15 cubes for compression and another 15 cubes for tension test. The size of 1 cube is 150mm X 150mm X 150mm.

$\therefore$ Volume of 1 cube X 30 cubes = (0.15) X (0.15) X (0.15) X 30

$= 0.101 m^3$

For concrete mix of 0.101 m^2, the calculated mix proportions are as the following:-

Table 4: Summary of Mix proportioning

Mix	Coarse aggregate (kg)	Fine aggregate (kg)	Cement (kg)	Water (kg)	PVA fibers (kg)
PVA 0%	128.14	66.02	34.32	17.86	0
PVA 1%	128.14	66.02	34.32	17.86	0.343
PVA 2%	128.14	66.02	34.32	17.86	0.686
PVA 3%	128.14	66.02	34.32	17.86	1.030

3.2.2 Concrete Mixing

All concrete should be mix thoroughly until it is uniform. The sequence of concrete mix is very important and it must be followed accordingly. The procedure of concrete mix incorporating with PVA fiber is shown below:

1. Pour all coarse and fine aggregates into the mixer and mix for 25 seconds to ensure uniform distribution between both materials.
2. Pour half of the water and mix for 1 minute.
3. Leave the mixes for 8 minutes to let both coarse and fine aggregates to absorb water
4. Pour all Portland cement into the mixer and mix for 1 minute.
5. Pour another half of the water and mix for 3 minutes.
6. Add PVA in the mix and mix for 2 minutes.
7. Finally perform hand mixing until the mix is in uniform stage.

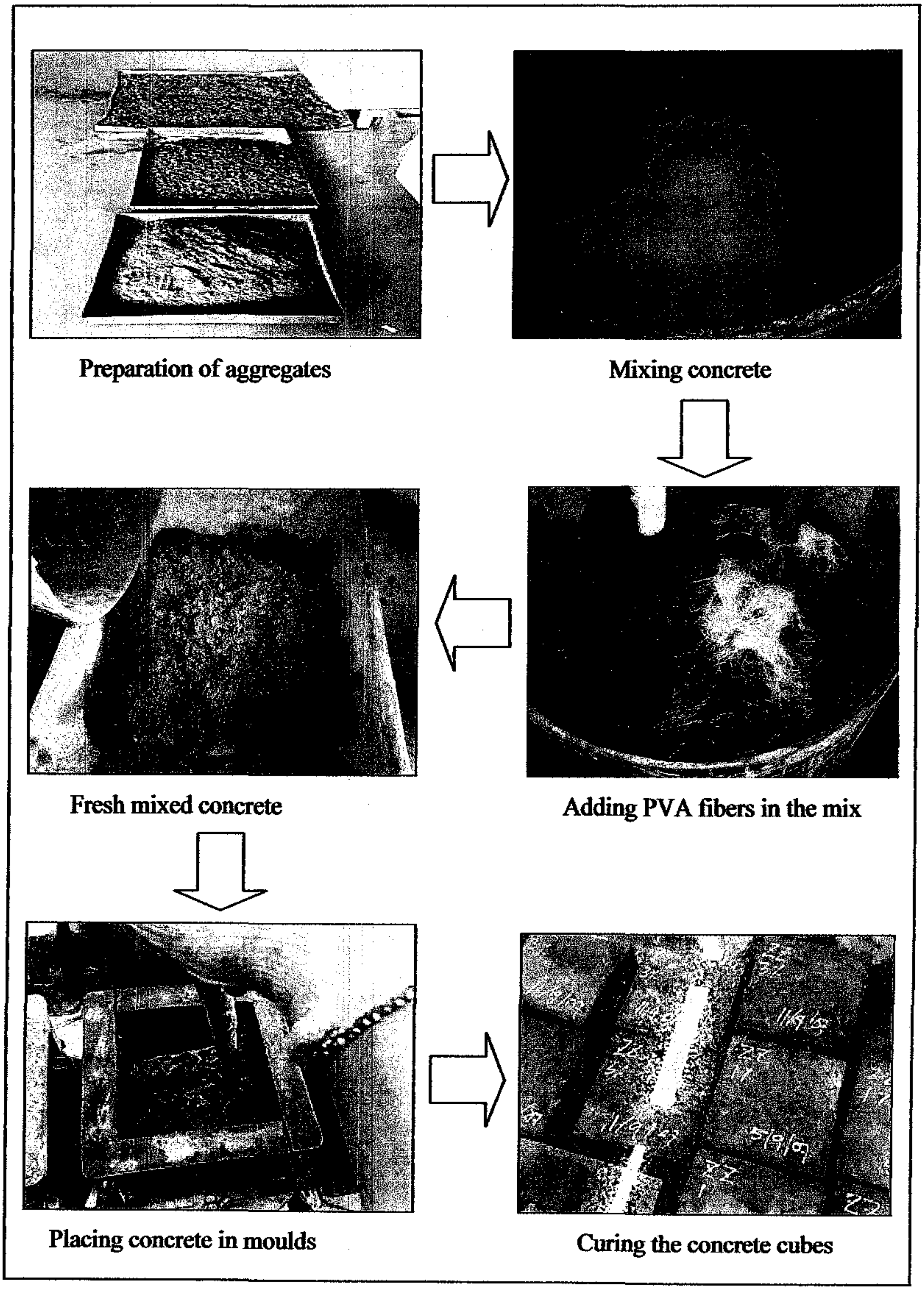


Figure 3.2.2: Process of concrete mixing

3.2.3 Concrete Testing

The concrete mixes are being produced in concrete laboratory. The concrete mixes are tested in order to know the compressive strength, and splitting tensile strength. The tests were carried through with ages of 1, 3, 7, 28, and 60 days, with curing in humid chamber. For fresh concrete test, the slump tests were conducted during every mixes.

3.2.3a Fresh Concrete Testing

i) Slump Test (ASTM C143-90 and BS 1881:Part 102:1983)

Objective

To measure the shear resistance of concrete to flowing under its own weight

Procedure

1) Start the test within 5 min. after obtaining the final portion of the mixed sample.
2) Dampen the mold (inside) and place on the dampened base plate.
3) Hold the mold firmly in place during the filling and rodding operation.
4) Fill the mold in 3 layers, each approximately one-third the volume of the mold.
5) Rod each layer with 25 strokes of the tamping rod. During filling and rodding the top layer, heap the concrete above the mold before rodding is started.
6) Strike off the surface by a screeding and a rolling motion of the tamping rod.
7) Remove the mold immediately by raising it in a vertical direction.
8) Place the empty mold (inverted) adjacent to the concrete sample and measure the vertical difference between the top of the mold and the displaced original center of the sample. The slump is measured.

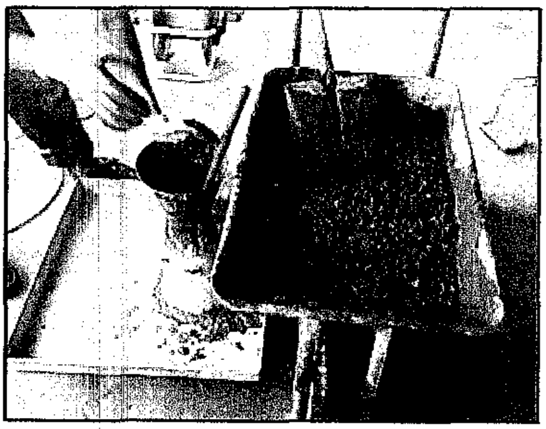


Figure 3.2.3a: Slump Test.

3.2.3b Hardened Concrete Testing

i) Compressive Strength Test (ASTM C39)

<u>Objective</u>

To measure the compressive strength of concrete specimens

<u>Procedure</u>

1) Maintain the specimen in a moist condition up to the time of compression testing. Compression tests are made as soon as practicable after removal from moist storage. The specimens are tested in this cured moist condition.
2) Wipe clean the bearing surfaces of the upper and lower platens of the compression testing machine. Also, wipe clean both end caps of the test specimen.
3) Center the specimen on the lower platen of the testing machine.
4) Carefully align the axis of the specimen with the center of thrust of the spherically seated upper platen.
5) Bring the upper platen to bear on the specimen, adjusting the load to obtain uniform seating of the specimen.
6) Apply the load at a loading rate based on the size of concrete specimen. The time to failure for 3000 psi concrete is 1 to 2.5 minutes.
7) Apply the load at the prescribed loading rate until the specimen fails. Record the maximum load (lb). Note the type of failure and the appearance of the concrete.

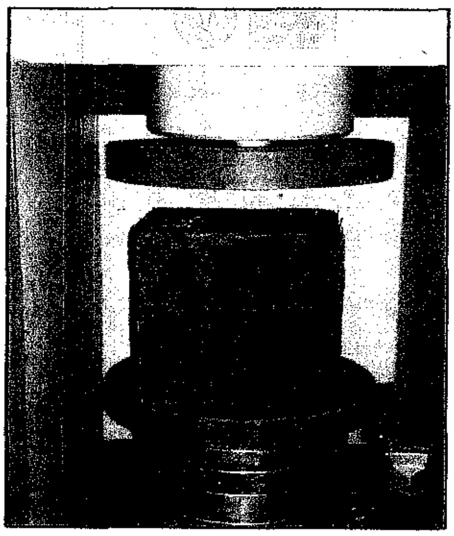


Figure 3.2.3b: Compressive Strength Test.

ii) Split Tensile Test (BS 1881 : Part 117 : 1983)

Objective

To measure the splitting tensile strength of concrete specimens

Procedure

1) Maintain the specimen in a moist condition up to the time of splitting tensile testing. Splitting tests are made as soon as practicable after removal from moist storage. The specimens are tested in this cured moist condition.
2) The cube samples are being brought from the curing tank to the testing machine.
3) While still wet, the hardened cube sample is placed in the centre of the test rig as in the figure below, with the cast faces in contact with the rig base.
4) Carefully align the axis of the test rig with the center of thrust of the spherically seated upper platen.
5) The setting of machine is changed to test 150mmX150mmX150mm test sample and the constant rate of load of 0.2-0.4MPa/second is to make sure to be applied.
6) Apply the load at the prescribed loading rate until the specimen fails. Record the maximum load (lb). Note the type of failure and the appearance of the concrete.

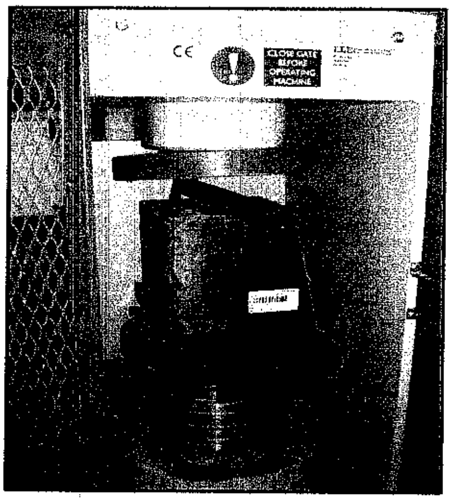


Figure 3.2.3c: Tensile Strength Test.

