DEPARTMENT OF AGRICULTURAL ENGINEERING
AHMADU BELLO UNIVERSITY, ZARIA

UTILISATION OF SELECTED VARIETIES OF COTTON PLANTS GROWN IN NIGERIA FOR PAPERMAKING

BY

MADUAKO, JOSAPHAT NWABUEZE

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MADUAKO, JOSAPHAT NWABUEZE

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DECLARATION

I hereby declare that I carried out the investigations reported in this thesis at the laboratories of Ahmadu Bello University, Zaria, Savannah Forestry Research Station, Samaru-Zaria and Nigerian Paper Mill Ltd., Jebba, under the supervision of Dr. O. J. Mudiare of Agricultural Engineering Department, Ahmadu Bello University, Zaria, and Dr. A. B. I. Igboanugo of Savannah Forestry Research Station, Samaru - Zaria.

The thesis is an original work carried out by myself, and no part of it has been presented elsewhere for any degree. The works of other investigators cited herein are duly acknowledged in the text and listed as references.



Maduako, J. N.

August, 1998

DEDICATION

To my beloved Wife

and Family Doctor,

Dr. (Mrs) Mary Chinonye Maduako

CERTIFICATION

This thesis entitled, "Utilisation of Selected Varieties of Cotton Plants Grown in Nigeria for Papermaking" by Maduako, J. N. meets the regulations governing the award of the degree of Doctor of Philosophy Ph.D (Agric. Engineering) of Ahmadu Bello University, and is approved for its contribution to knowledge and literary presentation.

DR. O. J. MUDIARE
CHAIRMAN, SUPERVISORY COMMITTEE

7/9/98
DATE

DR. A. B. I. IGBOANUGO
MEMBER, SUPERVISORY COMMITTEE

07-09-98
DATE

DR. O. J. MUDIARE
HEAD OF DEPARTMENT

7/9/98
DATE

DEAN, POSTGRADUATE SCHOOL

24/2/99
DATE

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ABSTRACT

The utilisation of cotton plant stalks for papermaking, as an alternative to the wasteful disposal of the crop residue by burning, was explored in this study, using four varieties of American upland cotton plants (Gossypium hirsutum), namely: SAMCOTs 6, 8, 9 and 10 grown in Nigeria. Wood and bast fibre characteristics, such as fibre wall thickness, fibre diameter, fibre length, runkel ratio, thickness index, flexibility coefficient and slenderness ratio were determined. The composition of alpha-cellulose, hemi-cellulose, lignin, ash and moisture were also determined.

The fibre length, runkel ratio and slenderness ratio were found to be 0.270mm, 0.540 and 12.7, respectively, on the average, for both wood and bast fibres. Varietal effects on most of the fibre characteristics were found to be significant at 95% probability level. SAMCOT 9 was found to be the best variety in most fibre characteristics, followed by SAMCOTs 10, 8 and 6. The alpha-cellulose content of the stalks averaged 54.0%, which was high enough to be explored for papermaking.

In view of the low runkel ratio and short fibre length of the stalks, thermo-mechanical pulp (TMP) was prepared from each variety and blended with at least 40% of waste paper (WP) whose fibre length averaged 2.00 mm, and it improved the sheet formation and the strength properties of the hand sheets. Factorial three-factor papermaking experiments involving two levels each (2x2x2) of furnish ratio (TMP/WP), pulp freeness

and additive were conducted. Standard hand sheets were produced and tested for physical and mechanical properties. For the furnish ratio (TMP/WP) of 60/40, freeness of 35°SR and additive of 1% rosin and 4% alum, the caliper, basis weight, burst strength and tear strength of the hand sheets averaged 0.510 mm, 127.8 g/m^2, 0.420 kPa and 0.820 kN, respectively. SAMCOT 8 hand sheets consistently maintained the highest tear strengths, followed by SAMCOTs 10, 9 and 6.

The basis weight versus caliper relationships for SAMCOTs 6, 8, 9 and 10 hand sheets were found to be linear, with high and positive correlations and the coefficients of determination r^2 were 0.958, 0.997, 0.914 and 0.866, respectively. The paper strength properties correlated positively with the original fibre characteristics of SAMCOTs 6, 8, 9 and 10 cotton plants and were found to have linear relationships. The tear strength versus runkel ratio, fibre length and slenderness ratio relationships had coefficients of determination r^2 of 0.674, 0.927 and 0.812, respectively.

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LIST OF SYMBOLS

a_b = Total Area of the Bark under View

a_f = Area of Fibre Bundle

ANOVA = Analysis of Variance

b = Bulk

BF = Burst Factor

BS = Burst Strength

BW = Basis Weight

c = Coefficient of Flexibility

d_f = Percentage of Fibre in the Bark

d_p = Percentage of Parenchyma in the Bark

df = Degrees of Freedom

e = Standard Error

f = Area occupied by Fibres

fd = Fibre Diameter

fl = Fibre Length

fld = Fibre Lumen Diameter

fwt = Fibre Wall Thickness

k = Caliper

MS = Mean Square

n = Sample Size

n_f = Number of Fibre Bundles.

p = Percentage of Void Space

P = Furnish Ratio

Q = Pulp Freeness

r = Runkel Ratio

R = Additive

s = Sample Standard Deviation

S6 = SAMCOT 6

S8 = SAMCOT 8

S9 = SAMCOT 9

S10 = SAMCOT 10

SS = Sum of Squares

SV = Source of Variation

t = Thickness Index

$t_{0.05}$ = t-statistic at 5% confidence level and n-1 degrees of freedom

TF = Tear Factor

TMP = Thermo-mechanical Pulp

TS = Tear Strength

v = Area occupied by Vessels

WP = Waste Paper

$\bar{x}$ = Mean

$\bar{z}$ = Slenderness Ratio

CHAPTER ONE

INTRODUCTION

1.1 Statement of Problem

The post-harvest handling of cotton plant stalks has been a problem to cotton farmers in Nigeria, mainly due to the ignorance on other possible uses of the crop residue. The stalks are left on the field after the cotton seed and lint have been harvested. With the arrival of the next season's rains, the stalks begin to sprout and if tended, produce much leaves with little or no useful lint and seeds. Hence, shortly before the rains, the farmers slash the regrown cotton plants, leaving the roots in the soil.

Thereafter, the unuprooted butts of stalks and roots in the soil sprout again and begin to compete with freshly planted cotton plants for soil nutrients and space, becoming like weeds. This problem has often been overcome by the use of mechanical stumpers to uproot the stalks and roots from the soil before ploughing. These stalks and roots are gathered in heaps and either burnt off or used as firewood for cooking when they dry. However, the disposal of cotton plant stalks by burning is a colossal waste of the crop residue which would otherwise have been utilised for some value-added products, such as paper and board, as an alternative to disposal.

1.2 Related Research

The other option of using cotton plant stalks as firewood for cooking has not been the best, because, the cotton plant sticks burn too fast to ashes and produce little heat due to the low energy value of 13.9 MJ/kg, as reported by Kumar et al (1984) for the Indian grown varieties.

It has been reported that cotton plant stalks can be gathered early, chopped up and graded with cotton seed hulls, and used as a feeding stuff in the group of coarse dry fodders, such as cornshucks, cornstover, rye, oat and wheat straw (True and Morton, 1896). To this effect, the nutritional contents of cotton plants grown in the United States of America have been analysed as shown in Table 1.1. Cocoa pod husk, rice bran and palm kernel cake have similarly been found useful as components of livestock feeds by some researchers (Adeyanju et al, 1975a & b).

Table 1.1: Nutritional Contents of Cotton Plants Grown in U.S.A.

S/N	Nutritional Content	Percentage (%)
1.	Cellulose	40.8
2.	Nitrogen-free extract	32.6
3.	Water	10.0
4.	Protein	9.54
5.	Ash	5.23
6.	Fat	1.83

Source: True and Morton (1896).

For medical applications, a homoeopathic drug called "Gossypium" has been produced from the roots of cotton plants as a remedy for a case of delayed menstruation (primary amenorrhoea) in women and for shedding an adherent or retained placenta after a pregnant woman has put to bed (True and Morton, 1896; Boericke, 1927; Farrington, 1987). Also, an edible mushroom has been cultivated on cotton plant stalks (Balasubramanya, 1981).

In industries, the use of natural vegetable fibres and wood in form of coarse-grained pulp as reinforcing fillers in thermoplastic composites has generated a great deal of interest for so many products, including interior automotive and packaging applications. Coarse-grained pulp can be used to produce woodfibre-plastic composites or fibre-reinforced thermoplastic containers and boards such as brake linings, gaskets, carpets, boxes, cardboards and shoe boards. Abd-Elrahim et al (1981) reported the manufacture of wafers from cotton plant stalks.

The production of various grades of paper and boards from Indian-grown cotton plants has been reported by Pandey and Shaikh (1985; 1987). Through fibre characterization and chemical compostion analysis, indications can be obtained on the specific grades of paper that Nigerian varieties of cotton plant stalks can be used for, and the pulping conditions to obtain optimum pulp yield.

Shaikh and Varadarajan (1995) produced corrugated boxes

from Indian Hybrid 4 cotton plant stalks for the packaging of fruits and gave their chemical composition as shown in Table 1.2. They concluded that their cotton plant stalks, being so rich in cellulose content, was a potential raw material for papermaking and the project was considered to be viable.

Table 1.2: Chemical Composition of Indian Hybrid 4 Cotton Plant Stalks

S/N.	Chemical Constituent	Percentage (%)
1.	Holo-cellulose	77.3
2.	Lignin	27.0
3.	Ash	7.13

Source: Shaikh and Varadarajan (1995).

Whereas Shaikh and Varadarajan (1995) used the expensive chemical pulping (alkaline digestion) technique to make kraft paper from cotton plant stalks, the pulping would have been cheaper if previous trials with thermo-mechanical pulping (TMP) had been done (Clark, 1978). Different pulping and fibre processing conditions produce different grades of paper, depending on the fibre characteristics. For instance, several agricultural residues, such as jute, kenaf and bamboo sticks, sugar-cane residue (bagasse) and some grass straw have been found suitable for making various grades of paper, according to their different fibre characteristics [Food and Agriculture Organisation (FAO), 1965].

Various grades of ground wood can be mixed with different binders in different proportions to manufacture various engineering products such as corrugated roofing sheets, ceiling boards, cardboard sheets, notice boards and table-tops. Lawal (1990) investigated the production of briquettes from sawdust (wood waste) using palm-oil sludge as a binder. Chipboards and particleboards can be made from various agricultural wastes as reported by Ahmed (1982) and Anosike (1993). Likewise, cotton plant stalks can be cut into chips, mixed with suitable binders and pressed to a high density to form chipboards and briquettes.

The development of technology for products from waste agricultural materials, including ligno-cellulosic fibre/plastic composites, dry-formed fibre-based composites, wet-formed moulded pulp structural products and composites fabricated with inorganic binders, is the concern of many present-day researchers on fibre-reinforced plastic composites. To further develop the technology for agricultural waste management and contribute to economic growth in the country, it will be of immense value to evolve other uses for local agricultural wastes.

Utilisation of agricultural wastes in Nigeria to produce value-added products will enhance self-reliance and reduce over-dependence on industrialised nations for the supply of spare parts, chemicals and long fibres for pulp in papermaking, as is still being practised in some local paper

mills. Recycling has been accepted as the viable alternative to disposal (Quimby, 1975). Waste management technology is desirable in the light of mounting waste disposal and environmental pollution problems, depleting foreign reserves, ever-increasing foreign debt, global economic recession and present national economic crisis.

1.3 Objectives

The primary aim of this study is to investigate the possibility of using SAMCOTs 6, 8, 9 and 10 cotton plants grown in Nigeria for papermaking. The specific objectives include:

1. To find relevant fibre characteristics of SAMCOTs 6, 8, 9 and 10 cotton plant stalks and determine how they can be used for papermaking.
2. To find whether there are varietal differences in the fibre characteristics of SAMCOTs 6, 8, 9 and 10 cotton plant stalks or not.
3. To find the chemical compositions of SAMCOTs 6, 8, 9 and 10 cotton plant stalks and determine their suitability for papermaking.
4. To determine the relationships between the mechanical properties of paper sheets made from SAMCOTs 6, 8, 9 and 10 cotton plant stalks and their fibre characteristics.

CHAPTER TWO

LITERATURE REVIEW

2.1 The Cotton Plant

2.1.1 Origin

Cotton has been a very ancient and popular economic crop of many countries. It was first cultivated in the Republic of India sometime before 1500 B.C. (True and Morton, 1896). However, it was first noticed as a wild, woody and perennial plant called Gossypium herbaceum var. africanum in the tropic of capricorn in Africa. From there, it spread to the tropic of cancer in India, possibly by sea, over the equator and remains the probable ancestor of all linted cottons in both the Old and the New world (Prentice, 1972).

2.1.2 Taxonomy

Cotton belongs to the genus Gossypium with sections Hirsuta, Herbacea and the Wild lintless varieties, all of which phylogenetically trace back through the sub-family Hibisceae and the family Bombacaceae and Malvaceae, to the sub-order Tiliaceae and natural order Malvales. The Herbacea consists of two species, G. herbaceum and G. arboreum, the old world cottons. The Hirsuta comprise two species, G. hirsutum var punctatum (weed cotton) and G. barbadense var brasiliense (kidney cotton) [Prentice, 1972].

New World annual forms of G. barbadense and G. hirsutum have long been preferred to both the Old and New World

perennial forms in Africa. G. barbadense (the Ishan variety) used to be the most successfully grown cotton in Nigeria (Ugbolue and Adegbile, 1979), but presently, the popular American Upland annual cotton (G. hirsutum) is the most widely grown in Nigeria.

2.1.3 Varieties

The varieties of Gossypium hirsutum grown in Nigeria include SAMCOT 6, SAMCOT 8, SAMCOT 9 and SAMCOT 10 of which SAMCOT 6 has been phased out and replaced with SAMCOT 9 in the northern cotton growing zone, while SAMCOT 8 is grown in the eastern zone and SAMCOT 10 in the southern zone. The release of the two new varieties; SAMCOT 9 and SAMCOT 10 was necessitated by the growing market demand for early-maturing, disease-resistant, high-yielding and long-staple cotton, with other desirable lint and seed-cotton qualities (Echekwu et al, 1992).

The three cotton-growing zones in Nigeria, that is, the northern, eastern and southern zones cover all the nineteen Northern States and the Federal Capital Territory. This leaves about 8 million tonnes of cotton plant stalks to waste every year, at the recommended rate of 50,000 plants/ha (Kumar and Ogunlela, 1992), probably because, commercial cotton is cultivated mainly for the lint and the seeds.

2.2 Types of Fibrous Raw Materials used for Paper and Board Making

Raw fibres for the manufacture of paper and board, have been conveniently divided into several categories by Higham (1963). They include: animal fibres such as wool, fur, hair, silk; synthetic fibres, such as nylon, rayon, glass; mineral fibres such as asbestos; and plant fibres, such as cotton lint, esparto, wood and straw. The most commonly used are the plant fibres.

On the basis of the location of vegetable fibres in plants, the plant fibres are further classified into seed hairs such as cotton lint and fuzz; bast fibres such as flax/ linen, hemp, jute, ramie, kenaf, Urena lobata; and wood fibres from softwood and hardwood species, including tropical heterogeneous hardwoods such as Gmelina arborea, eucalyptus species, Ceiba pentandra, Adansonia digitata and other tree species. Others include leaf fibres such as esparto, manila, sisal; and grasses such as straw, bamboo, bagasse and maize stalks.

Virtually, every fibrous raw material of plant origin, including waste papers and rags, can be pulped for papermaking, provided the fibre characteristics are found suitable for the desired grade of paper and board [British paper and Board Makers Association (BPBMA), 1950; Food and Agriculture Organisation (FAO), 1965; Heller, 1978]. Many agricultural residues have found applications in paper and

board making. Instances include sawdust, bagasse, jute sticks, maize stalks and cotton linters (FAO, 1965; Casey, 1980; Ahmed, 1982; Anosike 1993). Cotton plant stalks have also been pulped for papermaking in India as earlier indicated (Pandey and Shaikh, 1985 and 1987).

2.3 Physical Structure of Plant Fibre

Every plant fibre is a narrow elongated microscopic cell composed of several layers of micelles, each micelle being about 0.01 µm in length, and fibrils wound around each other as shown in Fig. 2.1. It consists of a hollow central canal called lumen, which is surrounded by four distinct fibril layers, the total of the thicknesses of which constitutes the fibre wall thickness, while the fibre diameter is the sum of the lumen diameter and two times fibre wall thickness.

The primary wall (also called middle Lamella) is the outermost fibril layer containing tough spiral windings of a water-resistant nature; a highly ligneous and distorted network of many fibrils. In papermaking, during beating and refining of pulp, the primary wall is partially or completely removed to expose the underlying secondary fibril layers to the action of water and refiner blades. The fibrils absorb water, swell and separate further under the controlled treatment; a process called fibrillation. This enhances inter-fibre bonding in the finished paper (Higham, 1963; Casey, 1980).

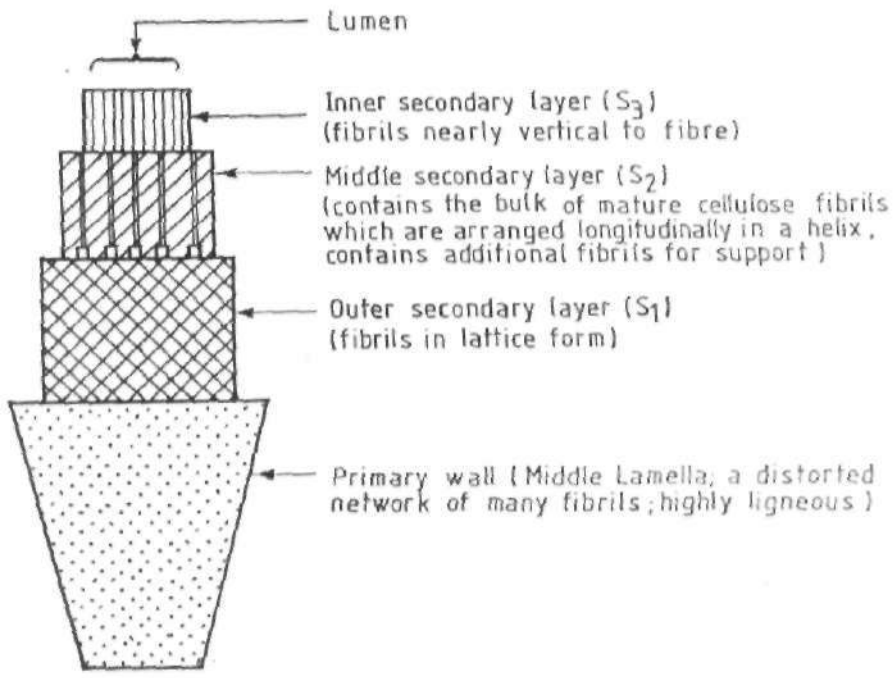


Fig. 2.1. Physical structure of plant fibre.
Source: Higham (1963)

The use of histological techniques in determining fibre characteristics from sections of plant stems viewed under a microscope, has been recommended by Davenport, (1969), Clark, (1978) and Stamm (1978). The physical characteristics of a plant fibre, such as fibre length, fibre diameter, fibre wall thickness, fibre lumen diameter and ratios calculated from them, such as coefficient of flexibility, slenderness ratio, runkel ratio, thickness index, percentage void space and percentages (by area) of fibre and parenchyma in the bark as expressed in Eqs. 2.1, 2.2, 2.3, 2.4, 2.5, 2.6 and 2.7, respectively, usually determine the suitability of the fibre for papermaking (FAO, 1965; Dinwoodie, 1965). The expressions for the parameters are as follows:

$$c = \frac{fld}{fd} \qquad \text{--- (2.1)}$$

$$z = \frac{fl}{fd} \qquad \text{--- (2.2)}$$

$$r = \frac{2(fwt)}{fld} \qquad \text{--- (2.3)}$$

$$t = \frac{fwt}{fd} \qquad \text{--- (2.4)}$$

$$p = \frac{100v}{v + f} \qquad \text{--- (2.5)}$$

$$d_f = \frac{a_f}{a_b} \frac{x\ n_f}{} \qquad \text{--- (2.6)}$$

$$d_p = 100 - d_f \qquad \text{--- (2.7)}$$

where, c = coefficient of flexibility

z = slenderness ratio

r = runkel ratio

fld = fibre lumen diameter (µm)

fd = fibre diameter (µm)

fl = fibre length (µm)

fwt = fibre wall thickness (µm)

v = area occupied by vessels (mm^2)

f = area occupied by fibres (mm^2)

t = thickness index

p = percentage of void space (%)

d_f = percentage (by area) of fibre in the bark (%)

d_p = percentage (by area) of parenchyma in the bark (%)

a_f = area of fibre bundle (mm^2)

n_f = number of fibre bundles

a_b = total area of the bark under view (mm^2)

The flexibility coefficient c, is related to the runkel ratio r, as follows:

$$c = \frac{1}{r + 1} \qquad \text{--- (2.8)}$$

Hence, when r = 1, c = 0.5. However, for papermaking fibres, $r \geq 2$ (Clark, 1978) and when r = 2, c = 0.33, which means that for $r > 0$, $c < 1$.

Similarly, the thickness index t, can be related to the runkel ratio r, as follows:

$$t = \frac{r}{2(r + 1)} \qquad \text{--- (2.9)}$$

Thus, when r = 1, t = 0.25 and when r = 2, t = 0.33. In other

words, the higher the runkel ratio, the higher the thickness index, up to the limit of t = 0.5 which will occur at an infinitely large value of r whereby r > 5000, which will be unattainable in nature. It follows that for good papermaking fibres with r > 2, the thickness index t, will vary between 0.33 and 0.5.

2.4 Wood Density

Wood density or specific gravity, also gives an approximate indication of the suitability of woods for papermaking. A dense wood produces more pulp per cook in a digester, that is, higher pulp yield, but if the high density is caused by thick-walled coarse fibres, the quality of the resulting paper will be inferior. The economic importance of wood density lies in the fact that pulp-wood is usually bought by volume and made into paper which is sold by weight. It has been established that as wood density increases above 0.70 kg/m^3, the wood becomes less and less suitable for pulp and paper (Clark, 1978).

2.5 Chemical Composition of Plant Fibre

A proximate analysis of plant fibres in terms of the percentage chemical compositions of cellulose, hemi-cellulose, lignin, ash and moisture is often necessary to be able to further establish the suitability of the fibre for paper-making. The pure and long-molecular alpha (α) cellulose

$(C_6H_{10}O_5)_n$ is the major component required for papermaking, where n is the degree of polymerization or number of units in the molecular chain. However, the degraded forms of cellulose, that is, the beta (ß) cellulose and the gamma (δ) cellulose (the hemi-cellulose), are also useful in papermaking.

While ß-cellulose consists of short molecular types of cellulose, the δ-cellulose consists mainly of the true hemi-celluloses, which are short-chained cellulose with other six-carbon polymerized sugar molecules (saccharide) associated with pentoses, or five-carbon saccharide like xylose (Clark, 1978). Most high hemi-cellulose pulps possess good cohesiveness, because, when abraded during beating, the surfaces of the fibres and the fibrils so produced, acquire a dense concentration of short-chained molecules which facilitate cohesion and strength development in paper.

The cellulose and hemi-cellulose contents give a good indication of the fibre yield to expect during pulping, while the lignin content determines the quantity of chemicals to be spent in bleaching the pulp (Casey, 1980). Lignin, tannins, resins, waxes, fats, minerals, pectins and colouring substances are the non-cellulosic constituents, of plant fibre. The lignin, being a binding polymeric material (of molecular weight, 2000 - 15000) surrounding the adult cells or fibrils, must be removed as much as possible in order to liberate the fibres for effective inter-fibre bonding in the

finished paper. The lignin content ranges from 23.0% in hardwoods to 39.5% in softwoods (Higham, 1963).

2.6 Types of Paper

Paper has been defined as an interlaced web of fibres, formed by the action of felting from a water suspension, which is dried and finished (Casey, 1980). The different types of paper are classified according to their usage and/or applications. They include writing papers, printing papers, book papers and wrapping papers. Others are blotting papers, filter papers, vegetable parchments, glassine, tissue and security papers (Higham 1963).

Moreover, different grades of paper are made from different furnishes or pulps which are obtained from different fibrous raw materials. The choice of any fibrous raw material for making any particular grade of paper, depends much on its fibre characteristics and chemical composition among other factors (FAO, 1965).

2.7 Types of Board

Generally, any paper whose thickness exceeds 0.30mm or whose basis weight is more than 220 g/m^2 is classified as a paperboard, or simply board (Quimby, 1975; Higham, 1963). According to the British paper-trade customs, boards include cardboard, pressboard, millboard (that is, boot, shoe and case boards), box board, ticket board and matrix board (that is,

stereo or flong board), according to usage. Other board grades include chipboard, clothboard, strawboard, woodpulp board, leather board, lined or laminated board and resin board, according to the furnish used. Board grades according to methods of manufacture, include cylinder board, duplex board, corrugated board, pasteless board, paste board and ivory boards.

Corrugated container boards manufactured by glueing together linerboard and fluted or corrugated paperboard in alternating layers are useful in making paperboard packages and containers like cartons, boxes, crates, book covers and picture mountings. The choice of furnish or pulp raw material for any desired grade of board depends on the fibre characteristics. Particle geometry which relates to the size dimensions of particles used for the production of the particle board, affects the properties of resin-bonded particle boards (Gatchell and Heebink, 1964; Post, 1958 and 1961).

Some studies have established that flexural strength, stiffness in bending and dimensional stability of boards, improve with increase in flake length used for board production (Brumbaugh, 1960; Shuler and Kelly, 1976; Turner, 1954). Also, the effects of particle dimensions on the properties of cement-bonded particle boards have been reported (Iida et al, 1983; Badejo, 1988). The longer and thinner the flakes or particles, the stronger, stiffer and more

dimensionally stable the experimental cement-bonded particle boards (Badejo, 1988).

2.8 Pulping of Wood

2.8.1 Wood Debarking and Chipping

For most woods, the bark contains no fibre and it either produces dirty specks or consumes much chemicals for its removal from the pulp [British Paper and Board Makers Association (BPBMA), 1950; Clark, 1978]. Mechanical barkers or debarkers of different designs, such as the disc barker, drum barker, frictional barker, hydraulic pressure barker, chain barker, knife barker and cambio debarker, are usually used to debark the logs of wood before chipping. A decorticating machine for ribboning the barks of cotton plant stalks and grinding the woody stem into a coarse-grained pulp for use as livestock feed component, has been patented since the 19th century in the United States of America (True and Morton, 1896).

However, barked cotton plant stalks have been pulped by chemical treatments to produce kraft paper in India (Shaikh and Varadarajan, 1995; Pandey and Shaikh, 1985 and 1987). Therefore, debarking appears to be unnecessary for cotton plant stalks, because, the bark may contain useful bast fibre for papermaking. Other fibre-producing plants like jute, Urena lobata and kenaf of the same family, Malvaceae, are notably rich in bast fibre content which is often extracted

from them for rope-making and other fibre applications, using ribboners and harvester-ribboners (Kirby, 1963).

After debarking logs of wood, the long logs are usually further cross-cut or chipped into short lengths which are more convenient to handle. Chipping is done mechanically by wood chippers and cutters such as an electrical chaff cutter or other motorised chipping and cutting blade or saw or chain machines. Chipping ensures the uniformity of chip sizes which is necessary for uniform cooking and other pulping treatments. Good-sized chips should measure about 6.30mm thick and 18.8mm wide (Higham, 1963).

2.8.2 Mechanical Pulping (Stone-groundwood SGW, and Refiner-Mechanical Pulping RMP).

Stone-ground wood (SGW) being the oldest form of mechanical pulp is simply prepared by grinding the water-soaked woodchips with a wood grinder or Burr mill and screening the diluted pulp on a set of sieves whose meshes range from 20mm to about 1.0mm in diameter, after which sandtrapping is done and the pulp is concentrated and pressed into laps and air-dried.

The idea of refiner-mechanical pulping (RMP) is that the woodchips and/or the rejected material from the 20mm sieve are passed through a refiner which has several steel-barred rotating discs for fine-quality grinding through several recycling and rescreening operations before proceeding to sand-table processing or sand-trapping over rifflers,

concentration to about 5 - 17% consistency, pressing into wet laps and drying. RMP has often been considered to be superior to SGW in quality, though, both have the same problem of high lignin content.

However, the yield of mechanical pulp can be as high as 90 - 95%, so that it is relatively cheap, despite the high power consumption involved. Mechanical pulp serves more or less as a filler for cheap grades of printing papers, especially newsprint which contains 75 - 80% of it. Groundwood adds opacity, bulk and good formation to the paper because of its fineness. The hydrophobic nature resulting from its lignin content makes groundwood very receptive to oily ink (Clark, 1978).

2.8.3 Semi-mechanical Pulping (Thermo-mechanical Pulping)

Thermo-mechanical pulping (TMP) involves producing pulp from wood chips by presteaming, refining (or grinding) under steam pressure and completing the defibering in a second refiner or wood grinder. The woodchips are preheated under steam pressure to a temperature between 100 and 170^{o}C to slightly soften the lignin surrounding the fibres, a process usually called the glass transition of lignin (Irvine, 1985).

Investigations on the thermoplastic behaviour of solid wood have shown that the thermal softening of wood occurs at 115 - 145^{o}C and the softening behaviour depends largely on the wood moisture content and the nature of the wood (Blechschmidt

et al, 1986). A satisfactory temperature for thermal softening of lignin varies from about 116 to about 130°C, depending on the wood species (Clark, 1978). Moreover, fibres from a pulp that has been pressure-refined at a low enough temperature of 116°C, which permits some fibrillation of the surfaces, are of better quality for newsprint papermaking, because of their better fibre separation and less breakage than fibres from normal refiner-mechanical pulping (RMP) [Clark, 1978].

Coarse-fibred wood requires much energy during thermo-mechanical pulp (TMP) refining, to achieve fibre collapse, but the fibre yield can be as high as 80 - 90%. Several paper mills throughout the world, have been producing commercial newsprint using thermo-mechanical pulp, though for some fibres, there is often a need for much reinforcing pulp to blend with the TMP for good sheet formation and strength (Mackie and Joyce, 1987).

2.8.4 Chemical Pulping

Full chemical digestion processes consist essentially of treating woodchips in a pressurized vessel (digester) under controlled conditions of time, liquor concentration, temperature and pressure. The most common types of full chemical pulping are the alkaline and acid digestion processes.

There are two common types of alkaline digestion

processes; the first being the caustic soda process which uses sodium hydroxide (NaOH) directly to dissolve the lignin in woodchips and remove it in the digestion liquor. Secondly, the sulphate (Kraft) process, which, being a modified soda process, uses a mixture of sodium hydroxide (NaOH), sodium sulphide (Na_2S) and sodium sulphate (or salt cake, Na_2SO_4) or sodium bisulphate ($NaHSO_4$) to dissolve the lignin. The alkaline sulphate process has predominated because of the ease of recovering chemicals from the spent cooking liquor and the special ability to pulp any wood including pine and other resinous and acid-resistant woods.

The acid digestion process (the bisulphite process) involves using an excess of sulphur dioxide (SO_2) or sulphurous acid (H_2SO_3) in combination with an alkaline base such as the bisulphite of calcium [$Ca(HSO_3)_2$] or a mixture of the bisulphites of calcium and magnesium or ammonium. The cooking by direct steaming at about 690 kPa pressure and 130 - 150^{o}C temperature can last for 6 - 24 hours or longer. Delignification takes place by the action of the bisulphite liquor or sulphurous acid on any lignin present, forming soluble sulphonic acid derivatives (ligno-sulphonates) which are usually removed later. Other non-cellulosic substances are also dissolved.

However, in chemical pulping, whether by alkali or acid, the useful hemi-celluloses are also dissolved or decomposed into sugars, leaving only the pure long-molecular alpha

cellulose. Hence, about half of the weight of the wood is removed in solution as the spent digestion liquor, giving rise to a low pulp yield of 45 - 55% (Clark, 1978). Besides, chemical pulping has become too expensive, and research has to be directed towards developing cheaper chemical methods, such as, alcohol pulping (Katzen, 1980; Adeleye, 1981) or cooking in wood ash (lye) solution (Heller, 1978). Also, there are semi-chemical methods which give higher fibre yields than full chemical methods (Mackie and Joyce, 1987). Pulp and papermaking cottage industries prefer the economical pulping methods for product cost effectiveness.

2.8.5 Semi-Chemical Pulping

Semi-chemical processes include the high yield cold soda semi-chemical pulping, acid sulphite semi-chemical pulping and neutral sodium sulphite semi-chemical (NSSC) pulping which are aimed at improving the yield of full chemical pulps to 70 - 75% or more. The cold soda pulping impregnates hardwood chips with 2% or more of dilute caustic soda (NaOH) solution before passing them through a disc refiner from where they emerge as a pulp at nearly boiling temperature and a yield of about 90% (Clark, 1978).

The acid sulphite semi-chemical process digests the woodchips with hot acid sulphite liquor at high pressure, shreds and screens them and finally mixes them with mechanical pulp. After defibering the mixture at medium consistency and

screening, the yield of pulp is about 65%.

The neutral sodium sulphite semi-chemical (NSSC) pulping involves cooking woodchips with 12 - 18% solution of sodium sulphite (Na_2SO_3) in the presence of a buffer of sodium bicarbonate (Na_2HCO_3) and disintegrating them with a disc refiner (Higham, 1963). However, in a modified process called chemi-thermo-mechanical pulping (CTMP), softwood chips are given a brief cook with 3 - 4% solution of sodium sulphite (Na_2SO_3) together with a little alkali added to make the pH about 6.5 in a steaming tube before pressure refining. The process results in a fibre yield of 80%, increased brightness gain and the utilisation of thick-walled fibres in newsprint furnishes (Mackie and Joyce, 1987).

2.9 Bleaching

Bleaching has been described as a continuation of the cooking or digestion process because it involves a chlorination of the residual lignin and an oxidation of the colouring impurities still remaining in the pulp [British Paper and Board Makers Association, (BPBMA), 1950]. About 3 - 4% lignin is normally left in the fibre walls of hardwood chemical pulp and 4 - 10% lignin in softwood chemical pulp, because further attempt to remove such residual lignin during digestion results in excessive degradation of the fibres by the digestion liquor (Othmer, 1968).

Chlorination involves treating the pulp with a bleach

liquor, usually calcium hypochlorite, $Ca(OCl)_2$ or sodium hypochlorite (NaOCl), thereby dissolving the residual lignin by the action of chlorine, into soluble derivatives which are afterwards washed away from the pulp. Usually, bleaching is done for an average of 4 hours only at low pulp consistency of 3 - 5% either in a single or two or multi-stage operation.

Oxidation aims at removing colouring impurities from the pulp in order to yield white pulp, because, chlorination has little or no effect on the colour of the fibre, even though, both chlorination and oxidation are accomplished by the same hypochlorite in the same bleaching operation(s). Oxidation takes effect by the non-selective reaction of excess chlorine which forms hypochlorous acid (HClO) and hydrogen chloride acid (HCl). The hypochlorous acid acts as the oxidising agent, with nascent oxygen, to convert the pulp fibres from a brownish mass to a pleasing white substance (Clark, 1978; Saltman, 1978).

2.10 Chemical Composition Analysis of Pulp

2.10.1 Tests for Cellulose and Hemi-cellulose contents

The alkali solubility test for alpha (α) cellulose content of pulp has been described by the Technical Association of Pulp and Paper Industries (TAPPI) in the method, T235 os - 76 (TAPPI, 1980). This involves treating a specimen of pulp with 18% solution of caustic soda (NaOH) at a temperature of $25^{o}C$ for about one hour, washing, drying and

weighing the residue which is the insoluble alpha cellulose.

The test for hemi-cellulose content is described in TAPPI method, T203 os - 74 and involves oxidizing an aliquot of the alkali solubility test with strongly acidified potassium chromate and adding potassium iodide, then back-titrating with potassium thiosulphate to determine the amount of dissolved cellulosic material, which consists of the beta (ß) and gamma (ß) celluloses, that is, the hemi-cellulose. Tests for cellulose and hemi-cellulose contents can give indications of the required pulping and fibre processing conditions, as well as the possible fibre yield and the paper quality to be expected from any fibrous raw material (Higham, 1963).

2.10.2 Tests for Lignin, Ash and Moisture

The lignin content test has been done with different methods, including the Willstatter method involving 41% concentrated hydrogen chloride acid (HCl), the Halse method which adds 10% concentrated hydrogen tetra oxo sulphate VI (H_2SO_4) to the usual 38% concentrated HCl and the Swanson method involving both 38% concentrated HCl and concentrated H_2SO_4 at chilling ice temperature, followed by boiling to coagulate the lignin, as described by Clark (1978) and TAPPI (1980).

The ash content test has to do with heating a sample of pulp in a furnace until all volatile matter has been given off and the remaining mineral ash and natural fibre ash attain a

constant weight. For groundwood, the moisture content test involves the use of an oven set at a temperature of 105 - 110°C for 24 hours (Clark, 1978).

The tests for lignin and moisture contents can also give indications of the required pulping conditions, as well as the bleaching requirements for papermaking fibres (Higham, 1963). Ash content test is usually conducted to determine the presence of major mineral constituents in a furnish (including the non-fibrous additives) in addition to the natural fibre ash. However, ash content test done before pulping any fibrous raw material gives only the natural fibre ash, because the mineral ash is not yet involved.

2.11 Fibre Processing

In papermills, fibre processing, also called stock or pulp or fibre preparation, includes all the papermaking processes between the receipt of the pulp at the paper or board mill and the delivery of the prepared stock to the paper or board-making machine for the formation of the paper web. They are the steps of disintegration, stock blending, beating/refining and methods of addition of non-fibrous additives to the pulp (Casey, 1980).

2.11.1 Disintegration

The disintegration process, also called defibering or fibre breaking separates the fibres individually so that they are not grouped or bonded in flocs or lumps or bundles, but are a suspension of pulp fibres in water which can be pumped continuously to the succeeding operations. The equipment for pulp preparation has been of different designs such as Chest and Rotor, Woodpulp and Rag breaker, Hydropulper and Kneader or Repulper.

2.11.2 Stock Blending

In a mill where two or more pulps from different sources are to be mixed, the correct number of bales of each pulp to give the desired proportion should be disintegrated together in the pulper. Alternatively, the pulps can be disintegrated separately and then blended in slurry form in a blending chest before being beaten and refined as a single fibre source (Clark, 1978). In practice, almost every paper in the market has been produced from a mixture of two or more fibre sources (Casey, 1980). Blending an expensive pulp with a cheaper pulp to achieve product cost effectiveness or blending a long-fibred pulp with a short-fibred pulp to get some desired characteristics in the paper product has been the practice in most commercial paper mills.

The fibre length of short-fibred pulps ranges from 1.0 mm to 2.0 mm, but that of long-fibred pulps ranges from 3.0 mm to

6.0 mm (Saltman, 1978). High quality papers manufactured in Nigeria are usually obtained from blending long-fibred pulps from pines imported from overseas with short-fibred pulps from hardwoods such as Gmelina arborea. Pines are poor in seeding ability and this has hampered large-scale plantation development of the species in Nigeria for sourcing long-fibred pulp locally, since imported pine pulps are becoming very expensive. In the need to explore avenues for sourcing long-fibred pulp locally, Forestry Research Institute of Nigeria (FRIN) has screened several woody perennials other than pines grown in Nigeria for suitability for papermkaing, based on their fibre characteristics. They have recommended Ricinocendron heudellioti, Sterculia setigera, Ceiba pentandra (Silk Cotton) and Adansonia digitata (Baobab tree or Hausa "Kuka") as being very suitable for papermaking. The Federal Institute for Industrial Research, Oshodi (FIIRO), Lagos, has equally recommended annual plants, such as, kenaf and sugar-cane residue (bagasse) for papermaking. Since cotton plant belongs to the same family with kenaf, it can as well be investigated for suitability for papermaking.

2.11.3 Beating and Refining

The beating and refining of a defibred pulp has to do with passing the thick pulp slurry through a relatively narrow gap between a revolving rotor and a stationary rotor, both of which carry bars (tackle) or knives aligned across the line of

flow of the stock. This usually results in the shortening of the fibre length, the abrasion and fibrillation of their exterior surfaces to remove their tough outer primary walls, the crushing, bruising and internal fibrillation to swell and rupture the outer secondary fibril layer to release fibril filaments and the opening up of secondary fibril layers to release more fibrils. Also, while the beating and refining progresses, there are longitudinal splitting of the cell walls to form ribbons of fibrils, the collapse of the fibres and the tendency of the fibrils to become "gelatinized" or hydrolysed into a creamy glucose syrup (Heller, 1978). The fibres having largely lost their fibril structure, increase in inter-fibre bonding affinity (Clark, 1978; Casey, 1980).

2.11.4 Additives

Fillers: Certain non-fibrous chemicals, mineral and non-mineral substances called loadings or fillers are usually added to pulp in the form of fibre processing assistants. Also, agents, such as, antifoams or defoamers, retention aids and microbiocides are added and some of them end up in the final sheet of most conventional papers. The most commonly used fillers include white china clay, that is, hydrated aluminum silicate especially non-hydrous kaolinite [$Al_2O_3.2(SiO_2H_2O)$], calcium carbonate ($CaCo_3$) and titanium dioxide (TiO_2), but titanium dioxide has become very expensive.

Fillers can be added to pulp as solids in the form of small granular particles or powder, or as liquids in the form of solutions or suspensions in water to fill up the voids between the fibres in printing paper so as to smoothen its surfaces and make them less hydrophilic and more receptive to oily printing inks. Fillers improve the opacity, brightness, colour and dimensional stability of the paper while preventing a strike-through of the ink.

Bonding (Sizing) Materials: The addition of bonding materials to pulp is aimed at enhancing the cohesion of the fibrillated fibres and the retention and distribution of fillers throughout the sheet as the wet paper web is being formed and drained on the paper machine. The most widely used sizing materials are rosin and alum [$Al_2(SO_4)_3.14H_2O$)]. Rosin, which is a resin extracted from the bark of pinewood, is precipitated and fixed by alum so that much of it is retained by the pulp on the wire of the paper machine, hence, the alum serves as a mordant or sizing agent. Up to 3 - 4 parts of alum to 1 part of rosin are frequently used in practice according to the British Paper and Board Makers Association (BPBMA, 1950).

Some auxiliary sizing agents also used by papermakers include starch solution which is either 2 - 3% for prepared starches or 10% for natural starch, sodium aluminate, sodium silicate, methyl and ethyl celluloses. Other inorganic bonding additives include rubber latex, neoprene latex,

synthetic and petroleum resins and waxes as well as gums such as locust bean gum, guar gum, gelatin, cellulose gel and ponalglue. "Gum arabic" extracted from the bark of a thorny shrub, Acacia senegal is also useful as a bonding additive for paper.

Studies on the effects of guar gum, cassava starch and guinea corn starch on the scuffing, surface and optical properties of paper and boards recommended 1 - 3% of each additive with pulp freeness within 30 - 50^{o}SR (Achimugu, 1977; Bugaje, 1980). The hydrophilic gum dispersion and the starch help to coat the surfaces of the fibres sufficiently to attract a thick water envelope around the fibre surfaces and prevent flocculation. The water envelope covers the fibrils smoothly and makes it more difficult for one fibre to cling to another when they touch as they move around in a water suspension (Clark, 1978).

Colourings: Apart from fillers and bonding materials, additives such as colourings in the form of pigments and dyes are also added. They are classified into natural dyestuffs such as cochineal and water-insoluble minerals which are inorganic pigments such as ultramarine and smalts. Also, there are water insoluble organic pigments derived from the coal-tar or aniline colours such as caledon and monolite colours. Others are water-soluble synthetic coal-tar dyes such as the acidic quinoline yellow, croceine scarlet and soluble blue or the basic auramine, methyl violet and victoria

blue (British paper and Board Makers Association, 1950; Heller, 1978).

2.12 Tests for Physical Characteristics of Pulp

It is usual to carry out some quality control tests on stock samples taken from the beater/refiner before being formed into sheets in order to obtain some indications of the effect of beating/refining on the properties of the fibres in the pulp and the progress of the beating treatment. They include the tests for freeness and wetness, specific surface, fibre length distribution, fibre flexibility and pulp consistency.

Certain fibre properties such as swelling, plasticity, primary wall removal, curling, redistribution of hydrogen bonds, microcreping, Zeta potential and fibre strength are generally too difficult to measure and the results too difficult to interpret in terms of the effect on the final paper sheet properties (Casey, 1980).

2.12.1 Drainage Tests

Drainage tests consist of the tests for the freeness, wetness and specific surface of the pulp. The most widely used instruments for measuring the freeness and wetness of pulp are the Canadian Standard Freeness (CSF) tester and the Schopper-Riegler (SR) wetness tester. These testers indicate the ease with which water drains away from the papermaking

fibres while they are being formed into a wet mat or wet paper web on the perforated drainage plate or wire mesh of the tester.

While the CSF-tester measures the volume (in cm^3) of "fast-running" water as degree CSF, the SR-tester measures the volume (in dm^3) of the "slow-running" water as the SR-wetness. Oftentimes, freeness and wetness are used interchangeably. For instance, wetness measurements can be simply called freeness, provided the units are expressed in ^{o}SR, as in the case of Achimugu (1977) and Bugaje (1980). The drainage time is measured on a British Standard Sheet Former as the time required for the water to drain away in the sheet former under standard conditions (Higham, 1963).

The tests for the specific surface of the pulp fibres are carried out with different methods, including geometric measurement, silvering, permeation, filtration and absorption, but the permeation and filtration methods are most widely used (Clark, 1978). Usually, the higher the specific surface, the slower the drainage rate because of increased surface available for inter-fibre bonding.

2.12.2 Tests for Fibre Length Distribution and Fibre Flexibility

Fibre Length Distribution: In a beaten and refined pulp, fibre length distribution can be determined either by using a microscope or by fractionation. The microscope method examines a slide of the pulp under a microscope and measures

the length of each fibre as discussed in TAPPI standards T232 (TAPPI, 1980). Fractionation method consists of screening the stock on a woven wire mesh with square apertures of the correct size for the fibre length to be measured using constant conditions of time and agitation. Fibre fractions retained on the screens are dried, weighed and plotted as a histogram to show fibre length distribution (Clark, 1978; TAPPI, 1980). Also, an optical scanning device has been used to scan the pulp field and produce a computer printout of the average fibre length and length distribution in a very short time.

However, it should be noted that the fibre length measured after beating and refining cannot be taken as the true fibre length of the raw material from which the pulp was prepared, because the original fibre dimensions have been reduced through pulping and beating/refining processes.

Fibre Flexibility: This is measured by the method of bonding potential or contact ratio, which compares the contact area of fibres to the total area of the fibres on a glass slide and relates it to the fibre flexibility (Casey, 1980). Usually, the fibre flexibility increases during beating and refining, because of internal fibrillation or bruising of the fibres. Therefore, the fibre flexibility measured after beating/refining can only give indication of the effect or progress of the beating/refining on the fibre properties, but not the true flexibility coefficient of the fibres in the

original raw material of the pulp.

2.12.3 Test for Pulp Consistency

Consistency defines the content of total suspended solids including fibres, fillers, bonding materials and colourings as percent by weight of fibre in the stock. Simply put, consistency expresses the total weight of fibre present in 100 ml of pulp slurry; that is, taking 100ml of pulp slurry as equivalent to 100g of pulp slurry, because, the density of water is $1g/cm^3$ and $1cm^3$ is 1ml.

For experimental purposes, pulp consistency is determined simply by draining 100ml of pulp slurry through a standard wire mesh or screen-plate, collecting all the fibres on the wire mesh, drying the fibres on a paper sheet drier and obtaining the weight of the fibres on a chemical balance. In many papermills, optical and electrical measurements are common, but the use of an on-line computer-controlled machine has been the best (Casey, 1980).

2.13 Paper Machine Operations

The conventional Fourdrinier paper machine has a continuous mode of operation from the wet end to the dry end. The wet end consists of the operations of forming, couching and pressing, while the dry end involves the drying and finishing operations (Casey, 1980)

2.13.1 **Forming**

The prepared stock/pulp at 2.5 - 3.0% consistency in the stock chests is diluted to 0.2 - 1.0% consistency in the headbox and pumped to an endless fine-mesh screen/cloth (the "wire") where suction pumps suck away all the visible "white water" from the forming stock and leaves a wet fibrous matt, that is, the wet paper web, with about 10 - 15% solids formed on the wire.

2.13.2 **Couching**

Couching operation involves the transfer of the wet paper web from the wire by the couch roll to the first press felt and the removal of sufficient water from the fibrous matt to make it sufficiently self-supporting to accomplish the transfer without rupture. The water removal is accomplished by suction pumps or vacuum pumps incorporated in the couch roll to create a pressure difference between the top and bottom of the paper web, coupled with the evaporation of water vapour by the stream of air which passes through the sheet and leaves the paper web with 18 - 25% solids.

2.13.3 **Pressing**

Usually, the paper web is given three successive nips by roll presses which removes more water from it and consolidates the fibres in the wet web, thereby, increasing the strength and specific gravity of the paper. Pressure is always applied

gradually at the three presses in order to allow the water held in the fibres by capillary attraction to be released without deforming the plastic paper web, while leaving the paper web with 35 - 40% solids.

2.13.4 Drying

Two dryer felts, one at the top and the other at the bottom, are made to hold the paper web in close contact with the surface of so many cylindrical steam-heated dryers, which evaporate most of the remaining water. The water vapour is drawn or blown away by air jets. Drying removes the absorbed capillary-held moisture, but not the adsorbed water taken up by the fibres themselves during the stock preparation. Adsorbed water can not be removed except by burning the paper, hence the paper still has a nominal moisture content of 5 - 7% and only 93 - 95% solids.

2.13.5 Finishing

The dried paper can be finished by the processes of calendering, reeling, slitting/cutting, trimming, sorting, tub-sizing, embossing or plating, coating, waxing, inspection sealing, labelling and packaging depending on the grade of paper desired.

Calendering involves pressing the paper heavily between one or more vertical stacks of polished steel rolls, called calenders, to impart a smooth surface to the paper via

consolidation. From the calenders, the smoothed paper web is reeled up to form a jumbo roll, which, when large enough, is removed to the slitters or cutters to be converted into the required smaller rolls or sheets of paper. Trimming follows after the cutting process to straighten and/or smoothen the edges of the small rolls or reams or sheets of paper. Next is sorting of the good products and separating them from the waste paper cuttings which can be recycled later.

Tub-sizing has to do with the application of machine additives to the paper web on the paper machine to further strengthen the paper and improve its machine-finish properties. In embossing or plating, the paper is placed between two layers of materials underneath the metal plates and run between very hot and heavy rolls of surface temperature, 121 - 143^{o}C, so that the paper takes on the impression on the surface of the imprinting or plating material. Commonly embossed paper grades include napkins, book covers, wall paper, table covers and laminated cushioning sheets or corrugated papers.

