# EFFECTS OF FABRIC ARCHITECTURE AND ALKALI TREATMENT ON THE MECHANICAL PROPERTIES OF COTTON FABRIC-REINFORCED UNSATURATED POLYESTER COMPOSITES

**BY**

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# DECLARATION

I declare that the work in this Thesis entitled "**EFFECTS OF FABRIC ARCHITECTURE AND ALKALI TREATMENT ON THE MECHANICAL PROPERTIES OF COTTON FABRIC-REINFORCED UNSATURATED POLYESTER COMPOSITES"** has been carried out by me in the Department of Textile Science and Technology. The information derived from the literature has been duly acknowledged in the text and a list of references provided. No part of this thesis was previously presented for another degree or diploma at this or any other Institution.

| | | |
|---|---|---|
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| Name of Student | Signature | Date |

# CERTIFICATION

This Thesis entitled "**EFFECTS OF FABRIC ARCHITECTURE AND ALKALI TREATMENT ON THE PROPERTIES OF COTTON FABRIC REINFORCED UNSATURATED POLYESTER COMPOSITES"** by Okechukwu Emmanuel ACHUKWU meets the regulations governing the award of the degree of Master of Science in Textile Science and Technology of Ahmadu Bello University, and is approved for its contribution to knowledge and literal presentation.

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# ABSTRACT

The effects of fabric architectures and alkali treatment on the properties of cotton fabric-reinforced unsaturated polyester composites have been studied. The problems of low mechanical properties of textile composites from natural origin have been a source of concern for researchers; insufficient utilization of cotton fibres has further reduced the economic returns of cotton growers. In this work, four different yarns of known count were twisted (plied) to obtain a single strand which was woven and knitted into fabrics of different architectures. The cotton fabrics were subjected to chemical modifications using 20% sodium hydroxide for 1 and 2 minutes and its influence on some mechanical properties were analyzed. The fabrics were used to reinforce unsaturated polyester resin as matrix, applying both single layer and two layers of fabrics to form different 2-ply laminate configurations. The tensile and flexural strength, tensile and flexural modulus, impact strength and hardness of the textile composites were compared. Alkali treatment improved the tensile strength and breaking extension of the fabrics by 10-30% and 31-56% respectively requiring a certain percentage concentration and duration of treatment, going by the fact that the close treatment times of 1 and 2 minutes with 20% concentration of sodium hydroxide gave inconsistent tensile strength and breaking extension. Fabric architecture was found to have great influence on the breaking strength of the fabrics. The tensile strength of the fabrics was found to decrease in this order: Plain woven fabric > twill fabric > knitted fabric when untreated, but when treated, twill fabric > plain fabric > knitted fabric. Composites reinforced with twill fabrics generally had better tensile strength and modulus as well as flexural strength and modulus than those reinforced with plain and knitted fabrics either when the reinforcing fabrics were untreated or treated with sodium hydroxide with an increase of 72–119%. The flexural strength of composite with twill, plain and knitted fabrics are 62.32%, 56.75% and 52.68% respectively and increased by 65%, 60% and 37% when treated with 20% NaOH. Results also showed that increase in the volume of reinforcement (increase in fabric layer) gave a corresponding increase in the mechanical properties of the composites; however, the increase was not proportional with respect to those composites reinforced with single fabric samples. The mechanical properties tested were optimized by the plying effect carried out on the yarns. The impact strength of the unsaturated polyester was improved by about 105% when reinforced with the fabrics. Composites reinforced with knitted fabrics showed better resistance to impact forces than other fabrics with good energy absorbing characteristics. There was an increase in the Rockwell hardness of polyester resin composite for both single and double layer reinforced laminates. Composites with twill fabrics gave highest hardness number (25.9) than those of other fabrics (plain, 24.4 and knitted, 22.2) for the single ply and same for 2-ply (twill-twill, 30.6; plain-plain, 29.9 and knitted-knitted, 25.6). Much variation in hardness numbers were not recorded for the various reinforcements. The behaviour of other hybrid composites reinforced with two layers of fabrics was seen to follow the properties of the fabrics reinforcing them.

**Keywords:** Cotton fabrics, Composites, Unsaturated polyester resin, Weaving, Mechanical properties

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# ABBREVIATION

| | |
|---|---|
| **ASTM** | American Society for Testing and Materials |
| **NIS** | Nigeria Industrial Standard |
| **MEKP** | Methyl Ethyl Ketone Peroxide |
| **RTM** | Resin Transfer Moulding |

# CHAPTER ONE

## 1.0 INTRODUCTION

Due to the ever increasing global interest on new structural materials from natural sources, efforts are on to reduce the cost in raw materials, manufacture and maintenance of composites. With a view to replacing the wooden fittings, fixtures and furniture, natural composites reinforced with jute, kenaf, sisal, coir, cotton, straw, hemp, banana, pineapple, coconut, rice husk, bamboo etc. can be used instead of the conventional polymer composites reinforced with man-made fibres such as glass, carbon, aramid etc. Until recently, there has been only limited information available towards understanding the behaviour of composites reinforced with natural fibres.

The development of textile composites has been mainly the investigation of textile fabrication techniques and evaluation of the mechanical properties. Researches on textile technologies such as weaving, knitting and braiding has resulted in the formation of textile composites that have higher mechanical properties, as continuous orientation of fibres is not restricted at any point (Yan, *et. al.*, 2002).

The increased interest in textile reinforcements is due to the enhanced strength, lower production cost and improved mechanical properties, which they offer, compared to their non-woven counterparts. Another special feature of textile reinforcement is the interconnectivity between adjacent fibres. This interconnectivity offers additional interface strength to improve the relatively weak fibre-resin interface. In addition, woven and knitted fabric composites may be more damage tolerant in the case of a delamination.

There has been report on the increase of lateral cohesion of filament for twisted yarns as well as improved ease of handling (Naik and Kuchibhotla, 2002). In fact, fibre twist is found to induce normal forces between fibres and this increasing inter-fibre friction gives yarn cohesion. However, by twisting yarns, there is the possibility of micro damages within the yarn, thus, leading to possible decrease in the strength of the yarn. Whatever be the fibre material, fibre architecture has been found to influence the composite properties based on the morphological and structural parameters (Bueno *et al.,* 2002)

Cotton is one of the most common agro-based fibres that have enormous potential in composite manufacture due to its cost-effective, renewable, versatile, nonabrasive, visco-elastic, biodegradable, compostable and insulating characteristics. The cellulosic textile fibres are obtained from fibres that grow in a ball, around the seeds. Cotton has a high crystallinity index of about 87%. The crystallinity of cellulosic fibres can influence the mechanical properties of their composites (Carrillo *et al.,* 2010).

The presence of surface impurities and the large amount of hydroxyl groups on plant fibres make them less attractive for reinforcement of polymeric materials. The attractive features of these fibres are light weight, non-toxicity, friendly processing and absorbed $CO_2$ during their growth (Abdelmouleh *et al.,* 2007; Tserki *et al.,* 2005).

Alkali treatment has been known to modify plant fibres, promoting the development of fibre-resin adhesion, which then will result in increased interfacial energy and hence, improvement in the mechanical and thermal stability of the composites (Mwaikambo and Ansell, 2002). The uses of natural fibres to make low cost and eco-friendly composite materials are a subject of great importance.

Studies on woven and knitted cotton fabrics made from plied yarns and their use as reinforcements for unsaturated polyester resin, to the best of the author’s knowledge, have not been reported yet. In this research work, four yarns were plied together to obtain 4-ply single strand which was then knitted and woven into different fabric architectures. The fabrics were treated with 20% sodium hydroxide for 1 and 2 minutes. Both the untreated and treated fabrics were used to reinforce the composite using unsaturated polyester resin as the matrix. The effects of these modifications on the surface characteristics and some mechanical properties of the fabrics and composite specimens were tested and analyzed.

## 1.1 STATEMENT OF RESEARCH PROBLEMS

Natural fibres can be used in many types of reinforcements and used for composites, such as continuous and discontinuous unidirectional fibres, random orientation of fibres, etc. By taking the advantages from these types of reinforced composites such as: good properties and reduced fabrication cost, they had been used in the development of automotive, packaging and building materials. The challenges here have always been the problem of low mechanical properties and incidence of fibre pull-out. Problem of low patronage of cultivated cotton lints especially in Northern Nigeria, as textile mills are struggling to remain in business, is a major concern for cotton growers. Also, there are very few reports on different fabric architectures and woven fabric composites reported so far.

Realizing the advantages of natural fibres, knitted architecture and woven pattern, these three factors would be considered in the present work. In this research project, cotton would be utilized as reinforcement because of its availability and ability to be produced in a continuous form, and hence could be produced into a woven mat form.

## 1.2 RESEARCH AIMS AND OBJECTIVES:

1. To characterize the properties of the plied cotton yarn.
2. To weave and knit the yarns into fabrics of different architectures.

3. To evaluate the effect of alkali treatments using sodium hydroxide (NaOH) on the properties of knitted and woven cotton fabrics
4. To prepare the cotton fabric-reinforced composites using hand laying technique and study of the effect of alkali on the reinforced unsaturated polyester composites.
5. To study the effect of different laminate configurations (2-ply laminated composites) on the properties of hybrid knitted and woven cotton fabrics reinforced unsaturated polyester resin composites.
6. To evaluate some of the mechanical properties of the reinforced composites (tensile strength, flexural, impact strength and hardness)
7. To achieve a better understanding of composite properties in the special case where the fibre part is of different architectures.
8. To introduce new class of materials that might find some industrial applications.

## 1.3 JUSTIFICATION

Due to poor patronage (or sale) of grown cotton as many textile mills are going out of business, the use of cotton for composite reinforcement provides an alternative market for cotton lint products. Composites of different fabric architectures are aimed at solving the problem of low mechanical properties and incidence of fibre pull-out. Some authors have noted the possibility of slightly altered mechanical properties depending on whether the yarns are twisted prior to weaving, (Naik and Shembekar, 1992b) and work in this area have shown that damage accumulation under static and cyclic loading is different in laminates fabricated from twisted or untwisted yarn. (Marsden *et al.*, 1994)

Also, the usage of woven composites has increased over the recent years due to their lower production costs, light weight, higher fracture toughness and better control over the thermo-mechanical properties.

## 1.4 SCOPE OF THE STUDY

The scope of the research work is as stated below:

1. Twisting together of four (4) single cotton yarns of known count.
2. The weaving and knitting of the twisted yarns into fabrics of different architectures.
3. Surface treatment of the fabrics with 20% concentration of Sodium hydroxide at different conditions.
4. Finally, the reinforcement of unsaturated polyester matrix with the knitted and woven cotton fabrics to form the reinforced composites.
5. Analysis of the tensile properties of the fabrics and the mechanical properties of the composite samples via:
    - ➢ Universal Testing Machine (Tensile and Flexural test)
    - ➢ Charpy Impact test (Ability of the composite to absorb shock)
    - ➢ Indentec Universal Hardness Testing Machine (Hardness of the composite).

# CHAPTER TWO

## 2.0 LITERATURE REVIEW

## 2.1 COMPOSITES

Composites are materials that comprise a strong load carrying component (known as reinforcement) embedded in a weaker component (known as matrix). Reinforcement provides strength and rigidity, helping to support structural load. The matrix or binder (organic or inorganic) maintains the position and orientation of the reinforcement. Significantly, constituents of the composites retain their individual, physical and chemical properties; yet together they produce a combination of qualities which the individual constituents would be incapable of producing alone (Hull and Clyne, 1996).

## 2.2 CONSTITUENTS OF COMPOSITES

### 2.2.1 Matrices

The role of the matrix in a fibre-reinforced composite is to distribute stress between the fibres, to provide a barrier against an adverse environment and to protect the surface of the fibres from mechanical abrasion. The binding agent or matrix in the composite is therefore of critical importance. Polymer resins used as matrix materials have been divided broadly into two categories: Thermosetting and thermoplastic resins.

#### 2.2.1.1 Thermosetting Resins

Thermoset (Sinha, 2000) is a hard and stiff cross-linked material that does not soften or become mouldable when heated. Thermosets are stiff and do not stretch the way that elastomers and thermoplastics do. Several of these classes of polymers have been used as matrices for natural fibre composites. Most commonly used thermoset polymers are epoxy resin, unsaturated polyester resins, Vinyl Ester, Phenolic Epoxy and Novolac (Bledzki *et al.*, 1998, and Ramires, *et al.*, 2010).

### 2.2.1.2 Epoxy resin

Epoxy is a copolymer; i.e. it is formed from two different chemicals. The resin consists of monomers or short chain polymers with an epoxide group at either end. Epoxy resins are produced from a reaction between epichlorohydrin and bisphenol-A.

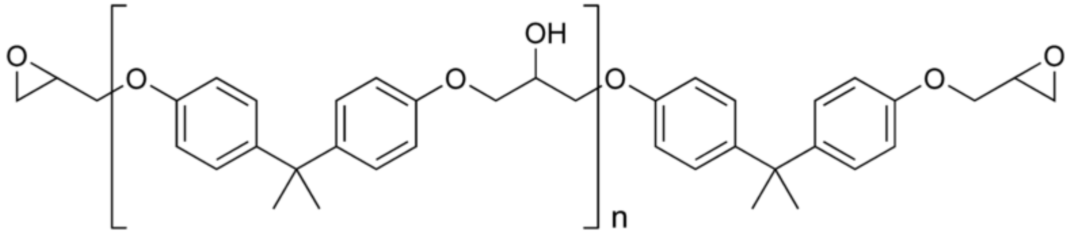


Figure: 2.1: Epoxy resin

These resins are thermosetting polymers and are used as adhesives, high performance coatings and potting and encapsulating materials. These resins have excellent electrical properties, low shrinkage, good adhesion to many metals and resistance to moisture, thermal and mechanical shock.

#### 2.2.1.2.1 Advantages of Epoxy

Epoxy resins are the most commonly used resins. They are low molecular weight organic liquids containing epoxide groups. The reaction of epichlorohydrin with phenols or aromatic amines makes most epoxies.

Although, epoxy is costlier than other polymer matrices, it is the most popular matrix used for polymer matrix composites (PMCs). More than two-thirds of the polymer matrices used in aerospace applications is epoxy based. The main reasons why epoxy is the most used polymer matrix material are:

- High strength
- Low viscosity and low flow rates, which allow good wetting of fibres and prevent misalignment of fibres during processing
- Low volatility during cure
- Low shrink rates, which reduce the tendency of gaining large shear stresses of the bond between epoxy and its reinforcement
- Available in more than 20 grades to meet specific property and processing requirements

The excellent properties of epoxy make it one of the best matrix materials for composites. The effect of fibre treatment on the mechanical properties of unidirectional sisal/epoxy composites was reported (Rong, *et al.,* 2001). Ganan *et al.,* (2005) evaluated the mechanical and thermal properties of sisal/epoxy composites as a function of fibre modification. Kenaf (Abubakar *et al.,* 2010), hemp and flax (Hepworth, *et al.,* 2000a), oil palm (Kalam, *et al.,* 2005), sisal (Yan, 2004, Kim and Seo, 2006), cotton (Khalid, *et al.,* 1998), flax (Oksman, 2001), sisal and hemp (Gonzalez-Murillo and Ansell, 2010), flax, hemp and kenaf (Sgriccia and Hawley, 2007), lantana camara fibre (Deo and Acharya, 2010) and sugar palm fibre (Leman, *et al.,* 2008) have all been used in reinforcing epoxy matrix. Their mechanical properties, processing methods, water absorption, and fracture toughness were evaluated. Epoxy resins, which were used as a matrix for hemp fibre-reinforced composites, were studied regarding the effect of fibre architecture on the falling weight impact properties (Santulli and Caruso, 2009), properties and performances of composites for curved pipes (Cicala, *et al.*, 2009). Others include the impact load performance of resin transfer moulded composites (Scarponi, *et al.*, 2009), micro-mechanics of the composites (Eichhorn and Young, 2004), the influence of hybrid blends made of soybean oil and nanoclay (Haq, *et al.*, 2008), and the usefulness of unretted hemp as a source of fibre for biocomposites (Hepworth, *et al.*, 2000b). Furthermore, epoxy resin was used as a matrix for sisal fibre-reinforced composites and was examined with respect to the influence of fibre orientation on the electrical properties (Chand and Jain, 2005), and the degree of reinforcement (Meddahi *et al.*, 2008) were examined. Towo and Ansell (2008b) prepared the treated sisal fibre composites with an epoxy and polyester resin matrices. Fatigue evaluation and dynamic thermal analysis tests were performed. Composites containing alkali treated fibre bundles proved to have better mechanical properties than those with untreated fibre bundles. Epoxy matrix composites have a longer fatigue life than polyester matrix composites. In another study, researchers used orthogonal bamboo fibre strip mats for fabrication of bamboo fibre-reinforced epoxy and polyester composites by using hand lay-up technique (Jain, *et al.*, 1992 and 1993). Dried bamboo fibres used for preparation of short bamboo fibres reinforced epoxy composites and their chemical resistance and tensile properties with fibre length have been studied (Rajulu *et al.*, 1998).

Van de Weyenberg and co-workers (2006) worked on enhancing the properties of unidirectional flax fibre-reinforced composites by applying an alkaline fibre treatment. A better adhesion between flax fibres and epoxy matrix was achieved resulting in improved properties of the composites (40% fibre volume fraction). This enhanced the properties by up to 280 MPa for longitudinal strength and 22 GPa for modulus (the fibres used were treated in 3% NaOH solution for 20 minutes). Their work also showed a clear improvement in the transverse properties of the resulting composites, with strengths up from 8 MPa for untreated flax fibre-reinforced composite to 35 MPa, by applying a mild treatment to flax fibres in a 4% NaOH solution for 45 seconds before they are resin-impregnated to produce the composite with 50% fibre volume fraction (Weyenberg *et al.*, 2006).

Bisanda and Ansell (1991) have studied the effect of silane treatment and alkali treatment on the mechanical and physical properties of sisal-epoxy composites. They have reported that incorporation of sisal fibres in an epoxy resin produces stiff and strong composite materials. The treatment of the sisal fibres with silane, preceded by mercerisation, led to improvement in wettability, mechanical properties and water resistance.

#### 2.2.1.1.2 Unsaturated Polyester Resins

Unsaturated polyester resins (UPR) are the workhorse of the composites industry and represent approximately 75% of the total resins used (American Composites Manufacturers Association, 2004). Thermoset polyesters are produced by the condensation polymerization of dicarboxylic acids and difunctional alcohols (glycols). In addition, unsaturated polyesters contain an unsaturated material, such as maleic anhydride or fumaric acid, as part of the dicarboxylic acid component. The finished polymer is dissolved in a reactive monomer such as styrene to give a low viscosity liquid. When this resin is cured, the monomer reacts with the unsaturated sites on the polymer converting it to a solid thermoset structure.

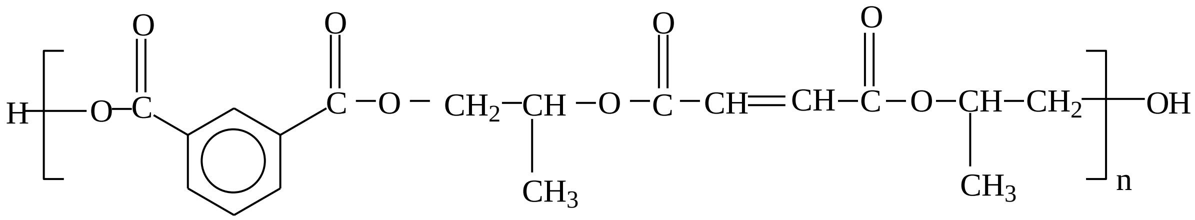


Figure 2.2: Unsaturated polyester (UPE) Resin (ortho type)

Unsaturated polyesters (Sharifah *et al.*, 2005) are extremely versatile in properties and applications and have been a popular thermoset used as the polymer matrix in composites. They are widely produced industrially as they possess many advantages compared to other thermosetting resins including room temperature cure capability, good mechanical properties and transparency. The reinforcement of polyesters with cellulosic fibres has been widely reported. Polyester-jute (De Albuquerque, 1999 and Sahoo *et al.*, 2007), Polyester-sisal (Pal, 1988 and Mishra *et al.*, 2002), polyester-coir (Owolabi, 1985) polyester-banana-cotton (Satyanarayana, 1983), polyester-straw (White and Ansell, 1983), polyester-pineapple leaf (Devi, 1997), and polyester- cotton-kapok (Mwaikambo and Bisanda, 1999), are some of the promising systems.

The possibility of using date palm fibres as reinforcement in polyester composites was investigated (Al-Kaabi *et al.,* 2005). Flexural properties and impact strength of date palm fibre/polyester composites were found to be influenced by fibre content and fibre treatment method. Soda treated fibres exhibited higher mechanical properties compared to untreated fibre/polyester composites. The fibre fraction and fibre length for this system were optimized for 9 wt% and 2 cm, respectively. Water absorption was lightly affected by surface modification of the fibres and was relatively low. The hybrid effect on the mechanical properties of abaca and sisal fibre-reinforced polyester composites was evaluated (Idicula, *et al.*, 2005a and 2005b). A positive hybrid effect was observed for the flexural properties. The tensile strength was found to increase when the volume fraction of banana was increased. A negative effect was observed for the impact properties. Recent studiess regarding the use of sisal and jute fibre (Mathur, 2006), abaca (Herrera-Estrada *et al.*, 2008), abaca and sisal (Idicula *et al.*, 2005), flax (Wambua *et al.*, 2003), sisal, abaca and bamboo fibre (Rao *et al.*, 2010) in reinforced polyester composites have also been reported.

#### 2.2.1.2 Thermoplastics

Thermoplastics (Sinha, 2000) are polymers that require heat to make them processable and after cooling, such materials harden and retain their shape. In addition, these polymers may be reheated and reformed, often without significant changes in their properties. The thermoplastics which have been used as matrix for natural fibre-reinforced composites are as follows: High density polyethene (HDPE) (Maiti and Singh,1986), Low density polyethene (LDPE) (Raj *et al.*, 1990), Chlorinated polyethylene (CPE) (Maldas and Kokta, 1995), Polypropylene (PP) (Simpson and Selke, 1991 and Sain and Kokta, 1994), Polystyrene (PS) (Raj *et al.*, 1989), Poly (Vinyl chloride) PVC) (Maldas *et al.*, 1989b), Mixtures of polymers (Hedenberg, 1995), Recycled Thermoplastics (Yam *et al.*,1990 and Sain *et al.*,1993). Only the aforementioned thermoplastics are useable for natural fibre-reinforced composites, because their processing temperatures (temperature at which fibre is incorporated into polymer matrix) do not exceed 230°C. They are mostly, polyolefins. Thermoplastics, like polyamides, polyesters and polycarbonates require processing temperatures greater than 250°C and are therefore not useable for such composite processing without fibre degradation.

### 2.2.2 Reinforcements

Fibre-reinforced polymers or fibre-reinforced plastics (FRPs) are combinations of fibres and/or particulate fillers in polymeric matrix material. Generally the fibres and particles are regarded as reinforcements to carry load or to control strain, whereas the matrix is regarded as a bonding medium to transfer load and to provide continuity and structural integrity. The most common reinforcements (fibres) are glass, carbon (graphite), aramid and other specialty fibres. They may also be of natural, polymeric, metallic or ceramic origin.

#### 2.2.2.1 Particle Reinforced Polymer

Several particles have used for the reinforcement of composite samples and these include ceramics and glasses such as small mineral particles, metal particles such as aluminum and amorphous materials, including polymers and carbon black. Particles are used to increase the elastic modulus of the matrix and to decrease the ductility of the matrix. Particles are also used to reduce the cost of the composites.

Various types of ceramics exhibit good electrical and thermal insulators. Some ceramics have special properties; some ceramics are magnetic materials; some are piezoelectric materials; and a few special ceramics are even superconductors at very low temperatures.
Ceramics and glasses have one major drawback: they are brittle. An example of particle reinforced composites is an automobile tire, which has carbon black particles in a matrix of poly-isobutylene elastomeric polymer.

## 2.3 NATURAL FIBRE-REINFORCED POLYMER COMPOSITES

Fibre-reinforced composite materials are an important class of engineering materials. They offer outstanding mechanical properties, unique flexibility in design capabilities and ease of fabrication (Agarwal *et al.*, 2006). Composites of high strength fibres such as graphite, aramid and glass are commonly used in broad range of applications from aerospace structure to automotive parts and from building materials to sporting goods (Arib *et al.*, 2004). However, the development of natural fibre-reinforced composites has become an attractive research line due to the non-recyclability, high density and health hazards of composites reinforced with fibres such as glass, carbon and aramids (Corrales et al., 2007; Herrera and Valadez, 2005). Besides, the greatest problem of using such materials is how to conveniently dispose of them once they have come to the end of their useful life span (Bodros *et al.*, 2007). Therefore, there has been growing interest in the use of natural cellulosic fibres as the reinforcement for polymeric matrix. Several natural fibres such as sisal (Chow *et al.*, 2007), jute (Ahmed *et al.*, 2007), flax (Baley *et al.*, 2006), bamboo (Shih, 2007), kenaf (Shibata *et al.*, 2006), bagasse (Cao *et al.*, 2006; Vilay *et al.*, 2008), etc. have been studied as reinforcements and fillers in polymer composites.

The utilization of natural fibre has gained attention due to the reduction of waste disposal problems especially in agricultural fields, environmental pollution (Nishino *et al.*, 2006) and can find various applications in engineering, electronic and automotive fields (Goda *et al.*, 2006). Green, environmentally friendly, sustainable, renewable, biodegradable, composites from natural fibres are among the most keenly required materials nowadays (Bledzki and Gassan, 1999; Mohanty *et al.*, 2001). Natural fibre-reinforced polymers also exhibit other advantages such as adequate mechanical properties, low weight, low cost, low density, high specific properties (Manfredi *et al.,* 2006), possess better electrical resistance, good thermal and acoustic insulating properties and higher resistance to fracture (Gowda *et al.,* 1999). Furthermore, the natural fibre-reinforced composites are attractive due to the absence of health hazards during processing, application and disposal (Goda *et al.,* 2006).