3.3 Data Analysis and Discussion

Data analyses are done based on collected data from the output of laboratory tests. The result obtain from data analysis will be discussed and concluded in the next chapter.

CHAPTER 4

4.0 RESULTS AND DISCUSSION

According to the topic, the research are concentrated more on the tensile behavior of the concrete with the addition of PVA fiber. Tensile strength is the basis for its ability to resist bending, or its flexural strength. Concrete is usually assumed to be about 10% as strong in tension as it is in compression. However, according to Hanson (1968) [7], splitting tensile strength is normally about 8% to 14% of the compressive strength. These low tensile strength and tensile strain capacity of concrete actually can be improved by infusing PVA fiber.

Compare with conventional concrete mixes, fiber reinforced concrete generally has higher cement content, a higher fine aggregate content and a smaller size of coarse aggregate. For a particular type of fiber, the mix proportions are the best determined by trial mixes and the final mix are adjusted as necessary to meet the requirements of workability, strength and durability.

A trial concrete has been done to determine the appropriate mix to be used for the first mix using PVA fibers and in order to come up with the proposed mix proportion. All 4 mixes for the concrete tests are done based on that mix proportion but with different content of PVA fiber which is 0%, 1%, 2%, and 3% for each mix. The concrete cubes are being tested for 1, 3, 7, 19, 28 and 60 days to see the behavior and strength development of concrete when infusing the PVA fibers in the concrete mix.

4.1 Result of Fresh Concrete Testing

4.1.1 Slump Test

Table 5: Result of slump test for each mix

Mix	Slump (mm)
Mix 1 - PVA 0%	150
Mix 2 - PVA 1%	62
Mix 3 - PVA 2%	25
Mix 4 - PVA 3%	0

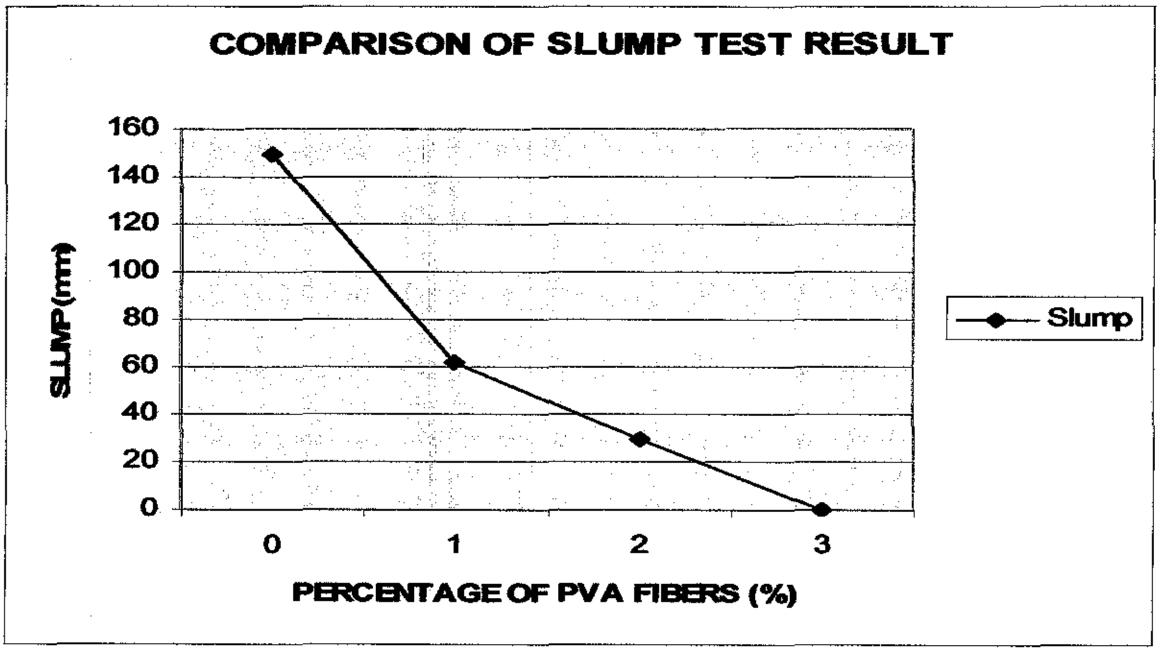


Figure 4.1.1a: Comparison of slump test samples

From the result of slump test, it shows reduction in concrete's workability when more PVA fibers added in the mix. The highest slump is concrete with 0% of PVA fibers and the lowest is concrete with 3% PVA fibers which indicates no slump. PVA fibers added in the mixes bonded the concrete matrix even more strongly hence it reduces the concrete's workability. It is desirable to infuse more PVA fibers in concrete in terms of its strength, but excessive use of PVA fiber would raise an issue on workability. So the most optimum content of PVA fiber must be determined with respect to its workability.

It is noted that standard slump test has been found to be an appropriate measure of the workability of fiber reinforced concrete since its mixtures with apparently low slump values can be quite workable in the field. For proper compaction, fiber reinforced concrete mixtures must be placed using vibration and so workability tests that involved vibration are more appropriate. It is therefore recommended that either Vebe test or the inverted slump cone test be used. The latter test involves the time required for the fiber reinforced concrete to flow through an inverted standard slump cone under internal vibration. Super plasticizer can be used as the admixture to improve the workability of fiber reinforced concrete.

Figure 4.1.1b: Slump test of concrete with 1% PVA fiber

4.2 Result of Hardened Concrete Testing

For the hardened concrete testing, 2 tests were conducted to the produced samples which are Compressive strength test and Splitting Tensile strength test.

4.2.1 Compressive Strength of Concrete Cubes

Compressive strength test were conducted using an automatic compression machine for 1, 3, 7, 19 and 28 days and results were obtained as shown in *Table 6.*

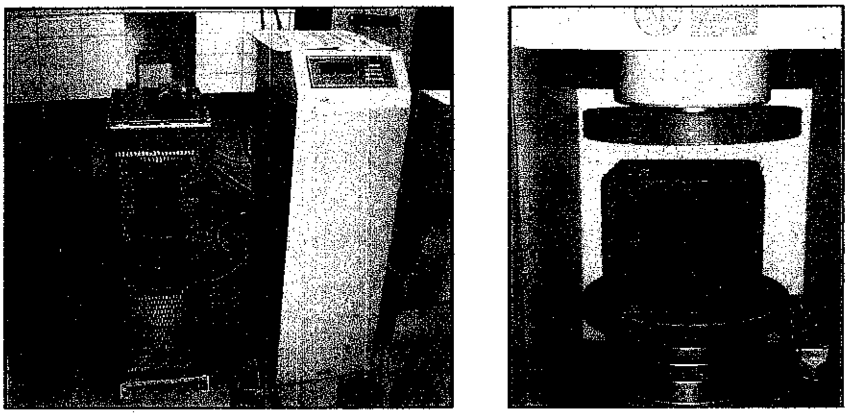


Figure 4.2.1a: Compression Machine

Table 6: Result of compression strength test

Mix	Compressive Strength (MPa)				
	1 day	3 days	7 days	19 days	28 days
PVA 0%	15.99	24.28	30.37	39.33	42.75
PVA 1%	23.03	35.33	40.81	49.66	52.15
PVA 2%	18.58	29.01	34.44	47.59	44.98
PVA 3%	22.01	28.41	32.77	45.59	54.33

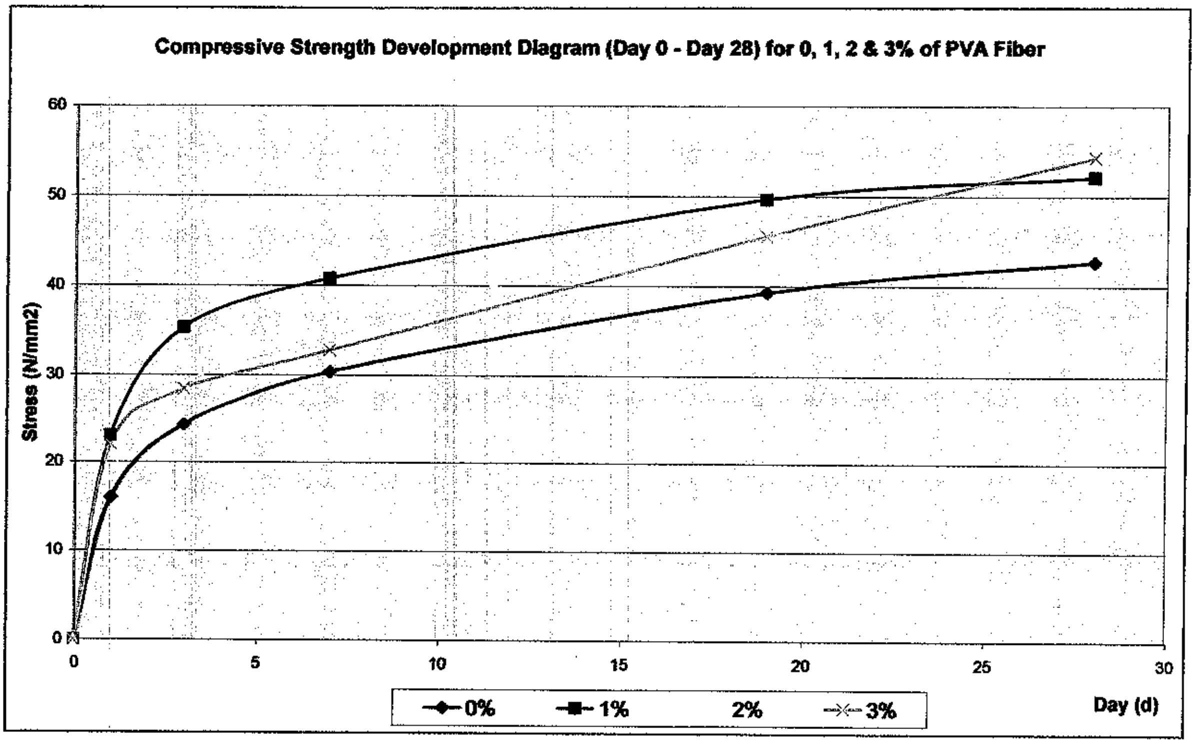


Figure 4.2.1b: Comparison of compressive strength test of sample.

Table 6 shows the results of compressive strength of all samples mixed until day 28. Based on 28 day result of 0% fiber which is about 42 MPa, the target design strength for mix proportioning is correct. From the graph, it is observed that the strengths of all mixes keep increasing due to effect of curing to the concrete and it is gradually gaining its strength from day another day. From the results there is strong evidence that the ability of concrete to withstand the compressive load increase when the PVA fibers are added in a concrete.