Coating aims at levelling up the minute "hills" and "valleys" on the paper surface by covering them with a layer or suspension of fine mineral pigment in a solution of an adhesive which binds the pigment to the paper surface. Such pigments include Blanc fixe or Barium sulphate ($BaSO_4$) used alone or mixed with white clay. Waxing is done to close the air-spaces in the paper with paraffin wax so as to make the

paper water-proof and with a glazed unbroken surface finish.

2.14 Board Machine Operations

Conventionally, paperboards are made on a cylinder or vat machine which is different from the Fourdrinier paper machine, in that the forming part is a hollow cylindrical wire screen revolving in a vat containing the diluted pulp of about 1% consistency. The water drains through the wire mesh, leaving the fibres on the surface of the cylinder.

A number of cylinder units can be arranged so that the fibrous mat from each is deposited as a layer, and all the layers can be combined to make a board, the thickness of which is limited only by the number of cylinders involved, hence it is called multiple-vat or multi-cylinder machine. The smooth endless felt passes over and presses against the top of each cylindrical wire screen in series to pick up the fibrous webs left on them as the white water drains into the interior of each cylinder.

The multiple wet paper web of about 85% moisture content formed is subsequently pressed together to about 60% moisture content by suction press rolls and dried to about 5 - 7% moisture content in vertically stacked cylindrical dryers (Clark, 1978). After drying, the boards are also taken through finishing operations. The series of vats permits the use of selected pulps in the first and last vats to constitute the outside plies or liners and thereby improves the

appearance and strength of the board.

2.15 Hand Sheet Making

For purposes of investigating the suitability of any fibrous raw material for papermaking, after the pulping on a small-scale, standard hand sheets are usually prepared and tested in a quality-control laboratory for various properties. Equipment used for producing such test sheets include the British Standard sheet former, the Rapid Kothen sheet former and the Noble and Wood sheet former. While the British Standard and the Rapid Kothen sheet formers produce circular sheets of 160mm and 190mm diameters, respectively, the Noble and Wood sheet former produces square sheets measuring 200mm each (Clark, 1978). The hand sheets are normally formed from a very dilute stock of 0.06% consistency.

2.16 Tests for Phyiscal Properties of Paper

The physical properties of paper which are commonly tested, include moisture content (% wet basis), basis weight (also called grammage or substance in g/m^2), thickness or caliper in mm, bulk or specific volume in m^3/g, porosity or permeability, sizing and absorbency (also called Cobb sizing figure), printability or oil penetration and furnish or ash content. Most of the tests for the physical properties of paper are described in TAPPI (1980) Standard Methods T220, 206 and 441m60.

The air porosity or permeability of a standard test sheet as measured with the Gurley permeability tester consists of the time in seconds required to displace 100cm^3 of air through 1 in^2 or 645.2 mm^2 of paper under a fixed pressure head. The air porosity being inversely related to air permeability of the paper depends on the slenderness of the fibre, the bulk of the sheet and the amount of debris present (Higham, 1963).

The capillarity of the sheet as measured by the Klemm test is the height in mm to which water rises in a vertical strip of the paper within 10 minutes of dipping it in distilled water (Clark, 1978). The absorbency or the Cobb sizing figure of a paper sheet is defined as the amount of water in grams picked up or absorbed by 1m^2 area of the paper at the standard temperature of 20^{o}C and in a given time. The bulk or specific volume of a paper sheet is calculated as follows:

$$b = \frac{1000k}{BW} \qquad \text{--- (2.10)}$$

where, b = bulk (m^3/g)

k = caliper (mm)

BW = basis weight (g/m^2)

2.17 Tests for Optical Properties of Paper

The optical properties of paper which are of interest to papermakers normally include the gloss, brightness, colour, optical bleaching agents (O.B.A.), opacity, smoothness and formation under standard lighting conditions obtainable with

tungsten and fluorescent light sources. The gloss has to do with the surface reflectance or percentage amount of light reflected by the paper as measured with Ingersol glarimeter or Sheen gloss meter.

The brightness is measured photometrically by the General Electric Brightness (G.E.B.) meter. The colour is determined by matching it with a standard on a colour chart, but optical bleaching agents (OBA) are fluorescent dyes which are often added to paper to enhance the whiteness. Whiteness can be detected by observation under ultra-violet light by use of spectrophotometers which employ the principle of wavelength measurement.

Opacity, being the opposite of transparency, is the extent to which light rays are scattered or refracted on their passage through the paper, that is, the extent to which the translucent paper is impervious to "show-through". Smoothness is measured by the rate of air flow between the paper sample and another standard surface in contact with it, that is, the time taken for a given volume of air to pass between the sample and the articulating surface of the instrument.

Formation can be judged by the degree of uniformity of transmitted light which passes through the sheet of paper when held and viewed against a light source, but the measurement is only of a qualitative nature (Higham 1963; Heller, 1978).

2.18 Mechanical Properties of Paper

The tests for the mechanical or strength properties of paper, include those of dynamic and static tensile tests for the stretch, breaking load or strength and breaking length, as well as tests for burst strength, burst factor, tear strength, tear factor and folding strength (Higham, 1963; TAPPI, 1980; Casey, 1980).

2.18.1 Tensile Test

This involves applying a load to a sample strip of paper of 15mm width until it breaks. The instruments used include the Schopper static tester and the Van der Korput dynamic tester. The breaking load or strength is expressed per unit width as KN/mm. The stretch is the elongation at rupture of the paper under tension, expressed as a percentage of the original length. The breaking length is the length of a uniform strip or width of the paper that is sufficient to break under its own weight when suspended at one end. It is calculated as the product of the average breaking load, length and width of the paper divided by the basis weight (g/m^2) of the paper.

2.18.2 Burst Test

For this test, pressure is exerted on a fluid-filled reservoir to expand a rubber diaphragm which produces a pressure against the paper. The maximum pressure (kPa)

required to rupture the paper under standard conditions of temperature of 20°C and relative humidity of 65 ± 2% is recorded. The two types of instruments used are the Mullen burst tester and the Schopper Dalen tester. The burst factor is calculated as follows:

$$BF = \frac{1000BS}{BW} \qquad \text{--- (2.11)}$$

where, BF = burst factor ($kPa.m^2/g$)

BS = burst strength (kPa)

BW = basis weight (g/m^2)

2.18.3 Tear Test

This involves the use of the Elemendorf tearing tester to measure the resistance to tearing of a paper sample as described in TAPPI (1980) method T220. The tear strength in kN is a measure of the work done in tearing the paper sample. The Standard tear factor is calculated as follows:

$$TF = \frac{100TS}{BW} \qquad \text{--- (2.12)}$$

where, TF = tear factor ($kN.m^2/g$)

TS = tear strength (kN)

BW = basis weight (g/m^2)

Hence, the tear factor expresses the resistance of the paper to tearing in relation to its substance.

2.18.4 Folding Test

The folding strength of a paper depends on the fibre length and the flexibility of the sheet (Casey, 1980). Folding test relies on the continuous creasing of a 15mm-wide strip of paper under a tension load of 1 kg, bending it back and forth through an angle of 135^{o} about a jaw whose edges have a radius of curvature of 0.38mm, at the rate of 175 double folds per minute. TAPPI (1980) methods T511 and T423 describe the use of M.I.T. instrument and Schopper folding tester, respectively for the test, but the Kohler-Molin tester can also be used for the folding test (Casey, 1980).

2.18.5 Miscellaneous Handsheet Tests

Additional tests that provide information for special purposes, include those of zero-span tensile strength, roughness, stiffness, lateral bonding or the z-direction tensile, lateral compressibility, hygro-expansivity, absorbency to liquids amongst others. Many of those tests involve complex factors and might be necessary only when they are directly applicable to the quality of paper being made (Casey, 1980).

CHAPTER THREE

3.0 MATERIALS AND METHODS

The methodology of fibre characterization involving mounting sections of the four local cotton plant stalks on microslides, viewing and determining the fibre characteristics directly under a light microscope, is outlined in section 3.1. Chemical composition analyses, involving tests for alpha-cellulose, hemi-cellulose, lignin, ash and moisture contents of the local cotton plant stalks as well as the determination of the wood densities of the stalks are reported in sections 3.2 and 3.3, respectively. The determination of the energy values of the local cotton plant stalks is presented in section 3.4, while the thermo-mechanical pulping of the stalks is reported in section 3.5.

The factorial three-factor experiments employed in the fibre processing and hand sheet making operations are explained in section 3.6. The experiments on fibre processing, (that is, disintegration, stock blending, beating/ refining and stock sizing), hand sheet making and testing of hand sheets for their physical and mechanical properties are presented in sections 3.7, 3.8 and 3.9, respectively.

3.1 Fibre Characterization

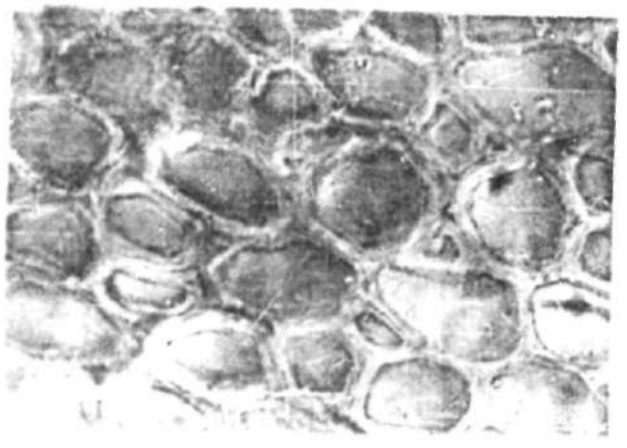
Samples of four boll-bearing varieties of cotton plants, of the American Upland annual species (Gossypium hirsutum), namely: SAMCOT 6, SAMCOT 8, SAMCOT 9 and SAMCOT 10, grown in

Nigeria, were harvested by uprooting from the research plots of the Institute for Agricultural Research (IAR), Ahmadu Bello University, Samaru - Zaria. Using a "REICHERT" sledge microtome, transverse sections (TS) and tangential longitudinal sections (TLS), 20 µm thick were taken from water-soaked shoot and tap-root samples of each variety cut to about 30 mm lengths with a secateur. Temporary slides were prepared with the sections stained in methylene blue and mounted in glycerol jelly (Davenport, 1969; Igboanugo, 1984). These were viewed under a light microscope (Olympus, Tokyo PM-7) at several magnifications (x40, x100, x250, x400 and x1000).

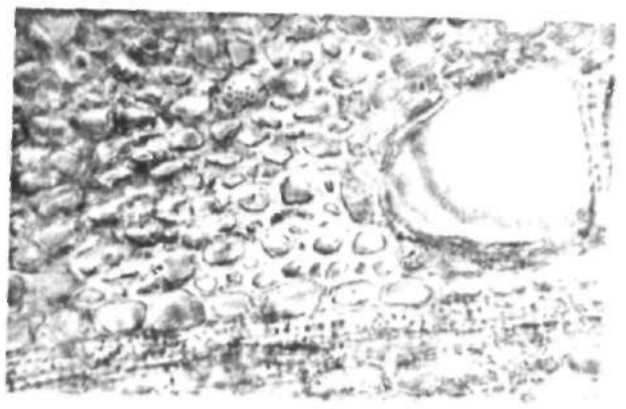
Measurements were made with the microscope using an ocular micrometer which had been calibrated with a stage micrometer. On the transverse section of the wood, fibre wall thickness, fibre lumen diameter and fibre diameter as well as the number and diameters of vessels and fibres and the area occupied by them in the field of view were determined. Likewise, on the transverse section of the bark, the length and width of each fibre bundle and the number of fibre bundles within the field of view, as well as the diameter, wall thickness and lumen diameter of each fibre were determined. The fibre length was measured on the tangential longitudinal section of the wood and the bark.

Photomicrographs of the sections were taken for the wood and the bark at x100 and x400 magnifications depending on the

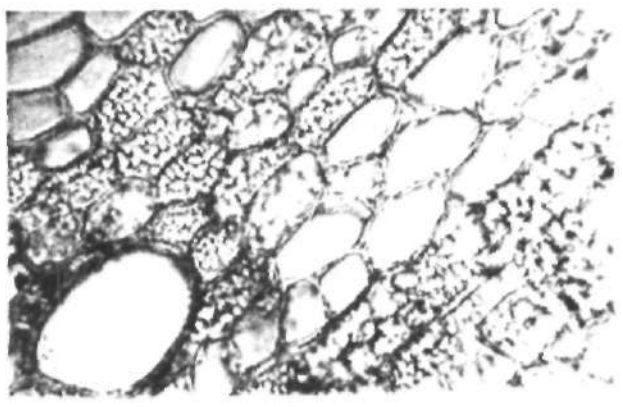
clarity of the representative sample of the tissue under view as shown in plates I - III. The coefficient of flexibility, slenderness ratio, runkel ratio, thickness index and percentage void space were calculated from the measured fibre characteristics of the wood and the bark, while the proportions by area of the fibres and parenchymatous cells were also calculated for the bark using Eqs. 2.1, 2.2, 2.3, 2.4, 2.5, 2.6 and 2.7, respectively.



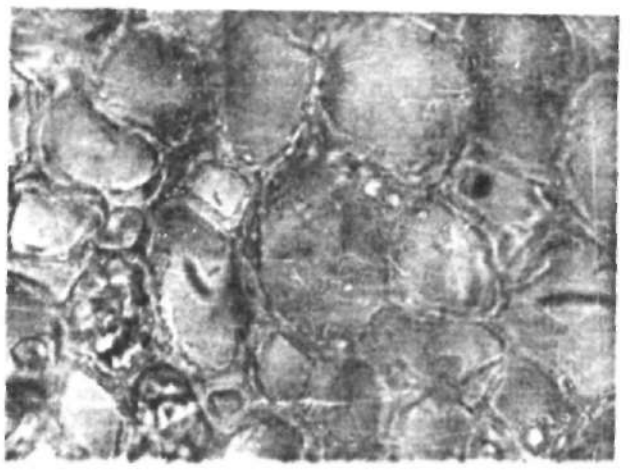
SAMCOT 6



SAMCOT 8

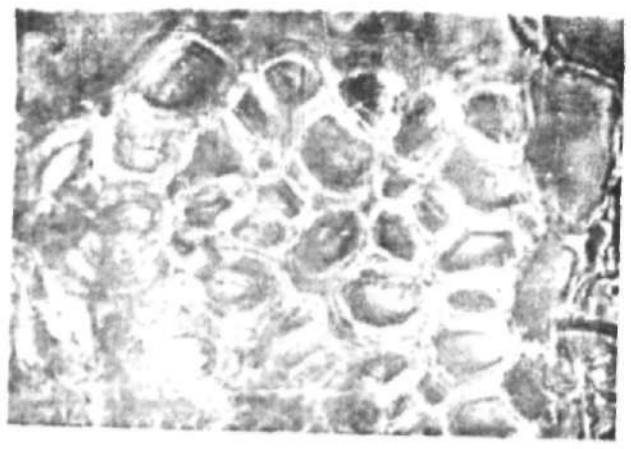


SAMCOT 9

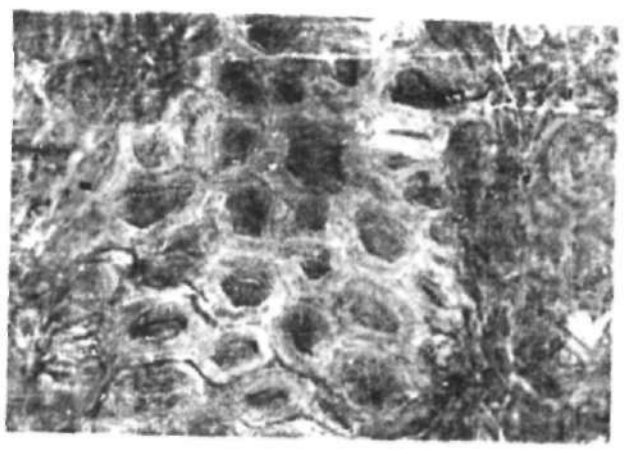


SAMCOT 10

Plate 1: Photomicrographs of the Transvere Sections (TS) of Wood Fibres in SAMCOTs 6, 8, 9 and 10 Cotton Plant Stalks (x400).



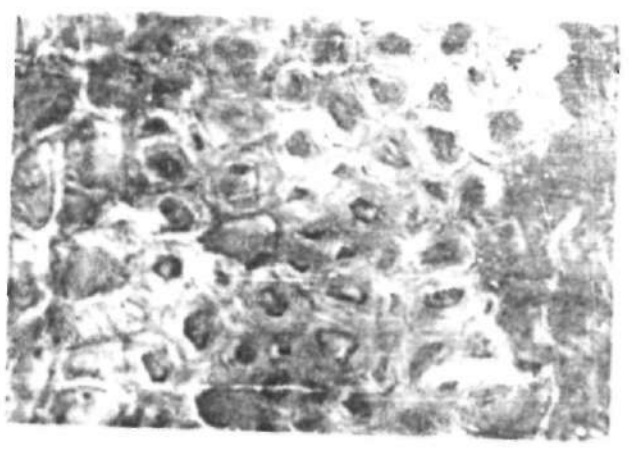
SAMOCT 6



SAMCOT 8



SAMCOT 9



SAMCOT 10

Plate II: Photomicrographs of the Transvere Sections (TS) of Bast Fibres in SAMCOTs 6, 8, 9 and 10 Cotton Plant Stalks (x400).



Plate III: Photomicrograph of a Typical Tangential Longitudinal Section (TLS) of Wood Fibres in the Local Cotton Plant Stalks (x400).

3.2 Chemical Composition Analysis

The proximate analysis of cotton plant stalks was carried out to determine the percentage chemical composition in terms of cellulose (alpha-cellulose), hemi-cellulose (beta and gamma celluloses), lignin, ash and moisture contents. Four samples were prepared from each of the four varieties (SAMCOTS 6, 8, 9 and 10). Each sample was ground with a Burr mill to powder of about 0.50 mm particle size, which was determined through sieve analysis.

3.2.1 Test for Cellulose Content

The test for alpha - cellulose content was the alkali solubility test mentioned in section 2.10.1. For each sample of ground cotton plant stalks, a specimen weighing 25.0g was put in a beaker and treated with 120.0cm^3 of 18% solution of caustic soda (sodium hydroxide, NaOH), stirred and left for one hour at 25^{o}C as described in TAPPI method T235 os - 76 (TAPPI, 1980).

After one hour, the residue was filtered, washed, dried and weighed. The weight of the undissolved residue, also called the 18% alkali-insoluble cellulose, which was the alpha-cellulose, was expressed as a percentage of the initial weight of the dry ground sample.

3.2.2 Test for Hemi-cellulose Content

Following the 18% alkali-solubility test for the α-cellulose, the dissolved cellulose portion (the aliquot) was collected separately at the end of one hour and treated with $30cm^3$ of O.IN dilute solution of hydrogen tetra oxo sulphate VI (H_2SO_4). The treatment caused a precipitate to form, which was the beta-cellulose. After thirty minutes, the clear liquor/aliquot was poured out gradually through a filter paper which separated it from the beta-cellulose precipitate. The precipitate was then washed, dried and weighed.

The aliquot was further oxidized with 3.0g of potassium chromate. Thereafter, 3.0g of potassium iodide was added to the aliquot which was then back-titrated with 0.1N solution of potassium thio-sulphate. The titration caused a precipitate to form, which was the remaining dissolved gamma-cellulose. The precipitate was filtered, washed, dried and weighed.

The weights of the beta and gamma celluloses were added together to get the weight of the hemi-cellulose which was then expressed as a percentage of the initial dry weight of the original sample of ground cotton plant stalks.

3.2.3 Test for Lignin Content

For each sample of ground cotton plant stalks, 10.0g was weighed out using the Mettler PN1210 balance of 0.01g precision. The lignin content was then determined, using the Swanson method described in section 2.10.2. The moisture free

specimen was placed in a 100 cm^3 wide-mouth bottle and packed in crushed ice for 30 minutes. Ten cubic centimeters (10 cm^3) of 38% concentrated hydrogen chloride acid (HCl) chilled also for 30 minutes was then poured on the sample in the beaker and the mixture was thoroughly stirred and left to cool in the ice for 15 minutes under a fume cupboard.

Thereafter, 5cm^3 of concentrated hydrogen tetra oxo sulphate VI (H_2SO_4) was added, one drop at a time, so as not to heat the cooled mixture unduly. The bottle was capped, swirled and replaced in the ice for another 30 minutes. The bottle was then removed from the ice and allowed to stand at room temperature overnight to complete the dissolution of the cellulose and the precipitation of the lignin.

The contents of the bottle were poured into a large beaker and diluted to 500cm^3 with water and boiled to coagulate the lignin. The boiled contents were filtered hot, through a tarred, medium-sintered glass filter crucible and rinsed alternately with concentrated hydrogen chloride acid and water. The coagulated lignin was dried and weighed and the weight was expressed as a percentage of the initial weight of the original dry sample.

3.2.4 Test for Ash Content

The weight of an oven crucible was measured using the Mettler PN 1210 balance and about 10g of the sample of ground cotton plant stalks was put inside it. The sample was heated

in a furnace for 24 hours to drive off all the volatile matter in the sample. The sample was brought out with the crucible every 6 hours, cooled in a desiccator and reweighed, until a constant weight was recorded three times, which was the weight of the remaining ash and crucible.

The ash content was determined by subtracting the weight of oven crucible from the final weight of the sample and crucible. The weight of the natural fibre ash was then expressed as a percentage of the air-dry weight (initial weight) of the sample of ground cotton plant stalks.

3.2.5 Test for Moisture Content

For each variety, four samples of ground cotton plant stalks, were prepared and the weights of four oven crucibles were measured on the Mettler PN 1210 balance to the nearest 0.01g. Thereafter, 15.0g of each sample was measured out and put in each of the crucibles.

Each crucible and the content were weighed and placed inside an oven set at 105^{o}C for 24 hours, after which, they were brought out and placed inside a desiccator to cool down. Their dry weight was then measured. The weight of moisture lost was calculated from the difference between the initial and final weights of the sample.

The moisture content (% wet basis) of each sample was determined by expressing the weight of moisture removed as a percentage of the initial weight of the sample. The average

moisture content of each variety was calculated from the four replications.

3.3 Determination of Wood Density

The mass density of cotton plant stalks at a harvest moisture content of 8.0% wet basis was determined for each of the four varieties, namely SAMCOT's 6, 8, 9 and 10. Four samples randomly picked from a bundle of 200 sticks were used for each variety. The wood density was calculated from measurements of the diameter, length and mass of the wood chips cut from the cotton plant stalks. The diameter and length were measured using Vernier Calipers with precision of 0.05 mm, while the mass was determined with Mettler PN 1210 weighing equipment with precision of 0.01g. The cross-sectional area was calculated from the diameter, while the volume was the product of the cross-sectional area and the length of the wood chip. The wood mass density was therefore determined by dividing the mass by the volume of each sample.

3.4 Determination of Energy Value

Some of the woodchips cut from each variety of cotton plant stalks at the harvest moisture content of 8.0% wet basis were ground with a Burr mill to about 0.50 mm particle size determined through sieve analysis. The energy value of each sample of groundwood was determined, using an Automatic Adiabatic Bomb Calorimeter (Gallenkamp, CBA - 301 series)

whose effective total heat capacity had been previously determined to be 22.9 KJ/^{o}C.

The weight of the groundwood that could give a temperature rise of 3.0 - 3.26^{o}C in the calorimeter thermometer was determined by preliminary tests with each sample and found to be 5.50, 5.35, 5.40 and 5.25g for SAMCOTs 6, 8, 9 and 10, respectively. Each sample was put inside a crucible whose weight was 10.2g. The sample was pressed gently inside the crucible to form it into a smooth level layer suitable for combustion. The crucible with the sample was inserted into the autobomb and a piece of nickel-chromium firing wire was stretched between the electrodes of the bomb. A single strand of cotton thread 80mm long was tied to the firing wire. The lengths of the firing wire and cotton thread were kept constant at 80mm for all the tests in order to facilitate the calculation of the energy value. The crucible was swung into position; the ring clamped and the ends of the cotton thread were arranged to be in contact with the sample.

The temperatures of the water jacket and the calorimeter vessel were allowed to stabilize for five minutes so that the calorimeter temperature became constant, and the thermometer reader/vibrator was used to read the initial calorimeter temperature to 0.001^{o}C accuracy after which the "FIRE" switch was depressed to ignite the sample. When the "FIRE" switch was released, the "READY TO FIRE" lamp stayed off indicating a satisfactory firing. After a few seconds, the heater relay

started switching more frequently, showing that the heat of the burning sample was being absorbed by the water in the calorimeter. Then, the apparatus was left for 10 minutes to obtain its final equilibrium temperature which was read off also to 0.001^{o}C accuracy two times at 5-minute interval. When the test was completed, the water jacket cover was raised and the heater was switched off.

After 30 minutes, the pressure in the bomb was released through the milled pressure release cap. The contents of the bomb were then washed into a borosilicate glass beaker with distilled water. The interior of the bomb and bomb cap were also washed into the beaker. The content of the beaker was diluted to 100ml with distilled water, filtered and boiled to remove carbon dioxide. While still hot, it was titrated with barium hydroxide [$Ba(OH)_2$] and phenolphthalein was used as indicator to determine the total acidity. Twenty millilitres of 0.1N sodium carbonate (Na_2CO_3) was added and the precipitate was warmed, filtered and washed with distilled water. After it was cooled, the filtrate was titrated with 0.1N hydrogen chloride acid (HCL) using Methyl orange as indicator. The corrections for the heat of formation of hydrogen tetra oxo sulphate VI (H_2SO_4) and nitric acid (HNO_3) were calculated and applied as indicated in the Autobomb Report Sheet shown in Appendix F.

The heat released from the standard length of firing cotton thread was calculated from the product of the calorific

value of cellulose (17.56kJ/g) and the weight (0.001g) of the known length (80mm) of cotton thread which had been dried at 105^{o}C, in which case the correction was 17.56J. The usual correction for the heat released from the recommended firing nickel- chromium wire was given in the calorimeter manual as 12.6J. Therefore, the sum of the corrections for the heat released from the firing cotton thread and nickel-chromium wire was 30.16J.

The total heat liberated was calculated from the effective heat capacity and the observed rise in temperature after correction for inaccuracies of the thermometer. This was corrected for the heat of firing/ignition due to the cotton thread and the nickel-chromium fuse wire and for the heat of formation of nitric acid. This was converted to the heat liberated by 1.0g of sample and then, the tetra oxo sulphate VI acid (H_2SO_4) correction was applied to obtain the true calorific value or energy value.

3.5 Thermo-mechanical Pulping (TMP)

Figure 3.1 shows a flowchart of the thermo-mechanical pulping processes. Each of SAMCOTs 6, 8, 9 and 10 cotton plants (barked stems and roots) was cut into chips of 15.0 mm length each. In the absence of a functional autoclave or a steaming tube for the presteaming and refining or grinding of the wood chips under steam pressure, three kilogrammes of the wood chips were ground with a Burr mill and screened into two

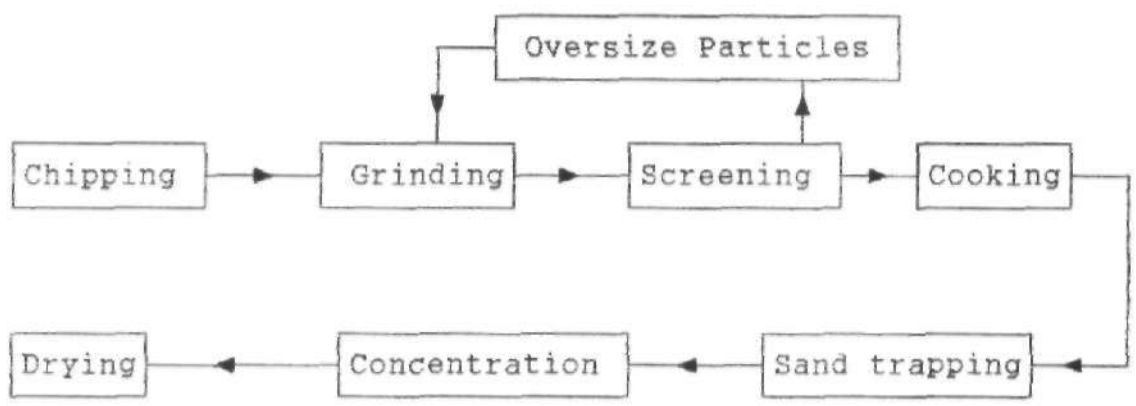


Fig. 3.1 Flowchart of Thermo-mechanical Pulping Processes.

fractions using a 1.0mm sieve. The groundwood of 0.50 mm particle size was collected while the oversize particles were recycled in the Burr mill and rescreened with the 1.0mm sieve until the groundwood was fully recovered. The groundwood was cooked slowly in a pH-neutral water until it boiled and attained a temperature of 116^{o}C, as measured by a mercury-in-glass thermometer, and which was maintained for 4 hours. The temperature of 116^{o}C had been suggested as appropriate and sufficient to effect the softening and dissolution or glass transition of the lignin in the pulp of most wood species, as indicated earlier in section 2.8.3.

The cooked pulp was diluted with cold water and stirred. A gradual pouring out of the pulp-water suspension into another container enabled the fibres and water to flow out, leaving a residue of dense particles of sand at the bottom of the bucket. The sand-trapping was done four times and the sand particles were thrown away.

Within 2 - 3 minutes, the pulp had sedimented into a thick pulp slurry and the black water was gradually poured out. The pulp was then pressed manually into wet crumbs and separated from the water. The black water was poured through a 0.50 mm sieve which allowed the water to pass, but held back the very fine fibres on the screen. The recovered fine pulp on the screen was also pressed into wet crumbs and mixed with other wet pulp crumbs or concentrated pulp.

The wet pulp crumbs were spread on a tray for sun-drying. After drying the pulp to a safe moisture content of 8.0% wet basis, the dry pulp crumbs were gathered together and weighed to determine the pulp yield which was the weight of pulp expressed as a percentage of the initial weight of the wood chips. Then, the pulp crumbs were bagged for transport to the Nigerian Paper Mill Ltd., Jebba, Kwara State for subsequent fibre processing and papermaking experiments.

3.6 The Factorial Three-factor Experiments

The experiments on fibre processing and hand sheet making were conducted to investigate the main and interactive effects of three factors on the physical and mechanical properties of the resulting hand sheets. The three factors were the furnish ratio, P, the pulp freeness, Q and the additive, R.

From the preliminary investigations on fibre characteristics of the local cotton plant stalks, it was found that the runkel ratio and the fibre length averaged 0.54 and 0.27 mm, respectively, for both wood and bast fibres as presented in sections 4.1.3 and 4.1.7, respectively. Since for papermaking fibres, the runkel ratio, $r \geq 2$ (Clark, 1978) as earlier indicated, the r value of 0.54 for cotton plant stalks was obviously too low, as low runkel ratio decreases the strength of paper (Dinwoodie, 1965).

In contrast with softwoods, which are known for long fibre lengths of 3.0 - 6.0 mm, most hardwoods have short fibre

lengths of 1.0 - 2.0 mm, and consequently low paper strength properties (Britt, 1970; Saltman, 1978), as earlier indicated. Therefore, it is a common practice in most paper mills to blend most tropical hardwood pulps with local long-fibred pulps or secondary fibres such as recycled waste paper for cost effectiveness and improved paper sheet formation and strength properties (Bautista, 1974). For cotton plant stalks with short average fibre length of 0.27mm, being shorter than those of most hardwoods, it was envisaged that the resulting hand sheets would be too weak.

Therefore, to make up for the deficiences in runkel ratio and fibre length of the local cotton plant stalks, it was decided to blend the thermo-mechanical pulp (TMP) prepared from them with at least 40% of waste paper pulp (WP) whose fibre length averaged 2.0 mm, after consultation with experienced papermakers (Ohiorhenuan, 1996; Jimoh, 1996). This was to enhance the paper sheet formation and strength properties. Hence, two levels of furnish ratio (TMP/WP) were investigated as follows: P_1 of 60/40; that is, 60% TMP and 40% WP and P_2 of 50/50; that is, 50% TMP and 50% WP.

Studies on the effects of guar gum, cassava starch and guinea corn starch on the frictional and scuffing characteristics of paperboards, established that to obtain best results, beating and refining should be done to the range of pulp freeness of 30 to 50^{o}SR (Achimugu, 1977), as earlier indicated. However, the practice recommended in the Quality

control Department of the Nigerian Paper Mill Ltd., Jebba, is to beat and refine pulp to the range of freeness of 25 to 30°SR. Therefore, it was decided to beat the thermo-mechanical pulp prepared from cotton plant stalks and the waste paper pulp as a single fibre source to 20°SR and 35°SR levels of freeness; that is, Q_1 of 20°SR and Q_2 of 35°SR.

Also, to obtain the best results on the frictional and scuffing properties of paperboards, Achimugu (1977) and Bugaje (1980) recommended the use of 1 - 3% of each of guar gum, cassava starch and guinea corn starch as bonding materials, as earlier indicated. Most papermakers use 1% of rosin size and 3 - 4% of alum in practice to make sure that all the rosin are precipitated on the fibres by the alum during the sheet formation (British Paper and Board Makers Association, 1950; Clark, 1978), as earlier indicated. This is because, rosin is expensive and therefore no fraction of it should be allowed to drain away with the white water. The usual practice in the Nigerian Paper Mill Ltd., Jebba, is to use 1% of rosin and 4% of alum as additive for most pulps. Hence, it was also decided to use 1% solution of rosin and 4% solution of alum as the additive on one hand, and no additive at all (0% rosin and 0% alum) on the other, in the hand sheet making experiments conducted, in order to establish their effects. That is, there were two levels of additive R (rosin, alum): R_1 of (0,0)% and R_2 of (1,4)%, respectively.

Therefore, from the factorial 2 x 2 x 2 experiments, it was possible to determine the main effects of the furnish ratio (P), pulp freeness (Q) and additive (R) as well as the interactive effects of PxQ, PxR, QxR and PxQxR on the physical and mechanical properties of the resulting hand sheets, as presented in chapter 5.

3.7 Fibre Processing

The fibre processing experiments were conducted in the central laboratory of the Quality-Control Department of Nigerian Paper Mill Ltd., Jebba in Kwara State. Fibre processing included the operations of disintegration, stock blending, beating and refining and stock sizing with the additive as shown in Fig. 3.2. The disintegration, blending, beating and refining of the pulp were carried out using the Laboratory Valley Beater of the VOITH Inc., model Appleton WI54911 and serial number 109-E-1499; VS 14032 whose minimum capacity was 365.0g of oven-dry pulp and 23.0 litres of water.

3.7.1 Disintegration and Blending

For each variety of the thermo-mechanical pulp (TMP) prepared from cotton plant stalks, the moisture content was rechecked with an oven set at the temperature of 105^{o}C for 24 hours in order to determine the quantities of oven-dry fibre and water to mix to fill the minimum capacity of the valley beater. The TMP/water mixture was left to soak for 24 hours,

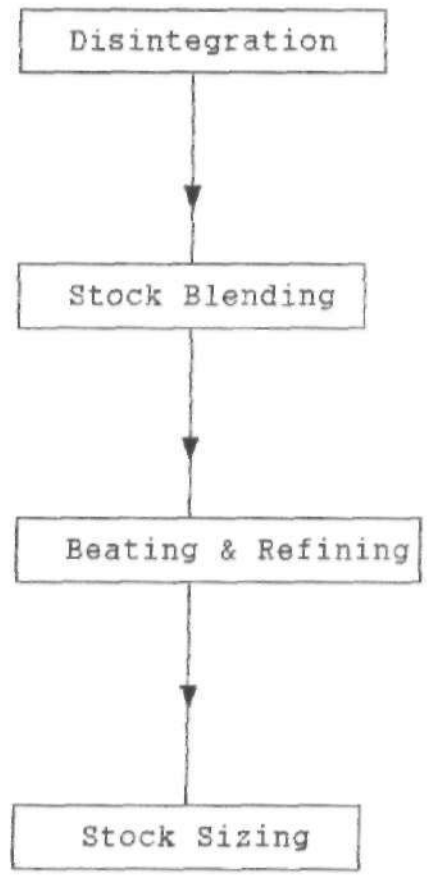


Fig. 3.2: Flowchart of Fibre Processing Operations.

after which the TMP slurry was agitated with the valley beater for 30 minutes; then, the valley beater was emptied and washed with water.

The grade of waste paper used for the stock blending was selected pure kraft cuttings obtained from the Paper Mill's finishing department. The waste paper had been disintegrated with the hydro-pulper and kept in the Paper Mill's waste paper storage tank from which the sample of waste paper slurry was taken. The waste paper pulp slurry was further agitated separately using the laboratory valley beater for the purpose of the experiment.

The consistencies of the thermo-mechanical pulp (TMP) and waste paper (WP) pulp slurries were determined separately as the percentage by weight of oven-dry fibre, over 100g of pulp slurry, in order to determine the volume of each pulp slurry to be blended with the other at the required furnish ratio, that is, either TMP/WP ratio of 60/40 or 50/50.

3.7.2 Beating and Refining

Calculated volumes of TMP and WP slurries were measured with beakers and cylinders and fed into the valley beater at the furnish ratio of 60/40 for the beating and refining process. The progress of the beating and refining was determined from measurements of the freeness in ^{O}SR of the blended pulp slurry samples taken directly from the valley

beater with the Schopper-Riegler freeness/wetness tester of the KARL SCHRODER KG. The freeness measurements were continued until pulp freeness of 20°SR was attained and the beating was stopped and the valley beater emptied.

Another batch of TMP/WP slurries, at the same furnish ratio of 60/40, was measured in calculated volumes into the valley beater and the beating and refining commenced. The progress of the beating and refining was also determined as described above, until a freeness of 35°SR was attained and the beating was stopped and the valley beater emptied.

The next batch of TMP/WP slurries at the next furnish ratio of 50/50 was beaten and refined likewise to the two freeness levels, 20°SR and 35°SR. This was carried out for each of the four varieties, namely SAMCOTs 6, 8, 9, and 10.

3.7.3 Stock Sizing

For each of the varieties and for each furnish ratio at each level of pulp freeness, two levels of stock sizing with the additive, rosin and alum were used. The alum acted as a mordant to precipitate the rosin size on the fibres during subsequent sheet forming operation, as earlier indicated. On one hand, no additive was used, that is, 0% Rosin and 0% Alum, and on the other hand, the additive was used, at a mixture of 1% Rosin and 4% Alum.

After determining the consistency of the pulp slurry as defined in section 2.12.3, the equivalent volume of additive

and pulp slurry required to form a standard 2.0g sheet was calculated. That is, using 2.0g as the required consistency, the 2.0g was divided by the original consistency of the pulp slurry and multiplied by 100 ml, to get the required volume of pulp slurry for forming the 2.0g sheet. The 1% solution of rosin and 4% solution of alum were pipetted into the beaten and refined pulp slurry and shaken vigorously.

3.8 Hand Sheet Making

Based on consistency measurements and calculations, given the consistency of the beaten and refined pulp slurry to be the weight of oven-dry fibre contained in 100ml or 100g of pulp slurry as defined in section 2.12.3, the required volume of pulp slurry to contain 2.0g of oven-dry fibre was calculated as described in section 3.7.3 and measured into a beaker. The weight measurements were taken with a Chemical Balance (SARTORIUS 2355) of accuracy 0.001g.

The hand sheet making was accomplished with the British Standard sheet former of the Testing Machines Inc., Amityville, New York. So, using each level of furnish ratio (TMP/WP), pulp freeness and additive, seven standard circular hand sheets, each being 160 mm in diameter and weighing 2.0g, were formed with each of the four varieties (See Fig. 3.3). This gave a total of 224 standard hand sheets formed and dried.

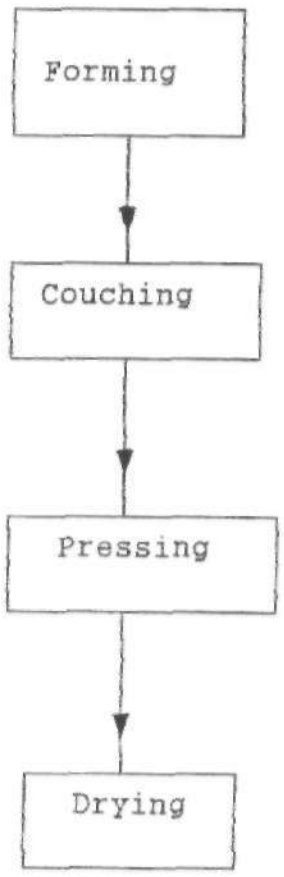


Fig. 3.3 Flowchart of Hand Sheet Making Operations.

The measured volume of pulp slurry was poured into the sheet former and water was pumped to fill the remaining volume of the deckle to give a very uniform and dilute consistency of 0.06%. The water was then quickly sucked by a suction pump through the mould or wire in the machine and all the fibres settled as a thin layer on the wire.

The deckle was removed simply by over-turning it to one side. A flat and thin, circular and stainless metal sheet, 200mm in diameter, was used to press a flat linerboard folder onto the wet paper web on the wire of the sheet former until the paper web stuck to the linerboard folder. The paper web was thereafter picked up or couched from the wire as the folder was lifted up gradually from one side to the other and transferred to the paper sheet drier [AB Lorentzen and Wettre (L & W) apparatus 257, type 3 - 1, number 199]. Samples of the hand sheets from the eight different treatments in each of the four varieties are shown in plates IV - VII.

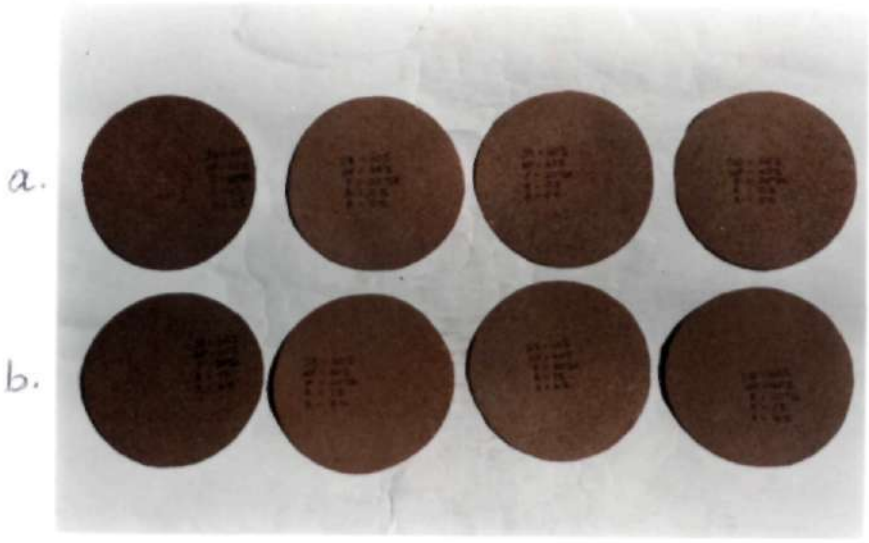


Plate IV: Standard Hand Sheets from the Treatments of Furnish Ratio (TMP/WP) of 60/40 and Pulp Freeness of 20°SR

(a) Without Additive (0,0)% for SAMCOTs 6, 8, 9 and 10 (from left to right)
(b) With Additive (1,4)% for SAMCOTs 6, 8, 9 and 10 (from left to right).

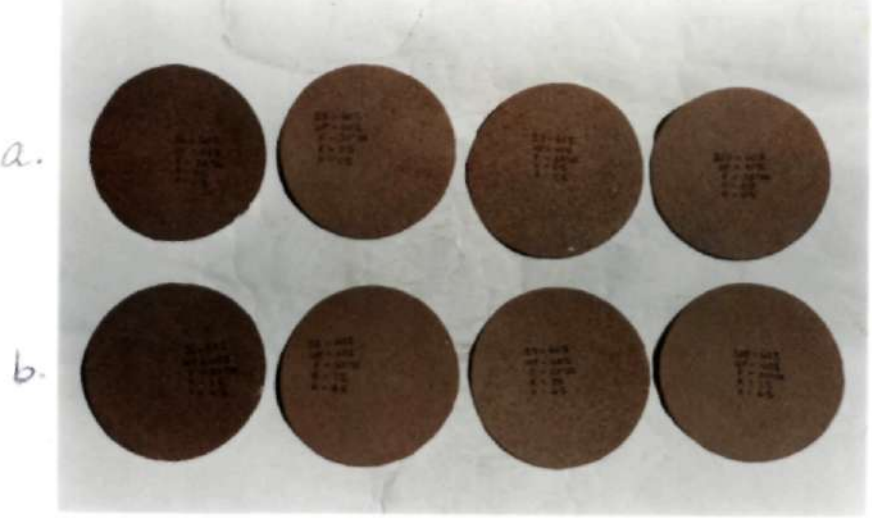


Plate V: Standard Hand Sheets from the Treatments of Furnish Ratio (TMP/WP) of 60/40 and Pulp Freeness of 35°SR

(a) Without Additive (0,0)% for SAMCOTs 6, 8, 9 and 10 (from left to right)
(b) With Additive (1,4)% for SAMCOTs 6, 8, 9 and 10 (from left to right).

3.9 Testing of Hand Sheets

The physical properties of the test sheets investigated were the thickness or caliper, basis weight and bulk, while the mechanical properties tested included the burst strength, burst factor, tear strength and tear factor. As soon as the hand sheets were dried, they were allowed to cool down to room temperature, after which, they were kept in an air-conditioned paper testing room for a conditioning period of 6 hours. The paper testing room was maintained at the standard conditions of temperature of 20°C and a relative humidity of 65%, as earlier stated.

3.9.1 Caliper, Basis Weight and Bulk

Caliper (mm): The caliper of the test sheets was measured using the Wennberg apparatus, type 11-1, number 103 of Elof Hansson, Goteborg, Sweden with accuracy of 0.01mm. For each test sheet, the thickness was measured at five spots including the centre, and the average caliper was noted.

Basis Weight (g/m^2): The basis weight, also called "gsm" of each test sheet was determined by the use of a rectangular template whose area in cm^2 was computed from the dimensions. The test sheet was then cut to the size of the template and weighed on the Chemical Balance (SARTORIUS 2355). The weight of the sheet cut to the size of the template was divided by its area in cm^2 and converted to g/m^2 by multiplying by 10,000 cm^2 to get the basis weight of the test sheet in g/m^2. This

was done for three sections of each test sheet and the average basis weight was noted.

Bulk (m^3/g): The bulk or specific volume of each test sheet was calculated from three measurements of the caliper and the basis weight using Eq. 2.10. The average bulk was calculated from the three replications of basis weight and the respective calipers.

3.9.2 Burst Strength and Burst Factor

Burst Strength (kPa): The burst strength of each test sheet was determined by clamping the sheet horizontally on a Mullen Tester of the B.F. Perkins, Standex Company, Chicopee, U.S.A whose accuracy was 0.07 kPa. After returning the pointer of the pressure gauge to zero, the pneumatic pressure was released and the maximum pressure required to burst the paper sheet was read off from the gauge and recorded. This was done at both the centre and three other spots on the sheet and the average of the four replications was noted.

Burst Factor($kPa.m^2/g$): The burst factor for each hand sheet was calculated from the burst strength and basis weight using Eq. 2.11. The average burst factor was calculated from the four replications of burst strength and the respective basis weights.

3.9.3 Tear Strength and Tear Factor

Tear Strength (kN): The tear strength of each hand sheet was determined with the Elemendorf Tearing Tester to an accuracy of 1.0kgf (9.81N). After clamping the paper in horizontal position on the tear strength machine, the free-moving pendulum was released to cut or tear the paper in the returning stroke. The tear resistance of the test sheet was read directly from the scale on the machine. This was done for four pieces of paper cut uniformly from each hand sheet. The average tear strength for each hand sheet was therefore calculated from the four replications.

Tear Factor (kNm^2/g): The tear factor for each test sheet was calculated from the tear strength and the basis weight of the sheet using Eq. 2.12. The average tear factor was calculated from the four replications of the tear strength and the respective basis weights.

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION OF PRELIMINARY INVESTIGATIONS

The preliminary investigations are those carried out to determine the suitability of the four local cotton plant stalks for papermaking and the results are presented and discussed in this chapter. While section 4.1 deals with the results of fibre characterization, section 4.2 explores the varietal differences in the fibre characteristics. The results of chemical composition analyses are discussed in section 4.3, while those of wood density and energy value determinations are presented in sections 4.4 and 4.5, respectively.

4.1 Fibre Characteristics

The raw data containing the measured and calculated wood fibre characteristics for both stems and roots of cotton plants from the four varieties, SAMCOTs 6, 8, 9 and 10 are shown in Appendices A-1, A-2, A-3 and A-4, respectively, while those of the bast fibre characteristics are given in Appendices B-1, B-2, B-3 and B-4, respectively. The summaries of the results based on statistical analyses of the raw data are presented in Tables 4.1 and 4.2 for wood fibre and bast fibre characteristics, respectively.

4.1.1 Fibre Wall Thickness

The wood fibre wall thickness of SAMCOT 6 ranged from 1.74 to 2.46 µm for the stem and 1.68 to 2.52 µm for the root (See Table 4.1). For SAMCOT 8, it ranged from 2.45 to 3.41 µm for the stem and 2.22 to 3.18 µm for the root, whereas in SAMCOT 9, it ranged from 2.22 to 3.18 µm for the stem and 3.50 to 4.76 µm for the root. In SAMCOT 10, the wood fibre wall thickness varied from 1.57 to 2.19 µm for the stem and 2.99 to 3.91 µm for the root. In other words, the wood fibre wall thickness for the stem ranged from 1.57 µm in SAMCOT 10 to 3.41 µm in SAMCOT 8 and that of the root varied from 1.68 µm in SAMCOT 6 to 4.76 µm in SAMCOT 9. Therefore, SAMCOTs 8 and 9 had the highest wood fibre wall thickness in the stem and root, respectively.

