BEHAVIOR OF CONCRETE WITH POLYVINYL ALCOHOL (PVA) FIBERS

BY

NUR HASLINA BT. TUKIMAN

Dissertation

Final Year Project

Bachelor of Engineering (Hons)
Civil Engineering

Universiti Teknologi PETRONAS
Bandar Seri Iskandar
31750 Tronoh
Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

Behavior of Concrete with Polyvinyl Alcohol (PVA) Fiber

By

Nur Haslina Bt. Tukiman

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

Approved by,

(Dr Victor R Macam Jr.)

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK
Jan 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 original work contained herein have not been undertaken or done by unspecified sources or persons.

NUR HASLINA BT. TUKIMAN

ACKNOWLEDGEMENT

First of all, I would like to express my gratitude to Allah S.W.T. for finally being able to complete my Final Year Project. It had been an astounding experience throughout 2 semesters of my FYP period.

My deepest appreciation goes to my UTP supervisor, Dr. Victor R. Macam Jr. for his keenness to teach and provide guideline to me in completing my final year project. I did not only view him as a superior but also a teacher, to whom I refer to whenever I need assistance and also seek advice related to not only the project but also on academic matters. Apart from the technical materials of the project, he also encouraged me to try new things and polish my personal and communication skills.

I would also like to thank the lecturers and technicians in civil engineering department for giving their full support and cooperation for me to finish my project. Mr. Johan and Mr. Zaini particularly had been a great aid for me in doing my laboratory work. Not to forget, any individuals who contributed in helping me completing this project.

Last but not least, thank you to my family and all my friends who have been very supportive during the past 8 months of my internship period. They always make an effort to help me in any way that they possibly can and I cannot thank them enough for that. I really appreciate what they did for me and will forever treasure it.

Final year project might not be the favorite subject for me, but still it thought me a lot of things and I am satisfied with what I manage to produce at the end of the project.

ABSTRACT

Concrete possessed characteristics whereby it has high strength in compression but weak in tension. In order to mend this disadvantage of concrete, Polyvinyl Alcohol (PVA) fibers are infused in concrete mix. It is considered as one of the most suitable polymeric fibers to be used as the reinforcement of concrete due to its advantages such as it will never rust, having high bond strength with concrete or mortar, having high modulus of elasticity etc.

Along the project period, properties of PVA fibers were studied as well as some other fibers commonly used in concrete technology. The characteristics of PVA fibers and concrete were also investigated in order to determine the ideality of mixing them together and what the significant impacts are. This project focuses on the properties of hardened PVA fiber reinforced concrete. In order to determine that, all concrete samples were tested for their compression and flexural strength. From the result obtained, it can be concluded that PVA fibers improved characteristics of concrete in terms of its strength.

TABLE OF CONTENT

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

1.1 Background of Study

Concrete, whether containing natural or waste glass aggregate is relatively brittle, and its tensile strength is typically only about one tenths of its compressive strength. Regular concrete is therefore normally reinforced with steel reinforcing bars. For many applications, it is becoming increasingly popular to reinforce the concrete with small, randomly distributed fibers. Their main purpose is to increase the energy absorption capacity and toughness of the material. But also the increase in tensile and flexural strength is often the primary objective. While steel fibers are probably the most widely used and effective fibers for many applications, other types of fiber are more appropriate for special applications. For example, architectural and decorative concrete products will call for fibers with a minimum of visual impact, so that nylon or polypropylene fibers may be called for.

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.
- Decreased handling damage during transport of dry-cast products to curing areas.

A wide variety of different types of fiber 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, akwara, and elephant grass.

This study would be looking into effects of infusing PVA fibers in self compacting concrete. Self-Compacting Concrete (SCC) is a highly flowable, stable concrete which flows readily into place, filling formwork without any consolidation and without undergoing any significant segregation. It exhibits tensile strain hardening behavior in the hardened state, while maintaining self-consolidating properties in the fresh state. The main concern of this study would be on the effect of PVA fibers in enhancing SCC in the hardened state which focus more on the tensile strength and durability. It was found that the use of 2% volume of PVA increase the tensile strength of SCC up to 5%. In this study, different percentages of volume of PVA fibers are used to scrutinize its effects on the strength of SCC. Tests conducted to investigate these effects are compressive strength test, tensile strength test etc.

1.2 Problem Definition

Concrete possessed characteristics whereby it has high strength in compression but weak in tension. In order to mend this disadvantage of concrete, PVA is to be infused in concrete mix. Polyvinyl alcohol (PVA) fiber is considered as one of the most suitable polymeric fibers to be used as the reinforcement of concrete due to its advantages such as it will never rust, having high bond strength with concrete or mortar, having high modulus of elasticity etc.

1.3 Objectives and Scope of Study

The main objectives of this project are:

- To study about PVA, what are its characteristics and the advantages it would bring to concrete
- To determine the behavior of concrete when added with PVA through experiment
- To determine whether PVA fiber is ideal in enhancing the properties of concrete

The scope of study would include:

- Research through journals and reading materials in relation to PVA fibers and concrete
- Lab experiment to determine behavior of concrete with PVA

2. LITERATURE REVIEW AND THEORY

2.1 Polyvinyl alcohol (PVA) fiber

PVA is polyvinyl alcohol, an organic material that is used to make concrete reinforcement fibers, among many other uses. It is made from carbon, hydrogen, and oxygen. PVA fibers are true structural concrete reinforcement fibers, like steel and glass. Common plastic fibers perform one task in concrete: 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 stretchier than concrete. To be a true structural fiber, the fiber should be stiffer than the concrete it is reinforcing.

Bond strength between fiber and concrete is another important consideration. Steel has very high tensile strength, but steel fibers have low bond strength with concrete or mortar. When the concrete is put 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.

PVA fibers have excellent characteristics for a concrete or mortar repair product. Polypropylene fibers can stretch and allow the concrete to break apart. Glass fibers are fragile and can be easily damaged. Steel fibers can stick out and cause damage and will rust. PVA fibers are superior in several ways:

1. High bond strength with the concrete or mortar will help keep the patch together even if 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 are resistant to UV rays and most chemicals

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. It also can lead to a tendency of fiber rupture and limit tensile strain capacity of the resulting composite. 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 [1]. This can improve strain hardening at the composite level as showed by Li et al [2].

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. 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.

High performance fiber reinforced composites are characterized by enhanced elastic limit, strain hardening response and toughed post-peak response. If the composite is adequately reinforced, the bridging fibers will share the load and transfer it to the other part of the composite. During the strain hardening response, number of crack increase and crack widen very little. Multiple cracking occurs when the subsequent transferred load cracks the matrix again. Hence, the initial flaw size and the fiber dispersion play important role on the initiation of the cracking and toughness. In one of the studies of PVA fibers in concrete by Kong et. al [3], it is found that increase in the size of the fiber free areas in the fiber free areas in the composite decreases the cracking stresses. It is shown that toughness of the composite depends on the fiber clumping at the first crack cross section using Electronic Speckle Pattern Interferometry(ESPI), as done by Akkaya et.al [4].

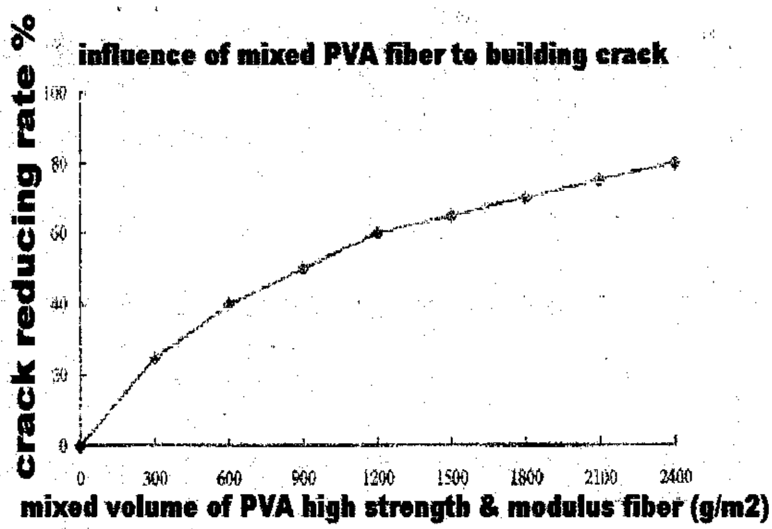


Figure 1: Crack reducing rate of concrete with PVA fibers

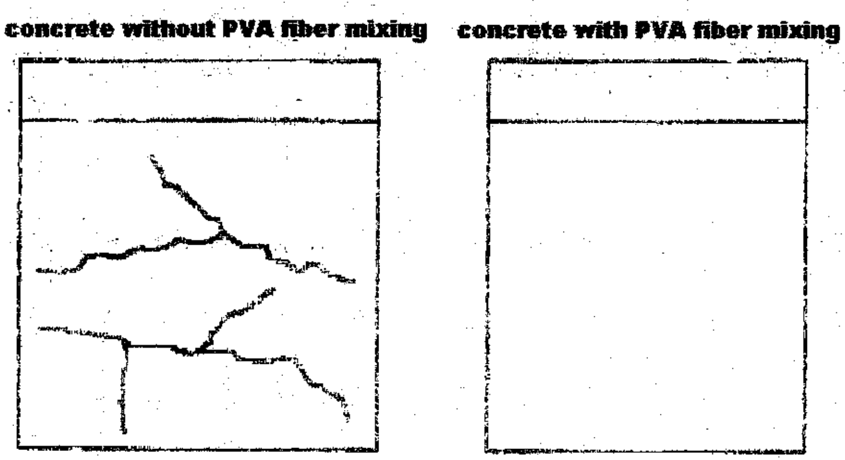


Figure 2: Concrete with and without PVA fibers

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

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

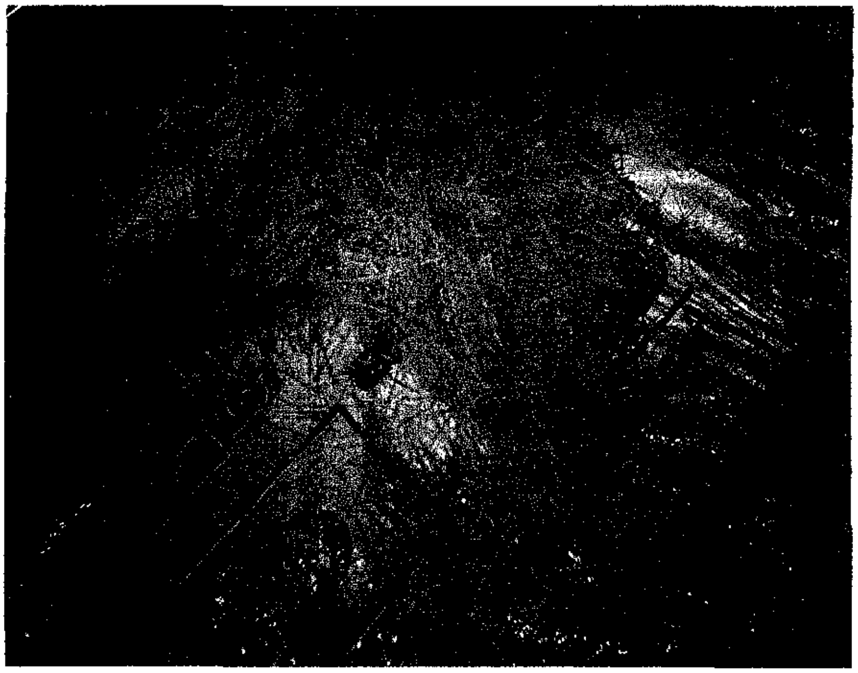


Figure 3: PVA Fibers (RF 4000)

2.2 Fiber Reinforced Concrete

Concrete made with Portland cement has certain characteristics: it is relatively strong in compression but weak in tension and tends to be 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. In the northeast, where sodium chloride de-icing salts are commonly used and a large amount of coastal area exists, chlorides are readily available for penetration into concrete to promote corrosion, which favors the formation of rust. Rust has a volume between four to ten times the iron, which dissolves to form it. The volume expansion produces large tensile stresses in the concrete, which initiates cracks and results in concrete spalling from the surface. Although some measures are available to reduce corrosion of steel in concrete such as corrosion inhibitive admixtures and coatings, a better and permanent solution may be replace the steel with a reinforcement that is less environmentally sensitive. 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.