The mechanical properties of short fibre-reinforced composites depend on several factors such as type of fibre, orientation and dispersion caused during processing, fibre volume fraction, type of matrix in which the fibre is dispersed and any treatment undergone before the compounding and importantly the type of technology used for consolidation (Eichhom, 2001).

## 2.4 EFFECT OF PROCESSING TEMPERATURE ON CELLULOSE COMPOSITES

Several authors have reported the effect of processing temperature on physical and mechanical properties of cellulosic based composites. It was claimed that temperatures above $170\,°C$ significantly reduced tenacity and degree of polymerization (Gassan and Bledzki, 1997). However it is well known that, when cellulose-based materials are heated in the range of 150 to $250\,°C$ some of the changes in physical properties of the fibres can be explained in terms of alterations in either physical or chemical structures such as depolymerisation, hydrolysis, oxidation, dehydration, decarboxylation (Peters, 1979) and recrystalisation. For instance, a thermal heating of cotton fibres for 6 hours at temperatures from 165 to $240\,°C$ leads to chain scission manifesting into a decrease in the degree of polymerization (DP) from 5360 to 320, determined with viscosity measurements.

## 2.5 CHEMICAL COMPOSITION OF NATURAL FIBRES

The chemical composition of natural fibres varies depending upon the type of fibres. The chemical composition as well as the structure of the plant fibres is fairly complicated (Chawla and Bastor, 1979). Plant fibres are a composite material designed by nature. The fibres are basically a rigid, crystalline cellulose microfibril-reinforced amorphous lignin and/or with hemicellulosic matrix. Most plant fibres, except for cotton, are composed of cellulose, hemicellulose, lignin, waxes, and some water-soluble compounds, where cellulose, hemicelluloses, and lignin are the major constituents (Bledzki and Gasssan, 1999). The properties of the constituents contribute to the overall properties of the fibre. Hemicellulose is responsible for the biodegradation, micro-absorption and thermal degradation of the fibre as it shows least resistance, whereas lignin is thermally stable but prone to UV degradation. The percentage compositions of each of these components vary for different fibres. Generally, the fibre contains 60-80 % cellulose, 5-20 % lignin and up to 20 % moisture. The cell wall of the fibres undergoes pyrolysis with increasing processing temperature and contributes to char formation. These charred layers help to insulate the lignocelluloses from further thermal degradation.

## 2.6 COTTON FIBRE

Cotton is a plant of the genus *Gossypium*, of which the stalks correspond to lignocellulosic materials (Kargarfard and Jahan-Latibari 2011). The cellulosic textile fibres are obtained from fibres that grow in a ball, around the seeds. To obtain yarns, the fibres are initially separated from the seeds (ginning), followed by spinning. Cotton is one of the most widely produced textile fibres for commercial use worldwide. Table 2.1 below shows the moisture content and chemical composition of cotton fibre.

Table 2.1: Chemical composition and moisture content of cotton fibre. (Saira, *et al.*, 2007)

| Fibre | Cellulose (Wt %) | Hemicelluloses (Wt %) | Lignin (Wt %) | Pectin (Wt %) | Moisture Content (Wt %) | Waxes | Microfi-brillar Angle (Deg) |
|---|---|---|---|---|---|---|---|
| Cotton | 85-90 | 5.7 | | 0-1 | 7.85-8.5 | 0.6 | -- |

Cotton has a high crystallinity index of about 87%. The crystallinity of cellulosic fibres can influence the mechanical properties of their composites (Carrillo *et al.,* 2010). The degree of crystallinity varies with the type of plant fibre; e.g. for wood fibres it is between 60 and 70 % (Siau, 1995). Moreover, physical and chemical treatments of plant fibres are known to change the degree of crystallinity (Zeronian *et al.*, 1990, Bhuiyan and Sobue, 2001).

Several works on cotton fibres and fabrics have been investigated in the time past. The tensile strength of ramie-cotton hybrid fabric-reinforced polyester composites was investigated by Junior *et al.,* (2004**).** The authors observed that tensile behaviour was dominated by volume fraction of ramie fibres aligned in the test direction. The fabric and diameter of the thread was found not to have any role in tensile characteristics. Cotton fabric was found to have minor reinforcement effect due to weak cotton/polyester interface. Similar studies were performed by Mwaikambo and Bisanda (1999) on kapok- cotton fabric-reinforced polyester composites. Parikh, *et al.*, (2002) found that nonwovens made of retted kenaf fibres blended with cotton fibres, recycled polyester, and off-quality polypropylene could meet industry specifications of flammability, odour, mildew and strength properties. Zhang (2003) studied properties of the softened kenaf fibres that were chemically extracted from the fibre bundle, and found that blending cotton into the pure kenaf yarn can increase the yarn's strength and elongation at break, and make the yarn less stiff. In her research, the yarn was also knitted into fabric and the KAWABATA system was used to test the properties of fabrics made of both pure kenaf and kenaf/cotton blends. If an efficient way of spinning kenaf fibre could be found, the cotton/kenaf blends can provide a new, profitable texture for textile and apparel industry.

The thermal diffusivity, thermal conductivity and specific heat of jute/cotton, Sisal/cotton and ramie/cotton hybrid fabric-reinforced unsaturated polyester composites were investigated by Alsina *et al.,* (2005). The thermal properties of the fabrics, i.e. without any resin, were also evaluated and were used to predict the properties of the composites from the theoretical series and parallel model equations. The effect of fabric pre-drying on the thermal properties of the composites was also evaluated. The results showed that the drying procedure used did not bring any relevant change in the properties evaluated.

## 2.7 ADVANTAGES AND DISADVANTAGES OF NATURAL FIBRES

Natural fibres, as reinforcement, have recently attracted the attention of researchers because of their advantages over other established materials. They are environmentally friendly, fully biodegradable, abundantly available, renewable and cheap and have low density. Plant fibres are light compared to glass, carbon and aramid fibres. The biodegradability of plant fibres can contribute to a healthy ecosystem while their low cost and high performance fulfils the economic interest of industry. When natural fibre-reinforced plastics are subjected, at the end of their life cycle, to combustion process or landfill, the released amount of $CO_2$ from the fibres is neutral with respect to the assimilated amount during their growth (Wambua, *et al.,* 2003). The abrasive nature of fibre is much lower which leads to advantages with respect to technical process and recycling process of the composite materials in general. Natural fibre-reinforced plastics, by using biodegradable polymers as matrices, are the most environmental friendly materials, which can decompose at the end of their life cycle. Natural fibre composites are used in place of glass mostly in non-structural applications. A number of automotive components previously made with glass fibre composites are now being manufactured using environmentally friendly composites (Dahlke, *et al.*, 1998). Although natural fibres and their composites are environmentally friendly and renewable however, they have some short comings which include: poor wettability, incompatibility with some polymeric matrices and high moisture absorption (Vazguez, *et al.*, 1999). Composite materials made with the use of unmodified plant fibres frequently exhibit unsatisfactory mechanical properties. To overcome this, in many cases, a surface treatment or compatibilizing agents need to be used prior to composite fabrication. The properties can be improved both by physical treatments (cold plasma treatment, corona treatment) and chemical treatments (maleic anhydride organosilanes, isocyanates, sodium hydroxide, permanganate and peroxide) (Luo and Netravali, 1999). Mechanical properties (Raczs and Hargitai, 2000) of natural fibres are much lower than those of glass fibres but their specific properties, especially stiffness, are comparable to the glass fibres.

## 2.8 FIBRE MODIFICATION

### 2.8.1 PHYSICAL METHODS OF MODIFICATION

#### 2.8.1.1 Cold Plasma

Surface modification by discharge treatment such as low temperature plasma, is of great interest in relation to the improvement in functional properties of vegetable fibres. Low temperature plasma treatment causes mainly chemical implantation, etching, polymerization, free radical formation, crystallization, whereas sputter etching brings about chiefly physical changes such as surface roughness and this leads to increase in adhesion and decreases light reflection (Wakida and Tokino, 1996). Low temperature plasma is a useful technique to improve the surface characteristics of the fibre and polymeric materials by utilizing the ingredients such as electron, ion, radical and excited molecules produced by electrical discharge. Low temperature plasma can be generated under atmospheric pressure in the presence of helium (Wakida and Tokino, 1996). The action of these plasmas involves abstraction of protons and creation of unstable radicals that modify functional groups such as alcohols, aldehydes, ketones and carboxylic acids. Electrical discharge methods are used for cellulose fibre modification to decrease the melt viscosity of cellulose- polyethylene composites (Dong, *et al.,* 1992) and to improve the mechanical properties of composites.

#### 2.8.1.2 Corona Treatment

Corona treatment is one of the most interesting techniques for surface oxidation activation. It changes the surface energy of the cellulosic fibres, which in turn affects the melt viscosity of composites (Belgacem, *et al.,* 1994). Mechanical and rheological properties of cellulose-PP composites subjected to corona treatment were reported by Belgacem *et al.,* (1994). Corona treatment modifies the surface composition and therefore the surface properties of the composite components.

### 2.8.2 CHEMICAL METHODS OF MODIFICATION

#### 2.8.2.1 Alkali Treatment of Natural Fibres

Alkali treatment and mercerization are two of the most frequently applied chemical treatments for the reinforcement of cellulose fibres. An important modification induced by the alkaline treatment is the disruption of hydrogen bonding in the network structure, which increases surface roughness (Klemm *et al.*, 1998). The treatment of vegetal fibres by aqueous sodium hydroxide (NaOH) promotes the ionization of the hydroxyl group to the alkoxide, as described by equation (1):

$$\text{Vegetal fibre- OH} + \text{NaOH} \longrightarrow \text{Vegetal fibre} -\text{O}^{-}\,\text{Na}^{+} + \text{H}_2\text{O} \qquad (1)$$

The alkali treatments remove a certain amount of lignin and extractives, which cover the external surface of the fibre cell wall, dissolve hemicelluloses and, to some extent, may lead to cellulose depolymerization and exposure of short length crystallites. Therefore, alkaline processing directly influences the vegetal fibre chemical composition. Mercerization of vegetal fibres involves immersion of the vegetal fibres into sodium hydroxide solutions for a given period of time. The duration of the treatment is variable, and the type of fibres, their percentage in cellulose content and the concentration of the sodium hydroxide solution used should be taken into account when establishing the duration of mercerization, to avoid irreversible fibre degradation. However, moderate or short time alkaline treatments have been reported to significantly improve the mechanical properties, impact fatigue and dynamic behaviour of fibre-reinforced composites. (Cao *et al.,* 2006) who used different concentrations of NaOH solutions for the alkaline treatment of bagasse fibres, concluded that the utilization of a 1% NaOH solution for the treatment led to the best results as to the mechanical properties of composites. The improvement was also the result of external fibrillation, which occurred during the alkaline treatment. An increased alkali concentration led to a loss of mechanical strength, due to depolymerisation. Similar results were also obtained by a large number of authors, who used different types of vegetal fibres, sodium hydroxide concentrations and polymeric matrices (Mishra *et al.*, 2003 and Jacob *et al.*, 2006).

Gassan and Bledzki (1999) reported that treating the fibre surface by 26 wt% NaOH for 20 minutes at 20°C improves the mechanical properties of unidirectional jute/epoxy composite up to 60% compared to untreated fibre composite, at a fibre content of 40 vol%. Prasad *et al.,* (1983) studied the alkali treatment of coir fibre by 5% NaOH for 72-96 hours at 28°C. An improvement of the tensile strength and Young's modulus of the fibre by 10-15% and 40%, respectively, was observed. The alkali treatment of the coir fibre improved the flexural strength of the polyester resin composites by 40%. Sydenstricker *et al.,* (2003) obtained increasing shear strength from 2.6 to 6.9 MPa in the case of fibre surface treatment by 2% NaOH for 1 hour at room temperature of sisal/polyester composites. Ray *et al.,* (2001) used a solution of 5% NaOH to treat the jute fibre for 0, 2, 4, 6 and 8 hours at 30°C. For the vinylester resin composites reinforced by 35 wt% jute fibre treated for 4 hours, an improvement of 20% for the flexural strength, of 23% for the flexural modulus and of 19% for the laminar shear strength was observed.

### 2.8.2.2 Acetylation

Acetylation of cellulose is one of the first discovered routes to obtain cellulosic derivatives. The results of the research on vegetal fibre composite production indicated an increased mechanical strength of the resulting biocomposites. Mishra *et al.,* (2003) investigated the possibilities of acetylating vegetal fibres for increasing the mechanical properties of some vegetal fibre-polyester composites, by acetylating treatment with previous mercerization.

Vegetal fibre – OH + $CH_3$ – C (=O) – O – C (=O) – $CH_3$ $\longrightarrow$ Fibre – $OCOCH_3$ + $CH_3COOH$

The fibres are usually immersed in glacial acetic acid for 1 hour, then immersed in a mixture of acetic anhydride and few drops of concentrated sulphuric acid for a few minutes, then filtered, washed and dried in ventilated oven. This is an esterification method which should stabilize the cell walls, especially in terms of humidity absorption and consequent dimensional variation.

### 2.8.2.3 Benzoylation

Benzoylation is another important transformation in organic synthesis and vegetal fibre treatment (Paul, 2003). Benzoyl chloride is most often used in fibre treatment. Benzoyl chloride includes benzoyl ($C_6H_5C=O$), which is responsible for the reduced hydrophilic nature of the treated fibre and improved interaction with the hydrophobic polymeric matrix. Benzoylation has also been found to contribute to the increase of the mechanical properties of vegetal fibre-polymer composites. The increase in mechanical strength (tensile and flexural properties) has been reported for vegetal fibre-reinforced composites with polystyrene matrix, (Paul, 2003) polyester resins, (Joshy *et al.,* 2006) high-density polyethylene (HDPE) and low-density polyethylene (LDPE), either individually or in mixture (Wang, 2007).

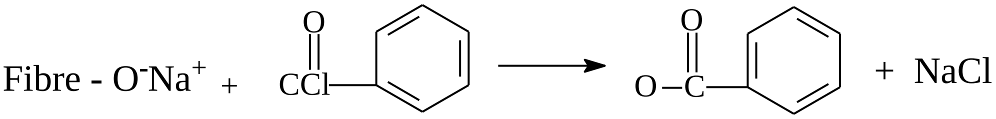


Figure 2.3: Reaction of alkaline-treated fibre with benzoyl chloride

The fibres were immersed in 10% NaOH and then stirred with benzoyl chloride for 1 hour, filtered, washed and dried, then immersed in ethanol for 1 hour, rinsed and dried in oven. This method decreased the hydrophilicity of the fibres.

#### 2.8.2.4 Anhydride Treatment

It is usually carried out by utilizing maleic anhydride or maleated polypropylene (or polyethylene) in a toluene or xylene solution, where the fibres are immersed for impregnation and reaction with the hydroxyl groups on the fibre surface. Literature reports significant reduction of water absorption.

***Maleic anhydride*** (*cis*-butenedioic anhydride, toxilic anhydride, dihydro-2, 5-dioxofuran), an organic compound with the formula $C_4H_2O_3$, is, in its pure state, a colourless or white solid with acrid odour. Maleic anhydride might be used as an esterification reagent for the free hydroxyl groups present on the surface of the vegetal fibres. Maleic anhydride easily hydrolyses to maleic acid, which is also used as a treatment agent. The main purpose of using maleic anhydride is to assure chemical bonding between the fibre and the polymeric matrix.

To this end, maleic acid or maleic anhydride is first reacted with the polymeric matrix, to be chemically linked to it. In a secondary stage of the process, the modified polymeric matrix is reacted with the cellulose contained in the fibre, by formation of ester linkages with the free hydroxyl groups. Positive results on the chemical bonding of polymer matrix to vegetal fibres by maleic acid or anhydride treatment were obtained by Elsabbagh et a*l*., (2009) in the effort of manufacturing flax/polypropylene composites. Other results confirmed the possibility of increasing interfacial energy in the vegetal fibres-polymeric (other than polypropylene) composites; the mechanical properties, as well as their hydrophobic characteristics were also improved (Bessadok *et al.,* 2007).

### 2.8.2.5 Silane Treatment:

Using silane coupling agents was found to be effective in modifying the natural fibre-matrix interface (Culler *et* al., 1986, Ghatge and Khisti 1989 and George *et al.,* 1998). Gassan and Bledzki (1997) investigated the influence of silane coupling agent on the performance of jute-epoxy composite. A treatment of jute fibre by epoxy functional-γ-lycidoxypropyltrimethoxy-silane (A-187 from Osi-Specialtis GmbH, Germany) solution in alcoholic with the concentration of 2% for 24 hours at 23°C was found to increase by approximately 30% of the static characteristic values of the composites compared to unmodified composites at standard humidity. Yan and Lin, (2005) showed the influence of fibre surface treatment on the performance of the sisal textile reinforced vinylester composites. Sisal fibre was treated with 3-aminopropyltriethoxy silane and γ-methacryloxypropyl trimethoxy silane solution in acetone with a concentration of 6% for 24 hours. Only marginal improvement of 3% and 14% of the tensile strength and tensile modulus of the composites, respectively, was obtained in the case of fibre surface treatment. The flexural strength and modulus of the silaned fibre composites increased by 15% and 30% respectively compared to untreated composites. However, the fibre surface treatment by silane did not affect the impact energy. Mäder and Gliesche (1995) investigated epoxy composites and found out that there was a reduction in the flexural strength and an increase by about 20% in flexural modulus of the flax composites, if an aqueous γ-aminopropyltriethoxy silane solution of 3% was used for treating the fibre surface at 80°C. That did not result, however, to any remarkable increase in flexural strength but resulted to an increase by about 20% for the flexural modulus of the ramie composites.

The fibres were immersed in a 3:2 alcohol– water solution, containing a silane-based adhesion promoter for 2 hour at pH ≈ 4, rinsed in water and oven dried. Silanes should react with the hydroxyl groups of the fibres and improve their surface quality.

#### 2.8.2.6 Isocyanate Treatment

Isocyanates, especially poly[methylene poly(phenyl isocyanate)] (PMPPIC), are known in wood chemistry as wood binders with successful application in particleboard in Europe. Extensive experimental work on the application of isocyanate as coupling agents for different types of cellulose materials and polymers has been carried out (Koma *et al.*, 1990). Composites were manufactured with cellulosic material, which was either pre-coated with an isocyanate polymer mixture, or the isocyanate was added directly into the mixture of fibre and polymer. George *et al.,* (1998) reported on the mechanical properties of isocyanate treated fibre-reinforced thermoplastics composites. The polymethylene (polypheny1 isocyanate) (PMPPIC) treatment has significant influence on the properties of composites, i.e., increased thermal stability, reduced water absorption etc (Joseph and Thomas, 1995 and George *et al.,* 1998). PMPPIC is chemically linked to the cellulose matrix through strong covalent bonds. The -N = C = O group of PMPPIC is highly reactive with the -OH group of cellulose.

### 2.8.2.7 Graft Copolymerization

Graft polymerization is the process of obtaining a polymer containing molecules whose main backbone chain of atoms has, at various points, side chains attached to it, containing atoms or groups different from those in the main chain. The main chain may be a copolymer or it may be derived from a single monomer. Acrylic acid, acrylonitrile or styrene might be used for graft polymerization of cellulosic vegetal fibres. Acrylic acid treatment might be performed in non-polar solvents, in the presence of benzoyl peroxide (Le Digabel *et al.,* 2004 and Bessadok *et al.*, 2007)**.** Li, (2008), improved tensile strength and lowered the water absorption capacity of flax fibre-HDPE composites after acrylic acid treatment of the above mentioned vegetal fibres. Acrylonitrile is also a good candidate for graft polymerization (eq. 3) onto the surface of the vegetal fibre:

$$\text{Vegetal fibre} - OH + CH_2 = CHCN \longrightarrow \text{Vegetal fibre} - OCH_2CH_2CN \qquad (3)$$

Grafting is an effective method for the modification of natural fibres. Grafting on the cellulose fibre may take place before or during compounding. In the former case, pre-treatment of fibres by compatibilizing agents generally occurs in solution. The excess of (unreacted) compatibilizing agent is eliminated by washing. In the latter case, treatment during compounding occurs at the mixing temperature of the matrix. Grafting efficiency, grafting proportion and grafting frequency determine the degree of compatibility of cellulose fibres with a polymer matrix. The grafting parameters are influenced by the type and concentration of initiator, the monomer to be grafted and the reaction conditions.

## 2.9 FIBRE/YARN ARCHITECTURE

### 2.9.1 Fibre Configuration or Architecture

The fibre configuration or architecture (short, long, straight, woven, braided, knitted laminated etc.) and the fibre surface treatment for the desired interface characteristics determine the final properties and the composite durability. The properties of polymer matrix composite (PMC) are strongly dependent on the factors such as the matrix and fibre material and their volume fractions, the fibre orientation, the applied stress levels and strain rates as well as the loading conditions and the nature of the fibre polymer interface.

The orientation of fibres can be in three directions:

1. **Parallel-laying of fibres**: In the parallel-laid webs, the fibres are laid in a lengthwise orientation. This implies that this type of web has greater strength in the lengthwise direction than the traverse direction. According to the demand of mass and fibre type, the parallel-laid web permits the repetition of fibrous webs.
2. **Cross-laying of fibres:** The fibres are laid in both the longitudinal and transverse orientation.
3. **Random-laying of fibres:** This is laying the fibres in disordered manner in various directions.

The study on various randomly oriented natural fibres like coir, bamboo, jute, palm, sisal, coir, and banana has been reported (Schaffer and Prakash, 2009). One of the main barriers to overcome is control of fibre orientation (i.e. alignment of the fibres), to ensure that the fibre mechanical properties are most efficiently utilized, and that the maximum obtainable fibre content is high.

The previously reported tensile properties of aligned plant fibre composites are mostly based on tests in the axial direction (i.e. the fibre direction). These tests are appropriate in order to analyze fibre properties in relation to composite properties. However, to characterize properties of the composite material as a whole requires tests in off-axis directions as well. In a larger perspective, if aligned plant fibre composites are to be used for structural applications, off-axis properties are fundamental to predict the response to loads in any given direction (e.g. by laminate theory) (Hull and Clyne, 1996). In open literature, only three studies of aligned plant fibre composites have been found that include off-axis properties: (i) a study of jute/polyester composites tested in the directions 0, 45 and 90° (Kumar, 1986), (ii) a study of flax/epoxy composites tested in the directions 0 and 90° (Van de Weyenberg *et al.*, 2006), and (iii) a study of jute/epoxy composites tested in the direction 0, 10, 17, 25, 37, 50, 63 and 80° (Cichocki and Thomason, 2002). In the latter study, composite stiffness was measured by dynamic mechanical analysis, and micro-mechanical models were applied to determine the elastic constants of both composites and fibres.

In the textile industry, a wide range of techniques for the alignment of plant fibres have long been developed and optimised to produce yarns with highly controlled fibre orientations (Klein, 1998). Previously, much research has been undertaken with the same objective, but based on plant fibre composites with a random fibre orientation (Robson *et al.*, 1993, Mohanty *et al.*, 2001, Eichhom, 2001, Bledzki *et al.*, 2002). However, if the fibres are aligned, the interfering effect of a non-uniform fibre orientation distribution is excluded, and this makes it less complicated to analyse fibre properties in relation to composite properties. Thus, an aligned fibre orientation is beneficial to point out the critical parameters in plant fibre composites in general. Furthermore, the properties of aligned plant fibre composites must be considered to form the necessary foundation, if the properties of composites with a more complex fibre orientation distribution are to be satisfactorily predicted.

Because of the short and random organization of the fibres, the resulting composites exhibit relatively poor mechanical properties and are not suitable for use in more structural components. Hence, research in recent years has been looking into the potential of aligned natural fibre composites (Goutianos & Peijs, 2003; Goutianos, *et al.*, 2006). Madsen and Lilholt (2003) prepared unidirectional flax/polypropylene composites with a fibre volume fraction ranging from 41% to 55% and reported axial stiffness values in excess of 27 GPa and axial strengths in the range of 250-320 MPa. Also, Madsen (2004) presented in his experimental investigations the properties of aligned plant fibre composites based on textile hemp yarn and thermoplastic matrices.

## 2.10 TEXTILE COMPOSITES

Textile composites for engineering structures draw on many traditional textile forms and processes. These textiles are generally those that most effectively translate stiff, strong yarns into stiff, strong composites. A textile composite has internal structure on several scales. At the molecular scale, both the polymer matrix and the fibres exhibit structural details that profoundly affect strength and stiffness. Matrix properties are determined by chain morphology and cross-linking, among other things.

Textile composites are being widely used in advanced structures in aerospace, automobile and marine industries. This is because they have favourable mechanical properties

(Vandeurzen *et al.,* 1995) and attractive reinforcing materials with low fabrication cost and easy handling (Ishikawa and Chou, 1983; Smith and Swanson, 1995). Characterization of textile composites becomes very important to structural design. However, since the material properties are anisotropic and inhomogeneous in nature, parameters controlling mechanical properties are numerous, such as fibre architecture, fibre properties, matrix properties, etc (Naik and Ganesh, 1992).

## 2.11 TYPICAL TEXTILE COMPOSITES

Textile composites are produced by impregnating matrix materials into dry preforms to hold the multidirectional yarns together. This is generally done by using liquid moulding techniques such as: resin transfer moulding process (RTM), structural reaction injection moulding (SRIM), resin film infusion (RFI), hand lay-up technique, etc.

