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RECYCLING OF RUBBER CHIPS INTO COMPOSITE ELASTOMERS

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DECLARATION

This thesis is my original work and has not been presented for a degree in any other University.

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DEDICATION

This work is dedicated to my wife Wanjikũ, and our kids Gathoni, Nyakaroh and Njireh.

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ABBREVIATIONS

ASTM	American Society for Testing and Materials
BPO	Benzoyl Peroxide
BR	Butadiene Rubber
CBS	Central Bureau of Statistics
DRC	Dry Rubber Content
DSC	Differential Scanning Calorimeter
EPDM	Ethylene Propylene Diene Monomer Rubber
Fstn	Firestone
HDPE	High Density Polyethylene
IIR	Isobutylene-Isoprene (Butyl) Rubber
KIPI	Kenya Industrial Property Institute
KNCPC	Kenya National Cleaner Production Center
MA	Maleic Anhydride
MBTS	Benzothyliazyl Disulphide
MFI	Melt Flow Index
$N660$	Carbon Black (technically classified)
NEMA	National Environmental Management Authority
NR	Natural Rubber
PHR	Per Hundred parts of Rubber
PP	Polypropylene
SBR	Styrene Butadiene Rubber
SDEV	Standard Deviation
SEM	Scanning Electron Microscope
TC	Technically Classified
TD	Tyre Dust
TMQ	Trimethyldihydroquinoline Polymer

$TMTD$	Tetramethyl Thiuram Disulphide
TS	Tensile Stress
UE	Ultimate Elongation
UTS	Ultimate Tensile Strength
$WAXS$	Wide Angle X-ray Spectrometer
WB	Wheelbarrow

NOMENCLATURE

ε_p	Polymeric matrix strain
ε_c	Composite strain
ϕ	Volume fraction of filler
E_c	Modulus of elasticity of composite [N/m^2]
σ	Tensile strength [N/m^2]
σ_m	Tensile strength of the polymer matrix [N/m^2]
σ_{yc}	Yield stress of composite [N/m^2]
σ_{yp}	Yield stress of unfilled polymer [N/m^2]
T_g	Glass transition temperature [^{0}C]
Δm	Change in mass [g]
ρ	Density [kg/m^3]

ABSTRACT

This research work focused on standardizing and optimizing the current local methods of recycling tread tyre chips that are generated as waste in re-treading industries. Existing factory processing methods, such as used in wheelbarrow tyre and car mat production were analysed and their shortcomings highlighted. These shortcomings were used as improvement areas in the research. Physical properties such as size and weight of various samples of scrap chips from different re-treading companies were compared and a grading code generated using meshes. The graded chips were surface treated with potassium permanganate to generate hydroxyl groups on the rubber surface, in order to facilitate a reaction with virgin natural rubber (NR). Various chips/NR volume ratios were prepared, processed and cured using conventional industrial procedures. The mechanical properties of the samples, such as tensile strength, hardness, elongation at break (%), resilience (%) and abrasion resistance were tested and compared with those of specimens prepared using existing manufacturing methods. Blend cost analysis and mechanical properties optimization are among the areas that were given extra emphasis due to their importance in this research. New formulations were generated to produce superior products that will create a new market for this plastic pollutant thereby reversing the effect it has on the environment.

The results showed that tread particle size form the fundamental basis for the control of most mechanical properties(toughness, elongation and abrasion) of recycled rubber vulcanizates. For a natural rubber based formulation such as used in wheelbarrow tyre manufacture, the tread buffings were found to be good extenders of natural rubber while still imparting moderate improvements on the mechanical properties. Also, the buffings were found to improve the tensile properties of virgin NR vulcanizates through blend aging.

Chapter 1

INTRODUCTION

1.1 Overview

Rubber is produced from natural or synthetic sources. Natural rubber is obtained from latex (milky white fluid) found in many plants, while synthetic rubbers are produced from unsaturated hydrocarbons.

Historical records show that natural rubber was used in religious ceremonies as early as the sixth century A.D [3]. However, it was not until the 18^{th} century that European scientists and manufacturers began to use rubber successfully on a commercial basis. The first person to fully commercialize the use of rubber products was Charles Macintosh who in 1823 established a plant in Glasgow for the manufacture of waterproof cloth and the rainproof garments [4].

The main plant that produces natural rubber (NR) today is *Hevea Brasiliensis*, a native of Brazil. As at 1981, no other plant could compare in respect of both the quantity and quality of natural rubber produced by this plant [5]. Table 1.1 shows a typical constituents of the coagulum obtained by treatment of the latex with acid, followed by washing and drying [6]. The *Hevea* latex is then concentrated to about 60% dry rubber content (DRC), usually by centrifuging or evaporation, or alternatively coagulated and dried [7].

Table 1.1: *Hevea* latex; typical constituents

Ingredient	Percentage weight
Hydrocarbon	94.5
Acetone solubles	2.8
Nitrogen	0.4
Ash	0.2
Others	2.1

Synthetic rubbers such as styrene-butadiene rubber (SBR) were discovered in the early 1930's and created an alternative to natural rubber, averting dependence on a single source of rubber. Raw rubber is not strong, does not withstand much heat without losing its shape and is adversely affected by many solvents, particularly petro-type solvents.

The discovery of vulcanisation by Goodyear in 1839 solved most of the problems that inhibited the success of the rubber industry at the time [8]. This unique property of either natural or synthetic rubber to change its physical properties from plastic to elastic revolutionized the rubber industry. However, it created one of the most difficult recycling problems ever encountered, as the chemical process is irreversible. Recycling methods like heating normally leads to chemical degradation and structural breakdown resulting in inferior products.

By the mid 1800s, carbon black powder was discovered to be a necessary reinforcement for improving the tear and abrasion properties of the vulcanised rubber [9]. If carbon black powder and sulphur are mixed with rubber, the mixture retains the plastic properties associated with un-vulcanised rubber. However, if the mixture is heated under pressure, the sulphur combines chemically by cross-linking with the hydrocarbon molecules to change the physical properties from plastic to elastic, as shown in Figure 1.1. Of prime importance to engineers is the improvement of the mechanical properties.

The designated letters in the figure represent;

(a) monosulphide cross-link

(b) disulphide cross-link

(c) polysulphide cross-link (x = 3-6)

(d) parallel vicinal cross-link (n = 1-6) attached to adjacent main-chain atoms and which have the same influence as a single cross-link

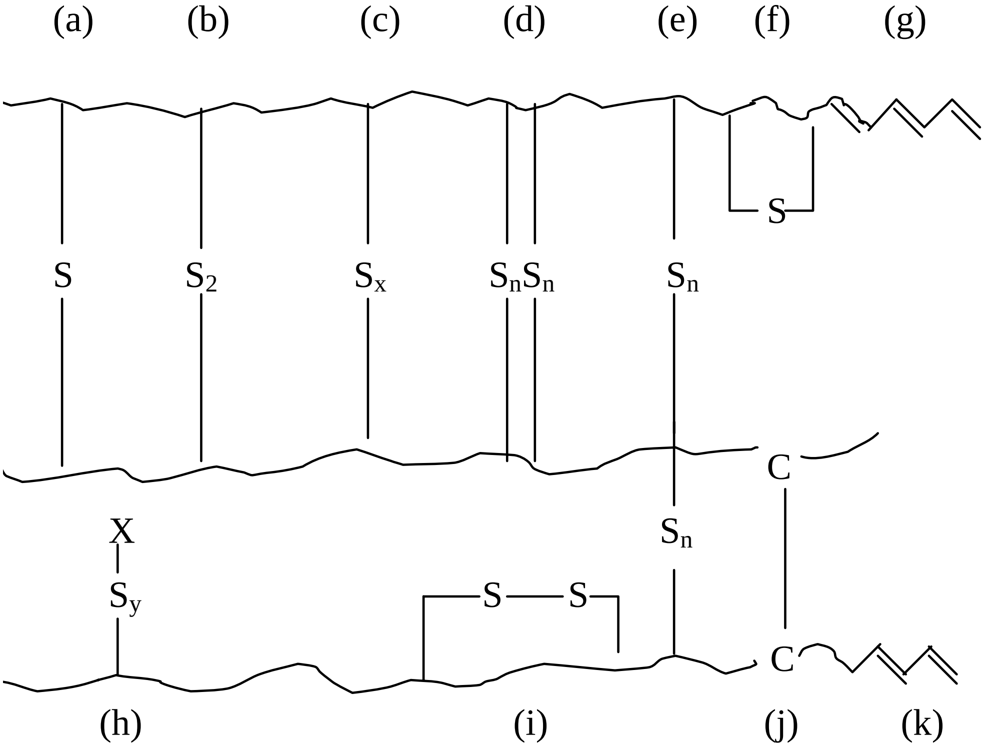


Figure 1.1: Typical chemical grouping in a sulphur vulcanised natural rubber network

(e) cross-links attached to common or adjacent carbon atom

(f) intra-chain cyclic monosulphide

(g) conjugate triene

(h) pendent sulphide group terminated by moiety X derived from accelerator

(i) intra-chain cyclic disulphide

(j)carbon-carbon cross-links (probably absent).

(k) conjugate diene

Although rubber has been found to be a very useful material in many products such as electrical insulations, sports equipments and shoe soles, its use in tyres is perhaps a more important contribution to our present economy than in any other field. This has led to excessive generation of non-biodegradable rubber scraps creating disposal problems. Records show that over 50 million tyres (just over 480,000 tonnes) were scrapped in the United Kingdom in 2001 while 80 million tonnes were disposed of in landfills [10]. Studies [11] estimate there are approximately 2 billion scrap tyres currently in United States of America landfills, with over 270 million additional tyres reaching the waste stream each year (170 million are burned as fuel, 60 million are incorporated into various low technology engineering uses such as athletic tracks and marine reefs, and the remaining 40 million end up in landfills).

Table 1.2 summarises the application of different classes of rubber in the manufacture of vehicle tyres [2].

Table 1.2: Typical application of various types of rubber

Type of rubber	Application
Natural rubber (NR)	Commercial vehicles such as lorries, buses and trailers
Styrene- butadiene rubber (SBR) and butadiene rubbers (BR)	Small lorries, private cars, motorbikes and bicycles
Butyl rubber (IIR)	Inner tubes

In the 150 years since Goodyear's patent, numerous ideas have been formulated to combat the problem of waste rubber, all with varying degrees of success. It is well documented in the literature [12] that tyre rubber is a thermoset, meaning the polymer is cross-linked into a complex infusible network. Vulcanized rubbers have three-dimensional chemical networks, and as a result they do not melt or dissolve. The presence of these networks creates a tremendous problem at the end of a product's life [13]. The cross-links are usually covalent bonds between polymer chains, which are difficult to break by heating as is done with thermoplastics. Interestingly, industrialists recognized the need for methods of reuse of waste rubber products, as early as 1853 when the rubber grinding process was patented. This ground rubber powder was then mixed with virgin uncross-linked rubber prior to vulcanisation; a process still used today [11].

There are many ways in which tyres can be reused or reclaimed. The waste management hierarchy dictates that reuse, recycling and energy recovery, in that order, are superior to disposal and waste management options as outlined in table 1.3 [2]. This hierarchy identifies retreading as the most efficient process of tyre waste management. Ultimately, the reuse of recycled rubber is important in terms of both waste disposal and reduction of product costs [14].

Table 1.3: Principal rubber recycling processing paths [2]

Kind of recovery	Method	Recovery process
Product reuse	Repair	• Retreading • Regrooving
Material reuse	Physical	• Tearing apart • Cutting • Processing to crumb
	Chemical	• Reclamation
	Thermal	• Pyrolysis • Combustion
Energy reuse	Thermal	• Incineration

In Kenya, road transport dominates other modes of transport in the transfer of both goods and people. This leads to high consumption of pneumatic tyres that generate a lot of scrap after usage. Due to the high cost of new tyres , most of the truck tyres are re-treaded to save on transport running costs thereby generating large volumes of tread buffings (retread chips). The amount of buffings generated from each tyre varies widely depending upon the tyre size (radius and width), percentage use and type of tread to be applied.

Table 1.4 shows comparative prices for new tyres (Ceat brand made in India), and cost of retreading the same tyre sizes with Elgitread (pre-cure) from India [15]. A maximum saving of 65.2% is recorded when retreading the 315/80 R 22.5 size tyre.

Table 1.4: Comparative prices for new and retreading tyres (2006)

Tyre size	Cost in Ksh.		Savings (%)
	New tyre (Ceat)	Retreading (Elgitread)	
7.5 0 × 16	7,600	3,700	51.3
8.25 × 20	11,000	6,000	45.5
9.00 × 20	18,000	6,500	63.9
10.00 × 20	18,000	6,800	62.2
11.00 × 20	20,500	7,300	64.4
12.00 × 20	21,500	7,800	63.7
12.00 × 24	25,000	9,000	64.0
11R × 22.5	20,000	7,300	63.5
295/80 ×22.5	22,000	8,000	63.6
315/80 × 22.5	23,000	8,000	65.2
11R × 24.5	27,000	10,000	63.0

Application of new treads is done using one of the two methods; pre-cure or mould-cure. In the pre-cure method, the tread rubber is vulcanised with the new tread design prior to application, while in the mould-cure process, unvulcanised rubber is applied to the buffed tyre before the tread is vulcanised. Pre-cure is bound to be cheaper than mould-cure and hence is commonly used by local retreaders. This leads to generation of large volumes of tread buffing that add pressure to existing disposal methods.

A few local companies, such as Plastic and Rubber Ltd. and isolated Jua-kali artisans have been involved in manufacturing products from these retread buffings thereby complementing the existing clean-up efforts. Their products include wheelbarrow tyres, car mats and damper sheets. Improvement and optimization of mechanical properties of these products is limited by inadequate technical information available in this area and hence this experimental research is indubitably important to generate data towards filling this gap.

Scrap tyre disposal is a worldwide problem and leads to tyre dumps/stockpiles that create a breeding habitat for disease-carrying mosquitoes, rodents and other pests [16]. This introduces both health and environmental hazards that need urgent solutions. Most recycling and disposal programs are in the developed world and are controlled by state departments to monitor the pollution level in industries [17]. In Kenya, government institutions such as the National Environmental Management Authority (NEMA) and Kenya National Cleaner Production Center (KNCPC) have only established scrap tyre regulations but are yet to come up with any form of scrap rubber recycling programs.

With the fast accumulation of scrap tyres and their primary derivatives from industries, there is inevitably an increased alarm on upcoming hazards, hence new markets and technologies must be created to clean up this industrial waste that clogs drainage systems and pollute rivers, tampering with the delicate freshwater and marine ecosystems.

1.2 Statement of the Problem

Almost all research work in scrap rubber revolves around analysing it in powder form, mainly because it can be obtained easily in reclaimed and standardized form from established rubber recycling factories, ready for use. Inadequate studies have been done to experiment and document the properties of recycled rubber chips (buffings), which would continuously open new dimensions to tackle this perennial industrial menace.

Waste tread tyre buffings are obtained from retread factories at almost zero cost making them cheaper than powder rubber (reclaimed) which has an estimated cost of Ksh. 39.50 per kg [18]. Several factories including Jua-Kali sheds have taken advantage of this cheap raw material to manufacture light duty products supplementing the existing cleanup efforts. A great deal of information may be gained from a study of the mechanical properties of these products with a view to optimising the mechanical properties by improving the mixing, blending and processing methods. This would lead both to the development of cheaper processes and superior products that would fetch higher profits thereby improving the living standard of the manufacturers in line with the government policy of poverty eradication.

Investigations have shown that recycled rubber crumb acts as a toughening agent for polystyrene (a brittle thermoplastic) [19]. The toughness of the resultant materials increases with the degree of rubber/matrix adhesion and decreases with increasing rubber particle size. However, the effect of surface treatment of rubber particles on reactive blends with polymethyl methacrylate has been studied [20] and it has been found that surface treatment could be used to enhance the mechanical properties of the blend by improving bonding between existing phases.

1.3 Objective

The main objective of this study is to develop an optimised process of recycling rubber buffings into composite elastomers using a modified industrial formulation. The research findings will be used to offer advise to the relevant manufacturing sector to spur growth in both rubber scrap recycling and environment hazard awareness. This will be achieved by:

- Generation of a grading code by classifying the scrap chips in standardised aggregates.

- Determination of the quantities and properties (size and weight) of the various samples of scrap buffings from different tyre brands sourced from different companies.

- Preparation of tread tyre chip blends of different compositions to evaluate the effect of compatibilizers on the mechanical properties (tensile strength, hardness, elongation at break (%) and abrasive resistance) of the ensuing composites.

- Establishing the optimum mechanical properties of vulcanised rubber composites, and optimum production costs of rubber composite blends.

Chapter 2

LITERATURE REVIEW

Recycled rubber blends are classified as particulate composites as they consist of particles of various sizes and shapes randomly dispersed within the matrix [21]. Because of the randomness of particle distribution, they are regarded as both quasi-homogeneous and quasi-isotropic on a scale larger than particle size and spacing. In their design, the large number of degrees of freedom available enable material optimisation for several given criteria simultaneously. However, the numerous available options make the process more involved and the analysis even more complex. This analysis of optimisation to yield the best mechanical properties is purely dependent on the type of covalent bonding between polymer molecules and the ground rubber. The deterioration of the mechanical properties, which limits the applicability of ground rubber in products, evidently occurs because the bonding force between the rubber and the matrix is often low and thermodynamic incompatibility leads to poor interfacial adhesion [14]. Figure 2.1 shows a morphology of a tensile fracture surface showing phase separation of ground rubber and matrix [1].

Blending recycled rubber with other materials has been an attractive alternative to dumping methods for many years [22]. The chief drawback has been the difficulty in obtaining adequate properties from the resultant blends and end products. Early research demonstrated that the incorporation of recycled rubber into either virgin rubber or plastics resulted in materials with inferior properties [6]. This has limited the use of this potentially beneficial technology, even as a greater understanding for the role of rubber particle size and surface reactivity has been developed. As a result, a number of compatibilization and modification techniques have been investigated yielding improved mechanical properties such as tensile strength, percentage elongation at break and toughness. Further complicating this issue is the wide variety of recycled rubber

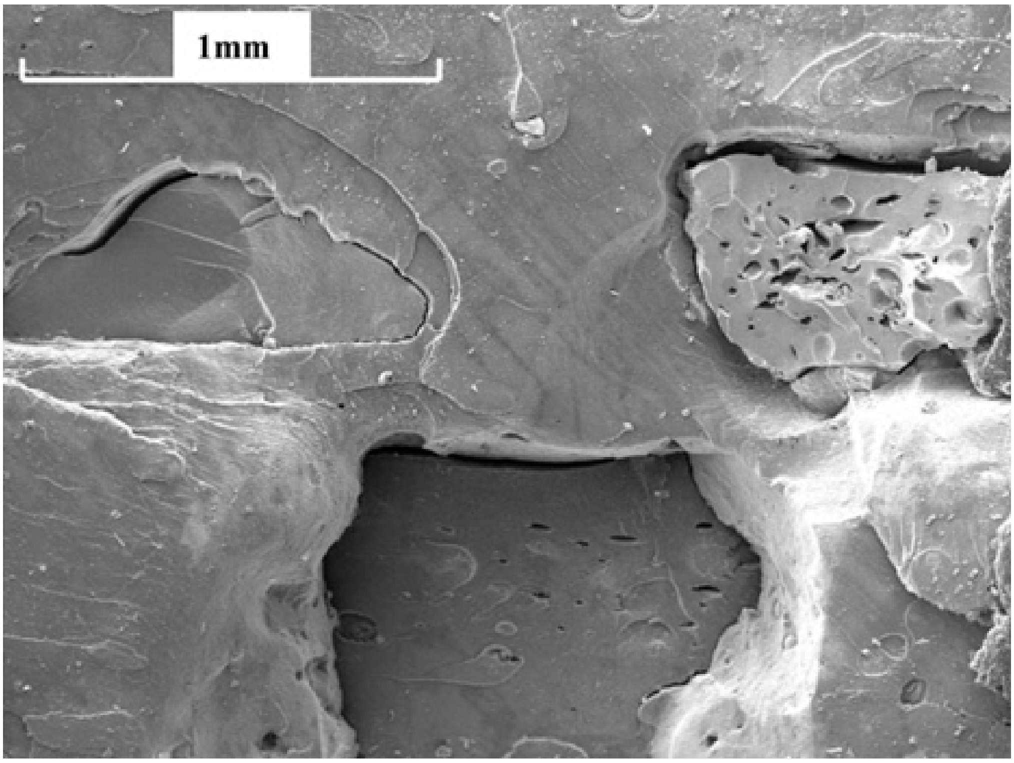


Figure 2.1: SEM photomicrograph of a recycled rubber composite [1]

compounds and, in many cases, their inherent commingled nature. Recycled rubber/thermoplastic blending technology has been built upon the science developed for the manufacture of thermoplastic elastomers and rubber-toughened plastics from virgin materials [23]. The first requirement is that the two components be thermodynamically incompatible enough to phase separate, but not so dissimilar to inhibit intimate intermixing. In a successful blend, the domain size of the dispersed phase is normally small, maximising the interfacial surface area. This requirement is found to occur within certain limits of the solubility parameter difference between the two materials in the blend. In cases where the solubility parameters mismatch may be large, compactibilizers that act as inter-phase bridges between hard and soft phases have successfully been used [1].

The recent technology developed to enable the use of recycled rubber in virgin polymer materials has attracted many rubber industries [24], however, only scant literature is available in this field.

2.1 Surface Treatment

A study on the effect of surface treatment of rubber particles on reactive blending with polymethylmethacrylate [20] established that, a great percentage of the double bonds in polymers are still available even after rubber is vulcanised. Figure 2.2 shows how the surface of a rubber particle is surface treated with potassium permanganate solution to generate hydroxyl groups by breaking the double bond at the particle surface. This exposes the rubber surface for reaction through this hydroxyl group. Figure 2.3 shows how maleated polypropylene (PP) reacts with the hydroxyl group attaching the polypropylene chain to the rubber particle.

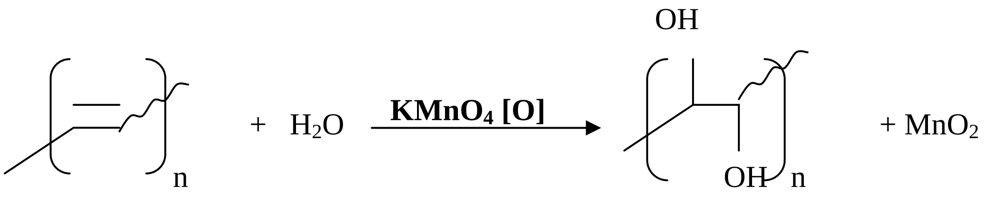


Figure 2.2: Hydroxyl group formation on rubber surface

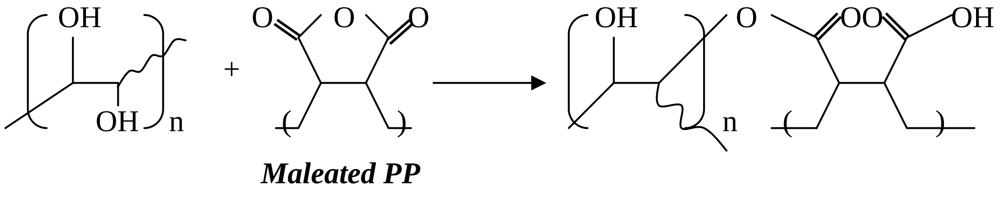


Figure 2.3: Attachment of the PP chain to the rubber particle.

In this research, the generation of the hydroxyl groups on the scrap rubber surface would be used to attach other virgin polymers, such as natural rubber, to form superior particulate composites.