FRC is Portland cement concrete reinforced with more or less randomly distributed fibers. 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 manmade and natural, have been incorporated into concrete. 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. Several 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 asbestos. Currently the commercial products are reinforced with steel, glass, polyester and polypropylene fibers. 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 etc 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. This leaflet aims to provide information on the properties of the more commonly available fibers and their uses to produce concrete with certain characteristics.

Apart from its excellent properties, concrete shows a rather low performance when subjected to tensile stress. Although in constructions pure tensile forces acting on concrete elements are rather scarce, this is not only an academic problem. Even a simple concrete bar under bending conditions has zones with high compressive as well as high tensile stresses. The traditional solution to this problem is reinforced concrete, where reinforcing bars or prestressed steel bars inside the concrete elements are capable of absorbing the appearing tensile stresses. Another rather recent development is steel fiber reinforced concrete (sfrc). 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 pseudoductile steel fiber reinforced concrete.

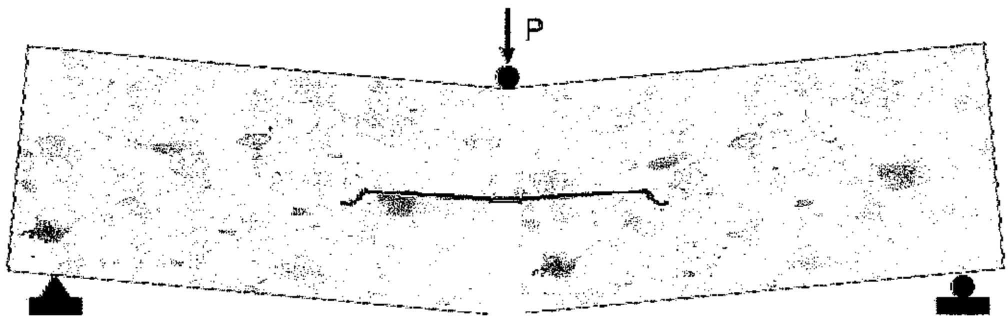


Figure 4: Principle of fiber reinforcement

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 3, 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.

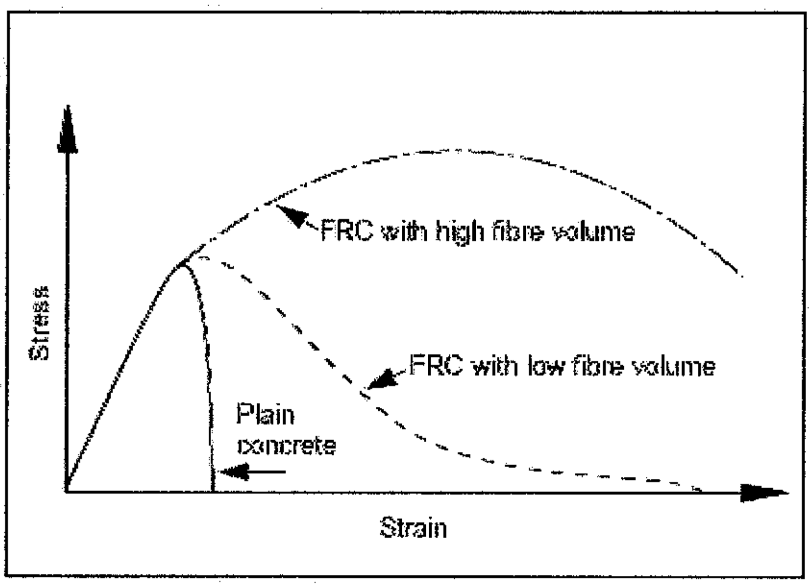


Figure 5: Stress strain curve of FRC

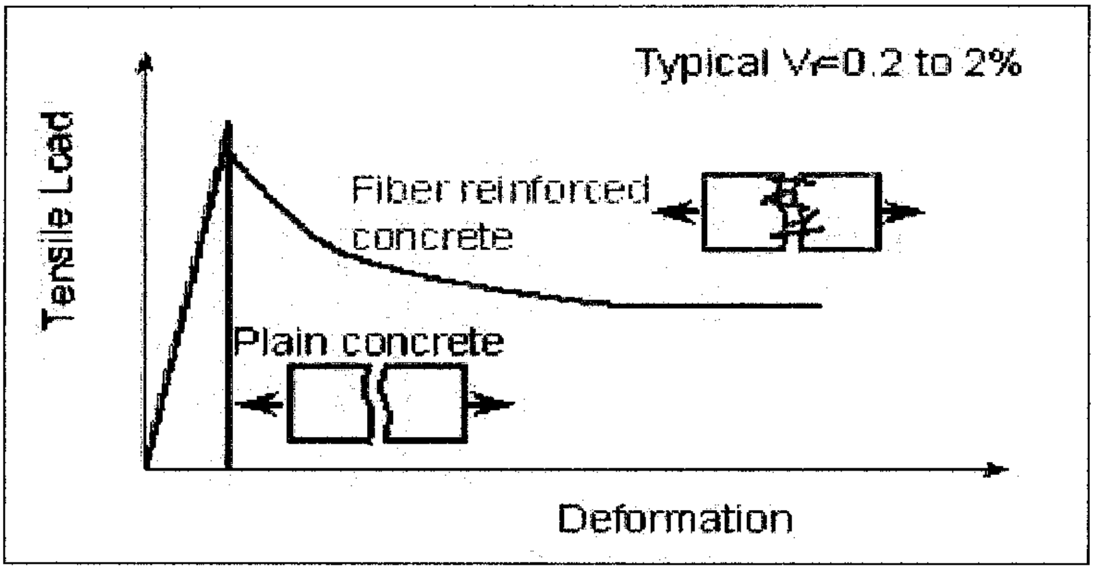


Figure 6: Tensile Load versus Deformation for Plain and FRC.

For the effective use of fibers in hardened concrete:

• Fibers should be significantly stiffer than the matrix, ie 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, ie 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 precasting 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.

Fiber reinforced concrete has started to find its place in many areas of civil infrastructure applications where the need for repairing, increased durability arises. Also FRCs are used in civil structures where corrosion can be avoided at the maximum. Fiber reinforced concrete is better suited to minimize cavitation /erosion damage in structures such as sluice-ways, navigational locks and bridge piers where high velocity flows are encountered. A substantial weight saving can be realized using relatively thin FRC sections having the equivalent strength of thicker plain concrete sections. When used in bridges it helps to avoid catastrophic failures. Also in the quake prone areas the use of fiber reinforced concrete would certainly minimize the human casualties. In addition, polypropylene fibers reduce or relieve internal forces by blocking microscopic cracks from forming within the concrete. The main disadvantage associated with the fiber reinforced concrete is fabrication. The process of incorporating fibers into the cement matrix is labor intensive and costlier than the production of the plain concrete. The real advantages gained by the use of FRC overrides this disadvantage.

Newly developed FRC named Engineered Cementitious Composite (ECC) is 500 times more resistant to cracking and 40 percent lighter than usual concrete. ECC can sustain strain-hardening up to several percent strain, resulting in a material ductility of at least two orders of magnitude higher in comparison to normal concrete or standard fiber reinforced concrete. ECC also has unique cracking behavior. When loaded to beyond the elastic range, ECC maintains crack width to below 100 μm, even when deformed to several percent tensile strains. Recent studies performed on high-performance fiber-reinforced concrete in a bridge deck found that adding fibers provides residual strength and controls cracking. There were fewer and narrower cracks in the FRC even though the FRC had more shrinkage than the control. The residual strength is directly proportional to the fiber content. A new kind of natural fiber reinforced concrete (NFRC) made of cellulose fibers processed from genetically modified slash pine trees are giving good results. The cellulose fibers are longer and greater in diameter than other timber sources. Some studies were performed on using waste carpet fibers in concrete in an environment friendly approach to recycle carpet waste. A carpet typically consists of two layers of backing (usually fabrics from polypropylene tape yarns), joined by CaCO3 filled styrene-butadiene latex rubber (SBR), and face fibers (majority being nylon 6 and nylon 66 textured yarns). Such nylon and polypropylene fibers can be used for concrete reinforcement. Studies have shown that FRC containing carpet waste show adequate structural qualities to make it a feasible choice of recyling and thus reducing need for landfilling.

2.2.1 Glass fibers

Glass fibers, in the form first used, were found to be alkali reactive and products in which they were used deteriorated rapidly. Alkali-resistant glass containing 16% zirconia was successfully formulated in the 1960s and by 1971 was in commercial production in the UK. Other sources of alkali resistant glass were developed during the 1970s and 1980s in other parts of the world, with higher zirconia contents. Alkali-resistant glass fiber is used in the manufacture of glass-reinforced cement (GRC) products, which have a wide range of applications. Glass fiber is available in continuous or chopped lengths. Fiber lengths of up to 35 mm are used in spray applications and 25-mm lengths in premix applications.

Glass fiber has high tensile strength (2 – 4 GPa) and elastic modulus (70 – 80 GPa) but has brittle stress-strain characteristics (2.5 – 4.8% elongation at break) and low creep at room temperature. Claims have been made that up to 5% glass fiber by volume has been used successfully in sand-cement mortar without balling. Glass-fiber products exposed to outdoor environment have shown a loss of strength and ductility. The reasons for this are not clear and it is speculated that alkali attack or fiber embrittlement are possible causes. 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 fibre 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.

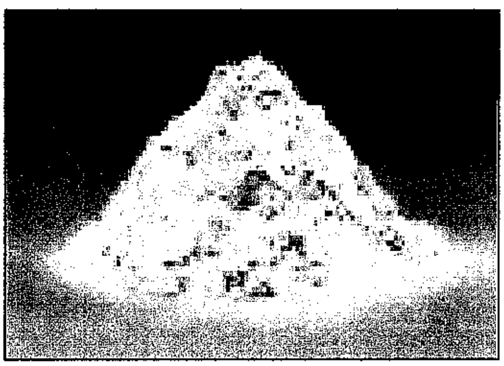


Figure 7: Glass Fiber

Table 2: 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	MOR	[N/mm²]	22 ÷ 32	9 ÷ 13
	Strength	LOP	[N/mm²]	7 ÷ 13	6 ÷ 9
		Young Modulus	[kN/mm²]	15 ÷ 25	14 ÷ 24
	Tensile	UTS	[N/mm²]	8 ÷ 12	3 ÷ 6
	Strength	BOP	[N/mm²]	4 ÷ 6	3 ÷ 5
		Ultimate strain	[%]	0.6 ÷ 1.2	0.1 ÷ 0.2
	Compressive	Out-of-plane	[N/mm²]	50 ÷ 80	40 ÷ 60
	Strength	In-plane	[N/mm²]	40 ÷ 70	40 ÷ 60
	Shear	Out-of-plane	[N/mm²]	25 ÷ 35	4 ÷ 6
	Strength	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 [5]

2.2.2 Steel Fibers

Steel fibers have been used in concrete since the early 1900s. The early fibers were round and smooth and the wire was cut or chopped to the required lengths. The use of straight, smooth fibers has largely disappeared and modern fibers have either rough surfaces, hooked ends or are crimped or undulated through their length. Modern commercially available steel fibers are manufactured from drawn steel wire, from slit sheet steel or by the meltextraction process which produces fibers that have a crescent-shaped cross section. Typically steel fibers have equivalent diameters (based on cross sectional area) of from 0.15 mm to 2 mm and lengths from 7 to 75 mm. Aspect ratios generally range from 20 to 100. (*Aspect ratio* is defined as the ratio between fiber length and its equivalent diameter, which is the diameter of a circle with an area equal to the cross-sectional area of the fiber.) Carbon steels are most commonly used to produce fibers but fibers made from corrosion-resistant alloys are available. Stainless steel fibers have been used for high-temperature applications. Some fibers are collated into bundles using water-soluble glue to facilitate handling and mixing. Steel fibers have high tensile strength (0.5 – 2 GPa) and modulus of elasticity (200 GPa), a ductile/plastic stressstrain characteristic and low creep. 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. Steel-fiber-reinforced concrete containing up to 1.5% fiber by volume has been pumped successfully using pipelines of 125 to 150 mm diameter. Steel fiber contents up to 2% by volume have been used in shotcrete applications using both the wet and dry processes. Steel fiber contents of up to 25% by volume have been obtained in slurry-infiltrated fiber concrete. Concretes containing steel fiber have been shown to have substantially improved resistance to impact and greater ductility of failure in compression, flexure and torsion. Similarly, it is reported that the elastic modulus in compression and modulus of rigidity in torsion are no different before cracking when compared with plain concrete tested under similar conditions. It has been reported that steel-fiber-reinforced concrete, because of the improved ductility, could find applications where impact resistance is important. Fatigue resistance of the concrete is reported to be increased by up to 70%. It is thought that the inclusion of steel fiber as supplementary reinforcement in concrete could assist in the reduction of spalling due to thermal shock and thermal gradients. The lack of corrosion resistance of normal steel fibers could be a disadvantage in exposed concrete situations where spalling and surface staining are likely to occur.