4.2.2 Tensile Strength of Concrete Cubes

Tensile strength test also were conducted using an automatic compression machine but added with a mould to let it be in the condition of splitting tensile. The cubes were also being tested for 1, 3, 7, 19 and 28 days and results were obtained as shown in *Table 7*.

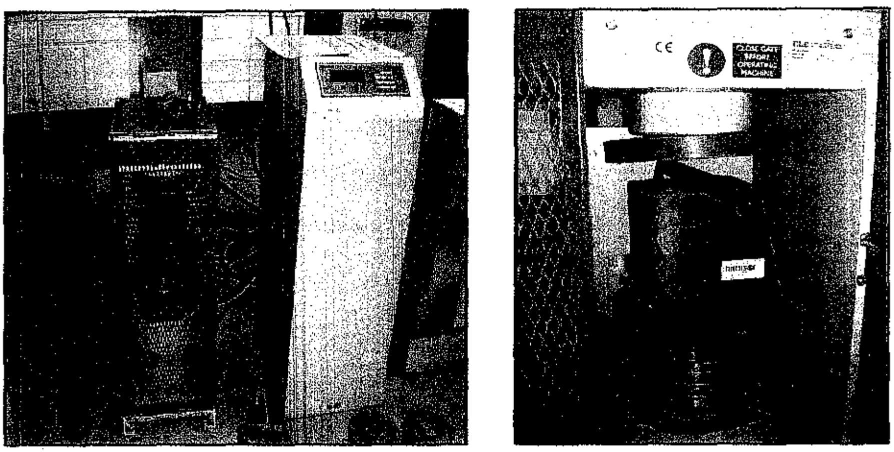


Figure 4.2.2a: Compression machine added with splitting tensile mould

Table 7: Result of tensile strength test

Mix	Tensile Strength (MPa)					
	1 days	**3 days**	**7 days**	**19 days**	**28 days**	**60 days**
PVA 0%	2.927	4.646	5.876	6.569	6.696	7.257
PVA 1%	5.052	6.556	7.55	10.185	10.402	10.567
PVA 2%	4.144	5.345	6.506	7.479	8.16	8.516
PVA 3%	4.739	5.749	6.716	7.944	9.221	9.315

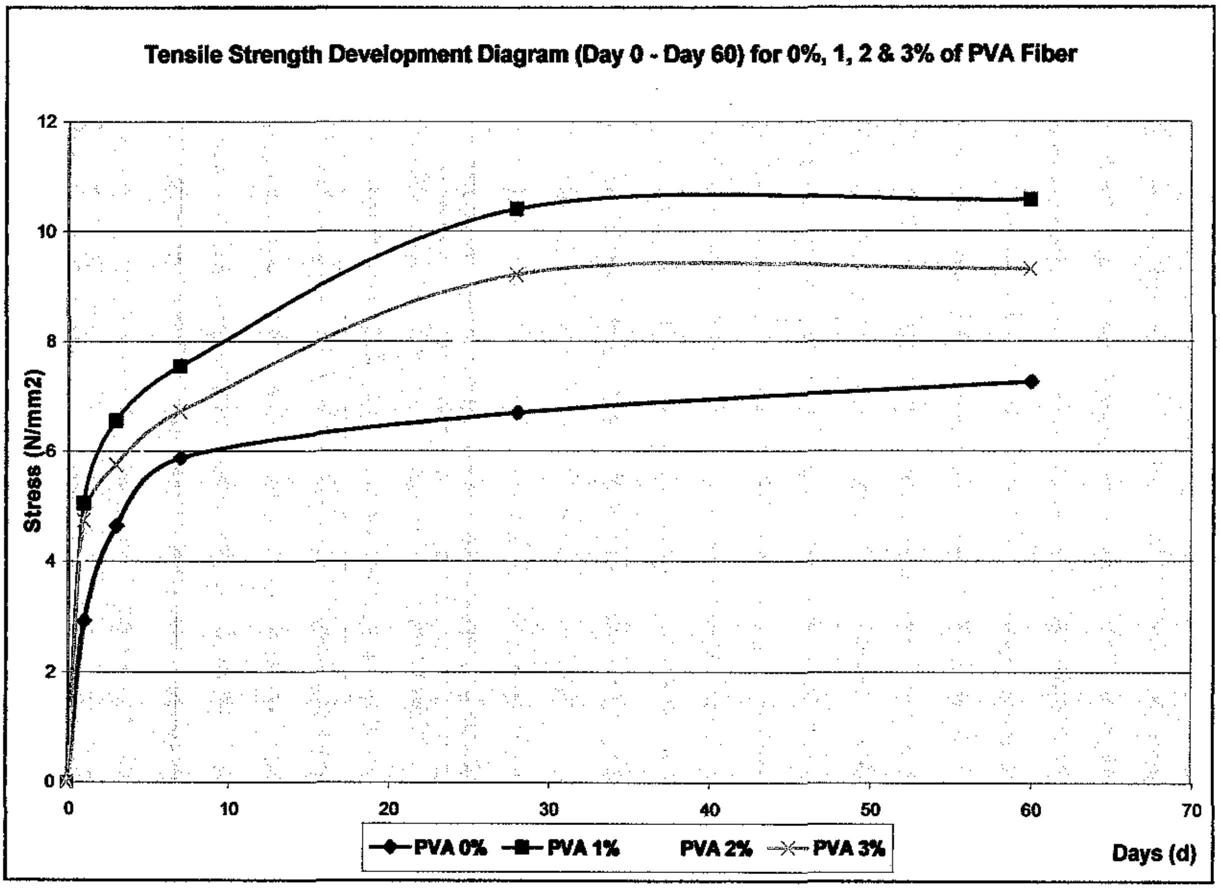


Figure 4.2.2b: Comparison of tensile strength test of sample.

The graph shows that the strengths of all mixes keep increasing due to effect of curing to the concrete and it is gradually gaining its strength from day to day. From the results, it is observed that the ability of concrete to withstand the tensile load increase when the PVA fibers are added in a concrete. Hence, it can be concluded that with increasing amount of PVA fibers inserted in a concrete, its tensile strength is also increasing.

However, the value of tensile strength obtained seems to be much higher compared that what it should. Compressive strength, which is easier to measure than tensile strength, can be used as an index of tensile strength, once the empirical relationship between them has been established for the materials to be used in the mix and the size of the element involved. According to Hanson (1968) [7], splitting tensile strength is normally about 8% to 14% of the compressive strength. This might be happened because of the wrong usage of prism bar in the test rig. For future testing on tensile splitting test, it is better to implement the test using the concrete cylinder instead of using concrete cubes.

About the effects of fiber content in concrete, the both graph shows that the highest compressive and tensile strength is produced by the concrete with 1% PVA fibers, followed by concrete with 2% PVA fibers and then 3% of PVA fibers. The concrete with high content of PVA fibers (2% and 3%) have lower strength mainly because of segregation of fibers or known as balling effect. Balling effect is the phenomena where the fibers glued together and tend to make the concrete toughness lower.

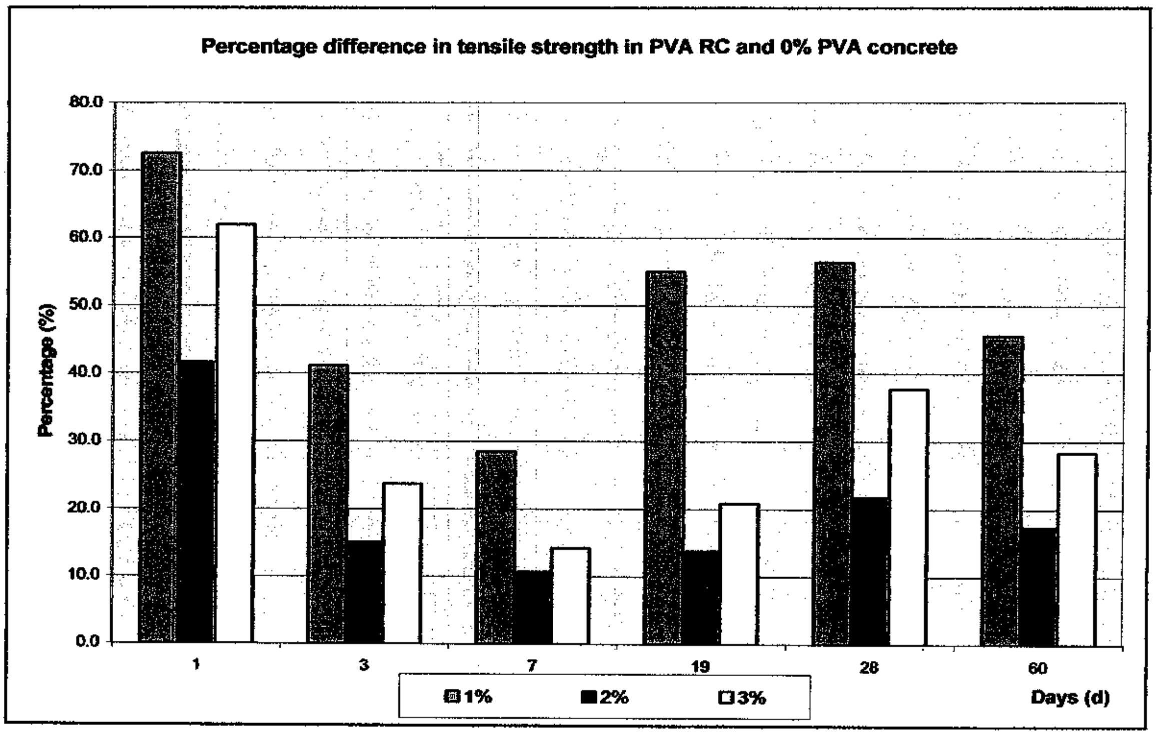


Figure 4.2.2c: Percentage Difference in tensile strength of PVA RC and 0% PVA concrete.

Figure 4.2.2d: Concrete cubes after the tests

CHAPTER 5

5.0 CONCLUSION

This project is based on researching the effect of PVA fiber to concrete's strength. Based on the literature reviews, PVA fiber has high tenacity and modulus of elasticity compare with other general organic fiber. Second, bonding strength between fiber and cement is strong. Also it is possible to control bonding strength by surface treatment. At last, PVA fiber has got wide acceptance because of it good durability, less hazardous and reasonable cost alternative. It is possible that the addition of fibers will increase the tensile strength of the concrete, thus making it a much more attractive material than plain concrete, which appears to have no such limit.

The concretes with PVA fibers have been mixed according to the mix proportioning that had been calculated. 4 concrete mixes were conducted; consist of 0% (control mix), 1%, 2% and 3% of PVA fibers. Several numbers of lab experiments have been carried out to determine the effects of infusing PVA fiber in concrete mix.