2.2 Mathematical Models

The interaction between the continuous polymer phase and the particulate filler phase has been correlated with a simple model to investigate adhesion in a bead filled composite [25].

$$\varepsilon_c = \varepsilon_p(11.105\phi^{1/3}) \tag{2.1}$$

where:

- ε_c = Composite strain
- ε_p = Polymeric matrix strain
- ϕ = Volume fraction of filler

Further analysis has shown that the modular ratio is a function of the strain imposed on the polymer [25]. This function can be described as follows for two different filler concentrations:

$$\frac{[E_c(t)]_2}{[E_c(t)]_1} = \frac{1 + (\varepsilon_p)_1}{1 + (\varepsilon_p)_2} \tag{2.2}$$

where:

- E_c = Modulus of elasticity of composite

The term $1 + (\varepsilon_p)$ accounts for the reduction in cross sectional area of the polymer that results from the addition of filler. This equation holds for only low concentration of the filler material hence further quantitative analysis of experimental relaxation data is needed.

Equation 2.3 shows an empirical model to describe the dependence of the tensile strengths with filler content [26].

$$\sigma = \frac{1-\phi}{1+A\phi}\sigma_m f(\phi) \tag{2.3}$$

where:

- σ = Tensile strength of the composite
- σ_m = Tensile strength of the polymer matrix

The value of constant A was found to depend on the type of packing of the filler material. Applying equation 2.3 to a number of different polymer/filler systems while taking the value of A= 2.5 (assumed as an approximate upper limit for different types of close packing) [26], the following expression results:

$$\sigma = \frac{1-\phi}{1+2.5\phi}\sigma_m exp(B\phi) \tag{2.4}$$

where:

- B = Parameter related to the interface properties (B = 0.246 for non-adhesion set up [26]).

The surface treatment of filler particles has also been found to increase the value of B, thus increasing the tensile strength of the composite [26].

It would be worthwhile to test the validity of equation 2.4 in vulcanized rubber composites and possibly analyse the variation of B with volume fraction of filler.

A model for dependence of yield stress on the fraction of filler similar to equation 2.1 has also been presented [27].

$$\sigma_{yc} = \sigma_{yp}(1 - 1.21\phi^{2/3}) \tag{2.5}$$

Where;

- σ_{yc} = yield stress of the composite
- σ_{yp} = yield stress of the unfilled polymer.

Equation 2.5 indicates that, $\sigma_{yc} = \sigma_{yp}$ for zero concentration of filler, and σ_{yc} = 0 at a packing of $\phi = 0.75$. This packing is assumed to be the theoretical maximum filler ratio. However, in practice, the maximum packing that can be achieved by normal mixing technique is approximately 0.6 [27].

2.3 Effect of Particle Size and Melt Flow Index

Development of thermoplastic elastomers (TPE) by blending more than 50% of EPDM rubber into the polypropylene composites [16] resulted in materials showing excellent mechanical properties as evidenced by stress and strain capability of blends, with reactive blending giving significant improvement in all cases. Elongation capability results identified the melt flow index of the polypropylene as a critical factor, i.e., the higher the melt flow index for polypropylene, the lower the elongation capability. A possible explanation of this unexpected behaviour was proposed to be due to the melt flow index of polypropylene such that, the lower the melt flow index, the higher the molecular weight and the lower the crystallinity resulting in a higher elongation due to the greater amount of amorphous material. It is expected that in this research, more experimental data on other polymers like natural rubber will be generated to explain this unexpected behaviour.

The size of rubber particles in the blend was also found to have a significant effect on the resulting mechanical properties of the thermosetting elastomers. These properties decreased with increase in particle size. This is due to the greater surface area to volume ratio in smaller particles, resulting in better bonding. It is therefore expected that rubber chips would yield even worse results due to their low surface area to volume ratio compared with the preceding case. However, they would decrease the amount of reactive reagents required for a given volume/weight of blend.

Blending of high-density polyethylene (HDPE) with recycled tyre rubber has also been studied [20] and it was found that tensile strength and hardness decreased with increase in rubber content. This can be explained through a volume rule of additivity where the higher strength polypropylene molecules are gradually replaced by the lower strength EPDM phases.

2.4 Effect of Sintering Time, Temperature and Pressure

A technique to rebuild 100% recycled rubber powder to new parts using a "High-Pressure High-Temperature Sintering" model [17] found sintering time to be a major factor, improving the strength and elongation at break with no effect on modulus of elasticity. This proves that adhesion of some type occurs between the particles, thus allowing them to sinter together by either a physical or chemical cross-link. Experimental result showed that these new parts retained greater than 60% of the virgin rubber properties of a typical tyre tread formulation. Higher pressures and temperatures were also found to give even better results. However, the long sintering time and excessively high temperature that would increase costs of production at an industrial set-up negate these advantages, hence the need to confine this parameters within the existing local production capacity of 100 MPa and 170^0C.

Other researchers [28] found the temperature of 80^0C to be the onset of the chemical stress relaxation/interchange chemistry for sulphur containing rubber when used in moulding parts. This indicates that, at temperatures below 80^0C, no mechanical gain is expected thus curing should be done above this temperature. However, temperatures should not exceed the critical temperature of 230^0C as the mechanical properties at break of the moulded parts begin to deteriorate [11].

Ideally, conversion of conventional elastomer (thermoset) chips into a composite elastomer through blending with un-vulcanised rubber introduces new market applications for scrap rubber. Overall, the main advantages of this process are two fold: to reduce both the amount of virgin rubber necessary for rubber production and amount of rubber reaching the waste stream. This research is therefore relevant and important to both environmentalists and rubber manufacturers.

Common uses of the resulting re-cycled rubber composites are in:

1. Pneumatic tyres
2. Wheelbarrow tyres
3. Rubber mountings and bushes
4. Roller casings
5. Shoe soles
6. Car carpets and doormats
7. Bumpers

Chapter 3

MATERIALS AND METHODS

The project was carried out at Sameerafrica Ltd. using the well-furnished laboratory facilities and assistance of experienced personnel both in the Technical Service and Quality Control Departments. To better analyse the end properties of recycled tread particles, samples were sourced from the locally manufactured products. This was necessary to make the research cheap and relevant so that end results can easily be blended using existing production methods to improve locally recycled rubber products.

3.1 Evaluation of Tyre Tread Buffings Cost Price

Tyre tread buffings are waste product from tyre retread companies. They are generated when the tyre to be retreaded is clumped on a rotating drum and a rotating buffing tool is applied on the outer surface of the tyre. The size and profile of the buffings are a function of the buffing tool design and the relative speed of the rotating drum and the buffing tool. They are a global disposal problem due to the environmental impact caused by this waste. With the stringent surveillance by the already established National Environment Management Authority (NEMA), local companies have resorted to contracting rubber scrap dumpers at a fee. Hence the most logical way to evaluate the cost of tread dust was based on the cost of transportation within the Nairobi area.

The approximate commercial cost of transporting seven (7) tons of tread dust within Nairobi industrial area was established to be Kenya shillings (Ksh.) 4000 or \$ 54.8 (using a dollar rate of 1\$ = Ksh. 73)

Hence cost of 1kg tyre tread dust

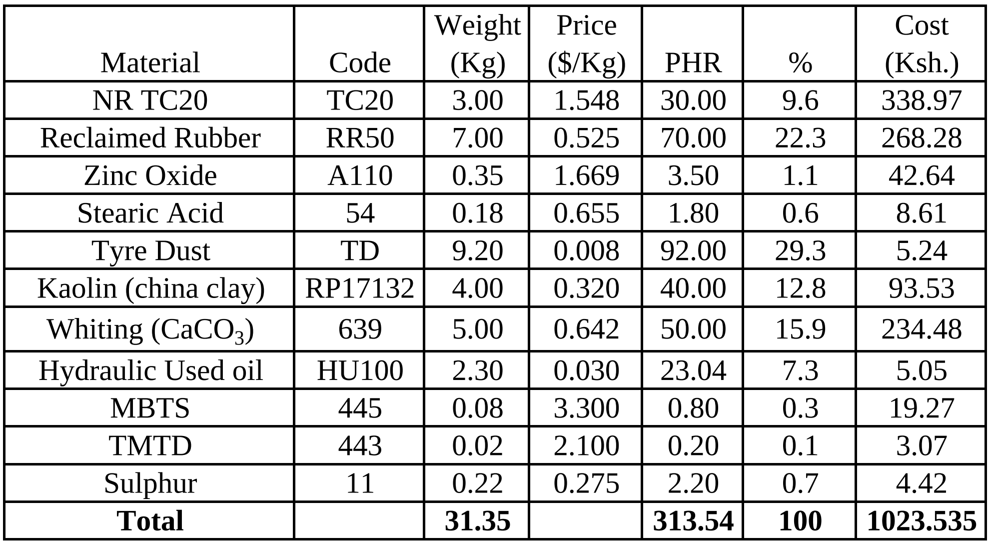
$$\frac{58.4}{7000} = \$0.0078$$

3.2 Sampling

3.2.1 Batch Formulation

The batch formulations of wheelbarrow tyre and the car black mat were sourced from Plastics and Rubber Industry; a rubber recycling factory in Nairobi. These formulations were designed using the PHR method (fillers and pigments are calculated as percentage of the total amount of polymer). Material cost was sourced from various suppliers in Nairobi and the dollar exchange rate was taken as 1\$ = Ksh. 73

Table 3.1: Wheelbarrow tyre formulation (single batch)



Material	Code	Weight (Kg)	Price (\$/Kg)	PHR	%	Cost (Ksh.)
NR TC20	TC20	3.00	1.548	30.00	9.6	338.97
Reclaimed Rubber	RR50	7.00	0.525	70.00	22.3	268.28
Zinc Oxide	A110	0.35	1.669	3.50	1.1	42.64
Stearic Acid	54	0.18	0.655	1.80	0.6	8.61
Tyre Dust	TD	9.20	0.008	92.00	29.3	5.24
Kaolin (china clay)	RP17132	4.00	0.320	40.00	12.8	93.53
Whiting ($CaCO_3$)	639	5.00	0.642	50.00	15.9	234.48
Hydraulic Used oil	HU100	2.30	0.030	23.04	7.3	5.05
MBTS	445	0.08	3.300	0.80	0.3	19.27
TMTD	443	0.02	2.100	0.20	0.1	3.07
Sulphur	11	0.22	0.275	2.20	0.7	4.42
Total		**31.35**		**313.54**	**100**	**1023.535**

where;

- NR (TC20) = Natural Rubber; Technically Classified with 20% dirt content
- MBTS = Benzothyliazyl disulphide (primary accelerator)
- TMTD = Tetramethyl thiuram disulphide (secondary accelerator)
- TMQ = Trimethyldihydroquinoline polymer (anti oxidant)
- PHR = Per hundred parts of rubber (polymer)

Table 3.2: Car black mat formulation (single batch)

Material	Code	Weight (Kg)	Price ($/Kg)	PHR	%	Cost (Ksh.)
NR TC20	TC20	5.00	1.548	41.67	18.7	564.95
Reclaimed Rubber	RR50	7.00	0.525	58.33	26.1	268.28
Zinc Oxide	A110	0.55	1.669	4.58	2.1	67.01
Stearic Acid	54	0.30	0.655	2.50	1.1	14.35
TMQ	A104	0.01	3.300	0.08		2.41
Flexon	FX1	2.30	1.025	19.17	8.6	172.10
Kaolin	RP17132	5.00	0.320	41.67	18.7	116.91
Whiting ($CaCO_3$)	639	6.00	0.642	50.00	22.4	281.37
MBTS	445	0.20	3.300	1.67	0.7	48.18
TMTD	443	0.02	2.100	0.17	0.1	3.07
Sulphur	11	0.40	0.275	3.33	1.5	8.03
Total		**26.78**		**223.17**	**100**	**1546.64**

Considering the formulations in Tables 3.1 and 3.2, tyre dust, Kaolin (china clay) and whiting ($CaCO_3$) are used as cheap fillers as depicted by the amount used and the low cost. However, these fillers impart different physical properties to the vulcanizate thus forming the basis of this experiment.

3.2.2 Tyre Treads Buffings

To broaden the scope of the experiment, treads buffings were selected from different tyre sizes and different manufacturers based in different countries as shown in Table 3.3. The idea was to capture the various technologies used in tyre tread building.

Table 3.3: Tyre tread sourcing

Tyre brand	Size	Country of origin
Firestone	1000 R20	Kenya
Kelly	315/80 R 22.5	S. Africa
Toyo	215/70 R 19.5	Japan
Goodyear	18.4 R 30	Egypt
Pirelli	195 R 14	Brazil

3.3 Samples Preparation and Testing

The ASTM D3182: 1982 was exclusively used as the guide to blend, prepare and cure different experiment specimens [29]. This was found to be the practice with leading tyre manufacturing divisions globally. Weighing was done using a Mettler P1000 (tolerance ±0.0005 grams) micro weighing machine.

3.3.1 Blending

Compound blending was done using a water-cooled 302.5mm (≈12 inch) laboratory mill (Figure3.1) at a temperature of 70 (±1)^{o}C to avoid compound scorching at elevated temperatures. The blending sequence was as in Table 3.1, such that, polymers (natural rubber and reclaimed rubber) were added first in the mill and vulcanising agent (sulphur) was added last. This sequence was necessary to avoid pre-vulcanisation during milling. Carbon black was conditioned by heating for 1 hour at 125 (±3)^{0}C in an oven to improve dispersion when blending as recommended in ASTM D 3182: 1982. Total milling time was confined to 22 (±5) minutes after which the mixing was concluded by passing the rolled batch endwise through the mill six times with an opening of 0.8 mm to improve dispersion. Good and consistent dispersion of ground rubber in virgin rubber is essential for optimum vulcanizate properties [30]

3.3.2 Vulcanised Sheet Preparation

The standard vulcanised sheet test material was sheeted out to 2.3 (±0.1) mm thickness from which specimens with a minimum of 3 mm less in width and length than corresponding dimensions of the curing mould cavity were cut (Figure3.2). The direction of sheeting out was marked on each test piece to indicate the direction of pull.

Figure 3.1: Laboratory mill

3.3.3 Curing

Curing was done using a steam heated laboratory press set at 100 MPa and 170^{o}C. Cure moulds were first preheated to a temperature of 170^{o}C. This was verified with a hand pyrometer after which the cure samples were sandwiched between the moulds (Figure3.2), inserted in the heating platens and cured at a pressure of 100 MPa. Care was taken not to allow the cure mould nearer than 75 mm to the edge of the heated platens during vulcanisation. After curing, the samples were removed and allowed to cool and age at room temperature ($\approx$23^{o}C) for 24 hours which is within limits specified by the standard (ASTM D 3182: 1982) [29]. This was necessary to allow post-vulcanisation structural stabilization, which would otherwise affect results [31].

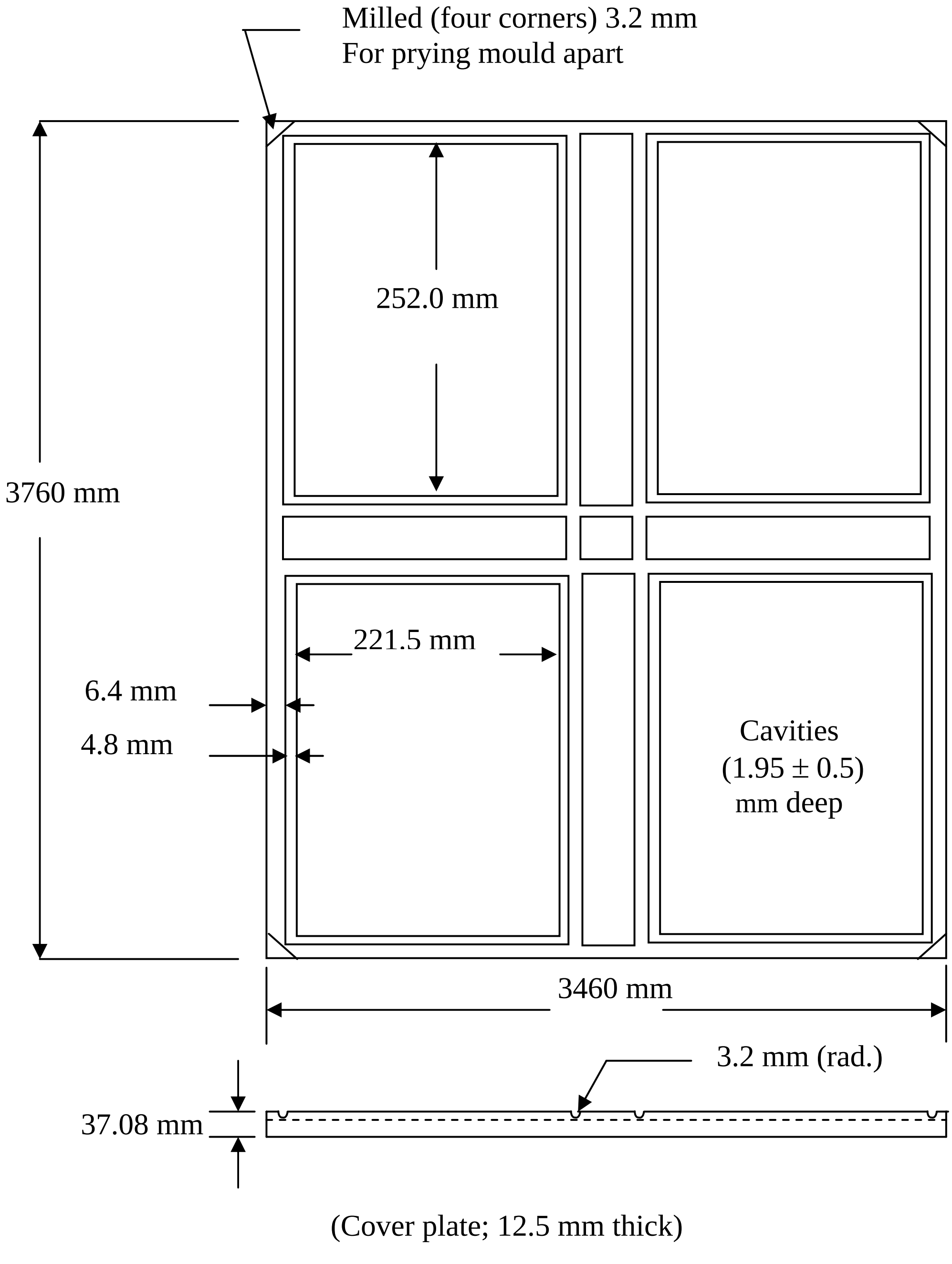


Figure 3.2: The four-cavity mould

3.3.4 Testing

3.3.4.1 Rheometer

Samples for cure meter were prepared in accordance with method ASTM D 2084: 1981 [32]. The Rheometer MDR 2000 (Monsanto) was used to generate characteristic cure curves (Figure4.1) at a chart motor period of 3 minutes, torque range selection of 50 lb-in (5.65 Nm), oscillation arc of $\pm 0.5^o$ and a temperature of 170^oC. A specimen cut from previously sheeted sample and of approximately 20 mm in diameter and 12.5 mm in thickness was used for each test. Apart from generating cure curves, the machine was extensively used to check homogeneity of specimens after mill mixing.

3.3.4.2 Tensile Modulus

Tensile test specimens were cut from the cured vulcanised sheets in section 3.3.3 using a standard die C cutter (Figure3.3) as specified by ASTM D 412: 1980 [33]. By overlapping the die cuts, each cured sheet yielded six (6) test samples. The test was carried out in a temperature and humidity controlled room (temperature 24 ± 2^oC, relative humidity $55 \pm 5\%$) using the Instron 1026 laboratory tensometer (Figure3.4).

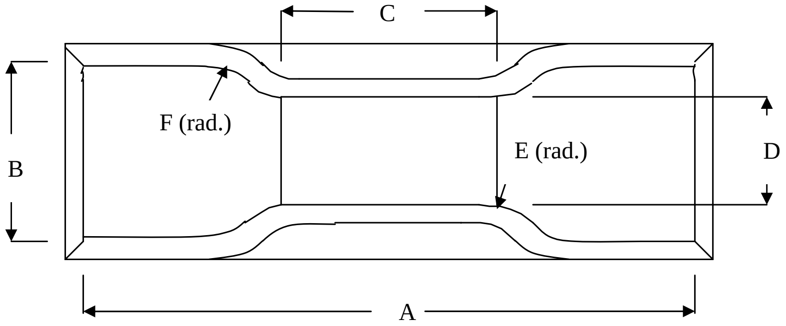


Figure 3.3: Die C

Table 3.4: Dimensions for die C (ASTM D 412: 1980)

Length	Dimension (mm)	Tolerance (mm)
A	115	
B	25.0	± 1
C	33.0	± 2
D	6.0	+0.05, -0.00
E	14.0	± 1
F	25.0	± 1

Figure 3.4: Instron 1026 tensometer

3.3.4.3 Resilience by Vertical Rebound

This method (ASTM D 2632: 1981) covered the determination of impact resilience of solid rubber from measurement of vertical rebound of a dropped mass [34].

The cylindrical specimens were specially prepared for this test using a multi-holed mould (each hole; diameter 37.5 mm, depth 19.5 mm). Mixing and sheeting were performed in accordance with ASTM D 3182 after which the specimens were cured as a batch for 25 minutes at 100 MPa and 170^{o}C. Curing for 25 minutes was necessary to allow complete curing up to the centre of each specimen, while batch curing would avert the effect of pressure, temperature and time variations. The samples were aged at room temperature for 24 hours before carrying out the resilience test.

To analyse the effect of temperature on impact resilience, a pair of rebound readings were taken at room temperature (23±2^{o}C) and at 100±2^{o}C using the Akron vertical rebound apparatus (Figure3.5). The first three rebounds were not recorded as recommended (ASTM D 3182).

Figure 3.5: Akron vertical rebound apparatus

3.3.4.4 Durometer Hardness

This test was carried out as specified in ASTM D 2240: 1981 [35] using the hand held Zwick 3100 type Shore D Durometer. This method is an empirical test intended primarily for control purposes. The standard permits hardness measurements based on either initial indentation or indentation after specified period of time. The former criterion was used to save on time since the data required was specifically for comparison purposes. Specimens for section3.3.3 were used as they conformed to the standard requirement for the test (flat surface with at least 6 mm in thickness, while lateral dimensions permits measurements at least 12 mm from any edge). Testing was done at a controlled room temperature of 24°C which is within the range recommended by the standard. Three random readings were taken within a radius of 12.75 mm from the centre of specimen on the upper flat surface as recommended.

3.3.4.5 Abrasion Resistance

The Abrasion Resistance test was carried out at Bata Shoe Company using the DIN abrader apparatus (Figure3.6). This apparatus serves to test the abrasion of rubbers or plastics according to German industrial standards DIN 53516 which is equivalent to ASTM D 5963.

Figure 3.6: DIN abrader apparatus

A 16.2 ±0.1 mm diameter × 6.10 ±0.1 mm long specimen with good cylindrical form was used for this test. The specimen was drilled out with a Morse taper on a drilling machine from rubber samples used in the resilience test section 3.3.4.3. Care was taken to protect the drilling device by placing a sole leather piece under the specimens. The specimen was then weighed, placed on the holder and adjusted by means of knurled nuts so that the specimen projected 2 mm over the edge of the holder as recommended by the standard (DIN 53516). Using a standard load of 1019 ±20 grams on each specimen, batch testing (3 specimen at a time) was carried out by rubbing an abrasive sheet made with aluminium oxide of grain size 60. A limit switch automatically stopped the motor when the test came to an end. The rest of the specimen was then released from the holder and weighed.