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. 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.

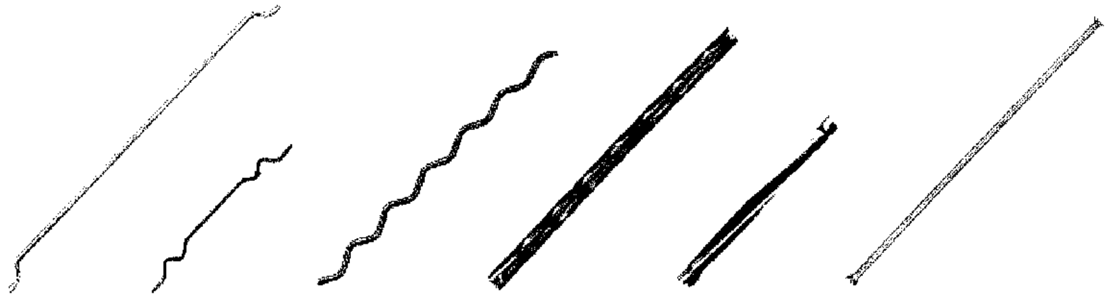


Figure 8: Different types of steel fibers

•

The majority of steel fibers used today has hooks or other deformations at the ends or are rough, crimped, or undulated along the length of the fibers. These designs are intended to improve the bond between the fiber and the surrounding concrete. Usually, either carbon or stainless steel is used. Fibers are typically one to two inches long. The amount of fiber in concrete mixes typically ranges from 0.5 percent to 2.0 percent by volume, although smaller amounts have been used successfully in reduction of plastic- and drying-shrinkage cracking. According to the Portland Cement Association, steel fiber contents greater than 2.0 percent result in poor workability and fiber dispersion within the concrete mix.

With the addition of steel fibers, the concrete can be expected to have increased tensile, flexural, and fatigue strength. The exact amount of increased strength depends on many variables, especially fiber content. With fiber contents of 1.5 percent to 2.0 percent by volume, direct tensile strength will increase 30 to 40 percent, and flexural strength (first crack) will increase 50 to 150 percent.

•

When choosing steel fibers, the durability of the fibers themselves and the aesthetics of the concrete surface must be taken into consideration. Like other embedded metal objects, steel fibers can rust if the surrounding concrete is cracked. Also, some surface-rust staining is possible, although corrosion-resistant steel fibers are available.

Material transport properties, especially permeability, affect the durability and integrity of a structure. High permeability, due to porosity or cracking, provides ingress for water, chlorides, and other corrosive agents. If such agents reach reinforcing bars within the structure, the bars corrode, thus compromising the ability of the structure to withstand loads, which eventually leads to structural failure.

Building codes require that cracks exposed to weathering be no larger than specified widths in order to assure mechanical structural integrity. However, if cracks of this size significantly increase permeability and allow corrosive agents to reach steel reinforcement, the cracks are clearly too large and the codes should be revised. Knowledge pertaining to permeability can help determine the maximum allowable size of exposed cracks in structures. In addition, if concrete casings are uses as shielding containers for pollutants and toxic wastes, permeability is of utmost importance in order to assure that no potentially harmful leakage occurs.

It was thought that increasing the volume of steel fibers would decrease the permeability of the cracked specimens due to crack stitching by the steel fibers. In addition, previous work performed by Aldea et al. showed that a permeability threshold exists for crack width: cracks under 100 microns in cement paste, mortar, normal strength, and high strength concrete had little effect on permeability [Aldea, 1999]. Cracks over 100 microns affected permeability significantly. It was expected that this threshold would still exist for the fiber–reinforced concrete because the steel fibers do not change material porosity.

2.2.3 Synthetics Fiber

Synthetic fibers are man-made fibers resulting from research and development in the petrochemical and textile industries. There are two different physical fibre forms: monofilament fiber, and fibers produced from fibrillated tape. Currently there are two different synthetic fiber volumes used in application, namely low-volume percentage (0,1 to 0,3% by volume) and high-volume percentage (0,4 to 0.8% by volume). 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. Fiber types that have been tried in cement concrete matrices include: acrylic, aramid, carbon, nylon, polyester, polyethylene and polypropylene. Table 3 summarizes the range of physical properties of some synthetic fibers.

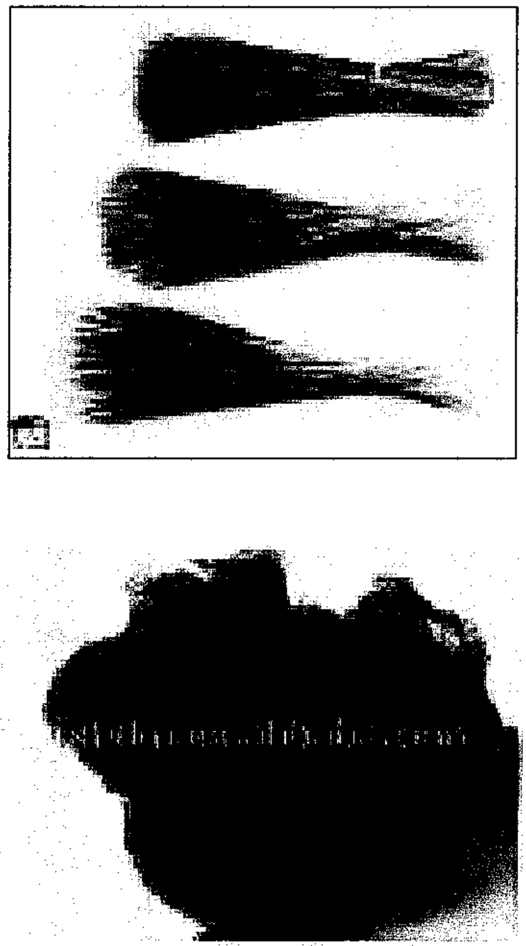


Figure 9: Synthetic Fibers

Table 3: Selected synthetic fiber types and properties

Fibre type	Equivalent diameter µm	Relative density	Tensile strength MPa	Elastic modulus GPa	Ultimate elongation %	Ignition temperature °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‡	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‡‡	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‡‡	25 - 1 000	0,92 - 0,96	75 - 590	5	3 - 80	-	130	nil
Polypropylene‡‡	-	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

‡ Polyacrylonitrile based, high modulus

§ Polyacrylonitrile based, high tensile strength

** Isotropic pitch based, general purpose

†† Mesophase pitch based, high performance

‡‡ Data listed is only for fibres commercially available for FRC

Details were extracted from [5]

2.2.4 Natural fiber

Natural reinforcing materials can be obtained at low cost and low levels of energy using local manpower and technology. Utilization of natural fibers as a form of concrete reinforcement is of particular interest to less developed regions where conventional construction materials are not readily available or are 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 corrugated sheet and non-pressure pipes. Typical properties of natural fibers are shown in Table 4. Natural fibers can be either unprocessed or processed.

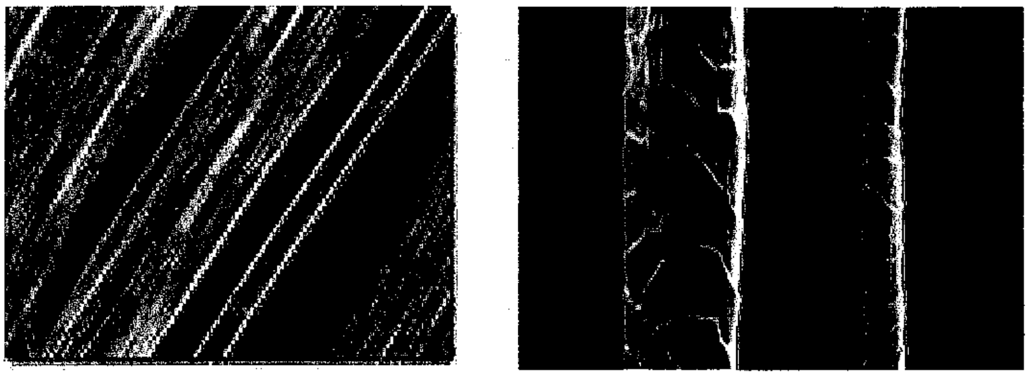


Figure 10: Natural fibers

Table 4: 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 [5]

2.3 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 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. These cracks, in addition to plastic cracking, is what PVA is designed to handle. In that regard it is a structural fiber like steel and AR glass.