The bast fibre wall thickness of SAMCOT 6 ranged from 2.35 to 2.97 µm for the stem and 2.96 to 3.72 µm for the root, but for SAMCOT 8, it ranged from 3.98 to 5.7 µm for the stem and 2.53 to 3.25 µm for the root as shown in Table 4.2. The values of bast fibre wall thickness in SAMCOTS 6 and 8 were therefore higher than those of wood fibre in both stems and roots (See tables 4.1 and 4.2). In SAMCOT 9, the bast fibre wall thickness varied from 4.48 to 6.32 µm for the stem and 2.98 to 3.78 µm for the root, whereas in SAMCOT 10, it varied from 3.69 to 4.57 µm for the stem and 2.21 to 2.97 µm for the root (Table 4.2). The values of bast fibre wall thickness in SAMCOTS 9 and 10 were therefore higher than those of wood

Table 4.1: Wood Fibre Characteristics of SAMCOTs 6, 8, 9 and 10 Cotton Plants (± e)

Fibre Characteristics	SAMCOT 6 Stem	SAMCOT 6 Root	SAMCOT 8 Stem	SAMCOT 8 Root	SAMCOT 9 Stem	SAMCOT 9 Root	SAMCOT 10 Stem	SAMCOT 10 Root
Fibre wall thickness (µm)	2.10±0.36	2.10±0.42	2.93±0.48	2.70±0.48	2.70±0.48	4.13±0.62	1.88±0.31	3.45±0.46
Fibre lumen diameter (µm)	20.8±2.30	24.9±2.89	19.9±2.51	19.8±2.51	22.3±2.60	27.9±2.03	31.3±3.39	17.8±1.47
Runkel ratio	0.21±0.04	0.18±0.04	0.30±0.06	0.30±0.06	0.26±0.06	0.31±0.06	0.13±0.02	0.41±0.06
Fibre diameter (µm)	25.0±2.66	29.1±2.95	25.8±2.68	25.2±2.47	27.7±2.70	36.1±3.01	35.1±3.27	24.7±1.36
Thickness index	0.08±0.02	0.07±0.02	0.12±0.02	0.11±0.02	0.10±0.02	0.12±0.02	0.06±0.01	0.14±0.02
Coefficient of flexibility	0.83±0.02	0.85±0.02	0.77±0.04	0.78±0.04	0.80±0.04	0.77±0.04	0.89±0.02	0.72±0.04
Fibre length (µm)	225.4±31.8	235.5±42.1	268.5±56.4	240.7±39.1	317.2±52.6	222.0±34.5	294.0±42.8	283.5±38.0
Slenderness ratio	9.37±1.49	8.76±2.24	10.8±2.57	10.3±2.28	11.8±2.11	6.33±1.17	8.79±1.57	11.8±2.03
% Void space	8.21±4.38	2.60±1.32	3.95±1.85	2.52±0.70	3.48±1.01	3.29±0.95	3.80±0.92	1.96±0.88

Note! Standard error $e = t_{0.05} \left(\frac{s}{\sqrt{n}}\right)$ for $n \leq 50$

Table 4.2: Bast Fibre Characteristics of SAMCOTs 6, 8, 9 and 10 Cotton Plants (± e).

Fibre Characteristics	SAMCOT 6		SAMCOT 8		SAMCOT 9		SAMCOT 10	
	Stem	Root	Stem	Root	Stem	Root	Stem	Root
Fibre wall thickness (µm)	2.66±0.31	3.34±0.38	4.84±0.86	2.89±0.36	5.4 ±0.92	3.38±0.40	4.13±0.44	2.59±0.38
Fibre lumen diameter (µm)	13.6±1.61	10.4±1.61	11.4±2.07	9.68±1.19	12.1±1.78	9.45±1.44	8.10±1.30	8.25±1.19
Runkel ratio	0.42±0.08	0.73±0.16	1.00±0.27	0.60±0.10	1.01±0.29	0.80±0.17	1.16±0.27	0.70±0.17
Fibre diameter (µm)	19.0±1.59	17.1±1.67	21.1±2.26	15.4±1.51	22.9±2.60	16.2±1.59	16.3±1.80	13.4±1.55
Thickness index	0.14±0.02	0.20±0.02	0.23±0.03	0.19±0.02	0.23±0.02	0.21±0.02	0.26±0.02	0.20±0.02
Coefficient of flexibility	0.71±0.04	0.58±0.06	0.54±0.06	0.62±0.04	0.53±0.06	0.58±0.04	0.49±0.04	0.61±0.04
Fibre length (µm)	229.9±32.9	270.4±39.8	260.2±48.8	277.2 ±37.3	286.6±39.6	220.6±30.3	235.5±25.3	281.7 ±32.9
Slenderness ratio	12.4±1.97	16.0±2.22	13.1±2.97	18.7±3.06	13.4±2.60	16.1±2.39	15.4±2.89	22.2±3.89
Area of fibre bundle (mm^2)	0.018±0.007	0.013±0.005	0.010±0.005	0.014±0.005	0.010±1.002	0.015±0.007	0.009±0.003	0.011±0.005

Table 4.2 contd.

Fibre Characteristics	SAMCOT 6		SAMCOT 8		SAMCOT 9		SAMCOT 10	
	Stem	Root	Stem	Root	Stem	Root	Stem	Root
No. of fibre bundles within the total bark area of $0.069mm^2$	2.2±0.56	2.4±0.67	4.2±1.61	2.4±0.67	2.4±0.47	2.2±0.3	2.2±0.56	3.0±0.89
Percentage of fibre in the bark (%)	57.4	45.2	60.9	48.7	34.8	47.8	28.7	47.8
Percentage of parenchyma in the bark (%)	42.6	54.8	39.1	51.3	65.2	52.2	71.3	52.2

Note! Standard error $e = t_{0.05} \left(\frac{s}{\sqrt{n}}\right)$ for $n \leq 50$

fibre in the stems and vice versa in the roots (See Tables 4.1 and 4.2). Hence, SAMCOT 9 had the highest bast fibre wall thickness in both stems and roots, followed by SAMCOTs 8, 10 and 6.

Moreover, the wood and bast fibres in all the varieties are relatively thin-walled fibres which are good for papermaking, because they collapse easily during pulping and beating/refining operations for papermaking. The thick-walled and coarse fibres consume more power to achieve fibre collapse during refiner-mechanical and thermo-mechanical pulping than thin-walled fibres (Mackie and Joyce, 1987).

4.1.2 Fibre Lumen Diameter

The wood fibre lumen diameter for the stem of SAMCOT 6 varied from 18.6 to 23.2 µm and that of the root from 22.0 to 27.8 µm, while in SAMCOT 8, it varied from 17.4 to 22.5 µm for the stem and 17.3 to 22.3 µm for the root as shown in Table 4.1. In SAMCOT 9, the wood fibre lumen diameter ranged from 19.8 to 25.0 µm for the stem and 24.9 to 30.0 µm for the root, while that of SAMCOT 10 ranged from 28.0 to 34.7 µm for the stem and 16.4 to 19.3 µm for the root (See Table 4.1).
In other words, the wood fibre lumen diameter for the stem varied from 17.4 µm in SAMCOT 8 to 34.7 µm in SAMCOT 10 and for the root, 16.4 µm in SAMCOT 10 to 30.9 µm in SAMCOT 9. Thus SAMCOTs 10 and 9 wood fibres had the largest lumen diameters in the stem and root, respectively.

Table 4.2 showed that the bast fibre lumen diameter for the stem of SAMCOT 6 varied from 12.0 to 15.3 µm and that of the root varied from 8.82 to 12.0 µm, while in SAMCOT 8, it varied from 9.33 to 13.5 µm for the stem and 8.49 to 10.9 µm for the root. In SAMCOT 9, the bast fibre lumen diameter ranged from 10.3 to 13.9 µm for the stem and 8.01 to 10.9 µm for the root, while that of SAMCOT 10 ranged from 6.80 to 9.40 µm for the stem and 7.06 to 9.44 µm for the root. Therefore, the bast fibre lumen diameter for the stem in these cotton varieties varied from 6.80 µm in SAMCOT 10 to 15.3 µm in SAMCOT 6 and for the root, 7.06 µm in SAMCOT 10 to 12.0 µm in SAMCOT 6 as shown in Table 4.2. That is, SAMCOT 6 bast fibres had the largest lumen diameter in both stem and root, followed by SAMCOTs 9, 8 and 10.

Contrary to the trend observed for fibre wall thickness, the values of bast fibre lumen diameter in SAMCOT 6, 8, 9 and 10 were lower than those of the wood fibre for the same varieties, both in the stems and roots. In a given plant species, the fibre lumen diameter is related to fibre wall thickness, in that, the larger the lumen diameter, the smaller the wall thickness and vice versa. The fibre lumen diameter is useful for calculating the coefficient of flexibility and the runkel ratio of papermaking fibres, as indicated in Eqs. 2.1 and 2.3, respectively.

4.1.3 Runkel Ratio

Table 4.1 showed that the runkel ratio for the wood fibre in the stem of SAMCOT 6 ranged from 0.17 to 0.25 and that of the root from 0.14 to 0.22, whereas in SAMCOT 8, it ranged from 0.24 to 0.36 in both stem and root. Also, the runkel ratio for the wood fibre in the stem of SAMCOT 9 varied from 0.20 to 0.32 and that of the root from 0.25 to 0.37, whereas for SAMCOT 10, it ranged from 0.11 to 0.15 in the stem and 0.35 to 0.47 in the root. That is, the runkel ratio of the wood fibre in the stem ranged from 0.11 in SAMCOT 10 to 0.36 in SAMCOT 8, but in the root, it ranged from 0.14 in SAMCOT 6 to 0.47 in SAMCOT 10 as shown in Table 4.1. Thus, SAMCOTs 8 and 10 wood fibres had the highest runkel ratios in the stem and root, respectively.

However, the runkel ratio for the bast fibre in the stem of SAMCOT 6 ranged from 0.34 to 0.50 and that of the root from 0.57 to 0.89, whereas in SAMCOT 8, it ranged from 0.75 to 1.27 in the stem and 0.53 to 0.73 in the root as shown in Table 4.2. The ratio varied from 0.72 to 1.30 in the stem and 0.63 to 0.97 in the root of SAMCOT 9, but in SAMCOT 10, it varied from 0.89 to 1.43 in the stem and 0.53 to 0.87 in the root (Table 4.2). Thus, the runkel ratio of the bast fibre was higher than that of the wood fibre in both stems and roots in all the varieties (See Tables 4.1 and 4.2) and ranged from 0.34 in SAMCOT 6 to 1.43 in SAMCOT 10 for the stem and from 0.53 in SAMCOT 8 to 0.97 in SAMCOT 9 for the roots.

Hence, SAMCOTs 10 and bast fibres had the highest runkel ratios in the stem and root, respectively.

It has been reported that the strength of hardwoods used for papermaking depends much on their runkel ratio r (Dinwoodie, 1965) and for papermaking fibres where r ≥ 2, the fibres would be considered good for papermaking (Clark, 1978), as earlier indicated. The runkel ratio expresses the proportion of solid material in the fibre and the ease with which the fibre walls can collapse during the pulping of wood and fibre processing. A low runkel ratio shows thin fibre walls that are readily collapsible during the pulping of wood and the subsequent beating/refining of the pulp. Hence, fibres with low runkel ratio require little beating and refining to achieve sufficient fibrillation.

However, the runkel ratio of cotton plant stalks averaging 0.54 for both wood and bast fibres is obviously too low, considering the recommended minimum of 2.0. The tendency may be for the resulting paper sheets to be too weak. Nevertheless, one can still make good paper and/or board with the local cotton plant stalks by blending them with secondary fibres, such as waste paper, as indicated earlier in sections 2.11.2 and 3.6.

4.1.4 Fibre Diameter

Table 4.1 shows that the wood fibre diameter for the stem of SAMCOT 6 varied from 22.4 µm to 27.7 µm and that of the

root from 26.2 to 32.1 µm, but for SAMCOT 8, it varied from 23.1 to 28.5 µm in the stem and 22.7 to 27.7 µm in the root. In SAMCOT 9, the wood fibre diameter ranged from 25.1 to 30.5 µm for the stem and 33.1 to 39.2 µm for the root, while in SAMCOT 10, it ranged from 31.8 to 38.4 µm for the stem and 23.4 to 26.1 µm for the root (See Table 4.1). Hence, the wood fibre diameter in the stem varied from 22.4 µm in SAMCOT 6 to 38.4 µm in SAMCOT 10, but in the root, it varied from 23.4 µm in SAMCOT 10 to 39.2 µm in SAMCOT 9. Therefore, SAMCOTs 10 and 9 wood fibre diameters were the highest for stem and root, respectively.

The bast fibre diameter for the stem of SAMCOT 6 varied from 17.4 to 20.6 µm and that of the root varied from 15.4 to 18.8 µm, while in SAMCOT 8, it varied from 18.8 to 23.3 µm for the stem and 13.9 to 17.0 µm for the root, as shown in Table 4.2. Also in SAMCOT 9, it varied from 20.3 to 25.5 µm in the stem and 14.6 to 17.8 µm in the root, while in SAMCOT 10, it ranged from 14.6 to 18.2 µm for the stem and 11.9 to 15.0 µm for the root (See Table 4.2). Hence, the bast fibre diameter in the stem varied from 14.6 µm in SAMCOT 10 to 25.5 µm in SAMCOT 9 and for the root, 11.9 µm in SAMCOT 10 to 18.8 µm in SAMCOT 6. Therefore, SAMCOTs 9 and 6 bast fibre diameters were the highest for stem and root, respectively.

The wood fibre and bast fibre diameters of the local cotton plant stalks, averaging 23.1µm, compared favourably with the wood fibre diameters of notable papermaking woods and

agricultural residues including sorghum (16 µm), bamboos (13-25 µm), jute sticks (26 µm), bagasse (20 µm), rubber wood (19 µm) and eucalyptus species (15-20 µm) as reported by Food and Agriculture Organisation (1965).

4.1.5 Thickness Index

The wood fibre thickness index for the stem of SAMCOT 6 varied from 0.06 to 0.10 and that of the root varied from 0.05 to 0.09, while in SAMCOT 8, it varied from 0.10 to 0.14 for the stem and 0.09 to 0.13 for the root as shown in Table 4.1. In SAMCOT 9, the thickness index of the wood fibre ranged from 0.08 to 0.12 in the stem, and 0.10 to 0.14 in the root, whereas in SAMCOT 10, it ranged from 0.05 to 0.07 for the stem and 0.12 to 0.16 for the root (See Table 4.1). Hence, the wood fibre thickness index for the stem ranged from 0.05 in SAMCOT 10 to 0.14 in SAMCOT 8 and for the root, 0.05 in SAMCOT 6 to 0.16 in SAMCOT 10. That is, the wood fibre thickness index was highest in SAMCOTs 8 and 10 for stem and root, respectively.

The bast fibre thickness index for the stem of SAMCOT 6 varied from 0.12 to 0.16, and that of the root varied from 0.18 to 0.22, while in SAMCOT 8, it varied from 0.20 to 0.26 for the stem and 0.17 to 0.21 for the root as shown in Table 4.2. However, in SAMCOT 9, it ranged from 0.21 to 0.25 in the stem and 0.19 to 0.23 in the root, whereas in SAMCOT 10, it ranged from 0.24 to 0.28 for the stem and 0.18 to 0.22 for the

root (See Table 4.2). Therefore, the bast fibre thickness index for the stem ranged from 0.12 in SAMCOT 6 to 0.28 in SAMCOT 10 and for the root, 0.17 in SAMCOT 8 to 0.23 in SAMCOT 9. That is, the bast fibre thickness index was highest in SAMCOTs 10 and 9 for stem and root, respectively.

The thickness index, t being a ratio of fibre wall thickness to fibre diameter, as defined in Eq. 2.4, gives an indication of the beatability of the fibre during fibre processing. If the index is low, the fibres have thin walls that can easily absorb water, and swell up, bruise, collapse and open up to release the fibrils under very little beating and refining. However, if the thickness index is too high, it shows relatively thick-walled or coarse fibres which will require severe beating and refining to adequately fibrillate the fibres for strong inter-fibre bonding during paper sheet formation.

For good papermaking fibres, the thickness index should vary between 0.33 and 0.50, provided the runkel ratio $r \geq 2$, as indicated earlier in Eq. 2.9. The low average value of 0.10 obtained in this study for the wood fibre thickness index in both stems and roots of cotton plant stalks, therefore shows that the fibres are relatively thin-walled and will easily fibrillate with little beating and refining, but may form very weak paper sheets because their thickness index is too low.

4.1.6 Coefficient of Flexibility

Table 4.1 shows that the wood fibre flexibility coefficient for the stem of SAMCOT 6 ranged from 0.81 to 0.85 while that of the root ranged from 0.83 to 0.87, but in SAMCOT 8, it varied from 0.73 to 0.81 for the stem and 0.74 to 0.82 for the root. In SAMCOT 9, the flexibility coefficient ranged from 0.76 to 0.84 for the stem and 0.73 to 0.81 for the root, whereas in SAMCOT 10, it varied from 0.87 to 0.91 for the stem and 0.68 to 0.76 for the root (See Table 4.1). Thus, the flexibility coefficient of the wood fibre in the stem of cotton plants ranged from 0.73 in SAMCOT 8 to 0.91 in SAMCOT 10, but in the roots, it ranged from 0.68 in SAMCOT 10 to 0.87 in SAMCOT 6. That is, SAMCOTs 10 and 6 had the most flexible wood fibres in the stem and root, respectively.

In Table 4.2, the bast fibre flexibility coefficient for the stem of SAMCOT 6 ranged from 0.67 to 0.75 and that of the root ranged from 0.52 to 0.64, while in SAMCOT 8, it varied from o.48 to 0.6 for the stem and 0.58 to 0.66 for the root. In SAMCOT 9, it ranged from 0.47 to 0.59 in the stem and 0.54 to 0.62 in the root, whereas in SAMCOT 10, it varied from 0.45 to 0.53 in the stem and 0.57 to 0.65 in the root. Hence, the flexibility coefficient of the bast fibre in cotton plants ranged from 0.45 in SAMCOT 10 to 0.75 in SAMCOT 6 for the stems and 0.52 in SAMCOT 6 to 0.66 in SAMCOT 8 for the roots. That is, SAMCOTs 6 and 8 had the most flexible bast fibres in the stem and root, respectively.

The values of flexibility coefficient for the wood and bast fibres in the stems and roots of the local cotton plants, averaging 0.692, compared favourably with those of some notable papermaking fibres such as Gmelina arborea (0.70 - 0.85), eucalyptus (0.30 - 0.60), tropical pine species (0.70 - 0.80), rubber wood (0.57), sorghum (0.81) and bagasse (0.50) as reported by the Food and Agriculture Organisation (1965). According to Okereke (1962) and Rydholm (1967), a flexibility coefficient of more than 0.50 is required for papermaking fibres, and this would correspond to a runkel ratio r > 1, as shown in Eq. 2.8.

Since flexibility coefficient is a ratio of fibre lumen diameter to fibre diameter, a high value of approximately unity indicates a large fibre lumen diameter or thin fibre walls. Thin-walled fibres are usually very flexible and readily collapsible during pulping and beating/refining as indicated earlier. Fibre flexibility enhances fibre-to-fibre contact during the drying of the paper web. Flexible fibres can easily be drawn into close surface contact with each other by the force of surface tension as the water is removed or sucked by the suction pumps of the sheet formers and driers. The close surface contact promotes inter-fibre bonding and good strength properties in the paper.

Besides, the close contact between the fibres will give a sheet of lower porosity, that is, a sheet with less air space and a greater solids fraction. This can increase the

apparent sheet density and have a marked effect on many other important properties of the paper, especially, the opacity, air permeability, grease proofness and expansion with moisture. Papermakers should therefore be interested in the flexibility of the fibre as a structural unit of the sheet, in the bending of the whole fibre as a deflection per unit load and unit length, rather than in the modulus of rigidity of the cellulosic fibre material (Casey, 1980).

4.1.7 Fibre Length

The length of the wood fibres in the stem of SAMCOT 6 ranged from 0.19 to 0.26mm and that of the root ranged from 0.19 to 0.28mm, whereas in SAMCOT 8, it varied from 0.21 to 0.33mm in the stem and 0.20 to 0.28mm in the root (See Table 4.1). In SAMCOT 9, the fibre length ranged from 0.26 to 0.37mm for the stem and 0.19 to 0.26mm for the root, while in SAMCOT 10, it varied from 0.25 to 0.34mm in the stem and 0.25 to 0.32 in the root (See Table 4.1). Hence, the wood fibre length in the stems of cotton plants ranged from 0.19mm in SAMCOT 6 to 0.37mm in SAMCOT 9 while in the roots, it ranged from 0.19mm in SAMCOT 9 to 0.32mm in SAMCOT 10. That is SAMCOTs 9 and 10 had the longest wood fibres in the stem and root, respectively.

In Table 4.2, the bast fibre length in the stem of SAMCOT 6 varied from 0.20 to 0.26mm and that of the root varied from 0.23 to 0.31mm, while in SAMCOT 8, it ranged from 0.21 to

0.31mm for the stem and 0.24 to 0.31mm for the root. In SAMCOT 9, it varied from 0.25 to 0.33mm in the stem, and 0.19 to 0.25mm in the root, while in SAMCOT 10, it varied from 0.21 to 0.26mm in the stem and 0.25 to 0.32mm in the root. Thus, the bast fibre length in the stems of cotton plants ranged from 0.20mm in SAMCOT 6 to 0.33mm in SAMCOT 9, while in the roots, it ranged from 0.19mm in SAMCOT 9 to o.32mm in SAMCOT 10. That is, SAMCOTs 9 and 10 had the longest bast fibres in the stem and root, respectively. Since the bast fibre lengths compared well with those of the wood fibre in both shoots and roots of all the varieties, it would be unnecessary to debark cotton plant stalks before or during pulping as the quality of the bast fibres also contributes meaningfully to the overall papermaking fibre quality of the stalks.

Fibre lengths for notable papermaking woods and agricultural residues have been reported, as follows:- tropical pine wood species (3.2 - 4.8mm), eucalyptus (0.9 - 1.1mm), rubber wood (1.4mm), jute sticks (1.0mm), bagasse (1.7 - 2.0mm) and Sorghum (1.9mm) [FAO, 1965]. Comparing the wood and bast fibre lengths of the stems of cotton plants (which averaged 0.28 mm and 0.26 mm, respectively), with those of the above-mentioned raw materials, the fibres in cotton plant stalks are extremely too short. However, they can still be useful in papermaking if they are blended with a long-fibred pulp, where locally available, or alternatively, with secondary fibres, such as waste paper, as indicated earlier.

Such stock blending is the practice in most paper mills, including the Nigerian Paper Mill Ltd, Jebba, which produces paper from short-fibred tropical hardwoods. Long fibres (3.0-6.0 mm long) are commonly found in softwoods like pinewood species, but hardwoods like eucalyptus, rubberwoods, gmelina and others are usually short-fibred (1.0 - 2.0 mm long), as indicated earlier.

Good fibre length has been recognised as an important factor for good tear strength and other strength properties of paper (Britt, 1970). For particle boards, stiffness in bending and dimensional stability improve with increase in particle/flake length. That is, the longer and thinner the flakes, the stronger, stiffer and more dimensionally stable the particeboard (Badejo, 1988). These findings notwithstanding, fibre length should not be seen to be the only factor affecting paper strength properties. Hence, Casey (1960), noted that the importance of fibre length in developing certain paper properties must have been unduly over-emphasized. Besides, Dinwoodie (1965) observed that in hardwoods, other fibre characteristics such as runkel ratio, coefficient of flexibility, thickness index and slenderness ratio, are more important than fibre length alone in determining paper properties.

The option of papermaking from cotton plant stalks is not intended to entirely substitute the use of other established papermaking woods and fibrous raw materials, but to supplement

the usual supplies of long-fibred pulp by way of stock blending with short-fibred pulp, in view of the high cost and short falls in the quantity of long-fibred pulp in the world market. This will enhance cost effectiveness in papermaking. Moreover, papermaking with cotton plant stalks is an economically viable alternative to the wasteful disposal of the stalks by burning.

4.1.8 Slenderness Ratio

The slenderness ratio of the wood fibre in the stem of SAMCOT 6 ranged from 7.88 to 10.9 and that of the root ranged from 6.52 to 11.0 while in SAMCOT 8, it varied from 8.23 to 13.4 for the stem and 7.99 to 12.6 for the root as shown in Table 4.1. In SAMCOT 9, the slenderness ratio ranged from 9.71 to 13.9 for the stem and 5.16 to 7.50 for the root, whereas in SAMCOT 10, it ranged from 7.22 to 10.4 for the stem and 9.76 to 13.8 for the root. Hence, the slenderness ratio for the wood fibre in the stems of cotton plants ranged from 7.22 in SAMCOT 10 to 13.9 in SAMCOT 9, but in the roots, it ranged from 5.16 in SAMCOT 9, to 13.8 in SAMCOT 10. That is, SAMCOTs 9 and 10 had the highest slenderness ratios for wood fibres in the stem and root, respectively.

In Table 4.2, the slenderness ratio for the bast fibre in the stem of SAMCOT 6 varied from 10.5 to 14.4 and that of the roots ranged from 13.8 to 18.3, while in SAMCOT 8, it varied from 10.1 to 16.0 for the stem and 15.6 to 21.8 for the root.

In SAMCOT 9, the slenderness ratio varied from 10.8 to 16.0 for the stem and 11.8 to 16.5 for the root, while in SAMCOT 10, it varied from 12.5 to 18.3 for the stem and 18.3 to 26.1 for the root. Therefore, the slenderness ratio for the bast fibre in the stems of cotton plants ranged from 10.5 in SAMCOT 6 to 18.3 in SAMCOT 10, but in the roots, it ranged from 11.8 in SAMCOT 9 to 26.1 in SAMCOT 10. Hence, SAMCOT 10 bast fibres had the highest slenderness ratio in both stem and root, followed by SAMCOTs 8, 9 and 6.

The slenderness ratios of some notable papermaking fibrous raw materials reported by FAO (1965) include those of eucalyptus (55 - 60), gmelina (40 - 45), bagasse (85 - 100) and jute sticks (38.5). The low values of slenderness ratio recorded in this study for the wood and bast fibres in cotton plant stalks being on the average 10.2 and 15.8, respectively, can be explained by the short fibre lengths involved. This further underscores the need to blend them with long or medium-fibred pulp, such as waste paper. The higher the slenderness ratio, the stronger the resistance to tearing of the paper sheet (Rydholm, 1967).

4.1.9 Percentage of Void Space

The percentage of void spaces in the transverse section (TS) of the wood in the stem of SAMCOT 6 varied from 3.83 to 12.6% and that of the roots varied from 1.28 to 3.92%, while in SAMCOT 8, it ranged from 2.10 to 5.80% for the stem and

1.82 to 3.22% for the roots (See Table 4.1). The percentage void space ranged from 2.47 to 4.49% for the stem and 2.34 to 4.24% for the root of SAMCOT 9. In SAMCOT 10, it ranged from 2.88 to 4.72% for the stem and 1.08 to 2.84% for the root. Hence, the percentage of void spaces in the woody stem of cotton plants varied from 2.47% in SAMCOT 9 to 12.6% in SAMCOT 6 and in the roots, it varied from 1.08% in SAMCOT 10 to 4.24% in SAMCOT 9. That is, SAMCOTs 6 and 9 had the highest percentages of void spaces in the stem and root, respectively. Therefore, the grand mean of the percentage of void spaces in the stem and root of the four varieties of cotton plants was 3.73%.

The percentage of void spaces in the cross-section of the woody cotton plant stalks gives an indication of the porosity of the stalks. Non-fibrous tissues like vessels, rays and parenchyma pose problems of low fibre yield in pulp mills. On the other hand, a high percentage of void spaces in a paper web leads to failure in bond properties and "lift" in newsprint, thereby causing fuzziness in printing (Byrd and Fahey, 1969). The low percentage of void spaces obtained for the local cotton plant stalks suggests that the stalks are high in fibre content and gives an indication of a high fibre yield during pulping, which is a good feature for papermaking.

4.1.10 Area and Number of Fibre Bundles

Table 4.2 shows that the cross-sectional area of each fibre bundle in the bark of the stem of SAMCOT 6 ranged from 0.011 to 0.025mm^2 and that of the root ranged from 0.008 to 0.018mm^2 whereas in SAMCOT 8, it varied from 0.005 to 0.015mm^2 for the stem and 0.009 to 0.019mm^2 for the root. In SAMCOT 9, the area of fibre bundle varied from 0.008 to 0.012mm^2 in the stem and 0.008 to 0.022mm^2 in the root, but in SAMCOT 10, it varied from 0.006 to 0.012mm^2 in the stem and 0.006 to 0.016mm^2 in the root as shown in Table 4.2. Hence, the area of each fibre bundle in the bark of the stem of cotton plants ranged from 0.005mm^2 in SAMCOT 8 to 0.025mm^2 in SAMCOT 6, while that of the root ranged from 0.006mm^{2}in SAMCOT 10 to 0.022mm^2 in SAMCOT 9. So, the area of fibre bundle in the bark was highest in the stem and root of SAMCOTs 6 and 9, respectively.

Table 4.2 also shows the number of fibre bundles within a given area of the bark covered by the field of view of the microscope, which was 0.069mm^2. For the stem of SAMCOT 6, the number of fibre bundles ranged from 1.64 to 2.76 and for the root, 1.73 to 3.07 while in SAMCOT 8, it varied from 2.59 to 5.81 for the stem and 1.73 to 3.07 for the root. In SAMCOT 9, it varied from 1.93 to 2.87 for the stem and 1.81 to 2.59 for the root, but in SAMCOT 10, it ranged from 1.64 to 2.76 for the stem and 2.11 to 2.89 for the root. Thus, the number of fibre bundles within the area of view of 0.069 mm^2 in the bark

of the stems of cotton plants varied from 1.64 in SAMCOTS 6 and 10 to 5.81 in SAMCOT 8, while in the root, it varied from 1.73 in SAMCOTS 6 and 8 to 3.89 in SAMCOT 10. So, the number of fibre bundles in the bark was highest in the stem and root of SAMCOTs 8 and 10, respectively.

Based on the mean cross sectional area and average number of fibre bundles within the given area of the bark of the stems and roots of cotton plants, the percentage of fibre in the bark can be computed by dividing the product of the area and number of fibre bundles by the given bark area as defined by Eq. 2.6.

4.1.11 Percentages of Fibre and Parenchyma in the Bark

The average percentages of fibre in the bark of the stem and root of SAMCOT 6 were 57.4% and 45.2%, respectively, while in SAMCOT 8, there were 60.9% and 48.7% of bast fibre in the stem and root, respectively, as shown in Table 4.2. Also, in SAMCOT 9, there were 34.8% and 47.8% of bast fibre in the stem and root, respectively, whereas in SAMCOT 10, they were 28.7% and 47.8% in the stem and root, respectively (See Table 4.2).

Therefore, there were higher quantities of bast fibre in the stems of SAMCOTS 6 and 8 than their roots, but for SAMCOTS 9 and 10, there were more bast fibres in their roots than their stems. SAMCOT 8 had the highest percentages of bast fibre in both stem and root, while SAMCOT 10 had the lowest percentage of bast fibre in the stem and SAMCOT 6 had the

lowest percentage of bast fibre in the root (See Table 4.2). It is interesting to find that the bark of cotton plant stalks is sufficiently fibrous just like the wood, and that the bast fibre characteristics compared favourably with those of the wood. Hence, the wood and the bark can be pulped together, without debarking.

The percentage of non-fibrous tissues or parenchyma in the bark of cotton plant stalks was calculated using Eq. 2.7. The average percentages of parenchyma in the bark of SAMCOT 6 stem and root were 42.6% and 54.8%, respectively, while in SAMCOT 8, there were 39.1% and 61.3% of parenchyma in the bark of the stem and root, respectively (See Table 4.2). In SAMCOT 9, there were 65.2% and 52.2% of parenchyma in the bark of the stem and root, respectively, while in SAMCOT 10, there were 71.3% and 52.2% of parenchyma in the bark of the stem and root, respectively. Thus, there was more parenchyma in the roots of SAMCOTS 6 and 8 than their stems but for SAMCOTS 9 and 10, there was more parenchyma in their stems than their roots. However, SAMCOT 8 had the lowest parenchyma in both stem and root, while SAMCOT 10 had the highest parenchyma in the stem and SAMCOT 6 had the highest parenchyma in the root as shown in Table 4.2.

The presence of parenchyma in pulp is generally undesirable for papermaking. Excess parenchyma can cause "fines" in pulp, resulting in slow paper machine drainage and effluent difficulties (Klungness and Sanyer, 1981). The

parenchyma being thin-walled non-fibrous tissues, will disintegrate or macerate and get washed away during pulping, but when in excess, they can constitute too much of fine solutes in the white water that drains through the wire of paper machine in the process of forming the wet paper web. They can clog the wire and prevent fast drainage of the white water by making the effluent slurry too viscous to drain or flow away fast. However, the percentages of parenchyma obtained for the bark of the local cotton plant stems and roots are tolerable for papermaking, since the bark constitutes only about 10% by weight of cotton plant stalks.

4.2 Varietal and Sample Effects on Fibre Characteristics

Analysis of variance (ANOVA) was carried out to determine the effects of each variety of cotton plant stalks (varietal effects) and each sample of stem and root from each variety (sample effects) on the fibre characteristics. This was done by comparing the mean values of the fibre characteristics shown in Tables 4.1 and 4.2, using the variations between and within the varieties and the variations between and within the samples of stem and root from each variety by way of a single-factor analysis of variance (ANOVA) model I (Neter and Wasserman, 1974; Kennedy and Neville, 1976; Box et al, 1978).

4.2.1 Varietal Effects

The analysis of variance tables showing the varietal effects on the wood and bast fibre characteristics of SAMCOTs 6, 8, 9 and 10 cotton plant stems and roots are given in Appendices C-1, C-2, C-3 and C-4. It was found that there were significant differences in the wood fibre characteristics of the stems of SAMCOTS 6, 8, 9 and 10 cotton plants, except slenderness ratio, at 95% probability level. Likewise, the bast fibre characteristics of the stems of SAMCOTS 6, 8, 9 and 10 cotton plants were found to be significantly different at 95% probability level, but the fibre length and slenderness ratio were not.

Also, the wood fibre characteristics of the roots of SAMCOTS 6, 8, 9 and 10 cotton plants were found to be significantly different between the varieties at the 95% probability level. However, the wood fibre length and the percentage of void spaces were not significantly different between the varieties. On the other hand, only the fibre wall thickness, fibre diameter, fibre length, and slenderness ratio of the bast fibre from the roots of the four varieties were found to be significantly different between the varieties at 95% probability level.

The implications of the varietal differences observed in the fibre characteristics of the four varieties of cotton plant stalks are apparent. The properties of paper made from the fibres of one variety cannot be generalized to apply to

other varieties. However, in a situation where the quantity of each variety of cotton plant stalks available is insufficient, it should be possible to blend the four varieties and produce the pulp and paper, thereby utilizing all the cotton plant stalks available in any season in the country.

4.2.2 Sample Effects

The analysis of variance tables showing the sample effects on the wood and bast fibre characteristics of SAMCOTs 6, 8, 9 and 10 cotton plant stems and roots are given in Appendices C5 - C12. It was found that the wood fibre characteristics of the stem and root samples from SAMCOT 6 cotton plant stalks were not significantly different at 95% probability level, except the fibre lumen diameter, fibre diameter and percentage of void spaces. Also, the bast fibre characteristics of the stems and roots of SAMCOT 6 were found to be significantly different at 95% probability level, except fibre diameter, fibre length and area of fibre bundle. On the other hand, it was found that the wood fibre characteristics of the stem and root samples of SAMCOT 8 cotton plants were not significantly different at 95% probability level. However, the bast fibre characteristics of the stems and roots of SAMCOT 8 were found to be significantly different at 95% probability level, except fibre lumen diameter, fibre length and area of fibre bundle.

The wood fibre and bast fibre characteristics of the stem and root samples of SAMCOT 9 cotton plants were found to be significantly different at 95% probability level, except most of the dimensionless parameters, such as runkel ratio, thickness index and flexibility coefficient. Also, the wood fibre characteristics of the stem and root samples of SAMCOT 10 cotton plants were found to be significantly different at 95% probability level, except the fibre length. Similarly, the bast fibre characteristics of the stem and root samples from SAMCOT 10 cotton plants were found to be significantly different at 95% probability level, except fibre lumen diameter and area of fibre bundle.

However, both stem and root samples can be conveniently pulped and beaten/refined together as a single fibre source for papermaking, since the wood fibre and bast fibre characteristics of the roots compared favourably with those of the stems. In fact, the mixing of the stem and root of each variety of cotton plant is desirable to avoid leaving any residue after utilising the stalks for papermaking.

4.3 Chemical Composition Analysis

The results of proximate analysis in terms of the percentage chemical compositions of SAMCOTS 6, 8, 9 and 10 varieties of cotton plant stalks are shown in Appendices D-1, D-2, D-3 and D-4, respectively, but the summary of the results is presented in Table 4.3.

4.3.1 Cellulose Content

Table 4.3 shows that the cellulose content of SAMCOT 6 varied from 51.9 to 54.1% and that of SAMCOT 8 varied from 53.8 to 56.5%. Also, cellulose content in SAMCOT 9 ranged from 53.4 to 55.0%, while in SAMCOT 10, it ranged from 52.3 to 55.3%. Thus, the alpha-cellulose content of the local cotton plant stalks varied from the lowest value of 51.9% in SAMCOT 6 to the highest value of 56.5% in SAMCOT 8, while the average cellulose content for the four varieties was 54.0%.

Table 4.3: Chemical Compositions of SAMCOTs 6, 8, 9 and 10 Cotton Plant Stalks (± e)

S/N	Chemical Composition	SAMCOT 6	SAMCOT 8	SAMCOT 9	SAMCOT 10
1.	Cellulose Content (%)	53.0±1.07	55.1±1.31	54.2±0.80	53.8±1.46
2.	Hemi-Cellulose Content(%)	8.64±0.20	8.56±0.20	8.23±0.41	8.15±0.29
3.	Lignin content (%)	24.1±0.66	22.1±0.63	23.3±0.53	23.3±0.33
4.	Ash Content (%)	6.25±0.10	6.23±0.19	6.50±0.33	6.53±0.16
5.	Moisture Content (%wb)	8.02±1.14	7.92±0.16	7.78±0.68	8.27±0.23

Note! Standard error $e = t_{0.05} \left(\frac{s}{\sqrt{n}}\right)$ for $n \leq 50$

The average cellulose content of 54.0% obtained for cotton plant stalks grown in Nigeria is higher than the cellulose content of 40.8% reported earlier for cotton plant stalks grown in the United States of America (True and Morton, 1896). The alpha-cellulose content is the major component required for papermaking, and 54.0% of it on the average, is

high enough to be explored for papermaking, especially SAMCOT 8 which had the highest mean value of cellulose content (55.1%)

4.3.2 Hemi-cellulose Content

In Table 4.3, the hemi-cellulose content in SAMCOT 6 varied from 8.44% to 8.84% while in SAMCOT 8, it ranged from 8.36 to 8.76%. Also in SAMCOT 9, it varied from 7.82 to 8.64% whereas in SAMCOT 10, it ranged from 7.86 to 8.44%. Hence, the hemi-cellulose content of the local cotton plant stalks varied from the lowest value of 7.82% in SAMCOT 9 to the highest value of 8.84% in SAMCOT 6, but the average hemi-cellulose content for the four varieties was 8.40%.

The hemi-cellulose content averaging 8.40% in the four local cotton plant stalks, constitutes useful cellulose as well for papermaking, because, the short-chained beta and gamma-cellulose components provide a dense concentration of short-chained molecules which facilitate cohesion or bonding affinity of fibres and improve the compactness of the finished paper. Hemi-cellulose also increases the "wetness" of pulp and the degree of sizing in paper, though when in excess, it can adversely affect the paper strength (Higham, 1963; Clark, 1978).

Adding the long-molecular alpha-cellulose (54.0%) and the short-chained hemi-cellulose (8.40%) puts the total useful holo-cellulose content of the local cotton plant stalks at

82.4% on the average, which compares favourably with the holocellulose content of 77.3% reported for Indian Hybrid 4 cotton plant stalks (Shaikh and Varadarajan, 1995).

4.3.3 Lignin Content

The lignin content of SAMCOT 6 cotton plant stalks ranged from 23.5 to 24.8% while that of SAMCOT 8 ranged from 21.5 to 22.8% as shown in Table 4.3. Also in SAMCOT 9, the lignin content varied from 22.8 to 23.9% while in SAMCOT 10, it varied from 23.0 to 23.6%. Therefore, the lignin content for the local cotton plant stalks ranged from the lowest value of 21.5% in SAMCOT 8 to the highest value of 24.8% in SAMCOT 6, while the average lignin content for the four varieties was 23.2%.

The lignin content averaging 23.2% for the four local varieties of cotton plant stalks compared favourably with the 27.0% reported for the Indian Hybrid 4 cotton plant stalks (Shaikh and Varadarajan, 1995) and with the 23.0% reported as the average lignin content for most hardwoods (Higham, 1963). The less the lignin content, the easier and less expensive it will be to pulp any plant fibre for papermaking, because, the requirement for the expensive chemicals for chemical pulping and bleaching will be reduced. Hence, SAMACOT 8 which had the lowest mean value of lignin content (22.1%) promises to liberate its wood and bast fibres more readily and will be cheaper to pulp in terms of bleaching chemical requirements.

4.3.4 Ash Content

Table 4.3 showed that the ash content of SAMCOT 6 cotton plant stalks ranged from 6.15 to 6.35% while that of SAMCOT 8 ranged from 6.04 to 6.42%. Also, the ash content of SAMCOT 9 varied from 6.17% to 6.83% and that of SAMCOT 10 varied from 6.37 to 6.69%. Hence, the ash content of the local cotton plant stalks ranged from the lowest value of 6.04% in SAMCOT 8 to the highest value of 6.83% in SAMCOT 9 while the average ash content for the four varieties was 6.38%.

The natural fibre ash content averaging 6.38% for cotton plant stalks grown in Nigeria, compared favourably with the 5.23% reported for cotton plant stalks in America (True and Morton, 1896) and the 7.13% reported for Indian Hybrid 4 cotton plant stalks (Shaikh and Varadarajan, 1995).

4.3.5 Moisture Content

The moisture content at harvest for SAMCOT 6 cotton plant stalks varied from 6.88 to 9.16% wet basis, but that of SAMCOT 8 varied from 7.76 to 8.08% wet basis (See Table 4.3). In SAMCOT 9, the moisture content at harvest ranged from 7.10 to 8.46% wet basis but in SAMCOT 10, it ranged from 8.04 to 8.50% wet basis as shown in Table 4.3. In other words, the moisture content of the local cotton plant stalks varied from the lowest value of 6.88 to the highest value of 9.16% wet basis both in SAMCOT 6, but the average moisture content for the four varieties was 8.00% wet basis.

The average moisture content of 8.0%, wet basis, recorded for dry cotton plant stalks at harvest in Nigeria, compared well with the 10.0% reported for the decorticated cotton plant stalks in America (True and Morton, 1896). The moisture content of wood affects the thermal softening behaviour of the wood (Blechschmidt et al, 1986).

4.4 Wood Density

The raw data of the wood density measurements for SAMCOT 6, 8, 9 and 10 cotton plant stalks are shown in Appendices E-1, E-2, E-3 and E-4 respectively, but the summary of the results is given in Table 4.4.

Table 4.4: Wood Densities of SAMCOTs 6, 8, 9 and 10 Cotton Plant Stalks (± e)

Variety	Wood Density (kg/m^3)
SAMCOT 6	0.397 ± 0.027
SAMCOT 8	0.392 ± 0.028
SAMCOT 9	0.396 ± 0.035
SAMCOT 10	0.438 ± 0.019

Note! Standard error $e = t_{0.05} \left(\frac{s}{\sqrt{n}}\right)$ for $n \leq 50$

The average wood density of the local cotton plant stalks being 0.41 kg/m^3 compares well with those of some papermaking woods such as pinewood species (0.43-0.58 kg/m^3), eucalyptus (0.43 - 0.50 kg/m^3), rubberwood (0.5kg/m^3) and light woods from natural stands in West African coast (0.22 - 0.50 kg/m^3)

as reported by the Food and Agriculture Organisation (1965). Since the average wood density of the local cotton plant stalks falls below 0.70 kg/m^3, it gives a good indication that they may be suitable for papermaking as discussed in section 2.4.

4.5 Energy Value

The report sheets of the automatic adiabatic bomb calorimeter used for the experiments on energy value determination for the four local varieties of cotton plant stalks are shown in appendices F-1, F-2, F-3 and F-4, but the summary of the energy values is given in Table 4.5.

Table 4.5: Gross Energy Values of SAMCOTs 6, 8, 9 and 10 Cotton Plant Stalks.

Variety	Gross Eenergy Value (MJ/kg)
SAMCOT 6	12.5
SAMCOT 8	13.4
SAMCOT 9	13.7
SAMCOT 10	13.2

The average gross energy value of the four varieties of cotton plant stalks was about 13.2 MJ/kg. This compared favourably with the 13.9 MJ/kg reported for cotton plant stalks grown in India (Kumar et al, 1984). There are other agricultural residues such as jute sticks, saw dust (from sal

wood) and coconut shell, whose gross energy values were also reported to be 17.1 MJ/kg, 18.7 MJ/kg and 17.9 MJ/kg, respectively (Kumar et al, 1984). The average gross energy value of cotton plant stalks grown in Nigeria being 13.2 MJ/kg is low when compared with those of the above-mentioned agricultural residues.

In many of the cotton-growing zones and localities in Nigeria, some farmers use cotton plant stalks as firewood, but they burn too fast and leave a residue of ash and no charcoal at all, which agrees with their low energy value obtained in this study. Woods with good to high energy value burn slowly and yield charcoal.

The average energy value of savannah wood species is about 17.5MJ/kg (Fuwape, 1985), but the average fuel end-use efficiency of firewood obtained from savannah wood species, using traditional wood stoves, is approximately 7.50%, as reported by the Afforestation Programme Co-ordinating Unit (APCU) [1991]. Therefore, the option of papermaking using the local cotton plant stalks may be a more economicaliy viable alternative, rather than using them as firewood or burning them off.

CHAPTER FIVE

5.0 RESULTS AND DISCUSSION OF PAPERMAKING EXPERIMENTS

This chapter presents the results and discussion of experiments on papermaking using SAMCOTs 6, 8, 9 and 10 cotton plant stalks as raw materials. Observations made during thermo-mechanical pulping (TMP) and fibre processing are presented in sections 5.1 and 5.2, respectively. The results of paper testing such as caliper, basis weight, bulk, burst strength, burst factor, tear strength and tear factor, as well as their analysis for the main effects and their interactions are discussed in sections 5.3 and 5.4, respectively. The relationships between the basis weights and calipers of the hand sheets, for the four varieties, as well as the relationships between the mechanical properties of hand sheets and the fibre characteristics of the four varieties of cotton plant stalks are described in sections 5.5 and 5.6, respectively.

5.1 Thermo-mechanical Pulping (TMP)

The thermo-mechanical pulp prepared from SAMCOT 6 cotton plant stalks appeared darkest in colour, while SAMCOT 8 was brightest compared to other varieties. SAMCOT 9 and SAMCOT 10 thermo-mechanical pulps had the same lighter colour than SAMCOT 6, but darker than SAMCOT 8. The different levels of darkening of the pulp varieties during the cooking process may

be attributed to the different levels of lignin content in the raw materials as discussed in section 4.3.3. SAMCOT 6 was reported to have the highest lignin content and SAMCOT 8 had the lowest, but SAMCOTs 9 and 10 had values close to average.

The thermo-mechanical pulping process usually melts and removes the lignin, and the resulting brownish pulp is slightly darkened, as evident in the "black water" effluent. It takes a chemi-thermo-mechanical pulping (CTMP), or an oxidative bleaching process, to improve the brightness gain of thermo-mechanical pulps, as indicated earlier in sections 2.8.5 and 2.9, respectively. However, bleaching is normally unnecessary for cheap grades of paper and board, such as, kraft linerboard and fluting paper (Ohiorhenuan, 1996; Jimoh, 1996).

The thermo-mechanical pulp yields from SAMCOTS 6, 8, 9 and 10 were found to be 78.8, 88.2, 85.2 and 84.8%, respectively, giving an average of 84.3% of the original weight of the wood chips. This compares favourably with the fibre yield of 80-90% reported for stone ground wood (SGW) and thermo-mechanical pulping (TMP) processes (Clark, 1978), but it is higher than the total yield of 50.6% obtained with 18% kraft liquor of caustic soda (Na_2O) by Shaikh and Varadarajan (1995). The advantage of thermo-mechanical pulping over chemical pulping in terms of fibre yield is therefore apparent. SAMCOT 8 gave the highest pulp yield (88.2%), followed by SAMCOTs 9, 10 and 6.

5.2 Fibre Processing

The oven-dry moisture contents of SAMCOTs 6, 8, 9 and 10 thermo-mechanical pulps were found to have increased to 12.3, 15.7, 14.0 and 13.1%, wet basis, respectively, at the Paper Mill's laboratory in Jebba, whereas each of them was formerly dried to 8.0% wet basis in Zaria as reported in section 3.5. The increase in moisture content of each of the pulp varieties enroute Jebba, showed that delignification by the method of thermo-mechanical pulping was complete. Hence, the hydrophilic molecules of cellulose and hemi-cellulose were exposed to absorb moisture from the air.

During the disintegration or agitation of each thermo-mechanical pulp slurry in the valley beater it was observed that the pulp slurry was foaming profusely and SAMCOT 6 foamed more than SAMCOTs 8, 9 and 10. The foaming may be attributed to the presence of some other chemical constituents such as tannins, resins and other polyphenols which were not determined (Clark, 1978). Papermakers usually prevent such development by the use of an antifoam additive, as indicated earlier in section 2.11.4. The defoamer, for example, Cojaloid 200 Defoamer, normally added to the pulp slurry before beating and refining, helps to prevent losses of fibre and additives during the fibre processing and also enhances paper sheet formation on the wire of the paper machine.

5.3 Results of Paper Testing

Appendix G contains the raw data and the statistical analysis of the results of paper testing for SAMCOTs 6, 8, 9 and 10 handsheets, but Tables 5.1, 5.2, 5.3 and 5.4 show the mean values of the physical and mechanical properties of the handsheets tested for SAMCOTs 6, 8, 9 and 10, respectively.

5.3.1 Caliper

Tables 5.1, 5.2, 5.3 and 5.4 show that for the furnish ratio (TMP/WP) of 60/40, with beating and refining to the level of pulp freeness of 20^{o}SR and without additive, the caliper of test paper sheets averaged 0.57, 0.61, 0.55 and 0.56mm for SAMCOTs 6, 8, 9 and 10, respectively, whereas with additive (1% Rosin and 4% Alum), it averaged 0.63, 0.57, 0.51 and 0.56mm for the same varieties, respectively. Hence, the grand average caliper of hand sheets for the furnish ratio of 60/40 and pulp freeness of 20^{o}SR was 0.57mm, both without and with additive, for all the varieties. In other words the additive made no difference on the caliper for pulp freeness of 20^{o}SR.