In general, classification of textile composites should reflect the macro geometry (e.g., shape and dimension), method of fabric formation/construction, and the resulting structural micro geometry. The micro geometry should include directions of reinforcement, linearity of reinforcement in each direction, continuity of reinforcement, fibre packing density, fibre bundle size in each direction and the geometrical feature of the fibre bundles (or yarns), etc. Fibre-reinforced polymer composites made by the textile processes of weaving, braiding, stitching and knitting were found to have tremendous potential for improving the performance of composite structures and reducing their cost of manufacture. The current applications of three-dimensional composites, including examples in the aerospace, maritime, automotive, civil infrastructure and biomedical fields are also enumerated.

### 2.11.1 Woven Fabrics

Woven fabrics are probably by far the most commonly used form of textile composites in structural applications (Laroche *et al.,* 1994). They are produced principally by the multiple warps weaving method, and generally consist of two sets of interlaced yarn components, known as warp and weft yarns according to the yarn orientation (Miller, 1973 and Naik *et al.,* 1991). Warp yarns run vertically or lengthwise in woven fabrics, while weft yarns run horizontally or crosswise. Each yarn is a bundle of filaments (or fibres) and its size is measured by the number of filaments in the yarn (Naik, 1995).

Nowadays there are various technologies suitable to create textiles, which all of them go by the name of fabrics (Giovanni *et al.,* 2000). Most fabrics are two-dimensional but an increasing number of three-dimensional textile structures are being developed and produced.

Three-dimensional (3D) woven fabrics have additional yarns placed in through-the-thickness direction (Kuo, 1995), and can be generally classified into three types, namely, 3-d, 3-x and interlock (Brandt *et al.,* 1990). They have higher delamination resistance and damage tolerance than 2D woven laminates (Cox *et al.,* 1992, 1994 and 1996). 3D woven fabrics can be produced by using either conventional looms with multilayer constructions or entirely new equipment (Du and Chou, 1991). The interlacing pattern of the warp and weft yarns is known as weave (Naik and Ganesh, 1992). To impregnate 3D orthogonal woven fabrics, a vacuum injection process has been found to be the best method for thermoset matrix systems, and a hybrid yarn technique, where the reinforcing fibres are woven together with thermoplastic fibres, has been promising for the thermoplastic matrix system (Brandt *et al.,* 1990).

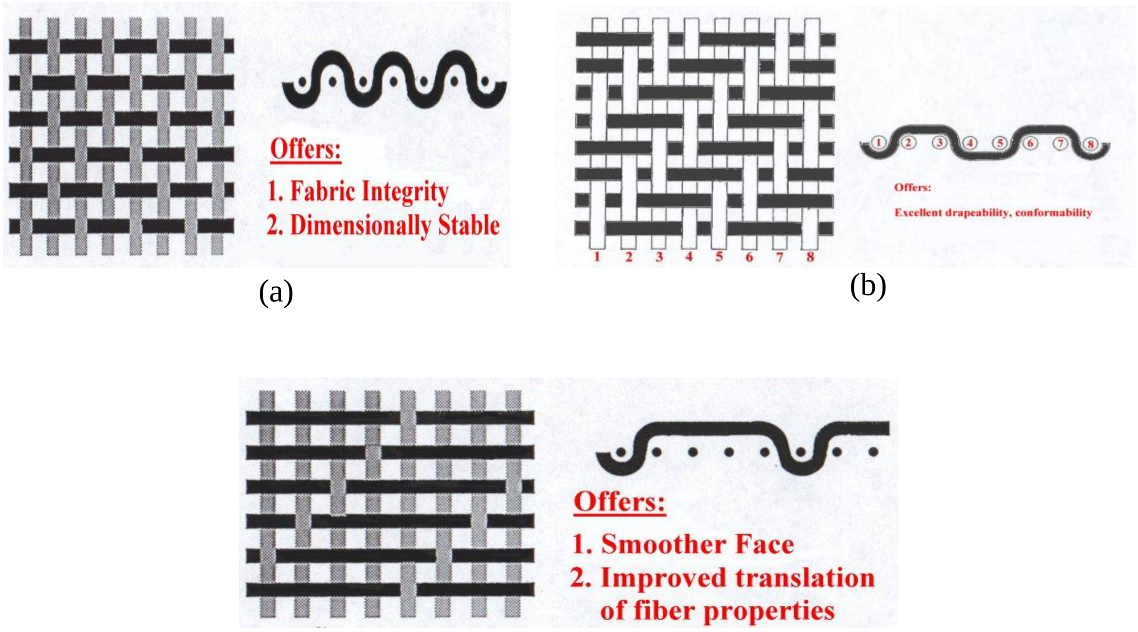
The properties of fabrics depend on the characteristics of the constituent yarns or fibres and on the geometry of the formed structure (Ormerod and Sondhelm, 1999).

Woven fabrics are attractive as reinforcements since they provide excellent integrity and conformability for advanced structural applications. The driving force for the increased use of woven fabrics compared to their non-woven counterparts are excellent drapeability, reduced manufacturing costs and better mechanical properties, especially the interlaminar or interfacial strength.

There are several geometries/architectures for woven composites. Various types of architecture can be formed depending on how the pattern in the interlaced regions is repeated. Woven fabrics contain fibres oriented along at least two axes and provide great strength and stiffness along those axes (Alavudeen *et al.*, 2011).

Currently, most of the pure and hybrid woven fabrics used in textile composites are simple 2D fundamental weaves, i.e., plain, twill and satin weaves, which are identified by the repeating patterns of the interlaced regions in warp and weft directions (Ishikawa and Chou, 1983, Zhang and Harding, 1990).

Plain weave is the most commonly used basic reinforcement for woven composites. In a plain weaving structure, one warp yarn is repetitively woven over and under weft yarns. Twill weave has a looser interlacing and the weave is characterized by a diagonal line. In a twill weaving structure, each warp yarn floats over two consecutive weft yarns, and under the following one weft yarn. The satin weave is characterized by four or more cool fill or weft yarns floating over a warp yarn or vice versa, four warp yarns floating over a single weft yarn. This explains the even sheen, as unlike in other weaves, the light reflecting is not scattered as much by the fibres, which have fewer tucks. Satin weave has a good drapability, with a smooth surface and minimum thickness.



(a) (b)

(c)

Figure 2.4: plain (a), twill (b) and satin (c) weaves

Woven fabrics can be classified into opened-packing weaves or closed-packing weaves. In an opened-packing weave there are gaps between two adjacent yarns, whereas in a closed-packing weave fabrics are tightly woven leaving no gap between any two adjacent yarns (Naik and Ganesh, 1992). In addition, woven fabrics can also be classified as balanced and unbalanced weaves (Cox *et al.*, 1994). A balanced one has the same properties and geometric dimensions in both the warp and weft directions, while the unbalanced one has different properties and/or different geometric dimensions.

Generally speaking, mechanical properties of woven fabrics are governed by: (1) weave parameters such as weave architecture, yarn size, yarn spacing (i.e. picks/cm and ends/cm), fibre orientation angle, fibre volume fraction; (2) laminate parameters such as stacking orientation and overall fibre volume fraction (Naik and Ganesh, 1992, Naik, 1995, Shembekar and Naik, 1992, Cox and Dadkhah, 1995, Xu *et al.*, 1995, Pochiraju *et al.*, 1994).

Goutianos *et al*., (2006) recently reported the development of high-performance natural fibre composite systems for structural applications using continuous flax fibres textile reinforcements like unidirectional tapes or woven fabrics in various thermosets. Different types of fabrics (i.e., biaxial plain weaves, unidirectional fabrics and non-crimp fabrics) were produced and evaluated as reinforcement in composites manufactured by well established manufacturing techniques such as hand lay-up, vacuum infusion, pultrusion and resin transfer moulding (RTM). The effect of yarn and textile processing were investigated and they discovered that an optimum twist yarn should be used to balance processability and mechanical properties of the resulting composites.

The mechanical properties and fracture surface morphology of woven date palm fibre (DPF) reinforced polyester resin composites were investigated by Wazzan (2005). Laminates with different orientation and volume fraction of reinforcement were prepared using resin transfer moulding (RTM) processing technique. The woven DPF reinforced composites recorded a tensile strength of 76.9 MPa. The tensile properties of jute fabric-reinforced polyester composites was analysed by Gowda *et al.,* (1999). They observed that there was increase of tensile strength and flexural properties upon reinforcement with jute fabric. The hardness of the composites was found to decrease due to the enormous differences in hardness of jute fabric and polyester resin. The impact properties were also found to improve considerably.

Pothan et al., (2002) conducted tensile and impact studies of woven sisal fabric-reinforced polyester composites prepared by RTM technique. It was found that the weave architecture was a crucial factor in determining the response of the composites. Researchers have studied the micromechanics of moisture diffusion in woven composites (Tang *et al.,* 2005). The weave pattern of the fabric was found to have a profound effect on the water uptake of the composites. They observed that woven composites exhibited quicker diffusion than that of a unidirectional laminate with the same overall fibre volume fraction. The plain weave with a lenticular tow and large waviness was seen to exhibit the quickest diffusion process.

Novolac type phenolic composites reinforced with jute/cotton hybrid woven fabrics were fabricated and its properties were investigated as a function of fibre orientation and roving/fabric characteristics (De Medeiros *et al.,* 2005). Results showed that the composite properties were strongly influenced by test direction and roving/fabric characteristics.

### 2.11.2 Braided Fabrics

Braided fabrics are the most commonly used fabric reinforcement in textile composites used for aircraft applications. They are produced at a lower cost and provide higher impact resistant/tolerant materials.

Braiding was the first textile process used to manufacture a 3D fibre preform for a composite. This process was developed in the late 1960s to produce 3D carbon–carbon composites to replace high temperature metal alloys in rocket motor components in order to achieve weight savings of 30–50% (Stover *et al.,* 1971). While only a few of these rocket motor components were made then, it did demonstrate the ability of braiding to produce a light-weight composite component with an intricate shape. Currently, different secondary and primary aircraft components are made of braided carbon reinforced epoxy composite materials. These fabrics are constructed by intertwining or orthogonally interlacing two (or more) sets of yarns to form an integral structure. One set of yarns is called axial yarns while the other is known as braided yarn (Du and Ko, 1993, and Byun and Chou, 1996). Hence, the structure of braided fabrics consists of parallel axial yarns, interconnected with braided yarns that are placed along complex spatial orientations (Du and Chou, 1991). The common fabrication methods for creating braided fabrics are traditional horn-gear method, solid braiding method, two-step braiding method, four-step braiding method and track and - column braiding method. These methods differ only in the way that the yarn carriers are moved. (Li and Shiekh, 1988, Du and Chou, 1991, Du and Ko, 1993).

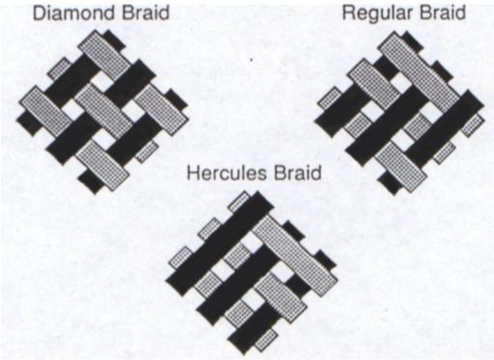


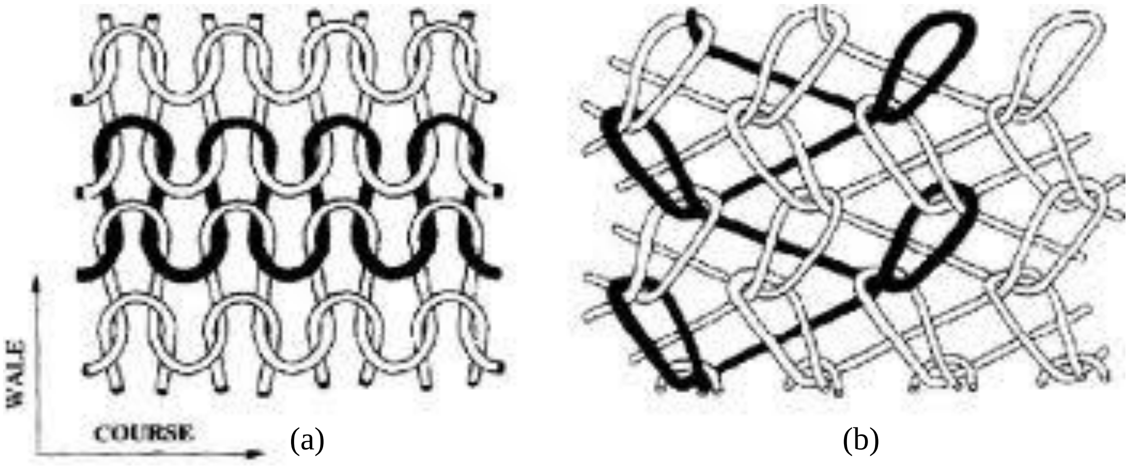
Figure 2.5: Different types of braided fabrics

The major parameters affecting the mechanical properties of braided fabrics include: (1) braid parameters such as braid architecture, yarn sizes, yarn spacing length, fibre volume fraction, fibre orientation angle; and (2) material parameters such as mechanical properties of the fibre and matrix (Naik, 1995, Du and Ko, 1993). The major process parameters adjustable to control the microstructure of braids are speed ratio between braiding and taking up, linear density ratio of braider and axial yarn. Crane and Camponeschi (1986) and Macander *et al.,* (1986) found that the tensile and compressive properties of 3D braided composites are low because most braided axial tows are off-axis from the loading direction and are heavily crimped. They have also shown that the Young's modulus and strength of the 3D braided composites are sensitive to factors such as braid angle, braid pattern and tow size. Flax braided fabrics prepared by vacuum assisted direct resin injection moulding method have been used as reinforcement and the composites were prepared with epoxy resin as a matrix. The flexural strength and flexural modulus of the prepared composites were tested by immersing the specimen in water and sulphuric acid (Vignesh *et al.,* 2011). The mechanical properties of three dimensionally braided carbon fibre epoxy composites were investigated by Wan *et al.,* (2002). The authors observed that flexural strength and modulus were found to be dependent on the braiding angle and are related to the presence of axial reinforcement but the shear and impact strengths were found to be independent of axial reinforcing fibres.

### 2.11.3 Knitted Fabrics

Knitted fabrics are characterized by their interlocking loops of yarns (Figure 2.6). Generally knitted fabrics can be divided into 2 types, i.e., the weft-knitted and warp-knitted fabric composites. In the weft-knitted fabric, yarns run across the width of the fabric, and loops are formed by a single weft yarn. A row of loops in the longitudinal direction is called 'wale' or 'warp', and that in the width direction is named as 'course' or 'weft' (see

Figure 2.6a). In the warp-knitted fabrics, the yarns loop in a vertical direction; the fabric is held together by interlocking vertical loops on alternate sides. The machine used is more complicated and therefore more expensive to produce.



(a) (b)

Figure 2.6: Weft knitted fabric (a) and warp knitted fabric (b)

The major parameters affecting the mechanical properties of knitted fabrics are knit architecture, mechanical properties of yarns in wale and course directions, matrix (or resin) properties. Fibre volume fraction and yarn orientation angle (Wu et al, 1993, Fujita *et al.*, 1995, Ruan and Chou, 1996).

Compared to other conventional textile fabrics, knitted fabrics possess high productivity and low cost. In addition, knitted fabrics have high extensibility which means good formability to fit in complicated shapes (Wu *et al.*, 1993, Ruan and Chou, 1996, Wang and Laird, 1994, and Chou and Wu, 1992). Hence, they are quite suitable for deep draw moulded composites.

Kaw (1997) used knitted fabric-reinforced composite to study the tensile properties. In the first, he focused about plain weft-knit glass fibre with epoxy as a matrix for the composite. He calculated the tensile properties in the course and wale directions, and then he used laminated plate and cross-over model to calculate the elastic property. Adine *et al.,* (2007) compared the durability of cotton warp knitted terry cloth with a nylon ground structure and cotton warp knitted terry cloth with a polyester ground structure after exposure to industrial laundering procedures to determine how important it is that industrial launderers and consumers should be made aware of the presence of small quantities of synthetic fibres in the construction of a fabric.

Compared to woven fabric composites, knitted fabric composite exhibited a better resistance to impact (Ruan and Chou, 1996). Knitted fabrics are not often used as reinforcement in composites unlike the woven and braided fabrics. This is because knitted fabric composites have lower in-plane mechanical properties than the conventional composites due to the low fibre volume fraction and the loop configuration of fibres. (Wu *et al.,* 1993, Fujita *et al.,* 1995).

## 2.12 MECHANICAL PROPERTIES OF TEXTILE COMPOSITES BASED ON NATURAL FIBRES

Developments in textile technologies such as weaving, knitting and braiding have resulted in the formation of textile composites that have superior mechanical properties. Pothan *et al.,* (2002) conducted tensile and impact studies of woven sisal fabric-reinforced polyester composites prepared by RTM technique (Pothan *et al.,* 2002). Three different weaving patterns, i.e., plain, twill and matt woven fabrics were made by keeping sisal fibre yarns in both the warp and weft direction. It was found that weaving pattern was a crucial factor in determining the response of the composites. Both tensile and impact properties are found to be the maximum for composites made with twill woven fabric in the study where fibre bundles were used in the weft direction unlike in the other two cases where fibre yarns have been used.

Jacob et al., (2006) studied the effects of different fibre surface treatments on the mechanical properties of sisal fabric-reinforced natural rubber composites. Sisal fabric was subjected to various chemical modifications like mercerization, silanation and heat treatments. A complete study of the mechanical properties which includes tensile strength, compressive strength, flexural strength, impact strength, in-plane shear strength, inter-laminar shear strength and hardness of jute woven fabric-reinforced polyester composites was conducted by Gowda *et al.*, (1999). In the research, a type of woven fabric having a count of 20 x 12 (for yarns of 245–302 tex) was used. 20 x 12 indicates 20 larger yarns in the warp direction and 12 smaller yarns in the weft direction per inch are used. The composites were made by hand lay-up and the fibre volume fraction was around 45%.

Although the mechanical properties of jute woven fabric-reinforced polyester composites do not possess strengths and moduli as high as those of conventional composites, they do have better strengths than wood composites and some plastics materials. Ballistic properties of natural fabric-reinforced composites were reported by Wambua, *et. al.*, (2007). The composites they studied were flax, hemp and jute fabrics reinforced polypropylene (PP) composites and the composites were made by compression moulding under heat.

# CHAPTER THREE

## 3.0 MATERIALS AND METHOD

### 3.1 Experimental

The materials, equipment and experimental procedures are presented below. The standards listed below were used for the mechanical property studies of the fabrics and fabricated composite samples:

ASTM - D790-08 - Bending (flexural) Strength test
ASTM - D638-06 - Tensile Strength test for Composites
NIS - 79: - Tensile Strength test for fabric Samples
ASTM – E23 - Impact Strength of Composites
ASTM – D785-08 - Rockwell Hardness of Composites

## 3.2 MATERIALS

### 3.2.1 Chemicals and Reagents

The chemicals used are of analytical grade and are as follows:

- Unsaturated polyester resin supplied by NYCIL NIG. LTD, Ikeja Lagos
- Methyl Ethyl Ketone Peroxide (MEKP)
- Cobalt Naphthalene (Accelerator)
- Sodium hydroxide pellets.
- Acetic acid
- Distilled water.

### 3.2.2 Materials

The 100% Cotton yarns of 236 Tex (4ply) used for this study was supplied by Zaria Industries Limited. The plying of the yarns was also carried at Zaria Industries Limited using Kaji Twisting machine (model No. 9290-10). Others include:

- Litmus paper
- Aluminium foil of 45cm X 08 m dimension

### 3.2.3 Equipment

- Universal Testing Machine (model 4204).
- Weaving Machine (AD-A-HARNESS floor loom (model B4 D))
- Instron Tensile Tester (model 1025)
- Digital Weighing Balance
- Charpy Impact Testing Machine (model SI-1C3)
- Indentec: Universal Hardness Testing Machine (Type 8187.5 LKV, Model B)
- Basic laboratory glasswares such as conical flasks, Beakers, Stirring rod, measuring cylinder, drop bottles,
- Flat bed weft knitting machine (model GS JX-1-52)

## 3.3 METHODS

### 3.3.1 Fabric production

The weaving of both plain and twill fabric patterns were carried out at the Department of Industrial Design, Ahmadu Bello University using the AD-A-HARNESS floor loom (model B4 D). The knitted fabrics were produced on flatbed weft knitting machine from commercial source using the adequate tension that corresponds to the required density of the woven fabrics. Weft knitted structure was used for the purpose of this work because the weft-knitted structures are preferred in developmental work owing to their superior formability (based on their less stable structure) and warp knitted structures are preferred for large scale production (owing to the increased production rate allowed by the knitting of many yarns at one time) (Leong *et al.*, 1997)

### 3.3.2 Fabric Surface-Treatment:

The knitted and woven (plain and twill) cotton fabrics all of the same count of yarn were surface-treated with solutions of NaOH at a concentration of 20%, for 1 and 2 minutes at room temperature ($26\pm2^{o}C$) followed by neutralization with 1% Acetic acid, washing and soaping in distilled water till neutral to litmus paper and then dried. The treatment was carried out without tension. This was compared with untreated knitted and woven fabrics.

### 3.3.3 Tensile properties of the yarn and fabrics:

Tensile tests were carried out on the yarn, fabric samples (plain, twill and knitted) for both the treated and untreated cotton fabric samples prior to composite fabrication using Instron Tensile Tester, model 1025 (plate I) and in accordance with the NIS: 79 standard. The tests on the fabric samples were carried out in the machine direction. At the end of the tests, numerical and graphical plots of the data were obtained through the computer inter-faced with the instrument. This analysis was carried out at the Textile and Leather Laboratory of Standard Organization of Nigeria located in Kaduna at 27 °C and relative humidity of 60%.

Plate I: Instron Tensile Tester

### 3.3.4 Mould fabrication

Glass moulds were designed and constructed in accordance with different specifications for testing materials as shown in plate II below. The woven fabrics were cut based on the mould sizes.

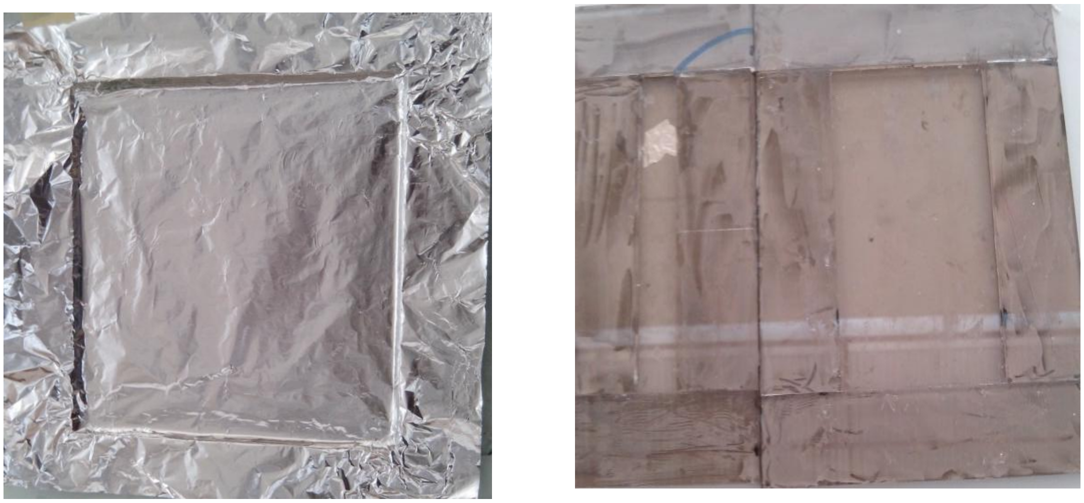


Plate II: Glass mould for various Mechanical properties test specimens

### 3.3.5 Preparation of Composites

The unsaturated polyester resin was mixed with the MEKP catalyst and naphthalene cobalt accelerator in the ratio 100:1:1. The composites were reinforced with predetermined weight of knitted and woven fabrics from cotton for both the sodium hydroxide treated and untreated samples using hand-lay-up technique. The fibre volume fraction for the composites reinforced with single layer of plain, twill and knitted fabrics are 0.38, 0.40 and 0.40 respectively while the composites with double layers of fabrics have fibre volume fraction of 0.79 each. Hand-lay-up technique provided high quality composite sample plates with minimal defects. Composites were obtained by impregnating the knitted and woven fabrics (plain and 1/3 twill) with the polyester matrix at room temperature of 30 °C in a mould. A layer of the unsaturated polyester was laid first on the mould, the fabric was placed over the resin. The remaining polyester was then poured into the mould until the required thickness was achieved. The curing time was between 3-4 minutes because of the presence of cobalt accelerator. Samples of the cured composites blocks are shown in plate III:

### 3.3.4.1 Determination of fibre volume fraction ($V_f$)

Volume fraction is the percent of fibre contained within a given volume (usually the composite in question). In the fibre reinforced material the fibres are distributed throughout the matrix in a pattern we could describe as somewhat repeating or periodic.

This fraction is an important parameter in composite materials and is called fibre volume fraction and it is a number between 0 and 1 (Hyer, 1998).

The fibre volume fraction was calculated using the equation shown below:

$$V_F = \frac{\frac{w_f}{\rho_f}}{\frac{w_f}{\rho_f} + \frac{w_m}{\rho_m}}$$

Where:

$V_f$ = Fibre volume fraction

$W_f$ = weight of fibre

$W_m$ = weight of matrix

$\rho_f$ = Density of fibre

$\rho_f$ = Density of matrix

Plate III: Some prepared Composite blocks

To create the laminated samples, a layer of unsaturated polyester resin was applied before each layer of woven natural cotton fabric was placed. Special care was taken to ensure that the correct amount of unsaturated polyester was used in addition to being evenly spread out.