From the results obtained, there is strong evidence that by incorporating the PVA fibers in the concrete matrix, the higher concrete strength can be achieved compared to normal concrete. According to both compressive and splitting tensile test, it is observed that the strength of all mixes keep increasing due to effect of curing. It means that concrete gradually gaining its strength from a day to another day of curing. About the effects of fiber content in concrete, both test showed that the highest strength is produced from concrete infused with 1% PVA fibers.

REFERENCES

1. Wang, S. and V. C. Li, May 2005. "Polyvinyl Alcohol Fiber Reinforced Engineered Cementitious Composites: Material Design and Performances." Proceedings of Int'l workshop on HPFRCC in structural applications, Honolulu, Hawaii, USA.

2. V.C. Li, C. Wu, S. Wang, A. Ogawa, and T. Saito, "Interface Tailoring for Strain-Hardening PVA-ECC, "ACI J. of Materials 99, 5, 463-472 (2002).

3. Li, V. C., Wu, H. C., and Chan, Y. W., "Effect of plasma treatment of polyethylene fibers on interface and cementatious composite properties." J. Am. Ceramic Soc., 79(3), 700-704.

4. M. K. Lee, B. I. G. Barr. November 2002. "An overview of the fatigue behaviour of plain and fibre reinforced concrete." Cardiff School of Engineering, Division of Civil and Structural Engineering, Cardiff University, UK.

5. Lange, David A., *Long-Term Strength Development of Concrete*, RP326, Portland Cement Association, 1994.

6. Abrams, D. A., *Design of Concrete Mixtures*, Lewis Institute, Structural Materials Research Laboratory, Bulletin No. 1, PCA LS001, http://www.portcement.org/pdf_files/LS001.pdf, 1918, 20 pages.

7. Hanson, J. A., *Effects of Curing and Drying Environments on Splitting Tensile Strength of Concrete*, Development Department Bulletin DX141, Portland Cement Association, http://www.portcement.org/pdf_files/DX141.pdf, 1968, page 11.

8. Li, V. C., Wang, S. and Wu, C., "Tensile Strain-Hardening Behavior of PVA-ECC," ACI Material Journals, V.98, No. 6, Nov-Dec 2001, pp.483-492

9. V.C. Li and T. Matsumoto, Fatigue crack growth analysis of fiber reinforced concrete with effect of interfacial bond degradation. *Cem. Concr. Compos.* 20 (1998), pp. 339–351

10. Ramakrishnan, V. and Lokvik, B. J. June 23-26, 1991, "Flexural Fatigue Strength of Fiber Reinforced Concretes" in High Performance Fiber Reinforced Cement Composites, *Proceedings of the International Workshop held by RILEM, ACI and others*, E & FN Spon, London, 1992, pp 271-287.

11. T.C.C. Hsu, Fatigue of plain concrete. *ACI J.* 78 (1981), pp. 292–305

12. Akkaya, Y., Ghandehari, M., Surendra, P. S., "Observing the multiple cracking of FRC composites by Electronic Speckle Pattern Interferometry." 15th ASCE Engineering Mechanics Conference (2002)

13. A.M Neville and J.J Brooks, 1999, *Concrete Technology*, England, Longman Group

14. Shan Somayaji. 2001. "Civil Engineering Materials." Prentice Hall, New Jersey.

15. Antonio Aguado, Ravindra Gettu, Surendra P. Shah. 1995. "Concrete Technology: New Trends, Industrial Applications." Chapman & Hall, London.

16. Li, V. C., Fischer, G., "Reinforced ECC – An evolution from materials to structures" Proceedings of the 1st Congress (2002)

17. Portland Cement Concrete Lab, Civil Engineering Department, University of New Mexico <http://civilx.unm.edu/laboratories_ss/pcc/pcc.html>

18. Cement and Concrete Institute <http://cnci.org.za/inf/publications.pdf/fibre.pdf>

19. Website refers to ©2007 Kuraray Co. <http://www.kuraray-am.com/pvaf.php>

APPENDICES

Appendix 1 – Properties of PVA fibers

A. Specifications and properties

Item Property	High strength & modulus I.	High strength & modulus II.	Super-short staple fiber I. for building materials	Super-short staple fiber II. for building materials
Density (g/cm^2)	1.26	1.26	1.26	1.26
Titre (dtex)	2.0 _0.3	2.0_0.3	1.7 - 3.0	1.7 - 3.0
Length (mm)	2 - 65	2 - 65	2 - 65	2 - 65
Tenacity (CN/dtex)	> 10.5	> 10.5	≥8	≥6
Modulus (CN/dtex)	> 240	> 240	>200	>150
Breaking elongation (%)	< 7_1.5	<7_1.5		
Reduction in hot water	< 2	< 3		
Acid proof	Good	good	good	good
Alkali resistance	Good	good	good	good
Ultraviolet resistance	Good	good	good	good
Electric conductivity	Low	low	low	low
Thermal conductivity	Low	low	low	low

B. Fiber breaking elongation comparisons

Fiber	Vinylon (high strength)	Vinylon (usual)	Nylon	PP fiber	Polyester (usual)	Polyester (high strength)
Breaking elongation %	7	15	20 - 40	15 - 35	14 - 25	10 - 14

C. Alkali resistance comparisons

Test condition			Fiber strength loss ratio (%)			
Density %	Temperature°C	Duration time (hr)	Vinylon-high strength	Viscose fiber yarn	Nylon 6	Polyester
1	20	10	0	12	0	1
1	100	100	7	29	25	71
40	20	10	0	100	18	4

D. Sunshine resistance comparisons

Exposed in the sunshine(hour)	Fiber strength loss ratio (%)			
	High strength vinylon	Nylon 6	Viscose fiber	Cotton
100	3.05	19.6	4.26	3.67
300	7.93	41.2	7.45	30.73
500	10.98	65.09	25.00	38.53
700	11.16	74.51	63.30	49.54

Appendix 1b – Typical properties of Glass reinforced concrete

PROPERTIES				Process	
				Spray	*Premix*
Fibre Content			[wt. %]	5	3
Density	(dry state)		[g/cm³]	1.8 ÷ 2.2	1.7 ÷ 2.1
Strength	Bending Strength	MOR	[N/mm²]	22 ÷ 32	9 ÷ 13
		LOP	[N/mm²]	7 ÷ 13	6 ÷ 9
		Young Modulus	[kN/mm²]	15 ÷ 25	14 ÷ 24
	Tensile Strength	UTS	[N/mm²]	8 ÷ 12	3 ÷ 6
		BOP	[N/mm²]	4 ÷ 6	3 ÷ 5
		Ultimate strain	[%]	0.6 ÷ 1.2	0.1 ÷ 0.2
	Compressive Strength	Out-of-plane	[N/mm²]	50 ÷ 80	40 ÷ 60
		In-plane	[N/mm²]	40 ÷ 70	40 ÷ 60
	Shear Strength	Out-of-plane	[N/mm²]	25 ÷ 35	4 ÷ 6
		In-plane	[N/mm²]	7 ÷ 12	4 ÷ 6
		Interlaminar	[N/mm²]	2 ÷ 4	4 ÷ 6
	Charpy impact		[N mm/mm²]	15 ÷ 25	7 ÷ 12
	Poisson's ratio			0.24 ÷ 0.3	0.24 ÷ 0.3
Water	Water absorbing ratio		[%]	10 ÷ 15	10 ÷ 15
	Drying shrinkage		[%]	0.1 ÷ 0.2	0.1 ÷ 0.2
Heat	Thermal conductivity		[W/m °C]	0.9 ÷ 1.5	0.9 ÷ 1.5
	Thermal expansion coefficient		[x 10⁻⁶/°C]	7 ÷ 12	7 ÷ 12

Legenda: MOR: Modulus of Rupture; LOP: Limit of Proportionality
UTS: Ultimate Tensile Strength BOP: Bend-Over Point

**Details were extracted from [16]

Appendix 1c – Typical properties of natural fibers

Fibre type	Coconut	Sisal	Sugar cane bagasse	Bamboo	Jute	Flax	Ele-phant grass	Water reed	Plan-tain	Mu-samba	Wood fibre (Kraft pulp)
Fibre length, mm	50 - 100	N/A	N/A	N/A	175 - 300	500	N/A	N/A	N/A	N/A	2,5 - 5,0
Fibre diameter, mm	0,1 - 0,4	N/A	0,2 - 0,4	0,05 - 0,4	0,1 - 0,2	N/A	N/A	N/A	N/A	N/A	0,025 - 0,075
Relative density	1,12 - 1,15	N/A	1,2 - 1,3	1,5	1,02 - 1,04	N/A	N/A	N/A	N/A	N/A	1,5
Modulus of elasticity, GPa	19 - 26	13 - 26	15 - 19	33 - 40	26 - 32	100	5	5	1,5	1,0	N/A
Ultimate tensile strength, MPa	120 - 200	275 - 570	180 - 290	350 - 500	250 - 350	1 000	180	70	90	80	700
Elongation at break, %	10 - 25	3 - 5	N/A	N/A	1,5 - 1,9	1,8 - 2,2	3,6	1,2	5,9	9,7	N/A
Water absorption, %	130 - 180	60 - 70	70 - 75	40 - 45	N/A	N/A	N/A	N/A	N/A	N/A	50 - 75

Notes
N/A Properties not readily available or not applicable.