The loss of volume brought by the abrasion test gives the degree of rubber resistance against abrasion wear. Abrasion is indicated as loss in volume and is computed from the loss of weight of specimen, the specific weight of material to be tested and abrasiveness of the emery paper. However, this method is prone to quantitative errors due to change in abrasive index of the emery paper during the exercise.

3.4 Compatibilizing Technique

To improve the compatibilization properties of rubber particles, grafting agents were added to the rubber buffings while the natural rubber was maleated [16].

3.4.1 Surface Treatment

Tyre tread particles were surface treaded by dispersing them in aqueous acetone solution (10% acetone) and oxidised by 2% $KMnO_4$ by weight [16]. After 2 hours, the purple colour of the permanganate was gone, indicating the completion of the reaction. The rubber particles were washed with distilled water until the filtrate was neutral. This was established when the filtrate indicated a ph of 7 on the universal indicator.

3.4.2 Preparation of Maleated Natural Rubber

5% (by weight of rubber) maleic anhydride and 0.5% (by weight of rubber) benzoyl peroxide (free radical initiator) were directly added to the natural rubber and mixed in the laboratory mill for 5 minutes until the mixture was homogeneous after which the mixture was batched out and allowed to react for 12 hours [36].

The surface treated particles and maleated natural rubber were then mixed and cured as described in section 3.3 and prepared for mechanical properties testing.

3.5 Experimental Procedure

3.5.1 Stage 1: Identifying the Optimum Tyre Tread Buffings

Step 1. Assorted tyres (Table 3.3) were buffed using the same tyre-buffing tool and machine (Engle land) at Car & General Retreaders. Particles sorting was done using different ASTM standardized meshes and mesh no. 8 (aperture size 2.38 mm) was selected as it allows at least two-third of the tread particles to go through. This fraction was arbitrary selected to capture the effect of aggregate size on the mechanical properties. The sieved tread buffings were then coded into three standard aggregates based on the particles that went through the sieve, the residue, and a mixture of the two aggregates.

Step 2. The commercial batch weight in Table 3.1 (31.35 kg) was found to be too large for the laboratory mill and was thus reduced to 0.75 kg as recommended by ASTM D3182: 1982 (the standard batch mass for the laboratory mill shall be three times the formula mass in parts per hundred grams of rubber) [29].

Step 3. To evaluate the optimum curing time for the experiment, the five mesh

8 tyre buffings (Table 3.3) were mixed in equal proportions to make the general sample coded TD#8mix. Using the formulation in Table 3.1, five samples were prepared using this TD#8mix and cured using the Firestone laboratory heated press at 100 MPa and 170°C. Allowing for different cure times of 5, 10, 15, 20, and 25 minutes, and by following the procedures in section 3.3.4, ultimate strength of the samples were evaluated. These results were used to plot the ultimate strength against specimen's cure time from which the optimum cure time was evaluated. Though cure rate increases with increase in crumb rubber (reclaimed rubber from used tyres) in a sample [37], the optimum cure time was universally used to cure the wheel barrow based formulations since the incorporation of waste rubber into virgin NR matrix does not significantly affect the cure time [14].

Step 4. To determine the best particle size, three samples were prepared using the different particle sizes in step 1. Blending, curing (at optimum time) and testing were done as described in section 3.3. The results were compared to determine the particle size with the optimum mechanical properties.

Step 5. To evaluate the most 'superior' tyre buffings from the five tyre brands (Table 3.3), test samples from these tyres were prepared using the selected optimum particle size in step 4 while following the same formulation as in Table 3.1. Blending, curing and testing were done as described in section 3.3 and the buffings with superior mechanical properties identified.

3.5.2 Stage 2. Surface Treatment Analysis

Step 6. Effects of surface treatment on superior buffings were analysed by following the procedures described in Section 3.4. The cost and mechanical properties of ensuing blend were compared with those of untreated superior buffings in step 5. The buffings yielding the optimum cost and mechanical properties were selected in line with the objectives of this research.

3.5.3 Stage 3. Effects of Experiment Fillers on Mechanical Properties of Vulcanizate

Step 7. To better control the experiment, fillers (tyre dust, kaolin and calcium carbonate) were removed from the control formulation and used hydraulic oil reduced to 3.33 PHR (a third of amount used in stage 1). The latter is necessary as it was observed that excess oil makes the milling process muddy leading to poor blending.

Three different comparison samples were then prepared using the control formulation and 60PHR of tyre dust, kaolin and calcium carbonate respectively. To capture the effect of one of the strongest rubber fillers (carbon black), a fourth sample using 60PHR carbon black (code N660) and the control formulation was prepared. All the samples were analysed as described in section 3.3

3.5.4 Stage 4. Analysis of Selected Vanderbilt Medium Quality Formulations

Step 8. Four medium quality rubber formulations suggested by Vanderbilt Chemical Corporation were selected [31]. These formulations were selected due to the high quality products made by this corporation and the technical command it has in the rubber industry. Since it was not possible to obtain all the starting materials recommended by the formulations, logical substitutes were used as shown in the Tables 3.5 to 3.8.

Where;

- SBR = Styrene Butadiene Rubber
- AGERITEHP-S^{TM}(antioxidant) = A blend of 65 parts Dioctlyated diphenyl amine and 35 parts Diphenyl-p- phenylene diamine

Table 3.5: Formulation of medium quality conveyor belt cover (VAN00A)

Suggested formulation (Vanderbilt)	Used formulation (Experiment)	Code	PHR
SBR (extended with aromatic oil)	SBR (extended with aromatic oil)	S1712	137.5
Carbon black	Carbon black	N660	100
Aromatic oil	Aromatic oil	A103	40
Zinc oxide	Zinc oxide	A110	4
Stearic acid	Stearic acid	54	2
AGERITE SUPERFLEX ™ (antioxidant)	AGERITE HP-S™ (antioxidant)	RP12924	1
ANTOZITE 67P ™ (antiozonant)	ANTOZITE 67P ™ (antiozonant)	RP15520	1
Sulphur	Sulphur	11	2
VANAX NS ™ (accelerator)	VANAX NS ™ (accelerator)	466	1.6
METHYL TUADS ™ (accelerator)	METHYL TUADS ™ (accelerator)	443	0.6
		Total	**289.7**

Table 3.6: Formulation of automotive mat (VAN00B)

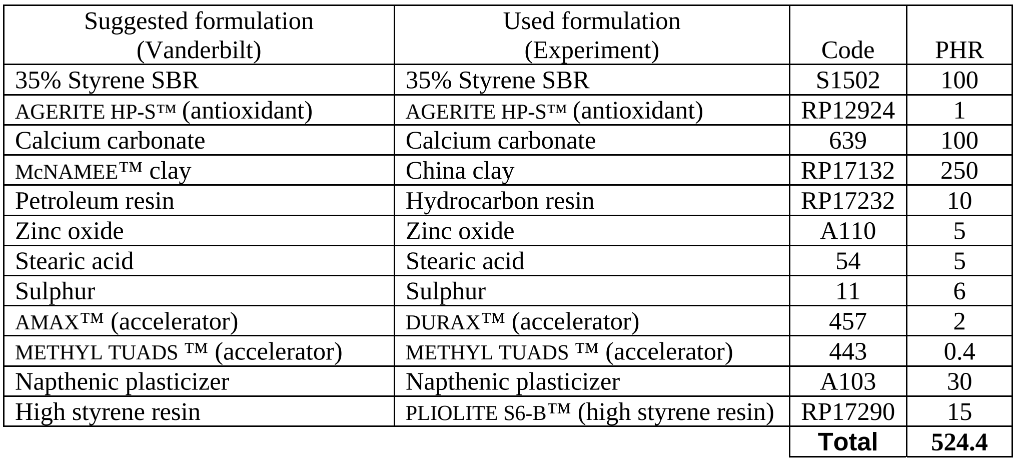
Suggested formulation (Vanderbilt)	Used formulation (Experiment)	Code	PHR
SBR (extended with naphthenic oil)	SBR (extended with aromatic oil)	S1712	150
Zinc oxide	Zinc oxide	A110	4
Stearic acid	Stearic acid	54	4
AGERITE SUPERFLEX ™ (antioxidant)	AGERITE HP-S™ (antioxidant)	RP12924	1.5
VANWAX H special protective wax	Petroleum wax	A117	3
Glycol activator	Stearic acid	54	2
McNAMEE™ clay	China clay	RP17132	200
Calcium carbonate	Calcium carbonate	639	100
Napthenic plasticizer	Aromatic oil	A103	30
AMAX™ (accelerator)	DURAX™ (accelerator)	457	2
METHYL TUADS ™ (accelerator)	METHYL TUADS ™ (accelerator)	443	0.4
Sulphur	Sulphur	11	4
Silica	Mica	RP10084	25
		Total	**523.9**

Table 3.7: Formulation of medium quality shoe sole (VAN00C)

Suggested formulation (Vanderbilt)	Used formulation (Experiment)	Code	PHR
SBR (45-55 ML4)	35% Styrene SBR	S1502	100
Napthenic plasticizer	Napthenic plasticizer	A103	5
Zinc oxide	Zinc oxide	A110	4
Stearic acid	Stearic acid	54	2
VANOX MBPC™ (antioxidant)	AGERITE HP-S™ (antioxidant)	RP12924	1
ALTAX™ (accelerator)	ALTAX™ (accelerator)	445	2
UNADS™ (accelerator)	METHYL TUADS ™ (accelerator)	443	0.5
Glycol activator	Glycol activator	54	2
Sulphur	Sulphur	11	2.5
Silica	Silica	RP10084	40
PLIOLITE S6-B™ (high styrene resin)	PLIOLITE S6-B™ (high styrene resin)	RP17290	25
DIXIE clay	China clay	639	120
		Total	**302.0**

- ANTOZITE 67P^{TM} (antiozonant)= N-(1,3Dimethylbutyl)n-phenyl-p- phenylediamine

Table 3.8: Formulation of flooring or cover base (VAN00D)



Suggested formulation (Vanderbilt)	Used formulation (Experiment)	Code	PHR
35% Styrene SBR	35% Styrene SBR	S1502	100
AGERITE HP-S™ (antioxidant)	AGERITE HP-S™ (antioxidant)	RP12924	1
Calcium carbonate	Calcium carbonate	639	100
McNAMEE™ clay	China clay	RP17132	250
Petroleum resin	Hydrocarbon resin	RP17232	10
Zinc oxide	Zinc oxide	A110	5
Stearic acid	Stearic acid	54	5
Sulphur	Sulphur	11	6
AMAX™ (accelerator)	DURAX™ (accelerator)	457	2
METHYL TUADS ™ (accelerator)	METHYL TUADS ™ (accelerator)	443	0.4
Napthenic plasticizer	Napthenic plasticizer	A103	30
High styrene resin	PLIOLITE S6-B™ (high styrene resin)	RP17290	15
		Total	**524.4**

- VANAX NS^{TM} (accelerator) = 2 Benzothiazole sulfenamide
- METHYL TUADS^{TM} (accelerator) = Tetra methylthiuram disulphide
- DURAX^{TM}(accelerator) = N-cyclohexyl-2- benzothiazole sulfenamide
- ALTAX^{TM}(accelerator) = Benzothiazyl disulphide
- Silica = silicon dioxide
- PLIOLITE S6-B^{TM} (high styrene resin) = Styrene/Butadiene copolymer

Step 9. To efficiently blend the suggested formulations in the laboratory mill, the batch weights were reduced to 0.75 kg (step 2). Blending, curing and testing were done as described in section 3.3 after which the mechanical properties were evaluated and tabulated. These results were to act as a comparative guide in the preceding stages of the experiment.

3.5.5 Stage 5. Effects of Varying the Amount of Fillers on Control Formulation

Step 10. By increasing the amount of fillers (carbon and tyre buffings) in steps of 60 PHR, Three analytical levels were established (60,120,180 PHR). This translates to a maximum weight ratio of 0.603 (180/298.5) which is equivalent to a volume fraction of 0.558 (0.603/1.08) which is within the recommended maximum packing of 0.6 as described in section 2.2. Effect of carbon (N660) loading was evaluated from 0 to 40 PHR at each level which is below 50% of the polymers PHR as recommended by ASTM D3182: 1982, to avert poor mixing in the mill. Nine specimens were prepared as shown in Tables 3.9 to 3.11. The batch weight was maintained at 0.75 kg for each specimen.

After mill mixing, each specimen was divided into two halves. One half was cured within 24hrs to minimise the effect of compound aging, while the other half was wrapped in an aluminium foil and stored at room temperature ($\approx 23\ ^o$ C) for 30 days, after which it was cured. Every specimen was physically tested 24 hours after curing to allow for structural stabilization. The results were compared with those of Vanderbilt Chemical Corporation blends.

Table 3.9: Analytical level 1; 60 PHR

	PHR of fillers		
Specimen	Firestone tread buffings	Carbon black	**Total**
WB009A1	60	0	**60**
WB009A2	40	20	**60**
WB009A3	20	40	**60**

Table 3.10: Analytical level 2; 120 PHR

	PHR of fillers		
Specimen	Firestone tread buffings	Carbon black	**Total**
WB009B1	120	0	**120**
WB009B2	100	20	**120**
WB009B3	80	40	**120**

Table 3.11: Analytical level 3; 180 PHR

	PHR of fillers		
Specimen	Firestone tread buffings	Carbon black	**Total**
WB009C1	180	0	**180**
WB009C2	160	20	**180**
WB009C3	140	40	**180**

Chapter 4

RESULTS AND DISCUSSION

In this section, the mechanical properties of different rubber formulations are presented and discussed. Suggested industrial formulations from Vanderbilt Chemical Corporation were used to compare the mechanical properties and costing of proposed recycled rubber formulations.

Wheelbarrow tyre formulation was exclusively used in this experiment to analyse the effects of recycled tyre tread buffings in rubber blends. This formulation was found to be cheaper than that of the car black mat while the formulation construction was almost the same.

4.1 Sample Sorting and Standardizing

In the general scrap tyre market there is no significant difference between tread buffings and scrap tyre rubber [38]. Crumb rubber describes shreds from scrap/waste tyre that have been reduced to a particle size of 9.525 mm or less [39]. However, in this research, it was observed that tyre tread buffings are made up of different sizes of rubber particles even greater than 9.525 mm, which largely depends on the buffing machine/tool. Using the Engle land buffing machine in Car & General Retreaders, the largest particle observed was approximately 14.2 mm.

Mesh 8 was selected to standardize the tread buffings as it allowed at least two-third of the scrap to go through, thus ensuring large usage of the scrap in line with the primary objective of the research.

Going by the results in Table 4.1, it was observed that Firestone tyre yielded the highest percent of mesh 8 particles while Toyo from Japan recorded the lowest. From these results it can be deduced that;

- Assorted tyres have different mechanical properties due to different manufacturing technologies.

Table 4.1: Variation in mesh 8 weights for assorted tyre tread buffings

Tyre Name	Size	Country of Origin	Mesh no. 8		> Mesh no. 8	
			Kg	%	Kg	%
Firestone	1000 R20	Kenya	1.118	74.5	0.382	25.5
Kelly	315/80 R 22.5	China	1.102	73.5	0.398	26.5
Toyo	215/70 R 19.5	Japan	0.863	57.5	0.637	42.5
Goodyear	18.4 R 30	Egypt	1.005	67.0	0.495	33.0
Pirelli	195 R 14	Brazil	0.932	62.1	0.568	37.9
		Average	**1.004**	**66.9**	**0.496**	**33.1**

Since the exercise of buffing is abrasive in nature, then variations in percentages of mesh weights could be due to different levels of cross-linking in the rubber vulcanizate.

Due to the range in particle sizes of the chips, the mesh grading method [11] was used to grade the rubber buffings. Rubber particle sizes were grouped into three aggregates (Table 4.2). The code TD>#8 was classified as the residue of mesh 8, hence was composed of very large grains which are thought to introduce poor compatibilization properties in rubber blends due to porosity [17]. Code TD8Mix was obtained by mixing TD#8 and TD>#8 in ratio of 2:1 respectively. This was necessary to capture the un-sieved ratio of the buffings.

Table 4.2: Standardized particle sizes code

Code	Details
TD#8	Particles that go through the mesh 8 sieve
TD>#8	Residue of mesh 8 sieve
TD8Mix	Obtained by mixing TD#8 and TD>#8 in a ratio of 2:1

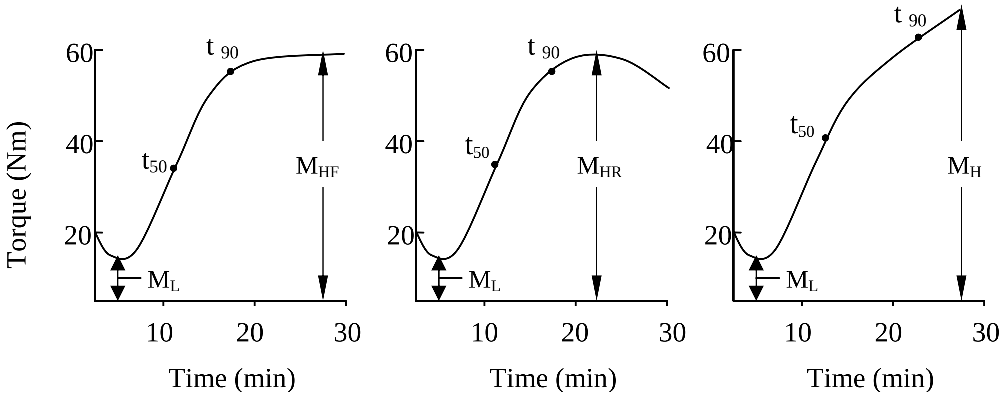
4.2 Evaluation of Experimental Batch Weight and Cost

The batch weight of 0.75 kg (Table4.3) which conformed to the ASTM D3182 was found to be adequate and economical for the experiment and was thus used as the universal weight for each specimen. This constant batch weight was envisaged to improve the repeatability of the rheometer results [40] which was extensively used to test for homogeneity. A thorough mix resulted in cure characteristic curves superimposing themselves on each other to yield a single curve.

Table 4.3: Mill batch weight and cost

Code	PHR	%	Batch Weight (Kg)	Price ($/Kg)	Batch Cost Ksh.
TC20	30	9.98	0.0749	1.548	8.46
RR50	70	23.30	0.1747	0.525	6.70
TD	92	30.62	0.2296	0.008	0.13
RP17132	40	13.31	0.0998	0.320	2.33
639	50	16.64	0.1248	0.642	5.85
HU100	10	3.33	0.0250	0.030	0.05
A110	3.5	1.16	0.0087	1.669	1.06
54	1.8	0.60	0.0045	0.655	0.21
445	0.8	0.27	0.0020	3.300	0.48
443	0.16	0.05	0.0004	2.100	0.06
11	2.2	0.73	0.0055	0.275	0.11
Total	**300.46**	**100.0**	**0.7500**		**25.46**

Figure4.1 shows different types of cure curves that are exhibited by assorted rubber blends. Figure4.1(a) show a cure to equilibrium torque curve which plateaus at maximum torque. This curve is common with hybrid rubbers (containing natural and synthetic rubbers). Natural rubber blends follow the cure curve in Figure4.1(b) such that they degrade after a defined optimum cure time. Figure4.1(c) show a case where no maximum torque is attained. This curve is common with synthetic rubber blends.



(a) (b) (c)

Where;

M_L = Minimum torque

M_{HF} = Maximum torque where curve plateaus

M_{HR} = Maximum torque of reverting curve

M_H = Highest torque attained during specific period of time when no Plateau or maximum torque is obtained

t_x = Minutes to x % of maximum torque (cure)

Figure 4.1: Rheometer cure characteristic curves

4.3 Determination of Optimum Curing Temperature

In line with the main objective of the research, the first step was to evaluate the optimum curing temperature for the test specimens. Five specimens were cured at 5, 10, 15, 20, and 25 minutes respectively. Subsequently, their mechanical properties (tensile strength, percent elongation and hardness) were determined and the results are presented in appendix A section A.1.

Average ultimate tensile strength was used as the criterion to determine the optimum curing temperature of the experiment [31].

Table 4.4: Ultimate tensile strength at different cure times

Cure time (min)	5	10	15	20	25
Ultimate Tensile Strength (MPa)	2.46	3.05	3.57	2.93	2.88
Standard Deviation (±)	0.16	0.164	0.092	0.149	0.253

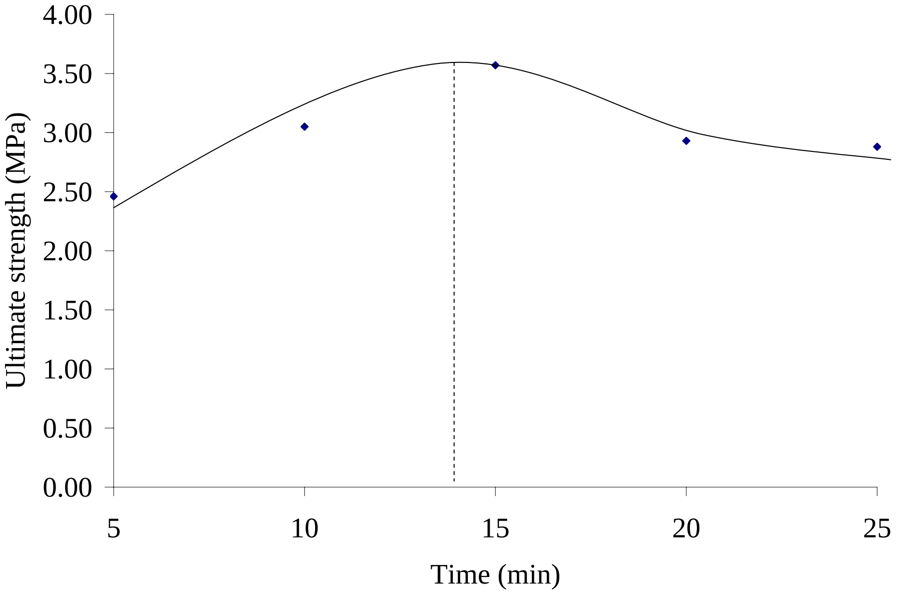


Figure 4.2: Effect of cure time on ultimate tensile strength

Using a polynomial approximation of 2^{nd} degree, the optimum cure time was found to be approximately 14 minutes, as illustrated in Figure 4.2.

4.4 Effect of Particle Size on Mechanical Properties

Following the formulation in Table 3.1, test samples were prepared using the three grades in Table 4.2 and their properties tested as described in section 3.3.4. The results are presented in appendix A section A.2

It was observed that, some samples snapped before reaching 200% elongation and in all these cases, the samples were from the TD>#8 code. Also, the point of failure of these samples was a clean knife-cut approximately perpendicular to the direction of pull. This could be due to the large tread particles orienting themselves almost perpendicularly across the gauge length thus introducing poor bonding with the cross linked polymer.

Table 4.5: Averaged tensile strength for specimens WB002A, B and C

	Elongation			
	100%	200%	Ultimate	
Sample	TS(MPa)	TS(MPa)	TS(MPa)	%
WB002A	1.82	3.22	3.53	250
WB002B	1.64	2.99	3.23	242
WB002C	1.61	2.92	3.10	220
Standard Deviation (±)	0.114	0.157	0.221	15.5

Table 4.6: Hardness and abrasion results for WB002A, B and C

Specimen	Shore D Hardness	Abrasion Volume Loss (mm^3)
WB002A	61	239
WB002B	62	281
WB002C	62	289

The tread buff particle size was found to influence the ultimate elongation, ultimate tensile strength and hardness. Finer grains were found to yield greater ultimate tensile properties than coarse grains. This could result from the finer particles availing more surface area for mechanical interlocking and possibly cross linking with the polymer, leading to better adhesion and hence superior tensile properties.