Table 5.1: Results of Paper Testing for SAMCOT 6

Furnish Characteristics				Caliper (mm)	Basis Weight (g/m^2)	Bulk (m^3/g)	Burst Strength (kPa)	Burst Factor ($kPam^2/g$)	Tear Strength (kN)	Tear Factor (kNm^2/g)
Furnish Ratio (TMP/WP)	Pulp Freeness (^oSR)	Additive Rosin (%)	Alum (%)							
60/40	20	0	0	0.57	139.0	4.10	0.34	2.47	0.47	0.34
60/40	20	1	4	0.63	150.0	4.20	0.34	2.29	0.31	0.21
60/40	35	0	0	0.57	135.0	4.22	0.42	3.09	0.47	0.35
60/40	35	1	4	0.59	139.0	4.24	0.42	3.00	0.47	0.34
50/50	20	0	0	0.54	123.0	4.39	0.42	3.39	0.47	0.38
50/50	20	1	4	0.55	104.0	5.29	0.42	4.00	0.63	0.60
50/50	35	0	0	0.47	124.0	3.79	0.48	3.87	0.63	0.51
50/50	35	1	4	0.40	113.0	3.54	0.49	4.29	0.78	0.69

Table 5.2: Results of Paper Testing for SAMCOT 8

Furnish Characteristics				Caliper (mm)	Basis Weight (g/m^2)	Bulk (m^3/g)	Burst Strength (kPa)	Burst Factor ($kPam^2/g$)	Tear Strength (kN)	Tear Factor (kNm^2/g)
Furnish Ratio (TMP/WP)	Pulp Freeness (^oSR)	Additive Rosin (%)	Alum (%)							
60/40	20	0	0	0.61	112.0	5.45	0.34	3.06	0.94	0.84
60/40	20	1	4	0.57	127.0	4.49	0.34	2.70	0.78	0.62
60/40	35	0	0	0.60	117.0	5.13	0.45	3.85	1.25	1.07
60/40	35	1	4	0.51	136.0	3.75	0.42	3.06	1.41	1.04
50/50	20	0	0	0.55	122.0	4.51	0.43	3.53	1.10	0.90
50/50	20	1	4	0.54	127.0	4.25	0.43	3.40	1.25	0.99
50/50	35	0	0	0.46	147.0	3.13	0.49	3.30	1.41	0.96
50/50	35	1	4	0.52	139.0	3.74	0.50	3.60	1.57	1.13

Table 5.3: Results of Paper Testing for SAMCOT 9

Furnish Characteristics				Caliper (mm)	Basis Weight (g/m^2)	Bulk (m^3/g)	Burst Strength (kPa)	Burst Factor ($kPam^2/g$)	Tear Strength (kN)	Tear Factor (kNm^2/g)
Furnish Ratio (TMP/WP)	Pulp Freeness (^oSR)	Additive Rosin (%)	Alum (%)							
60/40	20	0	0	0.55	142.0	3.87	0.34	2.42	0.47	0.33
60/40	20	1	4	0.51	130.0	3.92	0.34	2.63	0.47	0.36
60/40	35	0	0	0.48	127.0	3.78	0.42	3.28	0.63	0.49
60/40	35	1	4	0.48	122.0	3.93	0.45	3.69	0.63	0.51
50/50	20	0	0	0.56	121.0	4.63	0.42	3.44	0.63	0.52
50/50	20	1	4	0.53	136.0	3.90	0.42	3.06	0.63	0.46
50/50	35	0	0	0.51	127.0	4.02	0.50	3.93	0.94	0.74
50/50	35	1	4	0.57	116.0	4.91	0.50	4.31	0.94	0.81

Table 5.4: Results of Paper Testing for SAMCOT 10

Furnish Characteristics				Caliper (mm)	Basis Weight (g/m^2)	Bulk (m^3/g)	Burst Strength (kPa)	Burst Factor ($kPam^2/g$)	Tear Strength (kN)	Tear Factor (kNm^2/g)
Furnish Ratio (TMP/WP)	Pulp Freeness (^oSR)	Additive Rosin (%)	Additive Alum (%)							
60/40	20	0	0	0.56	117.0	4.79	0.34	2.93	0.47	0.40
60/40	20	1	4	0.56	132.0	4.24	0.34	2.60	0.47	0.36
60/40	35	0	0	0.44	106.0	4.15	0.45	4.25	0.63	0.59
60/40	35	1	4	0.46	114.0	4.04	0.42	3.66	0.78	0.69
50/50	20	0	0	0.49	132.0	3.71	0.42	3.16	0.94	0.71
50/50	20	1	4	0.51	130.0	3.92	0.42	3.20	0.94	0.72
50/50	35	0	0	0.48	115.0	4.17	0.47	4.05	1.20	1.04
50/50	35	1	4	0.52	135.0	3.85	0.49	3.59	1.41	1.04

Also, for the same furnish ratio of 60/40, but with increased beating and refining to the level of freeness of 35°SR, the caliper of test sheets averaged 0.57, 0.60, 0.48 and 0.44mm without additive for SAMCOTs 6, 8, 9 and 10 respectively, whereas it was 0.59, 0.51, 0.48 and 0.46mm with additive for the same varieties, respectively. Hence, the grand average caliper of test sheets for the furnish ratio of 60/40 and freeness of 35°SR was 0.52mm without additive and 0.51mm with additive, for all the varieties, which means that the additive still made no remarkable difference in the caliper, even at freeness of 35°SR. Thus, the caliper was reduced from 0.57mm to 0.51, on the average, because of increase in pulp freeness from 20°SR to 35°SR. The reduction in caliper of SAMCOTs 6, 8, 9 and 10 hand sheets with increased pulp freness (35°SR) can be attributed to the beating and refining which fibrillates the pulp fibres and enhances strong inter-fibre bonding in a thin layer.

On the other hand, Tables 5.1, 5.2, 5.3 and 5.4 also show that for the furnish ratio of 50/50 with beating and refining to the level of pulp freeness of 20°SR and without additive, the caliper of the hand sheets averaged 0.54, 0.55, 0.56 and 0.49mm for SAMCOTs 6, 8, 9 and 10, respectively, whereas with additive, it averaged 0.55, 0.54, 0.53 and 0.51mm for the same varieties, respectively. Therefore, the grand average caliper of test sheets for the furnish ratio of 50/50 and freeness of 20°SR was 0.54mm without additive and 0.53mm with additive for

all the varieties. For the same furnish ratio of 50/50 but with increased beating and refining to the level of freeness of 35°SR, the caliper of test sheets averaged 0.47, 0.46, 0.51 and 0.48mm without additive for SAMCOTs 6, 8, 9 and 10, respectively, whereas it was 0.40, 0.52, 0.57 and 0.52mm with additive for the same varieties, respectively. Therefore, the grand average caliper of hand sheets for the furnish ratio of 50/50 and freeness of 35°SR was 0.48mm without additive and 0.50mm with additive for all the varieties.

It has been established that any paper which is more than 0.30mm thick should be termed a paperboard, as earlier indicated in section 2.7. Most of the hand sheets obtained from cotton plant stalk thermo-mechanical pulps, have calipers more than 0.40mm. Therefore, they are simply classifiable as paperboards which can be useful as kraft linerboard (KLB) and fluting paper (FP), which are industrial grades of paper.

5.3.2 Basis Weight

Tables 5.1, 5.2, 5.3 and 5.4 show that for the furnish ratio of 60/40 and pulp freeness of 20°SR, the basis weight of the hand sheets averaged 139.0, 112.0, 142.0 and 117.0g/m^2 without additive for SAMCOTs 6, 8, 9 and 10, respectively whereas with additive, it averaged 150.0, 127.0, 130.0 and 132.0g/m^2 for the same varieties, respectively. Thus, the grand average basis weight of the test sheets for the furnish ratio of 60/40 and freeness of 20°SR was 127.5 g/m^2 without

additive and 134.7 g/m^2 with additive for all the varieties. For the same furnish ratio of 60/40, but with increased beating and refining to the level of freeness of 35^{O}SR, the basis weight of the hand sheets averaged 135.0, 117.0 and 106.0 g/m^2 without additive for SAMCOTs 6, 8, 9 and 10, respectively, whereas it was 139.0, 136.0, 122.0 and 114.0 g/m^2 with additive for the same varieties, respectively. Thus, the grand average basis weight of hand sheets for the furnish ratio of 60/40 and freeness of 35^{O}SR was 121.2 g/m^2 without additive and 127.7 g/m^2 with additive for all the varieties.

Also, Tables 5.1, 5.2, 5.3 and 5.4 also show that for the furnish ratio of 50/50, with pulp freeness of 20^{O}SR, the basis weight of the test sheets averaged 123.0, 122.0, 121.0 and 132.0 g/m^2 without additive for SAMCOTs 6, 8, 9 and 10, respectively, but with additive, it averaged 104.0, 127.0, 136.0 and 130.0 g/m^2 for the same varieties, respectively. Therefore, the grand average basis weight of hand sheets for the furnish ratio of 50/50 and freeness of 20^{O}SR was 124.0 g/m^2 without additive and 124.2g/m^2 with additive for all the varieties, which shows only a slight difference in the basis weight, made by the additive. Furthermore, for the same furnish ratio of 50/50, but with increased pulp freeness of 35^{O}SR, the basis weight of test sheets averaged 124.0, 147.0, 127.0 and 115.0 g/m^2 without additive for SAMCOTs 6, 8, 9 and 10, respectively, whereas it was 113.0, 139.0, 116.0 and 135.0

g/m^2 with additive for the same varieties respectively. Therefore, the grand average basis weight of hand sheets for the furnish ratio of 50/50 and freeness of $35^{o}SR$ was 128.2 g/m^2 without additive and 125.7 g/m^2 with additive for all the varieties.

In consideration of the basis weight of the hand sheets made from the thermo-mechanical pulp of cotton plant stalks, which averaged more than 110.0 g/m^2 in most cases, they are mostly paperboards, especially, kraft linerboard and fluting paper grades. In the Nigerian Paper Mill Ltd., Jebba, kraft linerboard is manufactured in 125-440 g/m^2 range and used for making corrugated boxes or cartons for packaging applications in industries that produce soaps, detergents and food items such as biscuits, beverages and drinks as well as fragile items. Also, fluting paper is manufactured in 112 - 127 g/m^2 range for making corrugated boxes to absorb impact and protect fragile items such as instruments, electric bulbs, glasswares, pharmaceuticals and bottled products.

By adding dyes and pigments, kraft linerboards can be utilised as coloured cover papers. The coloured cover paper is manufactured in the range of 100 - 300 g/m^2 and is used for exercise book covers, flat files, wrappings and packages.

5.3.3 Bulk

For the furnish ratio of 60/40 and pulp freeness of $20^{o}SR$, the bulk or specific volume of hand sheets from SAMCOTs

6, 8, 9 and 10 averaged 4.10, 5.45, 3.87 and 4.79 m^3/g, respectively, without additive, but it was 4.20, 4.49, 3.92 and 4.24 m^3/g with additive for the same varieties, respectively, as shown in Tables 5.1, 5.2, 5.3 and 5.4. The grand average bulk of the test sheets for the furnish ratio of 60/40 and freeness of 20°SR was therefore 4.55 m^3/g without additive and 4.21 m^3/g with additive for all the varieties. For the same furnish ratio of 60/40, but with pulp freeness of 35°SR, the bulk of the test sheets averaged 4.22, 5.13, 3.78 and 4.15 m^3/g without additive for SAMCOTs 6, 8, 9 and 10, respectively, whereas it was 4.24, 3.75, 3.93 and 4.04 m^3/g with additive for the same varieties, respectively. Therefore, the grand average bulk of test sheets for the furnish ratio of 60/40 and freeness of 35°SR was 4.32 m^3/g without additive and 3.99 m^3/g with additive for all the varieties.

Tables 5.1, 5.2, 5.3 and 5.4 also show that for the furnish ratio of 50/50 and pulp freeness of 20°SR, the bulk of the hand sheets averaged 4.39, 4.51, 4.63 and 3.71 m^3/g without additive for SAMCOTs 6, 8, 9 and 10, respectively, whereas with additive, it averaged 5.29, 4.25, 3.90 and 3.92 m^3/g for the same varieties, respectively. Hence, the grand average bulk of hand sheets for the furnish ratio of 50/50 and freeness of 20°SR was 4.31 m^3/g without additive and 4.34 m^3/g with additive for all the varieties. For the same furnish ratio of 50/50, but with increased pulp freeness of 35°SR, the

bulk of test sheets averaged 3.79, 3.13, 4.02 and 4.17 m^3/g without additive for SAMCOTs 6, 8, 9 and 10, respectively, whereas it was 3.54, 3.74, 4.91 and 3.85 m^3/g with additive for the same varieties, respectively. Therefore, the grand average bulk of test sheets for the furnish ratio of 50/50 and freeness of 35^oSR was 3.78 m^3/g without additive and 4.01 m^3/g with additive for all the varieties.

Low bulk value is desirable for ease of handling of the paper sheets. Since the bulk of the sheet is inversely proportional to the density (kg/m^3) of the paper, it gives a good indication of the possible weight of a ream of the paper or any corrugated box or carton that can be made from it for packaging applications. Hence, low bulk value is an advantage to ensure light weight of the containers. Above all, the bulk of the sheet shows the wet compactability and the relative bonded area of the wet fibres and the ease of drainage of the pulp on the paper machine (Clark, 1978), as earlier indicated.

5.3.4 Burst Strength

Tables 5.1, 5.2, 5.3 and 5.4 show that for the furnish ratio of 60/40 and pulp freeness of 20^oSR, the burst strength of hand sheets averaged 0.34 kPa both without and with additive for all the varieties. Nevertheless, with increased pulp freeness of 35^oSR and the same furnish ratio of 60/40, the burst strength was 0.42, 0.45, 0.42, and 0.45 kPa on the average, without additive for SAMCOTs 6, 8, 9 and 10,

respectively, whereas with additive, it averaged 0.42 kPa for SAMCOTs 6, 8 and 10 and 0.45 kPa for SAMCOT 9. Hence, the grand average burst strength of test sheets for the furnish ratio of 60/40 and freeness of 35°SR was 0.43 kPa without additive and 0.42 kPa with additive for all the varieties.

Also, Tables 5.1, 5.2, 5.3 and 5.4 show that for the furnish ratio of 50/50 and pulp freeness of 20°SR, the burst strength of hand sheets was 0.42 kPa on the average, both without and with additive for SAMCOTs 6, 9 and 10 and 0.43 kPa for SAMCOT 8, both without and with additive. Therefore, the grand average burst strength of test sheets for the furnish ratio of 50/50 and freeness of 20°SR was 0.42 kPa, both without and with additive for all the varieties. For the same furnish ratio of 50/50, but with increased pulp freeness of 35°SR, the burst strength of hand sheets averaged 0.48, 0.49, 0.50, and 0.47 kPa without additive for SAMCOTs 6, 8, 9 and 10, respectively, whereas with additive, it was 0.49, 0.50, 0.50 and 0.49 kPa on the average for the same varieties, respectively. Hence, the grand average burst strength of hand sheets for the furnish ratio of 50/50 and freeness of 35°SR was 0.48 kPa without additive and 0.49 kPa with additive for all the varieties.

The burst strength of kraft papers produced from the Indian Hybrid 4 cotton plant stalks ranged from 1.03 to 1.32 kPa (Shaikh and Varadarajan, 1995), which is more than twice the burst strength of the hand sheets obtained from cotton

plant stalks grown in Nigeria. This can be attributed to the difference in varieties. The low runkel ratio and short fibre length of SAMCOTs 6, 8, 9 and 10 cotton plant stalks contribute immensely to the low burst strength of the resulting paper sheets as discussed in sections 4.1.3 and 4.1.7, respectively. The low burst strengths of SAMCOTs 6, 8, 9 and 10 hand sheets show that the paper sheets are weak and will be good for use as shock-absorbing fluting papers.

5.3.5 Burst Factor

Tables 5.1, 5.2, 5.3 and 5.4 show that for the furnish ratio of 60/40 and pulp freeness of 20^{o}SR, the burst factor of the hand sheets averaged 2.47, 3.06, 2.42 and 2.93 $kPam^2/g$ without additive for SAMCOTs 6, 8, 9 and 10, respectively, whereas it was 2.29, 2.70, 2.63 and 2.60 $kPam^2/g$ with additive for the same varieties, respectively. Thus, the grand average burst factor of the test sheets for the furnish ratio of 60/40 and freeness of 20^{o}SR was 2.72 $kPam^2/g$, without additive and 2.56 $kPam^2/g$, with additive for all the varieties. For the same furnish ratio of 60/40, but with increased pulp freeness of 35^{o}SR, the burst factor of the test sheets averaged 3.09, 3.85, 3.28 and 4.25 $kPam^2/g$, without additive for SAMCOTs 6, 8, 9 and 10, respectively, whereas it was 3.00, 3.06, 3.69 and 3.66 $kPam^2/g$ with additive for the same varieties, respectively. Hence, the grand average burst factor of the test sheets for the furnish ratio of 60/40 and freeness of

35°SR was 3.62 kPam^2/g without additive and 3.84 kPam^2/g with additive for all the varieties. In most of the varieties, the burst factor increased as the pulp freeness was increased for both furnish ratios 60/40 and 50/50, except the 50/50 of SAMCOT 8.

Also, Tables 5.1, 5.2, 5.3 and 5.4 show that for the furnish ratio of 50/50 and pulp freeness of 20°SR the burst factor of hand sheets averaged 3.39, 3.53, 3.44 and 3.16 kPam^2/g, without additive for SAMCOTs 6, 8, 9 and 10, respectively, whereas with additive, it was 4.00, 3.40, 3.06 and 3.20 kPam^2/g on the average for the same varieties respectively. Hence, the grand average burst factor of test sheets for the furnish ratio of 50/50 and freeness of 20°SR was 3.38 kPam^2/g without additive and 3.42 kPam^2/g with additive for all varieties. For the same furnish ratio of 50/50, but with increased pulp freeness of 35°SR, the burst factor of the test sheets averaged 3.87, 3.30, 3.93 and 4.05 kPam^2/g without additive for SAMCOTs 6, 8, 9 and 10, respectively, whereas it was 4.29, 3.60, 4.31 and 3.59 kPam^2/g on the average with additive for the same varieties as shown in Tables 5.1, 5.2, 5.3 and 5.4, respectively. Therefore, the grand average burst factor of the hand sheets for the furnish ratio of 50/50 and freeness of 35°SR was 3.79 kPam^2/g, without additive and 3.95 kPam^2/g, with additive for all the varieties. For SAMCOTs 6 and 9 hand sheets, the additive increased the burst factor as the pulp freeness increased, but

in SAMCOTs 8 and 10 hand sheets, the additive rather decreased the burst factor, which shows that SAMCOTs 8 and 10 test sheets are so relatively good that they do not need the additive (rosin and alum) for good burst values.

Shaikh and Varadarajan (1995) had produced kraft papers of basis weights, 100 g/m^2 and 120g/m^2 and corresponding burst factors, 10.3 and 11.0 $kPam^2/g$ from the Indian hybrid 4 cotton plant stalks, using alkaline chemical pulping. The low burst factors obtained with paper sheets made from the Nigerian varieties of cotton plant stalks can be explained by their low runkel ratio and short fibre length, as earlier indicated. The low burst factors of SAMCOTs 6, 8, 9 and 10 hand sheets show that the paper sheets are weak, but can be useful as shock-absorbing fluting papers for packaging applications.

5.3.6 Tear Strength

Tables 5.1, 5.2, 5.3 and 5.4 show that for the furnish ratio of 60/40 and pulp freeness of 20^{o}SR, the tear strength of hand sheets averaged 0.47 kN without additive for SAMCOTs 6, 9 and 10, but it was 0.94 kN for SAMCOT 8. However, the tear strength averaged 0.31, 0.78, 0.47 and 0.47 kN with additive for SAMCOTs 6, 8, 9 and 10, respectively. Therefore, the grand average tear strength of test sheets for the furnish ratio of 60/40 and freeness of 20^{o}SR was 0.59 kN without additive and 0.51 kN with additive for all the varieties.

With increase in pulp freeness to 35°SR, the tear strength averaged, 0.47, 1.25, 0.63 and 0.63 kN without additive for SAMCOTs 6, 8, 9 and 10, respectively, but with additive, it was 0.47, 1.41, 0.63 and 0.78 kN for the same varieties, respectively. Hence, the grand average tear strength of test sheets for the furnish ratio of 60/40 and pulp freeness of 35°SR was 0.75 kN without additive and 0.82 kN with additive for all the varieties.

On the other hand, Tables 5.1, 5.2, 5.3 and 5.4 also show that for the furnish ratio of 50/50 and pulp freeness of 20°SR, the tear strength of the test sheets averaged 0.47, 1.10, 0.63 and 0.94 kN without additive for SAMCOTs 6, 8, 9 and 10, respectively, whereas with additive, it was 0.63, 1.25, 0.63 and 0.94 kN on the average for the same varieties, respectively. Therefore, the grand average tear strength of the hand sheets for the furnish ratio of 50/50 and freeness of 20°SR was 0.79 kN without additive and 0.86 kN with additive, for all the varieties. For the same furnish ratio of 50/50, but with increased pulp freeness of 35°SR, the tear strength of the test sheets averaged 0.63, 1.41, 0.94 and 1.20 kN without additive for SAMCOTs 6, 8, 9 and 10, respectively, whereas it was 0.78, 1.57, 0.94 and 1.41 kN on the average with additive for the same varieties, respectively. Hence, the grand average tear strength of the test sheets for the furnish ratio of 50/50 and pulp freeness of 35°SR was 1.05 kN without additive and 1.18 kN with additive, for all the

varieties. The additive tended to increase the tear strength of hand sheets at the furnish ratio of 50/50 in all the varieties. This is probably because the additive makes the naturally hydrophilic fibres become hydrophobic, so that in the absence of moisture during pressing and drying, the inter-fibre bonding becomes stronger. Also, increasing the waste paper content of the furnish from 40% to 50% helped to beef up the tear strength of the paper.

It can be observed that SAMCOT 8 hand sheets maintained consistently higher tear strength values in all the treatments than other varieties, while SAMCOT 6 hand sheets had the least tear strength values in most treatments. For instance, the highest tear strength obtained with SAMCOT 6 was 0.78 kN for the furnish ratio of 50/50, pulp freeness of 35^{o}SR with additive, while SAMCOT 8 was giving 1.57 kN for the same treatment, as shown in Tables 5.1 and 5.2. Incidentally, most of these tear strength values are higher than the 0.42 and 0.49 kN recorded for kraft papers made from the Indian Hybrid 4 cotton plant stalks with respective basis weights of 100 and 120 g/m^2 (Shaikh and Varadarajan, 1995). This, obviously, is the result of blending the Nigerian varieties of cotton plant stalks with waste paper, whose fibre length averaged 2.0mm, and it improved the tear strength of the resulting hand sheets considerably.

5.3.7 Tear Factor

Tables, 5.1, 5.2, 5.3 and 5.4 show that for the furnish ratio of 60/40 and pulp freeness of 20°SR, the tear factor of the hand sheets averaged 0.34, 0.84, 0.33 and 0.40 kNm^2/g without additive for SAMCOTs 6, 8, 9 and 10, respectively, while it was 0.21, 0.62, 0.36 and 0.36 kNm^2/g with additive for the same varieties, respectively. Hence, the grand average tear factor of the test sheets for the furnish ratio of 60/40 and freeness of 20°SR was 0.48 kNm^2/g without additive and 0.39 kNm^2/g with additive for all the varieties. For the same furnish ratio of 60/40, but with increased pulp freeness of 35°SR, the tear factor of the test sheets became 0.35, 1.07, 0.49 and 0.59 kNm^2/g on the average without additive for SAMCOTs 6, 8, 9 and 10, respectively, whereas it was 0.34, 1.04, 0.51 and 0.69 kNm^2/g with additive for the same varieties, respectively. Thus, the grand average tear factor of the test sheets for the furnish ratio of 60/40 and freeness of 35°SR was 0.63 kNm^2/g without additive and 0.64 kNm^2/g with additive, for all the varieties. As the pulp freeness was increased, the tear factor of test sheets increased, due to stronger inter-fibre bonding.

On the other hand, Tables 5.1, 5.2, 5.3 and 5.4 also show that for the furnish ratio of 50/50 and pulp freeness of 20°SR, the tear factor of test sheets averaged 0.38, 0.90, 0.52 and 0.71 kNm^2/g without additive for SAMCOTs 6, 8, 9 and 10, respectively, but with additive, it was 0.60, 0.99, 0.46

and 0.72 kNm^2/g on the average for the same varieties, respectively. Hence, the grand average tear factor of the handsheets for the furnish ratio of 50/50 and freeness of 20^oSR was 0.63 kNm^2/g without additive and 0.69 kNm^2/g with additive for all the varieties. For the same furnish ratio of 50/50, but with increased pulp freeness of 35^oSR, the tear factor of the hand sheets averaged 0.51, 0.96, 0.74 and 1.04 kNm^2/g without additive for SAMCOTs 6, 8, 9 and 10, respectively, while it averaged 0.69, 1.13, 0.81 and 1.04 kNm^2/g with additive for the same varieties, respectively. Therefore, the grand average tear factor of the test sheets for the furnish ratio of 50/50 and freeness of 35^oSR was 0.81 kNm^2/g without additive and 0.92 kNm^2/g with additive, for all the varieties.

The values of tear factor for SAMCOT 8 test sheets were consistently higher than those of other varieties, while SAMCOT 6 hand sheets had the least tear values. For instance, the highest tear factor obtained with SAMCOT 6 was 0.69 kNm^2/g for the furnish ratio of 50/50 and pulp freeness of 35^oSR with additive, while SAMCOT 8 had 1.13 kNm^2/g for the same treatment, as shown in Tables 5.1 and 5.2. SAMCOTs 9 and 10 had tear values that were mostly higher than those of SAMCOT 6, but were lower than those of SAMCOT 8, in maintaining high tear values, as shown in Tables 5.3 and 5.4. Tear values decreased in the order of SAMCOTs 8, 10, 9 and 6.

An interesting observation is the fact that the average tear factors of the hand sheets from most of the treatments in SAMCOTs 6, 8, 9 and 10 were higher than the tear factors of 0.42 and 0.41 kNm^2/g reported for the kraft papers whose basis weights were $100g/m^2$ and $120g/m^2$, respectively, produced with the Indian Hybrid 4 cotton plant stalks (Shaikh and Varadarajan, 1995). The low runkel ratios and short fibre lengths of SAMCOTs 6, 8, 9 and 10 cotton plant stalks notwithstanding, it was still possible to obtain paperboards of appreciable tear values from them by simply blending them with at least 40% of waste paper, whose fibre length averaged 2.0 mm, and the best strength properties were obtained in the test sheets at pulp freeness of 35^oSR and with additive of 1% rosin and 4% alum.

5.4 Statistical Analysis for Main Effects and their Interactions

Given the 2x2x2 factorial papermaking experiments, the variables can be denoted as follows:

Independent variables or the three factors:

P = Furnish ratio (TMP/WP)

Q = Pulp freeness (^oSR)

R = Additive (Rosin, Alum)%;

Two levels of each factor:

P_1 = 60/40 ; P_2 = 50/50

Q_1 = 20^oSR ; Q_2 = 35^oSR

R_1 = (0,0)% ; R_2 = (1,4)%.

The dependent variables are the physical and mechanical properties of the hand sheets, namely the caliper (mm), basis weight (g/m^2), bulk (m^3/g), burst strength (kPa), burst factor ($kPam^2/g$), tear strength (kN) and tear factor (kNm^2/g).

The eight combinations of the three factors at the two levels of each factor are as follows:

$P_1\ Q_1\ R_1$ = 60/40 ; 20^oSR ; (0,0)%

$P_1\ Q_1\ R_2$ = 60/40 ; 20^oSR ; (1,4)%

$P_1\ Q_2\ R_1$ = 60/40 ; 35^oSR ; (0,0)%

$P_1\ Q_2\ R_2$ = 60/40 ; 35^oSR ; (1,4)%

$P_2\ Q_1\ R_1$ = 50/50 ; 20^oSR ; (0,0)%

$P_2\ Q_1\ R_2$ = 50/50 ; 20^oSR ; (1,4)%

$P_2\ Q_2\ R_1$ = 50/50 ; 35^oSR ; (0,0)%

$P_2\ Q_2\ R_2$ = 50/50 ; 35^oSR ; (1,4)%

Therefore, there were eight papermaking experiments or treatments with each of the four varieties of thermo-mechanical pulp (TMP), which resulted to the eight different mean values for each of the seven parameters of hand sheets investigated in each treatment (See Tables 5.1, 5.2, 5.3 and 5.4). The geometric representation of the factorial 3-factor experiments at two levels by Kennedy and Neville (1976), Diamond (1989) and Maxwell and Delaney (1990), considered the eight treatments as co-ordinates of points on a system of axes P, Q and R with $P_1Q_1R_1$ as origin, as shown in Fig. 5.1.

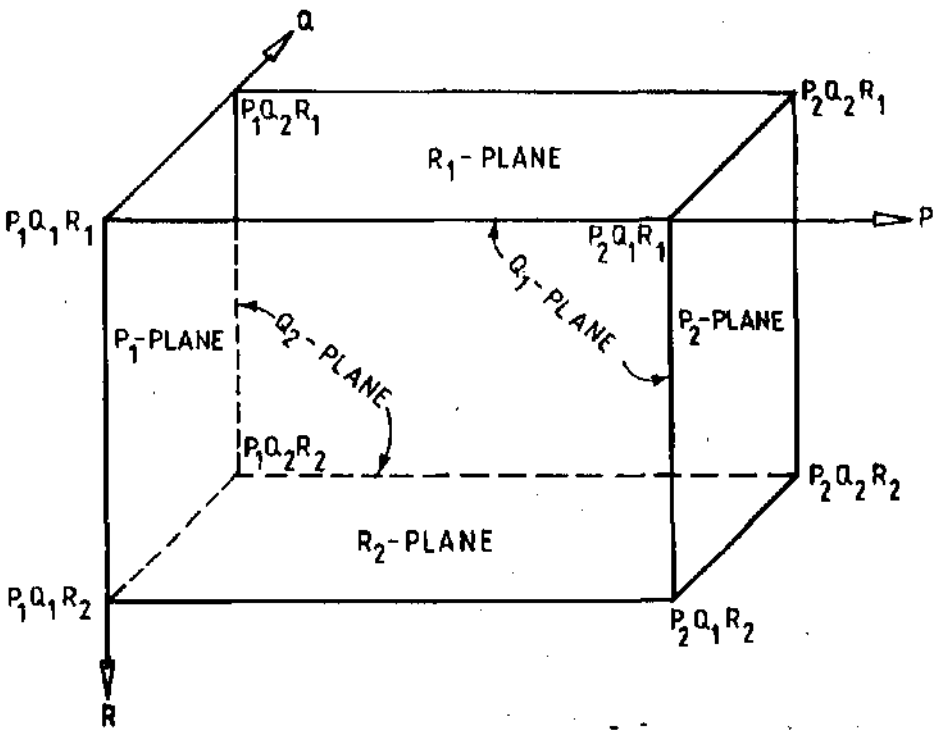


Fig. 5.1 Geometric representation of the factorial three-factor experiments at two levels (2x2x2).
Source: Kennedy and Neville (1976); Diamond (1989); Maxwell and Delaney (1990)

Hence, Fig. 5.1 represents each of the physical and mechanical properties of hand sheets geometrically using the eight mean values from the eight different treatments. The details of the statistical analysis for each parameter of the hand sheets from SAMCOTs 6, 8, 9 and 10 are contained in Appendix G. All the treatments mean squares tested for significance in each of the properties of the hand sheets from SAMCOTs 6, 8, 9 and 10, were found to be non-significant at 95% probability level. Hence, the treatments sums of squares, having t-1 = 7 degrees of freedom (where t is the number of treatments) have to be divided into seven components, each with one degree of freedom as follows:

Main Effects:

Sum of squares for P (Furnish ratio effect)

Sum of squares for Q (Pulp freeness effect)

Sum of squares for R (Additive effect)

Interactions:

Interaction between furnish ratio effect and pulp freeness effect (PxQ)

Interaction between furnish ratio effect and additive effect (PxR)

Interaction between pulp freeness effect and additive effect (QxR)

Interaction among furnish ratio, pulp freeness and additive effects (PxQxR).

The details of the analysis of variance for the estimates of the main effects (P, Q and R) and their interactions (PxQ, PxR, QxR and PxQxR) are also given in Appendix G. It was found that the main effects P, Q and R, were not significant at 95% probability level in all the physical and mechanical properties of the hand sheets from SAMCOTs 6, 8, 9 and 10. This means that the difference between the mean values of each parameter of the test sheets due to a main effect, for example furnish ratio effect (P) for a level of 60/40 (P_1) was not significantly different at 95% probability level from the difference between the mean values due to the same furnish ratio effect at the other level of 50/50 (P_2) when averaged over the two levels of pulp freeness (Q_1 and Q_2) and the two levels of additive (R_1 and R_2). The non-significance also held for pulp freeness (Q) or additive (R) effects when averaged over the two levels of furnish ratio (P_1 and P_2) and two levels of additive (R_1 and R_2) or over the two levels of furnish ratio (P_1 and P_2) and the two levels of pulp freeness (Q_1 and Q_2), respectively. Hence, each factor P, Q or R acting alone did not significantly affect the quality of the hand sheets.

However, the interactions of the main effects PxQ, PxR and QxR, were found to be significant in affecting the properties of the test sheets at the 95% probability level. The difference in the mean values of each property of hand sheets over the two levels of any factor, P or Q or R, can be

attributed to the combined effect of the three factors, P, Q and R through their interactions, PxQ, PxR and QxR. Nevertheless, for the basis weight of test sheets, the interactive effects PxQ, PxR and QxR, were not significant at 95% probability level in all the varieties, though in SAMCOT 10, the PxQ interaction was significant only at 95% probability level. The PxQxR interaction was not significant at 95% probability level for all properties of the hand sheets from all the varieties, except in the caliper of SAMCOT 6 hand sheets.

5.5 Relationships between Basis Weights and Calipers of Hand Sheets

For each of SAMCOTs 6, 8, 9 and 10, the basis weight and the caliper of the hand sheets from each treatment, can be correlated to establish the relationship between them. For instance, the tables of observed values of basis weight versus caliper for the treatment of furnish ratio (TMP/WP) of 60/40, pulp freeness of 35°SR and additive of 1% rosin and 4% alum, are shown in Appendices H-1, H-2, H-3 and H-4, for SAMCOTs 6, 8, 9 and 10, respectively. Also, the Appendices H-1, H-2, H-3 and H-4 show the estimates of the correlation coefficients and the regression constants.

Figure 5.2 shows that the relationships between basis weights and calipers of the hand sheets for SAMCOTs 6, 8, 9 and 10 are linear and the coefficients of determination r^2 are 0.958, 0.997, 0.914 and 0.866, respectively, which mean high

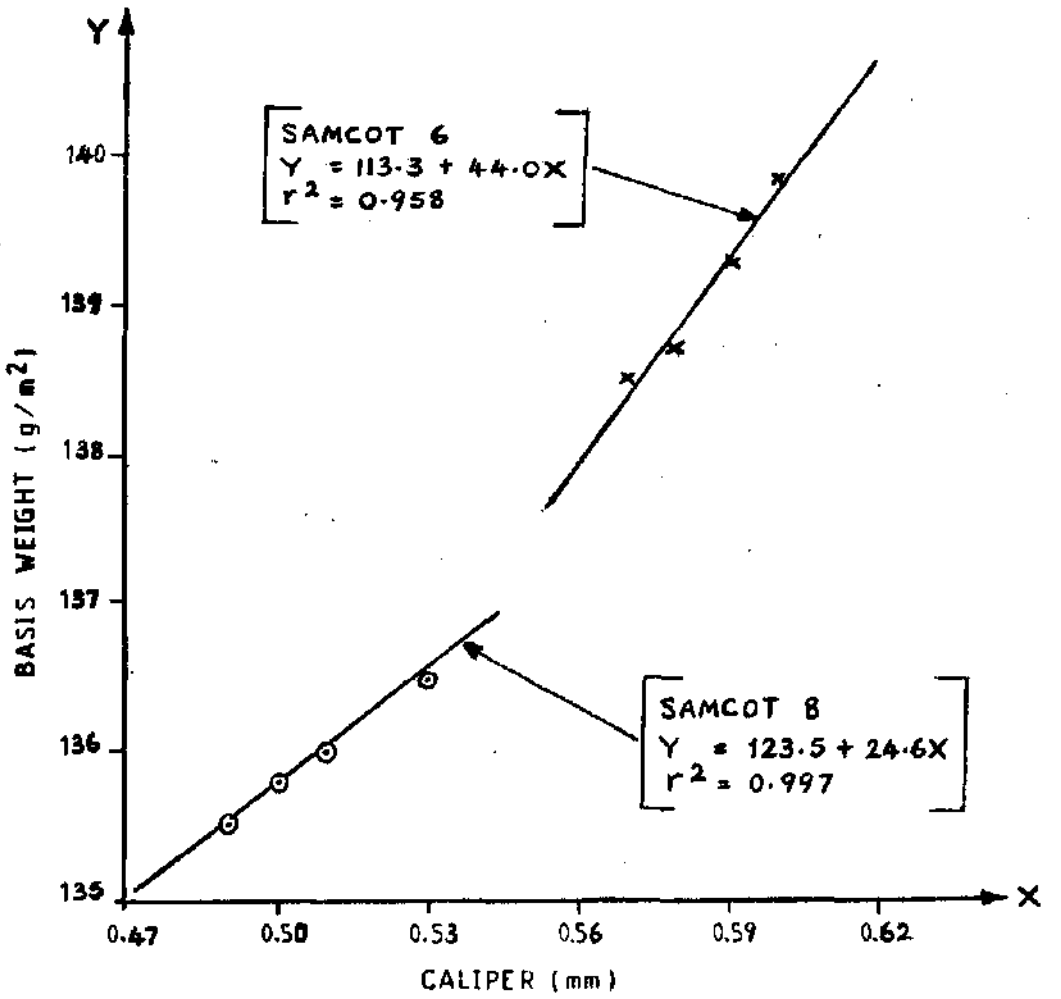


Fig.5.2 : Basis Weight versus Caliper .

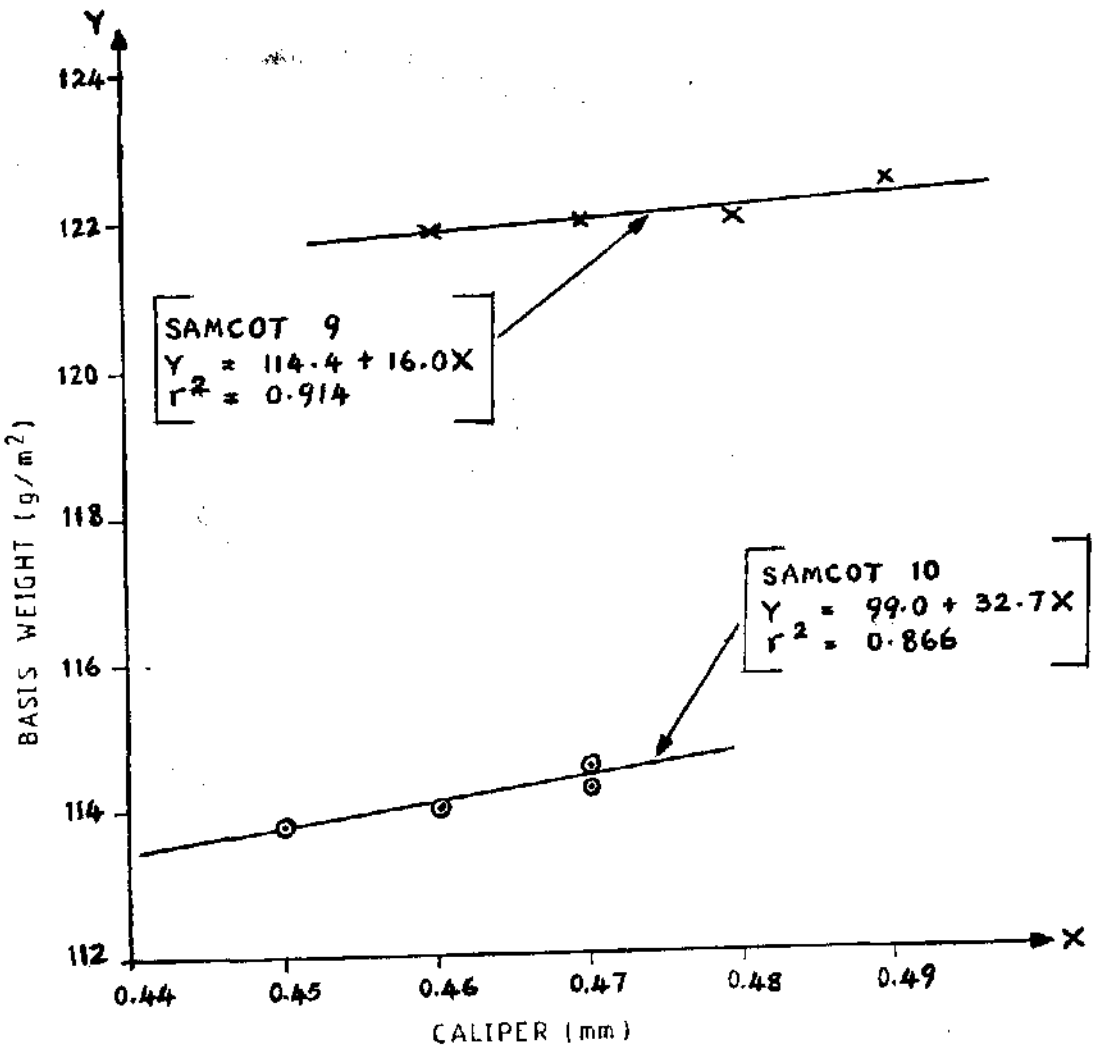

Y
124
122
120
118
116
114
112
BASIS WEIGHT (g/m²)
SAMCOT 9
Y = 114.4 + 16.0X
r² = 0.914
SAMCOT 10
Y = 99.0 + 32.7X
r² = 0.866
X
0.44
0.45
0.46
0.47
0.48
0.49
CALIPER (mm)

Fig.5.2 contd.

correlations. As the caliper or thickness of the hand sheets increased, the basis weight increased proportionately in all the varieties. This is expected, because, increasing the thickness of a paper sheet means increasing the weight of dried fibre per unit area of the paper sheet.

The significance of the basis weight versus caliper relationship lies in the importance of the weight of paper in paper mill economics. Pulp wood is usually bought by volume and converted into paper which is sold by weight, as earlier indicated in section 2.4. The price of a ream of paper depends on the weight of the ream, which is a product of the weight of each paper sheet times the number of sheets involved, usually 480-500 sheets per ream (Saltman, 1978). The total weight and volume of reams of paper also determine the required dimensions or size of cartons for the packaging applications and the cost of transport to the market.

5.6 Relationships between Mechanical Properties of Hand Sheets and Fibre Characteristics of Cotton Plant Stalks

The mechanical properties of SAMCOTs 6, 8, 9 and 10 hand sheets, such as burst strength and tear strength, can be correlated with the original wood and bast fibre characteristics of the local cotton plants, such as runkel ratio, fibre length and slenderness ratio. For each variety, the grand average of each mechanical property of the handsheets, for the eight treatment means shown in Tables 5.1, 5.2, 5.3 and 5.4, was plotted against the grand average of

each fibre characteristic for both wood and bast fibres in the stem and root shown in Tables 4.1 and 4.2. The use of grand average values of these pairs of parameters to correlate SAMCOTs 6, 8, 9 and 10 at the same time, became necessary, because for each variety, it was not possible to determine the properties of the paper product at the same time of measuring the original fibre characteristics of the raw material. Moreover, the paper mill's computerised scanning device used for pulp analysis just before forming the hand sheets, was not functional at the time of the experiment. The tables of the grand average values of the strength properties of hand sheets versus the original fibre characteristics, used for estimating the correlation coefficients and the regression constants, are shown in Appendices H-5, H-6, H-7 and H-8.

Figure 5.3 shows that the burst strength versus runkel ratio relationship is linear, with a coefficient of determination r^2 of 0.532. Also, the tear strength versus runkel ratio relationship is linear, with a coefficient of determination r^2 of 0.674 (see Fig. 5.3). As the runkel ratio increased from SAMCOT 6 to SAMCOT 10, the strength properties of the hand sheets increased proportionately. This is expected, because, the strength of paper sheets depends on the runkel ratio of fibres in the raw material, as earlier indicated. That is, higher strength properties were obtained in hand sheets whose thermo-mechanical pulp (TMP) fibres had higher runkel ratios than others.

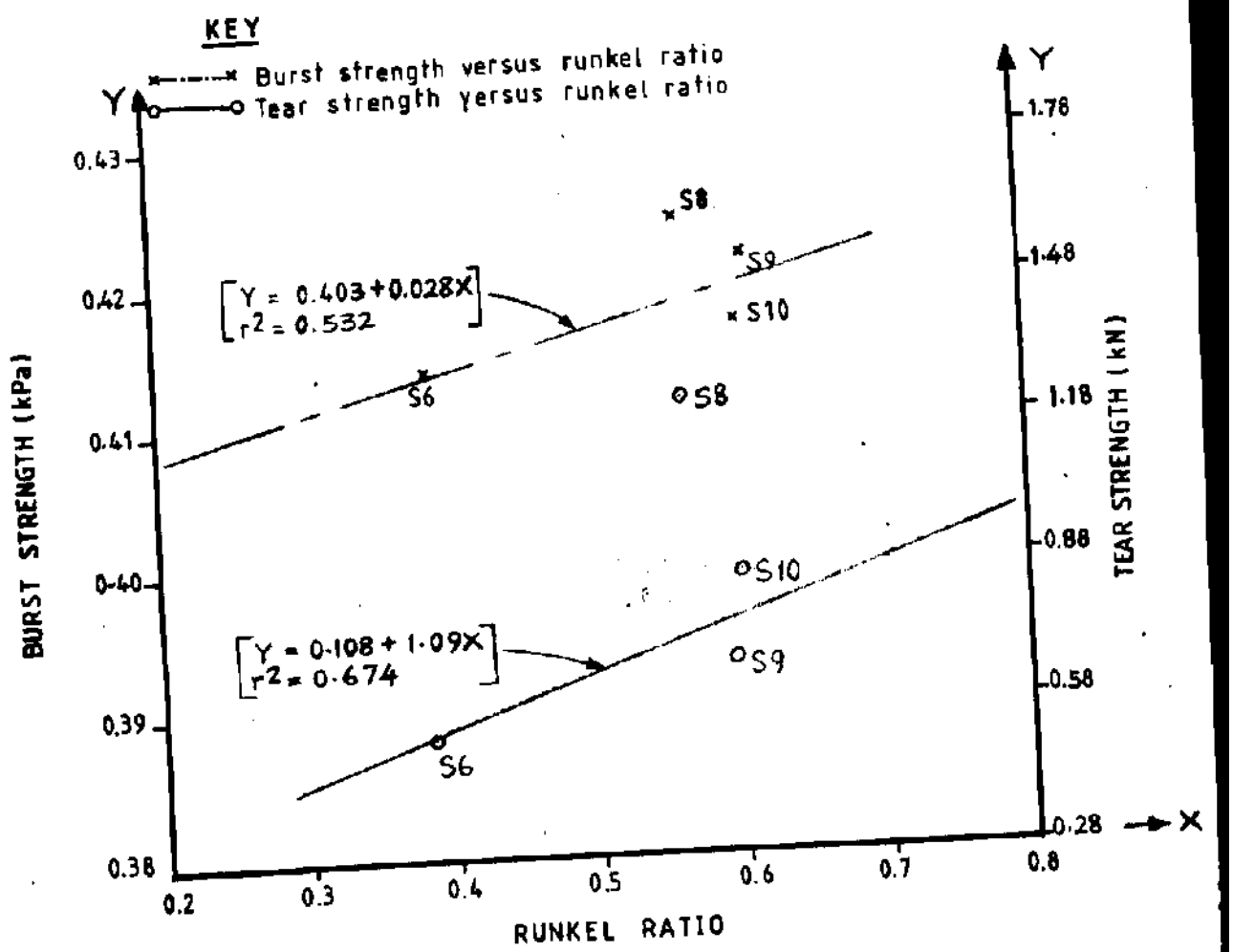


Fig. 5.3 Burst strength versus runkel ratio and tear strength versus runkel ratio .

For each treatment, the differences in the strength properties of SAMCOTs 6, 8, 9, and 10 hand sheets can not be attributed to the waste paper (WP), because the same waste paper was used in all the varieties. They are rather, a result of the differences in fibre characteristics of the four varieties of cotton plant stalks.

Similarly, the tear strength versus fibre length relationship is linear with a coefficient of determination r^2 of 0.927, as shown in Fig. 5.4. As the fibre length increased from SAMCOT 6 to SAMCOT 10, the tear strength increased proportionately, with a high degree of association. Higher tear values of hand sheets were obtained with cotton plant stalks having longer wood and bast fibres than others. This confirms the fact that the tear strength of paper sheets is enhanced by the use of long fibres, as earlier indicated.

The tear strength versus slenderneess ratio relationship is also a straight line having a coefficient of determination r^2 of 0.912, as shown in Fig. 5.5. The higher the slenderness ratio of the fibres from SAMCOT 6 to SAMCOT 10, the higher the tear strength of the hand sheets. This is expected, because, high slenderness ratio indicates long fibres which enhance the tear strength of paper sheets. Thus, the slenderness ratio also had a high correlation with the tear strength of the paper sheets, as the fibre length did.