**Details were extracted from [16]

Appendix 1d – Selected synthetic fiber types and properties

Fibre type	Equivalent diameter µm	Relative density	Tensile strength MPa	Elastic modulus GPa	Ultimate elongation %	Ignition tem-perature °C	Melt, oxidation, or decomposition temperature °C	Water absorption per ASTM D 570, % by mass
Acrylic	13 - 104	1,16 - 1,18	270 - 1 000	14 - 19	7,5 - 50,0	-	220 - 235	1,0 - 2,5
Aramid I*	12	1,44	2 900	60	4,4	high	480	4,3
Aramid II†	10	1,44	2 350	115	2,5	high	480	1,2
Carbon, PAN HM^Δ	8	1,6 - 1,7	2 500 - 3 000	380	0,5 - 0,7	high	400	nil
Carbon, PAN HT^§	9	1,6 - 1,7	3 450 - 4 000	230	1,0 - 1,5	high	400	nil
Carbon, pitch GP**	10 - 13	1,6 - 1,7	480 - 790	27 - 35	2,0 - 2,4	high	400	3 - 7
Carbon, pitch HP††	9 - 18	1,8 - 2,15	1 500 - 3 100	150 - 480	0,5 - 1,1	high	500	nil
Nylon^ΔΔ	23	1,14	970	5	20	-	200 - 220	2,8 - 5,0
Polyester	20	1,34 - 1,39	230 - 1 100	17	12 - 150	600	260	0,4
Polyethylene^ΔΔ	25 - 1 000	0,92 - 0,96	75 - 590	5	3 - 80	-	130	nil
Polypropylene^ΔΔ	-	0,90 - 0,91	140 - 700	3,5 - 4,8	15	600	165	nil

Notes

* Not all fibre types are currently used for commercial production of FRC

† High modulus

Δ Polyacrylonitrile based, high modulus

§ Polyacrylonitrile based, high tensile strength

** Isotropic pitch based, general purpose

†† Mesophase pitch based, high performance

ΔΔ Data listed is only for fibres commercially available for FRC

**Details were extracted from [16]

Appendix 2 – Tables and Figures for Mix Proportioning

*Based on Concrete Technology Book by A. M. Neville (1999) at [13]

Table 14.9 Approximate Compressive Strengths of Concretes Made with a Free Water/Cement Ratio of 0.5 According to the 1988 British Method[14.11]

Type of cement	*Type of coarse aggregate*	*Compressive strength* (MPa (psi)) at the age of (days):* 3	7	28	91
Ordinary Portland (Type I) / Sulfate-resisting Portland (Type V)	Uncrushed	22 (3200)	30 (4400)	42 (6100)	49 (7100)
	Crushed	27 (3900)	36 (5200)	49 (7100)	56 (8100)
Rapid-hardening Portland (Type III)	Uncrushed	29 (4200)	37 (5400)	48 (7000)	54 (7800)
	Crushed	34 (4900)	43 (6200)	55 (8000)	61 (8900)

*Measured on cubes

Table 14.9 (pg. 763): Approximate Compressive Strengths of Concretes Made with a Free Water/Cement Ratio of 0.5.

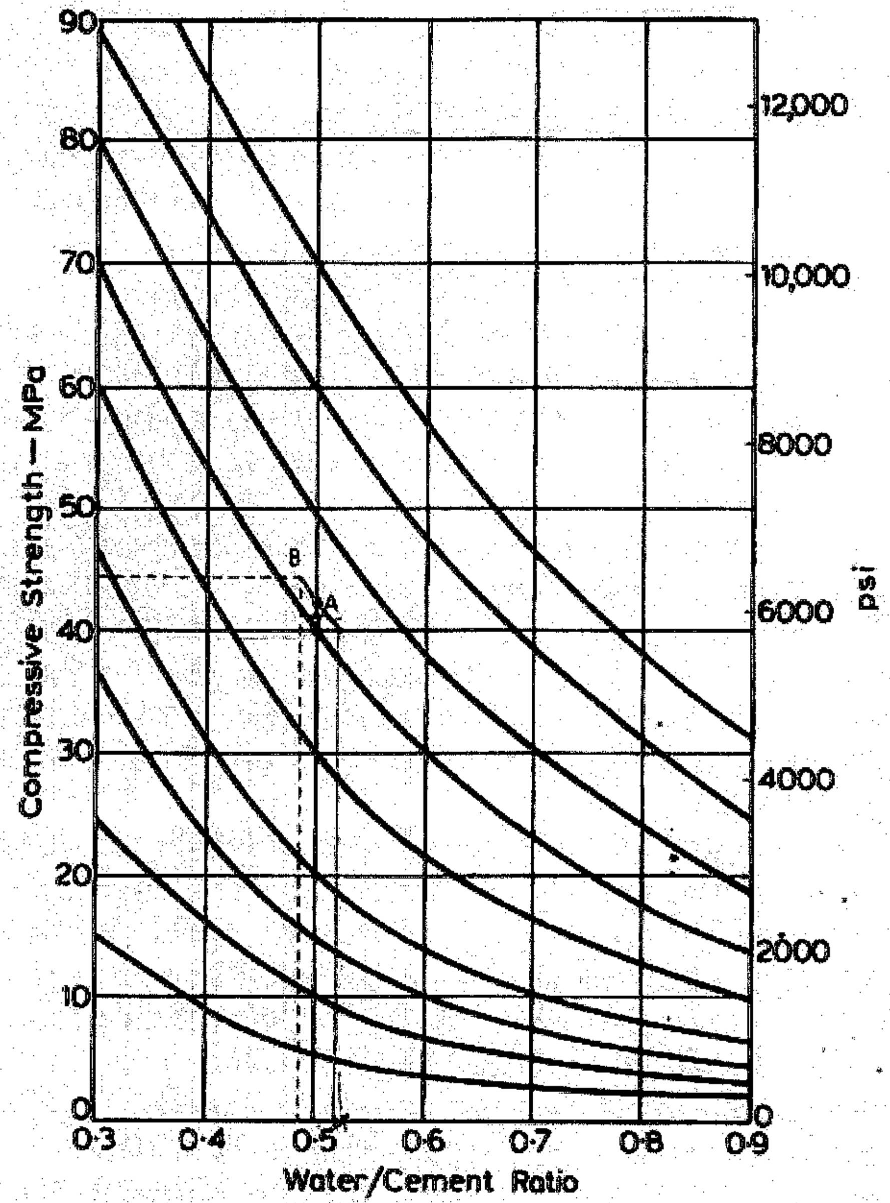


Fig. 14.12 Relation between compressive strength and free water/cement ratio for use British mix selection method[14.11] (see Table 14.9) (Crown copyright)

Figure 14.12 (pg. 764): Relation between compressive strength and free water/ratio for use British mix selection method.

Table 14.10 Approximate Free Water Contents Required to Give Various Levels of Workability According to the 1988 British Method[14.11] (Crown copyright)

Aggregate		Water content, kg/m³ (lb/yd³) for:				
Max size, mm (in.)	Type	Slump, mm (in.)	0–10 (0–½)	10–30 (½–1)	30–60 (1–2½)	60–180 (2½–7)
		Vebe time, s	>12	6–12	3–6	0–3
10 (⅜)	Uncrushed		150 (255)	180 (305)	205 (345)	225 (380)
	Crushed		180 (305)	205 (345)	230 (390)	250 (420)
20 (¾)	Uncrushed		135 (230)	160 (270)	180 (305)	195 (330)
	Crushed		170 (285)	190 (320)	210 (355)	225 (380)
40 (1½)	Uncrushed		115 (195)	140 (235)	160 (270)	175 (295)
	Crushed		155 (260)	175 (295)	190 (320)	205 (345)

Table 14.10 (pg. 765): Approximate Water Contents Required to Give Various Levels of Workability.

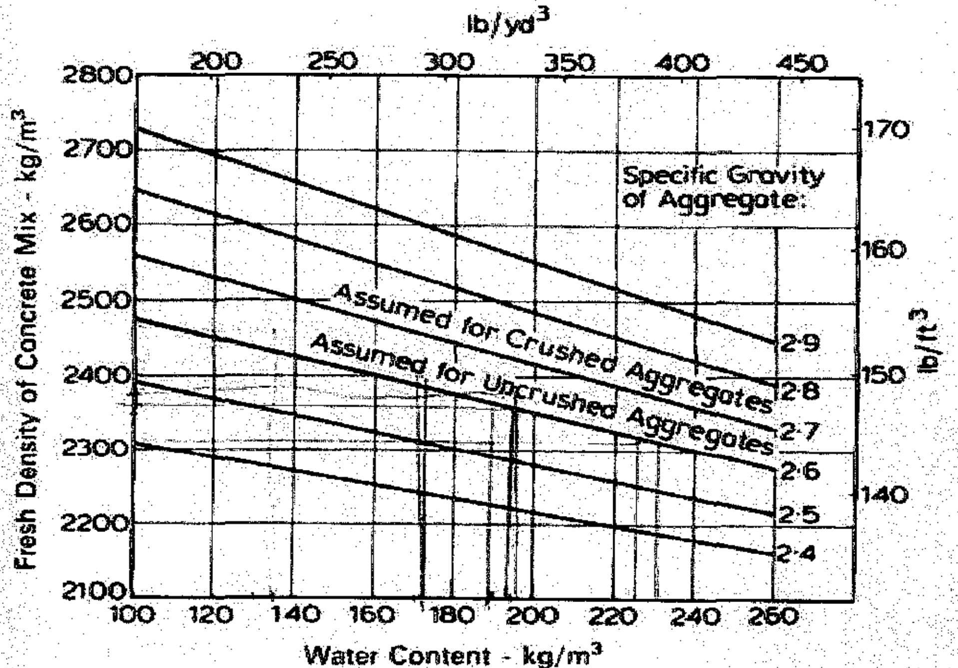


Fig. 14.13 Estimated wet density for fully compacted concrete[14.11] (specific gravity is given for saturated and surface-dry aggregate) (Crown copyright)

Figure 14.13 (pg. 765): Estimated wet density for fully compacted concrete.