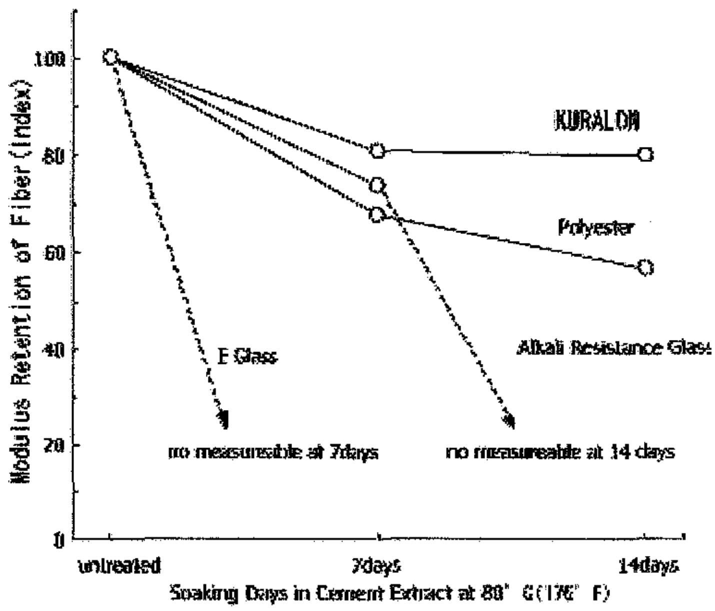


Figure 11: Comparison of Modulus Retention between KURALON and other fibers

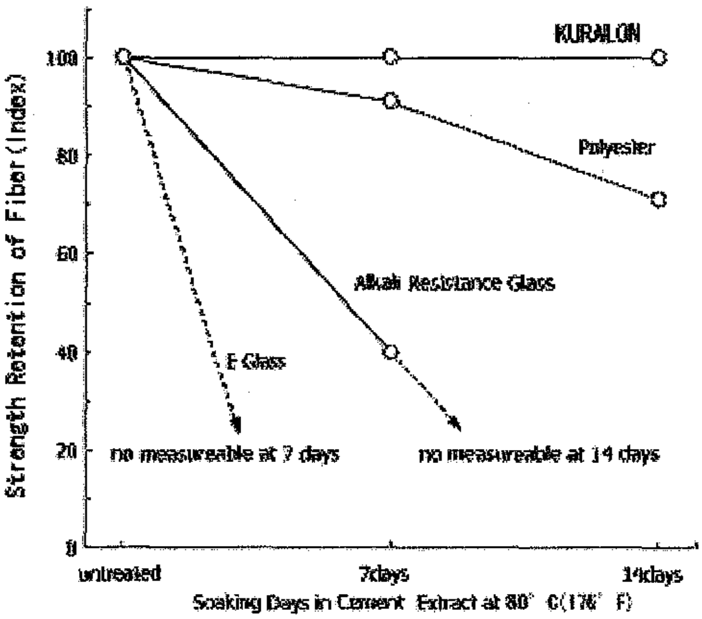


Figure 12: Comparison of Strength Retention between KURALON and other fibers

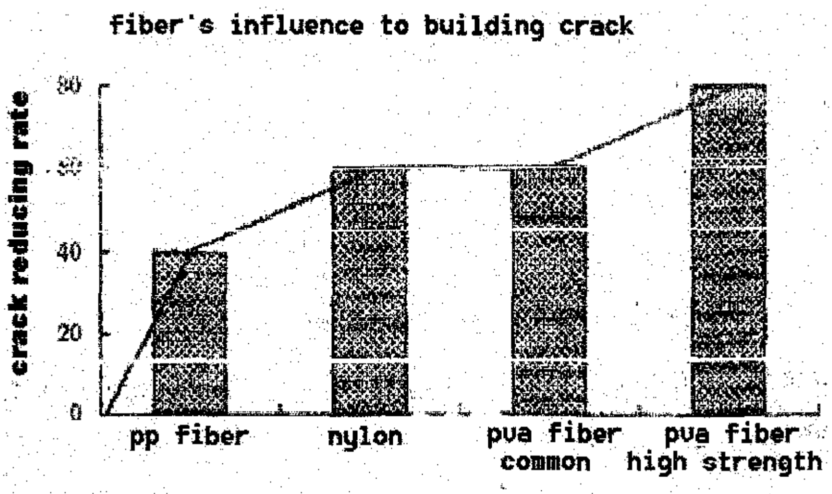


Figure 13: Comparison of crack reducing rate of PVA fibers and other fibers

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.

Polyvinylalcohol (PVA)

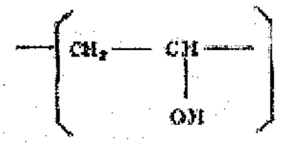


Table 5: Gases released during burning of fibers

Gas	CO		CO_2		NH_3		HCN		H_2S	
Fiber	600	400	600	400	600	400	600	400	600	400
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	0.05

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

Table 6: Result of 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	-

*measurement by Kuraray Co., Ltd.

3. METHODOLOGY

3.1 Calculation and mix proportioning

Initially, the PVA fibers were to be added to self compacting concrete (SCC). However, due to some constraints it was not able to be executed. Subsequently, normal concrete was used for concrete mix. For this project, 4 mixes were done which consist of 1 control mix without PVA fibers and the remaining are concrete mixes that contain 1%, 2% and 3% of PVA fibers.

For each mix, 3 beams and 3 concrete cylinders were produced as samples for testing. The calculation of mix proportioning is shown below:

Volume of beam = h x b x l

$$= 100\text{mm} \times 100\text{mm} \times 500\text{mm} \times \frac{1\text{m}^3}{1000\text{mm}^3}$$

$$= 0.005\ \text{m}^3$$

Since 3 beams are needed for testing:

$$0.005\ \text{m}^3 \times 3 = 0.015\ \text{m}^3$$

Volume of cylinder = $\pi r^2 h$

$$= \pi\,(50)^2\ (200)$$

$$= 1570000\text{mm}^3 \times \frac{1\text{m}^3}{1000\text{mm}^3}$$

$$= 1.57\text{x}10^{-3}\text{m}^3$$

Since 3 cylinders are needed for testing:

$$0.00157\ \text{m}^3 \times 3 = 0.005\ \text{m}^3$$

Hence, total volume of concrete for each mix is:

$$0.015\ \text{m}^3 + 0.005\ \text{m}^3 = 0.02\ \text{m}^3$$

Wc ratio = 0.45

Concrete ratio = 1:2:3 (cement: fine aggregate: coarse aggregate)

Cement (C)

Fine aggregate (FA)

Coarse aggregate (CA)

Water (W)

For 0.02 m^3 of concrete:

C = 450 kg/m3 x 0.02 m3

= 9 kg

FA = 9kg x 3

= 27 kg

Wc = 0.45 x 9 kg

= 4.05 kg

For 1% of fiber = 0.01 x 9 kg = 0.09 kg

For 2% of fiber = 0.02 x 9 kg = 0.18 kg

For 3% of fiber = 0.03 x 9 kg = 0.27 kg

Table 7: Summary of Mix proportioning

Mix	**Coarse aggregate (kg)**	**Fine aggregate (kg)**	**Cement (kg)**	**Water (kg)**	**PVA fibers (kg)**
PVA 1%	27	18	9	4.05	0.09
PVA 2%	27	18	9	4.05	0.18
PVA 3%	27	18	9	4.05	0.27

3.2 Concrete Mixing

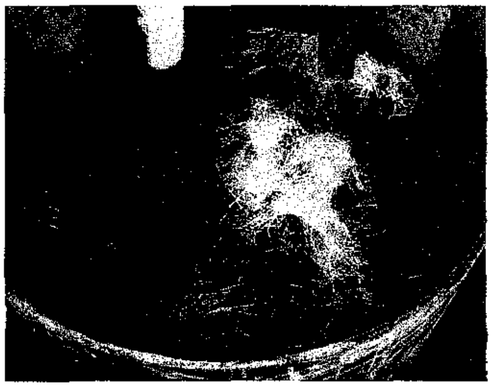
Concrete mixing adopted in this experiment is of the normal concrete. The procedure of mixing is as the following:

Procedure:

1. Pour all coarse aggregate and fine aggregate into mixer and mix for 25 seconds.
2. Pour half of the water and mix for 1 minute
3. Leave the mix for 8 minutes
4. Pour cement and mix for 1 minute
5. Pour another half of water and add for 3 minutes
6. Add PVA fibers gradually in the mix and mix for another 2 minutes

* procedures referred from Kuraray Co. Ltd.[9]

Mixing cement in the mix



Mixing PVA fibers in the mix

Placing concrete in moulds

Fresh mixed concrete

Figure 14: Process of concrete mixing

3.3 Concrete Testing

3.3.1 Fresh Concrete Testing

3.3.1.1 Slump Test (ASTM C143)

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 concrete 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 (by the operator standing on the two foot pieces).
4) Fill the mold in three 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. (steps 2 through 7 should be completed in less than 2.5 minutes).
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. This is the slump.

Figure 15: Slump Test

3.3.2 Hardened Concrete Testing

3.3.2.1Compressive Strength of Cylindrical Concrete Specimen (ASTM C39)

Objective

To measure the compressive strength of cylindrical concrete specimen

Procedure

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 of 20 to 50 psi/s (140 to 350 lb/s for 3" diameter cylinders, 250 to 630 lb/s for 4" diameter cylinders, 560 to 1400 lb/s for 6" diameter cylinders). 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.

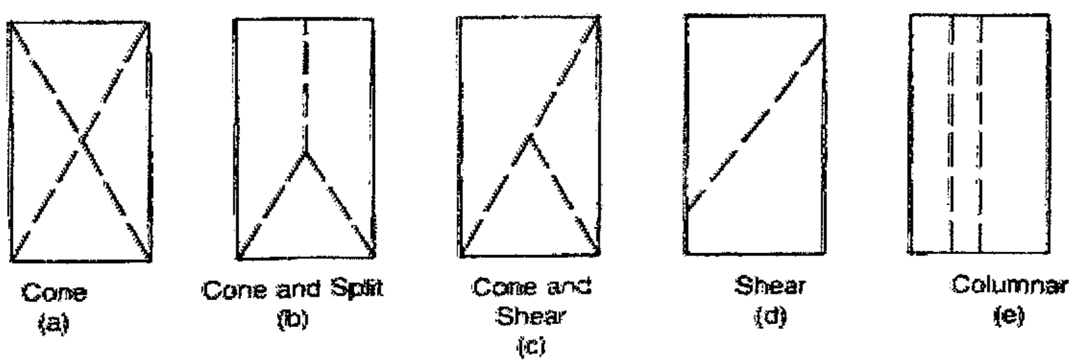


Figure 16: Types of Concrete Fracture

4. RESULTS AND DISCUSSION

4.1 Fresh Concrete Testing

4.1.1 Slump Test

Table 8: Result of slump test

Mix	Slump (mm)
PVA 0%	75
PVA 1%	55.5
PVA 2%	32.7
PVA 3%	0

From the result of slump test slump test, it shows reduction in workability the more PVA fibers added in the mix. The highest slump is concrete with 0% of PVA fibers and concrete with 3% PVA fibers indicates no slump. It is noted that standard slump test has been found to be not appropriate to measure 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.

The PVA RC is compared to the concrete without PVA fibers content and the graft is as shown in Figure 18. 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.