The composites reinforced with knitted, plain and twill single fabrics were designated as $C_{Knitted\text{-}Single}$, $C_{Plain\text{-}Single}$, $C_{Twill\text{-}Single}$ respectively. The different fabric samples were used to form 2-Ply laminate configuration of composites interchangeably such as: Plain-Plain, Twill-Twill, Knitted-Knitted, Plain-twill, etc to be denoted by: $C_{Plain\text{-}Plain}$, $C_{Twill\text{-}Twill}$, $C_{Knitted\text{-}Knitted}$, $C_{Plain\text{-}Twill}$, etc respectively, based on the experimental design.

### 3.3.6 Cutting of composite samples

The prepared composite samples were then cut into different shapes in accordance with standard specifications for various ASTM tests using motorized jigsaws shown in plate IV

Plate IV: Motorized jigsaw

## 3.4 TESTING AND CHARACTERIZATION

### 3.4.1 Tensile and Flexural Testing of composites

Tensile tests and 3-point flexural tests were conducted with a Universal testing machine (model 4204). Tensile tests were performed at a strain rate of 10mm per min and gauge length of 150mm according to ASTM D638-06. A flexure load involves the ability of the material to bend. Flexural loads combine together tensile, compression and shear loads. The upper surface of the composite laminate is put into compression, the central portion experiences shear, and the lower portion experiences tension. Flexural testing was also carried out in accordance with ASTM D-790-08, at a crosshead speed of 5mm/min and a span length of 60 mm. A three-point loading system was employed to determine the flexural strength of the various composites fabricated. The dimensions of the specimens in each case were 150mm x 20mm x 6mm. The tensile strength-at-break was calculated from the equation below:

Tensile strength = $\frac{Breaking\ force\ (N)}{Original\ Crossectional\ Area\ (m^2)}$

The flexural strength (F.S.) and flexural modulus of the composite specimens were determined using the following equations.

Flexural Strength = $\frac{3PL}{2bt^2}$

Flexural Modulus = $\frac{PL^3}{4bt^3w}$

Where, $L$ is the span length of the sample. P is the load applied; b and t are the width and thickness of the specimen respectively, w is the deflection.

Plate V: Universal Testing Machine

### 3.4.2 Impact Strength Testing

At least five replicate specimens were tested and the results were presented as an average of tested specimens. The test was performed in accordance to (ASTM-E23). Composites with different textile reinforcements were subjected to low velocity impact (25Joules) tested in house on instrumented impact tester (Charpy) with semi-spherical impactor. The machine consists of a suspended pendulum with a mass of 25.4 kg dropped at a velocity of 3.46 m/s as shown in plate VI.

Plate VI: Charpy impact testing machine

### 3.4.3 Rockwell Hardness Test

Hardness is the resistance of a material to deformations, indentations or scratching. For the purpose of this study, Indentec Hardness Test was performed to measure the hardness of the composite samples using Indentec of Type 8187.5 LKV Model B with 1/16″ Steel ball indenter and a major load of 60kg (plate VII). The method was based on the rate of penetration of a specified indenter forced into the material, under specified conditions. The sample was placed on flat surface. The pressure foot of the instrument was pressed on the specimen, making sure it was parallel to the surface of the specimen. According to ASTM D 785-08 standard for composites, the specimens were prepared for Rockwell-B hardness test. The specimen size was 25mm diameter and a length of 25mm. Each sample was subjected to 3 hardness readings at different positions on the sample bases. The average value for each sample was recorded. The results obtained are shown in Figures 4.16 and Figure 4.17

Plate VII: Indentec: Universal Hardness Testing Machine.

# CHAPTER FOUR

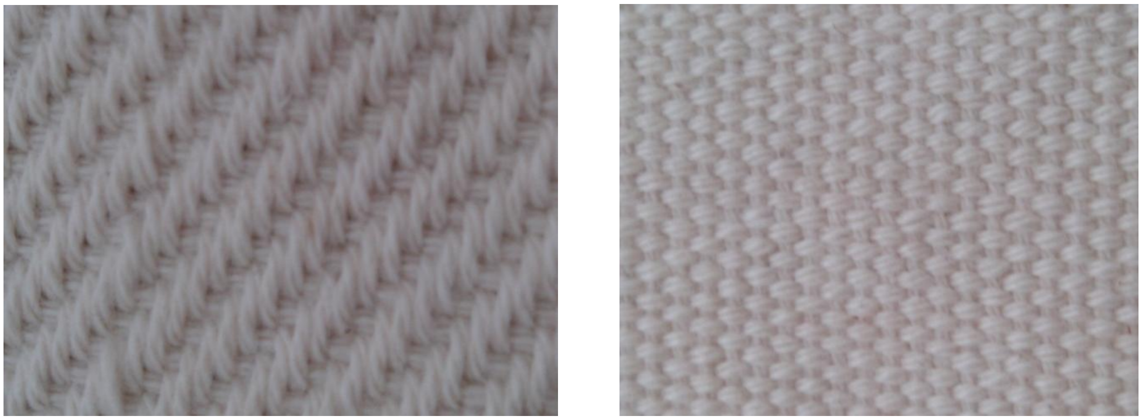
## 4.0 RESULTS AND DISCUSSION

### 4.1 Fabric Production

Samples of the yarn used for the knitting and weaving of the fabrics as well as the woven and knitted fabrics used in reinforcing the composites are shown in Plate VIII.

Weft Knitted fabric

Cotton yarn



Twill fabric

Plain fabric

Plate VIII: Yarn and fabrics used for composites reinforcement

### 4.1.1 Yarn and fabric parameters

The parameters for the yarns and fabrics used for the purpose of this research work are shown in Table 4.1

Table 4.1: Yarn and fabric parameters

| **Yarn and Fabric Samples** | **Yarn strength (N/Tex)** | **Fibre Volume Fraction** | **Yarn count (Tex)** | **Fabric Thickness (mm)** | **EPI** | **PPI** | **Warp cover factor** | **Weft cover factor** | **Fabric cover Factor (%)** |
|---|---|---|---|---|---|---|---|---|---|
| Yarn | 0.16 | | 236 | | | | | | |
| Plain fabric | | 0.38 | | 2.04 | 16 | 16 | 10.12 | 10.12 | 56.9 |
| Twill fabric | | 0.40 | | 2.35 | 31 | 21 | 19.61 | 13.28 | 81.6 |
| | | | | | **Stitch** | **density** | | | |
| Knitted fabric | | 0.40 | | 2.35 | 12 | | | | |

Woven reinforcements exhibited good stability in the warp and weft directions and offered the highest cover or yarn packing density in relation to fabric thickness.

## 4.2 FABRIC SURFACE-TREATMENT:

The physical observations noted after surface treatment of the fabrics with caustic soda were that the fabrics became whiter and swollen, the cross section became thicker and the length of the fabric was shortened. Because of fibre thickening, the fabric becomes denser, stronger and more elastic. It was found that the alkali treatment cleaned the fibre surface and effectively increased the surface roughness which improved extensively fibre-matrix adhesion due to mechanical interlocking of the fibres and matrix. Similar observation was made by Klemm *et al.,* (1998). This result can be attributed to the fact that the alkaline treatment removed the residual constituents such as pectin, hemicelluloses and waxy substances found in cotton fibres.

## 4.3 TENSILE PROPERTIES OF THE WOVEN AND KNITTED FABRICS

Fabric strength and elongation are useful for evaluation of the fabric performance. The strength is a measure of the force required to pull the yarn and the fabrics to a point where it breaks. The test was carried out in the machine direction as detailed in chapter three.

The tensile properties of the treated and untreated woven and knitted fabrics are as shown in Table 4.2.

Table 4.2: Effects of surface treatments on the tensile properties of the fabrics

| S/N | Samples | Fabric type | Tensile Strength (MPa) | Breaking Extension (%) |
|---|---|---|---|---|
| **1** | **Untreated Cotton fabric** | Plain fabric | 13.67 | 33.33 |
| | | Knitted fabric | 4.55 | 82.1 |
| | | Twill fabric | 13.14 | 29.2 |
| **2** | **1Minute Treated Cotton fabric** | Plain fabric | 14.11 | 43.67 |
| | | Knitted fabric | 5.12 | 114.19 |
| | | Twill fabric | 17.02 | 45.79 |
| **3** | **2 Minutes Treated Cotton fabric** | Plain fabric | 15.02 | 42.85 |
| | | Knitted fabric | 5.13 | 102.35 |
| | | Twill fabric | 14.48 | 44.68 |

It was established that firstly, the weave type (architecture) has great influence on the breaking force of woven fabrics. From Table 4.2 above it can be seen that the tensile strength of the fabrics have all increased by 10- 30% after being surface treated for 1 minute using a concentration of 20% NaOH. On treatment for 2 minutes with the same concentration, there was also an increase in the tensile strength of the fabrics except for the twill fabric which recorded a decrease in strength but not lower than the untreated fabric. The variation in the tensile strengths of the fabrics when treated for 1 and 2 minutes may be as a result of the different degree of conversion of native cellulose to alkali cellulose due to the thick plied yarn cross-section. The behaviour may also be due to the closeness of the treatment times which might not be sufficient to know the effect per time. Of the three fabrics, plain fabric had the highest tensile strength followed by the twill fabric and finally the knitted fabric when untreated. Secondly, the tensile properties of the knitted fabrics are poor in comparison with the other types of fabric used for the reinforcement, but they will be preferred in applications where their good energy-absorbing characteristics will be well utilized.

When treated for 1 minute, the twill fabric gave the highest tensile strength. The higher strength of the twill fabric over the plain fabric was unexpected because of the maximum number of interlacing points on the plain fabric. This however, could be ascribed to the effect of alkali treatment having dominance over the effect of fabric parameters since the plain fabric gave the highest tensile strength when untreated. The method of interlacing of the yarns in the weave architecture could also be a factor considering the twill pattern (1/3) used for the research work. These results show that fibre surface modification and weave architecture have effect on fabric performance and their mechanical properties.

The tensile strength of the fabrics was greatly improved when compared to the ones made from unplied yarns (Owen, 2013).

These values are well graphically illustrated in Figure 4.1**.**

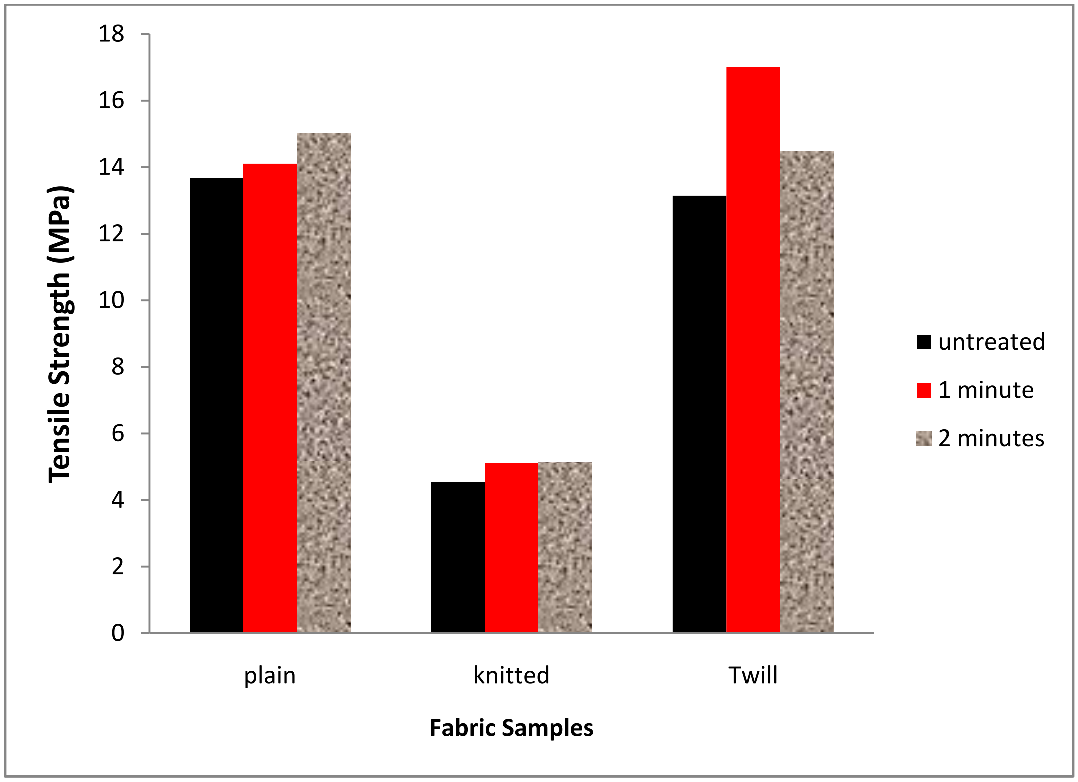


Figure 4.1: Effect of surface treatment on tensile strength of the fabrics

However, there was no much distinct variation in the behaviour of the tensile strength of the fabrics when treated for 2 minutes with 20% sodium hydroxide due to low rate of alkali penetration into the fabric structure leading to little difference in the degrees of conversion of native cellulose to cellulose II. This behaviour could be attributed to the effect of the thick plied yarns and the fabric construction, making the chemical treatment uniform and effective compared to the untreated. Similar results were obtained by Cao *et al.*, (2005) and Das and Chakraborty (2006), who showed that mechanical properties of cellulose fibres increased with alkali treatment.

## 4.4 BREAKING EXTENSION OF THE FABRICS

Table 4.2 and Figure 4.2 show the effects of surface treatment on breaking extension of the treated and untreated fabrics.

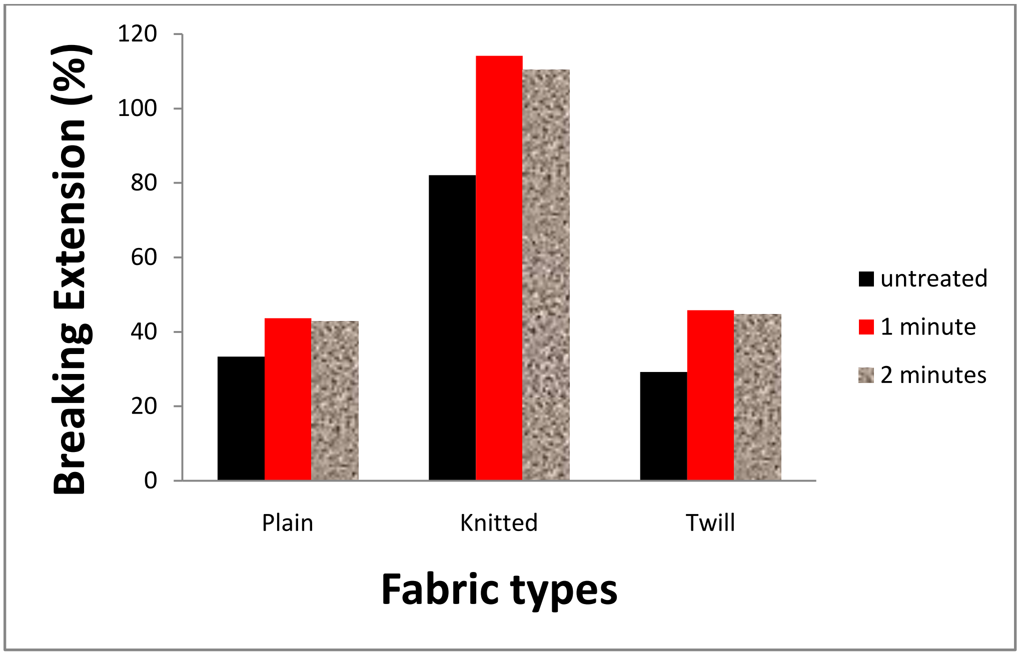


Figure 4.2: Effects of surface treatment on breaking extension of the fabrics

Figure 4.2 shows that the NaOH-treated samples have higher breaking extension than the untreated ones. This trend was generally expected of cotton fabric because of the shrinkage in fabric cross-section that was physically observed upon treatment with sodium hydroxide. When treated for 2 minutes with the same concentration of 20%, there was no much difference in the breaking extension as the treatment time of 1 and 2 minutes were just too close to enable clear determination of the effect of time on the alkali treatment.

It can be seen that there is 31-56 % improvement in the breaking extension of the 1 minute treated fabrics with respect to the untreated ones with the knitted fabric recording the highest extension at break. This increase in breaking extension could also be said to be as a result of the fibre shrinkage and increase in fabric density which occurred when the surface was treated with sodium hydroxide.

The interlocking loops on the knitted fabrics can be said to be responsible for the highest breaking extension recorded among the three set of fabrics.

However, the extensibility advantages which the knitted fabric architecture brings also lead to the disadvantages, which are the reduced in-plane stiffness and strength of the composites caused by the relatively poor use of the mechanical properties of the fibre

There is a slight decrease in the breaking extension of the fabrics when treated for 2 minutes as shown on the graph above, but the extent of treatment is not sufficient to make a clear conclusion about the effect of time on the breaking extension of the tested fabrics, thus requiring further investigation. The effect of using different mercerization media on some mechanical properties of local plant bast fibres, Roselle (*Hibiscus sabdariffa*), kenaf (*Hibiscus cannabinus*), okra (*Hibiscus esculentus*), Baobab (*Adansonia digitata*) was studied by Modibbo *et al.,* (2009) who mercerized with various concentrations of 10 - 25% of NaOH solutions. The result showed proportional increase in the breaking load with increase breaking elongation up to elastic point (1.5 mm).

## 4.5 TENSILE AND FLEXURAL TESTING OF COMPOSITES

The samples shown in Plate IX below were prepared for tensile tests and consist of different types and number of layers of reinforcement.

(a) (b)

Plate IX: (a) and (b) are some cut samples for tensile test

### 4.5.1 Tensile strength and Modulus of Composite samples

#### 4.5.1.1 Tensile strength and moduli of composites reinforced with single layer of fabrics

The results of the tensile tests on the different samples are shown in Figures 4.3 and 4.4.

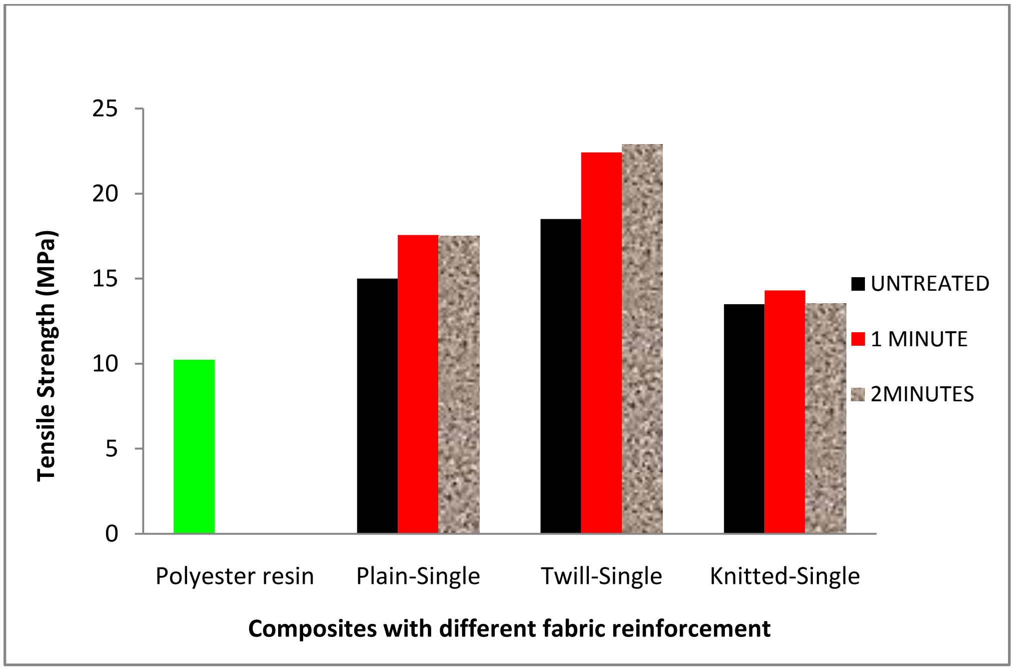


Figure 4.3: Effect of alkali treatment on the tensile strength of composites reinforced with single layer of fabric

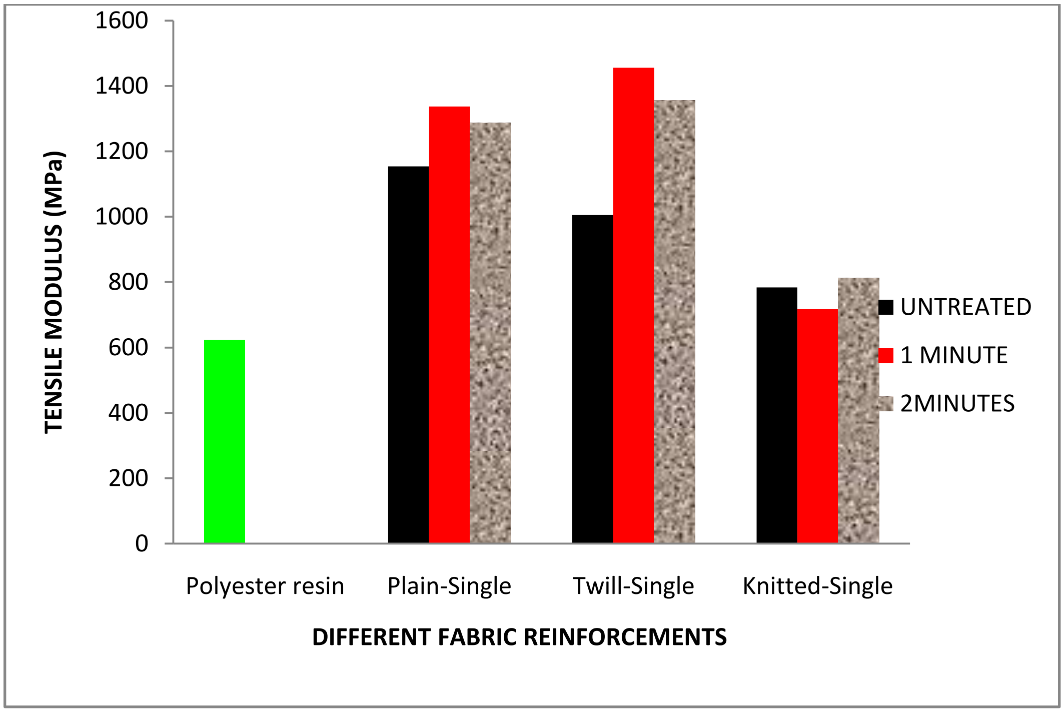


Figure 4.4: Effect of alkali treatment on the tensile modulus of composites reinforced with single layer of fabric

From the results of tensile test shown above (Figures 4.3 and 4.4), it is found that the maximum tensile strength for composites reinforced with single fabrics occurred on the samples reinforced with the twill fabrics for both the untreated and treated fabric samples. This is followed by those reinforced with plain fabrics and finally the knitted fabric in that order. There was a decrease in strength when the composite specimens were reinforced with fabrics treated for 2 minutes except for twill single fabrics which increased in strength. The composites had increment of between 72-119% in tensile strength with respect to the unreinforced unsaturated polyester showing the positive role of the single cotton fabrics in the composite samples. Similar result was obtained by Pothan *et al.*, (2002) who conducted tensile and impact studies of woven sisal fabric-reinforced polyester composites prepared by RTM technique. In his study, both tensile and impact properties were found to be the maximum for composites made with twill woven fabric in the study where fibre bundles were used in the weft direction; unlike in the other two cases where fibre yarns have been used. This was in turn found to be caused by the flow behaviour of the resin and the permeability of the various fabric geometries.

It can be said that the higher tensile strength of the composites with modified fabrics as compared to the untreated ones, may be due to the alkali which improves the adhesive characteristics of fabric surface by removing natural and artificial impurities thereby producing a rough surface topography. This has increased the proportion of the effective surface area available for contact with the unsaturated polyester matrix polymer.

Therefore, the composites can sustain higher loads before failure occurs compared to the unreinforced unsaturated polyester.

Similar improvement in the tensile properties of alkali-treated natural fibres reinforced composites were reported by Lai *et al.,* (2008). Generally, mechanical properties of the woven composites made from alkali-treated fibres are superior to the untreated fibres. This goes in consonance with the experimental results obtained in this work.

For the tensile modulus, (Figure 4.4) there was an increase in modulus of elasticity for both the untreated and treated composite specimens with respect to the unreinforced unsaturated polyester. Composite reinforced with plain fabric gave the highest modulus when untreated, greater than twill and knitted fabrics in that order. But when the fabrics were treated and used for the reinforcement of the composites, the twill fabric improved the tensile modulus better than other fabrics.

The composites with knitted fabrics gave the lowest tensile modulus both when the reinforcing fabrics were treated and untreated.