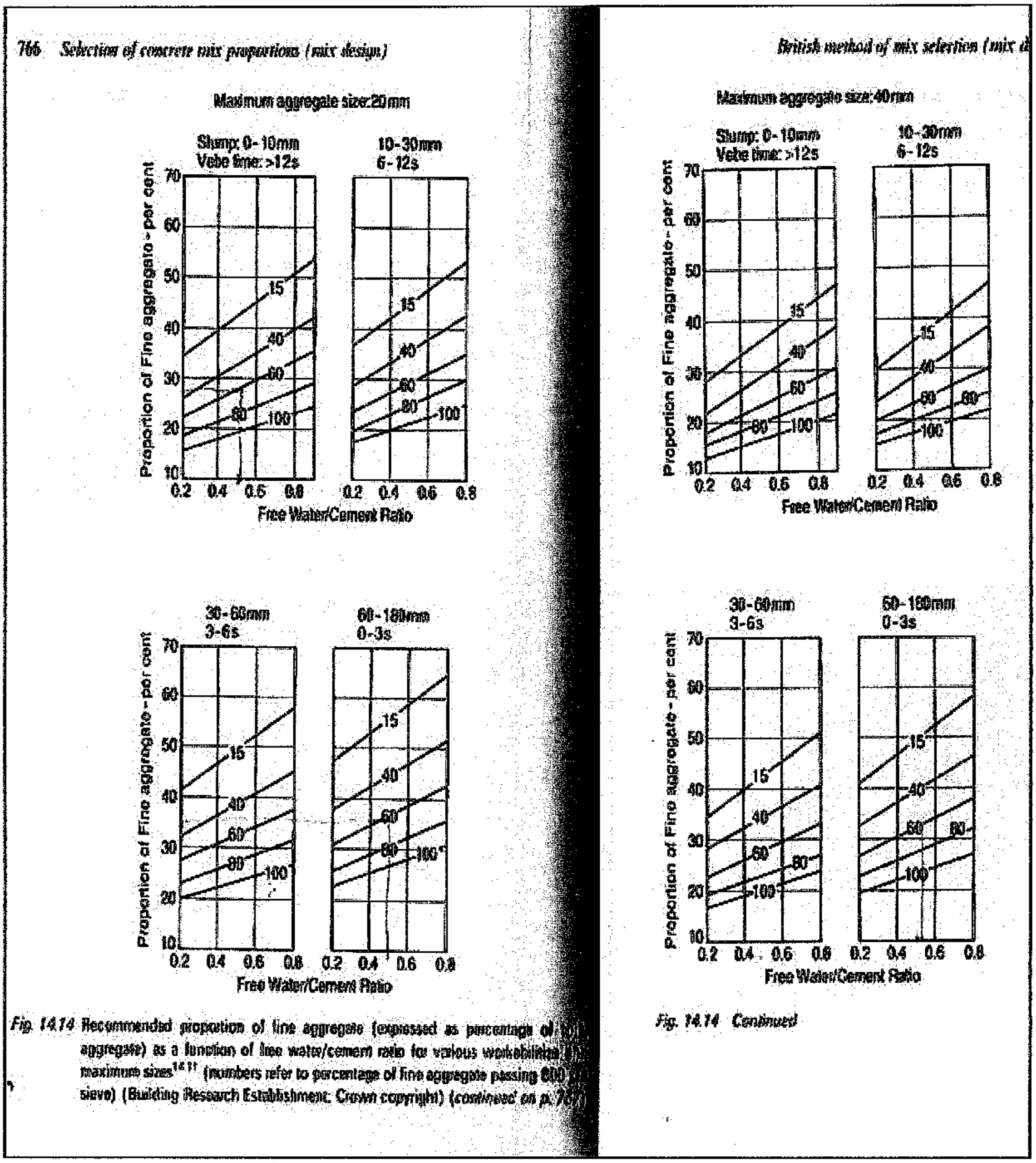


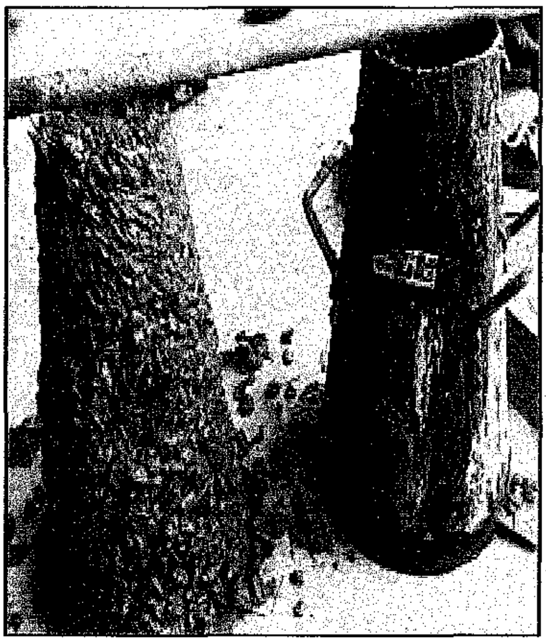
Figure 14.14 (pg. 766): Recommended proportion of fine aggregate as a function of free water/cement ratio for various workability and maximum sizes.

Appendix 3 – Pictures of Slump Test

Slump test of PVA 0% concrete

Slump test of PVA 1% concrete

Slump test of PVA 2% concrete



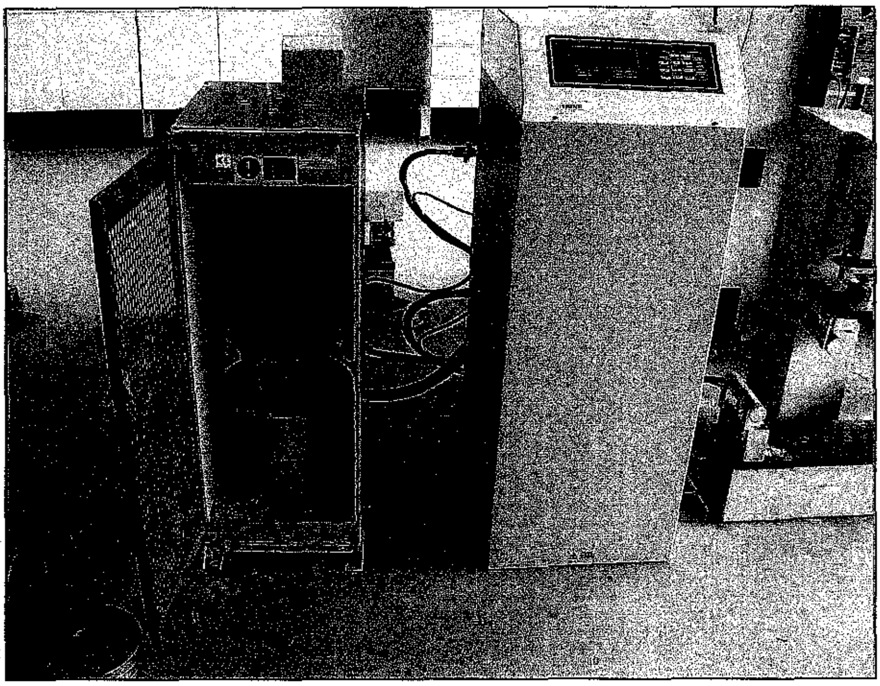
Slump test of 3% PVA concrete

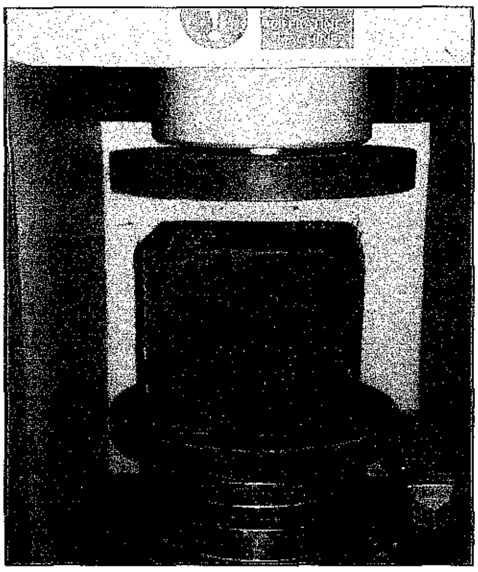
Appendix 4 – Results of Compressive Strength Test

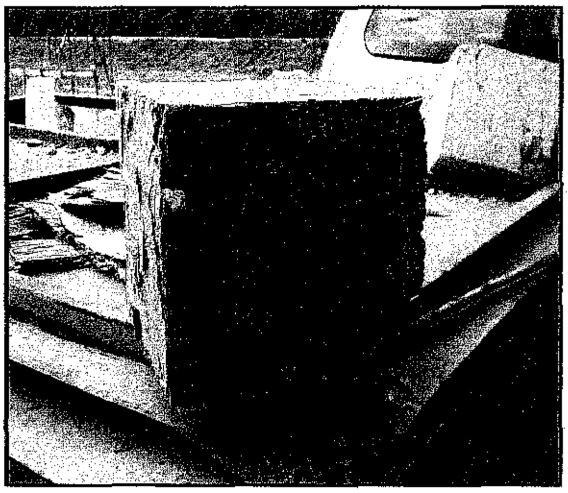
DAY	% PVA	COMPRESSION			
		WEIGHT, W, (kg)	MAXIMUM LOAD, P, (kN)	STRESS, F, $\frac{P \times 1000}{150 \times 150}$ (N/mm²)	AVERAGE STRESS (N/mm²)
1	0	8.33	357.5	15.89	15.99
		8.15	378.7	16.83	
		8.18	343.1	15.25	
	1	8.47	509.2	22.63	23.03
		8.32	524.9	23.33	
		8.18	520.4	23.13	
	2	8.26	410	18.22	18.58
		8.23	449.6	19.98	
		8.34	394.7	17.54	
	3	8.35	521.3	23.17	24.07
		8.26	583	25.91	
		8.33	520.4	23.13	
3	0	8.13	543.6	24.16	24.28
		8.14	536.9	23.86	
		8.21	558.5	24.82	
	1	8.38	785.7	34.92	35.33
		8.26	776.9	34.53	
		8.31	822.2	36.54	
	2	8.2	657.2	29.21	29.01
		8.25	645.1	28.67	
		8.31	655.9	29.15	
	3	8.27	641.5	28.51	28.41
		8.2	619	27.51	
		8.38	657.2	29.21	
7	0	8.22	684.5	30.42	30.37
		8.18	709.2	31.52	
		8.25	656.3	29.17	
	1	8.42	936.5	41.62	40.81
		8.39	933.8	41.5	
		8.24	884.5	39.31	
	2	8.12	725.9	32.26	33.44
		8.17	723.8	32.17	
		8.21	807.5	35.89	
	3	8.3	755.1	33.56	32.77
		8.38	684	30.4	
		8.28	772.9	34.35	

19	0	8.12	854.6	37.98	39.33
		8.2	893.9	39.73	
		8.14	906.3	40.28	
	1	8.32	1136.7	50.52	49.66
		8.3	1078	47.91	
		8.22	1137.4	50.55	
	2	8.26	930.6	41.36	41.36
		8.21	973.1	43.25	
		8.4	888.1	39.47	
	3	8.36	1109.9	49.33	47.59
		8.3	1049	46.62	
		8.28	1053.5	46.82	
28	0	8.31	989.8	43.99	42.75
		8.28	922.3	40.99	
		8.19	973.6	43.27	
	1	8.39	1152	51.2	50.31
		8.34	1090.6	48.47	
		8.37	1153.4	51.26	
	2	8.23	1009.4	44.86	44.92
		8.24	1037.7	46.12	
		8.22	985.1	43.78	
	3	8.34	1198.6	53.27	53.8
		8.44	1142.8	50.79	
		8.38	1290.2	57.34	
60	0	8.18	997	44.31	44.31
		8.09	1023.5	45.49	
		8.22	970.4	43.13	
	1	8.33	1228.5	54.6	55.75
		8.41	1280.3	56.9	
		8.32	1254.4	55.75	
	2	8.26	1063.8	47.28	45.34
		8.28	973.1	43.25	
		8.42	1023.5	45.49	
	3	8.31	1141	50.71	53.42
		8.38	1267.7	56.34	
		8.22	1197.2	53.21	