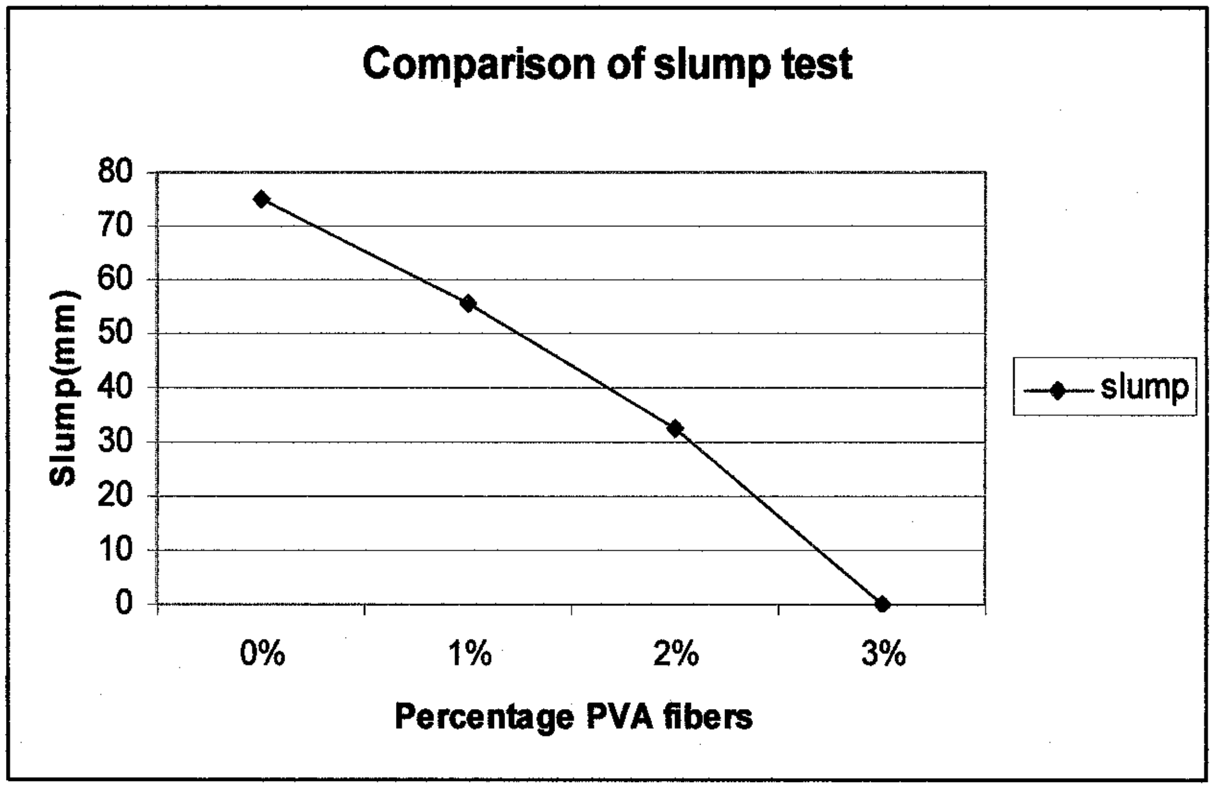


Figure 17: Comparison of slump test of samples

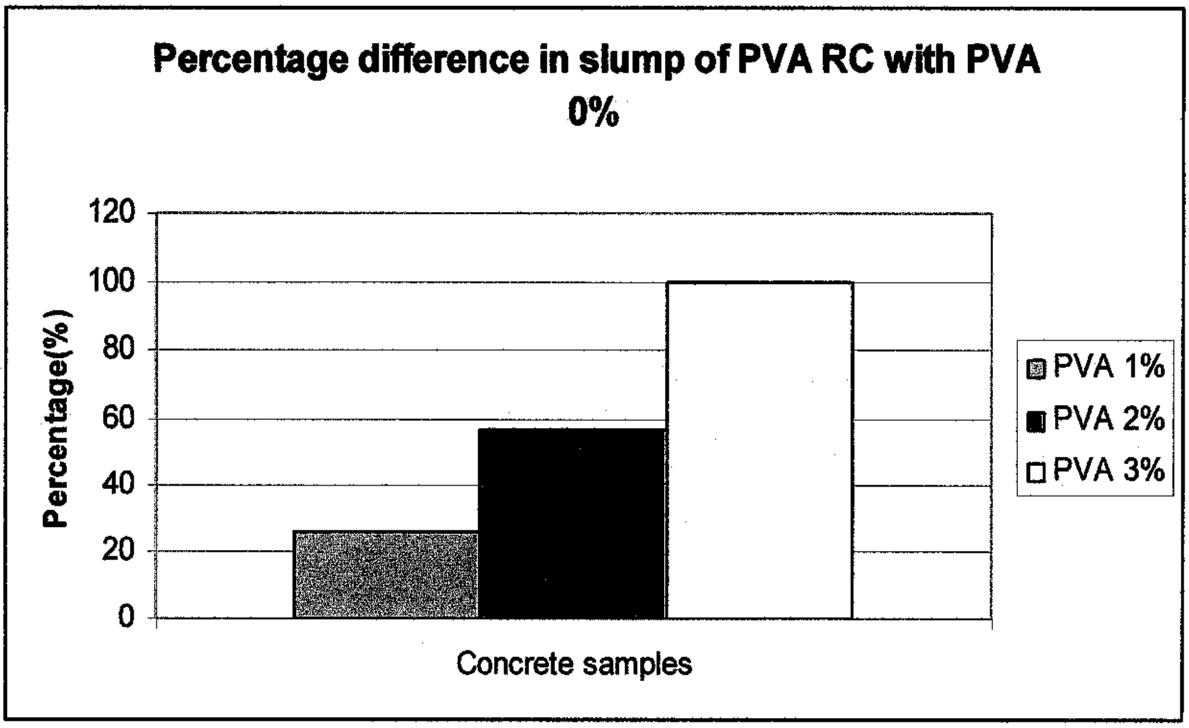


Figure 18: Percentage difference in slump of PVA RC with PVA 0%

4.2 Hardened Concrete Testing

4.2.1 Compressive Strength of Cylindrical Concrete Specimen

Table 9: Result of compression strength test

Mix	Compressive Strength (MPa)		
	3 days	7 days	28 days
PVA 0%	6.44	20.63	31.48
PVA 1%	6.6	22.7	38.41
PVA 2%	7.94	23.7	45.78
PVA 3%	8.04	25.2	58.16

For the hardened concrete, 2 tests were conducted to the samples which are Compressive strength test and bending test. Compressive strength test were conducted using an automatic compression machine for 3, 7 and 28 days and results were obtained as shown in Table 9. It is observed that with the addition of PVA fibers, the compressive strength increases.

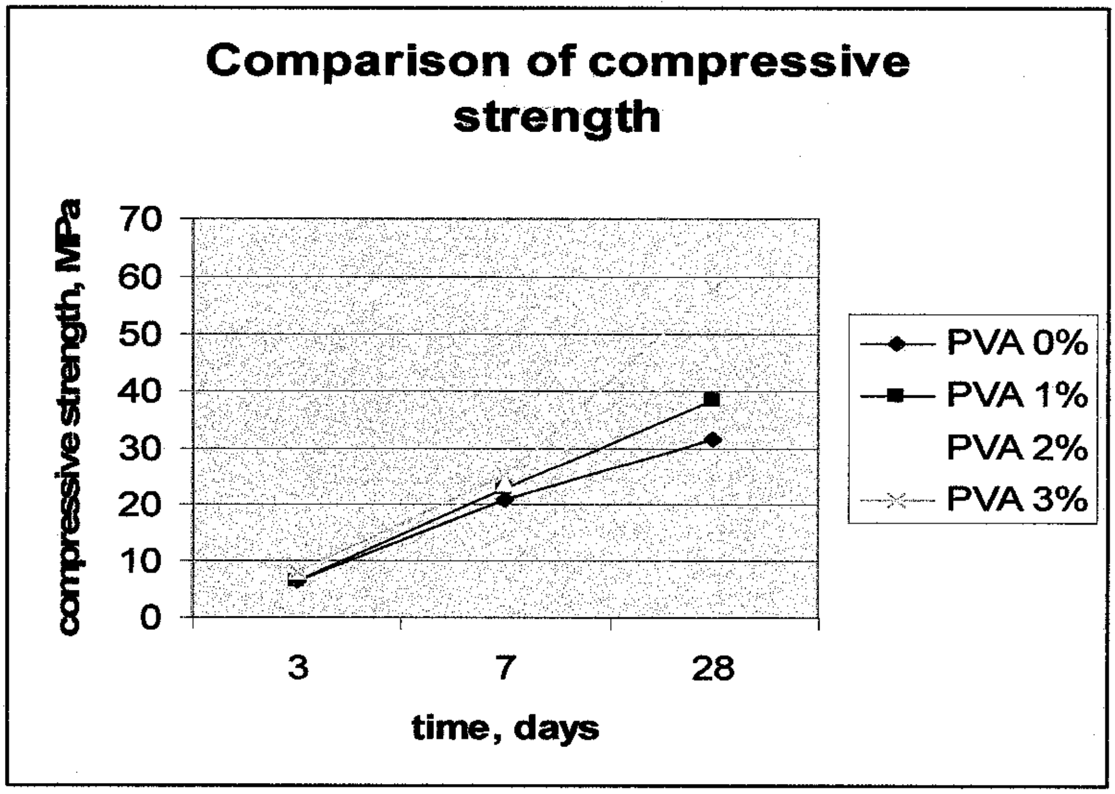


Figure 19: Comparison of compressive strength of samples

Figure 19 shows the comparison of compressive strength of all samples mixed. At 3 days, the strengths of all concrete do not differ much. They are at the range of 6.04 MPa to 8.04 MPa. At 7 days, significant differences are observed, ranging from 20.63 MPa to 25.2 MPa. At the last day of test, which was on the 28^{th} day, result shows major difference of compressive strength, from 31.48 MPa to 58.16 MPa. This is due to effect of curing to the concrete and it is gradually gaining its strength. As for concrete with PVA fibers, it shows that the compressive strength increase notably, especially with high content of fibers. This may due to the excellent bonding of PVA fibers with the concrete matrix over time.

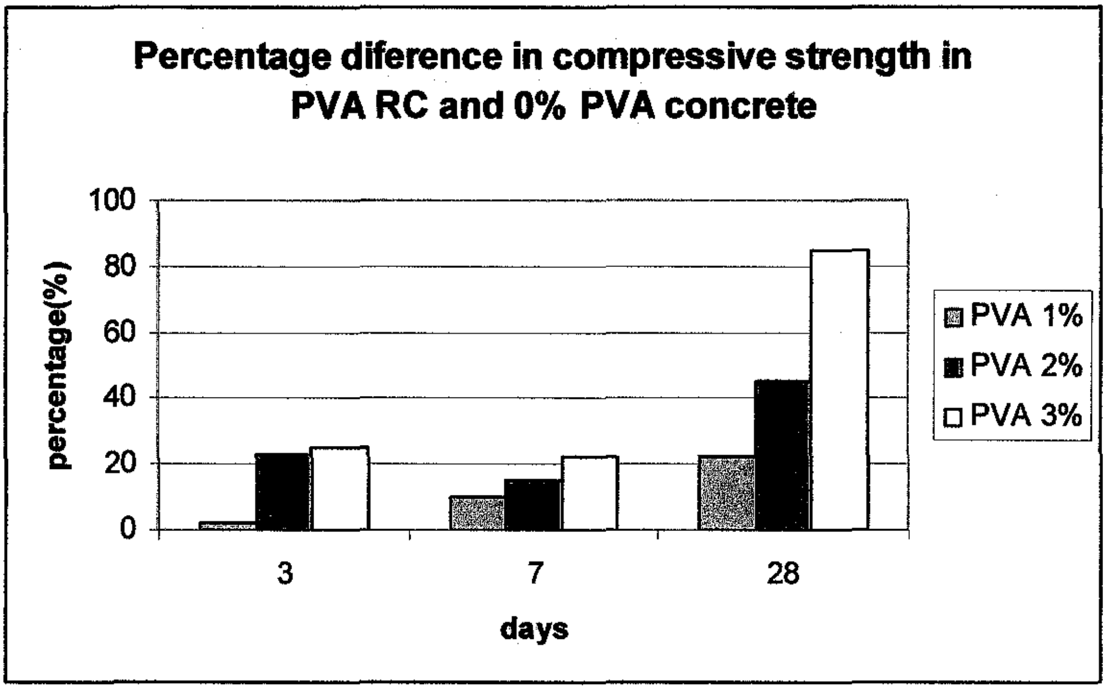


Figure 20: Percentage Difference in compressive strength of PVA RC and 0% PVA concrete

4.2.2 Bending Test

Table 10: Result of bending test

Sample	Max. Load (kN)	Max. Stress (MPa)
PVA 0%	8.44	6.33
PVA 1%	11.27	8.45
PVA 2%	11.67	8.75
PVA 3%	11.92	8.94

This bending test was conducted using a Universal Testing Machine (UTM). All samples were cured until 28 days before the test was performed. The purpose of conducting this test is to determine the maximum stress or tensile strength of concrete when loaded. The results obtained were tabulated in Table 10. It is observed that maximum stresses are increasing with the addition in amount of PVA fibers. The more PVA fibers added in a concrete, its ability to withstand load is also increasing. Hence, it can be concluded that with increasing amount of PVA fibers inserted in a concrete, its tensile strength is also increasing.

Figure 22 shows the percentage difference in tensile strength of PVA RC with PVA 0% concrete. Tensile strength of concrete with 1% PVA record an increase of 33.5% from 0% PVA concrete, while 2% PVA concrete is 38.23% and 3% PVA concrete is 41%. The tensile strength increases extensively after addition of PVA fibers. However, the rate of increase in tensile strength among concrete with PVA fibers is not very significant. The tensile strength is expected to rise with time but the percentage difference would be decreasing until at one point the tensile strength has no increase.