### 4.5.1.2 Tensile strength and moduli of composites reinforced with 2 layers of fabrics

For the composites reinforced with two layers of fabrics, their tensile strengths and moduli are shown in Figures 4.5 and 4.6

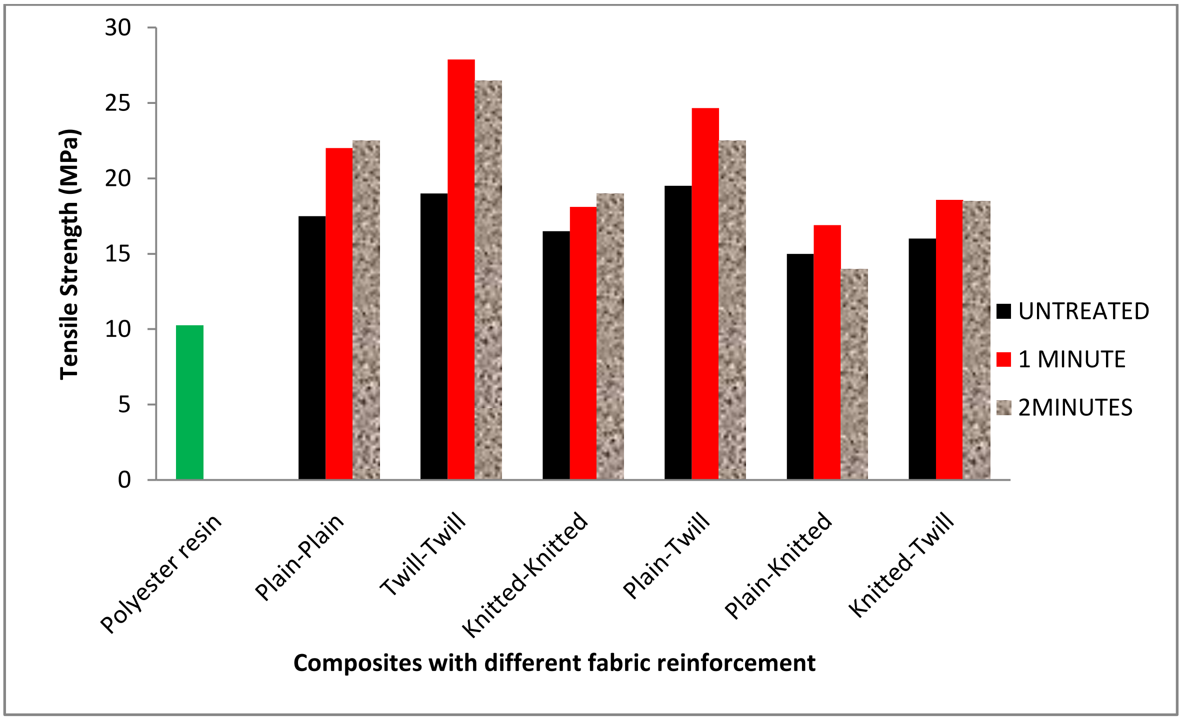


Figure 4.5: Effects of alkaline treatments on the tensile strength of composites reinforced with 2 layers of fabrics

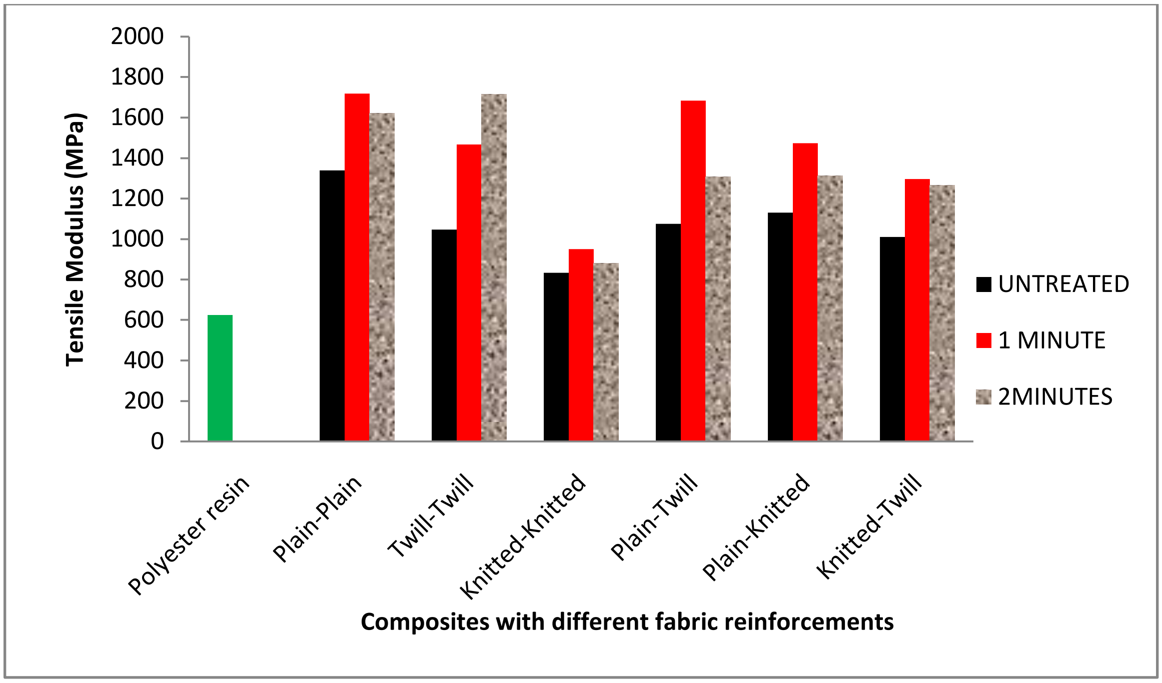


Figure 4.6: Effects of alkaline treatments on the tensile modulus of composites reinforced with 2 layers of fabrics

In general, there was increase in the tensile strength of the composites as the volume of reinforcement increased. The increase was not geometrical with respect to those composites reinforced with single fabric samples (Figure 4.5). Though, the geometry of increase could not be quantified but the results were far better. The composite reinforced with two layers of twill fabric gave the highest tensile strength for both the treated and untreated followed by the plain-twill fabric and the plain-plain fabrics in this hierarchy (Figure 4.5). The composite reinforced with two layers of plain and knitted fabric gave the lowest tensile strength. When composites reinforced with 2 minute-treated fabrics were used, there was a decrease in the tensile strength of all the composites relative to 1 minutes-treated samples except for the plain-plain and knitted-knitted fabrics which recorded marginal increases of 2% and 5% respectively. Similar result was obtained by Mishra *et* *al.,* (2003) who reported that 5% NaOH treated sisal fibre-reinforced polyester composite had better tensile strength than 10% NaOH treated composites. This is because at higher alkali concentration, excess delignification of natural fibre occurs resulting in a weaker or damaged fibre. The tensile strength of the composite decreased drastically after certain optimum NaOH concentration.

For the tensile modulus (Figure 4.6), it is evident from the graph above that there was increase in the modulus of elasticity for all the treated samples reinforced with cotton fabrics with different architectures. Those treated for 2 minutes with the same concentration of alkali made little difference as compared with treatment for 1 minute as a result of the reasons stated above. The composite reinforced with two layers of plain fabric gave the highest tensile modulus both when untreated (1339.29MPa) and treated (1718.75MPa). The lowest modulus was recorded for the composite samples reinforced with two layers of knitted fabrics both when untreated (833.33MPa) and when treated (949.83MPa) due to the high elongation properties of knitted fabrics. The superiority in stiffness of the twill fabric reinforced composites over the plain and knitted fabrics after treatment can be said to be due to the effect of alkali treatment dominating the effect of fabric parameter.

### 4.5.2 FLEXURAL PROPERTIES OF COTTON/UNSATURATED POLYESTER COMPOSITE

#### 4.5.2.1 Flexural strength of composites reinforced with single layer of fabric

This is graphically shown in Figure 4.7.

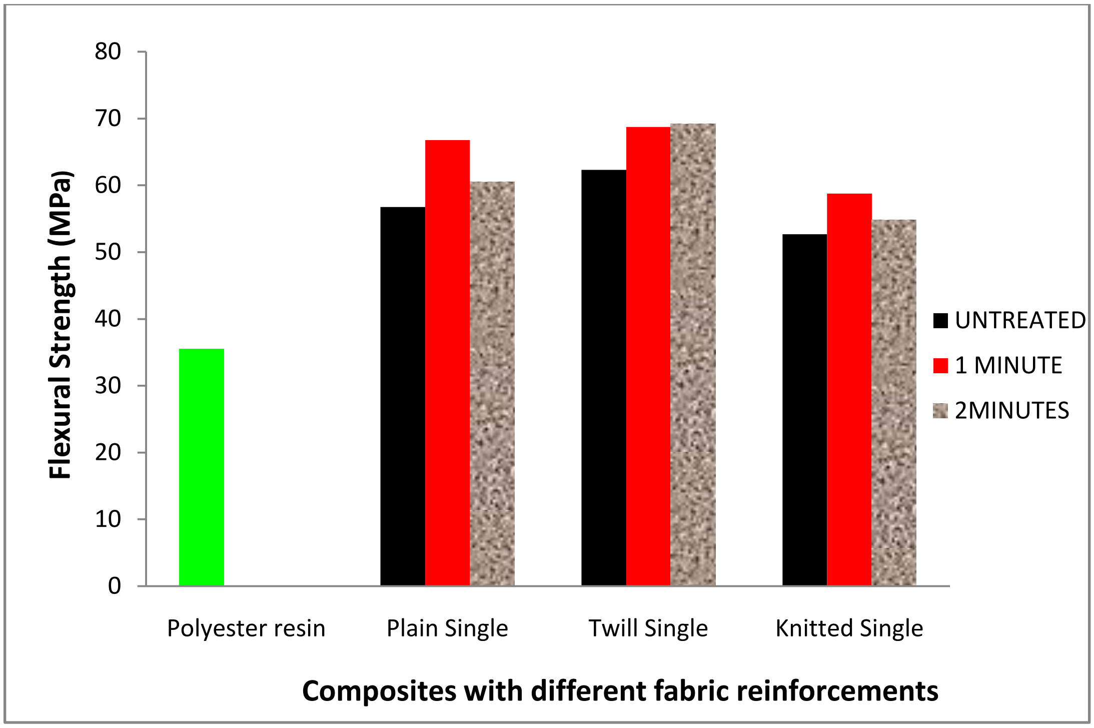


Figure 4.7: Effects of alkaline treatments on the flexural strength of composite samples reinforced with single layer of fabric

### 4.5.2.2 Flexural strength of composites reinforced with two layers of fabric

Figure 4.8 below also shows the result of the flexural tests for the composites reinforced with two (2) layers of fabric samples.

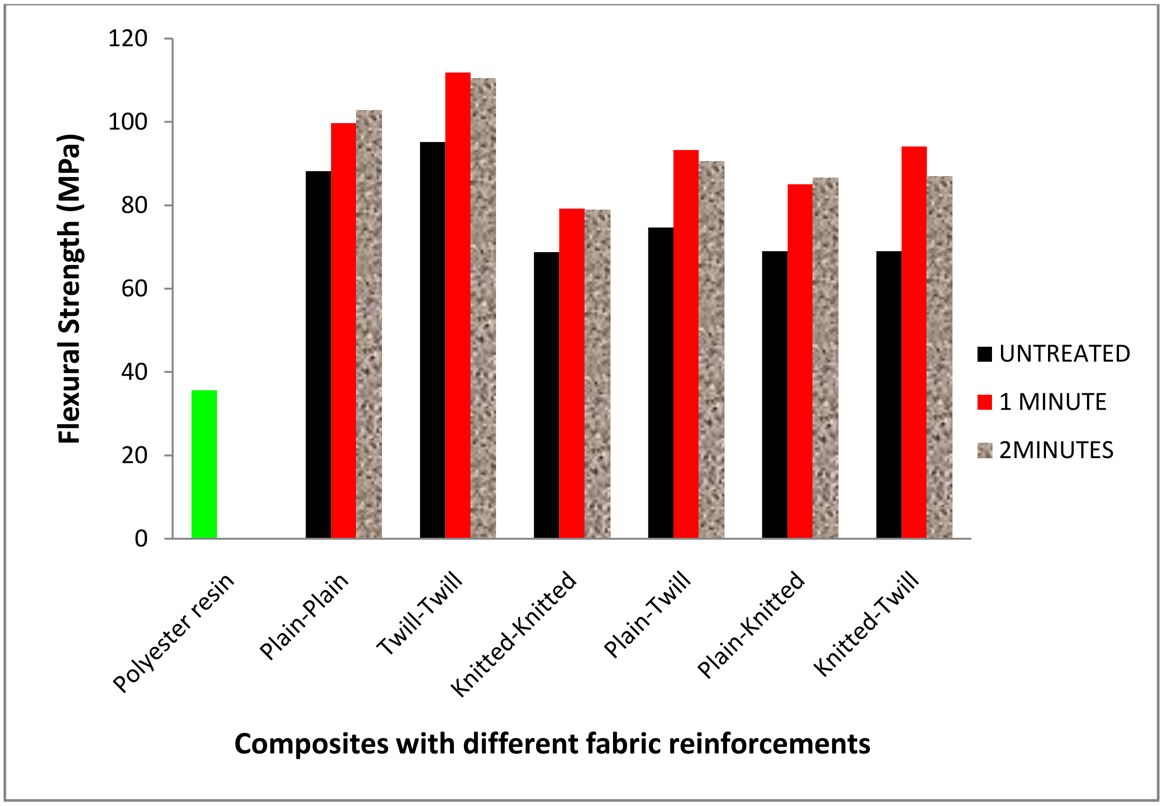


Figure 4.8: Effects of alkaline treatments on the flexural strength of composite samples reinforced with two (2) layers of fabrics

The results show that reinforcing polyester resin with cotton fabric increases the flexural strength in comparison to the unreinforced polyester composites. For the single reinforcement, there was 47%, 32% and 20% increase in flexural strength for the twill, plain and knitted fabrics respectively when untreated. But when reinforced with 1 minute treated fabrics, the flexural strength increased by 65%, 60% and 37% for the twill, plain and knitted fabrics respectively (Figure 4.7).

This may be due to the nature of the different architectures and the bonding of the fabric with the polyester matrix thereby improving their interactions with the matrix.

This behaviour showed that the flexural mechanical properties increased with alkali treatment and this can be explained by the increase of fibre roughness and contact area. The composites with 2 minutes treatment fabrics showed 7-9% decrease in the flexural strength of the composites relative to fabrics treated for 1 minute, for the plain and knitted single reinforcements and 1% increase for the twill reinforcement. The differences in value relative to the 1 minute treatment can be said to be negligible compared to the improvement in the flexural strength when the reinforcing fabric was untreated. Of the three reinforced composites shown in (Figure 4.7), the twill fabric reinforced composite is seen to have the highest flexural strength and the knitted fabric reinforced has the lowest flexural strength.

The trend was not different for the composites reinforced with two layers of fabric. Figure 4.8 shows increase of 38-112% across the different reinforcements when untreated with the reinforcement of two layers of twill fabrics recording the highest flexural strength. These values however, increased to 83-158% when treated for 1 minute. The increases and decreases in the mechanical properties found in the composites treated for 2 minutes should be mainly the result of the low permeation of alkali in the treatment time of the cotton fabrics. Despite these behaviours, the flexural strength of composites reinforced with the 2 minutes treated fabrics are better than those of untreated fabrics. This result indicates the variation of the mechanical behaviour with the change of the reinforcement structure and that cotton fabric-reinforced composite is stiffer and stronger than virgin unsaturated polyester.

### 4.5.2.3 Flexural modulus of composites reinforced with single layer of fabric

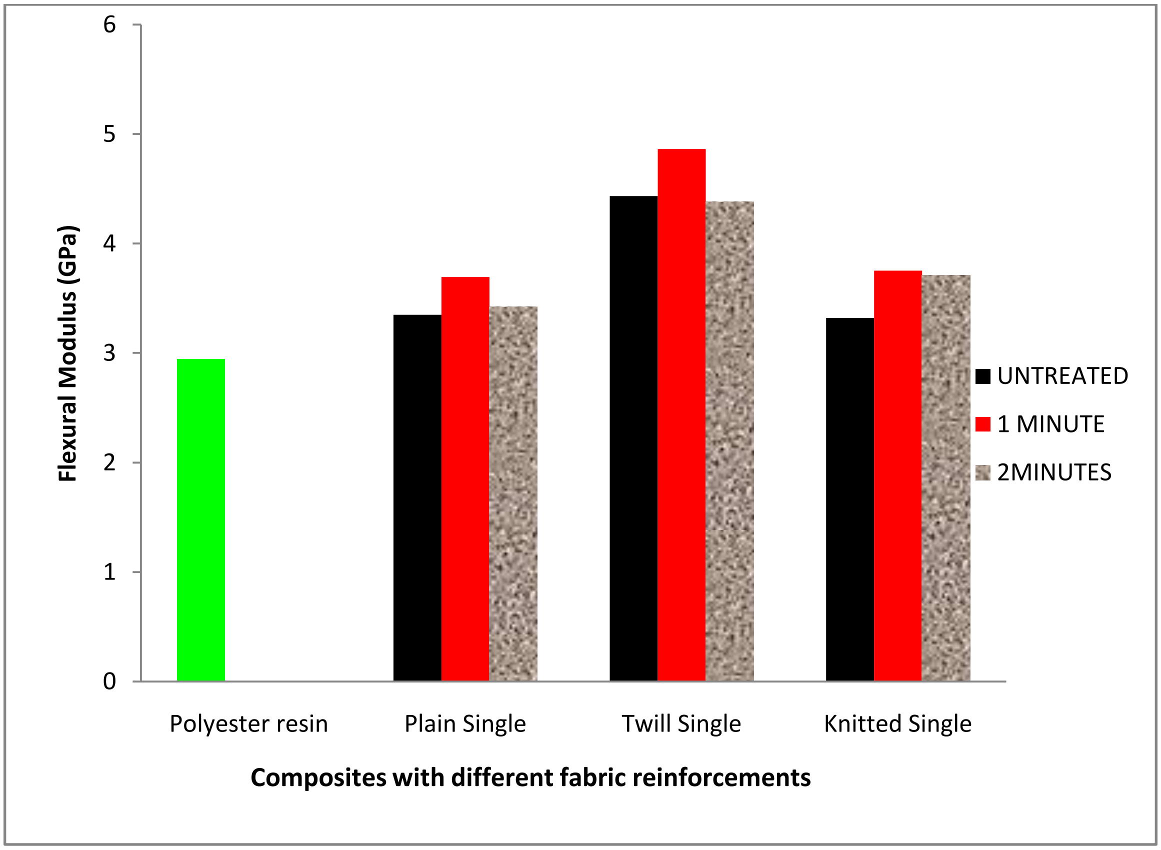


Figure 4.9: Effects of alkaline treatments on the flexural modulus of composite samples reinforced with single layer of fabric

### 4.5.2.4 Flexural modulus of composites reinforced with two layers of fabric

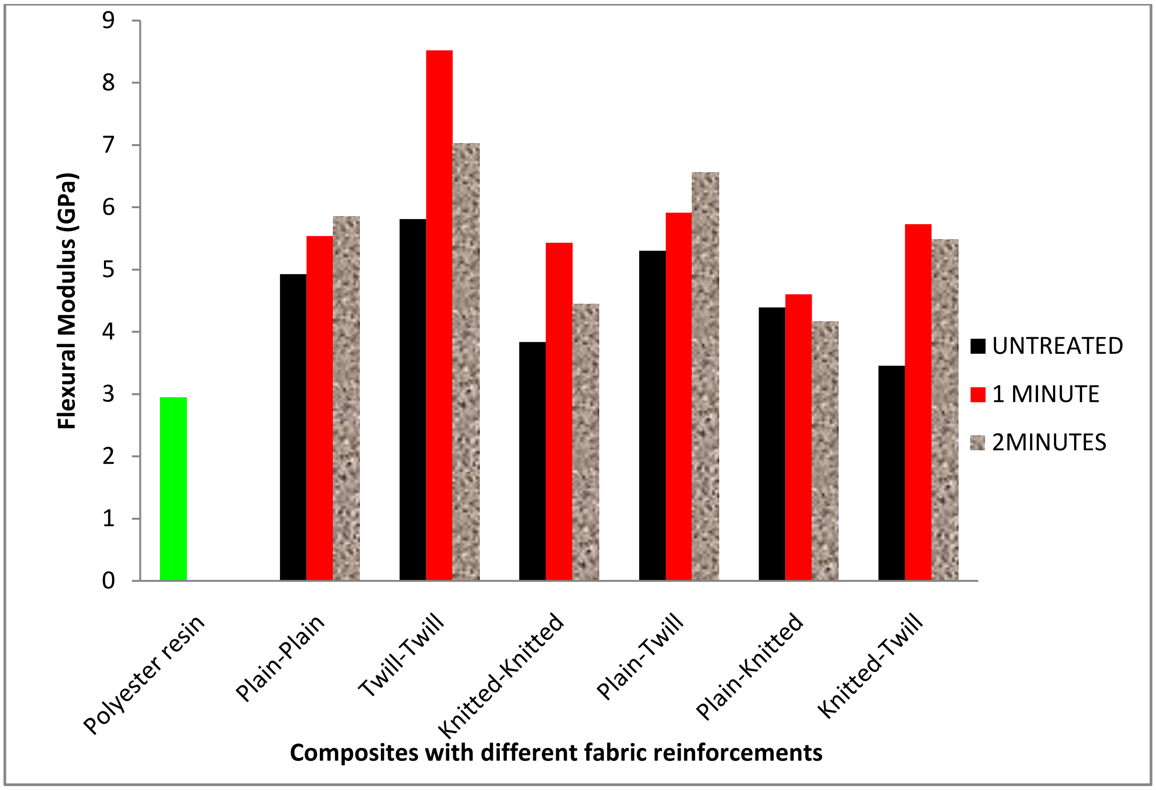


Figure 4.10: Effects of alkaline treatments on the flexural modulus of composite samples reinforced with two (2) layers of fabrics

Remarkable increase in flexural modulus was also obtained after reinforcing the polyester resin with cotton fabric both for the treated and untreated reinforcements (Figure 4.9). There was 25.58% increase in the flexural modulus of the single reinforced composites with the resin having a flexural modulus of 2.94 GPa. Composite reinforced with single layer of 1 minute treated twill fabric gave the highest flexural modulus of 4.86GPa. The least value was given by single layer of knitted fabric with a modulus of 3.75GPa. This result is in line with the research conducted by Boynard *et al.*, (2003) who studied the flexural properties of Luffa fibres-reinforced polyester composite. They noticed that the flexural modulus increased by 14% after the alkali treatment of the fibres. The improvement of the flexural strength and modulus was also reported by Cao *et al.*, (2006) who worked on the Mechanical Properties of Biodegradable Composites Reinforced with Bagasse Fibre before and after alkali treatments. They found out that the flexural mechanical properties increased with alkali treatment and explained this enhancement by the increase of fibre roughness and contact area.

Similar increase was also observed when the composite samples were reinforced with two layers of fabrics. The high values are indication of the high resistance of the composite specimens to bending. This shows that the stiffness of the composite depends highly on its reinforcement. This statement is clearly proved and demonstrated in Figure. 4.10, since the flexural modulus for the composites increased by a maximum of 92 % with respect to those reinforced with single layer of fabrics (Figure 4.9). The flexural modulus is in this order: twill-twill fabric > plain-plain fabric > knitted-knitted fabric both for the NaOH treated and untreated knitted and woven cotton fabrics. Other hybrid reinforcements showed varying degrees of stiffness based on the architecture of the reinforcing fabrics. A varying result in flexural modulus was observed for the 2 minutes treated fabrics probably as a result of short period of treatment as earlier established. The superiority of the modulus of twill fabrics over other reinforcements could be attributed to the increased thickness of the fabric owing to its weave pattern as shown in Table 4.1

In flexure, the relationship between strength and fabric layers appears to be linear; increasing the number of fabric plies brings an increase in the tensile and flexural properties of the laminates. This effect is expected because failure of a critically stressed layer in the composite does not necessarily mean that total catastrophic failure of the multilayered composite takes place.

It was also found that flexural strength and modulus are controlled by the strength of the extreme layer of reinforcements. No specimen has failed by delamination during loading and the failure mode shows little or no fibre pull-out.

## 4.6 CHARPY IMPACT STRENGTH TESTING

The tensile – impact energy is the energy required to break a standard tension –impact specimen in tension by a single swing of a standard calibrated pendulum under a set of standard conditions. Materials often absorb applied forces very quickly. Depending on the application, these could be falling objects, blows, collisions, drops, etc. The impact properties of the polymeric materials are directly related to the overall toughness of the material. The essence of this test was to overcome the deficiencies of flexural impact tests.

### 4.6.1 Impact strength of composites reinforced with single layer of fabric

The result of the impact strength of the composite samples which were reinforced with single layer of fabrics is shown in Figure 4.11.

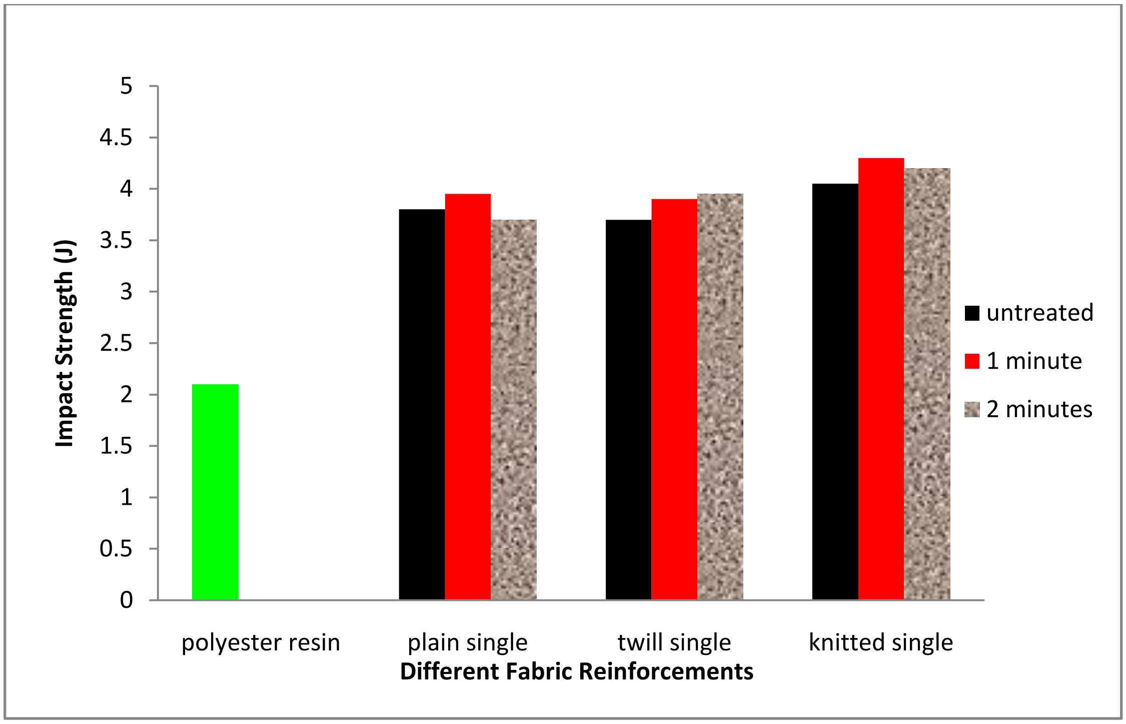


Figure 4.11: Effects of alkaline treatments on the impact strength of composite samples reinforced with single layer of fabric

It was found that weaving pattern was a crucial factor in determining the response of composite materials to impacting force

The impact strength of the unsaturated polyester was improved by about 105% when reinforced with the fabrics as shown in Figure 4.11 above, it can be seen that there is an increase in the impact strength of the composites reinforced with the treated fabrics as compared with the untreated fabrics showing the positive effect of the alkali treatment on the reinforcing fabrics. For the single reinforcement, the knitted fabrics gave the highest impact strength of 4.05Joules and 4.3Joules for the untreated and 1 minute treated samples respectively. This is followed by the plain fabric (3.8 Joules and 3.95Joules) and the twill fabric (3.7Joules and 3.9Joules) in that order. For the two minutes treated fabrics, there was a decrease in the impact strength of the composites specimens for the plain and knitted fabric-reinforced samples and a marginal increase in strength of 1.3% for the twill fabric. But, the values obtained are still better than the unreinforced polyester matrix.