Appendix 4 – Pictures of Compressive Strength Test





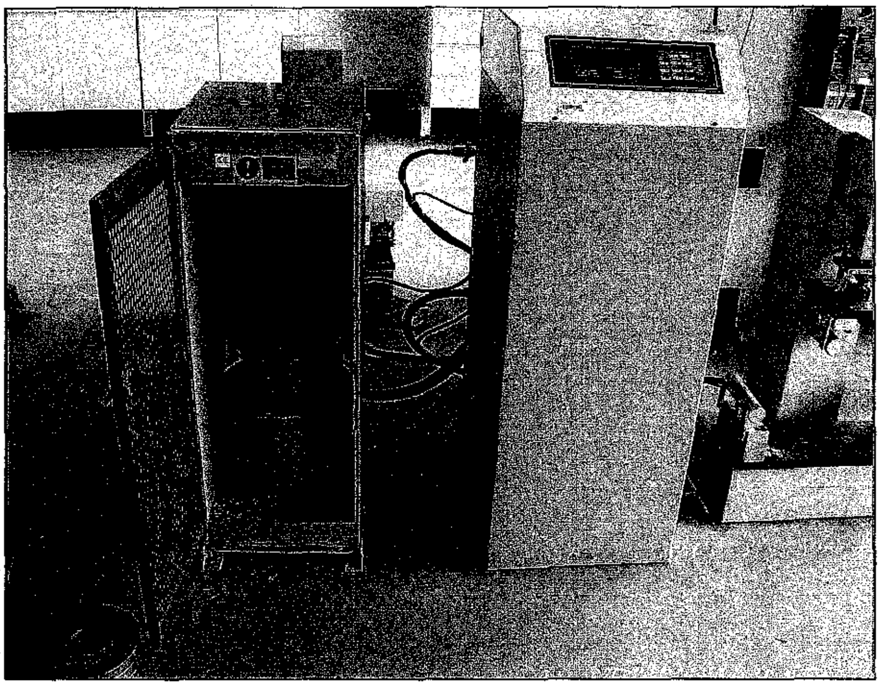


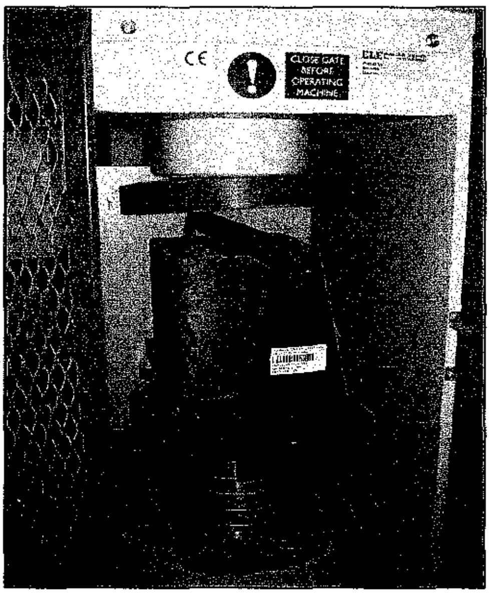
Appendix 5 – Results of Splitting Tensile Test

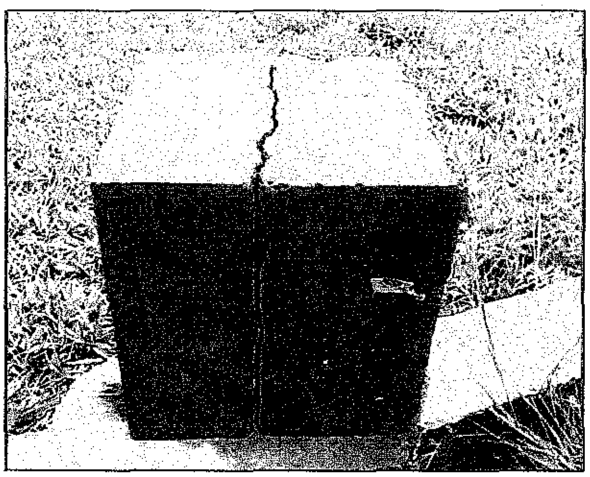
DAY	% PVA	TENSION			
		WEIGHT, W, (kg)	MAXIMUM LOAD, P, (kN)	STRESS, F, $\frac{2 P X 1000}{\pi X (150^2)}$, (N/mm^2)	AVERAGE STRESS, (N/mm^2)
1	0	8.14	103.5	2.928	2.927
		8.25	99.72	2.821	
		8.22	107.2	3.033	
	1	8.38	186.1	5.265	5.052
		8.24	178.4	5.047	
		8.31	171.2	4.843	
	2	8.23	134.0	3.791	4.144
		8.23	158.0	4.470	
		8.25	147.4	4.170	
	3	8.37	167.5	4.739	4.739
		8.29	152.8	4.323	
		8.19	182.2	5.155	
3	0	8.11	158.0	4.470	4.646
		8.093	164.5	4.654	
		8.2	170.2	4.815	
	1	8.52	267.7	7.573	6.556
		8.46	204.3	5.780	
		8.4	223.2	6.314	
	2	8.3	191.7	5.423	5.345
		8.25	189.0	5.347	
		8.41	186.1	5.265	
	3	8.35	180.7	5.112	5.749
		8.32	211.8	5.992	
		8.19	217.1	6.142	
7	0	8.08	214.0	6.054	5.876
		8.23	201.4	5.698	
		8.07	207.7	5.876	
	1	8.57	270.2	7.644	7.550
		8.42	252.7	7.149	
		8.26	277.7	7.856	
	2	8.33	207.5	5.870	6.506
		8.42	252.7	7.149	
		8.21	229.7	6.498	
	3	8.32	259.9	7.353	6.716
		8.21	222.1	6.283	
		8.13	230.2	6.512	

19	0	8.39	262.8	7.435	6.569
		8.22	227.7	6.442	
		8.43	206.1	5.831	
	1	8.45	360.2	10.190	10.185
		8.41	349.2	9.879	
		8.23	370.6	10.484	
	2	8.3	320.6	9.070	7.479
		8.12	225.9	6.391	
		8.34	246.6	6.976	
	3	8.25	292.7	8.281	7.944
		8.42	259.2	7.333	
		8.33	290.5	8.218	
28	0	8.17	214.3	6.063	6.696
		8.11	232.2	6.569	
		8.25	263.6	7.457	
	1	8.44	359.8	9.953	10.402
		8.34	378.7	10.714	
		8.85	372.6	10.541	
	2	8.22	290.7	8.224	8.160
		8.39	280.1	7.924	
		8.51	294.5	8.332	
	3	8.4	345.3	9.769	9.221
		8.4	354.4	10.026	
		8.35	278.1	7.868	
60	0	8.29	282.2	7.984	7.257
		8.31	252.7	7.149	
		8.16	234.7	6.640	
	1	8.31	378.0	10.694	10.567
		8.41	345.2	9.766	
		8.39	397.4	11.243	
	2	8.29	263.5	7.455	8.516
		8.34	336.5	9.520	
		8.44	303.1	8.575	
	3	8.45	351.2	9.936	9.315
		8.24	338.4	9.574	
		8.33	298.2	8.436	

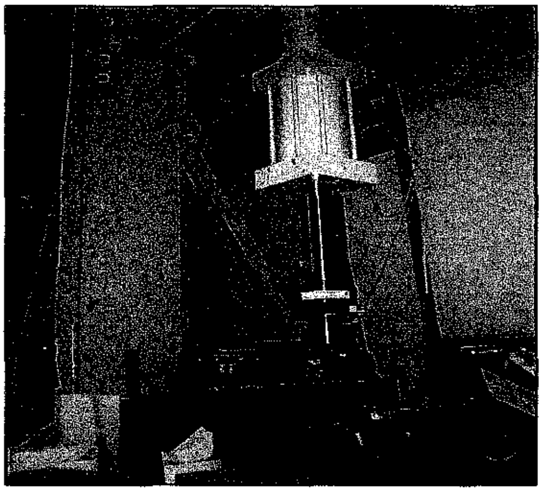
Appendix 5 – Pictures of Splitting Tensile Test

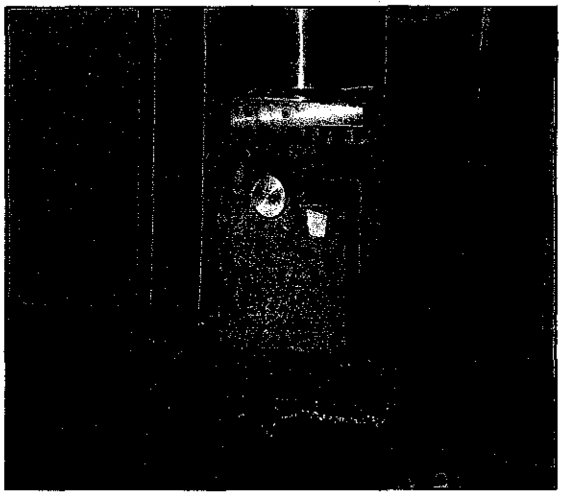


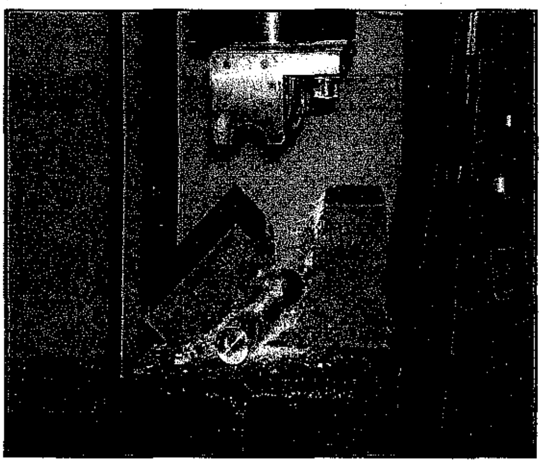


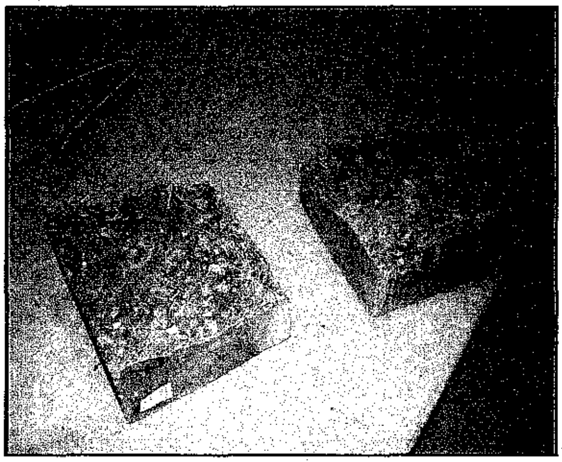


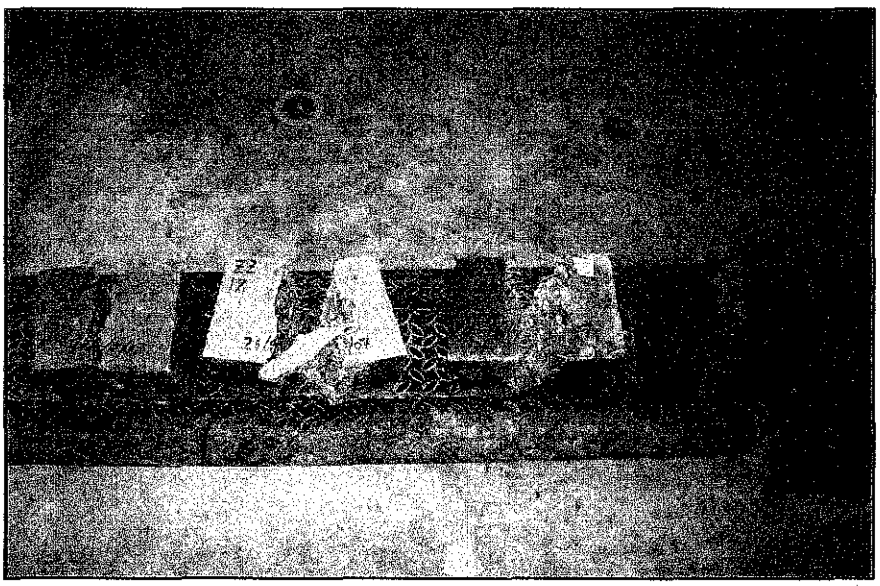
Appendix 6 - Picture of Splitting Tensile Test using Universal Testing Machine (UTM)