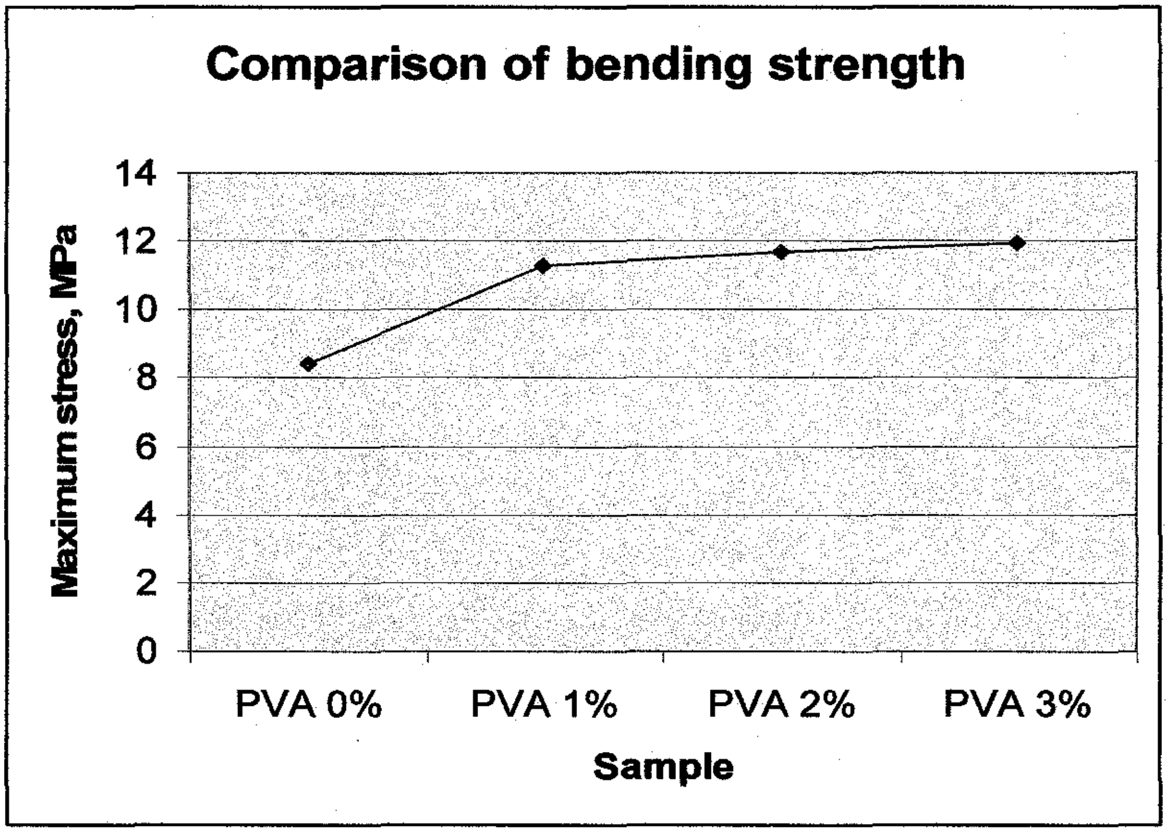


Figure 21: Comparison of maximum stress of samples

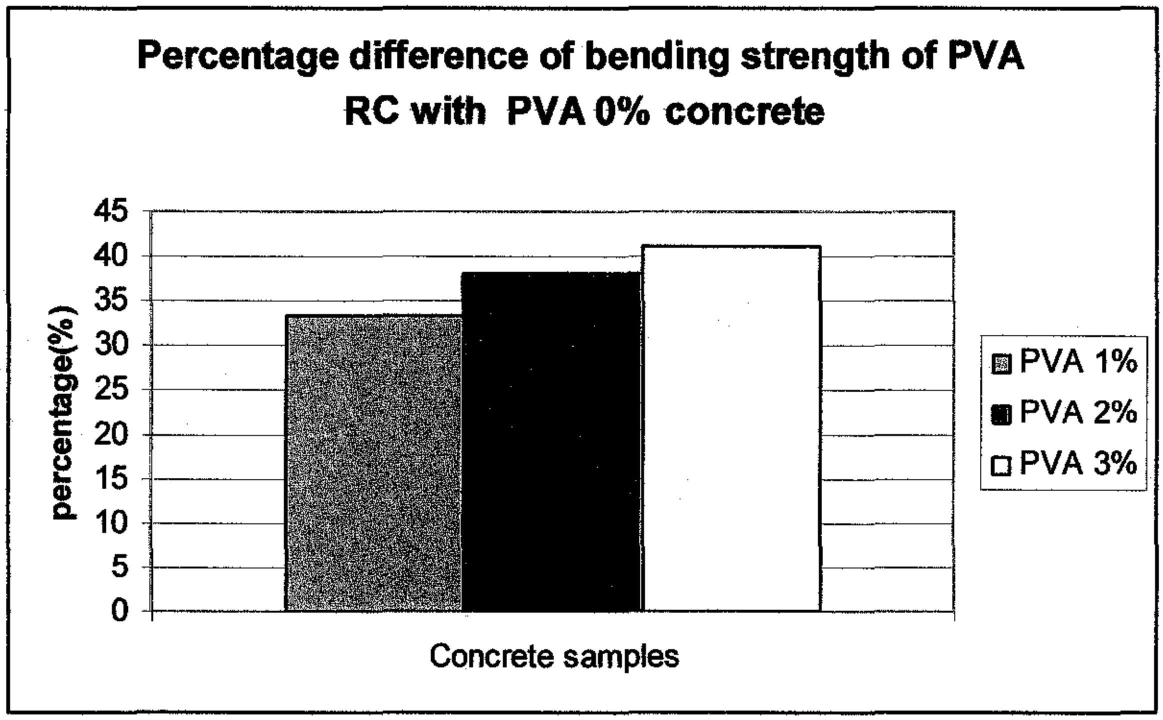


Figure 22: Percentage difference in bending strength of PVA RC with PVA 0% concrete

Table 11: Overall result of concrete tests

Sample	Slump test (mm)	Compressive strength (MPa)			Tensile strength (MPa)
		3 days	7 days	28 days	
0% PVA	75	6.44	20.63	31.48	6.33
1% PVA	55.5	6.6	22.7	38.41	8.45
2% PVA	32.7	7.94	23.7	45.78	8.75
3% PVA	0	8.04	25.2	58.16	8.94

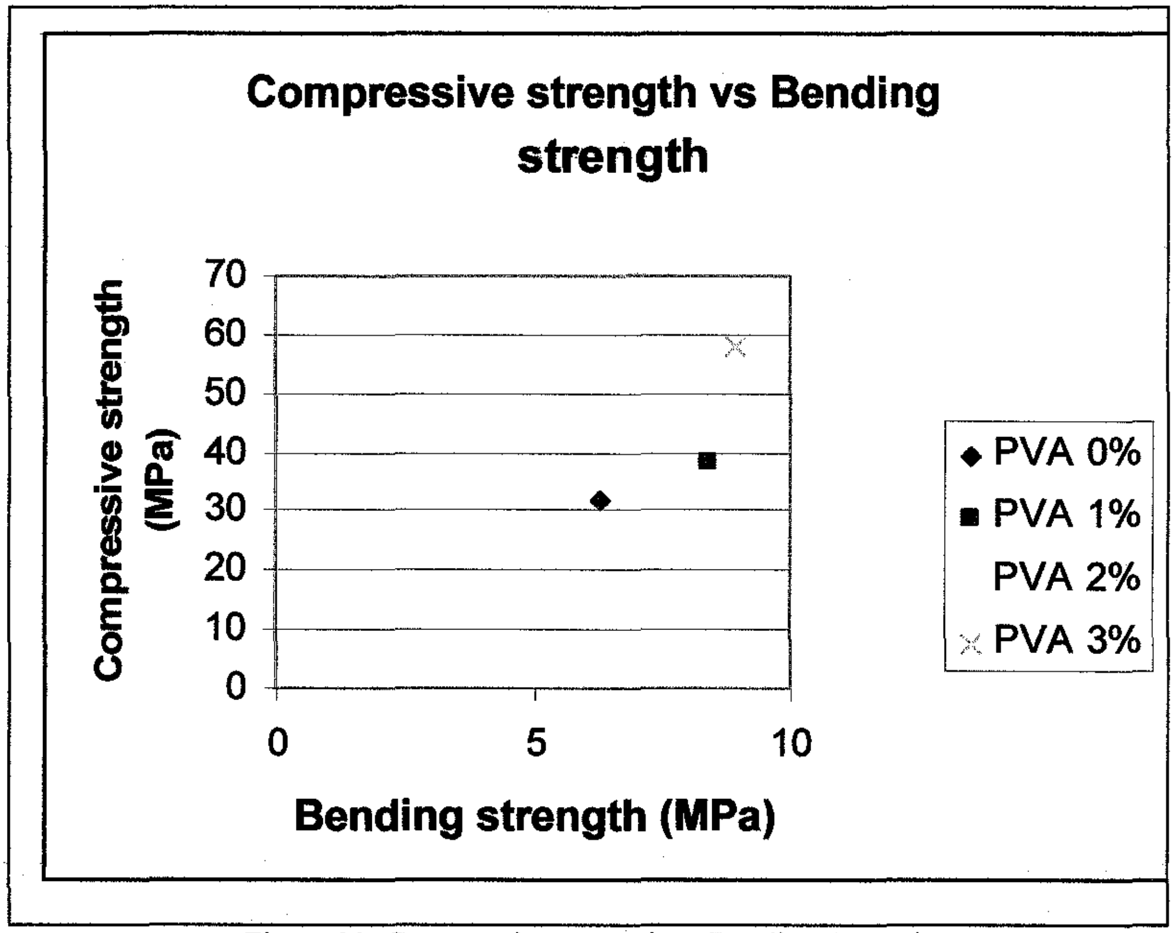


Figure 23: Compressive strength vs Bending strength

Figure 23 shows comparison between compressive and tensile strength of all concrete. Ratio of tensile to compressive strength for PVA 0% concrete is 0.2, PVA 1% concrete is 0.22, PVA 2% concrete is 0.19 and PVA 3% is 0.15. PVA 1% concrete dictates the highest ratio and then decreasing to 0.19 and finally 0.15. This may suggest the idea that with increasing amount of PVA fibers added, the compressive strength increases significantly as compared to the bending strength.

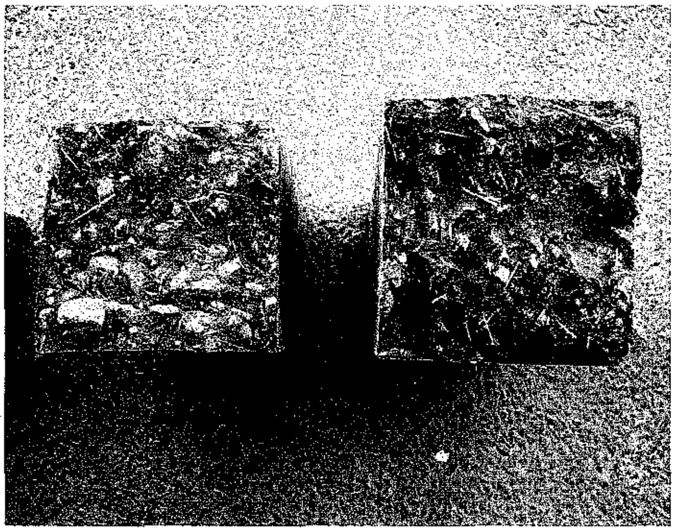


Figure 24: Concrete with PVA fibers

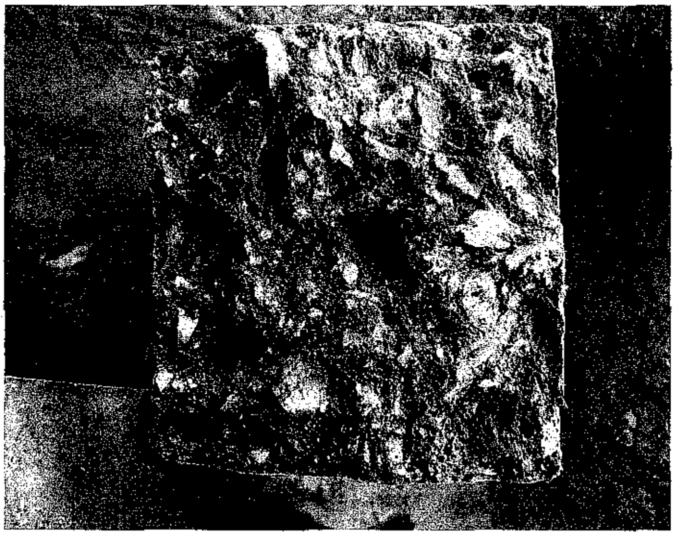


Figure 25: Concrete without PVA fiber

Figures show the surface of concrete beams that had been broken to demonstrate the bonding between concrete and PVA fibers. The fibers are scattered in the concrete and it is observed that the fibers hold together the matrix which would make the concrete possess higher bonding stress and resistance to cracking. The more PVA fibers added to the concrete, more surface area of concrete would be covered by them and the stronger the bonding would be. The fibers do not bend or deteriorate in the concrete and remain in its original form.