### 4.6.2 Impact strength of composites reinforced with two layers of fabrics

For the two layer reinforcements, the result is as shown in as shown in Figure 4.12 below:

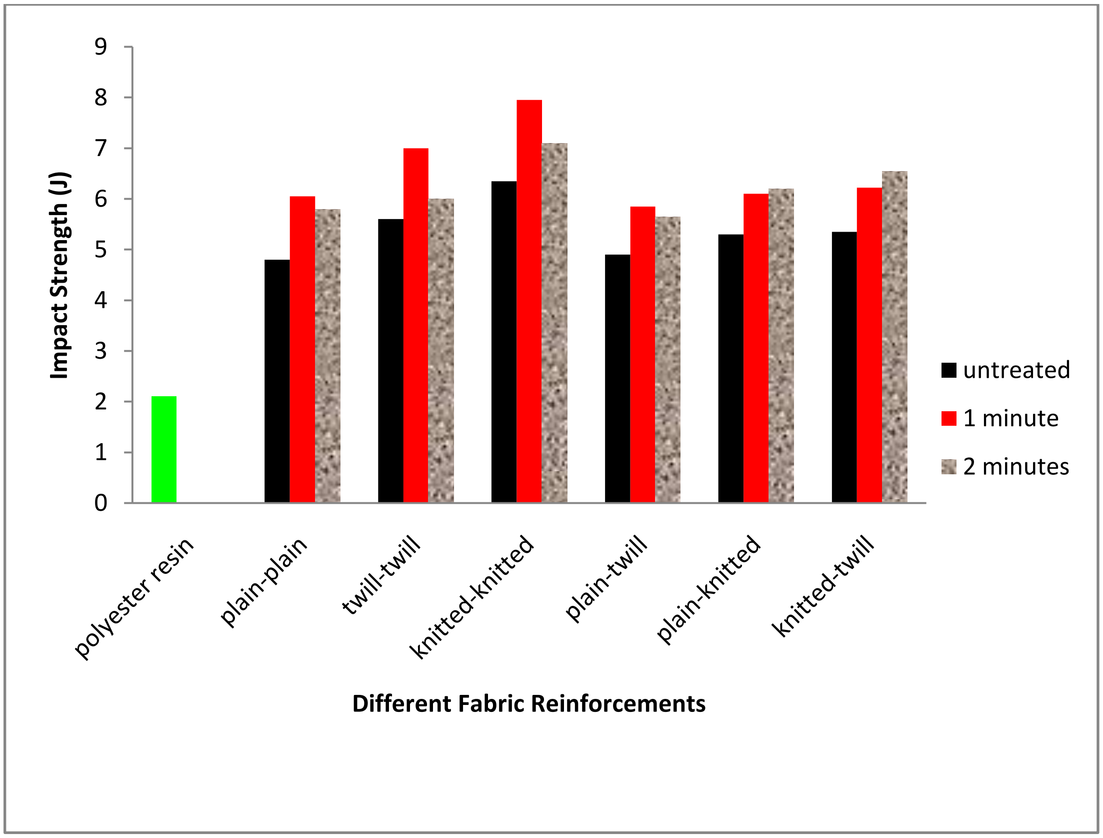


Figure 4.12: Effects of alkaline treatments on the impact strength of composite samples reinforced with two (2) layers of fabrics

The results show that composites with 1 minute-treated fabrics gave better impact strength than those with untreated fabrics (Figure 4.12). In the case of composites with fabrics treated for 2 minutes, there was an increase in the impact strength of composites with double layers of plain-knitted and knitted-twill fabrics relative to those treated for 1 minute and the untreated fabrics; others recorded decreases in the impact strengths of composites reinforced with them. This behaviour could be as a result of uneven effect of alkali treatment due to yarn construction or the excessive removal of the natural constituents of cotton such as hemicellulose making it lighter, hence a drop in the resistance of impacting force. The overall impact behaviour is better in composites reinforced with two layers of fabrics compared to those reinforced with single layers. For the double reinforced composites, samples reinforced with two layers of knitted fabrics gave the highest impact strength of 7.95 Joules for the treated fabric samples followed by that of all twill fabrics (7.0J) with the plain having the least impact strength of 6.05 Joules. It is observed that the combination of the fabric layers helped in decreasing the overall failure function, thus improving the impact damage resistance. Other hybrid reinforcements showed varying results depending on the properties of the reinforcing fabrics. When the reinforcing fabrics were untreated, those reinforced with two layers of plain fabrics recorded the least impact strength of 4.80 Joules with the highest being that of knitted fabrics with impact strength of 6.35Joules and was closely followed by that of twill fabric with a strength of 5.60 Joules. These different behaviours of the composites when reinforced with treated and untreated cotton fabrics may to some extent be due to the presence of natural impurities in the cotton fabric such as wax and gummy substances and probably those picked up during processing.

The performance of knitted fabrics as compared to woven fabric is better. It is found that the knitted fabrics distributed the stress better throughout the fabric structure and the composite reinforced with them showed better impact resistance due to higher isotropic behaviour. This occurrence can be attributed to the homogenous distribution of reinforcement in the matrix which resulted in a better ply nesting and close association of the knitted loops within the fabric layers, thus subduing the propagation of crack or delamination growth.

Similar investigations showed that the damage tolerance of knitted fabrics compares favourably with other reinforcement architectures. For example, it has been found that a higher percentage of impact energy in the range 0–10 Joules is absorbed by a weft-knitted glass reinforced composite ($V_f = 50\%$) than was absorbed by an equivalent woven fabric. Observations indicated, in addition, that the damaged area was approximately six times larger for the knitted fabric than for the woven fabric, presumably reflecting the increased availability of crack initiation sites in the knitted architecture. (Bannister and Herszberg, 1995).

On the overall impact result, these materials exhibited damage at relatively low load during impact tests, providing nevertheless a sufficient damage tolerance and the low values obtained are due to the typical mode of failure of cotton reinforced laminates, already observed, involving little or no delamination and mainly driven by matrix damage, due to the very limited elastic deflection of these laminates (Santulli, 2001).

## 4.7 ROCKWELL HARDNESS TEST

Figures 4.13 and 4.14 below show the hardness values for the different composition of composites for samples reinforced with both single and double layers of fabrics.

### 4.7.1 Hardness of composites reinforced with single layer of fabric

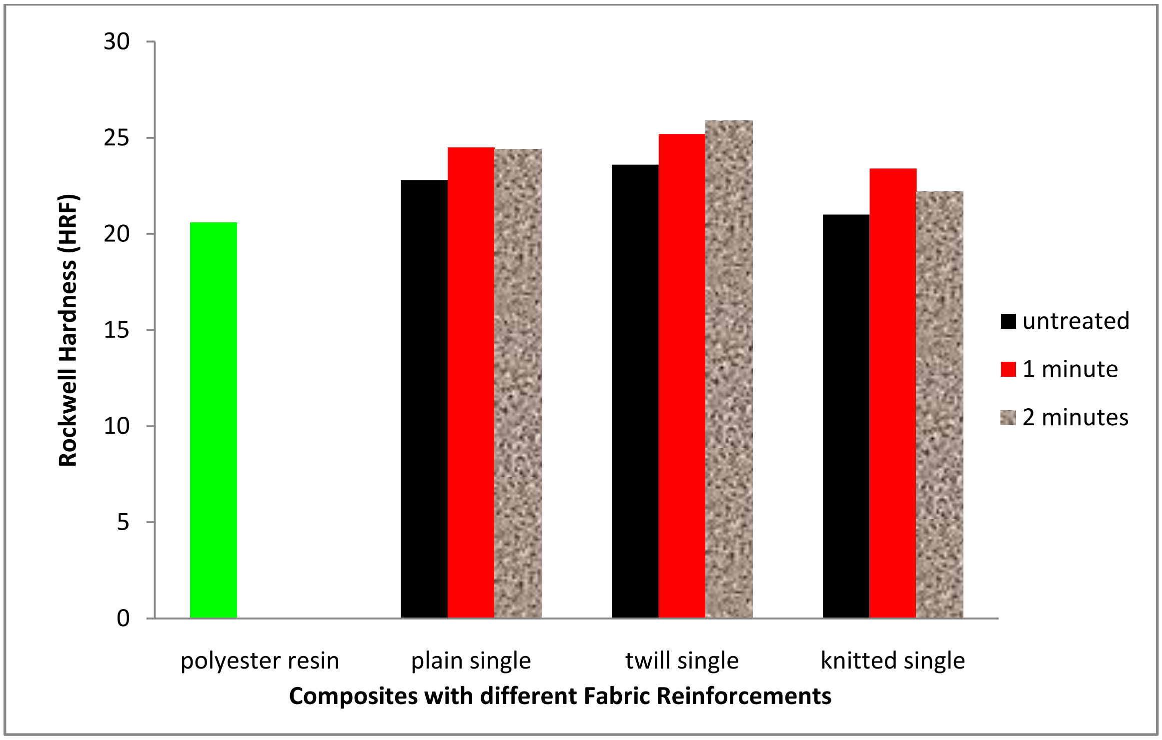


Figure 4.13: Effects of alkaline treatments on the hardness of composite samples reinforced with single layer of fabric

### 4.7.2 Hardness of composites reinforced with two layers of fabric

For the composite samples reinforced with two layers of fabrics, the results are as shown below:

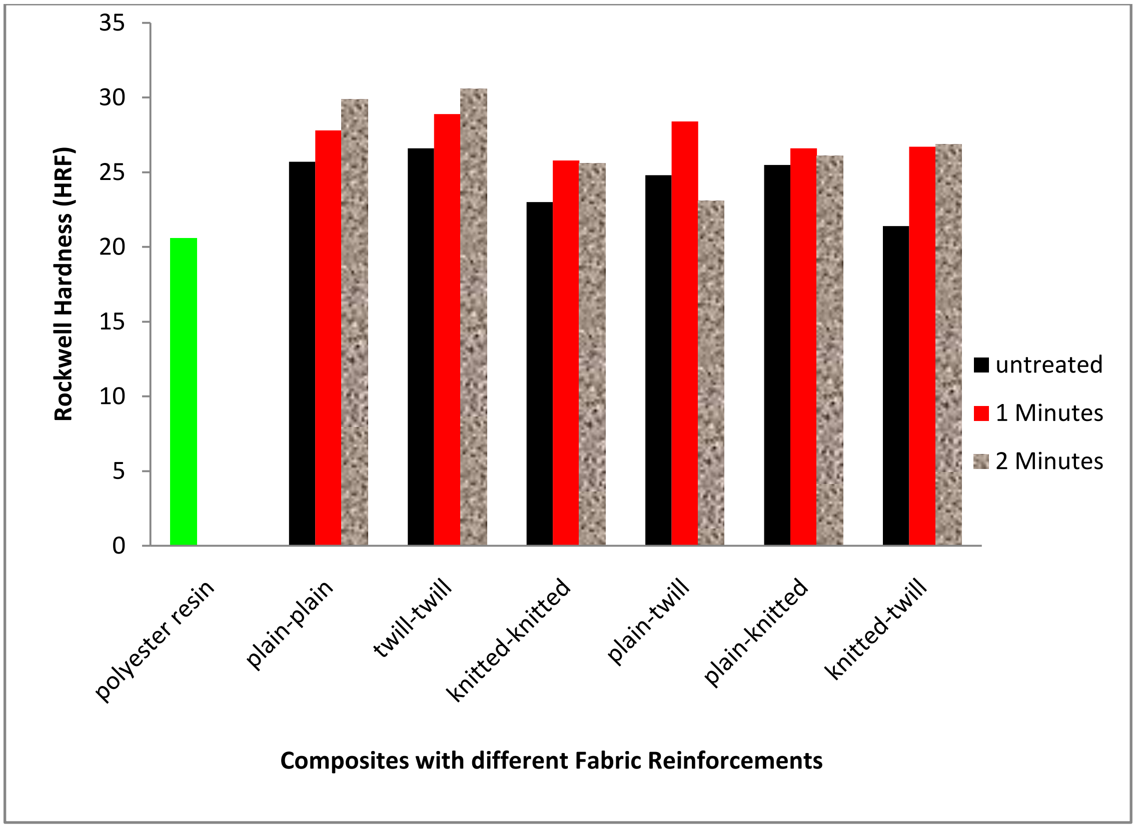


Figure 4.14: Effects of alkaline treatments on the hardness of composite samples reinforced with two layers of fabrics

As shown in Figures 4.13 and 4.14 above, the inclusion of the cotton fabrics improved the Rockwell hardness of the polyester resin by about 26-45% for both the single and double reinforced laminates. Before treatment, composites reinforced with twill fabrics had the highest hardness with Rockwell number of 23.6 HRF and 26.6 HRF when reinforced with single and double layers respectively. On treatment, the twill-fabric-reinforced composites recorded the highest hardness. Composites with plain fabrics followed similar trend. The hardness of the knitted fabric composite was found to be minimum with a value of 21 HRF and 23 HRF for the single and double layers respectively. It can be seen that the value of the hardness number for the composites increased by a maximum of 12% when the reinforcing fabrics were treated with alkali as shown in Figure 4.13 above; indicating the positive effect of alkaline treatment on hardness mechanical property. The variation in the hardness reading is caused by the difference in hardness between resin and reinforcing materials. Similar trend was reported by Al-Mosawi (2009) who found out that polymers have low hardness, an indication of the lowest value for araldite resin before reinforcement. But this hardness value greatly increased when the resin was reinforced by hybrid fibres, due to distribution of the test load on fibres which decreased the penetration of the test ball to the surface of composite material and by consequence raised the hardness of the material. Other reinforcements showed varying degrees of hardness based on the architecture and properties of the reinforcing materials. The limited effect of time of treatment of the reinforcing fabrics with NaOH was also seen on the result of the composites, as 2 minutes treatments recorded slight decreases and increases in the hardness number of the composites samples. A twist to this trend is found with the single reinforcement with twill fabric and double reinforcement with plain-plain, twill-twill and knitted-twill fabrics which had increases with 2 minutes treatment. This may be due to the low permeation of the NaOH into the fabric cross-section during treatment.

On the overall hardness result, major difference was not recorded with the different fabric architectures as was seen with other mechanical properties going by the 12% maximum difference in the hardness number between the different reinforcements. All the same, the positive influence of the different reinforcements on the virgin polyester is confirmed from the results obtained.

# CHAPTER FIVE

# SUMMARY, CONCLUSION AND RECOMMENDATIONS

## 5.1 SUMMARY

The aim of the whole research work was to investigate the effect of fabric architecture and sodium hydroxide treatment on the properties of cotton fabric-reinforced unsaturated polyester composites. Four yarns of known count were plied and the resultant yarns were used to produce plain and twill weave fabrics and weft knitted fabrics. Some of the fabrics were subjected to alkali treatment to study the effect on some mechanical properties. The fabrics were used to reinforce unsaturated polyester resin using single and 2-ply laminates in order to study the effects of different laminate configurations interchangeably for the woven and knitted fabrics.

Investigations on some of the mechanical properties of these composites were studied and the results compared. From results and discussion in the previous chapter, the following summary is hereby made:

On the tensile test carried out on the untreated fabrics, it was established that the weave type has great influence on the breaking force of woven fabrics as shown by the two woven patterns (plain and twill) and the weft knitted fabric. Plain woven fabric gave the highest tensile strength followed by the twill fabric and finally the knitted fabric as the tests were carried out in the machine direction. The tensile properties of the knitted fabrics are poor in comparison with the other types of fabric used for the reinforcement, From physical observations, it was seen that alkali treatment showed remarkable shrinkage of the cross-section of the fabric samples after treatment with sodium hydroxide (NaOH) as the cross section became thicker and the length of the fabric was shortened. It was found that this treatment improved greatly the tensile strength of the fabrics to a certain degree requiring a certain percentage concentration and duration of treatment. 2 minutes treatment with 20% sodium hydroxide concentration gave impaired tensile strength.

The tensile test carried out showed that the breaking extensions of fabrics are improved after treatment with alkali because of the fabrics becoming denser, stronger and more elastic. This increase in breaking extension could also be said to be as a result of the fibre shrinkage and increase in fabric density. The knitted fabric has the highest breaking extension over the twill and plain fabrics

The reinforcement of polyester resin with cotton fabrics woven and knitted from plied yarns improved the tensile strength and modulus of the composites made from them by 72-119%. Composites reinforced with treated and untreated twill fabrics had better tensile strength than those reinforced with plain and knitted fabrics. Composite with plain fabrics had superior tensile modulus over twill and knitted fabric, but, after treatment, twill fabric-reinforced composites gave superior tensile modulus.

The treatment of cotton fabric with alkali showed an increased proportion of the effective surface area available for contact with the unsaturated polyester matrix polymer thus leading to increase in the tensile strength and modulus of the reinforced composites

(Klemm 1998). This gives the composites the ability to sustain higher loads before failure occurred.

Increasing the number of fabric plies brings an increase in the tensile and flexural properties of the composite laminates. The increase in the volume of reinforcement gives a corresponding increase in the tensile strength and modulus of elasticity of the composites. However, the increase was not geometrical with respect to those composites reinforced with single fabric samples. Composites with layers of knitted fabrics showed the least tensile modulus.

The behaviour of composites reinforced with two layers of fabrics followed the properties of the fabrics reinforcing them. Composites reinforced with two layers of twill fabrics gave the highest tensile strength and was closely followed by plain-twill fabric, then, composites with plain-plain fabrics. It was found that flexural strength and modulus were controlled by the strength of the extreme layer of reinforcements.

The flexural strength and modulus showed an increase in the property when the reinforcing fabrics were alkali treated and when the volume of reinforcement increased indicating the variation of the mechanical behaviour with the change of the reinforcement structure. The resistance to bend was best for composites reinforced with twill fabric as they are stiffer than plain and knitted fabrics, both when singly and doubly reinforced.

The Charpy impact result obtained showed that fabric architecture is a crucial factor in determining the response of composite materials to impacting force; as the impact strength of the unsaturated polyester resin was improved by about 105% when reinforced with different fabrics. Composites with knitted fabrics had better response to impacting forces than other fabrics with good energy absorbing characteristics. The impact strength is found to be proportional to the volume of reinforcement as increase in fabric layer decreased the overall failure function, thus improving the impact damage resistance.

Rockwell hardness result of the composite specimens showed that the inclusion of the cotton fabrics improved the Rockwell hardness of the polyester resin for about 26-45% for both the single and double reinforced laminates. Composites reinforced with twill fabrics gave higher hardness number than other fabrics both for the single ply and 2-ply. Though, higher variations were not recorded with the different fabric architecture as was seen with other mechanical properties. Only 12% maximum difference in the hardness number between the different reinforcements was obtained.

## 5.2 CONCLUSION

This work resulted in the successful fabrication of cotton fabric-reinforced unsaturated polyester composites using simple hand lay-up technique and the following conclusions can be drawn:

Fabric architecture has great effect on the mechanical performance of the fabrics and this is translated to the properties of the composites reinforced with it, but, to a certain degree as there were little deviations in the properties of the composites reinforced with them as compared to the properties of the fabrics only. The woven reinforcements exhibited good stability in the warp and weft directions and offered the highest cover or yarn packing density in relation to fabric thickness as compared to the weft knitted fabric.

In this study the influence of surface modification and the reinforcement structure on the tensile and flexural proprieties of cotton-polyester composite were investigated. It is clear that the alkali treatments of cotton fabrics enhanced the adhesion between fabric and matrix thus, increasing the mechanical properties. The extent of improvement with time could not be determined as the treatment for 2 minutes was not enough to know the full extent behaviours of the composites in the mechanical properties tested. When untreated, the tensile strengths of the fabrics are in this order: plain fabric with 13.67MPa > twill fabric with 13.14MPa > knitted fabric with 4.55MPa. When treated with 20% sodium hydroxide for 1 minute, the tensile strengths of the fabrics are in this order: twill fabric with 17.02MPa > plain fabric with 14.11MPa > knitted fabric with 5.12MPa.

The tensile properties of the knitted fabrics are poor in comparison with the other types of fabric used for the reinforcement, but their good energy-absorbing characteristics are more preferred than their basic in-plane properties.

Alkali treatment greatly improves the breaking extensions of fabrics and this increase in breaking extension is found to be as a result of the fibre shrinkage and increase in fabric density. Knitted fabrics have higher breaking extension than twill and plain fabrics both before and after treatment with alkali.

The reinforcement of polyester resin with cotton fabrics woven and knitted from plied yarns improved the tensile strength and modulus of the composites made from them by 72-119%. Composites reinforced with twill fabrics generally had better tensile strength and modulus than those reinforced with plain and knitted fabrics either when the reinforcing fabrics are untreated or treated with sodium hydroxide.

The increase in the volume of reinforcement (increase in fabric ply) gives a corresponding increase in the mechanical properties of the composites. However, the increase is not geometrical with respect to those composites reinforced with single fabric samples.

Composites reinforced with twill fabrics have better tensile strength than those of plain and knitted. The modulus of elasticity is seen to be better in composites reinforced with plain fabrics. Composites with knitted fabrics were found to have the least tensile modulus.

The properties of fabrics are not fully translated to the composites as seen from the slight variation of the mechanical properties of the fabric samples and those of the reinforced composites. Twill fabric-reinforced composites have higher flexural strength and modulus (resistance to bending) than those reinforced with plain and knitted fabrics.

Fabric architecture is a crucial factor in determining the response of composite materials to impacting force. Composites reinforced with knitted fabrics have better response to impacting forces than other fabrics with good energy absorbing characteristics. The impact strength is found to be proportional to the volume of reinforcement as increase in fabric layer decreased the overall failure function, thus improving the impact damage resistance.

Reinforcing composites with cotton fabrics improves the Rockwell hardness of polyester resin for both single and double layer reinforced laminates. Composites reinforced with twill fabrics gave higher hardness number than those of other fabrics both for the single ply and 2-ply. Much variation in hardness numbers were not recorded for the various reinforcements.

Although the mechanical properties of cotton fabric/polyester composites do not possess strengths and moduli as high as those of conventional composites, they do have enough strength that qualifies them to be considered for future materials use. Since the reinforcing material is eco-friendly, non-toxic, non-health hazardous, low in cost and easily available as compared to fabrics from conventional fibres like glass, Kevlar, asbestos etc., the composites may serve as a good substitute for wood in indoors non-load bearing applications such as shelves, partitions panels, structural board products, mobile buildings as makeshift apartment for natural disasters in addition to providing alternative market for cotton growers.

## 5.3 RECOMMENDATION

The findings in this research work are restricted to the scope of the study and limited by the period of program. New areas of research have been identified during this period. These include:

i. The investigation of the performance of other low cost resin system like thermoplastics and biodegradable matrices such as starch and cellulose acetate reinforced with cotton fabric.

ii. The density and moisture absorption behaviour of the composites should be studied to know the extent of water uptake. This will help to find out wider areas of applications

iii. The time interval of treatment should be increased to say 5, 10, and 15 minutes to know how it affects the properties of fabrics made from these plied yarns. Other types of surface modifications should be explored apart from alkali treatment for comparison purposes and to know their effects on the composite mechanical properties.

iv. A study on the effect of the number of fabric plies on the mechanical properties of composite materials should also be carried out. This can be achieved by increasing the number of ply to a number greater than three (3).

v. To know the effect on mechanical properties, fabrics made from cotton fibre and other natural fibres should be hybridized with fabrics made from conventional fibres such as glass and carbon fibres and their composite properties studied.

## REFERENCES

Abdelmouleh, M., Boufis, S., Belgacem, M.N., and Dufresne, A. (2007). Short natural-fibre-reinforced polyethylene and natural rubber composites: Effect of silane coupling agents and fibre loading. *Composite Science and Technology, 67*(7-8), pp.1627-1639.

Abubakar M.A., Ahmad S., Kuntjoro W. (2010). The mechanical properties of treated and untreated kenaf fibre-reinforced epoxy composite. *Journal of Biobased Materials and Bioenergy*; 4: pp. 159–63.