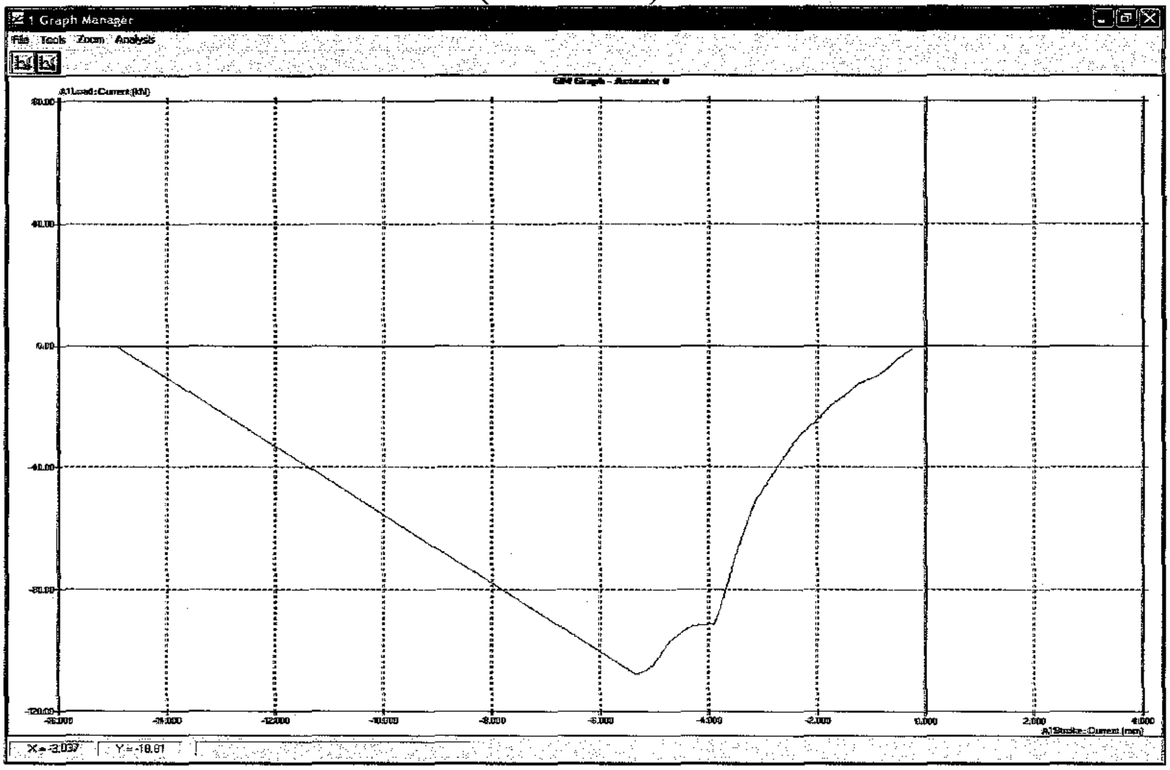




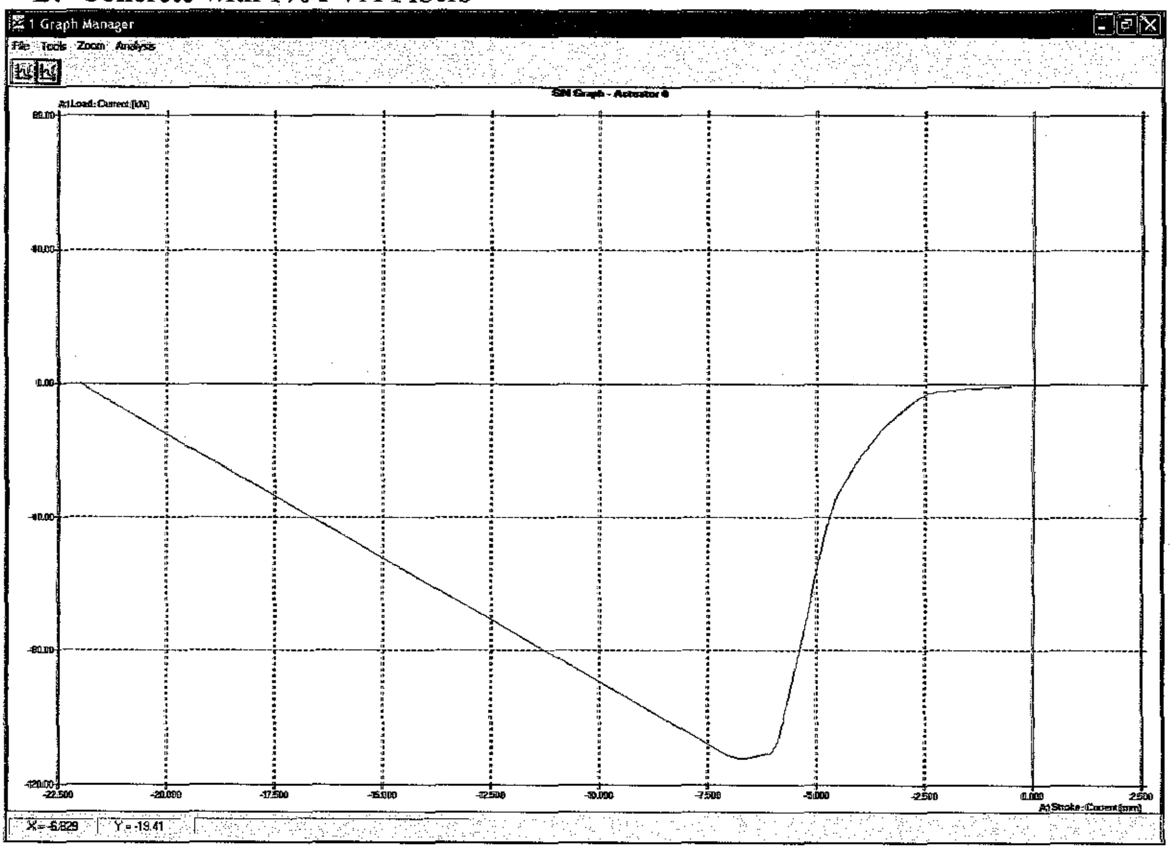


Appendix 7 – Result of Splitting Tensile Test using Universal Testing Machine (UTM)

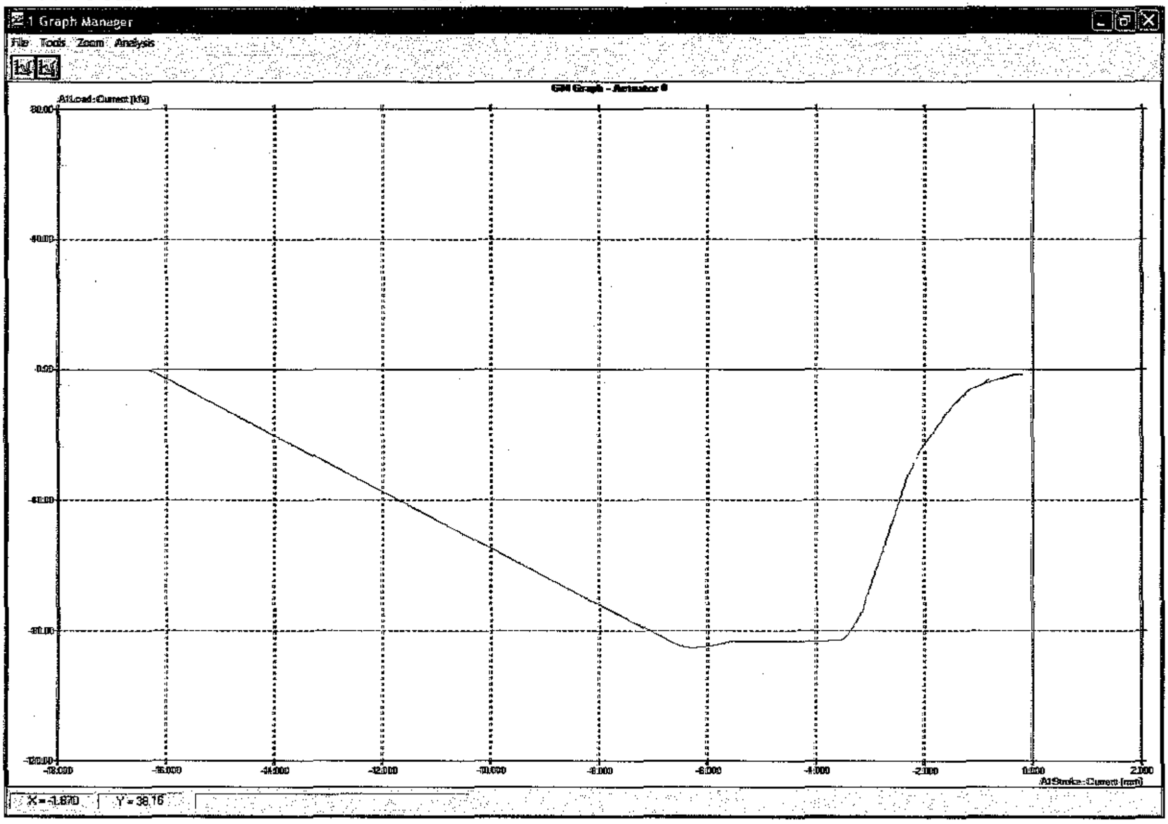
A. Concrete with 0% PVA Fibers (Control Mix)



B. Concrete with 1% PVA Fibers



C. Concrete with 2% PVA Fibers



D. Concrete with 3% PVA Fibers