5. CONCLUSION AND RECOMMENDATION

In the first semester, the project focused more on the literature review of PVA fibers and fiber reinforced concrete. No concrete mix or experiment was made using PVA fibers. However, a few self compacting concrete mixes were done to determine the appropriate mix to be used the in the next semester for the mix using PVA fibers and in order to come up with the proposed mix proportion. Those mixes were not successful and the optimum self compacting concrete were not able to be obtained.

In the second semester, a few more self compacting concrete mixes were conducted. However, due to some constraints and limitation, self compacting concrete was not able to be achieved. Eventually, concrete mixes with PVA fibers were conducted using normal concrete procedures. 4 PVA concrete mixes were conducted; consist of 0% (control mix), 1%, 2% and 3% PVA fibers. The main focus was to determine the hardened properties of the PVA fiber reinforced concrete, especially on the compressive and tensile strength.

Some recommendations to improve on this project would be to make more mixes with varying content of PVA fibers. The purpose is to observe in a bigger scope on how PVA fibers would act with concrete. In addition to that, more tests should also be conducted to determine other properties of PVA fiber reinforced concrete. Some other admixtures might also be infused in the concrete mix to alter or improve the properties of PVA reinforced concrete. Some of the constraints in this project came from the conditions and environment of the concrete lab. Tests were not able to be executed on specified time because testing machine was having some problem and could not function properly. It is critical to ensure all the equipments and machines in the lab are ready before any mix or test is going to be performed. It is also essential to follow all the procedures throughout the whole project to ensure it would flow smoothly. Time management plays an important role in ensuring the project success. A timeline should be constructed so that all the activities are going to run correspondingly.

REFERENCES

1. 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)
2. 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
3. Kong, H. J., Bike, S. G., and Li, V. C., "Constitutive rheological control to develop a self-consolidating engineered cementitious composite reinforced with hydrophilic poly(vinyl alchohol) fibers." Cement & Concrete Composites 25, 333-341 (2003)
4. 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)
5. Li, V. C., Fischer, G., "Reinforced ECC – An evolution from materials to structures" Proceedings of the 1st Congress (2002)
6. Li, V. C., "Engineered Cementitious Composites-Tailored composites through micromechanical modeling," Fiber reinforced Concrete: Present and the Future, N. Banthia, A. Bentur, and A. Mufti, eds., Canadian Society for Civil Engineering, Montreal, 1998, pp. 64-97
7. Shao, Y., and Shah, S. P., "Mechanical Properties of PVA Fiber Reinforced Cement Composites Fabricated by Extrusion Processing," ACI Material Journal, V. 94, No. 6, Nov-Dec. 1997, pp.555-564
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. Kuraray Co. Ltd <http://www.kuraray-am.com/pvaf/index.php>
10. Portland Cement Concrete Lab, Civil Engineering Department, University of New Mexico <http://civilx.unm.edu/laboratories_ss/pcc/pcc.html>
11. Cement and Concrete Institute <http://cnci.org.za/inf/publications.pdf/fibre.pdf>

APPENDICES

Appendix 1 – Properties of PVA fibers

A. Specifications and properties

Item Property	High strength & modulus □.	High strength & modulus □.	Super-short staple fiber □. for building materials	Super-short staple fiber □. 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

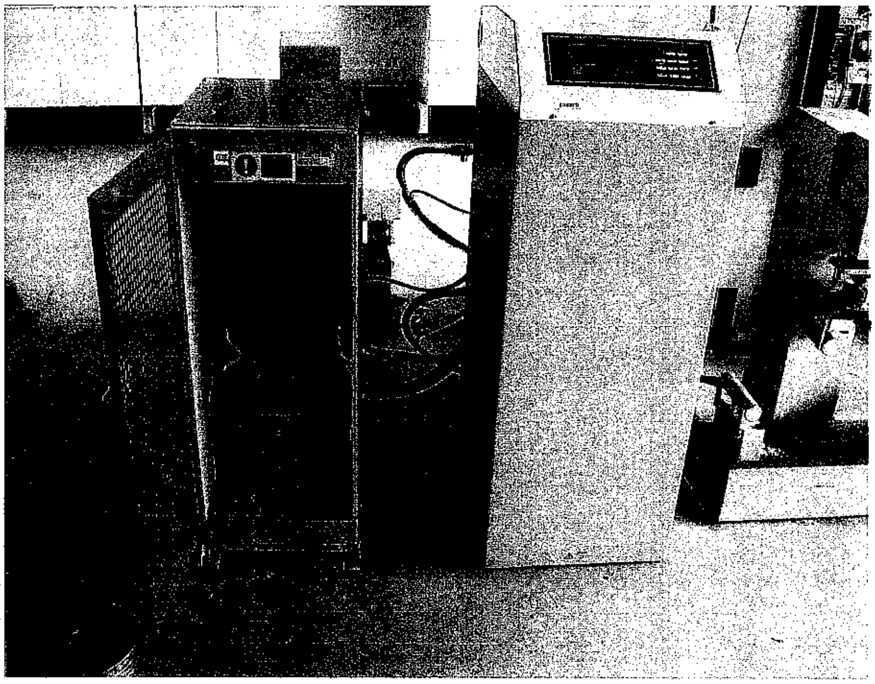
Test condition			Fiber strength loss ratio (%)			
Density %	Temperature□	Duration time (hr)	Vinylon-high strength	Viscose fiber yarn	Nylon 6	Polyester
1	20	10	0	12	0	1
1	100	100	7	29	25	71