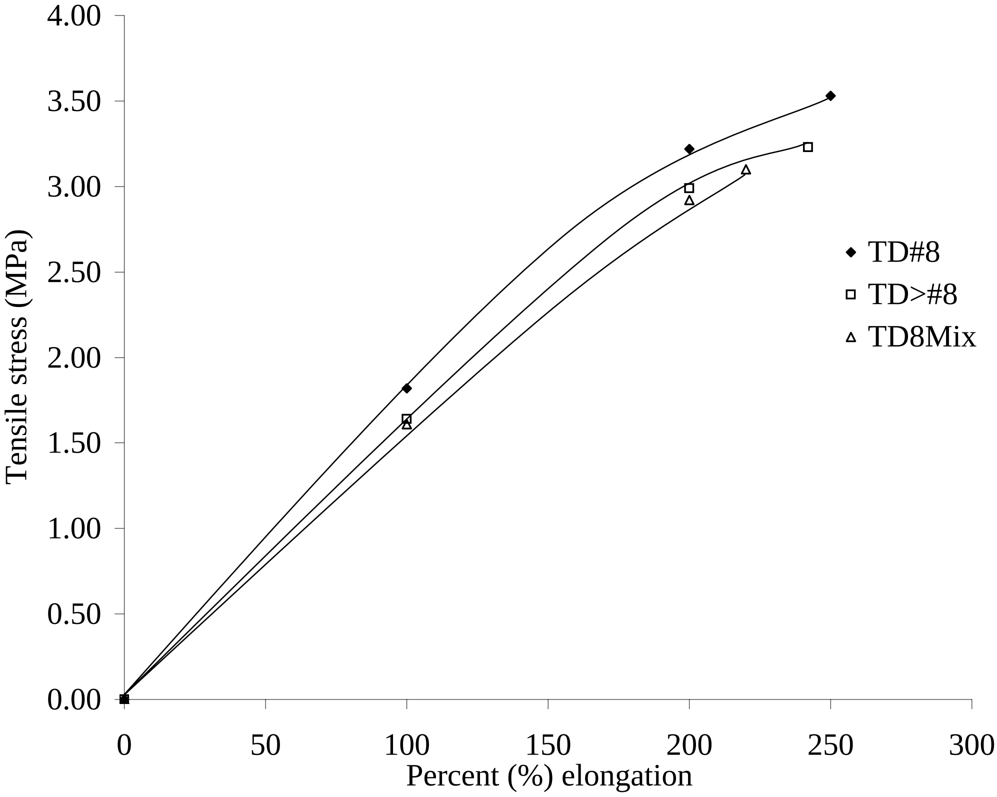


Figure 4.3: Effect of particle size on tensile stress

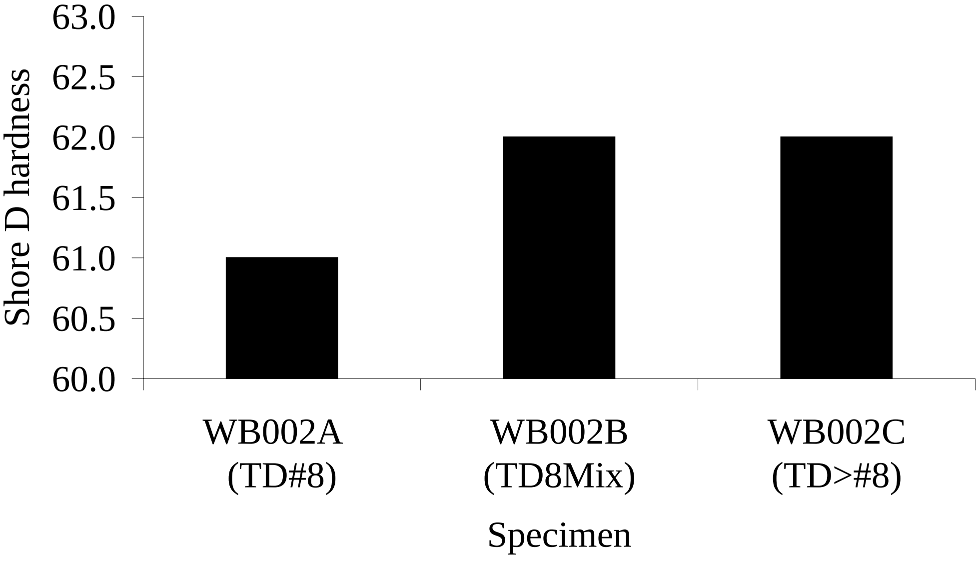


Figure 4.4: Effect of particle size on hardness of test samples

Hardness is inversely related to the penetration of indenter and dependent on the elastic modulus and viscoelastic behaviour of a material [35]. The hardness results show the fine grains to exhibit lower hardness value than coarse grains. This could be due to the ability of the fine particles to flow easily in the highly elastic polymer matrix influencing the vulcanizate to exhibit much less viscoelastic behaviour than in coarse grains. Also, the greater surface area exhibited by the smaller particles could result in a lowered viscosity of the vulcanizate.

4.5 Evaluation of the 'Superior' Tyre Tread Buffings

In the preceding section, finer particle sizes were found on average to result in better mechanical properties than large ones. Using this fine particle range (TD#8), it would then be possible to identify which of the five tyre brands will yield the optimum mechanical properties and thus the 'superior' tread buffings. Following the formulation in section 3.1, five samples were prepared using the different tread brands and tested as described in section 3.3.4. The detailed results are presented in appendix A section A.3

Table 4.7: Averaged TS results for specimens WB003A, B, C, D and E

	Elongation					
	100%	150%	200%	Ultimate		
Sample	TS (MPa)	TS (MPa)	TS (MPa)	%	TS (MPa)	SDEV (±)
WB003A	1.35	2.09	2.87	242	3.40	0.205
WB003B	1.58	2.41	3.23	269	4.28	0.383
WB003C	1.86	2.48	3.24	243	3.93	0.067
WB003D	1.6	2.42	3.17	243	3.72	0.184
WB003E	1.15	1.75	2.36	236	3.39	0.215

Table 4.8: Shore D hardness for specimens WB003A, B, C, D and E

	Specimens				
Readings	WB003A	WB003B	WB003C	WB003D	WB003E
1	61.0	61.0	62.0	61.0	60.0
2	61.0	61.0	62.0	60.0	61.0
3	62.0	61.0	62.0	60.0	59.0
Average	**61.3**	**61.0**	**62.0**	**60.3**	**60.0**

Though specimen WB003B (Firestone 1000 R20) exhibits a slightly lower av-

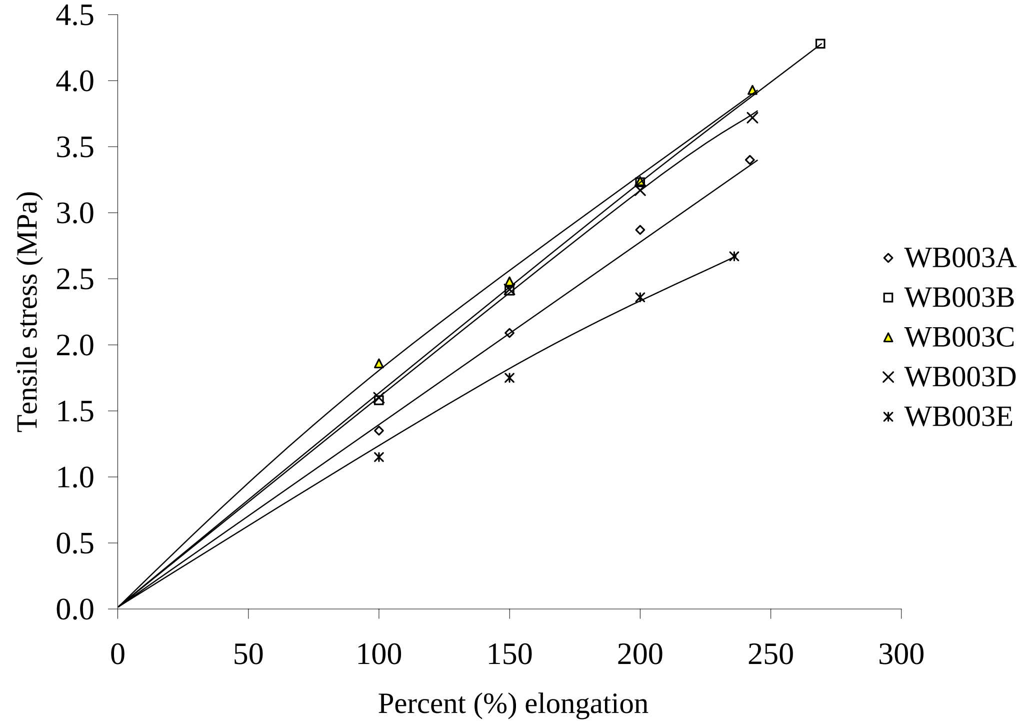


Figure 4.5: Tensile properties of vulcanizates using selected tyre buffings

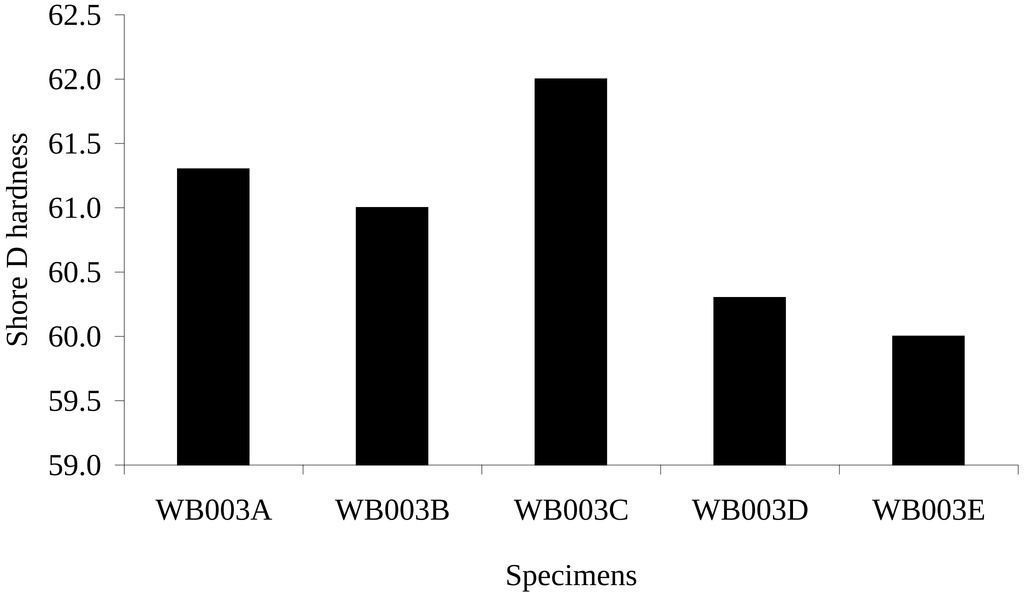


Figure 4.6: Variation of hardness due to different tyre buffings

erage Shore D hardness compared with specimens WB003C and WB003A, it exhibits both the greatest ultimate tensile strength (4.28 MPa) and ultimate percent elongation (269%). Specimen WB003B yielded the highest UTS compared with other tyre tread buffings that were tested.

In the rubber industry, ultimate strength parameter is considered a fundamental material property of the cured vulcanizate. Even though a typical rubber product probably is usually not stretched anywhere close to its ultimate tensile strength under normal conditions of use, many product users still consider it an important indicator of overall quality of the compound [31]. Based on this criterion and formulation, WB003B (Firestone 1000 R20, mesh 8) was selected as the most superior of the tested tread buffings and hence was used in the remaining stages of the experiment.

4.6 Effects of Surface Treating Tyre Tread Particles

Recent research [17] has shown that use of maleated polypropylene(PP) has little effect on the ultimate tensile strength of rubber blends and vulcanizates using untreated rubber particles. Thus in this research, it would be of interest to know the effect of surface treated rubber particles and maleated natural rubber on the mechanical properties of ensuing vulcanizates using the wheelbarrow formulation.

Sample WB004 was prepared following the wheelbarrow formulation using maleated natural rubber and surface treated tread buffings . The sample was then tested as described in section 3.3.4.

Table 4.9: Tensile test results for Sample WB004

Sample	Elongation								
	100%		150%		200%		Ultimate		
Thickness mm	Force (Kgf)	TS (MPa)	Force (Kgf)	TS (MPa)	Force (Kgf)	TS (MPa)	%	Force (Kgf)	UTS (MPa)
1.68	1.60	1.56	2.45	2.38	3.20	3.11	200	3.90	3.79
2.04	1.85	1.48						2.75	2.20
1.98	1.85	1.53	2.80	2.31	3.85	3.18	210	4.00	3.30
1.91	1.80	1.54	2.60	2.22	3.40	2.91	210	3.95	3.38

It was observed that WB004 (treated TD#8 firestone) exhibited poorer tensile

Table 4.10: Averaged tensile stress for WB003B and WB004

	Elongation					
	100%	150%	200%	Ultimate		
Sample	TS (MPa)	TS (MPa)	TS (MPa)	%	UTS (MPa)	SDEV (±)
WB004	1.52	2.31	3.07	207	3.17	0.680
WB003B	1.58	2.41	3.23	269	4.28	0.383

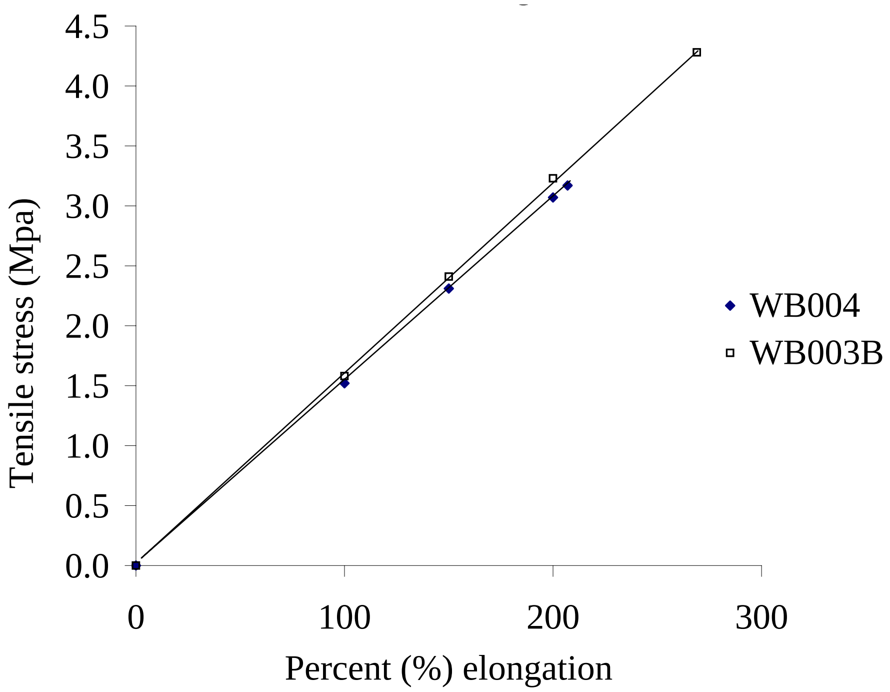


Figure 4.7: Effect of surface treating buffings on ultimate elongation

Table 4.11: Shore D hardness for WB003B and WB004

Readings	WB004	WB003B
1	63	61
2	64	61
3	65	61
Average	**64**	**61**

properties (strength and percent elongation) than WB003B (untreated TD#8 firestone). This could have resulted from the chemical treatment inhibiting formation of the stronger polysulfidic bond resulting in poorer mechanical properties. Hence the method of surface treating particles with maleic anhydride does not improve the bonding for tread buffings in the wheelbarrow formulation as envisaged. Though the Shore D hardness indicated an increase of 3 units,

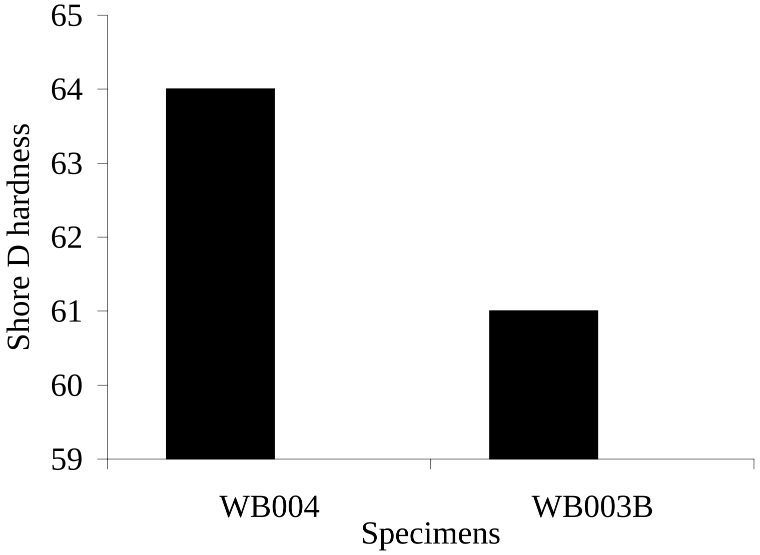


Figure 4.8: Effect of surface treating buffings on hardness

the surface treatment method was found to be too laborious and expensive to warrant any further consideration in the experiment.

4.7 Effects of Selected Fillers on Mechanical Properties of Wheelbarrow Vulcanizate

From its usage, a solid wheelbarrow tyre requires

- Good abrasion properties to increase life span
- Average ultimate elongation to inhibit flattening in compression
- High ultimate tensile strength to improve toughness
- Average hardness to maintain rigidity and absorb shocks
- Low input cost

Nevertheless, the design of the local solid wheelbarrow tyre formulation is largely based on average hardness, low input cost and weight. This inadvertently compromises the mechanical properties of this important rubber product due to excessive use of cheapeners in the formulation. It is thus important to analyse the individual effect of each constituent filler in the wheelbarrow formulation in order to optimize the mechanical properties. This was achieved by eliminating all the fillers in the control formulation, and then adding 60 PHR of each filler at a time to generate four samples. A fifth sample was prepared using carbon black (N660) to capture the effect of one of the traditional rubber fillers

Table 4.12: Control formulation with no fillers (WB005A)

Code	PHR	%	Batch Weight (Kg)	Price ($/Kg)	Batch Cost Ksh.
TC20	30.00	26.84	0.2013	1.548	22.74
RR50	70.00	62.62	0.4696	0.525	18.00
A110	3.50	3.13	0.0235	1.669	2.86
54	1.80	1.61	0.0121	0.655	0.58
HU100	3.33	2.98	0.0223	0.030	0.05
445	0.80	0.72	0.0054	3.300	1.29
443	0.20	0.18	0.0013	2.100	0.21
11	2.20	1.97	0.0148	0.275	0.30
Total	**111.79**	**100**	**0.7500**		**45.98**

Table 4.13: Control formulation with Kaolin (WB005B)

Code	PHR	%	Batch Weight (Kg)	Price ($/Kg)	Batch Cost Ksh.
TC20	30.00	17.46	0.1309	1.548	14.80
RR50	70.00	40.74	0.3055	0.525	11.71
A110	3.50	2.04	0.0153	1.669	1.86
54	1.80	1.05	0.0079	0.655	0.38
Kaolin	60.00	34.92	0.2619	0.3203	6.12
HU100	3.33	1.94	0.0145	0.030	0.03
445	0.80	0.47	0.0035	3.300	0.84
443	0.20	0.12	0.0009	2.100	0.13
11	2.20	1.28	0.0096	0.275	0.19
Total	**171.83**	**100.00**	**0.7500**		**36.06**

By following the procedures in section 3.3, the tensile strength, ultimate tensile strength and ultimate elongation of the samples were evaluated. The results are presented in appendix B section A.4

Table 4.14: Control formulation with Firestone buffings (WB005C)

Code	PHR	%	Batch Weight (Kg)	Price ($/Kg)	Batch Cost Ksh.
TC20	30.00	17.46	0.1309	1.548	14.80
RR50	70.00	40.74	0.3055	0.525	11.71
A110	3.50	2.04	0.0153	1.669	1.86
54	1.80	1.05	0.0079	0.655	0.38
TD#8Ftn	60.00	34.92	0.2619	0.0078	0.15
HU100	3.33	1.94	0.0145	0.030	0.03
445	0.80	0.47	0.0035	3.300	0.84
443	0.20	0.12	0.0009	2.100	0.13
11	2.20	1.28	0.0096	0.275	0.19
Total	**171.83**	**100.00**	**0.7500**		**30.09**

Table 4.15: Control formulation with $CaCO_3$(WB005D)

Code	PHR	%	Batch Weight (Kg)	Price ($/Kg)	Batch Cost Ksh.
TC20	30.00	17.46	0.1309	1.548	14.80
RR50	70.00	40.74	0.3055	0.525	11.71
A110	3.50	2.04	0.0153	1.669	1.86
54	1.80	1.05	0.0079	0.655	0.38
$CaCO_3$	60.00	34.92	0.2619	0.6424	12.28
HU100	3.33	1.94	0.0145	0.030	0.03
445	0.80	0.47	0.0035	3.300	0.84
443	0.20	0.12	0.0009	2.100	0.13
11	2.20	1.28	0.0096	0.275	0.19
Total	**171.83**	**100.00**	**0.7500**		**42.22**

Figure 4.9, shows the modulus curve of the experiment control (WB005A) and tread filled sample (WB005C) to follow almost the same path. This indicates that tread tyre buffings can be readily used as blend extender with natural rubber. It was also observed that tread buffs slightly improved the elongation of experiment control by 7.6%, which was the highest compared with other fillers. It also improves the ultimate tensile strength by 13.8%.

Kaolin (WB005B) is observed to improve the tensile stress of the control formulation at low elongation but this effect decreases with increase in elongation. ultimately, the mechanical properties (UTS and percent elongation) coincide

Table 4.16: Control formulation with carbon black (WB005E)

Code	PHR	%	Batch Weight (Kg)	Price ($/Kg)	Batch Cost Ksh.
TC20	30.00	17.46	0.1309	1.548	14.80
RR50	70.00	40.74	0.3055	0.525	11.71
A110	3.50	2.04	0.0153	1.669	1.86
54	1.80	1.05	0.0079	0.655	0.38
N660	60.00	34.92	0.2619	0.7641	14.61
HU100	3.33	1.94	0.0145	0.030	0.03
445	0.80	0.47	0.0035	3.300	0.84
443	0.20	0.12	0.0009	2.100	0.13
11	2.20	1.28	0.0096	0.275	0.19
Total	**171.83**	**100.00**	**0.7500**		**44.55**

Table 4.17: Averaged tensile strength results for WB005A, B, C, D, and E

Sample	Elongation						
	100%	150%	200%	250%	300%	Ultimate	
	MPa	MPa	MPa	MPa	MPa	MPa	%
WB005A	0.760	1.343	2.115	3.402	4.745	4.795	303
WB005B	1.774	2.661	3.450	4.161	4.715	4.926	308
WB005C	0.826	1.500	1.973	3.381	4.502	5.455	326
WB005D	1.211	1.674	2.168	2.919	3.813	4.177	317
WB005E	5.901					6.048	103

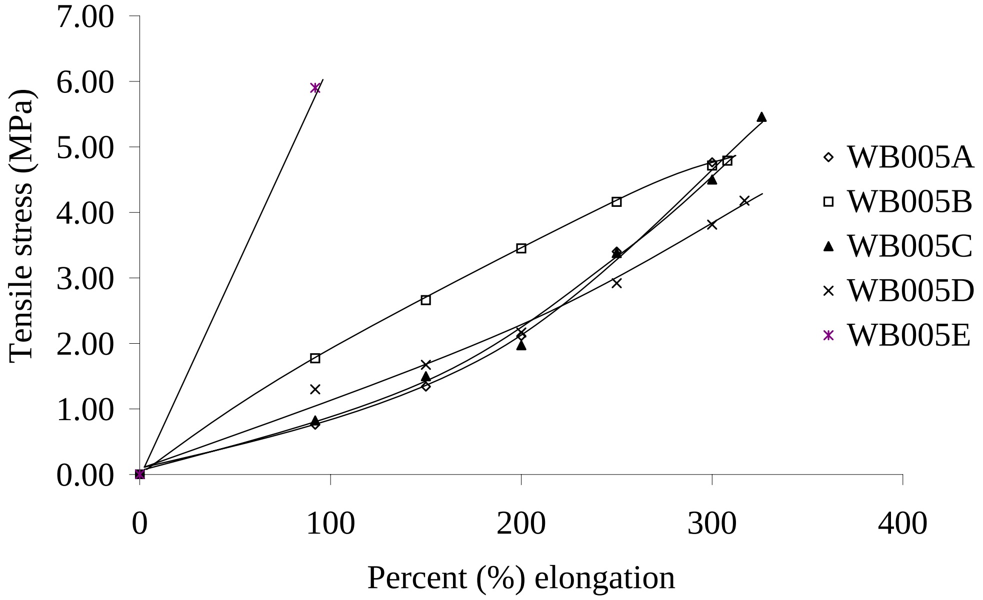


Figure 4.9: Effect of fillers on tensile stress of WB tyre vulcanizate

with those of control formulation.