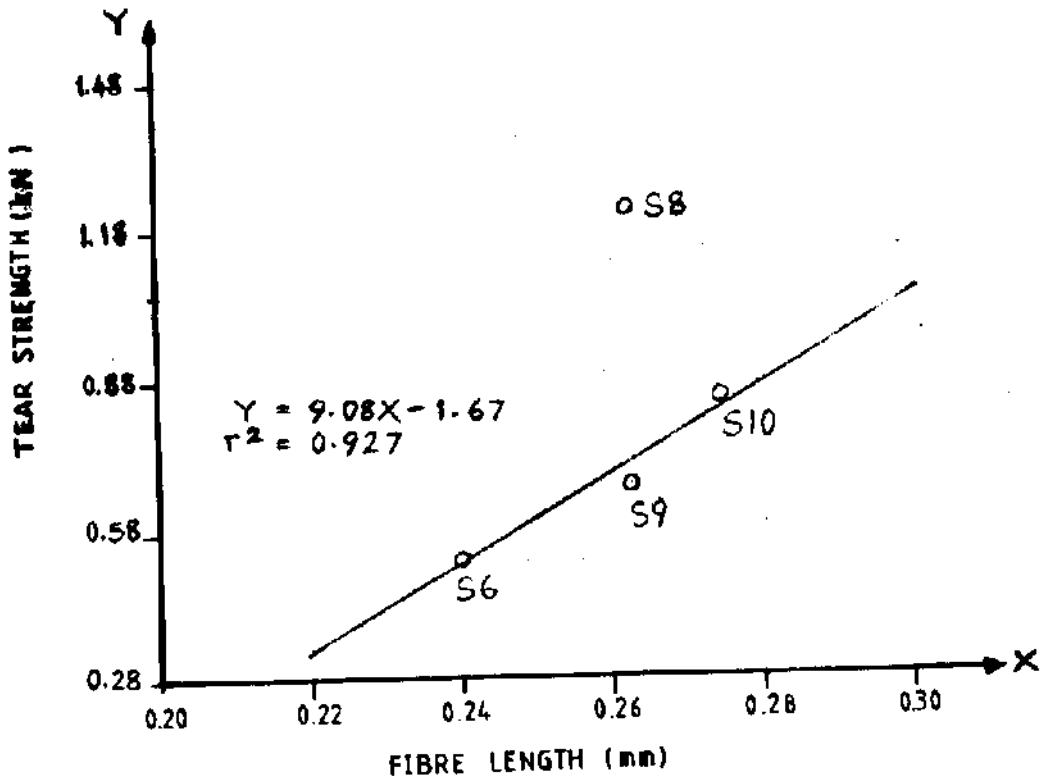


Fig. 5.4: Tear strength versus fibre length

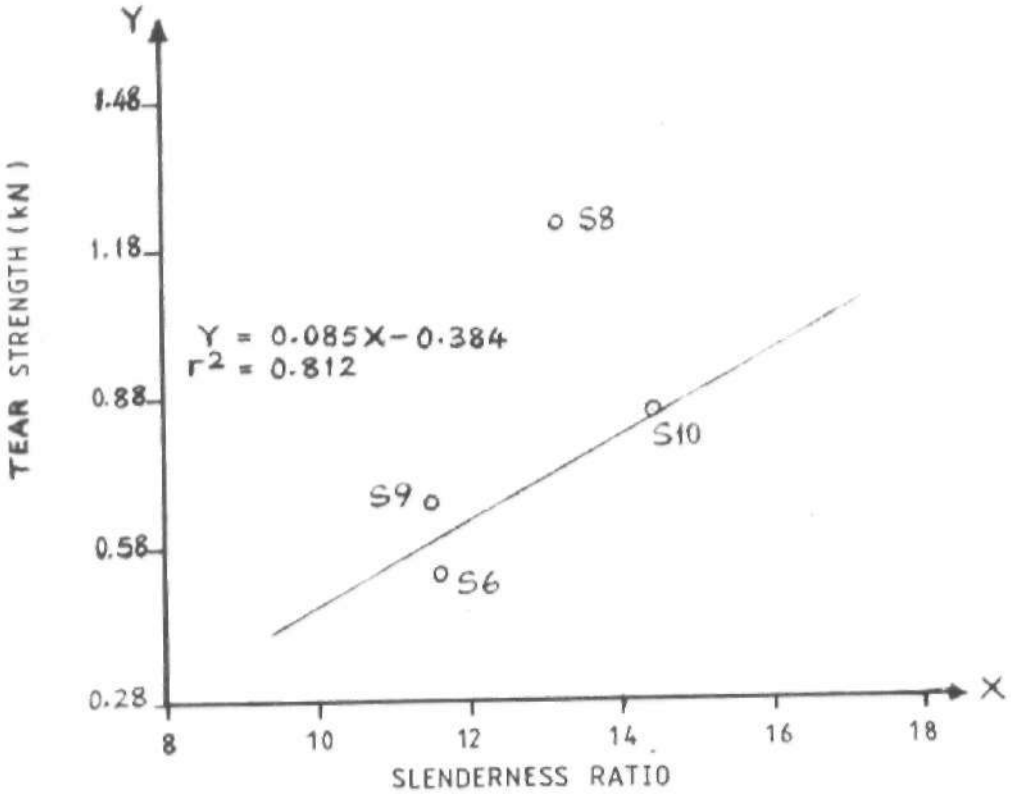


Fig. 5.5: Tear strength versus slenderness ratio

This confirms the observation made by Dinwoodie (1965), that in hardwoods, other fibre characteristics, such as runkel ratio and slenderness ratio, are as important as the fibre length is in determining paper properties, as earlier indicated in section 4.1.7.

As can be observed from Figs. 5.3, 5.4 and 5.5, the strength properties of SAMCOT 8 hand sheets were consistently higher than those of SAMCOTs 6, 9 and 10 hand sheets. Therefore, since SAMCOT 8 always differed from the trend defined by SAMCOTs 6, 9 and 10, it was ignored in fitting the regression lines to the points in Figs. 5.3, 5.4 and 5.5, as it tended to decrease the r^2 values and obscured the natural trend. SAMCOT 8 proved to be the best variety in the strength properties of hand sheets, probably because, it had a higher content of long-molecular alpha-cellulose than SAMCOTs 6, 9 and 10, as earlier indicated in section 4.3.1.

CHAPTER SIX

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

6.1 Summary

The possibility of utilising cotton plant stalks for papermaking, as an alternative to the wasteful disposal of the crop residue by burning, was investigated in this study, using four varieties of the American upland cotton plants (Gossypium hirsutum), namely SAMCOTs 6, 8, 9 and 10 grown in Nigeria. Wood and bast fibre characteristics, such as fibre wall thickness, fibre diameter, fibre length, runkel ratio, thickness index, flexibility coefficient and slenderness ratio, were determined from sections of the stalks mounted on microslides and viewed under a light microscope. Varietal effects on most of the fibre characteristics were evaluated, using statistical analysis of variance at 95% probability level.

The composition of alpha-cellulose, hemi-cellulose, lignin, ash and moisture in the stalks were determined. The wood density and energy value of the stalks were also evaluated. Thereafter, thermo-mechanical pulp (TMP) was prepared from each variety and blended with at least 40% of waste paper (WP) whose fibre length averaged 2.00 mm, because of the short fibre length and low runkel ratio of the local cotton plant stalks. Factorial three-factor papermaking experiments, involving two levels each (2x2x2) of furnish ratio (TMP/WP), pulp freeness and additive were conducted.

Standard hand sheets were produced and tested for physical and mechanical properties, such as caliper, basis weight, bulk, burst strength, burst factor, tear strength and tear factor. Statistical analysis of the results of the 2x2x2 factorial experiments was done to determine the main effects of furnish ratio, pulp freeness and additive, as well as their interactive effects on the properties of the hand sheets, and to test their significance at 95% probability level. The mechanical properties of the hand sheets were correlated with the original fibre characteristics of the local cotton plants to establish their relationships.

6.2 Conclusions

The following conclusions were drawn from the results of the study:

1. SAMCOTs 6, 8, 9 and 10 cotton plant stalks were found to be deficient in the relevant fibre characteristics, especially fibre length, runkel ratio and slenderness ratio, which averaged 0.270mm, 0.540 and 12.7, respectively. Statistical analyses showed that varietal effects on most of the fibre characteristics were significant at 95% probability level. SAMCOT 9 was found to be the best in most of the fibre characteristics followed by SAMCOTs 10, 8 and 6. Nevertheless, all the varieties can safely be blended together to form good paper sheets.

2. For SAMCOTs 6, 8, 9 and 10 cotton plant stalks, the alpha-cellulose and hemi-cellulose contents which were found to be 54.0% and 8.40%, respectively, on the average, were considered to be high enough to be explored for papermaking. SAMCOT 8 had the highest alpha-cellulose content, followed by SAMCOTs 9, 10 and 6.

3. The wood density of SAMCOTs 6, 8, 9 and 10 cotton plant stalks averaged 0.410 kg/m^3, which further qualified the stalks for use in papermaking, by being lower than the recommended maximum of 0.70 kg/m^3.

4. The gross energy value of SAMCOTs 6, 8, 9 and 10 cotton plant stalks averaged 13.2 kJ/kg, and was considered to be low when compared with those of jute sticks, saw dust and coconut shells which ranged from 17.1 to 18.7 kJ/kg. Thus, the option of exploring the possibility of using cotton plant stalks as firewood was discountenanced.

5. The blending of the thermo-mechanical pulp (TMP) prepared from SAMCOTs 6, 8, 9 and 10 cotton plant stalks with at least 40% of waste paper (WP) whose fibre length averaged 2.0mm, improved the sheet formation and the strength properties of the paper sheets, especially at pulp freeness of 35^{O}SR and with additive of 1% rosin and 4% alum. Hence, the burst strength and tear strength of the

hand sheets averaged 0.420 kPa and 0.820 kN, respectively, while the caliper and basis weight averaged 0.510 mm and 127.8 g/m^2, respectively.

6. SAMCOT 8 was found to be the best variety of cotton plant stalks for papermaking because its hand sheets consistently maintained the highest tear strengths and brightness, followed by SAMCOTs 10, 9 and 6.

7. For each variety, the differences in the properties of hand sheets between treatments resulted from the combined effects of furnish ratio (TMP/WP), pulp freeness and additive, because their interactive effects were found to be significant at 95% probability level.

8. The basis weights and calipers of SAMCOTs 6, 8, 9 and 10 test sheets were found to be positively correlated and the relationships were linear, with coefficients of determination r^2 of 0.953, 0.977, 0.914 and 0.866, respectively.

9. The mechanical properties of SAMCOTs 6, 8, 9 and 10 hand sheets, such as burst strength and tear strength, correlated positively with the original fibre characteristics of the cotton plant stalks, such as runkel ratio, fibre length and slenderness ratio, and the

relationships were found to be linear. The burst strength versus runkel ratio and tear strength versus runkel ratio relationships, had coefficients of determination r^2 of 0.532 and 0.674, respectively. Also, the tear strength versus fibre length and tear strength versus slenderness ratio relationships, had coefficients of determination r^2 of 0.927 and 0.812, respectively.

6.3 Recommendations

The following recommendations are pertinent in promoting further research work on paper and board making using cotton plant stalks and other agricultural residues:

1. Experiments on blending the short-fibred pulp prepared from cotton plant stalks with three or four levels (including 30% and less) of the medium-fibred waste paper pulp, should be carried out to determine the optimum furnish ratio required for optimum quality of the paper sheets.

2. Blending of the short-fibred pulp prepared from cotton plant stalks with long-fibred pulp prepared from another agricultural residue, such as cotton linters (by-product of cotton-seed oil mills), to see if a high quality paper can be obtained, should be investigated.

3. An antifoam, such as Cojalcid 200 Defoamer, should be added to the pulp slurry before beating and refining, to forestall losses of fibre and additives, via foaming, during the fibre processing.

4. Cheaper chemical pulping methods, which do not have much drastic degradation action on fibres, such as alcohol pulping, or cooking in wood ash (lye) solution, or the semi-chemical method called chemi-thermo-mechanical pulping (CTMP), involving little quantities of sodium sulphite and alkali, should be tried on cotton plant stalks, to improve the brightness gain of the pulp.

5. The use of cotton plant stalks for the manufacture of chipboards and particleboards, using appropriate adhesives or binders, should also be explored.

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APPENDIX A :- WOOD FIBRE CHARACTERISTICS

A - 1 :- Wood Fibre Characteristics of Stems and Roots of SAMCOT 6 Cotton Plants

S.N	Fibre wall thickness (µm)		Fibre lumen diameter (µm)		Pickel ratio		Fibre diameter (µm)		Thickness index		Coeff. of flexibility		Fibre length (µm)		Slenderness ratio		Ratio of no. of vessels to no. of fibres		% Void Space	
	Stem	Root	Stem	Root	Stem	Root	Stem	Root	Stem	Root	Stem	Root	Stem	Root	Stem	Root	Stem	Root	Stem	Root
1.	1.5	1.5	18	21	0.167	0.143	21	24	0.071	0.063	0.857	0.875	240	270	11.43	11.25	4:130	1:90	3.08	1.11
2.	1.5	3.0	18	27	0.167	0.222	21	33	0.071	0.091	0.857	0.818	195	255	9.29	7.73	3:150	1:80	2.00	1.25
3.	3.0	1.5	21	30	0.286	0.100	27	33	0.111	0.045	0.778	0.909	150	300	5.56	9.09	6:110	1:100	5.45	1.00
4.	1.5	1.5	15	24	0.200	0.125	18	27	0.083	0.056	0.833	0.889	195	270	10.83	10.00	14:70	2:70	20.00	2.86
5.	1.5	1.5	15	27	0.200	0.111	18	30	0.083	0.050	0.833	0.900	210	165	11.67	5.50	15:80	2:60	18.75	3.33
6.	3.0	3.0	12	36	0.500	0.167	18	42	0.167	0.071	0.667	0.857	195	195	10.83	4.64	12:80	3:50	15.00	6.00
7.	1.5	3.0	18	27	0.167	0.222	21	33	0.071	0.091	0.857	0.818	171	150	8.14	4.55	3:100	1:120	3.00	0.83
8.	1.5	1.5	18	18	0.167	0.167	21	21	0.071	0.071	0.857	0.857	180	420	8.57	20.00	10:70	1:105	1.43	0.95
9.	1.5	4.5	18	18	0.167	0.500	21	27	0.071	0.167	0.857	0.667	330	360	15.71	13.33	4:100	1:110	4.00	0.91
10.	3.0	1.5	21	24	0.286	0.125	27	27	0.111	0.056	0.778	0.889	315	240	11.67	8.89	3:120	3:60	2.50	5.00
11.	3.0	3.0	24	33	0.250	0.182	30	39	0.100	0.077	0.800	0.846	300	150	10.00	3.85	8:60	5:80	13.33	6.25
12.	3.0	1.5	30	30	0.200	0.100	36	33	0.083	0.045	0.833	0.909	210	165	5.83	5.00	7:70	2:120	10.00	1.67
13.	3.0	1.5	24	18	0.250	0.167	30	21	0.100	0.071	0.800	0.857	255	165	8.50	7.86				
14.	1.5	1.5	24	24	0.125	0.125	27	27	0.056	0.056	0.889	0.889	180	330	6.67	12.22				
15.	1.5	3.0	24	15	0.125	0.400	27	21	0.056	0.143	0.889	0.714	150	135	5.56	6.43				
16.	1.5	3.0	27	21	0.111	0.286	30	27	0.050	0.111	0.900	0.778	129	165	4.30	6.11				
17.	1.5	1.5	18	15	0.167	0.200	21	18	0.071	0.083	0.857	0.833	234	360	11.14	20.00				
18.	3.0	1.5	24	30	0.250	0.100	30	33	0.100	0.045	0.800	0.909	180	330	6.00	10.00				
19.	1.5	1.5	18	27	0.167	0.111	21	30	0.071	0.050	0.857	0.900	330	135	15.71	4.50				
20.	3.0	1.5	30	33	0.200	0.091	36	36	0.083	0.042	0.833	0.917	360	150	10.00	4.17				
Σ	2.10	2.10	20.85	24.90	0.21	0.13	25.05	29.10	0.09	0.07	0.83	0.85	225.45	235.50	9.37	8.76			8.21	2.60
σ	0.75	0.90	4.92	6.16	0.10	0.10	5.70	6.32	0.03	0.03	0.05	0.06	67.98	89.68	3.18	4.77			6.89	2.08
e	0.17	0.20	1.10	1.38	0.02	0.02	1.27	1.41	0.01	0.01	0.01	0.01	15.20	20.10	0.71	1.07			1.99	0.60

A - 1: Wood Fibre Characteristics of Stems and Roots of GAMCOT 6 Cotton Plants

S.N.	Fibre wall thickness (µm)		Fibre lumen diameter (µm)		Runkel ratio		Fibre diameter (µm)		Thickness index		Coeff. of flexibility		Fibre length (µm)		Slenderness ratio		Ratio of no. of vessels to no. of fibres		% Void Space	
	Stem	Root	Stem	Root	Stem	Root	Stem	Root	Stem	Root	Stem	Root	Stem	Root	Stem	Root	Stem	Root	Stem	Root
1.	3.0	3.0	15	18	0.400	0.333	21	24	0.143	0.125	0.714	0.750	150	141	7.14	5.88	2:100	3:100	2.00	3.00
2.	4.5	1.5	18	30	0.500	0.100	27	33	0.167	0.045	0.667	0.909	180	135	6.67	4.09	2:60	3:90	3.33	3.33
3.	3.0	1.5	18	15	0.333	0.200	24	18	0.125	0.083	0.750	0.833	150	285	6.25	15.83	5:40	3:100	12.50	2.75
4.	1.5	3.0	15	12	0.167	0.500	21	18	0.071	0.167	0.857	0.667	135	270	6.43	15.00	1:100	2:120	1.00	1.67
5.	3.0	1.5	18	18	0.333	0.167	24	21	0.125	0.071	0.750	0.857	195	135	8.13	6.43	2:70	2:100	2.86	2.00
6.	3.0	4.5	21	21	0.286	0.429	27	30	0.111	0.150	0.778	0.700	150	120	5.56	4.00	3:70	3:100	4.29	3.00
7.	1.5	3.0	21	15	0.143	0.400	24	21	0.063	0.143	0.857	0.714	135	360	5.63	17.14	3:80	4:80	3.75	5.00
8.	3.0	3.0	15	18	0.400	0.333	21	24	0.143	0.125	0.714	0.750	285	225	13.57	9.38	3:100	2:120	3.00	1.67
9.	4.5	1.5	18	24	0.500	0.125	27	27	0.167	0.056	0.667	0.889	240	330	8.89	12.22	2:60	2:110	3.33	1.82
10.	3.0	1.5	12	30	0.500	0.100	18	33	0.167	0.045	0.667	0.909	360	240	20.00	7.27	1:50	3:90	2.00	3.33
11.	3.0	1.5	18	21	0.333	0.143	24	24	0.125	0.063	0.750	0.875	240	210	10.00	8.75	3:60	2:100	5.00	2.00
12.	4.5	3.0	21	24	0.429	0.250	30	30	0.150	0.100	0.700	0.800	450	264	15.00	6.80	3:70	1:150	4.29	0.67
13.	3.0	4.5	15	12	0.400	0.500	21	27	0.143	0.167	0.714	0.667	540	270	25.71	10.00				
14.	4.5	1.5	24	12	0.375	0.200	33	18	0.136	0.083	0.727	0.833	450	315	13.64	17.5				
15.	3.0	3.0	24	24	0.250	0.250	30	30	0.100	0.100	0.800	0.800	330	120	11.00	5.00				
16.	1.5	3.0	30	27	0.100	0.222	33	33	0.045	0.091	0.909	0.818	150	360	4.55	10.91				
17.	1.5	3.0	18	21	0.167	0.286	21	27	0.071	0.111	0.857	0.778	360	180	17.14	6.67				
18.	1.0	3.0	33	15	0.182	0.400	39	21	0.077	0.143	0.846	0.714	360	300	9.23	14.29				
19.	3.0	4.5	27	18	0.083	0.500	33	27	0.091	0.167	0.818	0.667	270	195	8.18	7.22				
20.	1.5	3.0	15	12	0.200	0.400	18	18	0.083	0.167	0.833	0.667	240	360	13.33	20.00				
$\bar{x}$	2.93	2.70	19.95	19.80	0.30	0.30	25.80	25.20	0.12	0.11	0.77	0.78	268.5	240.75	10.80	10.27			3.95	2.52
s	1.03	1.04	5.36	5.37	0.14	0.14	5.71	5.25	0.03	0.04	0.10	0.10	120.58	88.45	4.48	4.90			2.92	1.12
e	0.23	0.23	1.20	1.20	0.03	0.03	1.28	1.18	0.01	0.01	0.02	0.02	26.96	19.66	1.23	1.09			0.84	0.32

A - 1: Wood Fibre Characteristics of Stems and Roots of SAMCOT 9 Cotton Plants

S/N	Fibre wall thickness (µm)		Fibre Lumen diameter (µm)		Runkel ratio		Fibre diameter (µ)		Thickness index		Coefficient of flexibility		Fibre length (µm)		Slenderness ratio		Ratio of no. of vessels to no. of fibres		% Void Space	
	Stem	Root	Stem	Root	Stem	Root	Stem	Root	Stem	Root	Stem	Root	Stem	Root	Stem	Root	Stem	Root	Stem	Root
1.	3.0	3.0	24	30	0.250	0.200	30	36	0.100	0.083	0.800	0.833	360	330	12.00	9.17	3:70	1:80	4.29	1.25
2.	1.5	4.5	18	27	0.167	0.333	21	36	0.071	0.125	0.857	0.750	390	150	18.57	4.17	3:80	2:70	3.75	2.86
3.	3.0	3.0	21	39	0.286	0.154	27	45	0.111	0.067	0.778	0.867	330	195	12.22	4.33	4:65	2:60	6.15	3.33
4.	3.0	3.0	21	30	0.286	0.200	27	36	0.111	0.083	0.778	0.833	270	150	10.00	5.00	2:50	3:50	2.50	6.00
5.	3.0	3.0	15	30	0.400	0.200	21	36	0.143	0.083	0.714	0.833	285	150	13.57	5.00	1:90	2:50	1.11	4.00
6.	1.5	3.0	18	24	0.167	0.250	21	30	0.071	0.100	0.857	0.800	390	360	18.57	12.00	2:100	2:40	2.00	5.00
7.	3.0	4.5	24	30	0.250	0.300	30	39	0.100	0.115	0.800	0.769	180	330	6.00	8.46	2:70	1:70	2.86	1.43
8.	3.0	4.5	24	24	0.250	0.375	30	33	0.100	0.136	0.800	0.725	300	180	10.00	5.45	4:80	3:60	5.00	5.00
9.	1.5	4.5	18	24	0.167	0.375	21	33	0.071	0.136	0.857	0.727	150	150	7.14	4.55	2:90	2:90	2.22	2.50
10.	3.0	7.5	12	24	0.500	0.625	18	39	0.167	0.192	0.667	0.615	360	240	20.00	6.15	2:80	3:90	2.50	3.33
11.	3.0	3.0	21	24	0.286	0.250	27	30	0.111	0.100	0.778	0.800	390	330	14.44	12.00	3:50	3-110	6.00	2.73
12.	4.5	3.0	27	45	0.333	0.133	36	51	0.125	0.059	0.750	0.882	180	150	5.00	2.94	2:60	2-100	3.33	2.00
13.	3.0	3.0	21	30	0.286	0.200	27	36	0.111	0.083	0.778	0.833	360	240	13.33	6.67				
14.	4.5	4.5	15	27	0.600	0.333	24	36	0.188	0.125	0.625	0.750	195	180	8.13	5.00				
15.	1.5	4.5	21	36	0.143	0.250	24	45	0.063	0.100	0.875	0.800	165	225	6.88	5.00				
16.	1.5	3.0	27	21	0.111	0.286	30	27	0.050	0.111	0.900	0.778	480	135	16.00	5.00				
17.	1.5	4.5	33	21	0.100	0.429	33	30	0.045	0.150	0.909	0.700	450	135	13.64	4.50				
18.	1.5	4.5	33	24	0.091	0.375	36	33	0.042	0.136	0.917	0.727	510	180	14.17	5.45				
19.	3.0	4.5	30	15	0.200	0.500	36	27	0.083	0.167	0.833	0.667	180	270	5.00	10.00				
20.	4.5	7.5	27	30	0.333	0.500	36	45	0.125	0.167	0.750	0.667	420	300	11.67	6.67				
$\bar{x}$	2.70	4.13	22.35	27.90	0.28	0.31	27.75	36.15	0.10	0.12	0.80	0.77	317.25	222.00	11.82	6.33			3.48	3.29
s	1.04	1.36	5.55	6.46	0.14	0.14	5.71	6.62	0.04	0.03	0.10	0.10	112.26	73.74	4.53	2.48			1.60	1.48
e	0.23	0.30	1.24	1.45	0.03	0.03	1.28	1.44	0.01	0.01	0.02	0.02	25.11	16.49	1.01	0.56			0.46	0.43

A - 1: Wood Fibre Characteristics of Stems and Roots of SAMCOT 10 Cotton Plants

S/N	Fibre wall thickness (µm)		Fibre lumen diameter (µm)		Runkel ratio		Fibre diameter (µm)		Thickness index		Coeff. of flexibility		Fibre length (µm)		Slenderness ratio		Ratio of no. of vessels to no of fibres		% Void Space	
	Stem	Root	Stem	Root	Stem	Root	Stem	Root	Stem	Root	Stem	Root	Stem	Root	Stem	Root	Stem	Root	Stem	Root
1.	1.5	3.0	30	15	0.100	0.400	33	21	0.045	0.143	0.909	0.714	210	330	6.36	15.71	2:80	1:120	2.50	0.83
2.	1.5	3.0	33	15	0.091	0.400	36	21	0.042	0.143	0.917	0.714	330	450	9.17	21.43	3:50	1:130	6.00	0.77
3.	1.5	3.0	32	18	0.093	0.333	35	24	0.039	0.125	0.923	0.750	270	300	6.92	12.50	6:110	2:100	5.45	2.00
4.	3.0	3.0	30	10	0.200	0.333	36	24	0.083	0.125	0.833	0.750	105	210	2.92	8.75	5:80	1:105	6.25	0.95
5.	3.0	1.5	37	21	0.200	0.143	36	24	0.083	0.063	0.833	0.875	315	390	8.75	16.25	4:100	1:110	4.00	0.91
6.	1.5	3.0	24	15	0.125	0.400	27	21	0.056	0.143	0.889	0.714	330	360	12.22	17.14	2:120	2:140	1.67	1.43
7.	1.5	4.5	30	15	0.100	0.600	33	24	0.045	0.188	0.909	0.625	330	195	10.00	8.13	2:100	2:150	2.00	1.33
8.	1.5	1.0	33	24	0.091	0.250	36	30	0.042	0.100	0.917	0.800	450	195	12.50	6.50	3:80	3:90	3.75	3.33
9.	1.5	3.0	18	15	0.167	0.400	21	21	0.071	0.143	0.857	0.714	270	255	12.86	12.14	3:90	1:150	3.33	0.67
10.	3.0	4.5	27	18	0.222	0.500	33	27	0.091	0.167	0.818	0.667	300	240	9.09	8.89	3:90	3:90	3.33	3.33
11.	1.5	3.0	33	18	0.091	0.333	36	24	0.042	0.125	0.917	0.750	105	285	2.92	11.88	2:60	4:80	3.33	5.00
12.	1.5	3.0	42	21	0.071	0.286	45	27	0.033	0.111	0.933	0.778	180	240	4.00	8.89	2:50	3:100	4.00	3.00
13.	1.5	3.0	24	18	0.125	0.333	27	24	0.056	0.125	0.889	0.750	360	210	13.33	8.75				
14.	1.5	1.5	27	15	0.111	0.600	30	24	0.050	0.188	0.900	0.625	390	195	10.00	8.13				
15.	1.5	4.5	35	12	0.083	0.750	38	21	0.038	0.214	0.923	0.571	330	420	8.46	20.00				
16.	1.5	1.5	51	18	0.059	0.500	54	27	0.028	0.167	0.944	0.667	255	225	4.72	8.33				
17.	1.5	4.5	36	18	0.083	0.500	39	27	0.038	0.167	0.923	0.667	300	210	7.69	7.78				
18.	1.5	4.5	36	21	0.083	0.429	39	33	0.038	0.150	0.923	0.700	360	270	9.23	9.00				
19.	3.0	1.5	27	21	0.222	0.125	33	27	0.091	0.056	0.818	0.889	450	300	13.64	11.11				
20.	3.0	4.5	24	18	0.250	0.500	30	27	0.100	0.167	0.800	0.667	330	390	11.00	14.44				
$\bar{x}$	1.98	3.45	31.35	17.85	0.13	0.41	35.10	24.75	0.06	0.14	0.89	0.72	294.00	283.50	8.79	11.79			3.80	1.96
s	0.66	0.98	7.75	3.15	0.06	0.14	6.96	2.90	0.02	0.04	0.04	0.10	91.36	81.27	3.35	4.34			1.47	1.39
e	0.15	0.22	1.62	0.70	0.01	0.03	1.56	0.65	0.005	0.01	0.01	0.02	20.43	18.17	0.75	0.97			0.42	0.40

APPENDIX B: BAST FIBRE CHARACTERISTICS

B - 1: Bast Fibre Characteristics of Stems and Roots of SAMCOT 6 Cotton Plants

S/N	Fibre wall thickness (µm)		Fibre lumen diameter (µm)		Runkel ratio		Fibre diameter µm		Coefficient of flexibility		Thickness index		Fibre length µm		Slenderness ratio		Length of fibre bundle (µm)		Width of fibre bundle (µm)		Area of fibre bundle (mm^2)		No. of fibre bundles within the total bark area of 0.069mm^2	
	Stem	Root	Stem	Root	Stem	Root	Stem	Root	Stem	Root	Stem	Root	Stem	Root	Stem	Root	Stem	Root	Stem	Root	Stem	Root	Stem	Root
1.	1.5	4.5	15	12	0.20	0.75	18	21	0.83	0.57	0.083	0.214	300	300	16.67	14.29	429	126	69	60	0.030	0.008	2	3
2.	1.5	3.0	18	15	0.17	0.40	21	21	0.86	0.71	0.071	0.143	180	420	8.57	20.00	402	150	75	66	0.030	0.010	2	2
3.	3.0	3.0	12	12	0.50	0.50	18	18	0.67	0.67	0.167	0.167	150	327	8.33	18.17	285	165	90	75	0.026	0.012	3	2
4.	1.5	4.5	15	9	0.20	1.00	18	18	0.83	0.50	0.083	0.250	210	195	11.67	10.83	270	180	75	60	0.020	0.011	2	2
5.	3.0	3.0	21	6	0.29	1.00	27	12	0.78	0.50	0.111	0.250	360	210	13.33	17.50	210	240	60	90	0.013	0.022	2	3
6.	3.0	3.0	12	9	0.50	0.67	18	15	0.67	0.60	0.167	0.200	225	135	12.50	9.00	180	195	60	75	0.011	0.015		
7.	3.0	2.25	15	10.5	0.40	0.43	21	15	0.71	0.70	0.143	0.150	120	240	5.71	16.00	210	165	60	60	0.013	0.010		
8.	3.0	3.0	9	9	0.67	0.67	15	15	0.60	0.60	0.200	0.200	150	300	10.00	20.00	240	135	45	45	0.011	0.006		
9.	3.0	3.0	9	10.5	0.67	0.57	15	16.5	0.60	0.64	0.200	0.182	210	180	14.00	10.91	195	240	60	75	0.012	0.018		
10.	3.0	3.0	15	18	0.40	0.33	21	24	0.71	0.75	0.143	0.125	165	210	7.86	8.75	150	285	75	75	0.011	0.021		
11.	3.0	3.0	18	7.5	0.33	0.80	24	13.5	0.75	0.56	0.125	0.222	180	195	7.50	14.44								
12.	3.0	4.5	18	6	0.33	1.50	24	15	0.75	0.25	0.125	0.300	150	120	6.25	8.00								
13.	3.0	3.0	12	12	0.50	0.50	18	18	0.67	0.67	0.167	0.167	270	297	15.00	16.50								
14.	1.5	2.25	15	9	0.20	0.50	18	13.5	0.83	0.50	0.083	0.167	330	300	18.33	22.22								
15.	3.0	3.0	12	15	0.50	0.40	18	21	0.67	0.71	0.167	0.143	300	360	16.67	17.14								
16.	3.0	4.5	9	15	0.67	0.60	15	24	0.60	0.63	0.200	0.188	210	390	14.00	16.25								
17.	2.25	4.5	12	9	0.38	1.00	16.5	18	0.73	0.50	0.136	0.250	195	375	11.82	20.83								
18.	3.75	3.0	12	6	0.63	1.00	19.5	12	0.62	0.50	0.192	0.250	300	300	15.38	25.00								
19.	3.0	2.25	15	12	0.40	0.38	21	16.5	0.71	0.57	0.143	0.136	300	330	14.29	20.00								
20.	2.25	4.5	9	6	0.50	1.50	13.5	15	0.67	0.40	0.167	0.300	285	225	21.11	15.00								
$\bar{x}$	2.66	3.34	13.65	10.43	0.42	0.73	18.98	17.1	0.71	0.55	0.144	0.20	229.5	270.45	12.45	16.04	257.1	188.1	66.9	68.1	0.018	0.013	2.2	2.4
s	0.67	0.82	3.44	3.46	0.16	0.35	3.42	3.59	0.08	0.12	0.04	0.05	70.37	85.04	4.22	4.72	92.79	51.73	12.49	12.49	0.008	0.005	0.45	0.55
e	0.15	0.18	0.77	0.77	0.37	0.77	0.76	0.80	0.02	0.03	0.009	0.01	15.74	19.02	0.94	1.06	29.35	16.36	3.95	3.95	0.003	0.002	0.20	0.24

B - 2: Bast Fibre Characteristics of Stems and Roots of SAMCOT 8 Cotton Plants

S/N	Fibre wall thickness (µm)		Fibre lumen diameter (µm)		Runkel ratio		Fibre diameter µm		Coefficient of flexibility		Thickness index		Fibre length µm		Slenderness ratio		Length of fibre bundle (µm)		Width of fibre bundle (µm)		Area of fibre bundle (mm^2)		No. of fibre bundles within the total bark area of 0.069mm^2	
	Stem	Root	Stem	Root	Stem	Root	Stem	Root	Stem	Root	Stem	Root	Stem	Root	Stem	Root	Stem	Root	Stem	Root	Stem	Root	Stem	Root
1.	4.5	3.0	15	15	0.60	0.40	24	21	0.63	0.71	0.188	0.143	180	390	7.50	18.57	210	195	69	60	0.015	0.012	3	2
2.	3.0	3.0	12	9	0.50	0.67	18	15	0.67	0.60	0.167	0.200	210	297	11.67	19.80	270	270	75	75	0.020	0.020	5	3
3.	3.0	3.0	9	6	0.67	1.00	15	12	0.60	0.50	0.200	0.250	135	210	9.00	17.50	135	300	90	90	0.012	0.027	4	3
4	3.0	3.0	12	7.5	0.50	0.80	18	13.5	0.67	0.56	0.167	0.222	270	150	15.00	11.11	165	75	75	75	0.012	0.006	3	2
5	31.5	3.75	6	10.5	0.50	0.71	9	18	0.67	0.58	0.167	0.208	210	270	23.33	15.00	225	240	60	60	0.014	0.014	6	2
6.	3.75	4.5	10.5	9	0.71	1.00	18	18	0.58	0.50	0.209	0.250	180	225	10.00	12.50	75	135	60	75	0.005	0.010		
7	4.5	2.25	9	12	1.00	0.38	16	16.5	0.50	0.73	0.250	0.136	255	297	14.17	18.00	90	90	60	75	0.005	0.007		
8	4.5	3.0	6	12	1.50	0.50	15	18	0.40	0.67	0.300	0.167	450	135	30.00	7.50	165	150	45	75	0.007	0.011		
9	6.0	2.25	15	12	0.80	0.38	27	16.5	0.56	0.73	0.222	0.136	150	270	5.56	16.36	120	240	60	66	0.007	0.016		
10	3.0	3.0	21	12	0.29	0.50	27	18	0.78	0.67	0.111	0.167	435	420	16.11	23.33	90	300	75	60	0.007	0.018		
11	4.5	3.0	15	9	0.60	0.67	24	15	0.63	0.60	0.188	0.200	360	450	15.00	30.00								
12	6.0	2.25	9	9	1.33	0.50	21	13.5	0.43	0.67	0.286	0.167	165	360	7.86	26.67								
13	7.5	3.0	9	12	1.67	0.50	24	18	0.38	0.67	0.313	0.167	195	270	8.13	15.00								
14	6.0	4.5	7.5	9	1.60	1.00	19.5	18	0.38	0.50	0.308	0.250	480	300	24.62	16.67								
15	4.5	3.0	12	9	0.75	0.67	21	15	0.57	0.60	0.214	0.200	225	255	10.71	17.00								
16	7.5	1.5	9	4.5	1.67	0.67	24	7.5	0.38	0.60	0.313	0.200	180	267	7.50	35.6								
17	6.0	2.25	15	6	0.80	0.75	27	10.5	0.56	0.57	0.222	0.214	345	240	12.78	22.86								
18	7.5	3.0	9	9	1.67	0.67	24	15	0.38	0.60	0.313	0.200	240	225	10.00	15.00								
19	7.5	3.0	6	12	1.50	0.50	21	18	0.29	0.67	0.357	0.167	210	264	10.00	14.67								
20	3.0	1.5	21	9	0.29	0.33	27	12	0.78	0.75	0.111	0.125	330	249	12.22	20.75								

B - 3: Bast Fibre Characteristics of Stems and Roots of SAMCOT 9 Cotton Plants

S/N	Fibre wall thickness (µm)		Fibre lumen diameter (µm)		Runkel ratio		Fibre diameter µm		Coefficient of flexibility		Thickness index		Fibre length µm		Slenderness ratio		Length of fibre bundle (µm)		Width of fibre bundle (µm)		Area of fibre bundle (mm^2)		No. of fibre bundles within the total bark area of 0.069mm^2	
	Stem	Root	Stem	Root	Stem	Root	Stem	Root	Stem	Root	Stem	Root	Stem	Root	Stem	Root	Stem	Root	Stem	Root	Stem	Root	Stem	Root
1.	4.5	3.0	12	9	0.75	0.67	21	15	0.57	0.60	0.214	0.200	126	240	6.00	16.00	135	300	96	120	0.013	0.036	2	2
2.	4.5	3.0	15	6	0.60	1.00	24	12	0.63	0.50	0.188	0.250	255	120	10.63	10.00	120	270	105	90	0.013	0.024	2	2
3.	7.5	3.0	21	9	0.71	0.67	36	15	0.58	0.60	0.205	0.200	240	130	6.67	12.00	210	165	60	60	0.013	0.010	3	2
4.	7.5	2.25	12	10.5	1.25	0.43	27	15	0.44	0.70	0.278	0.15	285	210	10.56	14.00	180	195	45	60	0.008	0.012	2	3
5.	7.5	3.0	6	12	2.50	0.50	21	18	0.29	0.67	0.357	0.167	300	240	13.29	13.33	150	135	60	60	0.009	0.008	3	2
6.	6.0	3.0	12	9	1.00	0.67	24	15	0.50	0.60	0.250	0.200	390	150	16.25	10.00	135	156	60	75	0.008	0.012		
7.	3.0	3.75	9	15	0.67	0.50	15	22.5	0.60	0.67	0.200	0.167	285	210	19.00	9.33	135	159	120	90	0.016	0.014		
8.	9.0	4.5	12	15	1.50	0.60	30	24	0.40	0.63	0.300	0.188	300	150	10.00	6.25	120	150	60	60	0.007	0.009		
9.	4.5	1.5	12	9	0.75	0.33	21	12	0.57	0.75	0.214	0.125	270	180	12.86	15.00	120	165	30	60	0.004	0.010		
10.	7.5	3.0	19.5	12	0.77	0.50	34.5	18	0.57	0.67	0.217	0.167	165	264	4.78	14.67	150	255	60	75	0.009	0.019		
11.	7.5	3.0	9	6	1.67	1.00	24	12	0.38	0.50	0.313	0.250	450	135	18.75	11.25								
12.	3.0	3.0	9	9	0.67	0.67	15	15	0.60	0.60	0.200	0.200	420	354	28.00	23.60								
13.	4.5	4.5	12	6	0.75	1.50	22	15	0.57	0.40	0.214	0.300	228	300	10.86	20.00								
14.	3.0	1.0	13	10.5	0.47	0.57	21	16.5	0.71	0.64	0.143	0.182	150	306	7.14	19.55								
15.	3.0	4.5	12	6	0.50	1.50	17	15	0.67	0.40	0.167	0.300	360	270	20.00	18.00								
16.	3.0	4.5	12	9	0.50	1.00	19	13	0.67	0.50	0.167	0.250	249	150	13.03	10.00								
17.	4.5	4.5	15	9	0.60	1.00	24	13	0.63	0.67	0.188	0.250	330	225	13.75	12.50								
18.	4.5	3.0	12	6	0.75	1.00	21	12	0.57	0.50	0.214	0.250	360	315	17.14	26.25								
19.	7.5	4.5	6	6	2.50	1.50	21	15	0.29	0.40	0.357	0.300	270	204	12.96	13.60								
20.	6.0	3.0	9	12	1.33	0.40	21	21	0.43	0.71	0.286	0.143	300	180	14.29	8.57								

B - 4: Bast Fibre Characteristics of Stems and Roots of SAMCOT 10 Cotton Plants

S/N	Fibre wall thickness (µm)		Fibre lumen diameter (µm)		Runkel ratio		Fibre diameter µm		Coefficient of flexibility		Thickness index		Fibre length µm		Slenderness ratio		Length of fibre bundle (µm)		Width of fibre bundle (µm)		Area of fibre bundle (mm^2)		No. of fibre bundles within the total bark area 0.069mm^2	
	Stem	Root	Stem	Root	Stem	Root	Stem	Root	Stem	Root	Stem	Root	Stem	Root	Stem	Root	Stem	Root	Stem	Root	Stem	Root	Stem	Root
1.	4.5	2.25	12	9	0.75	0.50	21	13.5	0.57	0.67	0.214	0.167	180	300	8.57	22.22	240	300	75	45	0.018	0.014	2	2
2.	4.5	3.0	9	9	1.00	0.67	18	15	0.50	0.60	0.250	0.200	165	315	9.17	21.00	189	330	60	66	0.011	0.022	2	3
3.	1.5	3.0	6	6	1.50	1.00	15	12	0.40	0.50	0.300	0.250	135	330	13.00	27.50	156	150	45	60	0.007	0.009	2	3
4.	3.0	3.0	6	9	1.00	0.67	12	15	0.50	0.60	0.250	0.200	165	285	13.75	19.00	300	180	45	51	0.014	0.009	2	4
5.	4.5	4.5	12	12	0.75	0.75	21	21	0.57	0.57	0.214	0.214	180	225	8.57	10.71	195	255	39	66	0.008	0.017	2	3
6.	3.0	3.0	9	12	0.67	0.50	15	18	0.60	0.67	0.200	0.167	165	195	11.00	10.82	225	135	60	45	0.014	0.006		
7.	4.5	1.5	9	9	1.00	0.33	13	11	0.50	0.75	0.250	0.125	180	180	10.00	15.00	150	120	45	51	0.007	0.006		
8.	3.0	2.25	6	6	1.00	0.75	12	10.5	0.50	0.57	0.250	0.214	270	150	22.50	14.29	60	150	60	45	0.004	0.007		
9.	3.0	1.5	9	6	0.67	0.50	15	9	0.60	0.67	0.200	0.167	300	135	20.00	15.00	120	150	30	51	0.004	0.008		
10.	4.5	3.0	6	9	1.50	0.67	15	15	0.40	0.60	0.300	0.200	240	300	16.00	20.00	90	180	75	60	0.007	0.011		
11.	4.5	3.0	12	9	0.75	0.67	21	15	0.57	0.60	0.214	0.200	315	270	15.00	18.00								
12.	4.5	3.0	3	6	3.00	1.00	12	12	0.25	0.50	0.375	0.250	240	330	20.00	27.5								
13.	4.5	3.0	6	3	1.50	2.00	15	9	0.40	0.33	0.300	0.333	195	294	13.00	32.67								
14.	2.0	1.5	1	12	2.00	0.25	5	15	0.33	0.80	0.400	0.100	300	300	33.33	20.00								
15.	4.5	3.0	9	12	1.00	0.50	18	18	0.50	0.67	0.250	0.167	225	330	12.50	18.33								
16.	6.0	2.25	3	3	1.33	0.50	21	13.5	0.43	0.67	0.286	0.167	285	345	13.57	25.56								
17.	3.0	3.0	9	9	0.67	0.67	15	15	0.60	0.60	0.200	0.200	240	360	16.00	24.00								
18.	4.5	1.5	12	6	0.75	0.50	21	9	0.57	0.67	0.214	0.167	307	390	14.29	43.33								
19.	3.0	3.0	6	6	1.00	1.00	12	12	0.50	0.50	0.250	0.250	300	270	25.00	22.50								
20.	6.0	1.5	9	6	1.33	0.50	21	9	0.43	0.67	0.286	0.167	270	330	12.86	36.67								
	4.13	2.58	9.10	8.25	1.16	0.70	16.75	13.41	0.49	0.61	0.26	0.20	239.5	293.7	15.85	22.21	172.5	195.0	53.4	54.0	0.009	0.011	2.2	3.0
	2.46	0.87	2.77	3.44	0.58	1.27	3.93	3.07	0.10	0.10	0.05	0.05	38.0	70.22	6.16	8.33	72.53	73.48	15.02	8.37	0.005	0.005	0.45	0.71
	0.71	0.19	0.61	0.97	0.23	0.73	0.44	1.24	0.02	0.03	0.01	0.01	12.97	15.70	1.33	1.86	22.34	23.24	4.75	2.65	0.0015	0.002	0.20	0.32

APPENDIX C: ANALYSIS OF VARIANCE TABLES FOR WOOD AND BAST FIBRE CHARACTERISTICS

C-1: Analysis of Variance Table for Wood Fibre Characteristics of the Stems of SAMCOTs 6, 8, 9 and 10 Cotton Plants.

Fibre Characteristics	SV	SS	df	MS	F-ratio (Observed)	F - ratio (F-table)	Difference at α = 5%
Fibre wall thickness	Between Varieties	14.64	3	4.88	6.18	2.74	*
	Within	60.04	76	0.79			
	Total	**74.68**	**79**				
Fibre lumen diameter	Between Varieties	1650.17	3	550.06	16.16	2.74	*
	Within	2586.47	76	34.03			
	Total	4236.64	79				
Runkel ratio	Between Varieties	0.32	3	0.11	11.00	2.74	*
	Within	1.03	76	0.01			
	Total	1.35	79				
Fibre diameter	Between Varieties	1265.87	3	421.96	11.52	2.74	*
	Within	2783.69	76	36.63			
	Total	4049.56	79				
Thickness index	Between Varieties	0.04	3	0.01	10.00	2.74	*
	Within	0.09	76	0.001			
	Total	0.13	79				

C-1 continued.

Fibre Characteristics	SV	SS	df	MS	F-ratio (Observed)	F - ratio (F-table)	Difference at α = 5%
Coefficient of flexibility	Between Varieties	0.16	3	0.05	5	2.74	*
	Within	0·48	76	0·01			
	Total	0.64	79				
Fibre length	Between Varieties	92735.12	3	30911.71	3.08	2.74	*
	Within	762166.38	76	10028.51			
	Total	854901.50	79				
Slenderness ratio	Between Varieties	113.23	3	37.74	2.10	2.74	n.s
	Within	1365.72	76	17.97			
	Total	1478.95	79				
% Void space	Between Varieties	180.94	3	60.31	3.98	2.82	*
	Within	667.15	44	15.16			
	Total	848.09	47				

Note: * = significant; n.s = not significant.
Between Varieties SS = Sum of Squares of deviations of the mean values from the grand mean and df = k-1
Within Varieties SS = Sum of Squares of deviations of the observed values from the mean and df = k(n-1)
where k = number of varieties = 4

C-2 Analysis of Variance Table for the Bast Fibre Characteristics of the Stems of SAMCOTs 6, 8, 9 and 10 Cotton Plants.

Fibre Characteristics	SV	SS	df	MS	F-ratio (Observed)	F - ratio (F-table)	Difference at α = 5%
Fibre wall thickness	Between Varieties	84.10	3	28.03	13.04	2.74	*
	Within	163.4	76	2.15			
	Total	247.5	79				
Fibre lumen diameter	Between Varieties	327.62	3	109.21	8.16	2.74	*
	Within	1016.5	76	13.38			
	Total	1344.12	79				
Runkel ratio	Between Varieties	6.40	3	2.13	7.89	2.74	*
	Within	20.25	76	0.27			
	Total	26.65	79				
Fibre diameter	Between Varieties	473.95	3	157.98	7.88	2.74	*
	Within	1523.23	76	20.04			
	Total	1997.18	79				
Coefficient of flexibility	Between Varieties	0.566	3	0.189	14.54	2.74	*
	Within	0.950	76	0.013			
	Total	1.516	79				

C-2 continued.

Fibre Characteristics	SV	SS	df	MS	F-ratio (Observed)	F - ratio (F-table)	Difference at α = 5%
Thickness index	Between Varieties	0.151	3	0.050	12.50	2.74	*
	Within	0.266	76	0.004			
	Total	0.417	79				
Fibre length	Between Varieties	40867.61	3	13622.54	2.10	2.74	n.s
	Within	492393.55	76	6478.86			
	Total	533261.16	79				
Slenderness ratio	Between Varieties	97.99	3	32.66	1.03	2.74	n.s
	Within	2414.90	76	31.78			
	Total	2512.89	79				
Area of fibre bundle	Between Varieties	0.00056	3	0.00019	5.43	2.87	*
	Within	0.00126	36	0.000035			
	Total	0.00182	39				

Note: * = significant
n.s = not significant

C-3 Analysis of Variance Table for the Wood Fibre Characteristics of the Roots of SAMCOTs 6, 8, 9 and 10 Cotton Plants.

Fibre Characteristics	SV	SS	df	MS	F-ratio (Observed)	F - ratio (F-table)	Difference at α = 5%
Fibre wall thickness	Between Varieties	46.86	3	15.62	13.24	2.74	*
	Within	89.87	76	1.18			
	Total	136.73	79				
Fibre lumen diameter	Between Varieties	1275.63	3	425.21	14.36	2.74	*
	Within	2251.31	76	29.62			
	Total	3526.94	79				
Runkel ratio	Between Varieties	1.38	3	0.46	23	2.74	*
	Within	1.33	76	0.02			
	Total	2.71	79				
Fibre diameter	Between Varieties	1669.45	3	556.48	18.97	2.74	*
	Within	2229.27	76	29.33			
	Total	3898.72	79				
Thickness index	Between Varieties	0.052	3	0.017	8.5	2.74	*
	Within	0.114	76	0.002			
	Total	0.166	79				

C-3 continued.

Fibre Characteristics	SV	SS	df	MS	F-ratio (Observed)	F - ratio (F-table)	Difference at α = 5%
Coefficient of flexibility	Between Varieties	0.17	3	0.06	6.0	2.74	*
	Within	0.65	76	0.01			
	Total	0.82	79				
Fibre length	Between Varieties	42374.95	3	14124.98	2.09	2.74	n.s
	Within	514635.9	76	6771.53			
	Total	557010.85	79				
Slenderness ratio	Between Varieties	325.06	3	108.35	6.04	2.74	*
	Within	1363.25	76	17.94			
	Total	1688.31	79				
% Void space	Between Varieties	10.70	3	3.57	1.48	2.82	n.s
	Within	106.59	44	2.42			
	Total	117.29	47				

Note: * = Significant.

n.s = Not significant.

C-4 Analysis of Variance Table for the Bast Fibre Characteristics of the Roots of SAMCOTs 6, 8, 9 and 10 Cotton Plants.

Fibre Characteristics	SV	SS	df	MS	F-ratio (Observed)	F - ratio (F-table)	Difference at α = 5%
Fibre wall thickness	Between Varieties	8.61	3	2.87	4.35	2.74	*
	Within	50.16	76	0.66			
	Total	58.77	79				
Fibre lumen diameter	Between Varieties	49.08	3	16.36	1.90	2.74	n.s
	Within	654.74	76	8.62			
	Total	703.82	79				
Runkel ratio	Between Varieties	0.30	3	0.10	0.91	2.74	n.s
	Within	8.42	76	0.11			
	Total	8.72	79				
Fibre diameter	Between Varieties	146.60	3	48.87	4.26	2.74	*
	Within	870.77	76	11.46			
	Total	1017.37	79				
Coefficient of flexibility	Between Varieties	0.026	3	0.006	0.55	2.74	n.s
	Within	0.798	76	0.011			
	Total	0.824	79				

C-4 continued.