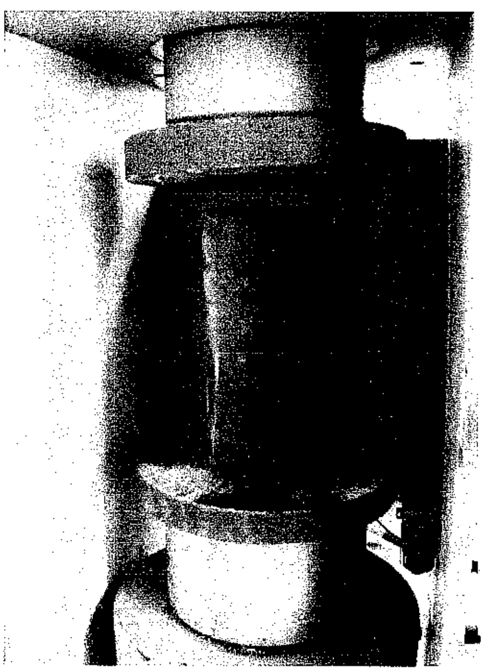
40	20	10	0	100	18	4

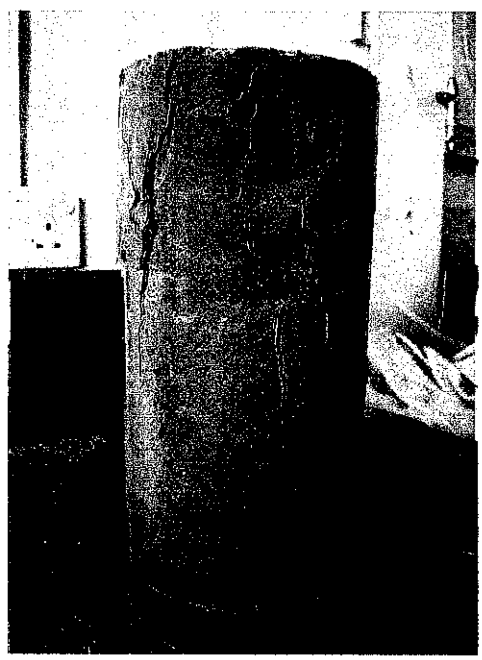
D. Sunshine resistance comparisons

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

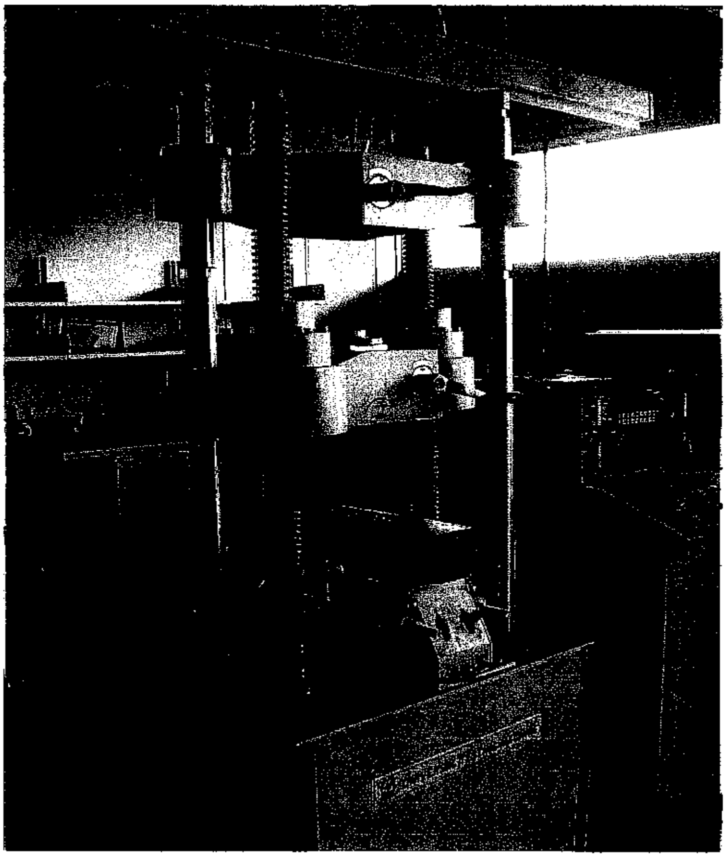
Appendix 2 - Compressive strength test

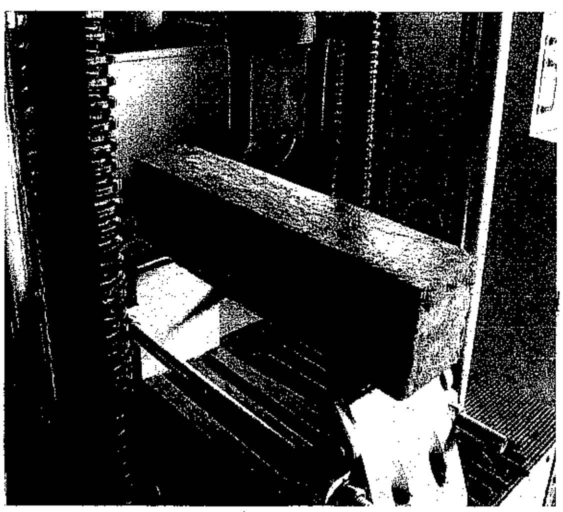


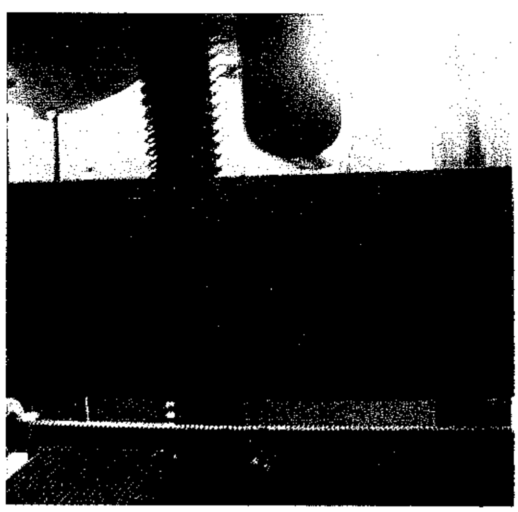




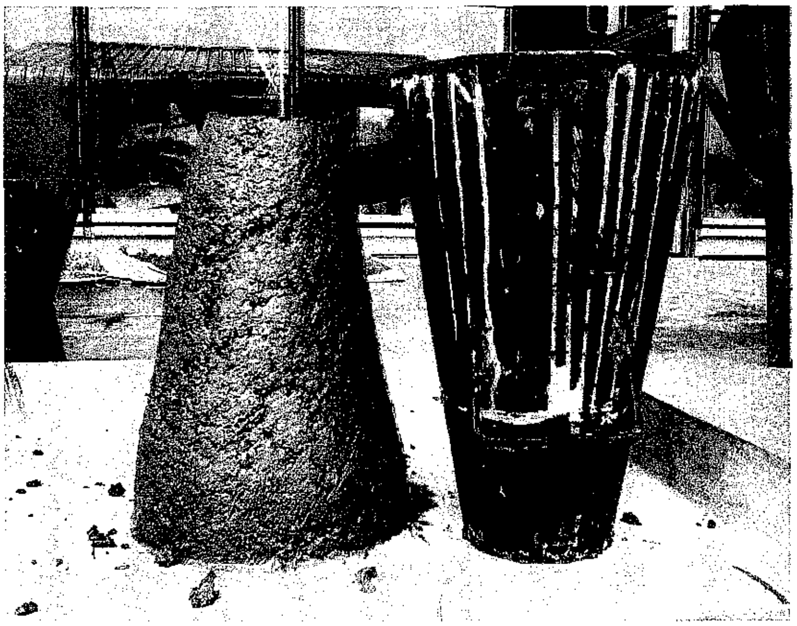
Appendix 3 - Bending Test







Appendix 4 – Slump Test



Slump test of PVA 2% concrete

Slump test of PVA 1% concrete

Slump test of 3% PVA concrete

Appendix 5 – Result of Bending Test using Universal Testing Machine (UTM)

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

C:\U55\BEND.GRT

File Setup Report Test Control Help

Open Save Setup Test Read Up Stop Down Print View Help X-483 Y-973

UNIVERSITI TEKNOLOGI PETRONAS

Civil Engineering Department

31750 Seri Iskandar, Tronoh, Perak Darul Ridzuan

Bending Test Report

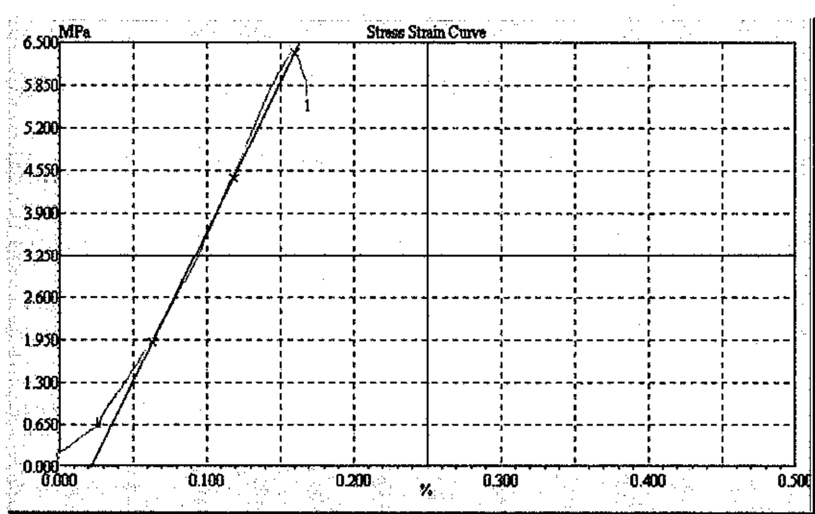
Report No : 00013	Max. Load : 8.44kN
Date : 2007-05-14	Max stress : 6.33MPa
Group :	Deformation at break : 0.85mm
Operator :	Strain at break : 0.17%
Diameter : 100.00mm	Yield Strength : 3.16MPa
Guage length : 500.00mm	Young's Modulus : 3787.65MPa

NUM

C:\U55\BEND.GRT

File Setup Report Test Control Help

Open Save Setup Test Read Up Stop Down Print View Help X-483 Y-538



Tested by :

Checked by :

NUM

B: Concrete with 1% PVA Fibers

C:\U55\BEND.GRT

File Setup Report Test Control Help

Open Save Setup Test Read Up Stop Down Print View Help X-483 Y-973

UNIVERSITI TEKNOLOGI PETRONAS

Civil Engineering Department

31750 Seri Iskandar, Tronoh, Perak Darul Ridzuan

Bending Test Report

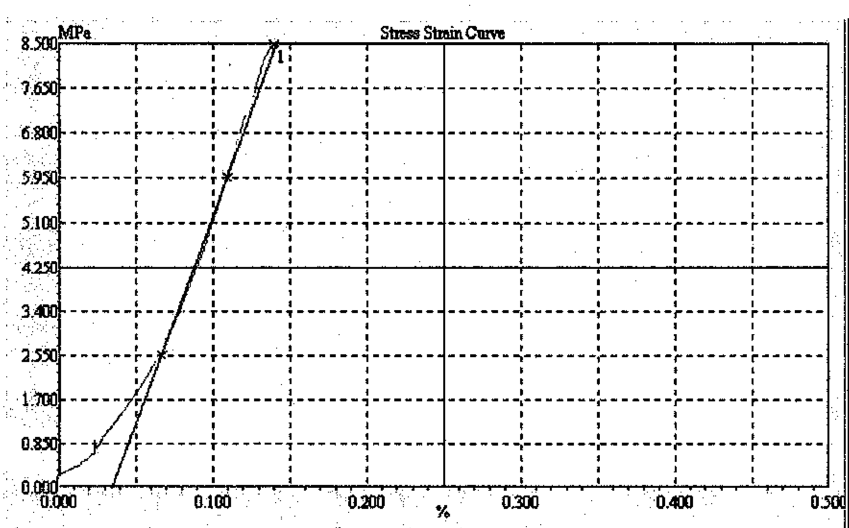
Report No : 00016	Max. Load : 11.27kN
Date : 2007-05-14	Max stress : 8.45MPa
Group :	Deformation at break : 0.72mm
Operator :	Strain at break : 0.14%
Diameter : 100.00mm	Yield Strength : 4.22MPa
Guage length : 500.00mm	Young's Modulus : 6499.10MPa

NUM

C:\U55\BEND.GRT

File Setup Report Test Control Help

Open Save Setup Test Read Up Stop Down Print View Help X-483 Y-549



Tested by : Checked by :

NUM

C. Concrete with 2% PVA Fibers

C:\U55\BEND.GRT

File Setup Report Test Control Help

Open Save Setup Test Read Up Stop Down Print View Help X-483 Y-973

UNIVERSITI TEKNOLOGI PETRONAS

Civil Engineering Department

31750 Seri Iskandar, Tronoh, Perak Darul Ridzuan

Bending Test Report

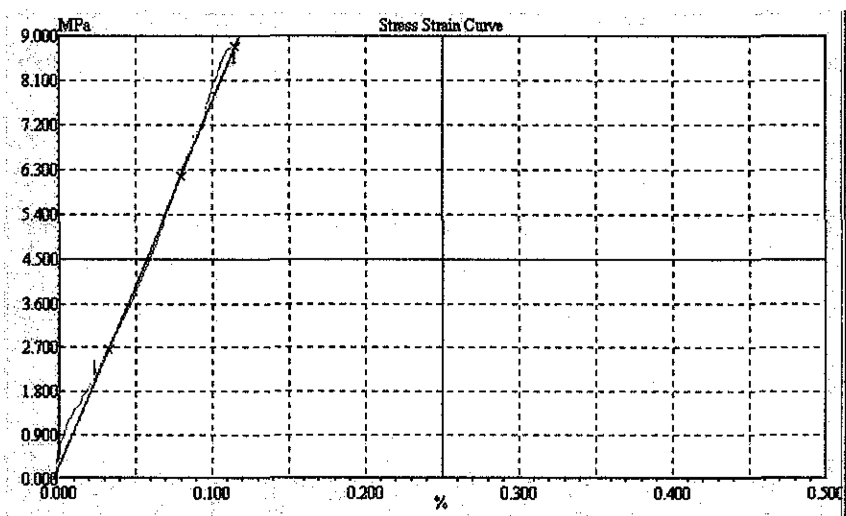
Report No : 00015	Max. Load : 11.67kN
Date : 2007-05-14	Max stress : 8.75MPa
Group :	Deformation at break : 0.57mm
Operator :	Strain at break : 0.11%
Diameter : 100.00mm	Yield Strength : 4.37MPa
Guage length : 500.00mm	Young's Modulus : 6161.70MPa

NUM

C:\U55\BEND.GRT

File Setup Report Test Control Help

Open Save Setup Test Read Up Stop Down Print View Help X-483 Y-519



Tested by : Checked by :

NUM

D. Concrete with 3% PVA Fibers

C:\U55\BEND.GRT

File Setup Report Test Control Help

Open Save Setup Test Read Up Stop Down Print View Help X-483 Y-973

UNIVERSITI TEKNOLOGI PETRONAS

Civil Engineering Department

31750 Seri Iskandar, Tronoh, Perak Darul Ridzuan

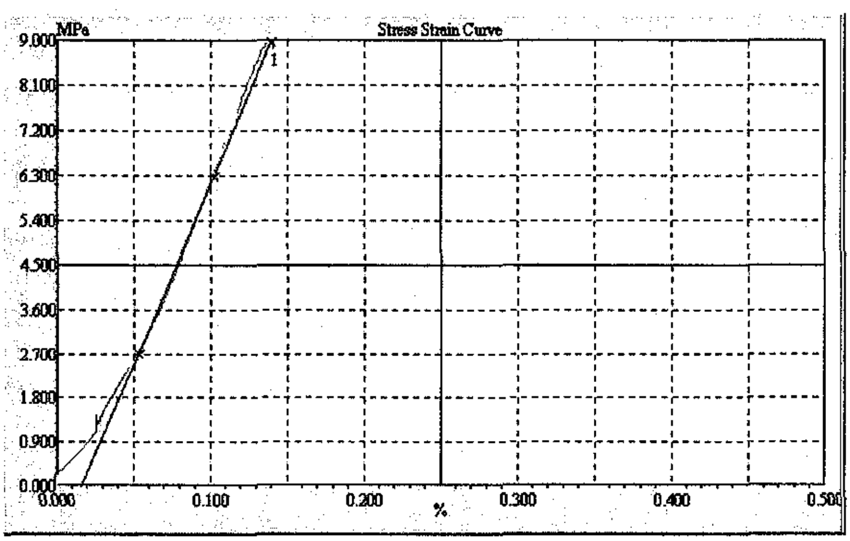
Bending Test Report

Report No : 00011	Max. Load : 11.92kN
Date : 2007-05-14	Max stress : 8.94MPa
Group :	Deformation at break : 0.71mm
Operator :	Strain at break : 0.14%
Diameter : 100.00mm	Yield Strength : 4.47MPa
Guage length : 500.00mm	Young's Modulus : 6062.38MPa

NUM

File Setup Report Test Control Help

Open Save Setup Test Read Up Stop Down Print View Help X-483 Y-509



Tested by : Checked by :

NUM

NUM