Calcium carbonate (WB005D) introduces insignificant improvement of tensile stress to the control formulation at low elongation while it significantly reduces the same beyond 220% elongations.

Though Carbon black was found to reduce the control ultimate elongation by 66%, it improved the ultimate tensile strength by 26.1% which was the highest compared with other fillers.

It then follows that, a combination of carbon black and firestone buffings as fillers will yield the best properties for the selected wheel barrow tyre formulation. Thus Kaolin (china clay) and whiting (calcium carbonate) were dropped from the tyre formulation.

4.8 Effect of Varying Amount of Firestone Buffings and Carbon Black in Wheelbarrow Formulation

From the results in section 4.7, a combination of carbon black (N660) and firestone tyre tread buffings was selected as the most effective combination of fillers for the wheelbarrow tyre formulation (carbon black to impart strength properties and the buffings to act as extender and improve elongation).

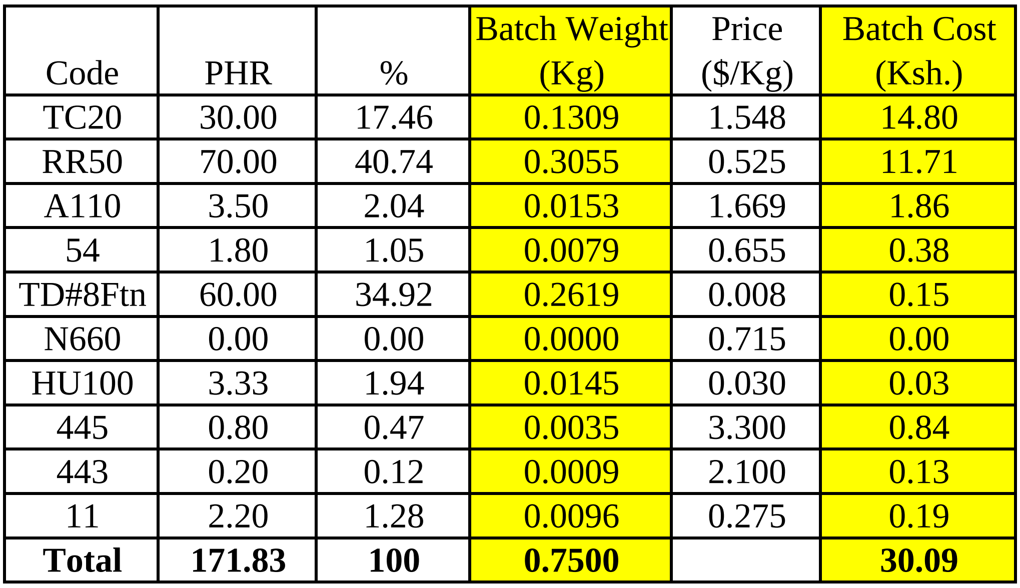
To exhaustively study the effect of varying each filler in the wheelbarrow vulcanizate, the experiment was analysed at three levels. In Table 3.1 the total amount of filler in the wheelbarrow formulation, was approximated to 180 PHR. This 180 PHR was divided in three to create the three filler levels of 60 PHR, 120 PHR, and 180 PHR.

The idea was to analyse the effect of varying the amount of carbon black (carbon loading) at these different levels on mechanical properties of resulting rubber specimens, and the respective cost of preparing the blends. The maximum amount of carbon was limited to 40 PHR at each level which was approximately 50% of polymer in the formulation as recommended by the ASTM D3182: 1982. Different formulations were designed and their mechanical properties determined.

4.8.1 Batch Weighing and Costing

Different amount of filler with varying ratio of both buffings (TD#8; Firestone) and carbon black (N660) was added to the control formulation (Table 4.12)

Table 4.18: WB006A1; Control formulation + 60 PHR filler {60PHR of TD#8 (Fstn) + 0PHR of N660}



Code	PHR	%	Batch Weight (Kg)	Price ($/Kg)	Batch Cost (Ksh.)
TC20	30.00	17.46	0.1309	1.548	14.80
RR50	70.00	40.74	0.3055	0.525	11.71
A110	3.50	2.04	0.0153	1.669	1.86
54	1.80	1.05	0.0079	0.655	0.38
TD#8Ftn	60.00	34.92	0.2619	0.008	0.15
N660	0.00	0.00	0.0000	0.715	0.00
HU100	3.33	1.94	0.0145	0.030	0.03
445	0.80	0.47	0.0035	3.300	0.84
443	0.20	0.12	0.0009	2.100	0.13
11	2.20	1.28	0.0096	0.275	0.19
Total	**171.83**	**100**	**0.7500**		**30.09**

Table 4.19: WB006A2; Control formulation + 60 PHR filler {40PHR of TD#8 (Fstn) + 20PHR of N660 }

Code	PHR	%	Batch Weight (Kg)	Price ($/Kg)	Batch Cost (Ksh.)
TC20	30.0	17.46	0.1309	1.548	14.80
RR50	70.0	40.74	0.3055	0.525	11.71
A110	3.5	2.04	0.0153	1.669	1.86
54	1.8	1.05	0.0079	0.655	0.38
TD#8Ftn	40.0	23.28	0.1746	0.008	0.10
N660	20.0	11.64	0.0873	0.715	4.56
HU100	3.3	1.94	0.0145	0.030	0.03
445	0.8	0.47	0.0035	3.300	0.84
443	0.2	0.12	0.0009	2.100	0.13
11	2.2	1.28	0.0096	0.275	0.19
Total	**171.83**	**100**	**0.7500**		**34.60**

Table 4.20: WB006A3; Control formulation + 60 PHR filler {20PHR of TD#8 (Fstn) + 40PHR of N660}

Code	PHR	%	Batch Weight (Kg)	Price ($/Kg)	Batch Cost (Ksh.)
TC20	30.0	17.46	0.1309	1.548	14.80
RR50	70.0	40.74	0.3055	0.525	11.71
A110	3.5	2.04	0.0153	1.669	1.86
54	1.8	1.05	0.0079	0.655	0.38
TD#8Ftn	20.0	11.64	0.0873	0.008	0.05
N660	40.0	23.28	0.1746	0.715	9.11
HU100	3.3	1.94	0.0145	0.030	0.03
445	0.8	0.47	0.0035	3.300	0.84
443	0.2	0.12	0.0009	2.100	0.13
11	2.2	1.28	0.0096	0.275	0.19
Total	**171.83**	**100**	**0.7500**		**39.10**

Table 4.21: WB006B1; Control formulation + 120 PHR filler {120PHR of TD#8 (Fstn) + 0PHR of N660}

Code	PHR	%	Batch Weight (Kg)	Price ($/Kg)	Batch Cost (Ksh.)
TC20	30.00	12.76	0.0957	1.548	10.81
RR50	70.00	29.77	0.2233	0.525	8.56
A110	3.50	1.49	0.0112	1.669	1.36
54	1.80	0.77	0.0057	0.655	0.27
TD#8Ftn	120.00	51.03	0.3827	0.008	0.22
N660	0.00	0.00	0.0000	0.715	0.00
HU100	6.66	2.83	0.0212	0.030	0.05
445	0.80	0.34	0.0026	3.300	0.61
443	0.20	0.09	0.0006	2.100	0.10
11	2.20	0.94	0.0070	0.275	0.14
Total	**235.16**	**100**	**0.7500**		**22.12**

Table 4.22: WB006B2; Control formulation + 120 PHR filler {100PHR of TD#8 (Fstn) + 20PHR of N660}

Code	PHR	%	Batch Weight (Kg)	Price ($/Kg)	Batch Cost (Ksh.)
TC20	30.00	12.76	0.0957	1.548	10.81
RR50	70.00	29.77	0.2233	0.525	8.56
A110	3.50	1.49	0.0112	1.669	1.36
54	1.80	0.77	0.0057	0.655	0.27
TD#8Ftn	100.00	42.52	0.3189	0.008	0.18
N660	20.00	8.50	0.0638	0.715	3.33
HU100	6.66	2.83	0.0212	0.030	0.05
445	0.80	0.34	0.0026	3.300	0.61
443	0.20	0.09	0.0006	2.100	0.10
11	2.20	0.94	0.0070	0.275	0.14
Total	**235.16**	**100**	**0.7500**		**25.41**

Table 4.23: WB006B3; Control formulation + 120 PHR filler {80PHR of TD#8 (Fstn) + 40PHR of N660}

Code	PHR	%	Batch Weight (Kg)	Price ($/Kg)	Batch Cost (Ksh.)
TC20	30.00	12.76	0.0957	1.548	10.81
RR50	70.00	29.77	0.2233	0.525	8.56
A110	3.50	1.49	0.0112	1.669	1.36
54	1.80	0.77	0.0057	0.655	0.27
TD#8Ftn	80.00	34.02	0.2551	0.008	0.15
N660	40.00	17.01	0.1276	0.715	6.66
HU100	6.66	2.83	0.0212	0.030	0.05
445	0.80	0.34	0.0026	3.300	0.61
443	0.20	0.09	0.0006	2.100	0.10
11	2.20	0.94	0.0070	0.275	0.14
Total	**235.16**	**100**	**0.7500**		**28.71**

Table 4.24: WB006C1; Control formulation + 180 PHR filler {180PHR of TD#8 (Fstn) + 0PHR of N660}

Code	PHR	%	Batch Weight (Kg)	Price ($/Kg)	Batch Cost (Ksh.)
TC20	30.00	10.05	0.0754	1.548	8.52
RR50	70.00	23.45	0.1759	0.525	6.74
A110	3.50	1.17	0.0088	1.669	1.07
54	1.80	0.60	0.0045	0.655	0.22
TD#8Ftn	180.00	60.30	0.4523	0.008	0.26
N660	0.00	0.00	0.0000	0.715	0.00
HU100	10.00	3.35	0.0251	0.030	0.06
445	0.80	0.27	0.0020	3.300	0.48
443	0.20	0.07	0.0005	2.100	0.08
11	2.20	0.74	0.0055	0.275	0.11
Total	**298.50**	**100**	**0.7500**		**17.53**

Table 4.25: WB006C2; Control formulation + 180 PHR filler {160PHR of TD#8 (Fstn) + 20PHR of N660}

Code	PHR	%	Batch Weight (Kg)	Price ($/Kg)	Batch Cost (Ksh.)
TC20	30.00	10.05	0.0754	1.548	8.52
RR50	70.00	23.45	0.1759	0.525	6.74
A110	3.50	1.17	0.0088	1.669	1.07
54	1.80	0.60	0.0045	0.655	0.22
TD#8Ftn	160.00	53.60	0.4020	0.008	0.23
N660	20.00	6.70	0.0503	0.715	2.62
HU100	10.00	3.35	0.0251	0.030	0.06
445	0.80	0.27	0.0020	3.300	0.48
443	0.20	0.07	0.0005	2.100	0.08
11	2.20	0.74	0.0055	0.275	0.11
Total	**298.50**	**100**	**0.7500**		**20.12**

Table 4.26: WB006C3; Control formulation + 180 PHR filler {140PHR of TD#8 (Fstn) + 40PHR of N660}

Code	PHR	%	Batch Weight (Kg)	Price ($/Kg)	Batch Cost (Ksh.)
TC20	30.00	10.05	0.0754	1.548	8.52
RR50	70.00	23.45	0.1759	0.525	6.74
A110	3.50	1.17	0.0088	1.669	1.07
54	1.80	0.60	0.0045	0.655	0.22
TD#8Ftn	140.00	46.90	0.3518	0.008	0.20
N660	40.00	13.40	0.1005	0.715	5.25
HU100	10.00	3.35	0.0251	0.030	0.06
445	0.80	0.27	0.0020	3.300	0.48
443	0.20	0.07	0.0005	2.100	0.08
11	2.20	0.74	0.0055	0.275	0.11
Total	**298.50**	**100**	**0.7500**		**22.72**

The batch cost of specimens was observed to increase with carbon loading at each level. This was due to weight displacement of the cheap tread buffings with the more expensive carbon black. Generally, the cost of blend decreased linearly at a rate of Ksh. 1.83 per percent with increase of tread buffings in the formulation as seen in Figure 4.10

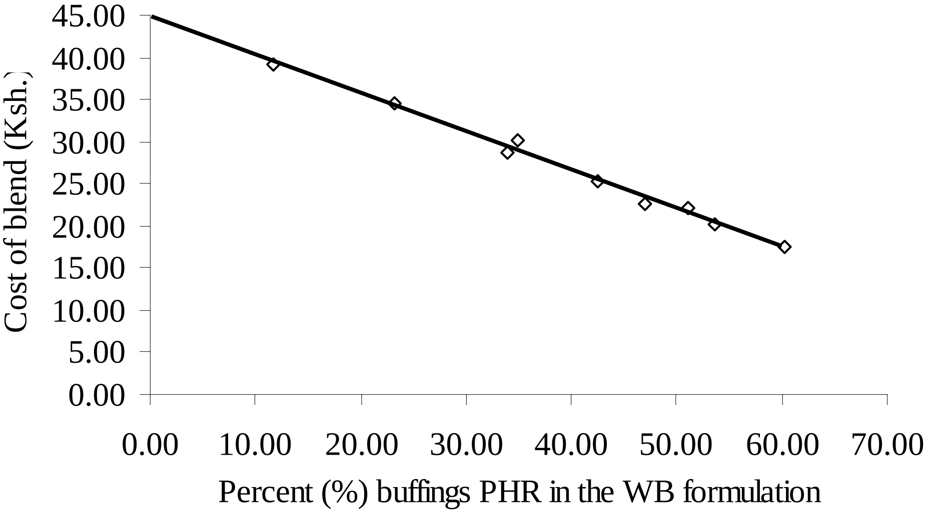


Figure 4.10: Variation of blend cost with increase in PHR of tread buffings

4.8.2 Evaluation of Mechanical (Tensile Strength, Elongation and Hardness) Properties

4.8.2.1 Un-Aged Specimens

The test samples for this section were cured 24 hours after mill mixing to allow for structural stabilization and reduce the effect of aging. The detailed tensile test results are presented in appendix B section A.6, while the abrasion test results are presented in appendix C.

Figures 4.11 and 4.12 show significant decrease in mechanical properties at each test level with increase in tread buffings PHR which can be caused by the successive dilution of the more superior virgin polymer with the poorer tread buffings.

Carbon loading was found to influence the ultimate tensile strength such that,

Table 4.27: Averaged mechanical results for un- aged specimens

Sample	Elongation							Shore D Hardness	Abrasion Volume Loss (mm^3)
	100%	150%	200%	250%	300%	Ultimate			
	TS (MPa)	TS (MPa)	TS (MPa)	TS (MPa)	TS (MPa)	TS (MPa)	%		
WB006A1	0.83	1.50	2.37	3.38	4.50	5.10	326	54	224
WB006A2	1.74	2.88	4.08	5.21		6.31	275	57	145
WB006A3	3.49	4.65	5.69			6.02	203	73	194
WB006B1	0.77	1.40	2.19	3.14		4.13	280	54	231
WB006B2	1.40	2.28	3.89			3.36	237	56	164
WB006B3	2.95	3.88				4.37	196	70	248
WB006C1	0.67	1.17	2.13	2.92		3.43	257	53	241
WB006C2	1.12	1.94	3.76			4.21	210	55	181
WB006C3	2.49					3.60	142	69	273

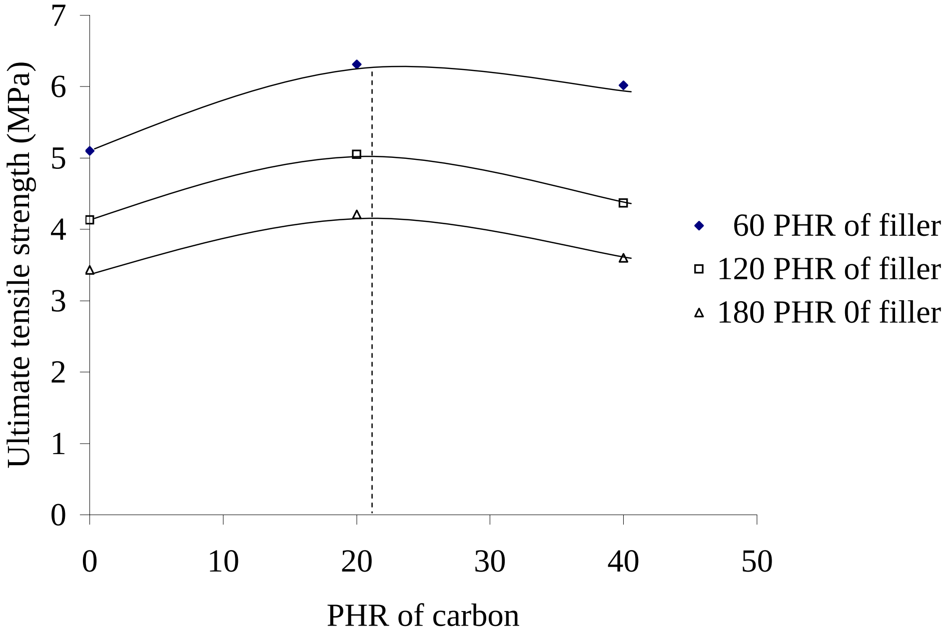


Figure 4.11: Effect of carbon loading on ultimate tensile strength

every test level went through an optimum ultimate tensile strength at between 16 and 26 PHR of carbon which is an indication that the optimum carbon loading for the wheel barrow tyre formulation would be approximately 21 PHR. The ultimate elongation was found to decrease with carbon loading at each level, such that it was lowest at the highest carbon PHR. This is expected as the fine carbon particles fill up the porous polymer phase locking the movement of cross

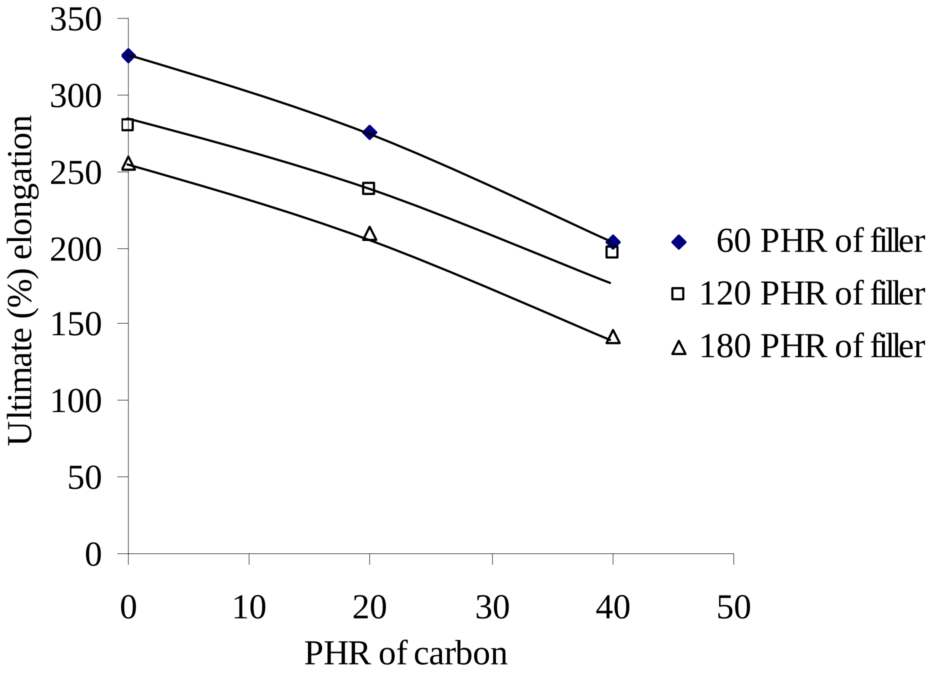


Figure 4.12: Effect of carbon loading on ultimate elongation

linked chains.