Adine G., Laetitia V., and Riette de B. (2007). Cotton/polyester and cotton/nylon warp knitted terry cloth: Why minority fibre content is important. *Journal of Family Ecology and Consumer Sciences*, Vol 35. pp. 1-8

Agarwal, B. D., Broutman, J.L. and chandrashekhara K. (2006). Analysis and Performance of Fibre Composites, 2nd Edition. USA: Wiley-Intescience, New York, 355– ISBN 0-471-26891-7

Agrawal, R. Saxena N. S., Sharma, K. B. Thomas, S. and Sreekala, M. S. (2000) *Materials Science and Engineering A*, **277**, pp. 77.

Ahmed, K. S., Vijayarangan, S., and Kumar, A. (2007). Low velocity impact damage characterization of woven jute–glass fabric-reinforced isophthalic polyester hybrid composites. *Journal of Reinforced Plastics and Composites*, 26(10), pp. 959–976.

Alavudeen A., Thiruchitrambalam M., Venkateshwaran N. and Athijayamani A. (2011). Review of Natural Fibre-Reinforced Woven Composite. *Rev. Advanced Material Science* 27, pp 146-150.

Al-Kaabi K, Al-Khanbashi A, Hammami A. (2005). Date palm fibres as polymeric matrix reinforcement: DPF/polyester composite properties. *Polymer Composites*; 26: pp. 604–13.

Al-Mosawi, A.I. (2009). Study of some mechanical properties for polymeric composite material reinforced by fibres. *Al-Qadisiya Journal for Engineering Science,* 2(1), pp. 14 – 24.

Alsina O. L. S., Carvalho L. H. D., Filho F. G. R. and. Almeida, J.R.M.D. (2005). Thermal properties of hybrid lignocellulosic fabric-reinforced polyester matrix composites, *Polymer Testing, 24*, pp.81-85.

American Composites Manufacturers Association (2004). Composites Basics: Materials (Part 2), 1010 North Glebe Road, Arlington, Va 22201, New York. P: 703-525-0511, F: 703-525-0743 E: Info@Acmanet.Org

Arib, R.M.N., Sapuan, S.M., Hamdan, M.A.M.M., Paridah, M.T. and Zaman, H.M.D.K. (2004). A Literature Review of Pineapple Fibre-Reinforced Polymer Composites. *Polymer and Polymer Composites*. 12(4): pp.341-348.

Baley, C, Busnel F, Grohens Y, Sire O. (2006). Influence of chemical treatments on surface properties and adhesion of flax fibre–polyester resin. *Composites Part A: Applied Science and Manufacturing*; 37: pp.1626–37.

Bannister, M., and Herszberg, I. (1995). The manufacture and analysis of composite structures from knitted preforms, in *Proceedings 4th International Conference on Automated Composites*, 6–7 September 1995 Nottingham, UK, 2: Institute of Materials. pp.397–404.

Belgacem, M.N., Bataille, P. and Sapieha, S. **(**1994). Effect of corona modification on the mechanical properties of polypropylene/cellulose composites. *Journal of Applied Polymer Science* 53: pp.379-385.

Bessadok, A., Marais, S., Gouanve, F., Colasse, L., Zimmerlin, I., Roudesli, S., and Metayer, M. (2007). “Effect of Chemical Treatments of Alfa (Stipa Tenacissima) Fibres on Water-Sorption Properties,” *Composites Science and Technology*, Vol. 67, No. 3-4, 2007, pp. 685-697. doi:10.1016/j.compscitech.2006.04.013

Bhuiyan, M.T.R. and Sobue N.H.N. (2001). Effect of intermittent heat treatment on crystallinity in wood cellulose. *Journal of Wood Science*. 47: pp. 336-341.

Bisanda, E.T.N. and Ansell, M. P, (1991). The effect of silane treatment on the mechanical and physical properties of sisal-epoxy composites. *Composites Science and Technology,* Oxford, v.41, pp.165-178.

Bledzki, A.K. and Gassan, J. (1999). Composites reinforced with cellulose-based fibres. *Prog. Polymer Science* 24: pp. 221-274. doi:10.1016/S0079-6700(98)00018-5

Bledzki A.K., Sperber V.E. and Faruk O. (2002). Natural and wood fibre reinforcement in polymers. *Rapra Review Reports*. Vol. 13; No. 8. pp. 1-144

Bledzki, A. K., Reinhmane, S. and Gassan, J. (1998). Thermoplastics reinforced with wood fillers. *Polymer Plastics, Technology and Engineering* 37: pp. 451-468.

Boynard, C. A., Monteiro S. N. and D’Almeida, J. R. M., (2003). “Aspects of Alkali Treatment of Sponge Gourd (Luffa Cylindrica) Fibres on the Flexural Properties of Polyester Matrix Composites,” *Journal of Applied Polymer Science*, Vol. 87, No. 12, pp. 1927-1932. doi:10.1002/app.11522

Brandt, J., Drechsler, K. and Meistring, R., (1990). The application of three-dimensional fibre preforms for aerospace composite structures. In *Proceedings of an international symposium organised by the European Space Agency and held at ESTEC*. Noordwijk, The Netherlands, 21-23 March, pp. 7 l-77.

Bueno M.A., Renner M., Pac M.J. (2002). (Influence of properties at micro – and meso-scopic levels on macroscopic level for weft knitted fabrics) *Journal of Materials Science* volume 37, issue 14 pp. 2965-2974

Burger, H. Koine, A. Maron, R. Mieck, K.P. Faser, G. K. (1995). Use of natural fibres and environmental aspects. *International Polymer Science Technology* vol.22, 18, pp.25-34.

Byun, J. H. and Chou, T. W. (1996). Process-microstructure relationships of 2-Step and 4-Step braided composites. *Composites Science and Technology*, 56, pp. 235-251.

Carrillo, F., Colom, X. and Canavate, X (2010). “Properties of regenerated cellulose lyocell fibre-reinforced composites,” *Journal of Reinforced Plastics and Composites* 29(3), pp. 359-371.

Cao, Y., Shibata S., and Fukumoto, I. (2006) “Mechanical properties of biodegradable composites reinforced with bagasse fibre before and after alkali treatments,” *Composite A. Applied Science and Manufacturing*, Vol. 37, No. 3, pp. 423-429. doi:10.1016/j.compositesa.2005.05.045

Chand, N., and Jain, D. (2005). Effect of sisal fibre orientation on electrical properties of sisal fibre-reinforced epoxy composites. *Composites Part A: Applied Science and Manufacturing*; 36: pp. 594–602.

Chawla, K.K. and Bastos, A.C. (1979). The mechanical properties of jute fibers and polyester/jute composites. *In the Proceedings of the 3rd International Conference on Mechanical Behaviour of Materials.* Cambridge, England. pp. 191-196.

Chou, S. and Wu, C. J., (1992). A study of the physical properties of epoxy resin composites reinforced with knitted glass fibre fabrics. *Journal of Reinforced Plastics* and *Composites*, ll (11, November), pp. 1239-1250.

Chow, C.P.L., Xing, X.S, Li, R.K.Y. (2007). Moisture absorption studies of sisal fibre-reinforced polypropylene composites. *Composites Science and Technology*; 67: pp.306–313.

Cicala, G., Cristaldi, G., Recca, G., Ziegmann, G., El-Sabbagh, A., and Dickert, M. (2009). Properties and performances of various hybrid glass/natural fibre composites for curved pipes. *Materials and Design*; 30: pp. 2538–42.

Cichocki, F.R. and Thomason, J.L. (2002). Thermo-elastic anisotropy of a natural fibre. *Composites Science and Technology*. 62: pp. 669-678.

Corrales F., Vilaseca,F., Llop, M.,Girones, J., Mendez, J.A. and Mutje,P. (2007).”Chemical treatment of jute fibres for the production of green composites” *Journal of Hazardous Materials* 144(3), pp.730-735.

Cox, B. N., Dadkhah, M. S. and Morris, W. L., (1996). On the tensile failure of 3D woven composites. *Composites,* Part *A, 27A,* pp. 447-458.

Cox, B. N., Dadkhah, M. S., Morris, W. L. and Flintoff, J. G., (1994). Failure mechanisms of 3D woven composites in tension, compression, and bending. *Acta Metallurgica et Marerialia* 42(12), pp.3967-3984.

Cox, B. N. and Dadkhah, M. S. (1995). The macroscopic elasticity of 3D woven composites. *Journal of Composite Materials*, 29(6), pp.785-819.

Cox, B. N., Dadkhah, M. S., Inman, R. V., Morris, W. L. and Zupon, J., (1992). Mechanisms of compressive failure in 3D composites. *Acta Metallurgica et Marerialia*, 40, pp. 3285-3298.

Crane, R.M, and Camponeschi, Jr ET. (1986). Experimental and analytical characterization of multidimensional braided graphite/epoxy composites. *Experimental Mechanics*: pp. 259–266.

Culler S.R., Ishida H. and Koenig J. L. (1986). The silane interphase of composites: effects of conditions on γ-aminopropyltriethoxysilane. *Polymer Composites*, 7(4), pp. 231-238.

Dahlke, B., Larbig, H., Scherzer, H., Poltrock, R. (1998). Natural fibre-reinforced foams based on renewable resources for automotive interior applications. *Journal of Cellular Plastics.* 34(4): pp. 361-379.

Das, M., Chakraborty, D. (2006). Influence of alkali treatment on the fine structure and morphology of bamboo fibres. *Journal of Applied Polymer Science*; 102: pp.5050–5056.

De Albuquerque, A., Joseph, K., Hecker de Carvalho, L. and Morais d’Almedia, J. (1999). Effect of wetability and ageing conditions on the physical and mechanical properties of uniaxiallly oriented jute-roving-reinforced polyester composites. *Compos. Sci. Technol.* 60: pp. 833-844.

Deo C, and Acharya S.K. (2010). Effect of moisture absorption on mechanical properties of chopped natural fibre-reinforced epoxy composite. *Journal of Reinforced Plastics and Composites*; 29: pp. 2513–21.

De Medeiros, E. S., Agnelli, J. A. M., Joseph, K., De Carvalho, L. H., and Mattoso, L. H. C. (2005). Mechanical properties of phenolic composites reinforced with jute/cotton hybrid fabrics. *Polymer Composites*, 26(1), pp.1–11.

Devi, L., Bhagawan, S. and Thomas, S. (1997). Mechanical properties of pineapple leaf fibre-reinforced polyester composites. *Journal of Applied Polymer Science* 64: pp. 1739-1748.

Dong, S., Sapieha, S. and Schreiber, H. P. (1992). *Polymer Engineering Science*, vol. 32, pp.1734-1739

Du, G. W. and Chou, T. W., (1991). Analysis of three-dimensional textile preforms for multidirectional reinforcement of composites. *Journal of Materials Science*. 26. pp. 3438-3448.

Du, G. W. and Ko, F. K., (1993). Unit cell geometry of 3-D braided structures. *Journal of Reinforced Plastics and Composites*, 12, pp. 752-768.

Eichhom, S.J., (2001). Review. Current international research into cellulosic fibres and composites. *Journal of Materials Science*. 36: pp. 2107-2131.

Eichhom, S.J, and Young R.J. (2004). Composite micromechanics of hemp fibres and epoxy resin micro-droplets. *Composites Science and Technology*; 64: pp. 767–72.

Elsabbagh, A., Steuernagel, L., and Ziegmann, G. (2009). Manufacturing of flax/polypropylene composites. *Journal of Applied Polymer Science*, **111**, pp. 2279.

Fujita, A., Yokoyama, A. and Hamada, H., (1995). Simulation of mechanical behaviours of knitted fabric composites by numerical analysis method. In *Proceedings of the American Society for Composites, Tenth Technical Conference. 18-20* October, 1995, pp. 581-590.

Ganan, P., Garbizu S., Llano-Ponte R., and Mondragon I. (2005). Surface modification of sisal fibres: effects on the mechanical and thermal properties of their epoxy composites. *Polymer Composites*; 26: pp.121–7.

Gassan, J. and Bledzk,i A. J. (1997). Effect of moisture content on the properties of silanized jute-epoxy. *Polymer Composites*, 18, 2, pp. 179-184.

Gassan, J. and Bledzki, A. K. (1999) Possibilities for improving the mechanical properties of jute/epoxy composites by alkali treatment of fibres. *Composites Science and Technology*, 59, pp. 1303-1309.

George, J., Bhagawan, S. S. and Thomas, S. (1998). Improved interactions in chemically modified pineapple leaf fibre-reinforced polyethylene composites. *Composite Interfaces*, 5(3), pp. 201-223.

Ghatge, N. D. and Khisti, R. S. (1989). Performance of new silane coupling agents along with phenolic no-bake binder for sand core. *Journal of Polymer Materials*, 6, pp. 145-149.

Giovanni, C., Salvatore M., Giuseppe S. and Ivo M. S. (2000). *'Reference Books of Textile Technology: Weaving'.* Fondazione ACIMIT Italian Association of Textile Machinery Producers Moral Body pp 8-9.

Goda, K., Sreekala, M.S., Gomes, A., Kaji, T. and Ohgi, J. (2006). Improvement of plant-based natural fibres for toughening green composites: Effect of load application during mercerization of ramie fibres. *Composites Part A. Applied Science and Manufacturing* **37**: pp. 2213-2220.

Gonzalez-Murillo, C, and Ansell, M.P. (2010). Co-cured in-line joints for natural fibre composites. *Composites Science and Technology*; 70: pp. 442–9.

Goutianos, S., Peijs, T., Nystrom, B. and Skrifvars, M. (2006). Development of Flax Fibre Based Textile Reinforcements for Composite Applications. *Applied Composite Materials* 13: pp. 199 – 215.

Goutianos, S., and Peijs, T. (2003). The optimization of flax fibre yarns for the development of high-performance natural fibre composites. *Advanced Composites Letters*, *12*(6), pp. 237-241.

Gowda, T. M., Naidu, A. C. B. and Chhaya. R. (1999). Some mechanical properties of untreated jute fabric-reinforced polyester composites, *Composites Part A: Applied Science and Manufacturing*, *30,* pp.277-284.

Haq M., Burgueno R., Mohanty A.K. and Misra M. (2008). Hybrid bio-based composites from blends of unsaturated polyester and soybean oil reinforced with nanoclay and natural fibres. *Composites Science and Technology*; 68: pp. 3344–51.

Hedenberg, P. and Gatenholm, P. (1995). Conversion of plastic/cellulose waste into composites. *Journal of Applied Polymer Science* 56: pp. 641-651.

Hepworth, D.G., Bruce, D.M., Vincent, J.F.V. and Jeronimidis G. (2000a). The manufacture and mechanical testing of thermosetting natural fibre composites. *Journal of Materials Science;* 35: pp. 293–8.

Hepworth, D.G, Hobson, R.N., Bruce D.M. and Farrent, J.W. (2000b). The use of unretted hemp fibre in composite manufacture. *Composites Part A: Applied Science and Manufacturing*; 31: pp. 1279–83.

Herrera-Estrada, L., Pillay S, Vaidya U. (2008). Banana fibre composites for automotive and transportation applications. In: 8th annual SPE automotive composites conference and exhibition. http://www.speautomotive.com/SPEACD/SPEA2008/pdf/c/BNF-02.pdf [accessed April 2012], BNF-02/1-9.

Herrera-Franco, P.J. and Valadez-Gonzalez, A., (2005). A study of the mechanical properties of short natural-fibre-reinforced composites. *Composites Part B*, 36(8), pp. 597–608.

Hull, D. and Clyne, T.W. (1996). *An Introduction to Composite Materials*, 2nd ed., Cambridge University Press, New York, pp. 47.

Hyer, M. W. (1998). Stress Analysis of Fibre-Reinforced Composite materials. The McGraw-Hill Companies Inc. USA.

Idicula, M., Neelakantan, N. R., Oommen, Z., Joseph, K., and Thomas, S. (2005a). A study of the mechanical properties of randomly oriented short banana and sisal hybrid fibre-reinforced polyester composites. *Journal of Applied Polymer Science*; 96: pp. 1699–709.

Idicula, M., Malhotra, S. K., Joseph, K., and Thomas, S. (2005b). Effect of layering pattern on dynamic mechanical properties of randomly oriented short banana/sisal hybrid fibre-reinforced polyester composites. *Journal of Applied Polymer Science*, 97(5), pp.2168–2174.

Ishikawa, T. and Chou, T. W. (1983). One-dimensional micromechanical analysis of woven fabric composites. *AZAA Journal*, 21(12), pp.1714-1721.

Jacob, M., Varughese, K.T. and Thomas, S. (2006). Novel woven sisal fabric-reinforced natural rubber composites: tensile and swelling characteristics, *Journal of Composite Materials.* vol. **41**, pp. 5538

Jain, S., Kumar, R. and Jindal, U.C. (1992). Mechanical behaviour of bamboo and bamboo composite. *Journal of Material Science*; 27: pp. 4598–604.

Jain, S., Kumar R. and Jindal, U.C. (1993). Development and fracture mechanism of the bamboo/polyester resin composite. *Journal of Material Science Letter*; 12: pp. 558–60.

Joseph, K. and Thomas, S. (1995). Effect of Ageing on the Physical and Mechanical Properties of Sisal Fibre-Reinforced Polyethylene Composites. *Composites Science & Technology* 53: pp. 99-110.

Joshy, M. K., Mathew, L. and Joseph, R. (2006). Studies on interfacial adhesion in unidirectional isora fibre-reinforced polyester composites Composite interfaces 13: pp. 4377-4390.

Junior, C.Z.P., Carvalho, L.H., Fonseca, V.M., Monteiro, S.N. and Almeida, J.R.M., (2004**)** Analysis of the tensile strength of polyester/hybrid ramie–cotton fabric composites, *Polymer Testing,* pp.131-135

Kargarfard., A. and Jahan-Latibari, A. (2011). The performance of corn and cotton stalks for medium density fibreboard production*, BioResources* 6(2*),* pp. 1147-1157.

Kaw, A. K. (1997). Mechanics of Composite Materials (second edition). CRC Press, New York, NY

Kalam, A., Sahari, B.B., Khalid, Y.A. and Wong S.V. (2005). Fatigue behaviour of oil palm fruit bunch fibre/epoxy and carbon fibre/epoxy composites. *Composite Structures*; 71: pp. 34–44.

Khalid, A.A., Sahari, B. and Khalid Y.A. (1998). Environmental Effects on the Progressive Crushing of Cotton and Glass Fibre/Epoxy Composite Cones. In: Proceedings of the Fourth International Conference on Advances in Materials and Processing Technologies, 98, Kuala Lumpur, pp. 680–89.

Kim, H.J. and Seo, D.W. (2006). Effect of water absorption fatigue on mechanical properties of sisal textile-reinforced composites. *International Journal of Fatigue*; 28: pp.1307–14.

Klein, W. (1998). The technology of short-staple spinning. 2nd ed. The Textile Institute, Manchester, United Kingdom. ISBN 0900739916, pp. 20-40

Klemm, D., Philipp, B., Heinze, T., Heinze, U. and Wagenknecht, W. (1998) in *Comprehensive Cellulose Chemistry"*, vols. I-II, Wiley-VCH, Chichester, 1998, pp. 35-42.

Koma. B. V., Maldas, D., Daneault, C. and Beland, P. (1990). (A review on interface modification and characterization ), *Journal of Vinyl Technology*. 12, pp. 146

Kumar, P. (1986). Mechanical properties of jute fibres and their composites. *Indian Journal of Technology* 24: pp. 29-32.

Kuo, W. S. (1995). Elastic behaviour and damage of three-dimensional woven fabric composites. In *The Tenth International Conference on Composite Materials.* Whistler, British Columbia, Canada, 14- 18 August, pp. 301-308.

Lai, W.L., Mariatti, M. and Mohammed, J.S. (2008). Betel Palm Woven Hybrid Composite Characteristics and Testing Features. *Polymer Plastics Technology and Engineering*, 44: pp. 235.

Laroche, D., Khanh, V. T. and Julien, H., (1994). Forming of woven fabric composites. *Journal of Composite Materials, 28(18), pp.1825- 1839.*

Le Digabel, F. Boquillon, N. Dole, P., Monties, B., and Averous, L. (2004). Properties of thermoplastic composites based on wheat straw linocellulosic fillers, *Journal of Applied Polymer Science*, vol **93**, pp. 428-436.

Leman, Z., Sapuan, S.M., Saifol, A.M., Maleque, M.A. and Ahmad M.M.H.M. (2008). Moisture absorption behaviour of sugar palm fibre-reinforced epoxy composites. *Materials and Design*; 29: pp. 1666–70.

Leong, K. H., Ramakrishna, S. and Hamada, H., (1997). 'The potential of knitting for engineering composites', in *Proceedings of 5th Japan SAMPE Symposium*, Tokyo, Japan. 197-220

Li, X. (2008). Development of flax fibre reinforced biocomposites for potential application for automotive industries (Unpublished Doctoral Dissertation), University of Saskatchewan, Canada, pp. 164-170.

Li, W. and Shiekh, A. E., (1988). The effect of processes and processing parameters on 3-D braided preforms for composites. In 33rd Inter*national SAMPE Symposium,* 7-10 March , pp. 104-115.

Luo, S. and Netravali, A. (1999). Mechanical and thermal properties of environment-friendly "green" composites made from pineapple leaf fibres and poly (hydroxybutyrate-co- valerate) resin. *Polymer Composite* 20: pp. 367-78.

Macander Jr. A.B, Crane, R.M. and Camponeschi, E.T. (1986). Fabrication and mechanical properties of multidimensional (X-D) braided composite materials, Composite Materials: Testing and Design (Seventh Conference), ASTM STP 893. Philadelphia, PA: American Society for Testing and Materials, pp. 422–443.

Mäder, E. and Gliesche, K. (1995). Langfaserverstärkte Kunststoffe auf der Basis von Naturfasern. 7th International Techtextile-Symposium, Frankfurt, Germany, pp. 20-22. 6.

Madsen, B. (2004). Properties of Plant Fibre Yarn Polymer Composites. An Experimental Study (Unpublished PhD Thesis). Department of Civil Engineering Technical University of Denmark, pp. 53-68

Madsen B. and Lilholt, H. (2003) Physical and mechanical properties of unidirectional plant fibre composites – an evaluation of the influence of porosity. *Composites Science and Technology*; 63: pp.1265–72.

Maiti, S.N. and Singh, K. (1986). Influence of wood flour on the mechanical properties of polyethylene. *Journal Applications of Polymer Science* 32: pp. 4285-4289.

Maldas, D. and Kokta, B.V. (1995). Composites of Chlorinated Polyethylene wood fibres. *Journal of Reinforced Plastic Composites.* 14: pp. 458-470.

Maldas, D. and Kokta, B.V. (1993). Performance of hybrid reinforcement in PVC composites. J*ournal of Testing Evaluation.* 2: pp. 68-72.

Maldas, D. Raj, R.G., Kokta B.V. and Daneault, C, (1989a). Influence of coupling agents and treatments on the mechanical properties of cellulose fibre-polystyrene composites. *Journal of Applied Polymer Science* 37: pp.751-775.

Maldas, D., Kokta, B.V. and Daneault, C. (1989b). Composites of polyvinyl chloride-wood fibres. IV. Effect of the nature of fibres. *Journal of Vinyl Technology* 11: pp. 90-99.

Manfredi, L.B., Rodríguez, E.S., Wladyka-Przyblak, M. and Vásquez, A. (2006). Thermal degradation and fire resistance of unsaturated polyester, modified acrylic resins and their composites with natural fibres. Polymer Degradation and Stability; 91: pp.255–61.

Marsden, W. Boniface, L., Ogin, S.L. and Smith, P. A., (1994). ‘Quantifying damage in woven glass fibre/epoxy laminates,’ in Proceedings *FRC ’94*, Sixth International Conference on fibre-reinforced Composites, Newcastle upon Tyne, Institute of Materials, paper 31, pp. 31/1–31/9.

Masters, J. E., Foye, R. L., Pastore, C. M. and Gowayed, Y. A., (1993). Mechanical properties of triaxially braided composites: Experimental and analytical results. *Journal of Composites Technology and Research*, G (2), pp. 112-122.

Mathur, V.K. (2006). Composite materials from local resources. *Construction and Building Materials*; 20: pp. 470–7.

Meddahi, A., Ait Tahar, K. and Bibi, M. (2008). Studies of sisal fibre-containing composites. *Journal of Natural Fibres*; 5: pp. 36–46.

Mishra, S., Mohanty, A.K., Drzal, L.T., Misra, M. and Parija S. (2003). Studies on mechanical performance of biofibre/glass reinforced polyester hybrid composites. *Composites Science and Technology* **63**: pp. 1377–85.

Mishra, S., Naik, J.B. and Patil, Y.P. (2000). The compatibilising effect of maleic anhydride on swelling and mechanical properties of plant-fibre reinforced novolac composites. *Composites Science and Technology*. 60: pp.1729-1735.

Mishra, S., Misra, M., Tripathy, S.S., Nayak, S.K, and Moha, K.K. (2002). The influence of chemical surface modification on the performance of sisal-polyester. *Biocomposites. Polymer Composites*; 23: pp. 164–70.

Modibbo, U. U., Aliyu, B. A. and Nkafamiya, I. I. (2009). The effect of mercerization media on the physical properties of local plant bast fibres, *International Journal of Physical Sciences* Vol. 4 (11), pp. 698-704.

Mohanty, A.K., Misra, M. and Hinrichsen, G. (2001). Biofibres, biodegradable polymers and biocomposites: An overview. *Macromolecular Materials and Engineering*. 276/277: pp.1-24.

Mwaikambo, L.Y. and Ansell, M.P. (2002). Chemical Modification of Hemp, Sisal, Jute and Kapok Fibres by Alkalization, *Journal of Applied Polymer Science*; 84(12): pp. 2222-2234.

Mwaikambo, L.Y. and Bisanda, E.T.N. (1999). The performance of cotton/kapok fabric-polyester composites. *Polymer Testing* 18: pp. 181-198.

Naik, R. A. (1995). Failure analysis of woven and braided fabric-reinforced composites. *Journal of Composite Materials*, 29(17), pp. 2334- 2363.