Fibre Characteristics	SV	SS	df	MS	F-ratio (Observed)	F - ratio (F-table)	Difference at α = 5%
Thickness index	Between Varieties	0.004	3	0.0013	0.46	2.74	n.s
	Within	0.209	76	0.0028			
	Total	0.213	79				
Fibre length	Between Varieties	47987.12	3	15995.71	2.82	2.74	*
	Within	431592.6	76	5678.85			
	Total	479579.72	79				
Slenderness ratio	Between Varieties	733.15	3	244.38	6.09	2.74	*
	Within	3051.02	76	40.15			
	Total	3784.17	79				
Area of fibre bundle	Between Varieties	0.0000875	3	0.0000292	0.65	2.87	n.s
	Within	0.00162	36	0.000045			
	Total	0.0017075	39				

Note: * = significant
n.s = not significant

C-5: Analysis of Variance Table for the Wood Fibre Characteristics of the Stems and Roots of SAMCOT 6 Cotton Plants.

Fibre Characteristics	SV	SS	df	MS	F-ratio (Observed)	F - ratio (F-table)	Difference at α = 5%
Fibre wall thickness	Between Samples	0	1	0	0	4.10	n.s
	Within	26.22	38	0.69			
	Total	**26.22**	**39**				
Fibre lumen diameter	Between Samples	164.03	1	164.03	5.28	4.10	*
	Within	1180.28	38	31.06			
	Total	1344.31	39				
Runkel ratio	Between Samples	0.009	1	0.009	0.90	4.10	n.s
	Within	0.38	38	0.01			
	Total	**0.389**	**39**				
Fibre diameter	Between Samples	164.03	1	164.03	4.53	4.10	*
	Within	1374.65	38	36.18			
	Total	1538.68	39				
Thickness index	Between Samples	0.001	1	0.001	1.0	4.10	n.s
	Within	0.038	38	0.001			
	Total	0.04	39				

C-5 contd.

Fibre Characteristics	SV	SS	df	MS	F-ratio (Observed)	F - ratio (F-table)	Difference at α = 5%
Coefficient of flexibility	Between Samples	0.004	1	0.004	1.0	4.10	n.s
	Within	0.133	38	0.004			
	Total	0.137	39				
Fibre length	Between Samples	1009.02	1	1009.02	0.16	4.10	n.s
	Within	241303.8	38	6350.1			
	Total	242312.82	39				
Slenderness ratio	Between Samples	3.72	1	3.72	0.23	4.10	n.s
	Within	624.34	38	16.43			
	Total	628.06	39				
% Void space	Between Samples	188.83	1	188.83	7.30	4.10	*
	Within	568.92	22	25.86			
	Total	757.75	23				

Note: * = significant; n.s = not significant.
Between Samples SS = Sum of Squares of deviations of the mean values from the grand mean and df = k-1
Within Samples SS = Sum of Squares of deviations of the observed values from the mean and df = k(n-1)
where k = number of samples (stem and root) = 2

C-6: Analysis of Variance Table for the Bast Fibre Characteristics of the Stems and Roots of SAMCOT 6 Cotton Plants.

Fibre Characteristics	SV	SS	df	MS	F-ratio (Observed)	F - ratio (F-table)	Difference at α = 5%
Fibre wall thickness	Between Samples	4.62	1	4.62	8.25	4.10	*
	Within	21.28	38	0.56			
	Total	**25.90**	**39**				
Fibre lumen diameter	Between Samples	103.68	1	103.68	8.71	4.10	*
	Within	452.2	38	11.90			
	Total		555.88		39		
Runkel ratio	Between Samples	0.96	1	0.96	12.97	4.10	*
	Within	2.83	38	0.074			
	Total	**3.79**	**39**				
Fibre diameter	Between Samples	35.40	1	35.40	2.88	4.10	n.s
	Within	467.21	38	12.30			
	Total	502.61	39				
Thickness index	Between Samples	0.169	1	0.169	16.90	4.10	*
	Within	0.38	38	0.01			
	Total	0.549	39				

C-6 contd.

Fibre Characteristics	SV	SS	df	MS	F-ratio (Observed)	F - ratio (F-table)	Difference at α = 5%
Coefficient of flexibility	Between Samples	0.0314	1	0.0314	12.56	4.10	*
	Within	0.095	38	0.0025			
	Total	0.1264	39				
Fibre length	Between Samples	16769.03	1	16769.03	2.75	4.10	n.s
	Within	231491.06	38	6091.87			
	Total	248260.09	39				
Slenderness ratio	Between Samples	128.88	1	128.88	6.43	4.10	*
	Within	761.71	38	20.05			
	Total	890.59	39				
Area of fibre bundle	Between Samples	0.000125	1	0.000125	2.78	4.41	n.s
	Within	0.00081	18	0.000045			
	Total	0.000935	19				

Note: * = significant
n.s = not significant.

C-7: Analysis of Variance Table for the Wood Fibre Characteristics of the Stems and Roots of SAMCOT 8 Cotton Plants.

Fibre Characteristics	SV	SS	df	MS	F-ratio (Observed)	F - ratio (F-table)	Difference at α = 5%
Fibre wall thickness	Between Samples	0.53	1	0.53	0.49	4.10	n.s
	Within	40.85	38	1.08			
	Total	**41.38**	**39**				
Fibre lumen diameter	Between Samples	0.23	1	0.23	0.01	4.10	n.s
	Within	1092.12	38	28.74			
	Total	1092.35		39			
Runkel ratio	Between Samples	0	1	0	0	4.10	n.s
	Within	0.76	38	0.02			
	Total	***0.76***	**39**				
Fibre diameter	Between Samples	3.6	1	3.6	0.12	4.10	n.s
	Within	1148.36	38	30.22			
	Total	1151.96	39				
Thickness index	Between Samples	0.001	1	0.001	0.5	4.10	n.s
	Within	0.057	38	0.002			
	Total	0.58	39				

C-7 contd.

Fibre Characteristics	SV	SS	df	MS	F-ratio (Observed)	F - ratio (F-table)	Difference at α = 5%
Coefficient of flexibility	Between Samples	0.001	1	0.001	0.1	4.10	n.s
	Within	0·38	38	0·01			
	Total	**0.381**	**39**				
Fibre length	Between Samples	7703.41	1	7703.41	0.72	4.10	n.s
	Within	408570.11	38	10751.85			
	Total	416273.53	39				
Slenderness ratio	Between Samples	2.81	1	2.81	0.10	4.10	n.s
	Within	1026.76	38	27.02			
	Total	1029.57	39				
% Void space	Between Samples	12.27	1	12.27	2.51	4.30	n.s
	Within	107.47	22	4.89			
	Total	119.74	23				

Note: * = significant
n.s = not significant.

C-8: Analysis of Variance Table for the Bast Fibre Characteristics of the Stems and Roots of SAMCOT 8 Cotton Plants.

Fibre Characteristics	SV	SS	df	MS	F-ratio (Observed)	F - ratio (F-table)	Difference at α = 5%
Fibre wall thickness	Between Samples	38.03	1	38.03	19.21	4.10	*
	Within	75.24	38	1.98			
	Total	113.27	39				
Fibre lumen diameter	Between Samples	29.58	1	29.58	2.26	4.10	n.s
	Within	497.99	38	13.11			
	Total	527.57	39				
Runkel ratio	Between Samples	1.37	1	1.37	6.85	4.10	*
	Within	7.60	38	0.20			
	Total	8.97	39				
Fibre diameter	Between Samples	316.97	1	316.97	18.78	4.10	*
	Within	641.44	38	16.88			
	Total	958.41	39				
Coefficient of flexibility	Between Samples	0.0314	1	0.0314	12.56	4.10	*
	Within	0.095	38	0.0025			
	Total	0.1264	39				

C-8 continued.

Fibre Characteristics	SV	SS	df	MS	F-ratio (Observed)	F - ratio (F-table)	Difference at α = 5%
Thickness index	Between Samples	0.016	1	0.016	4.57	4.10	*
	Within	0.133	38	0.0035			
	Total	0.149	39				
Fibre length	Between Samples	2873.03	1	2873.03	0.33	4.10	n.s
	Within	327290.2	38	8612.90			
	Total	330163.23	39				
Slenderness ratio	Between Samples	316.97	1	316.97	7.62	4.10	*
	Within	1581.18	38	41.61			
	Total	1898.15	39				
Area of fibre bundle	Between Samples	0.00008	1	0.00008	2.29	4.41	n.s
	Within	0.00063	18	0.000035			
	Total	0.00071	19				

Note: * = significant
n.s = not significant

C-9: Analysis of Variance Table for the Wood Fibre Characteristics of the Stems and Roots of SAMCOT 9 Cotton Plants.

Fibre Characteristics	SV	SS	df	MS	F-ratio (Observed)	F - ratio (F-table)	Difference at α = 5%
Fibre wall thickness	Between Samples	20.45	1	20.45	13.82	4.10	*
	Within	56.05	38	1.48			
	Total	76.50	39				
Fibre lumen diameter	Between Samples	308.03	1	308.03	8.49	4.10	*
	Within	1378.26	38	36.27			
	Total	1686.29	39				
Runkel ratio	Between Samples	0.025	1	0.025	1.25	4.10	n.s
	Within	0.76	38	0.02			
	Total	0.785	39				
Fibre diameter	Between Samples	705.60	1	705.60	19.01	4.10	*
	Within	1410.37	38	37.12			
	Total	2115.97	39				
Thickness index	Between Samples	0.004	1	0.004	2	4.10	n.s
	Within	0.057	38	0.002			
	Total	0.061	39				

C-9 contd.

Fibre Characteristics	SV	SS	df	MS	F-ratio (Observed)	F - ratio (F-table)	Difference at α = 5%
Coefficient of flexibility	Between Samples	0.009	1	0.009	0.9	4.10	n.s
	Within	0.38	38	0.01			
	Total	0.389	39				
Fibre length	Between Samples	90725.63	1	90725.63	10.06	4.10	*
	Within	342843.6	38	9022.2			
	Total	433569.23	39				
Slenderness ratio	Between Samples	301.40	1	301.40	22.59	4.10	*
	Within	506.73	38	13.34			
	Total	808.13	39				
% Void space	Between Samples	0.22	1	0.22	0.09	4.30	n.s
	Within	52.36	22	2.38			
	Total	52.58	23				

Note: * = significant
n.s = not significant.

C-10: Analysis of Variance Table for the Bast Fibre Characteristics of the Stems and Roots of SAMCOT 9 Cotton Plants.

Fibre Characteristics	SV	SS	df	MS	F-ratio (Observed)	F - ratio (F-table)	Difference at α = 5%
Fibre wall thickness	Between Samples	40.80	1	40.80	17.66	4.10	*
	Within	87.78	38	2.31			
	Total	128.58	39				
Fibre lumen diameter	Between Samples	69.17	1	69.17	5.82	4.10	*
	Within	451.82	38	11.89			
	Total	520.99	39				
Runkel ratio	Between Samples	0.441	1	0.441	1.73	4.10	n.s
	Within	9.69	38	0.255			
	Total	10.131	39				
Fibre diameter	Between Samples	446.22	1	446.22	21.27	4.10	*
	Within	797.24	38	20.98			
	Total	1243.46	39				
Coefficient of flexibility	Between Samples	0.025	1	0.025	1.92	4.10	n.s
	Within	0.494	38	0.013			
	Total	0.519	39				

C-10 continued.

Fibre Characteristics	SV	SS	df	MS	F-ratio (Observed)	F - ratio (F-table)	Difference at α = 5%
Thickness index	Between Samples	0.004	1	0.004	1.14	4.10	n.s
	Within	0.133	38	0.0035			
	Total	0.137	39				
Fibre length	Between Samples	43560.0	1	43560.0	7.66	4.10	*
	Within	216115.69	38	5687.26			
	Total	259675.69	39				
Slenderness ratio	Between Samples	5.93	1	5.93	0.21	4.10	n.s
	Within	1083.57	38	28.52			
	Total	1089.50	39				
Area of fibre bundle	Between Samples	0.000125	1	0.000125	2.5	4.41	n.s
	Within	0.0009	18	0.00005			
	Total	0.001025	19				

Note: * = significant
n.s = not significant

C-11: Analysis of Variance Table for the Wood Fibre Characteristics of the Stems and Roots of SAMCOT 10 Cotton Plants.

Fibre Characteristics	SV	SS	df	MS	F-ratio (Observed)	F - ratio (F-table)	Difference at α = 5%
Fibre wall thickness	Between Samples	24.65	1	24.65	34.72	4.10	*
	Within	26.79	38	0.71			
	Total	**51.44**	**39**				
Fibre lumen diameter	Between Samples	1822.5	1	1822.5	58.34	4.10	*
	Within	1187.12	38	31.24			
	Total	3009.62	39				
Runkel ratio	Between Samples	0.784	1	0.784	65.33	4.10	*
	Within	0.456	38	0.012			
	Total	**1.240**	**39**				
Fibre diameter	Between Samples	1071.23	1	1071.23	37.71	4.10	*
	Within	1079.58	38	28.41			
	Total	2150.81	39				
Thickness index	Between Samples	0.064	1	0.064	64	4.10	*
	Within	0.048	38	0.001			
	Total	0.112	39				

C-11 contd.

Fibre Characteristics	SV	SS	df	MS	F-ratio (Observed)	F - ratio (F-table)	Difference at α = 5%
Coefficient of flexibility	Between Samples	0.289	1	0.289	48.17	4.10	*
	Within	0.228	38	0.006			
	Total	0.517	39				
Fibre length	Between Samples	1102.5	1	1102.5	0.15	4.10	n.s
	Within	284084.77	38	7475.92			
	Total	285187.27	39				
Slenderness ratio	Between Samples	90.00	1	90.00	5.99	4.10	*
	Within	571.14	38	15.03			
	Total	661.14	39				
% Void space	Between Samples	20.31	1	20.31	9.91	4.30	*
	Within	44.99	22	2.05			
	Total	65.30	23				

Note: * = significant
n.s = not significant.

C-12: Analysis of Variance Table for the Bast Fibre Characteristics of the Stems and Roots of SAMCOT 10 Cotton Plants.

Fibre Characteristics	SV	SS	df	MS	F-ratio (Observed)	F - ratio (F-table)	Difference at α = 5%
Fibre wall thickness	Between Samples	23.72	1	23.72	30.81	4.10	*
	Within	29.26	38	0.77			
	Total	52.98	39				
Fibre lumen diameter	Between Samples	0.225	1	0.225	0.032	4.10	n.s
	Within	269.23	38	7.085			
	Total	269.455	39				
Runkel ratio	Between Samples	2.12	1	2.12	9.42	4.10	*
	Within	8.55	38	0.255			
	Total	10.67	39				
Fibre diameter	Between Samples	85.26	1	85.26	6.64	4.10	*
	Within	488.11	38	12.85			
	Total	573.37	39				
Coefficient of flexibility	Between Samples	0.144	1	0.144	14.42	4.10	*
	Within	0.38	38	0.01			
	Total	0.524	39				

C-12 continued.

Fibre Characteristics	SV	SS	df	MS	F-ratio (Observed)	F - ratio (F-table)	Difference at α = 5%
Thickness index	Between Samples	0.036	1	0.036	12.0	4.10	*
	Within	0.114	38	0.003			
	Total	0.150	39				
Fibre length	Between Samples	21344.4	1	21344.4	5.44	4.10	*
	Within	149089.2	38	3923.4			
	Total	170433.6	39				
Slenderness ratio	Between Samples	563.76	1	463.76	8.64	4.10	*
	Within	2039.46	38	53.67			
	Total	2503.22	39				
Area of fibre bundle	Between Samples	0.00002	1	0.00002	0.67	4.41	n.s
	Within	0.00054	18	0.00003			
	Total	0.00026	19				

Note: * = significant
n.s = not significant

APPENDIX D: CHEMICAL COMPOSITION

D - 1: Chemical Composition of SAMCOT 6 Cotton Plant Stalks

Sample	Cellulose Content(%)	Hemi-Cellulose Content(%)	Lignin Content(%)	Ash Content(%)	Moisture Content (% wb)
A	55.16	9.02	24.82	6.50	5.57
B	52.57	8.10	25.30	6.30	9.85
C	50.22	8.56	24.00	6.20	6.57
D	54.12	8.86	22.30	6.00	10.08
$\bar{x}$	53.00	8.64	24.11	6.25	8.02
s	2.15	0.40	1.32	0.21	2.29
e	1.07	0.20	0.66	0.10	1.14

D - 2: Chemical Composition of SAMCOT 8 Cotton Plant Stalks

Sample	Cellulose Content(%)	Hemi-Cellulose Content(%)	Lignin Content(%)	Ash Content(%)	Moisture Content(% wb)
A	58.00	9.04	23.00	6.60	7.58
B	56.50	8.60	22.50	6.30	8.06
C	54.05	8.08	22.80	6.30	7.72
D	52.04	8.52	20.30	5.70	8.30
$\bar{x}$	55.15	8.56	22.15	6.23	7.92
s	2.63	0.39	1.25	0.38	0.33
e	1.31	0.20	0.63	0.19	0.16

D - 3: Chemical Composition of SAMCOT 9 Cotton Plant Stalks

Sample	Cellulose Content(%)	Hemi-Cellulose Content(%)	Lignin Content(%)	Ash Content(%)	Moisture Content(% wb)
A	56.00	9.12	24.50	7.04	6.96
B	54.50	8.60	23.80	6.28	7.97
C	54.0	8.00	23.10	5.67	6.55
D	52.12	7.20	22.00	7.02	9.62
$\bar{x}$	54.16	8.23	23.35	6.50	7.78
s	1.60	0.83	1.07	0.66	1.37
e	0.80	0.41	0.53	0.33	0.68

D - 4: Chemical Composition of SAMCOT 10 Cotton Plant Stalks

Sample	Cellulose Content(%)	Hemi-Cellulose Content(%)	Lignin Content(%)	Ash Content(%)	Moisture Content(% wb)
A	57.20	8.72	23.60	6.81	7.94
B	55.00	8.48	24.00	6.72	8.49
C	52.50	8.00	23.00	6.50	8.80
D	50.50	7.40	22.50	6.10	7.84
$\bar{x}$	53.80	8.15	23.28	6.53	8.27
s	2.92	0.58	0.66	0.32	0.46
e	1.46	0.29	0.33	0.16	0.23

APPENDIX E
WOOD DENSITY

E - 1: Determination of Wood Density for SAMCOT 6 Cotton Plant Stalks

Replicate	Diameter (cm)	Length (cm)	Cross - sectional area (cm^2)	Volume (cm^3)	Mass (g)	Wood density (g/cm^3)
1	1.08	4.85	0.92	4.44	2.01	0.453
2	1.14	4.71	1.02	4.81	2.03	0.422
3	1.29	5.62	1.31	7.35	2.40	0.327
4	1.17	6.04	1.08	6.49	2.51	0.38
$\bar{x}$						0.397
s						0.054
e						0.027

E - 2: Determination of Wood Density for SAMCOT 8 Cotton Plant Stalks.

Replicate	Diameter (cm)	Length (cm)	Cross - sectional area (cm^2)	Volume (cm^3)	Mass (g)	Wood density (g/cm^3)
1	1.15	5.32	1.04	5.53	2.12	0.383
2	1.17	6.78	1.08	7.29	3.36	0.461
3	1.44	5.23	1.63	8.52	2.79	0.327
4	1.09	5.89	0.93	5.50	2.17	0.395
$\bar{x}$						0.392
s						0.055
e						0.028

E - 3: Determination of Wood Density for SAMCOT 9 Cotton Plant Stalks

Replicate	Diameter (cm)	Length (cm)	Cross - sectional area (cm^2)	Volume (cm^3)	Mass (g)	Wood density (g/cm^3)
1	1.05	6.51	0.87	5.64	2.81	0.498
2	1.12	5.72	0.99	5.64	2.05	0.363
3	1.23	4.96	1.19	5.89	2.02	0.343
4	1.15	6.32	1.04	6.56	2.49	0.380
$\bar{x}$						0.396
s						0.070
e						0.035

E - 4: Determination of Wood Density for SAMCOT 10 Cotton Plant Stalks.

Replicate	Diameter (cm)	Length (cm)	Cross - Sectional area (cm^2)	Volume (cm^3)	Mass (g)	Wood density (g/cm^3)
1	1.19	5.88	1.11	6.54	2.51	0.384
2	0.90	6.62	0.64	4.21	1.96	0.466
3	1.05	6.14	0.87	5.34	2.45	0.459
4	0.82	7.04	0.53	3.72	1.64	0.441
$\bar{x}$						0.438
s						0.037
e						0.019

APPENDIX F: ENERGY VALUE OF COTTON PLANT STALKS

ADIABATIC BOMB CALORIMETER REPORT SHEET

F - 1: Energy Value of SAMCOT 6 Cotton Plant Stalks

Sample Reference: SAMCOT 6 Analyst: Engr. J. N. Maduako Date: 15/5/96		
Crucible + fuel	15.54 g	
Crucible	10.04 g	
Fuel	5.50 g	
Final temperature of Calorimeter	25.03 ^{o}C	Correction + 0.005 ^{o}C
Initial temperature of Calorimeter	22.00 ^{o}C	Correction + 0.003 ^{o}C
Uncorrected temperature rise	3.03 ^{o}C	
Total thermometer correction (final - initial)	+0.002 ^{o}C	
Corrected temperature rise	3.032 ^{o}C	
Total heat capacity of apparatus	5450.2	cal/^{o}C
Total heat release	16525.0	cal
Constant heat gain (Cotton thread and Nickel - Chromium wire) 7.18 cal)		
Nitric acid correction 14.73 cal)	21.91	cal
Corrected heat from fuel	16503.09	cal
Heat from 1g of fuel	3000.56	cal
Sulphuric acid correction	19.44	cal
Gross calorffic value of fuel	2981.12	cal/g

Tests for Nitrogen and sulphur corrections		NOTES
Titration with barium hydroxide		
V_2	40.0 ml	1 Cal. = 4.2J
V_1	0.0 ml	
$V_2 - V_1$	40.0 ml	1 kcal/kg = 4.2kJ/kg
Solution normality	0.082	
ml 0.1N	40.0 ml (A)	
Sodium carbonate added		
20 ml normality	0.10	
ml 0.1N	20.3 ml (B)	
Titration with hydrochloric acid		
V_2	10.0 ml	
V_1	0.0 ml	
$V_2 - V_1$	10.0 ml	
Solution normality	0.085	
ml 0.1N	10.0 ml (C)	
Nitric acid correction	1.43 (B - C) cal.	
	1.43 (20.3-10.0) cal. = 14.73Cal	
Sulphuric acid correction	$\frac{3.6\ [A - (B - C)]}{\text{sample weight}}$ cal	
	$\frac{3.6\ (40.0 - 10.3)}{5.5}$ cal. = 19.44 Cal	

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ADIABATIC BOMB CALORIMETER REPORT SHEET

F - 2: Energy Value of SAMCOT 8 Cotton Plant Stalks

Sample Reference: SAMCOT 8 Analyst: Engr. J. N. Maduako Date: 16/5/96

Crucible + fuel	15.39 g	
Crucible	10.04 g	
Fuel	5.35 g	
Final temperature	24.65 ^{o}C	Correction +0.012 ^{o}C
Initial temperature	21.50 ^{o}C	Correction + 0.005 ^{o}C
Uncorrected temperature rise	3.15 ^{o}C	
Total thermometer correction (final - initial)	+ 0.007 ^{o}C	
Corrected temperature rise	3.157 ^{o}C	
Total heat capacity of apparatus	5450.2	cal/^{o}C
Total heat release	17206.28	cal
Constant heat gain (Cotton thread and Nickel - Chromium wire) 7.18 cal)		
Nitric acid correction 16.73 cal)	23.91	cal
Corrected heat from fuel	17182.37	cal
Heat from 1g of fuel	3211.66	cal
Sulphuric acid correction	22.54	cal
Gross calorific value of fuel	3189.12	cal/g

Tests for Nitrogen and sulphur corrections

Titration with barium hydroxide

V_2	45.20	ml
V_1	0.0	ml
$V_2 - V_1$	45.20	ml
Solution normality	0.082	
ml 0.1N	45.20	ml (A)

Sodium carbonate added

20 ml normality	0.10	
ml 0.1N	20.2	ml (B)

Titration with hydrochloric acid

V_2	8.5	ml
V_1	0.0	ml
$V_2 - V_1$	8.5	ml
Solution normality	0.085	
ml 0.1N	8.5	ml (C)

NOTES

1 Cal. = 4.2J

1 kcal/kg = 4.2kJ/kg

Nitric acid correction = 1.43 (B - C) cal.

= 1.43 (20.2- 8.5) cal. = 16.73Cal

Sulphuric acid correction = $\frac{3.6\ [A - (B - C)]}{\text{sample weight}}$ cal

= $\frac{3.6\ (45.2 - 11.7)}{5.35}$ cal. = 22.54 Cal

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F - 3: Energy Value of SAMCOT 9 Cotton Plant Stalks

Sample Reference: SAMCOT 9	Analyst: Engr. J. N. Maduako	Date: 17/5/96
Crucible + fuel	15.44 g	
Crucible	10.04 g	
Fuel	5.40 g	
Final temperature	25.45 ^{o}C	Correction + 0.010 ^{o}C
Initial temperature	22.20 ^{o}C	Correction + 0.008 ^{o}C
Uncorrected temperature rise	3.25 ^{o}C	
Total thermometer correction (final - initial)	+ 0.002 ^{o}C	
Corrected temperature rise	3.252 ^{o}C	
Total heat capacity of apparatus	5450.2	cal/^{o}C
Total heat release	17724.05	cal
Constant heat gain (Cotton thread and Nickel - Chromium wire) 7.18 cal)		
Nitric acid correction 11.15 cal)	18.33	cal
Corrected heat from fuel	17705.72	cal
Heat from 1g of fuel	3278.84	cal
Sulphuric acid correction	18.47	cal
Gross calorific value of fuel	3260.37	cal/g

Tests for Nitrogen and sulphur corrections

Titration with barium hydroxide

V_2	35.50 ml	
V_1	0.0 ml	
$V_2 - V_1$	35.50 ml	
Solution normality	0.082	
ml 0.1N	35.50 ml (A)	
Sodium carbonate added		
20 ml normality	0.10	
ml 0.1N	20.3 ml (B)	

Titration with hydrochloric acid

V_2	12.5 ml	
V_1	0.0 ml	
$V_2 - V_1$	12.5 ml	
Solution normality	0.085	
ml 0.1N	12.5 ml (C)	
Nitric acid correction	1.43 (B - C) cal.	
	1.43 (20.3-12.5) cal. = 11.15Cal	
Sulphuric acid correction	$\frac{3.6\ [A - (B - C)]}{\text{sample weight}}$ cal	
	$\frac{3.6\ (35.5 - 7.8)}{5.4}$ cal. = 18.47 Cal	

NOTES

1 Cal. = 4.2J

1 kcal/kg = 4.2kJ/kg

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ADIABATIC BOMB CALORIMETER REPORT SHEET

F - 4: Energy Value of SAMCOT 10 Cotton Plant Stalks

Sample Reference: SAMCOT 10 Analyst: Engr. J. N. Maduako Date: 12/5/96

Crucible + fuel	15.29 g	
Crucible	10.04 g	
Fuel	5.25 g	
Final temperature	25.55 ^{o}C	Correction + 0.015 ^{o}C
Initial temperature	21.50 ^{o}C	Correction + 0.009 ^{o}C
Uncorrected temperature rise	3.05 ^{o}C	
Total thermometer correction (final - initial)	+ 0.006 ^{o}C	
Corrected temperature rise	3.056 ^{o}C	
Total heat capacity of apparatus	5450.2	cal/^{o}C
Total heat release	16655.81	cal
Constant heat gain (Cotton thread and Nickel - Chromium wire)	7.18 cal)	
Nitric acid correction	15.16 cal)	18.33 cal
Corrected heat from fuel	16615.31	cal
Heat from 1g of fuel	3164.82	cal
Sulphuric acid correction	20.50	cal
Gross calorific value of fuel	3144.32	cal/g

Tests for Nitrogen and sulphur corrections

Titration with barium hydroxide

V_2	340.0 ml	
V_1	0.0 ml	
$V_2 - V_1$	40.50 ml	
Solution normality	0.082	
ml 0.1N	40.50 ml (A)	
Sodium carbonate added		
20 ml normality	0.10	
ml 0.1N	20.1 ml (B)	

Titration with hydrochloric acid

V_2	9.5 ml	
V_1	0.0 ml	
$V_2 - V_1$	9.5 ml	
Solution normality	0.085	
ml 0.1N	9.5 ml (C)	
Nitric acid correction	1.43 (B - C) cal.	
	1.43 (20.1- 9.5) cal.	= 15.16Cal
Sulphuric acid correction	$\frac{3.6\ [A - (B - C)]}{\text{sample weight}}$ cal	
	$\frac{3.6\ (40.5 - 10.6)}{5.25}$ cal.	= 20.50 Cal

NOTES

1 Cal. = 4.2J

1 kcal/kg = 4.2kJ/kg

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APPENDIX G
STATISTICAL ANALYSIS OF RESULTS OF PAPER TESTING

G - 1: Analysis of the Caliper (mm) for SAMCOT 6 Hand Sheets

	Furnish Ratio							
	60/40 (P_1)				50/50 (P_2)			
	Freeness				Freeness			
	20^{o}SR (Q_1)		35^{o}SR (Q_2)		20^{o}SR (Q_1)		35^{o}SR (Q_2)	
	Additive		Additive		Additive		Additive	
	(0,0%) (R_1)	(1,4)% (R_2)	(0,0)% (R_1)	(1,4)% (R_2)	(0,0)% (R_1)	(1,4)% (R_2)	(0,0)% (R_1)	(1,4)% (R_2)
	0.55	0.63	0.56	0.61	0.52	0.56	0.46	0.42
	0.58	0.65	0.58	0.59	0.56	0.56	0.45	0.40
	0.57	0.64	0.57	0.58	0.54	0.54	0.49	0.41
	0.56	0.62	0.55	0.57	0.53	0.53	0.47	0.39
	0.59	0.61	0.59	0.60	0.55	0.57	0.48	0.38
$\bar{x}$	0.57	0.63	0.57	0.59	0.54	0.55	0.47	0.40
s	0.016	0.016	0.016	0.016	0.016	0.016	0.016	0.016
Σx^2	1.63	1.99	1.63	1.74	1.46	1.51	1.11	0.80 $\underline{\Sigma(\Sigma x^2)}$ =11.87
Σx	2.85	3.15	2.85	2.95	2.70	2.75	2.35	2.00 $\Sigma(\Sigma x)$ = 21.6

(a) Correction factor, $C = \frac{[\Sigma(\Sigma x)]^2}{8n} = \frac{(21.6)^2}{8x5} = \frac{466.56}{40} = 11.66$

(b) Total sum of squares of all observations, $\Sigma(\Sigma x^2) = 11.87$

(c) Sum of squares of the totals of each column = $\Sigma(\Sigma x)^2$

$= 2.85^2 + 3.15^2 + 2.85^2 + 2.95^2 + 2.7^2 + 2.75^2 + 2.35^2 + 2.0^2$
$= 8.123 + 9.923 + 8.123 + 8.703 + 7.29 + 7.563 + 5.523 + 4.0$
$= 59.245$

(d) Dividing the sum of squares of the totals of each column by the number of individual observations, n = 5, we get $\frac{59.245}{5} = 11.849$ = 11.85

To test whether the treatment means differ significantly, we proceed as follows:

(e) Sum of squares for total = (b) - (a) = 11.87 - 11.66 = 0.21

(f) Between-treatments sum of squares = (d) - (a) = 11.85 - 11.66 = 0.19

(g) Within-treatments sum of squares = (b) - (f) = 11.87 - 0.19 = 11.68

Analysis of Variance Table for Treatment Means

SV	SS	df	MS	F-ratio (Observed)	F-ratio (F-table)	Significance at α = 5%
Between Treatments	0.19	t-1 = 7	0.027	0.074	2.31	n.s
Within Treatments	11.68	t(n-1)=32	0.365			
Total	11.87	39				

N.B. n. s = not significant at 95% probability level.

The Main Effects, P, Q and R

To compare P_1 and P_2, we sum the calipers as follows:

for P_1 = 2.85 + 3.15 + 2.85 + 2.95 = 11.80 mm

for P_2 = 2.70 + 2.75 + 2.35 + 2.00 = 9.80 mm

For each of these, the sum is based upon 5x4 = 20 measurements

∴ Sum of squares for P = $\frac{(11.80)^2}{20} + \frac{(9.80)^2}{20} - C = \frac{139.24 - 96.04}{20} - 11.66$

= 11.76 - 11.66 = 0.10

Similarly, to compare Q_1 and Q_2, we sum the calipers as follows:

for Q_1 = 2.85 + 3.15 + 2.70 + 2.75 = 11.45 mm

for Q_2 = 2.85 + 2.95 + 2.35 + 2.00 = 10.15 mm

$$\therefore \text{Sum of squares for } Q = \frac{(11.45)^2}{20} + \frac{(10.15)^2}{20} - C = \frac{131.10 - 103.02}{20} - 11.66$$

$$= 11.71 - 11.66 = 0.05$$

Likewise, to compare R_1 and R_2, we sum the calipers as follows:

for R_1: 2.85 + 2.85 + 2.70 + 2.35 = 10.75 mm

for R_2: 3.15 + 2.95 + 2.75 + 2.00 = 10.85 mm

$$\therefore \text{Sum of squares for } R = \frac{(10.75)^2}{20} + \frac{(10.85)^2}{20} - C$$

$$= \frac{115.56 + 117.72}{20} - 11.66 = 11.664 - 11.660 = 0.004$$

<u>The Interactions PxQ, PxR, QxR, PxQxR</u>

$$\text{Interaction sum of squares} = \frac{[(a+d)-(b-c)]^2}{(4)(n_1)}$$

where n_1 = 2x5 = 10 and a, b, c, d are the sums shown below

for P x Q

	Q_1	Q_2
P_1	a	b
P_2	c	d

for P x R

	R_1	R_2
P_1	a	b
P_2	c	d

for Q x R

	R_1	R_2
Q_1	a	b
Q_2	c	d

P_1Q_1 =a=2.85+3.15=6.00 P_1R_1 =a=2.85+2.85=5.70 Q_1R_1 = a=2.85+2.70 = 5.55

P_1Q_2 =b=2.85+2.95=5.80 P_1R_2 =b=3.15+2.95=6.10 Q_1R_2 = b=3.15+2.75 = 5.90

P_2Q_1 =c=2.70+2.75=5.45 P_2R_1 =c=2.70+2.35=5.05 Q_2R_1 = c=2.85+2.35 = 5.20

P_2Q_2 =d=2.35+2.00=4.35 P_2R_2 =d=2.75+2.00=4.75 Q_2R_2 = d=2.95+2.00 = 4.95

$$\therefore \text{P x Q interaction sum of squares} = \frac{[(6.0+4.35)-(5.80-5.45)]^2}{(4)(10)}$$

$$= \frac{10.35-0.35)^2}{40} = \frac{10^2}{40} = \frac{100}{40} = 2.5$$

PxR interaction sum of squares = $\frac{[(5.70+4.75)-(6.10-5.05)]^2}{(4)(10)}$

$= \frac{(10.45-1.05)^2}{40} = \frac{96.8^2}{40} = \frac{88.36}{40} = 2.21$

QxR interaction sum of squares = $\frac{[(5.55+4.95)-(5.90-5.20)]^2}{(4)(10)}$

$= \frac{(10.5-0.7)^2}{40} = \frac{9.8^2}{40} = \frac{96.04}{40} = 2.40$

PxQxR interaction sum of squares =(B/W Treatment sume of squares)

minus (Sum of the sum of squares for P,Q,R, PxQ, PxR, QxR)

= 0.19-(-9.50+0.05+0.004+2.5+2.21+2.40) = 0.19-(-2.336)
= 2.53

∴ The complete ANOVA Table for Main Effects and Interactions gives:

SV	SS	d.f	MS	F-ratio (observed)	F-ratio (F-table	Significance at α=5%
P	0.10	1	0.10	0.274	4.15	n.s
Q	0.05	1	0.05	0.137	"	n.s
R	0.004	1	0.004	0.011	"	n.s
PxQ	2.50	1	2.50	6.85	"	*
PxR	2.21	1	2.21	6.05	"	*
QxR	2.40	1	2.40	6.58	"	*
PxQxR	2.53	1	2.53	6.93	"	*
Error (Within Treatments)	11.69	32	0.365			
Total	21.474	39				

NB. * = significant at 95% probability level.
n.s = not significant at 95% probability level.

G - 2: Analysis of the Basis Weight (g/m^2) for SAMCOT 6 Hand Sheets

	Furnish Ratio							
	60/40 (P_1)				50/50 (P_2)			
	Freeness				Freeness			
	20^oSR (Q_1)		35^oSR (Q_2)		20^oSR (Q_1)		35^oSR (Q_2)	
	Additive		Additive		Additive		Additive	
	(0,0)% (R_1)	(1,4)% (R_2)	(0,0)% (R_1)	(1,4)% (R_2)	(0,0)% (R_1)	(1,4)% (R_2)	(0,0)% (R_1)	(1,4)% (R_2)
	139.5	149.6	134.5	138.7	122.9	103.7	124.5	113.2
	138.8	150.6	135.7	138.5	123.4	103.8	123.8	113.0
	138.7	149.8	135.3	139.8	122.7	104.5	123.7	112.8
$\bar{x}$	139.0	150.0	135.0	139.0	123.0	104.0	124.0	113.0
s	0.44	0.53	0.44	0.70	0.36	0.44	0.44	0.20
Σx^2	57963.4	67500.6	54675.4	57964.0	45387.3	32448.4	46128.4	38307.1
Σx	417.0	450.0	405.0	417.0	369.0	312.0	372.0	339.0

$\Sigma(\Sigma x^2) = 400374.6$

$\Sigma(\Sigma x) = 3081.$

(a) Correction factor, $C = \frac{[\Sigma(\Sigma x)]^2}{8n} = \frac{(3081.0)^2}{8x3} = \frac{9492561.0}{24} = 395523.4$

(b) Total sum of squares of all observations, $\Sigma(\Sigma x^2) = 400374.6$

(c) Sum of squares of the totals of each column = $\Sigma(\Sigma x)^2$

$= 417^2 + 450^2 + 405^2 + 417^2 + 369^2 + 312^2 + 372^2 + 339^2 = 1201113.0$

(d) Dividing the sum of squares of the totals of each column by the number of individual observations, n=3, we get $\frac{120113.0}{3} = 400371.0$

(e) Sum of squares for total = (b) - (a) = 400374 - 395523.4 = 4851.2

(f) Between-treatments sum of squares = (d) - (a)

= 400371.0 - 395523.4 = 4847.6

(g) Within-treatments sum of squares = (b) - (f) =

400374.6 - 4847.6 = 395527.0

Analysis of Variance Table for Treatment Means

SV	SS	df	MS	F-ratio (Observed)	F-ratio (F-table)	Significance at α = 5%
Between Treatments	4847.6	t-1 = 7	692.51	0.028	2.66	n.s
Within Treatments	395527.0	t(n-1)=16	24720.4			
Total	400374.6	23				

N.B. n. s = not significant at 95% probability level.

The Main Effects, P, Q and R

To compare P_1 and P_2 we have the sum of basis weights as follows:

for P_1 : 417 + 450 + 405 + 417 = 1689 g/m^2

for P_2 = 369 + 312 + 372 + 339 = 1393 g/m^2

For each of these, the sum is based upon 3x4 = 12 measurements

$\therefore$ Sum of squares for P = $\frac{(1689)^2 + (1392)^2}{12} - C = \frac{2852721+1937664}{12} - 395523.4$

$= 399198.75 - 395523.4 = 3675.35$

Similarly, to compare Q_1 with Q_2, we have the sum of basis weights as follows:

for Q_1 : 417 + 450 + 369 + 312 = 1548 g/m^2

for Q_2 : 405 + 417 + 372 + 339 = 1533 g/m^2

$\therefore$ Sum of squares for Q = $\frac{(1548)^2 + (1533)^2}{12} - C$

$= \frac{2396304 + 2350089}{12} - 395523.4 = 395532.75 - 395523.4 = 9.35$

$= 2.16 - 11.66 = - 9.50$

Likewise, to compare R_1 with R_2 we have sum of basis weights as follows:

for R_1 : 417 + 405 + 369 + 372 = 1563 g/m^2

for R_2 : 450 + 417 + 312 + 339 = 1518 g/m^2

$\therefore$ Sum of squares for R = $\frac{(1563)^2 + (1518)^2}{12} - C$

$= \frac{2442969 + 2304324}{12} - 395523.4 = 395607.75 - 395523.4 = 84.35$

The Interactions P x Q, PxR, QxR, PxQxR

Interaction sum of squares = $\frac{[(a+d)-(b-c)]^2}{(4)(n_1)}$

where n_1 = 2x3 = 6 and a, b, c, d are the sums shown below:

for P x Q

	Q_1	Q_2
P_1	a	b
P_2	c	d

for P x R

	R_1	R_2
P_1	a	b
P_2	c	d

for Q x R

	R_1	R_2
Q_1	a	b
Q_2	c	d

P_1Q_1 =a=417+450 = 867 P_1R_1 =a=417+405 =822 Q_1R_1 = a=417+369 = 786

P_1Q_2 =b=405+417 = 822 P_1R_2 =b=450+417 =867 Q_1R_2 = b=450+312 = 762

P_2Q_1 =c=369+312 = 681 P_2R_1 =c=369+372 =741 Q_2R_1 = c=405+372 = 777

P_2Q_2 =d=372+339 = 7115 P_2R_2 =d=312+339 =6515 Q_2R_2 = d=417+339 = 7565

$$\therefore \text{P x Q interaction sum of squares} = \frac{[(867+711)-(822-681)]^2}{(4)(6)}$$

$$= \frac{(1578 - 141)^2}{24} = \frac{1437^2}{24} = 86040.38$$

$$\text{PxR interaction sum of squares} = \frac{[(822+651)-(867-741)]^2}{(4)(6)}$$

$$= \frac{(1473-126)^2}{24} = \frac{134^2}{24} = 75600.38$$

$$\text{QxR interaction sum of squares} = \frac{[(786+756)-(762-777)]^2}{(4)(6)}$$

$$= \frac{[1542-(-15)]^2}{24} = \frac{1557^2}{24} = 101010.38$$

PxQxR interaction)
sum of squares) =(B/W Treatment sume of squares) -(Sum of the sum of squares for P,Q,R, PxQ, PxR and QxR)

= 4847.6-(3675.35+9.35+84.35+86040.38+75600.38+101010.38)

= 4847.6-266420.19 = -261572.59

∴ The complete ANOVA Table for Main Effects and Interactions gives:

SV	SS	d.f	MS	F-ratio (observed)	F-ratio (F-table	Significance at α=5%
P	3675.35	1	3675.35	0.149	4.49	n.s
Q	9.35	1	9.35	0.0004	"	n.s
R	84.35	1	84.35	0.003	"	n.s
PxQ	86040.38	1	86040.38	3.48	"	n.s
PxR	75699.38	1	75600.38	3.06	"	n.s
QxR	101010.38	1	101010.38	4.09	"	n.s
PxQxR	-261572.59	1	-261572.59	-10.58	"	n.s
Error (Within Treatments)	395527.0	16	24720.4			
Total	400374.6			23		

NB. n.s= not significant at 95% probability level

G - 3: Analysis of the Burst Strength (kg/cm^2) for SAMCOT 6 Hand Sheets

	Furnish Ratio								
	60/40 (P_1)				50/50 (P_2)				
	Freeness				Freeness				
	20^oSR (Q_1)		35^oSR (Q_2)		20^oSR (Q_1)		35^oSR (Q_2)		
	Additive		Additive		Additive		Additive		
	(0,0)% (R_1)	(1,4)% (R_2)	(0,0)% (R_1)	(1,4)% (R_2)	(0,0)% (R_1)	(1,4)% (R_2)	(0,0)% (R_1)	(1,4)% (R_2)	
	0.65	9.71	0.84	0.87	0.81	0.82	1.00	0.98	
	0.75	0.69	0.86	0.84	0.89	0.84	0.98	0.97	
	0.72	0.66	0.88	0.88	0.87	0.88	0.99	1.00	
	0.68	0.74	0.82	0.81	0.83	0.86	0.95	1.01	
$\bar{x}$	0.70	0.70	0.85	0.85	0.85	0.85	0.98	0.99	
s	0.04	0.03	0.03	0.03	0.04	0.03	0.02	0.02	
Σx^2	1.97	1.96	2.89	2.89	2.89	2.89	3.84	3.92	$\Sigma(\Sigma x^2) = 23.25$
Σx	2.80	2.80	3.40	3.40	3.40	3.40	3.92	3.92	$\Sigma(\Sigma x) = 27.08$

Note! Conversion factor: $1 kg/cm^2 = 0.49$ kPa

(a) Correction factor, $C = \frac{[\Sigma(\Sigma x)]^2}{8n} = \frac{(27.08)^2}{8x4} = \frac{733.33}{32} = 22.92$

(b) Total sum of squares of all observations, $\Sigma(\Sigma x^2) = 23.25$

(c) Sum of squares of the totals of each column = $\Sigma(\Sigma x)^2$

$=2.80^2 + 2.80^2 + 3.40^2 + 3.40^2 + 3.40^2 + 3.40^2 + 3.92^2 + 3.92^2$

$= 7.84 + 7.84 + 11.56 + 11.56 + 11.56 + 11.56 + 15.35 + 15.69$

(d) Dividing the sum of squares of the totals of each column by the number of individual observations, n = 4, we get $\frac{92.97}{4} = 23.24$

(e) Sum of squares for total = (b) - (a) = 23.25-22.92 = 0.33

(f) Between-treatments sum of squares = (d) - (a) = 23.24 - 22.92 = 0.32

(g) Within-treatments sum of squares = (b) - (f) = 23.25 - 0.32 = 22.93

Analysis of Variance Table for the Treatment Means

SV	SS	df	MS	F-ratio (Observed)	F-ratio (F-table) at α = 5%	Significance
Between Treatments	0.32	t-1 = 7	0.046	0.048	2.42	n. s
Within Treatments	22.93	t(n-1)=24	0.955			
Total	23.25	31				

N.B. n. s = not significant at 95% probability level.

The Main Effects, P, Q and R

To compare P_1 and P_2 we have the sum of burst strengths as follows:

for P_1 : 2.8 + 2.8 + 3.4 + 3.4 = 12.4kg/cm^2

for P_2 = 3.4 + 3.4 + 3.92 +3.96 = 14.68kg/cm^2

For each of these, the sum is based upon 4x4 = 16 measurements

∴ Sum of squares for P = $\frac{(12.4)^2 + (14.68)^2}{16} - C$

$= \frac{153.76+215.50}{16} - 22.92 = 23.08 - 22.92 = 0.16$

Similarly, to compare Q_1 with Q_2 we have the sum of burst strengths as follows:

for $Q_1 = 2.8 + 2.8 + 3.4 + 3.4 = 12.4$ kg/cm^2

for $Q_2 = 3.4 + 3.4 + 392 + 3.96 = 14.68$ kg/cm^2

∴ Sum of squares for Q = $\frac{(12.4)^2 + (14.68)^2}{16} - C$

$= 23.08 - 22.92 = 0.16$

Likewise, to compare R_1 with R_2 we have sum of burst strengths as follows:

for $R_1 = 2.8 + 3.4 + 3.4 + 3.92 = 13.52$ kg/cm^2

for $R_2 = 2.8 + 3.4 + 3.4 + 3.96 = 13.56$ kg/cm^2

∴ Sum of squares for R = $\frac{(13.52)^2 + (13.56)^2}{16} - C$

$= \frac{182.79 + 183.87}{16} - 22.92$

$= 22.92 - 22.92 = 0$

The Interactions P x Q, PxR, QxR, PxQxR

Interaction sum of squares = $\frac{[(a+d)-(b-c)]^2}{(4)(n_1)}$

where $n_1 = 2x4 = 8$ and a, b, c and d are the sums shown below:

for P x Q

	Q_1	Q_2
P_1	a	b
P_2	c	d

for P x R

	R_1	R_2
P_1	a	b
P_2	c	d

for Q x R

	R_1	R_2
Q_1	a	b
Q_2	c	d

P_1Q_1 =a=2.8+2.8=5.6 P_1R_1 =a=2.8+3.4 =6.2 Q_1R_1 = a=2.8+3.4= 6.2

P_1Q_2 =b=3.4+3.4=6.8 P_1R_2 =b=2.8+3.4 =6.2 Q_1R_2 = b=2.8+3.4= 6.2

P_2Q_1 =c=3.4+3.4=6.8 P_2R_1 =c=3.4+3.4 =7.32 Q_2R_1 = c=3.4+3.92=7.32

P_2Q_2 =d=3.92+3.96=7.88 P_2R_2 =d=3.4+3.96=7.36 Q_2R_2 = d=3.4+3.96=7.36

$$\therefore \text{P x Q interaction sum of squares} = \frac{[(5.6+7.88)-(6.6-6.8)]^2}{(4)(8)}$$

$$= \frac{(13.48-0)^2}{32} = \frac{181.71}{32} = 5.68$$

$$\text{P x R interaction sum of squares} = \frac{[(6.20+7.36)-(6.20-7.32)]^2}{(4)(8)}$$

$$= \frac{[(13.56-(-1.12)]^2}{32} = \frac{14.68^2}{32} = \frac{215.50}{32} = 6.73$$

$$\text{QxR interaction sum of squares} = \frac{[(6.20+7.36)-(6.20-7.32)]^2}{(4)(8)}$$

$$= \frac{[13.56-(-1.12)]^2}{32} = \frac{14.68^2}{32} = \frac{215.50}{32} = 6.73$$

P x Q x P interaction sum of squares = (B/W Treatment sum of squares)

-(Sum of the sums of squares for P, Q, R, PxQ, PxR and QxR)

= 0.32-(0.16+0.16+0+5.68+6.73+6.73)

= 0.32-19.46 = -19.14

∴ The complete ANOVA Table for Main Effects and Interactions gives:

SV	SS	d.f	MS	F-ratio (observed)	F-ratio (F-table	Significance at α = 5%
P	0.16	1	0.16	0.17	4.26	n.s
Q	0.16	1	0.16	0.17	"	n.s
R	0.0	1	0.0	0.0	"	*
PxQ	5.68	1	5.68	5.95	"	*
PxR	6.73	1	6.73	7.05	"	*
QxR	6.73	1	6.73	7.05	"	n.s
PxQxR	-19.14	1	-19.14	-20.04	"	n.s
Error (Within Treatments)	22.93	24	0.955			
Total	23.25	31				

NB. * = significant at 95% probability level
n.s= not significant at 95% probability level

G - 4: Analysis of the Tear Strength (kgf) of SAMCOT 6 Hand Sheets

	Furnish Ratio								
	60/40 (P_1)				50/50 (P_2)				
	Freeness				Freeness				
	20^{O}SR (Q_1)		35^{O}SR (Q_2)		20^{O}SR (Q_1)		35^{O}SR (Q_2)		
	Additive		Additive		Additive		Additive		
	(0,0)% (R_1)	(1,4)% (R_2)	(0,0)% (R_1)	(1,4)% (R_2)	(0,0)% (R_1)	(1,4)% (R_2)	(0,0)% (R_1)	(1,4)% (R_2)	
	48.50	32.5	48.30	47.90	47.95	63.60	64.10	79.95	
	47.40	31.80	47.80	48.40	48.03	64.20	64.30	80.05	
	48.50	32.10	47.70	48.30	48.02	63.80	63.90	79.70	
	47.60	31.60	48.20	47.40	48.00	64.45	63.70	80.33	
$\bar{x}$	48.0	32.0	48.0	48.0	48.0	64.0	64.0	80.0	
s	0.58	0.39	0.29	0.45	0.04	0.38	0.26	0.26	
Σx^2	9217.0	4096.5	9216.3	9216.6	9216.0	16390.8	16384.2	25605.0	$\Sigma(\Sigma x^2)$ = 99342.4
Σx	192.0	128.0	192.0	192.0	192.0	256.05	256.0	320.03	$\Sigma(\Sigma x)$ = 1728.08

Note! Conversion factor: 1 kgf = 9.81N = 0.0098kN

(a) Correction factor, $C = \frac{[\Sigma(\Sigma x)]^2}{8n} = \frac{(1726.08)^2}{8 \times 4} = \frac{2966260.49}{32} = 93320.6$

(b) Total sum of squares of all observations, $\Sigma(\Sigma x^2) = 99342.4$

(c) Sum of squares of the totals of each column = $\Sigma(\Sigma x)^2$

$= 192^2 + 128^2 + 192^2 + 192^2 + 192^2 + 256.05^2 + 256^2 + 320.03^2$

$= 36864 + 16384 + 36864 + 36864 + 36864 + 65561.6 + 65536 + 102419.2$
$= 397356.8$

(d) Dividing the sum of squares of the totals of each column by the number of individual observations, n = 4, we get $\frac{397356.8}{4} = 99339.2$

(e) Sum of squares for total = (b) - (a) = 99342.4- 93320.6 = 6021.8

(f) Between-treatments sum of squares = (d) - (a)

= 99339.2 - 93320.6 = 6018.6

(g) Within-treatments sum of squares = (b) - (f) =

99342.4 - 6018.6 = 93323.8

Analysis of Variance Table for Treatment Means

SV	SS	df	MS	F-ratio (Observed)	F-ratio (F-table)	Significance at α = 5%
Between Treatments	6018.6	t-1 = 7	859.8	0.22	2.42	n. s
Within Treatments	93323.8	t(n-1)=24	3888.5			
Total	99342.4	31				

N.B. n. s = not significant at 95% probability level.