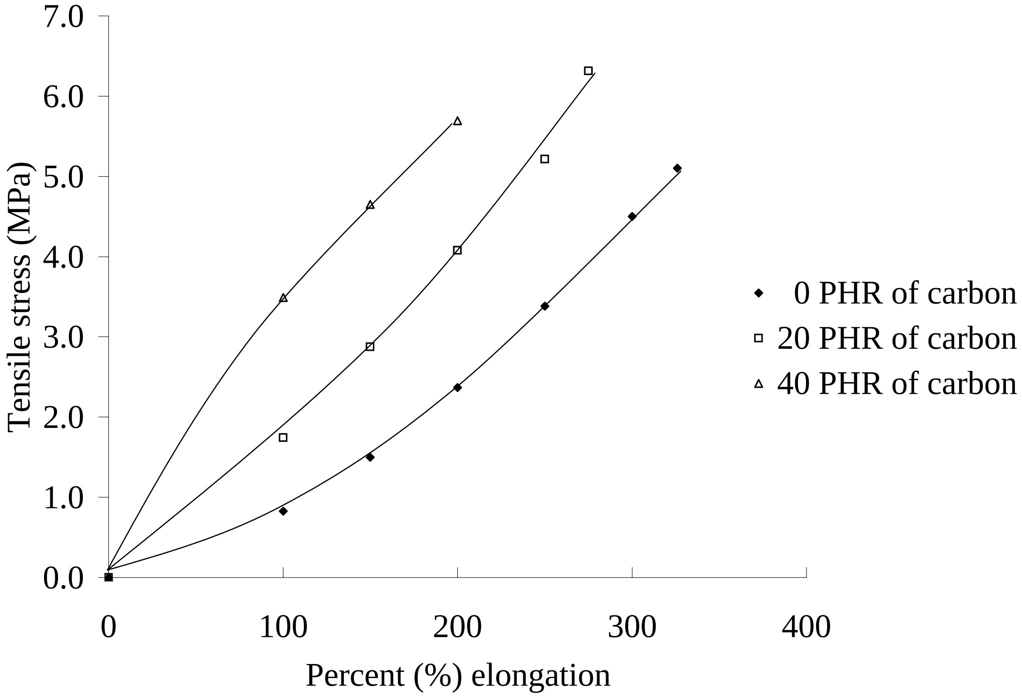


Figure 4.13: Effect of carbon loading at 60PHR of filler

In Figures 4.13 to 4.15, a clear ordering of the modulus curves is observed at

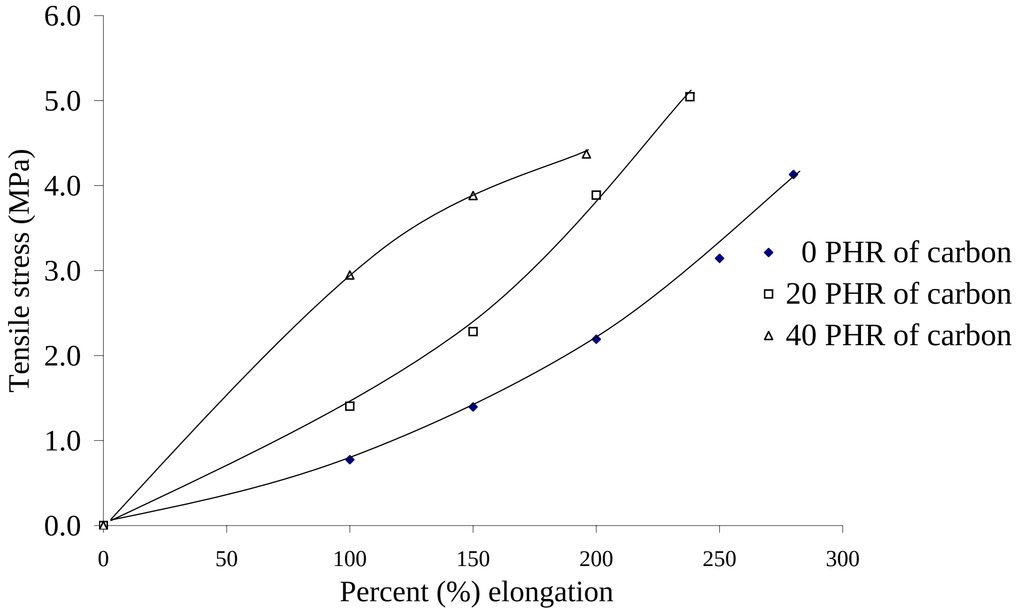


Figure 4.14: Effect of carbon loading at 120PHR of filler

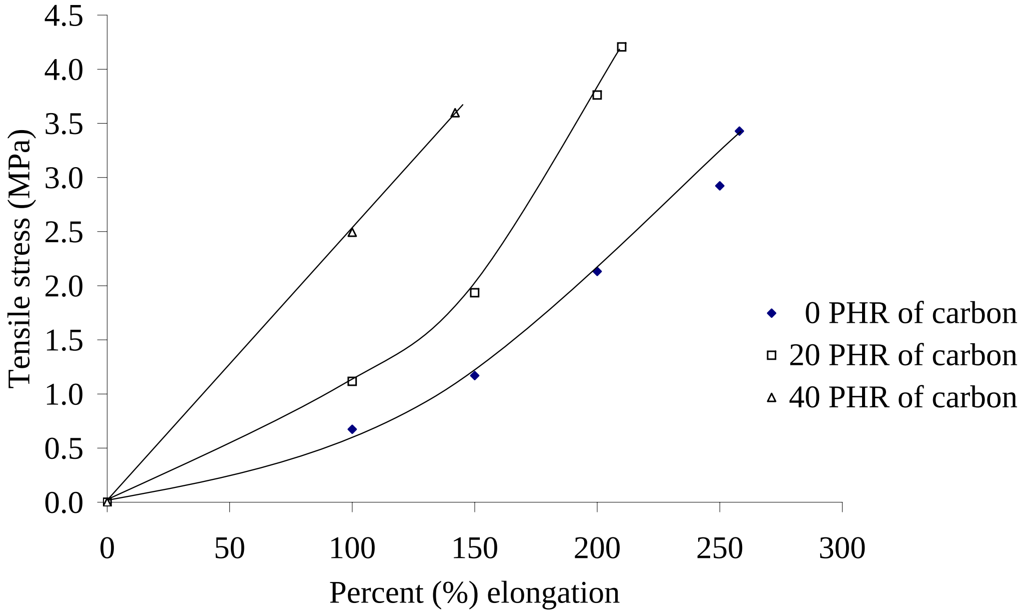


Figure 4.15: Effect of carbon loading at 180 PHR of filler

each PHR level of filler, where tensile modulus is seen to increase with carbon loading. These results tally with previous work [24], where addition of reclaimed rubber to NR compounds was found to increase the carbon black, which acted as an effective reinforcing filler, resulting in restriction of rubber molecular mobility under tension force, and hence increased modulus. Similar results are also

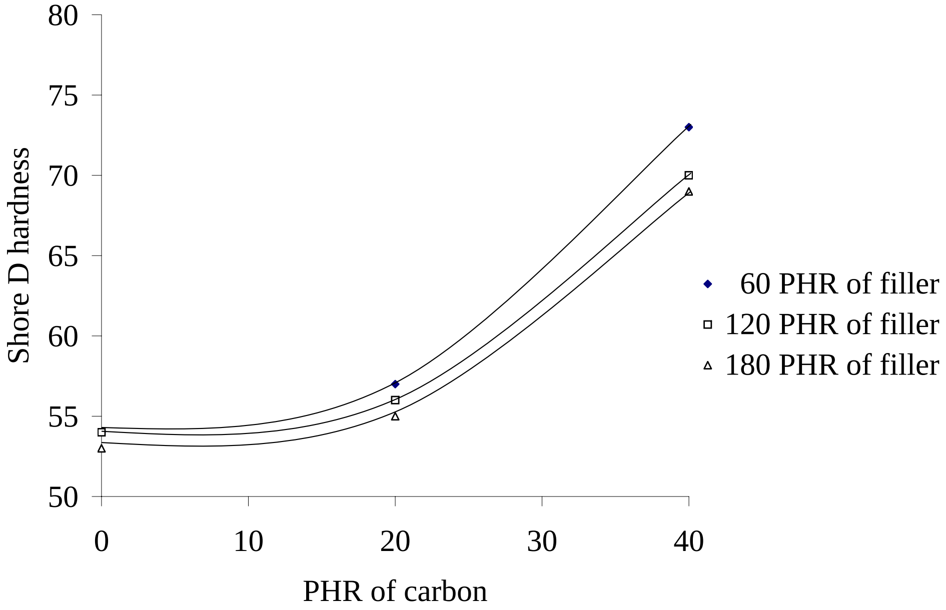


Figure 4.16: Effect of carbon loading on Shore D hardness of specimens

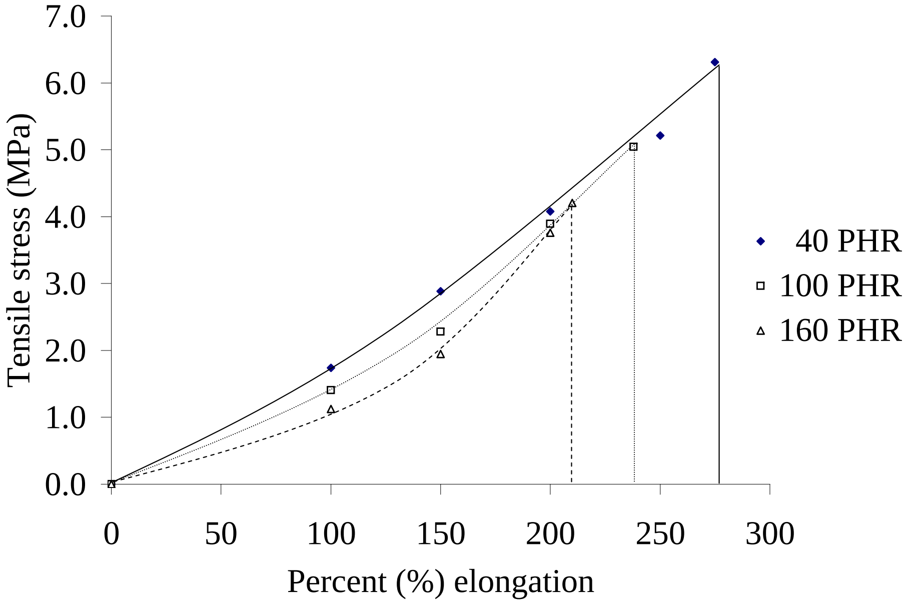


Figure 4.17: Effect of increasing buffings at 20 PHR of carbon

reported by other researchers [41, 42].

Effect of carbon loading on Shore D hardness was observed to be insignificant up to the optimum carbon loading of 21 PHR after which a drastic increase in hardness is observed as shown in Figure 4.16. Ultimately, the hardness was

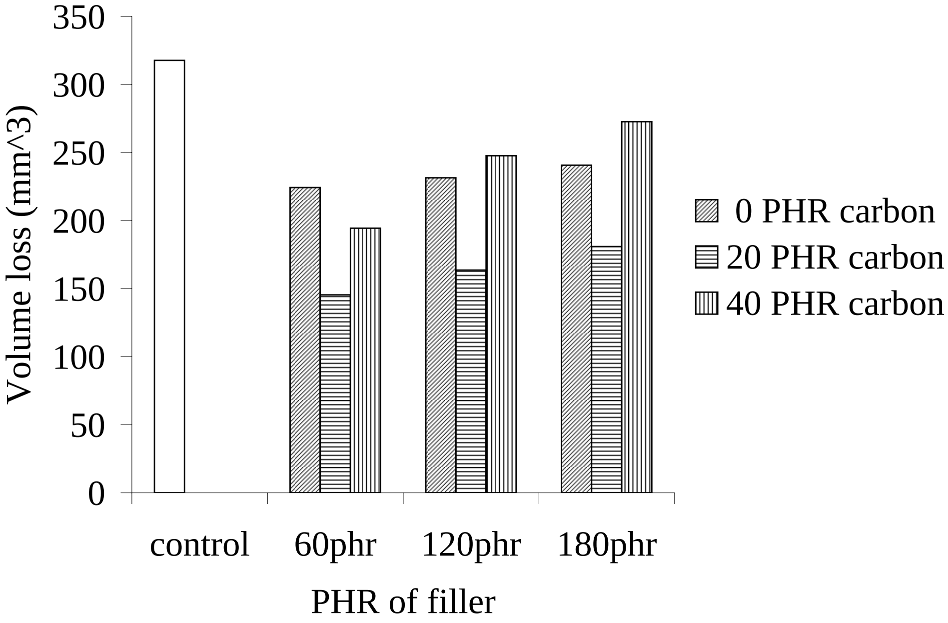


Figure 4.18: Effect of increasing buffings and carbon on abrasion loss

highest at every 40 PHR of carbon at each level. Effect of increasing the PHR of tyre buffings at constant carbon PHR on hardness was found to be very low.

Figure 4.17 shows the rate of change of modulus for each specimen to increase with increase in buffings PHR at constant (20) PHR of carbon. However, there is a marked decrease in ultimate (%) elongation with increase of the buffings PHR leading to successful decrease in toughness (proportional to area under the curve). This is an indication that, at constant PHR of carbon, the vulcanizate's toughness decreases with increase in tread buffings PHR. This can be due to successive dilution of the more superior virgin polymer with the buffings.

Improvement of abrasion property by addition of low amount of buffings is evident as shown in Figure 4.18. The control formulation (specimen WB005A; no filler) yielded the highest volume loss compared with buffing filled specimens. However, the abrasion property deteriorates with increasing amount of buffings. It is possible that optimum abrasion properties would be obtained at the optimum carbon loading of 21 PHR at each level of filler. These results follow almost the same pattern as the ultimate tensile strength results confirming the inherent relationship between the two properties.

4.8.2.2 Aged Specimens

The specimens in section 4.8.2.1 were aged by wrapping with aluminium foils and storing at a room temperature ($\approx 23^{o}$C) for 30 days after which they were cured as described in section 3.3.3. Every specimen was tested 24 hours after curing to allow for structural stabilization. The tensile results are presented in appendix B section A.7

Table 4.28: Averaged mechanical properties for aged (30 days)specimens

Sample	Elongation							Shore D Hardness	Abrasion Volume Loss (mm^3)
	100%	150%	200%	250%	300%	Ultimate			
	TS (MPa)	TS (MPa)	TS (MPa)	TS (MPa)	TS (MPa)	TS (MPa)	%		
WB006A1	0.83	1.50	2.37	3.38	4.50	5.10	326	54	224
WB006A2	1.74	2.88	4.08	5.21		6.31	275	57	145
WB006A3	3.49	4.65	5.69			6.02	203	73	194
WB006B1	0.77	1.40	2.19	3.14		4.13	280	54	231
WB006B2	1.40	2.28	3.89			5.05	237	56	164
WB006B3	2.95	3.88				4.37	196	70	248
WB006C1	0.67	1.17	2.13	2.92		3.43	257	53	241
WB006C2	1.12	1.94	3.76			4.21	210	55	181
WB006C3	2.49					3.60	142	69	273

The most important observation in this research was the influence of aging to mechanical properties of the specimens. It was found that, after aging uncured specimens at room temperature ($\approx 23^{o}$C) for 30 days, the ultimate tensile strength for the 60 PHR level increased by more than 52.33% as shown in Figure 4.19, while the ultimate elongation increased by an average of 12% as seen in Figure 4.20. This is probably attributable to increased crystallinity as the samples were aged for 30 days. However, the crystallinity could not be determined due to lack of facilities such as differential scanning calorimeter (DSC) and wide angle x-ray spectrometer (WAXS).

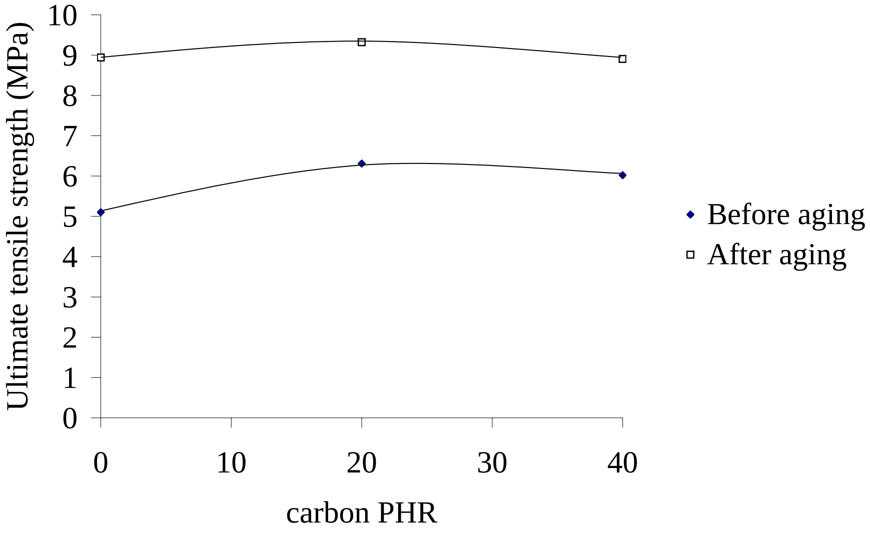


Figure 4.19: Effect of aging (30 days) on UTS at 60 PHR of filler

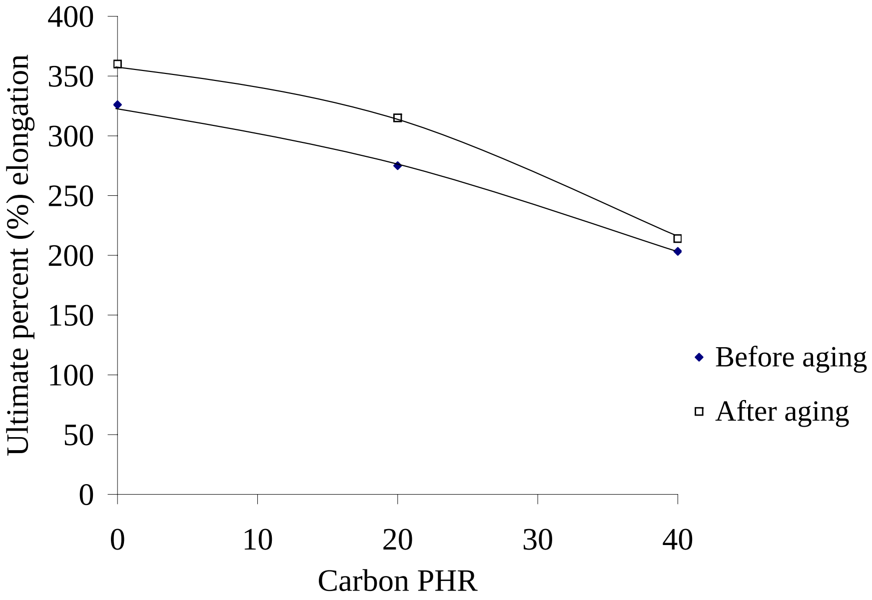


Figure 4.20: Effect of aging (30 days) on UE at 60 PHR of filler

Generally, it can be seen from Figure 4.21 that the percentage increase in ultimate tensile strength decrease with increase in carbon loading. However, beyond 21.5 PHR of carbon, which is very close to the approximated optimum carbon loading of 21 PHR, the rate of decrease is almost zero. This is an indication that, after specimens aging, carbon loading has very little effect on the percent increase in ultimate tensile strength above the optimum point of 21 PHR. In-

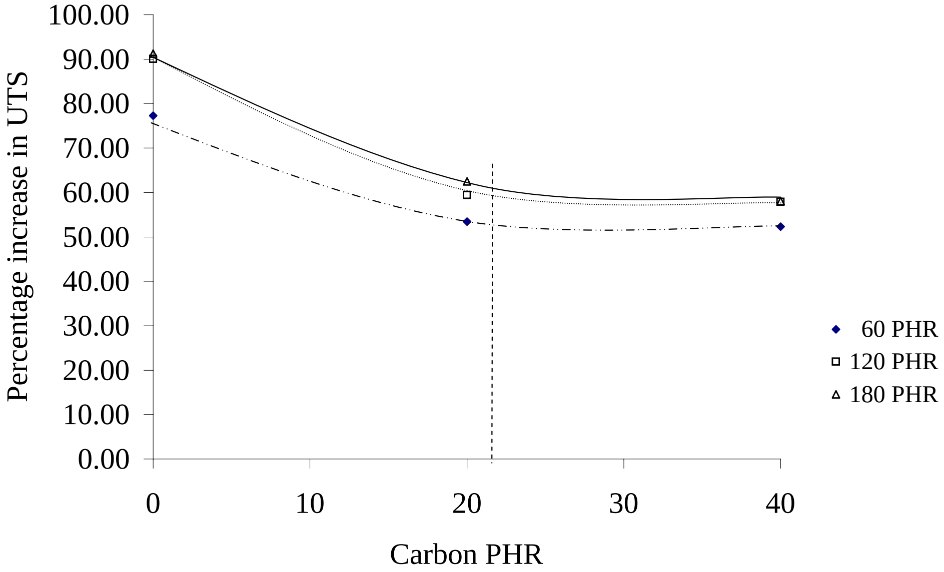


Figure 4.21: Percentage improvement of UTS for 30 days aged specimens

crease in buffings at constant PHR of carbon is also seen to yield better tensile properties after aging. This is thought to result from an increase in cross-link density during aging. Thus rubber buffings can be used to improve the tensile properties of virgin NR vulcanizates through aging.

4.9 Suggested Rubber Formulations (Vanderbilt Chemical Corporation)

Actual rubber formulations are usually classified as proprietary information by manufacturing companies as they hold the key to profitability, competitiveness and success of a company. The suggested rubber formulations by the Vanderbilt Chemical Corporation [31] were used as a relevant guide to prepare competent rubber samples for comparison with those of recycled tyre tread buffings in the experiment.

4.9.1 Batch Weighing and Costing

Specimen batch weight was confined to 0.75 kg to avoid change of weight parameter, while the formulation pigments and procurement costs were sourced from different local suppliers.

Table 4.29: Formulation for medium quality conveyor belt cover (VAN00A)

Code	PHR	%	Batch Weight (Kg)	Price ($/Kg)	Batch Cost Ksh.
S1712	137.50	47.46	0.3560	1.410	36.64
N660	100.00	34.52	0.2589	0.715	13.51
A103	40.00	13.81	0.1036	0.665	5.03
A110	4.00	1.38	0.0104	1.669	1.26
54	2.00	0.69	0.0052	0.655	0.25
RP12924	1.00	0.35	0.0026	4.140	0.78
RP15520	1.00	0.35	0.0026	4.200	0.79
11	2.00	0.69	0.0052	0.275	0.10
466	1.60	0.55	0.0041	3.700	1.12
443	0.60	0.21	0.0016	2.100	0.24
Total	**289.70**	**100.00**	**0.7500**		**59.73**

Table 4.30: Formulation for automotive mat (VAN00B)

Code	PHR	%	Batch Weight (Kg)	Price ($/Kg)	Batch Cost Ksh.
S1712	150.00	28.63	0.2147	1.410	22.10
A110	4.00	0.76	0.0057	1.669	0.70
54	4.00	0.76	0.0057	0.655	0.27
RP12924	1.50	0.29	0.0021	4.140	0.65
A117	3.00	0.57	0.0043	1.100	0.34
RP17132	200.00	38.18	0.2863	0.320	6.69
639	100.00	19.09	0.1432	0.642	6.71
A103	30.00	5.73	0.0429	0.665	2.08
457	2.00	0.38	0.0029	3.600	0.75
443	0.40	0.08	0.0006	2.100	0.09
11	4.00	0.76	0.0057	0.275	0.11
RP10084	25.00	4.77	0.0358	1.542	4.03
Total	**523.90**	**100.00**	**0.7500**		**44.54**

Table 4.31: Formulation for medium quality shoe sole (VAN00C)

Code	PHR	%	Batch Weight (Kg)	Price ($/Kg)	Batch Cost Ksh.
S1502	100.00	33.11	0.2483	1.545	28.01
A103	5.00	1.66	0.0124	1.669	1.51
A110	4.00	1.32	0.0099	0.655	0.47
54	2.00	0.66	0.0050	0.655	0.24
RP12924	1.00	0.33	0.0025	4.140	0.75
445	2.00	0.66	0.0050	2.750	1.00
443	0.50	0.17	0.0012	2.100	0.19
11	2.50	0.83	0.0062	0.275	0.12
RP10084	40.00	13.25	0.0993	2.100	15.23
RP17290	25.00	8.28	0.0621	0.275	1.25
639	120.00	39.74	0.2980	0.642	13.98
Total	**302.00**	**100.00**	**0.7500**		**62.75**

Table 4.32: Formulation for flooring or cover base (VAN00D)

Code	PHR	%	Batch Weight (Kg)	Price ($/Kg)	Batch Cost Ksh.
S1502	100.00	19.07	0.1430	1.545	16.13
RP12924	1.00	0.19	0.0014	4.410	0.46
639	100.00	19.07	0.1430	0.642	6.71
RP17132	250.00	47.67	0.3576	0.320	8.36
RP17232	10.00	1.91	0.0143	1.250	1.31
A110	5.00	0.95	0.0072	1.669	0.87
54	5.00	0.95	0.0072	0.655	0.34
11	6.00	1.14	0.0086	0.275	0.17
457	2.00	0.38	0.0029	3.600	0.75
443	0.40	0.08	0.0006	2.100	0.09
A103	30.00	5.72	0.0429	0.275	0.86
RP17290	15.00	2.86	0.0215	2.334	3.65
Total	**524.40**	**100.00**	**0.7500**		**39.70**

4.9.2 Curing and Testing

Rheometer cure results (at t_{90}) were used to estimate the respective optimum cure time for the assorted Vanderbilt specimens. The time t_{90} is equivalent to time taken to attain 90% of maximum shear torque in the rheometer cure characteristic curve corresponding to 90% of the optimum cure time. The optimum cure time for WB001A had already been identified as 14 min (section 4.3) hence was used as the reference.