Naik, N. K. and Ganesh, V. K. (1992). Prediction of on-axes elastic properties of plain weave fabric composites. *Composites Science and Technology, 45(2),* pp.135-152.

Naik, N.K. and Kuchibhotla, R. (2002). Analytical study of strength and failure behaviour of plain weave fabric composites made of twisted yarns. *Composites Part A: Applied Science and Manufacturing* **33**:5, pp.697-708

Naik, N. K., Shembekar, P. S. and Hosur, M. V. (1991). Failure behaviour of woven fabric composites. *Journal of Composites Technology and Research*, 13(l), pp.107-l 16.

Naik, N. K. and Shembekar, P. S. (1992a). Elastic behaviour of woven fabric composites: I- Lamina analysis. *Journal of Composite Materials*, 26 (15), pp. 2197-2225.

Naik, N. K. and Shembekar, P. S., (1992b). Elastic behaviour of woven fabric composites: III-Laminate design. *Journal of Composite Materials*, 26(17), pp. 2523-2541.

Naik, R. A., Ifju, P. G. and Masters, J. E. (1994). Effect of fibre architecture parameters on deformation fields and elastic moduli of 2-D braided composites. *Journal of Composite Materials*, 28(7), pp. 656-68 1.

Nishino, T., Hirao, K. and Kotera, M. (2006). X-ray diffraction studies on stress transfer of kenaf reinforced poly (l-lactic acid) composite. *Composites Part A*, 37(12), pp. 2269–2273.

Oksman, K. (2001). High quality flax fibre composites manufactured by the resin transfer moulding process. *Journal of Reinforced Plastics and Composites*; 20: pp. 621–627.

Ormerod, A. and Sondhelm, W. S. (1999). Weaving Technology and Operations, Woodhead Publishing Limited, Textile Institute, Manchester ISBN: 978-1-87081-276-4,

Owen, M. M. (2013). Effect of weaving parameters and fabric surface treatment on the mechanical properties of cotton fabric reinforced epoxy composites (Unpublished Master’s thesis). Ahmadu Bello University Zaria, Nigeria.

Owolabi, O., Czvikovszky, T. and Kovacs, I. (1985). Coconut fibre-reinforced thermosetting plastics. *Journal of Applied Polymer Science* 30: pp. 1827-1836.

Pal, S.K., Mukhopadhyay, D., Sanyal, S.K. and Mukherjee, R.N. (1988). Studies on process variables for natural fibre composites-effect of PEAP as interfacial agent. *Journal of Applied Polymer Science* 35: pp. 973-985.

Parikh, D.V., Calamari, T.A., Sawhney, A.P.S., Blanchard, E.J., Screen, F.J., Myatt, J.C., Muller, D.H. and Stryjewski, D.D. (2002). Thermoformable automotive composites containing kenaf and other cellulose fibres. *Textile Research Journal* ,72(8), pp. 668-672.

Paul, S., Nanda, P. and Gupta, R. (2003). PhCOCl-Py/Basic Alumina as a Versatile Reagent for Benzoylation in Solvent-Free Conditions, *Molecules*, 8, pp. 374.

Peters, R. H. (1979). *In Applied Fibre Science,* F. Happey, Ed.; Academic Press: London, Vol. 2. pp.47

Pochiraju, K., Ning, Q., Pravizi-majidi, A. and Chou, T. W. (1994). Prediction of mechanical and thermal properties of 3-D textile structural composites. *ICCE,* 1, pp. 95-96.

Pothan, L.A., Thomas, S., Li, R. K. Y. and Mai. Y.W. (2002). Tensile and impact properties of sisal fabric-reinforced polyester composites prepared by RTM technique, *Proceedings of International Conference on Textile Composites*, IIT Delhi, February.

Prakash, T., (2009). Processing and Characterization of Natural fibre-reinforced Polymer Composites. B.Tech Thesis, Dept of Mechanical Engineering, National Institute of Technology. ROURKELA-769008.

Prasad, S.V., Pavithran, C. and Pohatgi, P.K. (1983). Alkali treatment of coir fibres for coir–polyester composites. *Journal of Material Science* 18, pp. 1443-1454.

Raczs, I. and Hargitai, H. (2000). Influence of water on properties of cellulosic fibre-reinforced polypropylene composites. *International Journal of Polymer Material* 47: pp. 667-674.

Raj, R.G., Kokta, B.V. and Daneault, C.A. (1990). A comparative study on the effect of ageing on mechanical properties of LDPE-glass fibre, mica, and wood fibre composites. *Journal of Applied Polymer Science* 40: pp. 645- 655.

Raj, R. G., Kokta, B.V., Maldas, D. and Daneault, C. (1989). Use of wood fibres in thermoplastics. VII. The effect of coupling agents in polyethylene-wood fibre composites. *Journal of Applied Polymer Science* 37: pp. 1089- 1103.

Rajulu, A.V., Baksh, S.A., Reddy, G.R. and Chary, K.N. (1998). Chemical resistance and tensile properties of short bamboo fibre-reinforced epoxy composites. *Journal of Reinforced Plastic Composites*; 17: pp. 1507–11.

Ramires, E.C., Megiatto Jr., J.D, Gardrat, C., Castellan, A. and Frollini E. (2010) 'Biobased composites from glyoxal-phenolic matrices reinforced with microcrystalline cellulose,' *plimeros* 20 (2), pp. 126-133.

Rao, K.M.M., Rao, K.M. and Prasad, A.V.R. (2010). Fabrication and testing of natural fibre composites: vakka, sisal, bamboo and banana. *Materials and Design*; 31: pp. 508–13.

Ray, D., Sarkar, B. K., Rana, A. K. and Bose N. R. (2001) Effect of alkali treated jute fibres on composite properties. *Bulletin of Materials Science*, 24, 2: pp.129-135.

Robson, D., Hague, J., Newman, G., Jeronimidis, G., and Ansell, M. P., (1993). 'Survey of natural materials for use in structural composites as reinforcement and matrices, Natural materials for composites, EC/4316/92', The Biocomposites Centre, University of Wales, Bangor, pp. 1-71.

Roe, P. and Ansell, M. (1985). Jute reinforced polyester composites. *Journal of Materials Science* 20: pp. 4015-4020.

Rong, M.Z., Zhang, M.Q., Liu, Y., Yang, G.C. and Zeng, H.M. (2001). The effect of fibre treatment on the mechanical properties of unidirectional sisal-reinforced epoxy composites. *Composites Science and Technology*; 61: pp. 1437–47.

Ruan, X. P. and Chou, T. W., (1996). Experimental and theoretical studies of the elastic behaviour of knitted-fabric composites. *Composites Science and Technology* 56, pp. 1391- 1403.

Sahoo, S., Nakai, A., Kotaki, M., Ishiaku, U.S., Mohanty, A.K., Misra, M. and Hamada, H. (2007). Mechanical properties and durability of jute reinforced thermosetting composites. *Journal of Biobased Materials and Bioenergy*; 1: pp. 427–36.

Sain, M.M., Imbert, C. and Kokta, B.V. (1993). Composites of surface treated wood fibre and recycled polypropylene. *Angew. Makromol. Chem.* 210: pp. 33-46.

Sain, M.M. and Kokta, B.V. (1994). Polyolefin-wood filler composite. I. Performance of m-phenylene bismaleimide-modified wood fibre in polypropylene composites. *Journal of Applied Polymer Science* 54: pp. 1545-1559.

Saira, T., Munawar, A. M. and Shafiullah, K. (2007) Natural Fibre-Reinforced Polymer Composites *Proc. Pakistan Acad. Sci. 44(2)*: pp. 129 -144.

Santulli, C., (2001). "Post-impact damage characterization on natural fibres-reinforced composites using acoustic emission", *Independent Nondestructive Testing and Evaluation International (NDT&E)* 34, pp. 531-536.

Santulli, C., and Caruso, A.P. (2009). Effect of fibre architecture on the falling weight impact properties of hemp/epoxy composite. *Journal of Biobased Materials and Bioenergy*; 3: pp. 291–297.

Satyanarayana, K. (1983). Performance of banana fabric-polyester resin composites. In: *Composite structures.* Proceedings of the International Conference, London, Applied Science. Ed. Marshall, I.H., pp. 535-48.

Scarponi, C., Pizzinelli, C.S., Sanchez-Saez, S. and Barbero E. (2009). Impact load behaviour of resin transfer moulding (RTM) hemp fibre composite laminates. *Journal of Biobased Materials and Bioenergy*; 3: pp. 298–310.

Schaffer and Prakash, (2009). *The Science and Design of Engineering Materials*: Published by IRWIN. Chicago. pp. 12-48

Sgriccia, N. and Hawley, M.C. (2007). Thermal, morphological, and electrical characterization of microwave processed natural fibre composites. *Composites Science and Technology*; 67: pp. 1986–91.

Sharifah, H. A., Martin, P. A., Simon, J. C. and Simon, R. P. (2005). "Modified Polyester Resins for Natural Fibre Composites," *Composites Science and Technology*, Vol. 65, No. 3-4, pp. 525-535.

Shembekar, P. S. and Naik, N. K. (1992). Elastic behaviour of woven fabric composites: II-Laminate analysis. *Journal of Composite Materials*, 26(15), pp.2226-2246.

Shih, Y.F. (2007). Mechanical and thermal properties of waste water bamboo husk fibre-reinforced epoxy composites. *Material Science and Engineering Structures;* 445–446: pp 289–95.

Shibata, S., Cao, Y. and Fukumoto, I. (2006). Lightweight laminate composites made from kenaf and polypropylene fibres. *Polymer Testing*, 25(2), pp. 142–148.

Siau, J.F. (1995). Wood: Influence of moisture on physical properties. Department of Wood Science and Forest Products, Virginia Polytechnic Institute and State University, USA. pp. 98 - 100

Simpson, R. and Selke, S. (1991). Composite materials from recycled multi-layer polypropylene bottles and wood fibres. *Polymer Preparation. American Chemical Society, Division of Polymer Chemistry* 32: pp. 148-149.

Sinha, R., (2000). *Outlines of Polymer Technology. Prentice-Hall by India private Ltd.* New Delhi – pp. 10001.

Smith, L. V. and Swanson, S. R., (1995). Micro-mechanics parameters controlling the strength of braided composites. *Composites Science and Technology*. 54(2), pp.177-184.

Stover, E.R., Marck, W.C., Marfowitz, I. and Mueller W. (1971). Preparation of an omniweave-reinforced carbon–carbon cylinder as a candidate for evaluation in the advanced heat shield screening program, Report AFML-TR-70-283, March 1971.

Sydenstricker, T.H.D., Mochnaz, S. and Amico, S.C. (2003). Pull-out and other evaluations in sisal-reinforced polyester biocomposites. *Polymer Testing*, 22, pp. 375-380.

Tang, X. Whitcomb, J. D. Li, Y. and Sue, H.J. (2005). Micromechanics modeling of moisture diffusion in woven composites, *Composites Science and Technology, 65,* pp.817-826.

Tao, W. Y., Calamari, J. T. A., Shih, F. F. and Cao C.Y. (1997). Characterization of Kenaf-Fibre Bundles and Their Nonwoven Mats. *Tappi Journal* 80(12) pp.162-166.

Towo, A.N. and Ansell, M.P. (2008a). Fatigue of sisal fibre-reinforced composites: constant-life diagrams and hysteresis loop capture. *Composites Science and Technology*; 68: pp. 915–24.

Towo, A.N. and Ansell, M.P. (2008b). Fatigue evaluation and dynamic mechanical thermal analysis of sisal fibre-thermosetting resin composites. *Composites Science and Technology*; 68: pp. 925–32.

Tserki, V., Zafeiropoulos, N.E., Simon, F., and Panayiotou, C. (2005). A study of the effect of acetylation and propionylation surface treatments on natural fibres. *Composites: Part A, 36*(8), 1110–1118.

Vandeurzen, P., Ivens, J. and Verpoest, I., (1995). Structure-performance analysis of two-dimensional woven fabric composites. In The Tenth *International Conference on Composite Materials,* Vol. IV, Whistler, British Columbia, Canada, 14-18 August, pp. 261-268.

Van de Weyenberg I, Chi Truong, T., Vangrimde, B. and Verpoest, I. (2006). Improving the properties of Uni-Directional flax fibre-reinforced composites by applying an alkaline fibre treatment. *Compos Part A – Applied Science*; 37: pp.1368–76.

Vazguez, A., Riccieri, J. and Carvalho, L. (1999). Interfacial properties and initial step of the water sorption in unidirectional unsaturated polyester/ vegetable fibre composites. *Polymer Composites* 20:pp. 29- 37.

Vignesh, R.S.B., Giri, V.R.D. and Mohamed, P. A. (2011). Acid resistance of flax-braided reinforced epoxy composite tubes, *Indian Journal of Fibre & Textile Research* Vol. 36, pp. 215-220

Vilay, V., Mariatti, M., Taib, R.M. and Todo M. (2008). Effect of fibre surface treatment and fibre loading on the properties of bagasse fibre-reinforced unsaturated polyester composites. Composites Science and Technology; 68: pp.631–8

Wakida, T. and Tokino, S. (1996).  Polymeric materials by discharge treatment and its application to textile processing Indian Journal of Fibre & Textile Research Vol. 21, pp. 69-78

Wambua, P., Ivens, U. and Verpoest, I. (2003). Natural fibres: can they replace glass in fibre-reinforced plastics? *Composites Science and Technology* 63: pp.1259- 1264.

Wambua, P., Vangrimde, B., Lomov, S. and Verpoest. I. (2007). The response of natural fibre composites to ballistic impact by fragment simulating projectiles *Composite Structures* 77 (2), pp. 232-240

Wan, Y.Z., Wang, Y.L., Cheng, G.X., Han, K.Y. (2002**).** Three-dimensionally braided carbon fibre–epoxy composites, a new type of material for osteosynthesis devices. I. Mechanical properties and moisture absorption behaviour, *Journal of Applied Polymer Science* 85 pp.1031-1039.

Wang, B., Panigrahi, S., Tabil, L. and Crerar, W. (2007). (Pre-treatment of flax fibers for use in rotationally moulded biocomposites), *Journal of Reinf*orced *Plastic Composite*, **26**,pp. 447–463

Wang, M. and Laird, C., (1994). Damage and fracture mechanisms in cross-woven composite subjected to tensile loading. In *The Nineth International Conference on Composite material*, pp. 117- 124.

Wazzan, A.A., (2005**)** Effect of fibre orientation on the mechanical properties and fracture characteristics of date palm fibre reinforced composites, *International Journal of Polymeric Materials*, Vol. 54 (3), pp.213-225.

White, N. and Ansell, M., (1983). Straw-reinforced polyester composites. *Journal of Material Science* 18: pp.1549-1556.

Woodhams, R.T., Thomas, G. and Rogers, D.K, (1984) Wood fibres as reinforcing fillers for polyolefins. *Polymer Engineering Science* 24(15): pp.1166-1171.

Wu, W. L., Kotaki, M., Fujita, A., Hamada, H., Inoda, M. and Maekawa, Z. I. (1993). Mechanical properties of warp-knitted, fabric-reinforced composites. *Journal of Reinforced Plastics and Composites*, 12, pp. 1096-l 110.

Xu, J., Cox, B. N., Mcglockton, M. A. and Carter, W. C. (1995). A binary model of textile composites-II. The elastic regime. *Acta Metallurgica et Materialia*, 43(9), pp. 351 l-3524.

Yam, K.L., Gogi, B.K., Lai, C.C and Selke S.E. (1990). Composites from compounding wood fibres with recycled high density polyethylene. *Polymer Engineering Science* 30: pp. 693-699.

Yan, L. (2004). The investigation of fracture properties of sisal textile reinforced polymers. *Acta Mechanica Solida Sinica*; v 17: pp. 95–103.

Yan, L., Sreekala, M. S., Jacob, M. (2002). Textile Composites based on natural fibres. School of Aerospace Engineering and Applied Mechanics, Key Laboratory of Advanced Civil Engineering Materials, Ministry of Education, Tongji University, Shanghai, 200092, P.R.China, pp.1 -26

Yan L., Yiu-Wing M. and Lin Y. (2005). Effects of fibre surface treatment on fracture-mechanical properties of sisal-fibre composites. *Composite Interfaces*, 12, 1-2, pp. 141–163.

Zeronian, S.H., Kawabata, H. and Alger, K.W. (1990). Factors affecting the tensile properties of non-mercerized and mercerized cotton fibres. Textile Research Journal. 60: pp. 179-183.

Zhang, T. (2003). Improvement of kenaf yarn for apparel applications, [electronic resource]. (Unpublished Master thesis), The School of Human Ecology, Louisiana State University, (Baton Rouge, La.).

Zhang, Y. C. and Harding, J., (1990). A numerical micromechanics analysis of the mechanical properties of a plain weave composite. *Computer and Structures*, 36(5), pp. 839-844.

# APPENDICES

## APPENDIX A: TENSILE STRENGTH AND MODULUS OF COMPOSITES

Table A1: Effects of alkaline treatments on the tensile strength of composites reinforced with single fabric

| S/N | TENSILE STRENGTH (MPa) | | | | |
|---|---|---|---|---|---|
| | **Reinforcements** | **Polyester** | **Untreated** | **1 minute** | **2 minutes** |
| | | 10.23 | | | |
| **1** | **Plain single** | | 15.0 | 17.57 | 17.50 |
| **2** | **Twill single** | | 18.50 | 22.42 | 22.9 |
| **3** | **Knitted single** | | 13.50 | 14.30 | 13.55 |

Table A2: Effects of alkaline treatments on the tensile modulus of composites reinforced with single fabric

| S/N | TENSILE MODULUS (MPa) | | | | |
|---|---|---|---|---|---|
| | **Reinforcements** | **Polyester** | **Untreated** | **1 minute** | **2 minutes** |
| | | 623.78 | | | |
| **1** | **Plain single** | | 1153.85 | 1337.81 | 1287.5 |
| **2** | **Twill single** | | 1005.43 | 1455.84 | 1356.82 |
| **3** | **Knitted single** | | 783.37 | 717.39 | 813 |

Table A3: Effects of alkaline treatments on the tensile strength of composites reinforced with two (2) layers of fabrics

| **S/N** | **TENSILE STRENGTH (MPa)** | | | | |
|---|---|---|---|---|---|
| | **Reinforcements** | **Polyester** | **Untreated** | **1 minute** | **2 minutes** |
| | | 10.23 | | | |
| **1** | **Plain-Plain** | | 17.50 | 22.0 | 22.50 |
| **2** | **Twill-Twill** | | 19.0 | 27.88 | 26.50 |
| **3** | **Knitted-Knitted** | | 16.50 | 18.11 | 19.0 |
| **4** | **Plain-Twill** | | 19.50 | 24.65 | 22.50 |
| **5** | **Plain-Knitted** | | 15.0 | 16.89 | 14.0 |
| **6** | **Knitted-Twill** | | 16.0 | 18.58 | 18.50 |

Table A4: Effects of alkaline treatments on the tensile modulus of composites reinforced with 2 layers of fabrics

| **S/N** | **TENSILE MODULUS (MPa)** | | | | |
|---|---|---|---|---|---|
| | **Reinforcements** | **Polyester** | **Untreated** | **1 minute** | **2 minutes** |
| | | 623.78 | | | |
| **1** | **Plain-Plain** | | 1339.29 | 1718.75 | 1288.17 |
| **2** | **Twill-Twill** | | 1045.87 | 1467.37 | 1024.48 |
| **3** | **Knitted-Knitted** | | 833.33 | 949.83 | 879.63 |
| **4** | **Plain-Twill** | | 1075.37 | 1684.51 | 1308.14 |
| **5** | **Plain-Knitted** | | 1130.65 | 1472.97 | 1312.50 |
| **6** | **Knitted-Twill** | | 1009.62 | 1296.28 | 925.0 |

## APPENDIX B: FLEXURAL STRENGTH AND MODULUS OF COMPOSITES

Table B1: Effects of alkaline treatments on the Flexural strength of composites reinforced with single layer of fabric

| S/N | FLEXURAL STRENGTH (MPa) | | | | |
|---|---|---|---|---|---|
| | **Reinforcements** | **Polyester** | **Untreated** | **1 minute** | **2 minutes** |
| | | 35.56 | | | |
| **1** | **Plain single** | | 56.75 | 66.75 | 56.51 |
| **2** | **Twill single** | | 62.32 | 68.73 | 63.22 |
| **3** | **Knitted single** | | 52.68 | 58.78 | 51.84 |

Table B2: Effects of alkaline treatments on the Flexural modulus of composites reinforced with single fabric

| S/N | FLEXURAL MODULUS (GPa) | | | | |
|---|---|---|---|---|---|
| | **Reinforcements** | **Polyester** | **Untreated** | **1 minute** | **2 minutes** |
| | | 2.9423 | | | |
| **1** | **Plain single** | | 3.3501 | 3.695 | 3.0469 |
| **2** | **Twill single** | | 4.4329 | 4.8631 | 4.3811 |
| **3** | **Knitted single** | | 3.3202 | 3.7536 | 2.6171 |

Table B3: Effects of alkaline treatments on the flexural strength of composite samples reinforced with two (2) layers of fabrics

| S/N | FLEXURAL STRENGTH (MPa) | | | | |
|---|---|---|---|---|---|
| | **Reinforcements** | **Polyester** | **Untreated** | **1 minute** | **2 minutes** |
| | | 35.56 | | | |
| **1** | **Plain-Plain** | | 88.16 | 99.72 | 102.81 |
| **2** | **Twill-Twill** | | 95.21 | 111.82 | 108.54 |
| **3** | **Knitted-Knitted** | | 68.78 | 79.20 | 78.87 |
| **4** | **Plain-Twill** | | 74.70 | 93.28 | 90.57 |
| **5** | **Plain-Knitted** | | 69.02 | 85.01 | 83.56 |
| **6** | **Knitted-Twill** | | 69.02 | 94.13 | 86.91 |

Table B4: Effects of alkaline treatments on the flexural modulus of composite samples reinforced with two (2) layers of fabrics

| S/N | FLEXURAL MODULUS (GPa) | | | | |
|---|---|---|---|---|---|
| | **Reinforcements** | **Polyester** | **Untreated** | **1 minute** | **2 minutes** |
| | | 2.9423 | | | |
| **1** | **Plain-Plain** | | 4.9249 | 5.5397 | 5.8559 |
| **2** | **Twill-Twill** | | 5.8103 | 8.5229 | 7.0229 |
| **3** | **Knitted-Knitted** | | 3.8356 | 5.4318 | 4.4481 |
| **4** | **Plain-Twill** | | 5.3027 | 5.9146 | 4.7332 |
| **5** | **Plain-Knitted** | | 4.3906 | 4.6009 | 4.1621 |
| **6** | **Knitted-Twill** | | 3.4569 | 5.7287 | 5.4855 |

## APPENDIX C: IMPACT STRENGTH OF COMPOSITES

Table C1: Effects of alkaline treatments on the impact strength of composite samples reinforced with single layer of fabric

| S/N | IMPACT STRENGTH (Joules) | | | | |
|---|---|---|---|---|---|
| | **Reinforcements** | **Polyester** | **Untreated** | **1 minute** | **2 minutes** |
| | | 2.1 | | | |
| **1** | **Plain single** | | 3.80 | 3.95 | 3.70 |
| **2** | **Twill single** | | 3.70 | 3.90 | 3.95 |
| **3** | **Knitted single** | | 4.05 | 4.30 | 4.2 |

Table C2: Effects of alkaline treatments on the impact strength of composite samples reinforced with two (2) layers of fabrics

| S/N | IMPACT STRENGTH (Joules) | | | | |
|---|---|---|---|---|---|
| | **Reinforcements** | **Polyester** | **Untreated** | **1 minute** | **2 minutes** |
| | | 2.1 | | | |
| **1** | **Plain-Plain** | | 4.80 | 6.05 | 5.80 |
| **2** | **Twill-Twill** | | 5.60 | 7.0 | 6.0 |
| **3** | **Knitted-Knitted** | | 6.35 | 7.95 | 7.10 |
| **4** | **Plain-Twill** | | 4.90 | 5.85 | 5.65 |
| **5** | **Plain-Knitted** | | 5.30 | 6.10 | 6.20 |
| **6** | **Knitted-Twill** | | 5.35 | 6.22 | 6.55 |

# APPENDIX D: ROCKWELL HARDNESS OF COMPOSITES

Table D1: Effects of alkaline treatments on the hardness of composite samples reinforced with single layer of fabric

| S/N | ROCKWELL HARDNESS | | | | |
|---|---|---|---|---|---|
| | **Reinforcements** | **Polyester** | **Untreated** | **1 minute** | **2 minutes** |
| | | 20.6 | | | |
| **1** | **Plain single** | | 22.8 | 24.5 | 24.4 |
| **2** | **Twill single** | | 23.6 | 25.2 | 25.9 |
| **3** | **Knitted single** | | 21 | 23.4 | 22.2 |

Table D2: Effects of alkaline treatments on the hardness of composite samples reinforced with two (2) layers of fabrics

| S/N | ROCKWELL HARDNESS | | | | |
|---|---|---|---|---|---|
| | **Reinforcements** | **Polyester** | **Untreated** | **1 minute** | **2 minutes** |
| | | 20.6 | | | |
| **1** | **Plain-Plain** | | 25.7 | 27.8 | 29.9 |
| **2** | **Twill-Twill** | | 26.6 | 28.9 | 30.6 |
| **3** | **Knitted-Knitted** | | 23 | 25.8 | 25.6 |
| **4** | **Plain-Twill** | | 24.8 | 28.4 | 23.1 |
| **5** | **Plain-Knitted** | | 25.5 | 26.6 | 26.1 |
| **6** | **Knitted-Twill** | | 21.4 | 26.7 | 26.9 |