The Main Effects, P, Q and R

To compare P_1 and P_2 we have the sum of tear strengths as follows:

for P_1 : 192 + 128 + 192 + 192 = 704.0 kgf

for P_2 = 192 + 256.05 + 256 + 320.03 = 1024.08 kgf

For each of these, the sum is based upon 4x4 = 16 measurements

:. Sum of squares for P = $\frac{(704)^2 + (1024.06)^2}{16}$ - C

= $\frac{495616.0+1048739.85}{16}$ - 93320.6 = 96522.24 - 93320.6 = 3201.6

Similarly, to compare Q_1 and Q_2 we sum the tear strengths as follows:

for Q_1 : 192 + 128 + 192 + 256.05 = 768.05 kgf

for Q_2 : 192 + 192 + 256 + 320.03 = 960.03 kgf

:. Sum of squares for Q = $\frac{(768.05)^2 + (960.03)^2}{16}$ - C

= $\frac{589900.8 + 921657.6}{16}$ - 93320.6 = 94472.4 -93320.6 = 1151.8

Likewise, to compare R_1 and R_2, we sum the tear strengths as follows:

for R_1 : 192 + 192 + 192 + 256 = 832 kgf

for R_2 : 128 + 192 + 256.05 + 320.03 = 896.08 kgf

:. Sum of squares for R = $\frac{(832)^2 + (896.08)^2}{16}$ - C

= $\frac{692224 + 802959.37}{16}$ - 93320.6 = 93448.96 - 93320.6 = 128.3

The Interactions P x Q, PxR, QxR, PxQxR

Interaction sum of squares = $\frac{[(a+d)-(b-c)]^2}{(4)(n_1)}$

where n_1 = 2x4 = 8 and a, b, c, d are the sums shown below:

for P x Q

	Q_1	Q_2
P_1	a	b
P_2	c	d

for P x R

	R_1	R_2
P_1	a	b
P_2	c	d

for Q x R

	R_1	R_2
Q_1	a	b
Q_2	c	d

P_1Q_1 =a=192+128 = 320 P_1R_1 =a=192+192 =384 Q_1R_1 = a=192+192 = 384

P_1Q_2 =b=192+192 = 384 P_1R_2 =b=192+256 =448 Q_1R_2 = b=128+256.05 =384.05

P_2Q_1 =c=192+256.05=448.05 P_2R_1 =c=192+256 =448 Q_2R_1 = c=192+256 = 448

P_2Q_2 =d=256+320.03=576.03 P_2R_2 =d=256.05+320.03 =576.08 Q_2R_2 = d=192+320 = 512.03

∴ P x Q interaction sum of squares

$$= \frac{[(320+576)-(382-446.05)]^2}{(4)(8)} = \frac{(896.03 - (-64.05)^2}{32}$$

$$= \frac{(960.80^2}{32} = \frac{921753.6}{32} = 28804.8$$

PxR interaction sum of squares = $\frac{[(384+576.06)-(320-448)]^2}{(4)(8)}$

$$= \frac{(960.08)-(-128)^2}{32} = \frac{(1088.08)^2}{32} = \frac{1183918.09}{32} = 36997.44$$

QxR interaction sum of squares = $\frac{[(384+572.03)-(384.05-446)]^2}{(4)(8)}$

$$= \frac{[(896.03)-(-63.95)]^2}{32} = \frac{(959.98)^2}{32} = \frac{921561.6}{32} = 28798.8$$

PxQxR interaction sum of squares =(B/W Treatment sume of squares) minus (Sum of the sum of squares for P,Q,R, PxQ, PxR and QxR)

$$= 6018.6-(3201.64+1151.8+128.36+28804.8+36997+28798.8)$$

$$= 6018.6-99082.84 = -93064.24$$

∴ The complete ANOVA Table for Main Effects and Interactions gives:

SV	SS	d.f	MS	F-ratio (observed)	F-ratio (F-table)	Significance at α = 5%
P	3201.64	1	3201.64	0.823	4.26	n.s
Q	1157.80	1	1157.80	0.296	"	n.s
R	128.36	1	128.36	0.033	"	n.s
PxQ	28804.8	1	28804.8	7.41	"	*
PxR	36997.44	1	36997.44	9.51	"	*
QxR	28798.8	1	28798.8	7.41	"	*
PxQxR	-93064.24	1	-93064.24	-23.93	"	n.s
Error (Within Treatments)	93323.8	24	3888.50			
Total	99442.49	31				

NB. * = significant at 95% probability level
n.s = not significant at 95% probability level

3 - 5: Analysis of the Caliper (mm) for SAMCOT 8 Hand Sheets

	Furnish Ratio							
	60/40 (P_1)				50/50 (P_2)			
	Freeness				Freeness			
	20^{O}SR (Q_1)		35^{O}SR (Q_2)		20^{O}SR (Q_1)		35^{O}SR (Q_2)	
	Additive		Additive		Additive		Additive	
	(0,0)% (R_1)	(1,4)% (R_2)	(0,0)% (R_1)	(1,4)% (R_2)	(0,0)% (R_1)	(1,4)% (P_2)	(0,0)% (R_1)	(1,4)% (R_2)
	0.63	0.55	0.60	0.49	0.53	0.52	0.45	0.52
	0.58	0.59	0.60	0.51	0.55	0.54	0.47	0.51
	0.62	0.60	0.59	0.53	0.57	0.53	0.46	0.54
	0.62	0.55	0.61	0.50	0.56	0.55	0.48	0.53
	0.60	0.56	0.58	0.52	0.54	0.56	0.44	0.50
$\bar{x}$	0.61	0.57	0.60	0.51	0.55	0.54	0.46	0.52
s	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Σx^2	1.86	1.63	1.80	1.30	1.51	1.46	1.06	1.35
Σx	3.05	2.85	3.00	2.55	2.75	2.70	2.30	2.60

$\Sigma(\Sigma x^2) = 11.97$

$\underline{\Sigma(\Sigma x)} = 21.80$

(a) Correction factor, $C = \frac{[\Sigma(\Sigma x)]^2}{8n} = \frac{(21.80)^2}{8 \times 5} = \frac{475.24}{40} = 11.88$

(b) Total sum of squares of all observations, $\Sigma(\Sigma x^2) = 11.97$

(c) Sum of squares of the totals of each column = $\Sigma(\Sigma x)^2$

$= 3.05^2 + 2.85^2 + 3.00^2 + 2.55^2 + 2.75^2 + 2.70^2 + 2.30^2 + 2.60^2$

$= 9.30 + 8.12 + 9.00 + 6.50 + 7.56 + 7.29 + 5.29 + 6.76$
$= 59.82$

(d) Dividing the sum of squares of the totals of each column by the number of individual observations, n = 5, we get $\frac{59.82}{5} = 11.96$

(e) Sum of squares for total = (b) - (a) = 11.97- 11.88 = 0.09

(f) Between-treatments sum of squares = (d) - (a) 11.96 - 11.88 = 0.08

(g) Within-treatments sum of squares = (b) - (f) = 11.97 - 0.08 = 11.89

Analysis of Variance Table for Treatment Means

SV	SS	df	MS	F-ratio (Observed)	F-ratio (F-table)	Significance at α = 5%
Between Treatments	0.08	t-1 = 7	0.01	0.03	2.31	n. s
Within Treatments	11.89	t(n-1)=32	0.37			
Total	11.97	39				

N.B. n. s = not significant at 95% probability level

The Main Effects, P, Q and R

To compare P_1 and P_2 we have the sum of Calipers as follows:

for P_1 : 3.05 + 2.85 + 3.00 + 2.55 = 11.45 mm

for P_2 = 2.75 + 2.70 + 2.30 + 2.60 = 10.35 mm

For each of these, the sum is based upon 4x5 = 20 measurements

∴ Sum of squares for P = $\frac{(11.45)^2 + (10.35)^2}{20} - C$

$= \frac{131.10 + 107.12}{20} - 11.88 = 11.91 - 11.88 = 0.03$

Similarly, to compare Q_1 and Q_2 we have the sum of Calipers as follows:

for Q_1 : 3.05 + 2.85 + 2.75 + 2.70 = 11.35 mm

for Q_2 : 3.00 + 2.55 + 2.30 + 2.60 = 10.45 mm

∴ Sum of squares for Q = $\frac{(11.35)^2 + (10.45)^2}{20} - C$

$= \frac{128.82 + 109.20}{20} - 11.88 = 11.90 - 11.88$

Likewise, to compare R_1 and R_2, we sum the Caliper as follows

for R_1 : 3.05 + 3.00 + 2.75 + 2.30 = 11.10 mm

for R_2 : 2.85 + 2.55 + 2.70 + 2.60 = 10.70 mm

∴ Sum of squares for R = $\frac{(11.10)^2 + (10.70)^2}{20} - C$

$= \frac{123.21 + 114.49}{20} - 11.88 = 12.39 - 11.88 = 0.51$

The Interactions P x Q, PxR, QxR, PxQxR

Interaction sum of squares = $\frac{[(a+d)-(b-c)]^2}{(4)(n_1)}$

where n_1 = 2x5 = 10 and a, b, c, d are the sums shown below:

for P x Q

	Q_1	Q_2
P_1	a	b
P_2	c	d

for P x R

	R_1	R_2
P_1	a	b
P_2	c	d

for Q x R

	R_1	R_2
Q_1	a	b
Q_2	c	d

P_1Q_1 =a=3.05+2.85=5.90 P_1R_1 =a=3.05+3.00 =6.05 Q_1R_1=a=3.05+2.75 = 5.80

P_1Q_2 =b=3.00+2.55=5.55 P_1R_2 =b=2.85+2.55 =4.40 Q_1R_2=b=2.85+2.70 = 5.55

P_2Q_1 =c=2.75+2.70=4.45 P_2R_1 =c=2.75+2.30 =5.05 Q_2R_1=c=3.00+2.30 =5.30

P_2Q_2 =d=2.30+2.60=4.90 P_2R_2 =d=2.70+2.60.=5.30 Q_2R_2=d=2.55+2.60 =5.15

∴ P x Q interaction sum of squares = $\frac{[(5.90+4.90)-(5.55-5.45)]^2}{(4)(10)}$

$= \frac{(10.80-0.10^2}{40} = \frac{10.70^2}{40} = \frac{114.49}{40} = 2.86$

PxR interaction sum of squares = $\frac{[(6.05+5.30)-(5.40-5.05)]^2}{(4)(10)}$

$= \frac{(11.35-0.35)^2}{40} = \frac{11.0^2}{40} = \frac{121}{40} = 3.03$

QxR interaction sum of squares = $\frac{[(5.80+5.15)-(5.55-5.30)]^2}{(4)(10)}$

$= \frac{(10.95-0.25)^2}{40} = \frac{10.75^2}{40} = \frac{115.56}{40} = 2.89$

PxQxR interaction sum of squares =(B/W Treatment sum of squares) minus (Sum of the sum of squares for P,Q,R, PxQ, PxR and QxR)

= 0.08-(0.03+0.02+0.57+2.86+3.03+2.89)

= 0.08-9.34 = -9.26

∴ The complete ANOVA Table for Main Effects and Interactions gives:

SV	SS	d.f	MS	F-ratio (observed)	F-ratio (F-table)	Significance at α=5%
P	0.03	1	0.03	0.081	4.15	n.s
Q	0.02	1	0.02	0.054	"	n.s
R	0.516	1	0.51	1.38	"	n.s
PxQ	2.86	1	2.86	7.73	"	*
PxP	3.03	1	3.03	8.191	"	*
QxR	2.89	1	2.89	7.811	"	*
PxQxR	-9.264	1	-9.26	-25.03	"	n.s
Error (Within Treatments)	11.89	32	0.37			
Total	11.97	39				

NB. * = significant at 95% probability level
n.s = not significant at 95% probability level

G - 6: Analysis of the Basis Weight(g/m^2) for SAMCOT 8 Hand Sheets

	Furnish Ratio								
	60/40 (P_1)				50/50 (P_2)				
	Freeness				Freeness				
	20^oSR (Q_1)		35^oSR (Q_2)		20^oSR (Q_1)		35^oSR (Q_2)		
	Additive		Additive		Additive		Additive		
	(0,0%) (R_1)	(1,4)% (R_2)	(0,0)% (R_1)	(1,4)% (R_2)	(0,0)% (R_1)	(1,4)% (R_2)	(0,0)% (R_1)	(1,4)% (R_2)	
	112.5	126.8	117.0	135.5	122.0	126.8	146.9	139.5	
	111.8	127.3	116.7	136.0	122.3	126.9	146.9	138.8	
	111.7	126.9	117.3	136.5	121.7	127.3	147.2	138.7	
$\bar{x}$	112.0	127.0	117.0	136.0	122.0	127.0	147.0	139.0	
s	0.44	0.26	0.30	0.50	0.30	0.26	0.17	0.44	
Σx^2	37632.4	48387.1	41067.2	55488.5	44652.2	48387.1	64827.1	57963.3	$\Sigma(\Sigma x^2)$ =398405.0
Σx	336.0	2.85	351.0	408.0	366.0	381.0	441.0	417.0	$\Sigma(\Sigma x)$ = 3081.0

(a) Correction factor, $C = \frac{[\Sigma(\Sigma x)]^2}{8n} = \frac{(3081.0)^2}{8 \times 3} = \frac{949256.0}{24} = 395523.4$

(b) Total sum of squares of all observations, $\Sigma(\Sigma x^2) = 398405.0$

(c) Sum of squares of the totals of each column = $\Sigma(\Sigma x)^2$

$= 336^2 + 381^2 + 351^2 + 408^2 + 366^2 + 381^2 + 441^2 + 417^2$

$= 112896 + 145161 + 123201 + 166464 + 133956 + 145161 +$

$+ 194481 + 173889 = 1195209.0$

(d) Dividing the sum of squares of the totals of each column by the number of individual observations, n = 3, we get

$\frac{1195209.0}{3} = 398403.0$

(e) Sum of squares for total = (b) - (a) = 398405-395523.4
= 2881.6

(f) Between-treatments sum of squares = (d) - (a)

= 398403.0 - 395523.4 = 2879.6

(g) Within-treatments sum of squares = (b) - (f)
= 398405.0 - 2879.6 = 395525.4

ANOVA Table for Treatment Means

SV	SS	df	MS	F-ratio (Observed)	F-ratio (F-table)	Significance at α = 5%
Between Treatments	2879.6	t-1 = 7	411.37	0.017	2.66	n. s
Within Treatments	395525.4	t(n-1)=16	24720.34			
Total	398405.0	23				

N.B. n. s = not significant at 95% probability level.

The Main Effects, P, Q and R

To compare P_1 and P_2 we have the sum of Basis weights as follows:

for P_1 : 336 + 381 + 357 + 408 = 1476.0 g/m^2

for P_2 = 366 + 381 + 441 + 417 = 1605 g/m^2

For each of these, the sum is based upon 4x3 = 12 measurements

∴ Sum of squares for P = $\frac{(1476)^2 + (1605)^2}{12}$ - C

= $\frac{(2178576 + 2576025)}{12}$ - 395523.4

= 396216.75 - 395523.4 = 693.35

Similarly, to compare Q_1 and Q_2 we sum the basis weights as follows:

for Q_1 : 336 + 381 + 366 + 381 = 1464 g/m^2

for Q_2 : 351 + 408 + 441 + 417 = 1617 g/m^2

∴ Sum of squares for Q = $\frac{(1464)^2 + (1617)^2}{12}$ - C

= $\frac{2143296 + 2614689}{12}$ - 395523.4

= 396498.75 - 395523.4 = 975.35

Likewise, to compare R_1 and R_2, we sum the basis weights as follows

for R_1 : 336 + 351 + 366 + 441 = 1494 g/m^2

for R_2 : 381 + 408 + 381 + 417 = 1587 g/m^2

∴ Sum of squares for R = $\frac{(1494)^2 + (1587)^2}{12}$ - C

$\frac{2232036 + 2518569}{12}$ - 395523.4 = 395883.75 - 395523.4 = 360.35

The Interactions P x Q, PxR, QxR, PxQxR

Interaction sum of squares = $\frac{[(a+d)-(b-c)]^2}{(4)(n_1)}$

where n_1 = 2x3 = 6 and a, b, c, d are the sums shown below:

for P x Q

	Q_1	Q_2
P_1	a	b
P_2	c	d

P_1Q_1 =a=336+381 = 717

P_1Q_2 =b=351+408 = 759

P_2Q_1 =c=366+381 = 747

P_2Q_2 =d=441+417 = 858

for P x R

	R_1	R_2
P_1	a	b
P_2	c	d

P_1R_1 =a=336+351 =687

P_1R_2 =b=381+408 =789

P_2R_1 =c=366+441 =807

P_2R_2 =d=381+417.=798

for Q x R

	R_1	R_2
Q_1	a	b
Q_2	c	d

Q_1R_1 = a=336+366 = 702

Q_1R_2 = b=381+381 = 762

Q_2R_1 = c=351+441 = 792

Q_2R_2 = d=408+417 = 825

∴ P x Q interaction sum of squares $= \frac{[(717+856)-(759-747)]^2}{(4)(6)}$

$= \frac{(1575-12)^2}{24} = \frac{1563^2}{24} = \frac{2442969}{24} = 101790.38$

PxR interaction sum of squares $= \frac{[(687+798)-(789-807)]^2}{(4)(6)}$

$= \frac{(1485)-(-18)^2}{24} = \frac{1503^2}{24} = \frac{2259009}{24} = 94125.38$

QxR interaction sum of squares $= \frac{[(702+825)-(762-792)]^2}{(4)(6)}$

$= \frac{[(1527)-(-30)]^2}{24} = \frac{1557^2}{24} = \frac{2424249}{24} = 101010.38$

PxQxR interaction sum of squares =(B/W Treatment sum of squares) minus (Sum of the sum of squares for P,Q,R, PxQ, PxR and QxR)

$= 2879.6 - (693.35 + 975.35 + 360.35 + 101790.38 + 94125.38 + 101010.38)$
$= 2879.6 - 298955.19 = -296075.6$

∴ The complete ANOVA Table for Main Effects and Interactions gives:

SV	SS	d.f	MS	F-ratio (observed)	F-ratio (F-table	Significance at α=5%
P	693.35	1	693.35	0.028	4.49	n.s
Q	975.35	1	975.35	0.039	"	n.s
R	360.35	1	360.35	0.015	"	n.s
PxQ	101790.38	1	101790.38	4.12	"	n.s
PxR	94125.38	1	94125.38	3.81	"	n.s
QxR	101010.38	1	101010.38	4.09	"	n.s
PxQxR	-296075.6	1	-296075.6	-11.98	"	n.s
Error (Within Treatments)	395525.4	16	24720.34			
Total	398405.0	23				

NB. n.s = not significant at 95% probability level.

G-7: Analysis of the Burst Strenth (kg/cm^2) for SAMCOT 8 Hand Sheets

Furnish Ratio								
60/40 (P_1)				50/50 (P_2)				
Freeness				Freeness				
20^oSR (Q_1)		35^oSR (Q_2)		20^oSR (Q_1)		35^oSR (Q_2)		
Additive		Additive		Additive		Additive		
(0,0%) (R_1)	(1,4)% (R_2)	(0,0)% (R_1)	(1,4)% (R_2)	(0,0)% (R_1)	(1,4)% (R_2)	(0,0)% (R_1)	(1,4)% (R_2)	
0.67	0.69	0.90	0.82	0.91	0.90	0.97	1.03	
0.72	0.71	0.94	0.88	0.85	0.87	1.01	1.02	
0.68	0.72	0.89	0.87	0.86	0.90	0.98	0.99	
0.73	0.68	0.95	0.83	0.90	0.85	1.00	1.04	
$\bar{x}$ 0.70	0.70	0.92	0.85	0.88	0.88	0.99	1.02	
s 0.03	0.02	0.03	0.03	0.03	0.02	0.02	0.02	
Σx^2 1.96	1.96	3.39	2.69	3.10	3.10	3.92	4.16	$\underline{\Sigma(\Sigma x^2)}$=24.48
Σx 2.8	2.8	3.68	3.40	3.52	3.52	3.96	4.08	$\underline{\Sigma(\Sigma x)}$ =27.76

Note! Conversion factor: $1kg/cm^2$ = 0.49 kPa.

(a) Correction factor, $C = \frac{[\Sigma(\Sigma x)]^2}{8n} = \frac{(27.76)^2}{8 \times 4} = \frac{770.62}{32} = 24.08$

(b) Total sum of squares of all observations, $\Sigma(\Sigma x^2) = 24.48$

(c) Sum of squares of the totals of each column = $\Sigma(\Sigma x)^2$

$= 2.8^2 + 2.8^2 + 3.68^2 + 3.4^2 + 3.52^2 + 3.52^2 + 3.96^2 + 4.08^2$

$= 7.84 + 7.84 + 13.54 + 11.56 + 12.39 + 12.39 + 15.68 + 16.65$
$= 97.89$

(d) Dividing the sum of squares of the totals of each column by the number of individual observations, n = 4, we get $\frac{97.89}{4} = 24.47$

(e) Sum of squares for total = (b) - (a) = 24.48-24.08 = 0.40

(f) Between-treatments sum of squares = (d) - (a) = 24.47-24.08 = 0.39

(g) Within-treatments sum of squares = (b) - (f) = 24.48-0.39 = 24.09

ANOVA Table for Treatment Means

SV	SS	df	MS	F-ratio (Observed)	F-ratio (F-table)	Significance at α = 5%
Between Treatments	0.39	t-1 = 7	0.056	0.056	2.42	n. s
Within Treatments	24.09	t(n-1)=24	1.004			
Total	24.48	31				

N.B. n. s = not significant at 95% probability level.

The Main Effects, P, Q and R

To compare P_1 and P_2 we have the sum of burst strengths as follows:

for P_1 : 2.8 + 2.8 + 3.68 + 3.40 = 12.68 kg/cm^2

for P_2 = 3.52 + 3.52 + 3.96 + 4.08 = 15.08 kg/cm^2

For each of these, the sum is based upon 4x4 = 16 measurements

∴ Sum of squares for P = $\frac{(12.66)^2 + (15.08)^2}{16} - C$

$= \frac{(160.78 + 227.41)}{16} - 24.08 = 24.26 - 24.08 = 0.18$

Similarly, to compare Q_1 and Q_2 we sum the burst strengths as follows·

for Q_1 : 2.8 + 2.8 + 3.52 + 3.52 = 12.64 kg/cm^2

for Q_2 : 3.68 + 3.40 + 3.96 + 4.08 = 15.12 kg/cm^2

∴ Sum of squares for Q = $\frac{(12.64)^2 + (15.12)^2}{16} - C$

$= \frac{159.77 + 228.61}{16} - 24.27 - 24.08 = 0.19$

Likewise, to compare R_1 and R_2, we sum the burst strengths as follows

for R_1 : 2.8 + 3.68 + 3.52 + 3.96 = 13.96 kg/cm^2

for R_2 : 2.8 + 3.40 + 3.52 + 4.08 = 13.80 kg/cm^2

∴ Sum of squares for R = $\frac{(13.96)^2 + (13.80)^2}{16} - C$

$= \frac{194.88 + 190.44}{16} - 24.08 = 24.083 - 24.08 = 0.003$

The Interactions P x Q, PxR, QxR, PxQxR

Interaction sum of squares = $\frac{[(a+d)-(b-c)]^2}{(4)(n_1)}$

where n_1 = 2x4 = 8 and a, b, c, d are the sums shown below:

for P x Q

	Q_1	Q_2
P_1	a	b
P_2	c	d

for P x R

	R_1	R_2
P_1	a	b
P_2	c	d

for Q x R

	R_1	R_2
Q_1	a	b
Q_2	c	d

P_1Q_1 =a=2.8+2.8 = 5.60 P_1R_1 =a=2.8+3.68 =6.48 Q_1R_1 = a=2.8+3.52 = 6.32

P_1Q_2 =b=3.68+4.40=7.08 P_1R_2 =b=2.8+3.40 =6.20 Q_1R_2 = b=2.8+352 = 6.32

P_2Q_1 =c=3.52+3.52=7.04 P_2R_1 =c=3.52+3.96 =7.48 Q_2R_1 = c=3.68+3.96=7.64

P_2Q_2 =d=3.96+4.08=8.04 P_2R_2 =d=3.52+4.08 =7.60 Q_2R_2 = d=3.40+4.08=7.48

∴ P x Q interaction sum of squares = $\frac{[(5.60+8.04)-(7.06-7.04)]^2}{(4)(8)}$

$= \frac{[(13.64)-(0.04)]^2}{32} = \frac{13.60^2}{32} = \frac{184.96}{32} = 5.78$

PxR Interaction sum of squares = $\frac{[(6.48+7.60)-(6.20-7.48)]^2}{(4)(8)}$

$= \frac{(14.08)-(-1.20)^2}{32} = \frac{15.36^2}{32} = \frac{235.93}{32} = 7.37$

QxR Interaction sum of squares = $\frac{[(6.32+7.48)-(6.32-7.64)]^2}{(4)(8)}$

$= \frac{[(13.80)-(-1.32)]^2}{32} = \frac{15.12^2}{32} = \frac{228.61}{32} = 7.14$

PxQxR Interaction sum of squares =(B/W Treatment sum of squares)

- (Sum of the sum of squares for P,Q,R, PxQ, PxR and QxR)

= 0.39 -(0.19 + 0.19 + 0.003 + 5.78 + 7.37 + 7.14)

= 0.39 -20.66 = -20.27

= 29976.6 - 29995.19 = -29460.6

The complete ANOVA Table for Main Effects and Interactions gives:

	SS	d.f	MS	F-ratio (observed)	F-ratio (F-table at α=5%	Significance
P	0.19	1	0.19	0.19	4.26	n.s
Q	0.195	1	0.19	0.19	"	n.s
R	0.003	1	0.003	0.003	"	n.s
PxQ	5.78	1	5.78	5.79	"	*
PxR	7.370	1	7.37	7.37	"	*
QxR	7.14	1	7.14	7.14	"	*
PxQxR	-20.27	1	-20.27	-20.27	"	n.s
Error (Within Treatments)	24.09	24	1.004			
Total	24.48	31				

NB * = significant at 95% probability level
n.s = not significant at 95% probability level

G - 8: Analysis of the Tear Strenth (Kgf) for SAMCOT 8 Hand Sheets

Furnish Ratio								
60/40 (P_1)				50/50 (P_2)				
Freeness				Freeness				
20^{O}_{SR} (Q_1)		35^{O}_{SR} (Q_2)		20^{O}_{SR} (Q_1)		35^{O}_{SR} (Q_2)		
Additive		Additive		Additive		Additive		
(0,0)% (R_1)	(1,4)% (R_2)	(0,0)% (R_1)	(1,4)% (R_2)	(0,0)% (R_1)	(1,4)% (R_2)	(0,0)% (R_1)	(1,4)% (R_2)	
96.0	80.2	127.4	144.6	111.9	127.8	143.5	159.8	
96.5	79.8	127.7	143.4	112.3	128.2	144.6	160.2	
95.6	80.6	128.6	145.8	112.2	128.3	143.6	160.5	
95.9	79.4	128.3	144.2	111.6	127.7	144.3	159.5	
$\bar{x}$ 96.0	80.0	128.0	144.0	112.0	128.0	144.0	160.0	
s 0.37	0.52	0.55	0.52	0.32	0.29	0.54	0.44	$\Sigma(\Sigma x^2) = 24.48$
Σx^2 36864.4	25600.96	65536.9	82944.8	50176.5	65536.3	82944.9	102400.6	$\Sigma[\Sigma x] = 27.76$
Σx 384.0	320.0	512.0	576.0	448.0	512.0	576.0	640.0	

b. Correction factor, $C = \frac{[\Sigma(\Sigma x)]^2}{8n} = \frac{(3968)^2}{8 \times 4} = \frac{1745024}{32} = 492032$

c. Total sum of squares of all observations, $\Sigma(\Sigma x^2) = 572005.0$

d. Sum of squares of the totals of each column = $\Sigma(\Sigma x)^2$

$= 964^2 + 920^2 + 810^2 + 976^2 + 448^2 + 810^2 + 976^2 + 640^2$

$= 929L + 102400 + 262144 + 331776 + 200704 + 262144$

$+ 672144 + 331776 + 409600 = 2048000$

e. Dividing the sum of squares of the totals of each column by the number of individual observations, n = 4, we get

$\frac{2048000}{4} = 512000$

f. Sum of squares due total = (b) - (a) = 512000-492032 = 19968

g. Between-treatments sum of squares = (e) - (a)

$= 512000 - 492032 = 19968$

h. Within-treatments sum of squares = (c) - (e) = 572005-512000 = 60005

Table for Treatment Means

Source	DF	MS	F-ratio (Observed)	F-ratio (F-table) at α = 5%	Significance
Between Treatments	(TDF) = n - 1 = 7	2852.57	0.140	1.41	n.s
Within Treatments	TDF(n-1) = 8(4-1)=24	20500.54			
Total	TDF(n) = 31				

n.s. = not significant at 95% probability level

The Main Effects, P_1 & P_2 and P

To compare P_1 and P_2 we have the sum of tear strengths as follows:

for P_1 : 964 + 920 + 812 + 976 = 1792 kgf

for P_2 = 448 + 512 + 576 + 640 = 2176 kgf

For each of these, the sum is based upon 4x4 = 16 measurements

Sum of squares for P = $\frac{(1792)^2 + (2176)^2}{16} - C$

$= \frac{3211264 + 4734976}{16} - 492032 = 496640 - 492032 = 4608$

Similarly, to compare Q_1 and Q_2 we sum the tear strengths as follows:

for Q_1 = 384 + 320 + 448 + 512 = 1664 kgf

for Q_2 = 512 + 576 + 576 + 640 = 2304 kgf

Sum of squares for Q = $\frac{(1664)^2 + (2304)^2}{16} - C$

$= \frac{2768896 + 5308416}{16} - 492032 = 504832 - 492032 = 12800$

Similarly, to compare R_1 and R_2, we sum the tear strengths as follows:

for R_1 = 384 + 512 + 448 + 576 = 1920 kgf

for R_2 = 320 + 576 + 512 + 640 = 2048 kgf

Sum of squares for R = $\frac{(1920)^2 + (2048)^2}{16} - C$

$= \frac{3686400 + 4194304}{16} - 492032$

$= 492544 - 492032 = 512$

The interactions P x Q, PxR, QxR, PxQxR

Interaction sum of squares = $\frac{[(a+d)-(b-c)]^2}{(4)(n_1)}$

where n_1 = 2x4 = 8 and a, b, c, d are the sums shown below:

for P x Q

	Q_1	Q_2
P_1	a	b
P_2	c	d

for P x R

	R_1	R_2
P_1	a	b
P_2	c	d

for Q x R

	R_1	R_2
Q_1	a	b
Q_2	c	d

P_1Q_1 = a = 384+320 = 704 P_1R_1 = a = 384+512 = 896 Q_1R_1 = a = 384+448 = 832

P_1Q_2 = b = 512+576 = 1088 P_1R_2 = b = 320+576 = 6.20 Q_1R_2 = b = 320+572 = 832

P_2Q_1 = c = 448+512 = 960 P_2R_1 = c = 448+576 = 1024 Q_2R_1 = c = 512+576 = 1088

P_2Q_2 = d = 576+640 = 1216 P_2R_2 = d = 512+640 = 1152 Q_2R_2 = d = 576+640 = 1216

∴ P x Q interaction sum of squares $= \frac{[(704+1216)-(1086-960)]^2}{(4)(8)}$

$= \frac{[(1920-(128)]^2}{32} = \frac{1792^2}{32} = \frac{321164}{32} = 100352$

∴ PxR interaction sum of squares $= \frac{[(896+1152)-(896-1024)]^2}{(4)(8)}$

$= \frac{(2048)-(-128)^2}{32} = \frac{2176^2}{32} = \frac{4734976}{32} = 147968$

∴ QxR interaction sum of squares $= \frac{[(832+1216)-(832-1088)]^2}{(4)(8)}$

$= \frac{[(2048)-(-256)]^2}{32} = \frac{2304^2}{32} = \frac{5308416}{32} = 165888$

∴ PxQxR interaction sum of squares =(B/W Treatment sum of squares)

- (Sum of the sum of squares for P,Q,R, PxQ, PxR and QxR)

= 19968.0 -(4608 + 12800 + 512 + 100352 + 147968 + 165888)

= 19968.0 -432128 = -412160.0

∴ The complete ANOVA Table for Main Effects and Interactions gives:

SV	SS	d.f	MS	F-ratio (observed)	F-ratio (F-table	Significance at α=5%
P	4608	1	4608	0.22	4.26	n.s
Q	12800	1	12800	0.62	"	n.s
R	512	1	512	0.02	"	n.s
PxQ	100352	1	100352	4.89	"	*
PxR	147968	1	147968	7.22	"	*
QxR	165888	1	165888	8.09	"	*
PxQxR	412160	1	-412160	-20.10	"	nil
Error (Within Treatments)	492037	24	20501.54			
Total	512005	31				

NB. * = significant at 95% probability level
n.s = not significant at 95% probability level

G-9: Analysis of the Caliper (mm) for SAMCOT 9 Hand Sheets

Furnish Ratio								
60/40 (P_1)				50/50 (P_2)				
Freeness				Freeness				
20^{o}SR (Q_1)		35^{o}SR (Q_2)		20^{o}SR (Q_1)		35^{o}SR (Q_2)		
Additive		Additive		Additive		Additive		
(0,0)% (R_1)	(1,4)% (R_2)	(0,0)% (R_1)	(1,4)% (R_2)	(0,0)% (R_1)	(1,4)% (R_2)	(0,0)% (R_1)	(1,4)% (R_2)	
0.55	0.51	0.50	0.46	0.58	0.50	0.53	0.57	
0.57	0.49	0.48	0.50	0.54	0.56	0.50	0.56	
0.53	0.52	0.47	0.49	0.56	0.53	0.51	0.59	
0.56	0.53	0.49	0.48	0.57	0.52	0.49	0.55	
0.54	0.50	0.46	0.47	0.55	0.54	0.52	0.59	
$\bar{x}$ 0.55	0.51	0.48	0.48	0.56	0.53	0.51	0.57	
S 0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	
Σx^2 1.51	1.30	1.15	1.15	1.57	1.41	1.30	1.64	$\Sigma(\Sigma x^2)=24.48$
Σx 2.75	2.55	2.40	2.40	2.80	2.65	2.55	2.86	$\Sigma(\Sigma x) = 27.76$

(a) Correction factor, $C = \frac{[\Sigma(\Sigma x)]^2}{8n} = \frac{20.96^2}{8 \times 5} = \frac{439.32}{40} = 10.98$

(b) Total sum of squares of all observations, $\Sigma(\Sigma x^2) = 11.03$

(c) Sum of squares of the totals of each column = $\Sigma(\Sigma x)^2$

$= 2.75^2 + 2.55^2 + 2.40^2 + 2.40^2 + 2.80^2 + 2.65^2 + 2.55^2 + 2.86^2$

$= 7.56 + 6.50 + 5.76 + 5.76 + 7.84 + 7.02 + 6.50 + 8.18 = 55.12$

(d) Dividing the sum of squares of the totals of each column by the number of individual observations, n = 5, we get $\frac{55.12}{5} = 11.04$

(e) Sum of squares for total = (b) - (a) = 11.03-10.98 = 0.05

(f) Between-treatments sum of squares = (d) - (a)

= 11.024 - 10.98 = 0.044

(g) Within-treatments sum of squares = (b) - (f) = 11.03-0.044 = 10.986

ANOVA Table for Treatment Means

SS	SS	df	MS	F-ratio (Observed)	F-ratio (F-table)	Significance at α = 5%
Between Treatments	0.044	t-1 = 7	0.006	0.018	2.31	n. s
Within Treatments	10.986	t(n-1)=32	0.343			
Total	11.03	39				

N.B. n. s = not significant at 95% probability level.

The Main Effects, P, Q and R

To compare P_1 and P_2 we have the sum of Calipers as follows:

for P_1 : 2.75 + 2.55 + 2.40 + 2.40 = 10.10 mm

for P_2 = 2.80 + 2.65 + 2.55 + 2.86 = 10.86 mm

For each of these, the sum is based upon 4x5 = 20 measurements

∴ Sum of squares for P = $\frac{(10.10)^2 + (10.86)^2}{20} - C$

$= \frac{102.01 + 117.94}{16} - 10.98 = 10.998-10.98 = 0.018$

Similarly, to compare Q_1 and Q_2 we sum the Calipers as follows:

for Q_1 : 2.75 + 2.55 + 2.80 + 2.65 = 10.75 mm

for Q_2 : 2.80 + 2.65 + 2.55 + 2.86 = 10.21 mm

∴ Sum of squares for Q = $\frac{(10.75)^2 + (10.21)^2}{20} - C$

$= \frac{115.56+104.24}{20} - 10.98 = 10.99-10.98 = 0.01$

Likewise to compare R_1 and R_2, we sum the Calipers as follows:

for R_1 : 2.75 + 2.40 + 2.80 + 2.55 = 10.50 mm

for R_2 : 2.55 + 2.40 + 2.65 + 2.86 = 10.46 mm

∴ Sum of squares for R = $\frac{(10.50)^2 + (10.46)^2}{20} - C$

$= \frac{110.25 + 109.41}{20} - 10.98 = 10.983 - 10.98 = 0.003$

The Interactions P x Q, PxP, QxR, PxQxP

Interaction sum of squares = $\frac{[(a+d)-(b-c)]^2}{(4)(n_1)}$

where n_1 = 2x5 = 10 and a, b, c, d are the sums shown below:

for P x Q		
	Q_1	Q_2
P_1	a	b
P_2	c	d

for P x P		
	R_1	R_2
P_1	a	b
P_2	c	d

for Q x R		
	R_1	R_2
Q_1	a	b
Q_2	c	d

P_1Q_1 =a=2.75+2.55 = 5.30 P_1R_1 =a=2.75+2.4 =5.15 Q_1R_1 = a=2.75+2.8 = 5.55

P_1Q_2 =b=2.8 + 2.4 = 4.80 P_1R_2 =b=2.55+2.4 =4.95 Q_1R_2 = b=2.55+2.65= 5.20

P_2Q_1 =c=2.8 + 2.65 = 5.45 P_2R_1 =c=2.8 +2.55=5.35 Q_2R_1 = c=2.4 +2.55= 4.95

P_2Q_2 =d=2.55 +2.86 = 5.41 P_2R_2 =d=2.65+2.86=5.51 Q_2R_2 = d=2.4 +2.86= 5.26

∴ P x Q interaction sum of squares = $\frac{[(5.30+5.41)-(4.8-5.45)]^2}{(4)(10)}$

$= \frac{[(10.71-(-0.65)]^2}{40} = \frac{11.36^2}{40} = \frac{129.05}{40} = 3.23$

$\therefore$ PxA interaction sum of squares = $\frac{[(5.15+5.51)-(4.95-5.35)]^2}{(4)(10)}$

$= \frac{(10.66)-(0.4)^2}{40} = \frac{11.06^2}{40} = \frac{122.32}{40} = 3.06$

$\therefore$ QxA interaction sum of squares = $\frac{[(5.55+5.26)-(5.20-4.95)]^2}{(4)(10)}$

$= \frac{[(10.81)-(0.25)]^2}{40} = \frac{10.56^2}{40} = \frac{111.51}{40} = 2.79$

$\therefore$ PxQxR interaction sum of squares =(B/W Treatment sum of squares)

- (Sum of the sum of squares for P,Q,R, PxQ, PxR and QxR)

$= 0.044 - (0.018 + 0.01 + 0.003 + 3.23 + 3.06 + 2.79)$

$= 0.044 - 9.11 = -9.07$

$\therefore$ The complete ANOVA Table for Main Effects and Interactions gives:

SV	SS	d.f	MS	F-ratio (observed)	F-ratio (F-table at α=5%	Significance
P	0.018	1	0.018	0.05	4.15	n.s
Q	0.010	1	0.010	0.03	"	n.s
R	0.003	1	0.003	0.009	"	n.s
PxQ	3.23	1	3.23	9.42	"	*
PxR	3.06	1	3.06	8.92	"	*
QxR	2.79	1	2.79	8.13	"	*
PxQxR	-9.07	1	-9.07	-26.44	"	n.s
Error (Within Treatments)	10.986	32	0.343			
Total	11.026	39				

NB. * = significant at 95% probability level
n.s = not significant at 95% probability level

G - 10: Analysis of the Basis Weight(g/m^2) for SAMCOT 9 Hand Sheets

Furnish Ratio								
60/40 (P_1)				50/50 (P_2)				
Freeness				Freeness				
20^{o}SR (Q_1)		35^{o}SR (Q_2)		20^{o}SR (Q_1)		35^{o}SR (Q_2)		
Additive		Additive		Additive		Additive		
(0,0)% (R_1)	(1,4)% (R_2)	(0,0)% (R_1)	(1,4)% (R_2)	(0,0)% (R_1)	(1,4)% (R_2)	(0,0)% (R_1)	(1,4)% (R_2)	
141.5	130.2	126.9	122.3	121.2	135.8	126.9	116.0	
142.3	130.2	126.8	121.9	120.3	136.5	126.6	115.8	
142.2	129.6	127.3	121.8	121.5	135.7	127.5	116.2	
$\bar{x}$ 142.0	30.0	127.0	122.0	121.0	136.0	127.0	116.0	
s 0.44	0.35	0.26	0.26	0.62	0.44	0.46	0.20	
Σx^2 80492.4	50760.2	48387.1	44652.1	43923.8	55488.4	48387.4	40368.1	$\underline{\Sigma(\Sigma x^2)}$=392399.5
Σx 426.0	390.0	381.0	366.0	363.0	408.0	381.0	348.0	$\underline{\Sigma(\Sigma x)}$ = 3063.0

(e) Correction factor, $C = \frac{[\Sigma(\Sigma x)]^2}{8n} = \frac{(3063^2}{8 \times 3} = \frac{9381969}{24} = 390915.4$

(b) Total sum of squares of all observations, $\Sigma(\Sigma x^2) = 392399.5$

(c) Sum of squares of the totals of each column = $\Sigma(\Sigma x)^2$

$= 426^2 + 390^2 + 381^2 + 366^2 + 363^2 + 408^2 + 381^2 + 348^2$

$= 181467 + 152100 + 145161 + 133956 + 131769 + 166464$

$+ 145161 + 121104 = 1177191.0$

(d) Dividing the sum of squares of the totals of each column by the number of individual observations, n = 3, we get $\frac{1177191.0}{3} = 392397.0$

(e) Sum of squares for total = (b) - (a) = 392399.5 -390915.4
= 1484.1

(f) Between-treatments sum of squares = (d) - (a)

= 392397.0 - 390915.4 = 1481.6

(g) Within-treatments sum of squares = (b) - (f)

= 392399.5 - 1481.6 = 390917.9

ANOVA Table for Treatment Means

SS	SS	df	MS	F-ratio (Observed)	F-ratio (F-table)	Significance at α = 5%
Between Treatments	1481.6	t-1 = 7	211.66	0.009	2.66	n. s
Within Treatments	390917.9	t(n-1)=16	24432.4			
Total	392399.5	23				

N.B. n. s = not significant at 95% probability level.

The Main Effects, P, Q and R

To compare P_1 and P_2 we have the sum of Basis weights as follows:

for P_1 : 426 + 390 + 381 + 366 = 1563 g/m^2

for P_2 = 363 + 408 + 381 + 348 = 1500 g/m^2

For each of these, the sum is based upon 4x3 = 12 measurements

$\therefore$ Sum of squares for P = $\frac{(1563)^2 + (1500)^2}{12} - C$

$= \frac{(2442969 + 2250000)}{12} - 390915.4$

$= 390915.4 - 391080.75 = 390915.4 = 165.35$

Similarly, to compare Q_1 and Q_2 we sum the basis weights as follows:

for Q_1 : 426 + 390 + 363 + 408 = 1587 g/m^2

for Q_2 : 381 + 366 + 381 + 348 = 1476 g/m^2

$\therefore$ Sum of squares for Q = $\frac{(1587)^2 + (1476)^2}{12} - C$

$= \frac{2518569 + 2178576}{12} - 390915.4 = 391428.75 - 390915.4 = 513.35$

Likewise, to compare R_1 and R_2, we sum the basis weights as follows

for R_1 : 426 + 381 + 363 + 381 = 1551 g/m^2

for R_2 : 390 + 366 + 408 + 348 = 1512 g/m^2

$\therefore$ Sum of squares for R = $\frac{(1551)^2 + (1512)^2}{12} - C$

$= 390978.75 - 390915.4 = 63.35$

The Interactions P x Q, PxR, QxR, PxQxR

Interaction sum of squares = $\frac{[(a+d)-(b-c)]^2}{(4)(n_1)}$

where n_1 = 2x3 = 6 and a, b, c, d are the sums shown below:

for P x Q

	Q_1	Q_2
P_1	a	b
P_2	c	d

for P x R

	R_1	R_2
P_1	a	b
P_2	c	d

for Q x R

	R_1	R_2
Q_1	a	b
Q_2	c	d

P_1Q_1 =a=426+390 = 816 P_1R_1 =a=426+381 =807 Q_1R_1 = a=426+363 = 789

P_1Q_2 =b=381+366 = 747 P_1R_2 =b=390+366 =756 Q_1R_2 = b=390+408 = 798

P_2Q_1 =c=363+408 = 771 P_2R_1 =c=363+481 =744 Q_2R_1 = c=381+381 = 762

P_2Q_2 =d=381+348 = 729 P_2R_2 =d=408+348 =756 Q_2R_2 = d=366+348 = 714

$\therefore$ P x Q interaction sum of squares $= \frac{[(616+729)-(747-771)]^2}{(4)(6)}$

$= \frac{(1345-24}{24}^2 = \frac{1569^2}{24} = \frac{2461761}{24} = 102573.4$

PxR interaction sum of squares $= \frac{[(607+756)-(756-744)]^2}{(4)(6)}$

$= \frac{(1563)-(12)}{24}^2 = \frac{1551^2}{24} = \frac{2405601}{24} = 100233.4$

QxR interaction sum of squares $= \frac{[(789+714)-(796-762)]^2}{(4)(6)}$

$= \frac{[(1503)-36)]}{24}^2 = \frac{1467^2}{24} = \frac{2152089}{24} = 89670.4$

PxQxR interaction sum of squares =(B/W Treatment sum of squares) minus
(Sum of the sum of squares for P,Q,R, PxQ, PxR and QxR)

$= 1481.6 - (165.35 + 513.35 + 63.35 + 102573.4$

$+ 100233.4 + 89670.4)$

$= 1481.6 - 293219.25 = -291737.66$

$\therefore$ The complete ANOVA Table for Main Effects and Interactions gives:

S	SS	d.f	MS	F-ratio (observed)	F-ratio (F-table	Significance at α=5%
P	165.35	1	165.35	0.007	4.49	n.s
Q	513.35	1	513.35	0.021	"	n.s
R	63.35	1	63.35	0.003	"	n.s
PxQ	102573.4	1	102573.4	4.20	"	n.s
PxR	100233.4	1	100233.4	4.10	"	n.s
QxR	89670.4	1	89670.4	3.67	"	n.s
PxQxR	-291737.65	1	-291737.65	-11.94	"	n.s
Error (Within Treatments)	390917.9	16	24432.4			
Total	392399.5	23				

NB. n.s = not significant at 95% probability level

G - 11: Analysis of the Burst Strenth (kg/cm^2) for SAMCOT 9 Hand Sheets

	Furnish Ratio								
	60/40 (P_1)				50/50 (P_2)				
	Freeness				Freeness				
	20^oSR (Q_1)		35^oSR (Q_2)		20^oSR (Q_1)		35^oSR (Q_2)		
	Additive		Additive		Additive		Additive		
	(0,0)% (R_1)	(1,4)% (R_2)	(0,0)% (R_1)	(1,4)% (R_2)	(0,0)% (R_1)	(1,4)% (R_2)	(0,0)% (R_1)	(1,4)% (R_2)	
	0.70	0.68	0.86	0.94	0.88	0.88	1.06	1.05	
	0.73	0.74	0.85	0.89	0.83	0.87	0.99	0.99	
	0.65	0.70	0.87	0.95	0.82	0.85	0.98	1.00	
	0.72	0.68	0.82	0.90	0.87	0.80	1.05	1.04	
$\bar{x}$	0.70	0.70	0.85	0.92	0.85	0.85	1.02	1.02	
s	0.04	0.03	0.02	0.03	0.03	0.04	0.04	0.03	
Σx^2	1.96	1.96	2.89	3.39	2.89	2.89	4.17	4.16	$\Sigma(\Sigma x^2)=24.31$
Σx	2.80	2.80	3.40	3.68	3.40	3.40	4.08	4.08	$\Sigma(\Sigma x) =27.64$

Note! Conversion factor: 1 kg/cm^2 = 0.49 kPa

(a) Correction factor, $C = \frac{[\Sigma(\Sigma x)]^2}{8n} = \frac{(27.64)^2}{8 \times 4} = \frac{763.97}{32} = 23.87$

(b) Total sum of squares of all observations, $\Sigma(\Sigma x^2) = 24.31$

(c) Sum of squares of the totals of each column = $\Sigma(\Sigma x)^2$

$= 2.8^2 + 2.8^2 + 3.4^2 + 3.68^2 + 3.4^2 + 3.4^2 + 4.08^2 + 4.08^2$

$= 7.84 + 7.84 + 11.56 + 13.54 + 11.56 + 11.56 + 16.65 + 16.65 = 97.20$

(d) Dividing the sum of squares of the totals of each column by the number of individual observations, n = 4, we get $\frac{97.20}{4} = 24.30$

(e) Sum of squares for total = (b) - (a) = 24.31-23.87 = 0.44

(f) Between-treatments sum of squares = (d) - (a) = 24.30-23.87 = 0.43

(g) Within-treatments sum of squares = (b) - (f) = 24.31-0.43 = 23.88

ANOVA Table for Treatment Means

SV	SS	df	MS	F-ratio (Observed)	F-ratio (F-table) at α = 5%	Significance
Between Treatments	0.43	t-1 = 7	0.061	2.42		n. s
Within Treatments	23.88	t(n-1)=24	0.995			
Total	24.31	31				

N.B. n. s = not significant at 95% probability level.