Table 4.33: Optimum cure times for specimens VAN00A, B, C and D

Specimen	t_{90} (sec.)	Optimum cure time(min.)
WB001A	78	13.0
VAN00A	203	33.8
VAN00B	471	78.5
VAN00C	318	53.0
VAN00D	513	85.5

The tensile and abrasion results for specimens VAN00A,B,C and D are presented in appendix B section A.5 and appendix C respectively.

Table 4.34: Averaged tensile results for specimens VAN00A, B, C and D

	Elongation											
	100%	150%	200%	250%	300%	400%	500%	600%	700%	800%	Ultimate	
	TS	TS	TS	TS	TS	TS	TS	TS	TS	TS	TS	
Sample	(MPa)	(MPa)	(MPa)	(MPa)	(MPa)	(MPa)	(MPa)	(MPa)	(MPa)	(MPa)	(MPa)	%
VAN00A	0.83	1.98	3.01	4.24	5.68	7.68	9.73	10.89			11.08	595
VAN00B	1.15	1.76	1.42	1.53	1.64	1.89	2.20	2.68	3.56	4.83	5.09	817
VAN00C	1.96	2.30	2.71	3.21							3.41	272
VAN00D	4.65	5.06	5.21								5.23	190

The rheometer cure characteristic results predict high cure times for the suggested formulation, which is expected since the formulations are purely synthetic rubber based [31].

Compared with natural rubber, the SBR based vulcanizates exhibit poorer abrasion properties thus confirms the superiority of natural rubber vulcanizates re-

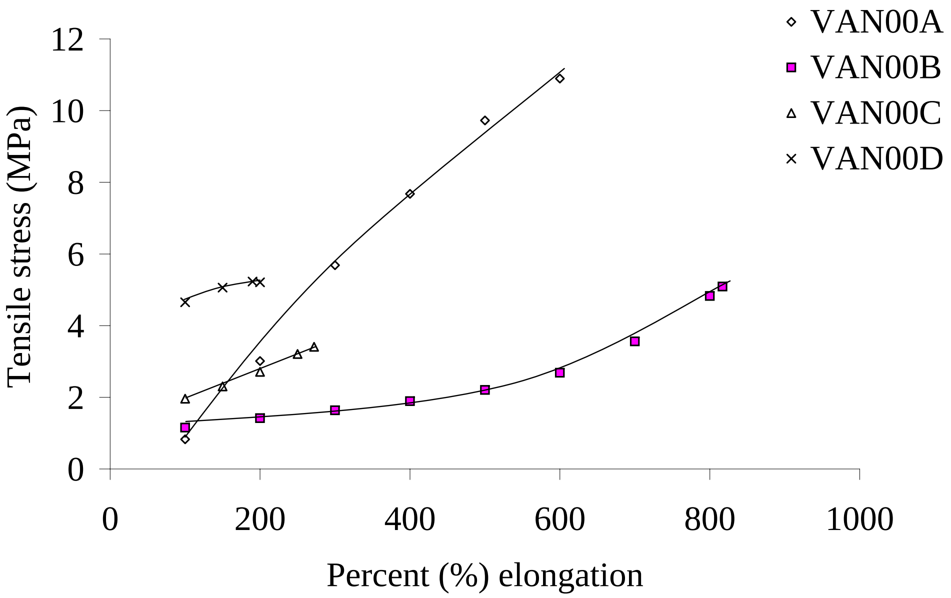


Figure 4.22: Tensile stress for selected Vanderbilt products

Table 4.35: Hardness and abrasion results for specimens VAN00A, B, C, D

Specimen	Shore D Hardness	Abrasion Volume Loss (mm^3)
VAN00A	53	178
VAN00B	59	586
VAN00C	73	430
VAN00D	91	560

sistance against tear.

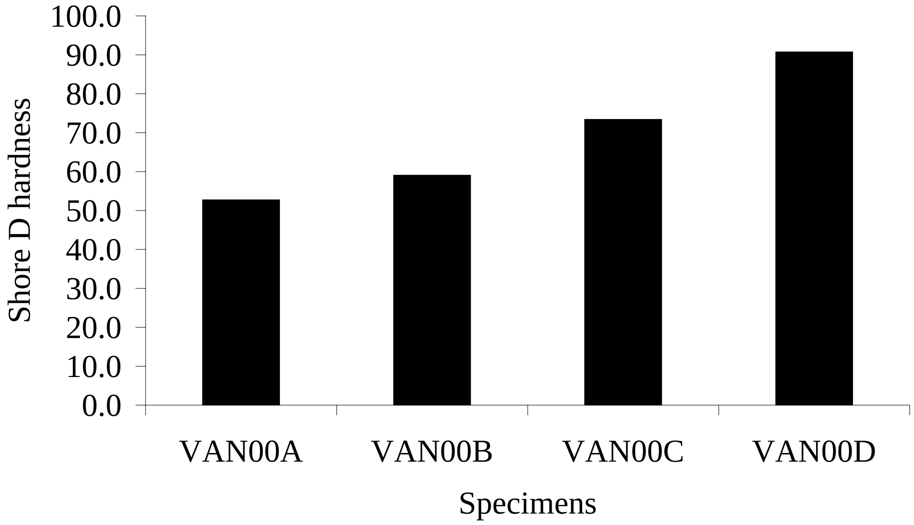


Figure 4.23: Shore D hardness for selected Vanderbilt products

4.10 Comparison of Mechanical Properties and Blend Costs

Selection of a rubber product is governed by the conditions of usage. In rubber industries, different criteria are used to identify different products depending on the most critical property (mechanical, electrical or chemical). The mechanical criteria include; ultimate tensile strength, ultimate elongation, hardness, resistance to abrasion and resilience/hysteresis.

The resilience/hysteresis data is used to indicate both the dynamic modulus and internal friction of rubber which are inherent characteristics used by manufacturers to specify the dynamic usage of the end rubber products.

From the experiments it was possible to tabulate the lower and upper limits of the tested mechanical properties of rubber vulcanizates that can be tailored based on the wheel barrow formulation (Table 4.36). The total cost of blending 0.75 kg of material for each specimen was seen to vary between Ksh. 17.53 and Ksh. 39.10.

Table 4.36: Limits of mechanical properties for the WB formulation

Mechanical property	Lower limit	Upper limit
Hardness	53	76
Ultimate elongation (%)	142	364
Ultimate tensile strength (MPa)	3.43	9.68
Resilience at 24°C (%)	32	46
Resilience at 100°C (%)	46	63

Table 4.37: Limits of mechanical properties for the Vanderbilt formulations

Specimen	UTS (MPa)	UE (%)	Shore D hardness	Resilience at 24º C (%)	Blend Cost (Ksh.)
VAN00A	11.08	595	53	32	59.73
VAN00B	5.09	817	59	19	44.54
VAN00C	3.41	272	73	31	62.75
VAN00D	5.23	190	91	10	39.70

Table 4.38: Substitutable Vanderbilt products based on different criteria

Mechanial criterion	Vanderbilt products
Shore D hardness	VAN00A, VAN00B, VAN00C
Ultimate elongation (%)	VAN00C, VAN00D
Ultimate tensile strength (Mpa)	VAN00B, VAN00C, VAN00D
Resilience at 24ºC (%)	VAN00A

Table 4.38 elaborates possible substitution for the expensive Vanderbilt blends with cheap recycled tread buffings blends using wheelbarrow tyre formulation based on selected mechanical criteria.

Table 4.39: Local wheelbarrow tyre mechanical properties and blend cost

Ultimate elongation (%)	Ultimate tensile strength (Mpa)	Shore D hardness	Blend cost (Ksh)
242	3.24	61.67	**25.46**

Table 4.40: Superior and cheap substitute for local wheelbarrow tyre

Specimens	Ultimate elongation (%)	Ultimate tensile strength (Mpa)	Shore D hardness	Blend cost (Ksh)
WB007C2	298	6.84	57	20.12
WB007C3	155	5.69	71	22.72

The mechanical properties and material cost to prepare 0.75 kg of a local wheelbarrow tyre blend using existing local formulation was identified in section 4.4 (specimen WB002A) and are presented in Table 4.39.

From results obtained in section 4.8, cheap and superior formulations for the local wheelbarrow tyre were identified as WB007C2 and WB007C3. The criteria for selection were based on ultimate tensile strength and hardness respectively. However, comparing the toughness and blend cost, the formulation for specimen WB007C2 is more optimal than WB007C3 and hence was selected to substitute WB002A. This was envisaged to improve both the ultimate tensile strength and ultimate elongation by 111.8% and 23.1% respectively while reducing the blend cost by 21%. Hardness is expected to reduce by a mere 8.2%.

4.11 Evaluation of B Parameter for Recycled Rubber Vulcanizates

The evaluation of the B value was based specifically on the local wheelbarrow tyre formulation (Table 3.1) using equation 2.4.

Results of specimens WB005A, WB006A1, WB006B1 and WB006C1, coinciding with weight fractions of 0.000, 0.349, 0.510 and 0.603 respectively, were selected to eliminate the effect of carbon filler in the samples. Table 4.41 presents the variation of stress with strain at different volume fraction of filler.

Table 4.41: Variation of stress with strain at different volume fraction of filler

Specimen	Strain(ε) 1.0 (MPa)	1.5 (MPa)	2.0 (MPa)	2.5 (MPa)	Specific gravity	Weight fraction of filler	Volume fraction of filler (ø)
WB005A	0.76	1.34	2.11	3.40	1.07	0.000	0.000
WB006A1	0.83	1.50	2.37	3.38	1.07	0.349	0.326
WB006B1	0.77	1.40	2.19	3.14	1.08	0.510	0.472
WB006C1	0.69	1.17	2.13	2.92	1.08	0.603	0.558

Table 4.42: Variation of B with volume fraction of filler (ϕ) at constant strains

B value at various strains	Volume fraction of filler (ø) 0.326	0.472	0.558
$B_{1.0}$	0.46	0.34	0.33
$B_{1.5}$	-1.78	-0.63	-0.20
$B_{2.0}$	-10.85	-2.47	-1.44
$B_{2.5}$	-16.02	-6.48	-4.12

Generally, the magnitude of the interface parameter (B) decreases with increase in volume fraction of filler as shown in Figure4.24. The parameter remains fairly constant at low strains irrespective of volume fraction of filler. However, the figure shows an inversion of B value at a strain between 1 and 1.5 when the composite tensile strength is dictated by equation 4.1

$$\sigma = \frac{1-\phi}{1+2.5\phi} \tag{4.1}$$

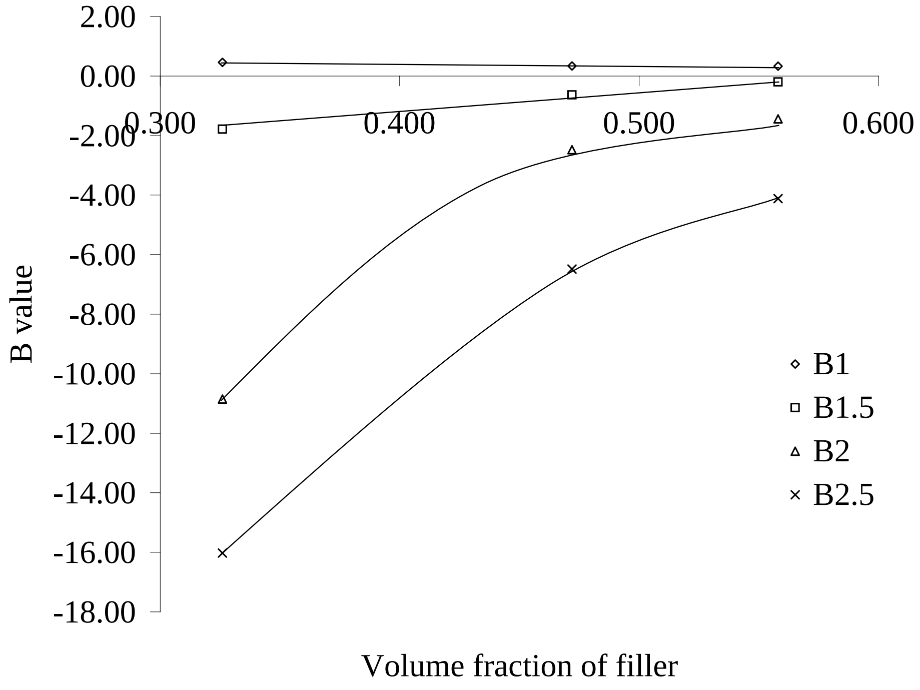


Figure 4.24: Variation of B value with fraction of filler

This equation implies that the composite tensile strength is independent of matrix tensile strength and solely depend on volume fraction of filler at various strains. Such a scenario is practically impossible since fundamentally, matrix strength inherently defines the strength of a particulate composite [9]. Thus the mathematical model does not hold for recycled buffings rubber composites.

Chapter 5

CONCLUSIONS

This work involved a step by step elimination method to optimise the usage and mechanical properties of recycled tread buffings with a bias to the wheelbarrow tyre formulation. The recycled rubber properties obtained by this process are consistent with much of the current work in the field of rubber recycling.

- The rubber buffings are classified into three standardized aggregates; TD#8, TDmix8, and TD>#8 using a standard mesh 8 sieve.
- The standard mesh 8 aggregate for selected tyres (firestone, Kelly, Goodyear, Pirelli, and Toyo) vary from 74.5% to 57.5%.
- From the selected tyre buffings, Firestone buffings impart optimum mechanical properties (UTS of 4.28 MPa and ultimate percent elongation of 269 %) to the wheelbarrow tyre formulation.
- The chemical compatibilization technique considered in this study is modeled around those of thermoplastic/recycled rubber blends whereby a potassium permanganate solution is used to generate hydroxyl groups on the rubber particle surface to improve the grafting properties. Preliminary results show the method to be relatively costly and to yield poorer mechanical properties than non-grafted samples.
- The optimization of carbon black in the wheelbarrow formulation shows optimum mechanical properties at a carbon loading of approximately 21 PHR. However, by using different mechanical criteria such as ultimate yield strength, percent elongation, hardness, abrasion resistance and resilience, assorted optimized products can be made by varying the amount of buffings in the formulations.

- Specimen WB007C2 {control formulation with addation of 160 PHR TD#8 (Firestone) and 20 PHR N660} yield optimum properties for the wheelbarrow formulation. The specimen improves both the ultimate tensile strength and ultimate elongation by 111.8% and 23.1% respectively while reducing the blend cost by 21%. hardness reduces by a mere 8.2%.
- Addition of low amounts of buffings improve the abrasion properties of unfilled vulcanizates even at 0 PHR of carbon. This could result due to presence of carbon black in the buffings.

RECOMMENDATIONS

Going with the results obtained in this research, further investigations on tyre tread recycling are recommended in the following areas:

- The effect of using laboratory internal mixer instead of laboratory mill to improve blends homogeneity and repeatability of vulcanizate properties should be investigated.
- Though the smaller tread particle size enhances strain capability in the considered wheelbarrow tyre formulation, these improvement in mechanical properties do not appear to be sufficient to justify additional refining costs associated with the finer particle size, hence a cost/properties trade-off study may be appropriate for applications demanding superior properties.
- Any improvement of mechanical properties is largely believed to rely on phase interaction between the matrix, fillers and the surface properties of the rubber particles. Thus a great deal of polymer chemistry knowledge should be input to develop cheap compatibilization techniques for recycled rubber composites to realise optimal mechanical properties at reduced costs.
- The power input to masticate and blend different samples is assumed to be constant in this work. In any case, the variations are bound to be insignificant for laboratory batches. For an industrial set up however, it would be worthwhile to analyse the rheological properties of samples, which is believed to be dependent on the initial weight average molar mass of rubber, in view of evaluating the actual power input.
- More time should be invested on specimens aging to ascertain the optimum aging time. Though the specimens storage would equally add the inventory

costs, the mechanical properties gain may outweigh such costs leading to material savings and hence lower cost of production.

- Though the correlated mathematical model to evaluate the value of B seem to hold at low tensile strains, it should be re-modeled to capture the basic principal that relates composite strength and matrix strength at all levels of strain.

The results of this research are highly recommended to rubber recyclers including Jua-Kali artisans to improve the properties of their end products as the results can be easily assimilated with minimum process redesigning.

One of the major benefit of this research is cleaning environment which would lead to improved human health. Thus, the Government through the Ministry of Industry and concerned Non-Government agencies should promote the awareness of tyre scrap recycling as a valuable activity and possibly introduce tax incentives and rebates for players involved in rubber recycling.

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Appendix A

Tensile Test Results

Various tensile test results for different specimens showing the indicated kilogramforce at different percent (%) elongations are presented in this appendix.

A.1 Effect of Cure Time on Ultimate Strength

Table A.1: Sample WB001A5 (cured for 5min.)

			100% Elongation		200% Elongation		Ultimate Elongation		
Sample	Thickness (mm)	X-Area (mm$^{2)}$	Force (Kgf)	TS (MPa)	Force (Kgf)	TS (MPa)	%	Force (Kgf)	UTS (MPa)
1	1.88	11.28	1.05	0.91	2.00	1.74	200	3.10	2.70
2	1.86	11.16	1.00	0.88	1.95	1.71	220	2.80	2.46
3	1.86	11.16	1.00	0.88	2.05	1.80	210	2.60	2.28
4	1.80	10.80	0.95	0.86	1.60	1.45	240	2.75	2.50
5	1.78	10.68	1.10	1.01	1.60	1.47	240	2.60	2.39

Table A.2: Sample WB001A10 (cured for 10 min.)

			100% Elongation		200% Elongation		Ultimate Elongation		
Sample	Thickness (mm)	X-Area (mm$^{2)}$	Force (Kgf)	TS (MPa)	Force (Kgf)	TS (MPa)	%	Force (Kgf)	UTS (MPa)
1	1.70	10.20	1.25	1.20	2.50	2.40	260	3.10	2.98
2	1.78	10.68	1.50	1.38	2.80	2.57	270	3.35	3.08
3	1.78	10.68	1.50	1.38	2.70	2.48	240	3.40	3.12
4	1.80	10.80	1.50	1.36	2.60	2.36	250	3.10	2.81
5	1.86	11.16	1.40	1.23	2.70	2.37	250	3.70	3.25

Table A.3: Sample WB001A15 (cured for 15 min.)

			100% Elongation		200% Elongation		Ultimate Elongation		
Sample	Thickness (mm)	X-Area (mm$^{2)}$	Force (Kgf)	TS (MPa)	Force (Kgf)	TS (MPa)	%	Force (Kgf)	UTS (MPa)
1	2.05	12.30	1.90	1.51	3.30	2.63	265	4.40	3.51
2	1.98	11.88	1.95	1.61	3.20	2.64	240	4.30	3.55
3	1.82	10.92	1.80	1.62	2.90	2.60	245	4.00	3.59
4	1.87	11.22	2.00	1.75	3.20	2.80	250	4.25	3.71
5	1.93	11.58	1.95	1.65	3.30	2.79	250	4.10	3.47

Table A.4: Sample WB001A20 (cured for 20 min.)

			100% Elongation		200% Elongation		Ultimate Elongation		
Sample	Thickness (mm)	X-Area (mm$^{2)}$	Force (Kgf)	TS (MPa)	Force (Kgf)	TS (MPa)	%	Force (Kgf)	UTS (MPa)
1	1.90	11.40	1.60	1.38	3.00	2.58	230	3.50	3.01
2	1.90	11.40	1.35	1.16	2.70	2.32	240	3.20	2.75
3	1.88	11.28	1.35	1.17	2.65	2.30	230	3.20	2.78
4	1.84	11.04	1.55	1.38	2.70	2.40	230	3.40	3.02
5	1.73	10.38	1.30	1.23	2.50	2.36	250	3.25	3.07

Table A.5: Sample WB001A25 (cured for 25 min.)

			100% Elongation		200% Elongation		Ultimate Elongation		
Sample	Thickness (mm)	X-Area (mm$^{2)}$	Force (Kgf)	TS (MPa)	Force (Kgf)	TS (MPa)	%	Force (Kgf)	UTS (MPa)
1	1.77	10.62	1.35	1.25	2.65	2.45	230	3.10	2.86
2	1.75	10.50	1.40	1.31	2.60	2.43	240	3.25	3.04
3	1.75	10.50	1.35	1.26	2.40	2.24	250	3.30	3.08
4	1.80	10.80	1.40	1.27	2.55	2.32	210	2.70	2.45
5	1.83	10.98	1.40	1.25	2.65	2.37	230	3.30	2.95

A.2 Effect of Particle Size on Mechanical Properties

Table A.6: Tensile test results for WB formulation with TD#8 (WB002A)

			100% Elongation		200% Elongation		Ultimate Elongation		
	Thickness	X-Area	Force	Modulus	Force	Modulus		Force	U Strgth
Sample	mm	mm^2	Kgf	MPa	Kgf	MPa	%	Kgf	MPa
1	2.00	12.00	2.25	1.84	3.95	3.23	250	4.30	3.51
2	2.00	12.00	2.10	1.72	3.80	3.11	255	4.40	3.60
3	2.04	12.24	2.45	1.96	4.10	3.28	250	4.45	3.57
4	1.94	11.64	2.20	1.85	3.80	3.20	260	4.00	3.37
5	1.86	11.16	2.00	1.76	3.70	3.25	260	4.15	3.65
6	2.01	12.06	2.20	1.79	4.00	3.25	240	4.30	3.50

Table A.7: Tensile test results for WB formulation with TD#8Mix (WB002B)

			100% Elongation		200% Elongation		Ultimate Elongation		
Sample	Thickness (mm)	X-Area (mm$^{2)}$	Force (Kgf)	TS (MPa)	Force (Kgf)	TS (MPa)	%	Force (Kgf)	UTS (MPa)
1	1.77	10.62	1.70	1.57	3.30	3.05	250	3.60	3.32
2	1.72	10.32	1.65	1.57	3.50	3.33	250	3.55	3.37
3	1.80	10.80	1.85	1.68	3.30	3.00	250	3.40	3.09
4	1.88	11.28	1.90	1.65	3.30	2.83	250	3.90	3.39
5	1.93	11.58	1.75	1.68	3.40	2.88	225	3.70	3.13
6	1.98	11.88	1.80	1.68	3.50	2.85	225	3.70	3.05

Table A.8: Tensile test results for WB formulation with TD>#8 (WB002B)

			100% Elongation		200% Elongation		Ultimate Elongation		
Sample	Thickness (mm)	X-Area (mm$^{2)}$	Force (Kgf)	TS (MPa)	Force (Kgf)	TS (MPa)	%	Force (Kgf)	UTS (MPa)
1	1.71	10.26	1.75	1.67		0.00	175	2.45	2.34
2	1.80	10.80	1.75	1.59	3.15	2.86	200	3.15	2.86
3	1.87	11.22	1.95	1.70	3.50	3.06	225	3.70	3.23
4	1.91	11.46	1.85	1.58	3.35	2.87	230	3.80	3.25
5	2.06	12.36	1.90	1.51		0.00	195	2.85	2.26
6	2.02	12.12	2.00	1.62	3.60	2.91	225	3.75	3.03

A.3 Effect of Various Fillers on WB Tyre Formulation

Table A.9: Tensile test results for WB formulation with Kelly buffings (WB003A)

Sample Thickness mm	Elongation								
	100%		150%		200%		Ultimate		
	Force (Kgf)	TS (MPa)	Force (Kgf)	TS (MPa)	Force (Kgf)	TS (MPa)	%	Force (Kgf)	UTS (MPa)
1.69	1.35	1.31	2.10	2.03	2.85	2.76	230	3.20	3.09
1.71	1.35	1.29	2.15	2.05	3.05	2.92	230	3.40	3.25
1.80	1.55	1.41	2.30	2.09	3.20	2.91	260	3.90	3.54
1.91	1.60	1.37	2.45	2.10	3.40	2.91	240	3.95	3.38
1.91	1.55	1.33	2.45	2.10	3.30	2.82	250	4.25	3.64
1.95	1.65	1.38	2.60	2.18	3.50	2.93	240	4.20	3.52