The Main Effects, P, Q and R

To compare P_1 and P_2 we have the sum of burst strengths as follows:

for P_1 : 2.80 + 2.80 + 3.40 + 3.68 = 12.68 kg/cm^2

for P_2 = 3.40 + 3.40 + 4.08 + 4.08 = 14.96 "

For each of these, the sum is based upon 4x4 = 16 measurements

∴ Sum of squares for P = $\frac{(12.68)^2 + (14.96)^2}{16} - C$

$= \frac{(160.78 + 223.81)}{16} - 23.87 = 24.0426 - 234.87 = 0.17$

Similarly, to compare Q_1 and Q_2 we sum the burst strengths as follows:

for Q_1 : 2.80 + 2.80 + 3.40 + 3.40 = 12.40

for Q_2 : 3.40 + 3.68 + 4.08 + 4.08 = 15.24

∴ Sum of squares for Q = $\frac{(12.40)^2 + (15.24)^2}{16} - C$

$= \frac{153.76 + 232.26}{16} - 23.87 = 24.13 - 23.87 = 0.26$

Likewise, to compare R_1 and R_2, we sum the burst strengths as follows

for R_1 : 2.8 + 3.4 + 3.4 + 4.08 = 13.68

for R_2 : 2.8 + 3.68 + 3.4 + 4.08 = 13.96

∴ Sum of squares for R = $\frac{(13.68)^2 + (13.96)^2}{16} - C$

$= \frac{187.14 + 194.88}{16} - 23.87 = 23.88-23078 = 0.01$

<u>The Interactions P x Q, PxR, QxR, PxQxR</u>

Interaction sum of squares = $\frac{[(a+d)-(b-c)]^2}{(4)(n_1)}$

Where n_1 = 2x4 = 8 and a, b, c, d are the sums shown below:

for P x Q

	Q_1	Q_2
P_1	a	b
P_2	c	d

for P x R

	R_1	R_2
P_1	a	b
P_2	c	d

for Q x R

	R_1	R_2
Q_1	a	b
Q_2	c	d

P_1Q_1 =a=2.8+2.8 = 5.6 P_1R_1 =a=2.8+3.4 =6.2 Q_1R_1 = a=2.8+3.4 = 6.2

P_1Q_2 =b=3.4+4.68 = 7.08 P_1R_2 =b=2.8+3.68 =6.48 Q_1R_2 = b=2.8+3.4 = 6.2

P_2Q_1 =c=3.4+3.4 = 7,48 P_2R_1 =c=3.4+4.08 =7.48 Q_2R_1 = c=3.4+4.08 =7.48

P_2Q_2 =d=4.08+408 = 8.16 P_2R_2 =d=3.4+4.08 =7.48 Q_2R_2 = d=3.68+4.08=7.48

∴ P x Q interaction sum of squares = $\frac{[(5.6+8.16)-(7.08-6.8)]^2}{(4)(8)}$

$= \frac{[(13.76-(0.28)]^2}{32} = \frac{13.48^2}{32} = \frac{181.71}{32} = 5.68$

∴ PxR interaction sum of squares = $\frac{[(6.2+7.48)-(6.48-7.48)]^2}{(4)(8)}$

$= \frac{(13.66)-(-1.0)^2}{32} = \frac{14.68^2}{32} = \frac{215.5}{32} = 6.73$

∴ QxR interaction sum of squares = $\frac{[(6.2+7.76)-(6.2-7.48)]^2}{(4)(8)}$

$= \frac{[(13.96)-(-1.28)]^2}{32} = \frac{15.24^2}{32} = \frac{2328.26}{32} = 7.26$

∴ PxQxR interaction sum of squares =(B/W Treatment sum of squares)

- (Sum of the sum of squares for P,Q,R, PxQ, PxR and QxR)

= 0.43 -(0.17 + 0.26 + 0.01 + 5.68 + 6.73 + 7.26)

= 0.43 -20.11 = -19.68

∴ The complete ANOVA Table for Main Effects and Interactions gives:

SV	SS	d.f	MS	F-ratio (observed)	F-ratio (F-table at α=5%	Significance
P	0.17	1	0.17	0.17	4.26	n.s
Q	0.26	1	0.26	0.26	"	n.s
R	0.01	1	0.01	0.01	"	n.s
PxQ	5.68	1	5.68	5.71	"	*
PxR	6.73	1	6.73	6.76	"	*
QxR	7.26	1	7.26	7.30	"	*
PxQxR	-19.68	1	-19.68	-19.78	"	n.s
Error (Within Treatments)	23.89	24	0.995			
Total	24.31	31				

NB. * = significant at 95% probability level
n.s = not significant at 95% probability level

G - 12: Analysis of the Tear Strength (gram-force) for SAMCOT 9 Hand Sheets

	Furnish Ratio								
	60/40 (P_1)				50/50 (P_2)				
	Freeness				Freeness				
	20^{o}_{SR} (Q_1)		35^{o}_{SR} (Q_2)		20^{o}_{SR} (Q_1)		35^{o}_{SR} (Q_2)		
	Additive		Additive		Additive		Additive		
	(0,0)% (R_1)	(1,4)% (R_2)	(0,0)% (R_1)	(1,4)% (R_2)	(0,0)% (R_1)	(1,4)% (R_2)	(0,0)% (R_1)	(1,4)% (R_2)	
	48.4	47.9	64.5	64.2	64.3	64.2	96.6	95.7	
	47.6	48.2	63.7	63.8	64.6	63.9	96.2	96.4	
	48.2	47.8	64.3	63.6	63.7	63.8	95.8	95.6	
	47.8	48.1	63.5	64.4	63.4	64.1	95.4	96.3	
$\bar{x}$	48.0	48.0	64.0	64.0	64.0	64.0	96.0	96.0	
s	0.37	0.18	0.48	0.37	0.55	0.18	0.52	0.41	
Σx^2	9216.4	9216.1	16384.7	16384.4	16384.9	16384.1	36864.8	36864.5	$\Sigma(\Sigma x^2)$ 157699.9
Σx	192.0	192.0	256.0	256.0	256.0	256.0	384.0	384.0	$\Sigma(\Sigma x)$ = 2176.0

Note! Conversion factor: 1 kgf = 9.81N = 0.0098kN

(a) Correction factor, $C = \frac{[\Sigma(\Sigma x)]^2}{8n} = \frac{(2176)^2}{8 \times 4} = \frac{4734976}{32} = 147966.0$

(b) Total sum of squares of all observations, $\Sigma(\Sigma x^2) = 157699.9$

(c) Sum of squares of the totals of each column = $\Sigma(\Sigma x)^2$

$= 192^2 + 192^2 + 256^2 + 256^2 + 256^2 + 256^2 + 384^2 + 384^2$

$= 36864 + 36864 + 65536 + 65536 + 65536 + 65536$

$+147456 + 147456 = 630784$

(d) Dividing the sum of squares of the totals of each column by the number of individual observations, n = 4, we get $\frac{630784}{4} = 157696$

(e) Sum of squares for total = (b) - (a) = 157699.9-147968 = 9731.9

(f) Between-treatments sum of squares = (d) - (a)

$= 157696 - 147968 = 9728.0$

(g) Within-treatments sum of squares = (b) - (f) = 17699.9-9728.0

$= 147971.9$

ANOVA Table for Treatment Means

SV	SS	df	MS	F-ratio (Observed)	F-ratio (F-table)	Significance at α = 5%
Between Treatments	9728.0	t-1 = 7	1389.7	0.23	2.42	n. s
Within Treatments	147971.9	t(n-1)=24	6165.5			
Total	157699.9	31				

N.B. n. s = not significant at 95% probability level.

The Main Effects, P, Q and R

To compare P_1 and P_2 we have the sum of tear strengths as follows:

for P_1 : 192 + 192 + 256 + 256 = 896 kgf

for P_2 = 256 + 256 + 384 + 384 = 1280 kgf

For each of these, the sum is based upon 4x4 = 16 measurements

∴ Sum of squares for P = $\frac{(896)^2 + (1280)^2}{16} - C$

$= \frac{802816 + 1638400}{16} - 147968.0 = 152576-147968 = 4608$

Similarly, to compare Q_1 and Q_2 we sum the tear strengths as follows:

for Q_1 : 192 + 192 + 256 + 256 = 896 kgf

for Q_2 : 256 + 256 + 384 + 384 = 1280 kgf

∴ Sum of squares for Q = $\frac{(896)^2 + (1280)^2}{16} - C$

$= \frac{802816+1638400}{16} - 147968.0 = 152576-147968 = 4608$

Likewise, to compare R_1 and R_2, we sum the tear strengths as follows:

for R_1 : 192 + 256 + 256 + 384 = 1088 kgf

for R_2 : 192 + 256 + 256 + 384 = 1088 kgf

∴ Sum of squares for Q = $\frac{(1088)^2 + (1088)^2}{16} - C$

$= \frac{1183744+1183744}{16} - 147968.0 = 147968-147968 = 0$

The Interactions P x Q, PxR, QxR, PxQxR

Interaction sum of squares = $\frac{[(a+d)-(b-c)]^2}{(4)(n_1)}$

where n_1 = 2x4 = 8 and a, b, c, d are the sums shown below:

for P x Q

	Q_1	Q_2
P_1	a	b
P_2	c	d

for P x R

	R_1	R_2
P_1	a	b
P_2	c	d

for Q x R

	R_1	R_2
Q_1	a	b
Q_2	c	d

P_1Q_1 =a=192+192 = 384

P_1Q_2 =b=256+256 = 512

P_2Q_1 =c=256+256 = 512

P_2Q_2 =d=384+384 = 768

P_1R_1 =a=192+256 =448

P_1R_2 =b=192+256 =448

P_2R_1 =c=256+384 =640

P_2R_2 =d=256+384 =640

Q_1R_1 = a=192+256 = 448

Q_1R_2 = b=192+256 = 448

Q_2R_1 = c=256+384 = 640

Q_2R_2 = d=256+384 = 640

$$\therefore \text{ P x Q interaction sum of squares } = \frac{[(364+768)-(512-512)]^2}{(4)(8)}$$

$$= \frac{(1152-0)^2}{32} = \frac{1327104}{32} = 41472$$

$$\therefore \text{ PxR interaction sum of squares } = \frac{[(448+640)-(448-640)]^2}{(4)(8)}$$

$$= \frac{(1088)-(-192)^2}{32} = \frac{1280^2}{32} = \frac{1638400}{32} = 51200$$

$$\therefore \text{ QxR interaction sum of squares } = \frac{[(448+640)-(448-640)]^2}{(4)(8)}$$

$$= \frac{[(1088)-(-192)]^2}{32} = \frac{1280^2}{32} = \frac{1638400}{32} = 51200$$

∴ PxQxR interaction sum of squares =(B/W Treatment sum of squares)

- (Sum of the sum of squares for P,Q,R, PxQ, PxR and QxR)

= (9728.0) -(4608 + 4608 + 0 + 41472 + 51200 + 51200)

= 9728.0 -153088 = -143360.0

∴ The complete ANOVA Table for Main Effects and Interactions gives:

SV	SS	d.f	MS	F-ratio (observed)	F-ratio (F-table	Significance at α=5%
P	4608.0	1	4608.0	0.75	4.26	n.s
Q	4608.0	1	4608.0	0.75	"	n.s
R	0.0	1	0.0	0.0	"	n.s
PxQ	41472.0	1	41472.0	6.73	"	*
PxR	51200.0	1	51200.0	8.30	"	*
QxP	51200.0	1	51200.0	8.30	"	*
PxQxR	-143360.0	1	-143360.0	-23.25	"	n.s
Error (Within Treatments)	147971.9	24	147975.5			
Total	157699.9	31				

NB. * = significant at 95% probability level
n.s = not significant at 95% probability level

G-13: Analysis of the Caliper (mm) for SAMCOT 10 Hand Sheets

	Furnish Ratio								
	60/40 (P_1)				50/50 (P_2)				
	Freeness				Freeness				
	20^{O}SR (Q_1)		35^{O}SR (Q_2)		20^{O}SR (Q_1)		35^{O}SR (Q_2)		
	Additive		Additive		Additive		Additive		
	(0,0)% (R_1)	(1,4)% (R_2)	(0,0)% (R_1)	(1,4)% (R_2)	(0,0)% (R_1)	(1,4)% (R_2)	(0,0)% (R_1)	(1,4)% (R_2)	
	0.56	0.55	0.45	0.47	0.49	0.50	0.47	0.53	
	0.56	0.55	0.43	0.46	0.48	0.52	0.48	0.52	
	0.55	0.57	0.44	0.45	0.50	0.51	0.49	0.51	
	0.56	0.56	0.44	0.45	0.49	0.52	0.50	0.53	
	0.57	0.57	0.45	0.47	0.50	0.50	0.47	0.51	
$\bar{x}$	0.56	0.56	0.44	0.46	0.49	0.51	0.48	0.52	
s	0.007	0.01	0.008	0.01	0.008	0.01	0.01	0.01	
Σx^2	1.57	1.57	0.98	1.06	1.21	1.30	1.16	1.35	$\Sigma(\Sigma x^2) = 10.20$
Σx	2.80	2.80	2.21	2.30	2.46	2.55	2.41	2.60	$\Sigma(\Sigma x) = 20.13$

(a) Correction factor, $C = \frac{[\Sigma(\Sigma x)]^2}{8n} = \frac{20.13^2}{8 \times 5} = \frac{405.2}{40} = 10.13$

(b) Total sum of squares of all observations, $\Sigma(\Sigma x^2) = 10.20$

(c) Sum of squares of the totals of each column = $\Sigma(\Sigma x)^2$

$= 2.8^2 + 2.8^2 + 2.21^2 + 2.3^2 + 2.46^2 + 2.55^2 + 2.41^2 + 2.60^2$

$= 7.84 + 7.84 + 4.88 + 5.29 + 6.05 + 6.50 + 5.81 + 6.76 = 50.97$

(d) Dividing the sum of squares of the totals of each column by the number of individual observations, n = 5, we get $\frac{50.97}{5} = 10.19$

(e) Sum of squares for total = (b) - (a) = 10.20-10.13 = 0.07

(f) Between-treatments sum of squares = (d) - (a)

$= 10.20 - 10.13 = 0.06$

(g) Within-treatments sum of squares = (b) - (f) = 10.20-0.06 = 10.14

ANOVA Table for treatment Means

SV	SS	df	MS	F-ratio (Observed)	F-ratio (F-table) at α = 5%	Significance
Between Treatments	0.06	t-1 = 7	0.009	0.028	2.31	n. s
Within Treatments	10.14	t(n-1)=32	0.317			
Total	10.20	39				

N.B. n. s = not significant at 95% probability level

The Main Effects, P, Q and R

To compare P_1 and P_2 we have the sum of Calipers as follows:

for P_1 : 2.80 + 2.80 + 2.21 + 2.30 = 10.11 mm

for P_2 = 2.46 + 2.55 + 2.41 + 2.60 = 10.02 mm

For each of these, the sum is based upon 4x5 = 20 measurements

∴ Sum of squares for P = $\frac{(10.11)^2 + (10.02)^2}{20} - C$

$= \frac{102.21 + 100.40}{20} - 10.13 = 10.131-10.13 = 0.001$

Similarly, to compare Q_1 and Q_2 we sum the Calipers as follows:

for Q_1 : 2.8 + 2.8 + 2.46 + 2.55 = 10.61 mm

for Q_2 : 2.21 + 2.3 + 2.41 + 2.60 = 9.52 mm

$\therefore$ Sum of squares for Q = $\frac{(10.61)^2 + (9.52)^2}{20} - C$

$= \frac{112.57+90.63}{20} - 10.13 = 10.16-10.13 = 0.03$

Likewise, to compare R_1 and R_2, we sum the Calipers as follows:

for R_1 : 2.8 + 2.21 + 2.46 + 2.41 = 9.88 mm

for R_2 : 2.8 + 2.30 + 2.55 + 2.60 = 10.25 mm

$\therefore$ Sum of squares for Q = $\frac{(9.68)^2 + (10.25)^2}{20} - C$

$= \frac{97.61 + 105.06}{20} - 10.13 = 10.134 - 10.13 = 0.004$

The Interactions P x Q, PxR, QxR, PxQxR

Interaction sum of squares = $\frac{[(a+d)-(b-c)]^2}{(4)(n_1)}$

where n_1 = 2x5 = 10 and a, b, c, d are the sums shown below:

for P x Q

	Q_1	Q_2
P_1	a	b
P_2	c	d

for P x R

	R_1	R_2
P_1	a	b
P_2	c	d

for Q x R

	R_1	R_2
Q_1	a	b
Q_2	c	d

P_1Q_1 =a=2.8 + 2.8 = 5.6 P_1R_1 =a=2.8 +2.21 =5.01 Q_1R_1 = a=2.8 +2.46= 5.26

P_1Q_2 =b=2.21+ 2.3 = 4.51 P_1R_2 =b=2.8 +2.30 =4.95 Q_1R_2 = b=2.8 +2.55= 5.35

P_2Q_1 =c=2.46+ 2.55 = 5.01 P_2R_1 =c=2.46+2.41 =4.87 Q_2R_1 = c=2.21+2.41= 4.62

P_2Q_2 =d=2.41+ 2.60 = 5.01 P_2R_2 =d=2.55+2.60 =5.15 Q_2R_2 = d=2.3 +2.6 = 4.90

$\therefore$ P x Q interaction sum of squares = $\frac{[(5.6+5.01)-(4.51-5.01)]^2}{(4)(10)}$

$= \frac{[(10.61)-(-0.5)]^2}{40} = \frac{11.11^2}{40} = \frac{123.43}{40} = 3.09$

∴ PxR interaction sum of squares = $\frac{[(5.01+5.15)-(5.1-4.67^2}{(4)(10)}$

$= \frac{(10.1-0.23)^2}{40} = \frac{9.93^2}{40} = \frac{99.60}{40} = 2.47$

∴ QxR interaction sum of squares = $\frac{[(5.26+4.90)-(5.35-4.62)]^2}{(4)(10)}$

$= \frac{[(10.16-(0.73)]^2}{40} = \frac{9.43^2}{40} = \frac{88.92}{40} = 2.22$

∴ PxQxR interaction sum of squares =(B/W Treatment sum of squares)

- (Sum of the sum of squares for P,Q,R, PxQ, PxR and QxR)

= 0.06 -(0.001 + 0.03 + 0.004 + 3.09 + 2.47 + 2.22)

= 0.06 - 9.815 = -7.755 = -7.76

∴ The complete ANOVA Table for Main Effects and Interactions gives:

SV	SS	d.f	MS	F-ratio (observed)	F-ratio (F-table)	Significance at α=5%
P	0.001	1	0.001	0.003	4.15	n.s
Q	0.03	1	0.03	0.095	"	n.s
R	0.004	1	0.004	0.013	"	n.s
PxQ	3.09	1	3.09	9.75	"	*
PxR	2.47	1	2.47	7.79	"	*
QxR	2.22	1	2.22	7.00	"	*
PxQxR	-7.76	1	-7.76	-24.48	"	n.s
Error (Within Treatments)	10.14	32	0.317			
Total	10.195	39				

NB. * = significant at 95% probability level
n.s = not significant at 95% probability level

G - 14: Analysis of the Basis Weight(g/m^2) for SAMCOT 10 Hand Sheets

	Furnish Ratio								
	60/40 (P_1)				50/50 (P_2)				
	Freeness				Freeness				
	20^oSR (Q_1)		35^oSR (Q_2)		20^oSR (Q_1)		35^oSR (Q_2)		
	Additive		Additive		Additive		Additive		
	(0,0%) (R_1)	(1,4)% (R_2)	(0,0)% (R_1)	(1,4)% (R_2)	(0,0)% (R_1)	(1,4)% (R_2)	(0,0)% (R_1)	(1,4)% (R_2)	
	117.1	132.5	106.4	114.5	132.3	130.2	115.2	135.0	
	116.6	131.7	105.3	113.4	132.0	129.5	115.2	134.8	
	117.3	131.8	106.3	114.1	131.7	130.3	114.6	135.2	
$\bar{x}$	117.0	132.0	106.0	114.0	132.0	130.0	115.0	135.0	
s	0.36	0.44	0.61	0.56	0.30	0.44	0.35	0.20	
Σx^2	41067.3	52272.4	33708.7	38968.6	52272.2	50700.4	39675.2	54675.1	$\Sigma(\Sigma x^2)=363359.9$
Σx	351	396	381	342	396	390	345	405.0	$\Sigma(\Sigma x) = 2943.0$

(a) Correction factor, $C = \frac{[\Sigma(\Sigma x)]^2}{8n} = \frac{(2943^2}{8 \times 3} = \frac{8661249}{24} = 360885.4$

(b) Total sum of squares of all observations, $\Sigma(\Sigma x^2) = 363359.9$

(c) Sum of squares of the totals of each column = $\Sigma(\Sigma x)^2$

$= 351^2 + 396^2 + 318^2 + 342^2 + 396^2 + 390^2 + 345^2 + 405^2$

$= 123201 + 156816 + 101124 + 116964 + 156816 + 152100$

$+ 119025 + 164025 = 1090071.0$

(d) Dividing the sum of squares of the totals of each column by the number of individual observations, n = 3, we get

$\frac{1090071.0}{3} = 363357$

(e) Sum of squares for total = (h) - (a) = 363359.9 -360885.4
= 2474.5

(f) Between-treatments sum of squares = (d) - (a)
= 363357 - 360885 = 2471.6

(g) Within-treatments sum of squares = (h) - (f)
= 363359.9 - 2471.6 = 360888.3

ANOVA Table for Treatment Means

SV	SS	df	MS	F-ratio (Observed)	F-ratio (F-table)	Significance at α = 5%
Between Treatments	2471.6	t-1 = 7	353.09	0.016	2.66	n. s
Within Treatments	363359.9	t(n-1)=16	22555.5			
Total	392399.5	23				

N.B. n. s = not significant at 95% probability level.

The Main Effects, P, Q and P

To compare P_1 and P_2 we have the sum of basis weights as follows:

for P_1 : 351 + 396 + 318 + 342 = 1407 g/m^2

for P_2 = 396 + 390 + 345 + 405 = 1536 g/m^2

For each of these, the sum is based upon 4x3 = 12 measurements

$\therefore$ Sum of squares for P = $\frac{(1407)^2 + (1536)^2}{12} - C$

$= \frac{1979649 + 2359296}{12} - 360885.4$

$= 361578.75 - 360885.4 = 693.35$

Similarly, to compare Q_1 and Q_2 we sum the basis weights as follows:

for Q_1 : 351 + 396 + 396 + 390 = 1533 g/m^2

for Q_2 : 318 + 342 + 345 + 405 = 1410 g/m^2

$\therefore$ Sum of squares for Q = $\frac{(1533)^2 + (1410)^2}{12} - C$

$= \frac{2350089 + 1988100}{12} - 360885.4$

$= 361515.75 - 360885.4 = 630.35$

Likewise, to compare R_1 and R_2, we sum the basis weights as follows

for R_1 : 351 + 318 + 396 + 345 = 1410 g/m^2

for R_2 : 396 + 342 + 490 + 405 = 1533 g/m^2

$\therefore$ Sum of squares for R = $\frac{(1410)^2 + (1533)^2}{12} - C$

$= \frac{1988100 + 2350089}{12} - 360885.4 = 351515.75 - 360885.4 = 630.35$

The Interactions P x Q, PxR, QxR, PxQxR

Interaction sum of squares = $\frac{[(a+d)-(b-c)]^2}{(4)(n_1)}$

where n_1 = 2x3 = 6 and a, b, c, d are the sums shown below:

for P x Q

	Q_1	Q_2
P_1	a	b
P_2	c	d

for P x P

	R_1	R_2
P_1	a	b
P_2	c	d

for Q x P

	P_1	P_2
Q_1	a	b
Q_2	c	d

P_1Q_1 =a=351+396 = 747 P_1R_1 =a=351+318 =669 Q_1R_1 = a=351+396 = 747

P_1Q_2 =b=318+342 = 660 P_1R_2 =b=396+342 =738 Q_1R_2 = b=396+390 = 786

P_2Q_1 =c=396+390 = 786 P_2R_1 =c=396+345 =741 Q_2R_1 = c=318+345 = 663

P_2Q_2 =d=345+405 = 750 P_2R_2 =d=390+405.=795 Q_2R_2 = d=342+405 = 747

∴ P x Q interaction sum of squares $= \frac{[(747+750)-(660-786)]^2}{(4)(6)}$

$= \frac{(1497)-(-126^2}{24} = \frac{1623^2}{24} = \frac{2634129}{24} = 109755.4$

PxR interaction sum of squares $= \frac{[(669+795)-(736-741)]^2}{(4)(6)}$

$= \frac{(1464)-(-3)^2}{24} = \frac{1467^2}{24} = \frac{2152089}{24} = 89670.4$

QxR interaction sum of squares $= \frac{[(747+747)-786-663)]^2}{(4)(6)}$

$= \frac{[(1494)-123)]^2}{24} = \frac{1371^2}{24} = \frac{1879641}{24} = 78318.4$

PxQxR interaction sum of squares =(B/W Treatment sum of squares) minus (Sum of the sum of squares for P,Q,R, PxQ, PxR and QxR)

$= 2471.6 - (693.35 + 630.35 + 630.35 + 109755.4 + 98670.4 + 78318.4)$

$= 2471.6 - 279698.25 = -277226.7$

∴ The complete ANOVA Table for Main Effects and Interactions gives:

SV	SS	d.f	MS	F-ratio (observed)	F-ratio (F-table at α=5%	Significance
P	693.35	1	693.35	0.031	4.49	n.s
Q	630.35	1	630.35	0.028	"	n.s
R	630.35	1	630.35	0.028	"	n.s
PxQ	109755.4	1	109755.4	4.87	"	*
PxR	89670.4	1	89670.4	3.98	"	n.s
QxR	78318.4	1	78318.4	3.47	"	n.s
PxQxR	-277226.7	1	-277226.7	-12.29	"	n.s
Error (Within Treatments)	360888.3	16	22555.5			
Total	363359.9	23				

NB. * = significant at 95% probability level
n.s = not significant at 95% probability level

G - 15: Analysis of the Burst Strenth (kg/cm^2) for SAMCOT 10 Hand Sheets

	Furnish Ratio								
	60/40 (P_1)				50/50 (P_2)				
	Freeness				Freeness				
	20^oSR (Q_1)		35^oSR (Q_2)		20^oSR (Q_1)		35^oSR (Q_2)		
	Additive		Additive		Additive		Additive		
	(0,0%) (R_1)	(1,4)% (R_2)	(0,0)% (R_1)	(1,4)% (R_2)	(0,0)% (R_1)	(1,4)% (R_2)	(0,0)% (R_1)	(1,4)% (R_2)	
	0.73	0.69	0.90	0.83	0.87	0.83	0.96	1.00	
	0.67	0.71	0.89	0.87	0.86	0.83	0.94	0.97	
	0.72	0.66	0.95	0.82	0.84	0.88	0.98	1.01	
	0.68	0.74	0.94	0.88	0.83	0.86	0.92	0.98	
$\bar{x}$	0.70	0.70	0.92	0.85	0.85	0.85	0.95	0.99	
s	0.03	0.03	0.03	0.03	0.02	0.02	0.03	0.02	
Σx^2	1.96	1.96	3.39	2.89	2.89	2.89	3.61	3.92	$\Sigma(\Sigma x^2) = 23.51$
Σx	2.80	2.80	3.68	3.40	3.40	3.40	3.80	3.96	$\Sigma(\Sigma x) = 27.24$

Note! Conversion factor: 1 kg/cm^2 = 0.49 kPa

(a) Correction factor, $C = \frac{[\Sigma(\Sigma x)]^2}{8n} = \frac{(27.64)^2}{8 \times 4} = \frac{742.02}{32} = 23.19$

(b) Total sum of squares of all observations, $\Sigma(\Sigma x^2) = 23.51$

(c) Sum of squares of the totals of each column = $\Sigma(\Sigma x)^2$

$= 5.8^2 + 2.8^2 + 3.68^2 + 3.4^2 + 3.4^2 + 3.4^2 + 3.8^2 + 3.96^2$

$= 7.84 + 7.84 + 13.54 + 11.56 + 11.56 + 11.56 + 14.44 + 15.68$
$= 94.02$

(d) Dividing the sum of squares of the totals of each column by the number of individual observations, n = 4, we get $\frac{94.02}{4} = 23.51$

(e) Sum of squares for total = (b) - (a) = 23.51-23.19 = 0.32

(f) Between-treatments sum of squares = (d) - (a) = 23.51-23.19 = 0.32

(g) Within-treatments sum of squares = (b) - (f) = 23.51-0.32 = 23.19

ANOVA Table for Treatment Means

SV	SS	df	MS	F-ratio (Observed)	F-ratio (F-table)	Significance at α = 5%
Between Treatments	0.32	t-1 = 7	0.046	0.048	2.42	n. s
Within Treatments	23.19	t(n-1)=24	0.996			
Total	23.51	31				

N.B. n. s = not significant at 95% probability level.

The Main Effects, P, Q and R

To compare P_1 and P_2 we have the sum of burst strengths as follows:

for P_1 : 2.8 + 2.8 + 3.68 + 3.4 = 12.68 kg/cm^2

for P_2 = 3.4 + 3.4 + 3.8 + 3.96 = 14.56 kg/cm^2

For each of these, the sum is based upon 4x4 = 16 measurements

∴ Sum of squares for P = $\frac{(12.68)^2 + (14.56)^2}{16} - C$

$= \frac{(160.78 + 211.99)}{16} - 23.19 = 23.30 - 23.19 = 0.11$

Similarly, to compare Q_1 and Q_2 we sum the burst strengths as follows:

for Q_1 : 2.8 + 2.8 + 3.4 + 3.4 = 12.40 kg/cm^2

for Q_2 : 3.68 +3.4 + 3.8 + 3.96 = 14.84 kg/cm^2

$\therefore$ Sum of squares for Q = $\frac{(12.40)^2 + (14.84)^2}{16} - C$

$= \frac{153.76 + 220.23}{16} - 23.19 - 23.37 - 23.19 = 0.18$

Likewise, to compare R_1 and R_2, we sum the burst strengths as follows

for R_1 : 2.8 + 3.68 + 3.4 + 3.8 = 13.68 kg/cm^2

for R_2 : 2.8 + 3.40 + 3.4 + 3.96 = 13.56 kg/cm^2

$\therefore$ Sum of squares for R = $\frac{(13.68)^2 + (13.56)^2}{16} - C$

$= \frac{187.14 + 183.87}{16} - 23.19 = 23.19-23.19 = 0$

<u>The Interactions P x Q, PxR, QxR, PxQxR</u>

Interaction sum of squares = $\frac{[(a+d)-(b-c)]^2}{(4)(n_1)}$

where n_1 = 2x4 = 8 and a, b, c, d are the sums shown below:

for P x Q			for P x P			for Q x R		
	Q_1	Q_2		R_1	R_2		R_1	R_2
P_1	a	b	P_1	a	b	Q_1	a	b
P_2	c	d	P_2	c	d	Q_2	c	d

P_1Q_1 =a=2.8+2.8 = 5.60 P_1R_1 =a=2.8+3.68 =6.48 Q_1R_1 = a=2.8+3.4 = 6.20

P_1Q_2 =b=3.68+3.4= 7.08 P_1R_2 =b=2.8+3.4 =6.20 Q_1R_2 = b=2.8+3.4 = 6.20

P_2Q_1 =c=3.4+3.4 = 7.8 P_2R_1 =c=3.4+3.8 =7.20 Q_2R_1 = c=3.68+3.8 =7.48

P_2Q_2 =d=3.8+3.96 =7.76 P_2R_2 =d=3.4+3.96 =7.36 Q_2R_2 = d=3.4 +3.96=7.36

$\therefore$ P x Q interaction sum of squares = $\frac{[(5.60+7.76)-(7.08-6.80)]^2}{(4)(8)}$

$= \frac{[(13.36-(0.28)]^2}{32} = \frac{13.08^2}{32} = \frac{171.09}{32} = 5.35$

$\therefore$ PxR interaction sum of squares = $\frac{[(6.48+7.36)-(6.2-7.2)]^2}{(4)(8)}$

$= \frac{(13.84)-(-1.0)^2}{32} = \frac{14.84^2}{32} = \frac{220.23}{32} = 6.88$

$\therefore$ QxR interaction sum of squares = $\frac{[(6.2+7.36)-(6.2-7.48)]^2}{(4)(8)}$

$= \frac{[(13.56)-(-1.28)]^2}{32} = \frac{14.84^2}{32} = \frac{220.23}{32} = 6.88$

$\therefore$ PxQxR interaction sum of squares =(B/W Treatment sum of squares)

- (Sum of the sum of squares for P,Q,R, PxQ, PxR and QxR)

= 0.32 -(0.11 + 0.18 + 0 + 5.35 + 6.88 + 6.88)

= 0.32 -19.4 = -19.08

$\therefore$ The complete ANOVA Table for Main Effects and Interactions gives:

SV	SS	df	MS	F-ratio (observed)	F-ratio (F-table	Significance at α=5%
P	0.11	1	0.11	0.11	4.26	n.s
Q	0.18	1	0.18	0.19	"	n.s
P	0.0	1	0.0	0.0	"	n.s
PxQ	5.35	1	5.35	5.54	"	*
PxR	6.88	1	6.88	7.12	"	*
QxR	6.88	1	6.88	7.12	"	*
PxQxR	-19.08	1	-19.08	-20.75	"	n.s
Error (Within Treatments)	23.19	24	0.966			
Total	23.51	31				

NB. * = significant at 95% probability level
n.s = not significant at 95% probability level

G – 16: Analysis of the Tear Strength (kgf) for SAMCOT 10 Hand Sheets

Furnish Ratio								
60/40 (P_1)				50/50 (P_2)				
Freeness				Freeness				
$20^{O}SR$ (Q_1)		$35^{O}SR$ (Q_2)		$20^{O}SR$ (Q_1)		$35^{O}SR$ (Q_2)		
Additive		Additive		Additive		Additive		
(0,0)% (R_1)	(1,4)% (R_2)	(0,0)% (R_1)	(1,4)% (R_2)	(0,0)% (R_1)	(1,4)% (R_2)	(0,0)% (R_1)	(1,4)% (R_2)	
47.8	46.9	63.6	80.5	96.6	95.8	122.3	144.4	
48.3	48.5	63.6	79.8	95.4	96.2	122.2	143.8	
47.7	48.1	63.4	80.2	96.2	96.5	121.7	144.2	
48.2	47.5	64.4	79.5	95.8	95.5	121.9	143.6	
$\bar{x}$ 48.0	48.0	64.0	80.0	96.0	96.0	122.0	144.0	
s 0.29	0.42	0.59	0.44	0.52	0.44	0.28	0.37	
Σx^2 9216.3	9216.5	16385.0	25600.6	36864.8	36864.6	59560.6	82944.4	$\Sigma(\Sigma x^2)$ = 276652.8
Σx 192.0	192.0	256.0	320.0	384.0	384.0	488.1	476.0	$\Sigma(\Sigma x)$ = 2792.1

Note! Conversion factor: 1 kgf = 9.81N = 0.0098kN

(a) Correction factor, $C = \frac{[\Sigma(\Sigma x)]^2}{8n} = \frac{2792.1}{8 \times 4} = \frac{7795822.4}{32} = 243619.5$

(b) Total sum of squares of all observations, $\Sigma(\Sigma x^2) = 276652.8$

(c) Sum of squares of the totals of each column = $\Sigma(\Sigma x)^2$

$= 192^2 + 192^2 + 256^2 + 320^2 + 384^2 + 384^2 + 488^2 + 576^2$

$= 36864 + 36864 + 65536 + 102400 + 147456 + 147456$

$+ 238144 + 331776 = 1106496.0$

(d) Dividing the sum of squares of the totals of each column by the number of individual observations, n = 4, we get

$\frac{1106496.0}{4} = 276624.0$

(e) Sum of squares for total = (b) - (a) = 276652.8-243619.5
= 33033.3

(f) Between-treatments sum of squares = (d) - (a)
= 276624 - 243619.5 = 33004.5

(g) Within-treatments sum of squares = (b) - (f) = 276652.8-33004.5
= 243648.3

ANOVA Table for Treatment Means

SV	SS	df	MS	F-ratio (Observed)	F-ratio (F-table) at α = 5%	Significance
Between Treatments	33004.5	t-1 = 7	4714.97	0.46	2.42	n. s
Within Treatments	243648.8	t(n-1)=24	1012.0			
Total	276652.8	31				

N.B. n. s = not significant at 95% probability level

The Main Effects, P, Q and R

To compare P_1 and P_2 we have the sum of tear strengths as follows:

for P_1 : 192 + 192 + 256 + 320 = 960 kgf

for P_2 = 384 + 384 + 488.1 + 576 = 1832.1 kgf

For each of these, the sum is based upon 4x4 = 16 measurements

$\therefore$ sum of squares for P = $\frac{(960)^2 + (1832)^2}{16} - C$

$= \frac{921600 + 3356590.4}{16} - 243619.5 = 267386.9 - 243619.5 = 23767.4$

Similarly to compare Q_1 and Q_2 we sum the tear strengths as follows:

for Q_1 : 192 + 192 + 384 + 384 = 1152 kgf

for Q_2 : 256 + 320 + 488.1 + 576 = 1640.1 kgf

$\therefore$ Sum of squares for Q = $\frac{(1152)^2 + (1640.1)^2}{16} - C$

$= \frac{1327104 + 2689928.01}{16} - 243619.5 = 251064.5 - 243619.5 = 7445.0$

Likewise, to compare R_1 and R_2, we sum the tear strengths as follows:

for R_1 : 192 + 256 + 384 + 488.1 = 1320.1 kgf

for R_2 : 192 + 320 + 384 + 576 = 1472.0 kgf

$\therefore$ Sum of squares for R = $\frac{(1320.1)^2 + (1472)^2}{16} - C$

$= \frac{1742664.0 + 2166784}{16} - 243619.5 = 244340.5 - 243619.5$

$= 721.0$

The Interactions P x Q, PxR, QxR, PxQxR

Interaction sum of squares = $\frac{[(a+d)-(b-c)]^2}{(4)(n_1)}$

where n_1 = 2x4 = 8 and a, b, c, d are the sums shown below:

for P x Q

	Q_1	Q_2
P_1	a	b
P_2	c	d

for P x R

	R_1	R_2
P_1	a	b
P_2	c	d

for Q x R

	R_1	R_2
Q_1	a	b
Q_2	c	d

P_1Q_1 =a=192+192 = 384 P_1R_1 =a=192+256 =448 Q_1R_1 = a=192+384 = 576

P_1Q_2 =b=256+320 = 576 P_1R_2 =b=192+320 =512 Q_1R_2 = b=192+384 = 576

P_2Q_1 =c=384+384 = 768 P_2R_1 =c=384+488.1=872.1 Q_2R_1 = c=256+488.1=744.1

P_2Q_2 =d=488.1+576 = 1064.1 P_2R_2 =d=384+576 =134.4 Q_2R_2 = d=320+576 = 896

$\therefore$ P x Q interaction sum of squares $= \frac{[(384+1064.1)-(576-766)]^2}{(4)(8)}$

$= \frac{[(1448.1)-(-192)]^2}{32} = \frac{(1640.1)^2}{32} = \frac{2689928.0}{32} = 84060.25$

$\therefore$ PxR interaction sum of squares $= \frac{[(448+1344)-(512-872.1)]^2}{(4)(8)}$

$= \frac{(1792)-(-360.1)^2}{32} = \frac{2152.1^2}{32} = \frac{4631534.4}{32} = 144735.45$

$\therefore$ QxR interaction sum of squares $= \frac{[(576+896)-(576-744.1)]^2}{(4)(8)}$

$= \frac{[(1472)-(-168.1)]^2}{32} = \frac{1640.1^2}{32} = \frac{2689928.0}{32} = 84060.25$

$\therefore$ PxQxR interaction sum of squares =(B/W Treatment sum of squares)

- (Sum of the sum of squares for P,Q,R, PxQ, PxR and QxR)

$= 33004.5 - (23767.4 + 7445.0 + 721.0 + 84060.25 + 144735.45 + 84060.25)$

$= 33004.5 - 344789.35 = -311784.85$

$\therefore$ The complete ANOVA Table for Main Effects and Interactions gives:

S.V	SS	d.f	MS	F-ratio (observed)	F-ratio (F-table	Significance at α=5%
P	23767.4	1	23767.4	2.34	4.26	n.s
Q	7445.0	1	7445.0	0.73	"	n.s
R	721.0	1	721.0	0.07	"	n.s
PxQ	84060.25	1	84060.25	8.28	"	*
PxR	144735.45	1	144735.45	14.26	"	*
QxR	84060.25	1	84060.25	8.28	"	*
PxQxR	-311784.85	1	-311784.35	-30.71	"	n.s
Error (Within Treatments)	243648.3	24	10152.0			
Total	276652.8	31				

NB. * = significant at 95% probability level
n.s = not significant at 95% probability level

APPENDIX H: ESTIMATES OF CORRELATION COEFFICIENTS AND REGRESSION CONSTANTS

Y - 1. Basis Weight, y (g/m^2) versus Caliper, x (mm) for SAMCOT 6 Hand sheets

Replication	X	Y
1	0.60	139.8
2	0.57	138.5
3	0.59	138.7
4	0.59	139.2
Σ	2.34	556.2

Correlation Coefficient, $r = \frac{\Sigma XY}{\sqrt{\Sigma X^2 \Sigma Y^2}}$

Where, $X = x - \bar{x} = x - 0.585$

$Y = y - \bar{y} = y - 139.05$

$\therefore r \approx 0.979987$

$\therefore$ Coefficient of determination, $r^2 \approx 0.958$

Regression Line: $y = a + bx$

To estimate the regression constants, a and b:

$b = \frac{n\Sigma XY - \Sigma X \Sigma Y}{n\Sigma X^2 - (\Sigma X)^2} \approx 44.0$

$\therefore a = \bar{y} - b\bar{x} \approx 113.3$

$\therefore$ Line of best fit: $y = 113.3 + 44.0x$

F - 2 Basis Weight, Y (g/m^2) versus Caliper, X (mm) for SAMCOT 8 Hand sheets

Replication	X	Y
1	0.49	135.5
2	0.51	136.0
3	0.53	136.5
4	0.50	135.8
Σ	2.03	543.8

Correlation Coefficient, $r = \frac{\Sigma XY}{\sqrt{\Sigma X^2 \Sigma Y^2}}$

Where, $X = x - \bar{x} = x - 0.5075$

$Y = Y - \bar{Y} = Y - 135.95$

$\therefore r = 0.999301439$

$\therefore$ Coefficient of determination, $r^2 \approx 0.997$

Regression Line: $y = a + bx$

$\therefore$ To estimate the regression constants, a and b:

$b = \frac{n\Sigma XY - \Sigma X \Sigma Y}{n\Sigma X^2 - (\Sigma X)^2} \approx 24.6$

$\therefore a = \bar{y} - b\bar{x} \approx 123.5$

$\therefore$ Line of best fit: $y = 123.5 + 24.6x$

H - 3 Basis Weight, Y (g/m^2) versus Caliper, x (mm) for SAMCOT 9 Hand sheets

Replication	x	Y
1	0.48	122.0
2	0.46	121.8
3	0.47	121.9
4	0.49	122.3
Σ	1.90	488.0

Correlation Coefficient, $r = \frac{\Sigma XY}{\sqrt{\Sigma X^2 \Sigma Y^2}}$

where, $X = x-\bar{x} = x-0.475$

$Y = y-\bar{Y} = Y-122.0$

$\therefore r = 0.956182887$

$\therefore$ Coefficient of determination, $r^2 \approx 0.914$

Regression Line: $y = a + bx$

$\therefore$ To estimate the regression constants, a and b:

$b = \frac{n\Sigma XY - \Sigma X\Sigma Y}{n\Sigma X^2 - (\Sigma X)^2} \approx 16.0$

$\therefore a = \bar{y} - b\bar{x} \approx 114.4$

$\therefore$ Line of best fit: $Y = 114.4 + 16.0x$

H - 4 Basis Weight, y (g/m^2) versus Caliper, x (mm)
for SAMCOT 10 Hand sheets

Replication	x	y
1	0.46	114.0
2	0.47	114.5
3	0.45	113.7
4	0.47	114.2
Σ	1.85	456.4

Correlation Coefficient, $r = \frac{\Sigma XY}{\sqrt{\Sigma X^2 \Sigma Y^2}}$

where, $X = x-\bar{x} = x-0.4625$

$Y = y-\bar{y} = y-114.1$

$\therefore r = 0.930757842$

$\therefore$ Coefficient of determination, $r^2 \approx 0.866$

Regression Line: $y = a + bx$

$\therefore$ To estimate the regression constants, a and b:

$b = \frac{n\Sigma XY - \Sigma X\Sigma Y}{n\Sigma X^2 - (\Sigma X)^2} \approx 32.7$

$\therefore a = \bar{y} - b\bar{x} \approx 99.0$

$\therefore$ Line of best fit: $y = 99.0 + 32.7x$

H - 5 Burst Strength, y (kg/cm^2) versus Runkel Ratio, x

Variety	x	y
S6	0.385	0.845
S8*	0.560*	0.868*
S9	0.595	0.864
S10	0.600	0.851
Σ	1.58	2.56

* S8 is excluded in the regression of y on x

Correlation Coefficient, $r = \frac{\Sigma XY}{\sqrt{\Sigma X^2 \Sigma Y^2}}$

where, $X = x-\bar{x} = x-0.526666666$

$Y = y-\bar{y} = y-0.853333333$

$\therefore r = 0.729260948$

$\therefore$ Coefficient of determination, $r^2 \approx 0.532$

Regression Line: $y = a + bx$

$\therefore$ To estimate the regression constants, a and b:

$b = \frac{n\Sigma XY - \Sigma X\Sigma Y}{n\Sigma Y^2 - (\Sigma Y)^2} \approx 0.058$

$\therefore a = \bar{y} - b\bar{x} \approx 0.823$

$\therefore$ Line of best fit: $y = 0.823 + 0.058x$ kg/cm^2

$= 0.403 + 0.028x$ kPa.

Note! Conversion factor: 1 kg/cm^2 = 0.49 kPa.

H - 7 Tear Strength, y (kgf) versus Fibre Length, x(mm)

Variety	x	y
S6	0.240	54.0
S8*	0.262*	124.5*
S9	0.262	67.5
S10	0.274	87.0
Σ	0.776	209.5

* S8 is excluded in the regression of y on x

Correlation Coefficient, $r = \frac{\Sigma XY}{\sqrt{\Sigma X^2 \Sigma Y^2}}$

Where, $X = x-\bar{x} = x-0.258666666$

$Y = y-\bar{y} = y-69.5$

$\therefore r = 0.963021551$

$\therefore$ Coefficient of determination, $r^2 = 0.927$

Regression Line: $y = a + bx$

$\therefore$ To estimate the regression constants, a and b:

$b = \frac{n\Sigma XY - \Sigma X\Sigma Y}{n\Sigma X^2 - (\Sigma X)^2} \approx 926.6$

$\therefore a = \bar{y} - b\bar{x} \approx -170.2$

$\therefore$ Line of best fit: $y = 926.6x - 170.2$ kgf

$= 9.08x - 1.67$ kN

Note! Conversion factor: 1 kgf = 9.81 N = 0.0098 kN.

H - 6 Tear Strength, y (kgf) versus Runkel Ratio, x

Variety	x	y
S6	0.385	54.0
S8*	0.560*	124.5*
S9	0.595	67.5
S10	0.600	87.0
Σ	1.58	208.5

* S8 is excluded in the regression of y on x.

Correlation Coefficient, $r = \frac{\Sigma XY}{\sqrt{\Sigma X^2 \Sigma Y^2}}$

where, $X = x-\bar{x} = x-0.526666666$

$Y = y-\bar{y} = y-69.5$

$\therefore \quad r = 0.820898205$

$\therefore$ Coefficient of determination, $r^2 \approx 0.674$

Regression Line: $y = a + bx$

$\therefore$ To estimate the regression constants, a and b:

$b = \frac{n\Sigma XY - \Sigma X\Sigma Y}{n\Sigma X^2 - (\Sigma X)^2} \approx 111.0$

$\therefore \quad a = \bar{y} - b\bar{x} \approx 11.0$

$\therefore$ Line of best fit: $y = 11.0 + 111.0x$ kgf

$= 0.108 + 1.09x$ kN

<u>Note!</u> Conversion factor: 1 kgf = 9.81 N = 0.0098 kN.

H - 9 Tear Strength, y (kgf) versus Slenderness Ratio, x

Variety	x	y
S6	11.60	54.0
S8*	13.20*	124.5*
S9	11.50	67.5
S10	14.54	82.0
Σ	37.64	208.5

* S8 is excluded in the regression of y on x

Correlation Coefficient, $r = \frac{\Sigma XY}{\sqrt{\Sigma X^2 \Sigma Y^2}}$

where, $X = x - \bar{x} = x - 12.54666667$

$Y = y - \bar{y} = y - 69.5$

$\therefore \quad r = 0.901330388$

$\therefore$ Coefficient of determination, $r^2 \approx 0.812$

Regression Line: $y = a + bx$

$\therefore$ To estimate the regression constants, a and b:

$b = \frac{n\Sigma XY - \Sigma X \Sigma Y}{n\Sigma X^2 - (\Sigma X)^2} \approx 8.66$

$\therefore \quad a = \bar{y} - b\bar{x} \approx -39.15$

$\therefore$ Line of best fit: $y = 8.66x - 39.1$ kgf

$= 0.085x - 0.384$ kN

Note! Conversion factor: 1 kgf = 9.81 N = 0.0098 kN.