Table A.10: Tensile test results for WB formulation with Firestone buffings (WB003B)

Sample Thickness mm	Elongation								
	100%		150%		200%		Ultimate		
	Force (Kgf)	TS (MPa)	Force (Kgf)	TS (MPa)	Force (Kgf)	TS (MPa)	%	Force (Kgf)	UTS (MPa)
1.65	1.50	1.49	2.35	2.33	3.20	3.17	235	3.65	3.62
1.97	1.70	1.41	2.70	2.24	3.85	3.19	270	4.90	4.07
1.73	1.65	1.56	2.55	2.41	3.35	3.16	275	4.60	4.35
1.95	2.05	1.72	2.95	2.47	3.80	3.19	285	5.30	4.44
1.88	1.90	1.65	2.80	2.43	3.70	3.22	280	5.25	4.56
1.79	1.80	1.64	2.85	2.60	3.80	3.47	270	5.10	4.66

Table A.11: Tensile test results for WB formulation with Pirelli buffings (WB003C)

Sample Thickness mm	Elongation								
	100%		150%		200%		Ultimate		
	Force (Kgf)	TS (MPa)	Force (Kgf)	TS (MPa)	Force (Kgf)	TS (MPa)	%	Force (Kgf)	UTS (MPa)
1.87	1.80	1.57	2.85	2.49	3.70	3.23	250	4.55	3.98
1.84	1.90	1.69	2.85	2.53	3.70	3.29	240	4.35	3.86
1.98	2.10	1.73	3.05	2.52	3.90	3.22	240	4.75	3.92
1.87	2.00	1.75	2.85	2.49	3.70	3.23	240	4.45	3.89
1.89	1.85	1.60	2.65	2.29	3.60	3.11	250	4.50	3.89
1.82	1.95	1.75	2.85	2.56	3.75	3.37	240	4.50	4.04

Table A.12: Tensile test results for WB formulation with Toyo buffings (WB003D)

Sample	Elongation								
	100%		150%		200%		Ultimate		
Thickness mm	Force (Kgf)	TS (MPa)	Force (Kgf)	TS (MPa)	Force (Kgf)	TS (MPa)	%	Force (Kgf)	UTS (MPa)
1.82	1.75	1.57	2.55	2.29	3.40	3.05	230	3.80	3.41
1.88	1.80	1.56	2.80	2.43	3.70	3.22	225	4.20	3.65
1.74	1.70	1.60	2.55	2.40	3.25	3.05	250	3.95	3.71
1.67	1.65	1.61	2.55	2.50	3.30	3.23	250	3.95	3.87
1.85	1.85	1.63	2.75	2.43	3.70	3.27	250	4.45	3.93
1.80	1.75	1.59	2.70	2.45	3.50	3.18	250	4.15	3.77

Table A.13: Tensile test results for WB formulation with Goodyear buffings (WB003E)

Sample	Elongation								
	100%		150%		200%		Ultimate		
Thickness mm	Force (Kgf)	TS (MPa)	Force (Kgf)	TS (MPa)	Force (Kgf)	TS (MPa)	%	Force (Kgf)	UTS (MPa)
1.75	1.10	1.03	1.85	1.73	2.50	2.33	230	2.67	2.49
1.78	1.25	1.15	1.90	1.74	2.60	2.39	240	2.72	2.50
1.83	1.30	1.16	1.90	1.70	2.55	2.28	230	2.81	2.51
1.83	1.35	1.21	2.05	1.83	2.75	2.46	260	3.36	3.00
1.86	1.35	1.19	2.00	1.76	2.70	2.37	230	3.25	2.86
1.97	1.40	1.16	2.10	1.74	2.80	2.32	225	3.20	2.65

A.4 Effects of Selected Fillers on Mechanical Properties of WB Vulcanizate

Table A.14: Tensile test results for Control formulation (no filler)

Sample	Thickness (mm)	Elongation						
		100%	150%	200%	250%	300%	Ultimate	
		Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	%
1	1.95	0.85	1.40	2.40	3.70		4.75	280
2	1.67	0.70	1.30	1.95	3.30	4.50	5.20	320
3	1.69	0.90	1.55	2.45	3.80	5.30	5.60	320
4	1.77	0.85	1.55	2.35	3.90		4.90	290

Table A.15: Tensile test results for Control formulation with Kaolin (WB005B)

Sample	Thickness (mm)	Elongation						
		100%	150%	200%	250%	300%	Ultimate	
		Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	%
1	1.77	2.00	2.90	3.75	4.40	5.15	5.15	300
2	1.93	2.30	3.40	4.55	5.40	5.80	6.20	310
3	1.73	2.00	2.80	3.80	4.45	5.00	5.00	300
4	1.94	2.00	3.15	4.00	4.80	5.40	5.40	310
5	1.85	1.80	2.85	3.55	4.45	5.10	6.15	320
6	1.89	1.95	3.00	3.80	4.80	5.60	5.60	310

Table A.16: Tensile test results for Control formulation with Firestone buffings (WB005C)

Sample	Thickness (mm)	Elongation						
		100%	150%	200%	250%	300%	Ultimate	
		Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	%
1	1.63	0.80	1.50	2.45	3.20	4.60	4.90	330
2	1.83	1.00	1.70	2.60	4.05	5.30	6.00	320
3	1.64	0.80	1.40	2.20	3.20	4.45	5.25	330
4	1.92	1.00	1.70	2.90	3.90	4.35	5.45	340
5	1.74	0.90	1.65	2.55	3.80	5.35	5.70	310

Table A.17: Tensile test results for Control formulation with $CaCO_3$ (WB005D)

Sample	Thickness (mm)	Elongation						
		100%	150%	200%	250%	300%	Ultimate	
		Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	%
1	1.69	1.20	1.75	2.20	3.05	4.00	4.05	305
2	1.62	1.20	1.65	2.20	2.90	3.70	4.10	325
3	1.70	1.25	1.70	2.20	3.05	4.00	4.35	320
4	1.77	1.40	1.85	2.35	3.20	4.25	4.55	310
5	1.92	1.40	1.90	2.45	3.30	4.40	4.75	310
6	1.89	1.40	2.00	2.65	3.40	4.35	5.30	330

Table A.18: Tensile test results for Control formulation with Carbon black (WB005E)

Sample	Thickness (mm)	Elongation						
		100%	150%	200%	250%	300%	Ultimate	
		Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	%
1	2.00	6.80					7.00	105
2	1.90	7.20					7.70	110
3	1.83	6.70					6.70	100
4	1.83	6.55					6.55	100
5	1.75	6.35					6.35	100
6	1.72	6.20					6.50	105

A.5 Suggested Rubber Formulations (Vanderbilt Chemical Corporation)

Table A.19: Tensile test results for medium quality conveyor belt cover

Thickness (mm)	Elongation							
	100%	200%	300%	400%	500%	600%	Ultimate	
	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	%
1.62	1.00	3.35	5.80	7.90	9.50	10.40	11.00	600
1.68	0.80	2.60	5.60	7.60	9.60		10.80	560
1.67	0.90	3.20	5.90	8.00	10.20		11.20	570
1.54	0.70	2.90	5.50	7.30	9.50		10.40	600
1.64	0.80	3.00	5.70	7.80	9.70	11.40	11.60	620
1.60	0.75	2.90	5.40	7.20	9.50	10.60	11.10	620

Table A.20: Tensile test results for automotive mat

Thickness (mm)	Elongation									
	100%	200%	300%	400%	500%	600%	700%	800%	Ultimate	
	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	%
1.83	1.20	1.40	1.70	2.00	2.30	3.00	3.90	5.40	5.40	800
1.74	1.30	1.55	1.80	2.10	2.40	2.90	3.90	5.20	5.70	840
1.69	1.20	1.50	1.75	2.00	2.30	2.80	3.70	5.10	5.20	810
1.59	1.15	1.45	1.65	1.80	2.15	2.60	3.45	4.80	5.05	820
1.62	1.20	1.50	1.65	1.95	2.30	2.70	3.60	4.70	4.70	800
1.51	1.00	1.25	1.45	1.70	2.00	2.40	3.20	4.30	5.00	830

Table A.21: Tensile test results for medium quality shoe sole

Thickness (mm)	Elongation					
	100%	150%	200%	250%	Ultimate	
	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	%
1.78	2.00	2.40	2.90	3.60	3.75	300
1.66	2.00	2.30	2.75	3.25	3.50	270
1.51	1.80	2.10	2.50	2.90	3.20	260
1.55	1.90	2.20	2.55	3.00	3.15	260
1.51	1.80	2.20	2.50	3.00	3.25	270
1.58	2.00	2.30	2.70	3.10	3.15	270

Table A.22: Tensile test results for flooring or cover base

	Elongation					
	100%	150%	200%	250%	Ultimate	
Thickness (mm)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	%
1.75	4.67	5.30	5.40		5.50	210
1.74	4.95	5.25			5.40	180
1.73	4.70	5.10	5.40		5.40	200
1.69	5.10	5.50			5.40	160
1.70	4.90	5.30			5.60	190
1.73	5.10	5.55	5.80		5.80	200

A.6 Un-Aged Specimens

Table A.23: Tensile test results for Control formulation with 60PHR TD#8 (Fstn) and 0PHR N660 (specimen WB006A1)

Thickness (mm)	Elongation						
	100%	150%	200%	250%	300%	Ultimate	
	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	%
1.63	0.80	1.50	2.45	3.20	4.60	4.90	330
1.83	0.95	1.80	2.60	4.05	5.30	6.00	320
1.64	0.80	1.40	2.20	3.20	4.45	5.25	330
1.92	1.00	1.70	2.90	3.90	4.35	5.45	340
1.74	0.90	1.65	2.55	3.80	5.35	5.70	310

Table A.24: Tensile test results for Control formulation with 40PHR TD#8 (Fstn) and 20PHR N660 (specimen WB006A2)

Thickness (mm)	Elongation						
	100%	150%	200%	250%	300%	Ultimate	
	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	%
1.73	1.80	3.10	4.20	5.60		6.85	280
1.82	1.95	3.30	4.35	5.80		7.05	275
1.79	1.85	3.00	4.55	5.45		6.20	260
1.64	1.80	2.75	3.95	5.30		6.60	270
1.74	1.90	3.20	4.70	5.65		6.95	290

Table A.25: Tensile test results for Control formulation with 20PHR TD#8 (Fstn) and 40PHR N660 (specimen WB006A3)

Thickness (mm)	Elongation						
	100%	150%	200%	250%	300%	Ultimate	
	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	%
1.88	3.80	5.10	6.40			7.00	220
1.76	3.95	4.95	6.40			6.40	200
1.74	3.90	5.00	6.00			6.55	220
1.67	3.55	4.90				6.45	190
1.90	4.10	5.45	6.55			6.80	200
1.81	3.65	5.20				6.40	190

Table A.26: Tensile test results for Control formulation with 120PHR TD#8 (Fstn) and 0PHR N660 (specimen WB006B1)

Thickness (mm)	Elongation						
	100%	150%	200%	250%	300%	Ultimate	
	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	%
1.55	0.70	1.35	2.00	3.00		3.90	280
1.73	0.80	1.55	2.30	3.15		4.10	270
1.80	0.90	1.60	2.45	3.40	4.40	5.15	310
1.76	0.80	1.40	2.10	3.35	4.30	5.20	300
1.88	0.95	1.60	2.75	3.80		3.80	250
1.70	0.80	1.40	2.40	3.35		4.15	270

Table A.27: Tensile test results for Control formulation with 100PHR TD#8 (Fstn) and 20PHR N660 (specimen WB006B2)

Thickness (mm)	Elongation						
	100%	150%	200%	250%	300%	Ultimate	
	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	%
1.63	1.40	2.30	3.90			5.10	240
1.70	1.45	2.60	4.10				230
1.83	1.70	2.75	4.20	6.00		6.00	250
1.64	1.35	2.10	4.10			5.30	240
1.92	1.70	2.50	4.50			5.20	220
1.74	1.40	2.35	4.05				240

Table A.28: Tensile test results for Control formulation with 80PHR TD#8 (Fstn) and 40PHR N660 (specimen WB006B3)

Thickness (mm)	Elongation						
	100%	150%	200%	250%	300%	Ultimate	
	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	%
1.70	3.10	4.10				5.10	180
1.78	3.20	4.15				4.15	150
1.64	2.90	3.90				3.90	150
1.57	2.85	3.60				4.80	170
1.63	3.00	4.00				4.00	150
1.80	3.20	4.30				5.10	180

Table A.29: Tensile test results for Control formulation with 180PHR TD#8 (Fstn) and 0PHR N660 (specimen WB006C1)

	Elongation						
	100%	150%	200%	250%	300%	Ultimate	
Thickness (mm)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	%
1.75	0.70	1.25	2.35	3.15		4.50	280
1.56	0.65	1.10	1.90	2.80		3.20	250
1.63	0.70	1.20	2.00	2.90		2.90	250
1.74	0.70	1.25	2.20	3.10		3.70	260
1.84	0.75	1.30	2.75			3.30	240
1.68	0.70	1.20	2.15	3.00		3.80	260

Table A.30: Tensile test results for Control formulation with 160PHR TD#8 (Fstn) and 20PHR N660 (specimen WB006C2)

	Elongation						
	100%	150%	200%	250%	300%	Ultimate	
Thickness (mm)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	%
1.76	1.20	2.10	4.00			4.90	220
1.77	1.25	2.05	3.90			4.50	210
1.67	1.10	1.90	4.05			4.05	200
1.78	1.30	2.25	4.10			5.00	230
1.80	1.15	2.10				4.15	190

Table A.31: Tensile test results for Control formulation with 140PHR TD#8 (Fstn) and 40PHR N660 (specimen WB006C3)

	Elongation						
	100%	150%	200%	250%	300%	Ultimate	
Thickness (mm)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	%
1.88	2.85					4.10	140
1.92	3.10	4.20				4.20	150
1.76	2.70					3.75	140
1.71	2.55					3.70	130
1.84	2.80	3.90				3.90	150
1.69	2.50					4.10	140

A.7 Aged Specimens

Table A.32: Tensile test results for specimen WB007A1 (WB006A1 aged for 30days)

	Elongation							
	100%	150%	200%	250%	300%	350%	Ultimate	
Thickness (mm)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	%
2.02	1.50	2.50	3.60	5.60	8.10	10.80	11.40	380
1.90	1.20	2.10	3.50	5.40	7.60	10.10	10.60	360
2.32	1.60	2.65	4.40	7.00	10.00	12.20	12.20	350
1.79	1.20	2.10	3.30	5.00	7.20	9.40	9.70	360
2.20	1.60	2.60	4.10	6.30				
2.09	1.50	2.60	4.00	6.10	8.40	11.00	12.00	370

Table A.33: Tensile test results for specimen WB007A2 (WB006A2 aged for 30days)

	Elongation							
	100%	150%	200%	250%	300%	350%	Ultimate	
Thickness (mm)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	%
2.02	1.50	2.50	3.60	5.60	8.10	10.80	11.40	380
1.90	1.20	2.10	3.50	5.40	7.60	10.10	10.60	360
2.32	1.60	2.65	4.40	7.00	10.00	12.20	12.20	350
1.79	1.20	2.10	3.30	5.00	7.20	9.40	9.70	360
2.20	1.60	2.60	4.10	6.30				
2.09	1.50	2.60	4.00	6.10	8.40	11.00	12.00	370

Table A.34: Tensile test results for specimen WB007A3 (WB006A3 aged for 30days)

	Elongation							
	100%	150%	200%	250%	300%	350%	Ultimate	
Thickness (mm)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	%
2.30	4.20	7.80	11.00	12.70			13.20	260
2.30	5.00	8.00	11.10	13.00			13.00	250
2.31	4.20	7.20	9.80				11.80	240
2.30	4.00	7.20	10.40	12.60			12.60	250
2.26	4.60	8.20	10.30	12.10			13.70	280

Table A.35: Tensile test results for specimen WB007B1 (WB006B1 aged for 30days)

	Elongation							
	100%	150%	200%	250%	300%	350%	Ultimate	
Thickness (mm)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	%
2.31	1.40	2.20	3.70	5.60	7.80	10.80	10.80	350
2.22	1.30	2.10	3.60					
2.37	1.60	2.50	4.10	6.00	8.50	11.20	12.10	360
2.16	1.30	2.20	3.90	5.70	7.90		9.20	340
2.20	1.50	2.40	4.00	5.90	8.20	10.90	10.90	350
2.19	1.20	1.90	3.50	5.40	7.30	9.90	11.00	360

Table A.36: Tensile test results for specimen WB007B2 (WB006B2 aged for 30days)

	Elongation							
	100%	150%	200%	250%	300%	350%	Ultimate	
Thickness (mm)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	%
2.39	1.70	3.00	5.20	7.60	10.90		11.70	320
2.24	1.70	2.80	4.70	7.20	10.40		10.40	300
2.24	1.60	2.70	5.00	7.40			10.60	290
2.27	2.00	3.10	5.20	8.20	11.60		12.20	310
2.31	1.60	2.80	4.60	7.40	10.20		11.50	320

Table A.37: Tensile test results for specimen WB007B3 (WB006B3 aged for 30days)

	Elongation							
	100%	150%	200%	250%	300%	350%	Ultimate	
Thickness (mm)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	%
2.73	6.20	9.60					11.30	180
2.75	6.40	10.10					12.10	190
2.72	6.40	9.20					10.60	170
2.64	5.70	8.65					9.80	170
2.75	6.00	10.50					13.60	200

Table A.38: Tensile test results for specimen WB007C1 (WB006C1 aged for 30days)

	Elongation							
	100%	150%	200%	250%	300%	350%	Ultimate	
Thickness (mm)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	%
2.45	1.40	2.10	3.50	5.00	7.10	9.30	9.30	300
2.49	1.50	2.30	3.60	5.40	7.60	10.00	10.10	370
2.40	1.20	2.00	3.40	5.00	7.20	9.80	9.80	350
2.38	1.30	2.30	3.40	5.20	7.60	10.00	10.20	360
2.30	1.20	2.10	3.60	4.80	6.80	9.00	9.20	360
2.35	1.20	2.10	3.20	5.00	7.10	9.10	9.10	350

Table A.39: Tensile test results for specimen WB007C2 (WB006C2 aged for 30days)

	Elongation							
	100%	150%	200%	250%	300%	350%	Ultimate	
Thickness (mm)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	%
2.37	1.60	2.60	4.20	6.60	8.80		9.30	310
2.55	1.80	3.20	4.20	7.60			8.90	290
2.15	1.60	2.60	4.00	6.00	8.40		11.40	310
2.10	1.50	2.60	4.20	6.20	8.40		8.40	300
2.24	1.60	2.60	4.40	6.80			9.40	280
2.41	2.00	3.40	5.40	8.10				

Table A.40: Tensile test results for specimen WB007C3 (WB006C3 aged for 30days)

	Elongation							
	100%	150%	200%	250%	300%	350%	Ultimate	
Thickness (mm)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	Force (Kgf)	%
2.70	5.60	8.40					9.60	170
2.62	5.50	8.20					9.80	170
2.52	5.80						7.90	140
2.27	5.00	7.40					7.40	150
2.32	5.40	8.20					8.20	150
2.36	5.80	8.60					8.60	150

Abrasion Test Results

Abrasion test results were evaluated using the volume loss method as described in section 3.3.4.5

Table A.41: Detailed abrasion results for assorted specimens

Specimen	Weight of Specimen (mg)		Specific gravity	Abrasion loss (mm^3)
	Before	After		
WB002A	2.04	1.7	1.21	280.99
WB002B	2.00	1.72	1.17	239.32
WB002C	2.11	1.76	1.21	289.26
WB005A	2.02	1.68	1.07	317.76
VAN00A	1.84	1.65	1.07	177.57
VAN00B	2.61	1.79	1.40	585.71
VAN00C	2.26	1.68	1.35	429.63
VAN00D	2.93	2.09	1.50	560.00
WB006A1	2.37	2.13	1.07	224.30
WB006A2	1.73	1.57	1.10	145.45
WB006A3	2.07	1.86	1.08	194.44
WB006B1	1.91	1.66	1.08	231.48
WB006B2	2.08	1.90	1.10	163.64
WB006B3	1.83	1.56	1.09	247.71
WB006C1	1.86	1.60	1.08	240.74
WB006C2	1.66	1.47	1.05	180.95
WB006C3	1.62	1.32	1.10	272.73

Appendix B

Definitions

The followings are some of the standard definitions of technical terms relating to rubber as used in the text (ASTM D1566 :1982).

Abrasion the surface loss of a material due to frictional forces.

Aging (rubber) the irreversible change of material properties after exposure to an environment for a period of time.

Antioxidant compounding material used to retard deterioration caused by oxidation.

Batch (rubber compounding) the product of one mixing operation.

Carcass the fabric, cord, or metal reinforced section, or all three, of a rubber product distinguished from the rubber tube, covered by tread.

Coagulation (rubber latex) irreversible agglomeration of particles originally dispersed in a rubber latex.

Compound an intimate admixture of a polymer(s) with all the materials necessary for the finished article.

Copolymer a polymer formed from two or more types of monomers.

Crystallization, polymer arrangement of previously disordered polymer segments of repeating patterns into geometric symmetry.

Cure meter a testing device that measures the progress of vulcanization at a vulcanizing temperature.

Dumbbell specimen (rubber) a flat specimen having a narrow straight central portion of essentially uniform cross section with enlarged ends.

Durometer an instrument for measuring the hardness of rubber and plastic.

Elastomer a term often used for rubber and polymers that have properties similar to those of rubber.

Extender an organic material used to augment the polymer in a compound.

Filler a solid compounding material, usually in finely divided form, which may be added in relatively large portions to a polymer for technical or economic reasons.

Formulation a list of materials and their amounts used in preparation of a compound.

Hardness the resistance to indentation as measured under specified conditions.

Hysteresis the lagging of strain behind stress during deformation.

Latex, rubber colloidal aqueous dispersion of rubber.

Masticate to work rubber on a machine so as to make it softer and more plastic before mixing with compounding ingredients.

Monomer a low molecular weight substance consisting of molecules capable of reacting with like or unlike molecules to form a polymer.

Optimum cure the state of vulcanization at which a desired property value or combination of property values is obtained

Overcure a state of vulcanization beyond the state of optimum cure.

Plasticity the characteristic of an unvulcanized material manifested by retention of deformation after removal of the deforming stress.

Porosity the presence of numerous small cavities.

resilience the ratio of energy output to input energy input in a rapid (or instantaneous) full recovery of a deformed specimen.

Resin a solid, semi-solid, or pseudo-solid organic material which has an indefinite and often high molecular weight, exhibits a tendency to flow when subjected to stress, usually has a softening or melting range and usually fractures conchoidally.

Retarder a material used to reduce the tendency of a rubber compound to vulcanize prematurely.

Scorch premature vulcanization of a rubber compound.

Tack the property that causes the contacting surfaces of contacting unvulcanized rubber to adhere to each other.

Viscoelasticity a combination of viscous and elastic properties in a material with the relative contribution of each being dependent on time, temperature, stress, and strain rate.

Viscosity the resistance of a material to flow under stress.

Vulcanization an irreversible process during which a rubber compound through a change in its chemical structure (such as crosslinking), becomes less plastic and more resistant to swelling by organic liquids while elastic properties are conferred, improved, or extended over a greater range of temperature.

Waterproofness the property of impenetrability by liquid water.