INVESTIGATION ON CHARACTERIZATION AND VARIABILITY OF MECHANICAL PROPERTIES OF REINFORCING STEEL BARS MADE FROM SCRAP

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Investigation on Characterization and Variability of Mechanical Properties of Reinforcing Steel Bars made from Scrap

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DECLARATION

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

Signature:.. Date:..........................

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This thesis has been submitted for examination with our approval as University Supervisors.

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DEDICATION

This work is dedicated to my wife Uwineza Immaculée and my two children Irumva Blessing and Gwiza Joy.

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I first thank the Almighty God for his protection from the start to the completion of this work.

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LIST OF ABBREVIATIONS AND SYMBOLS

AES	Atomic Emission Spectrometer
ASTM	American Society of Testing Materials
BCC	Body Centered Cubic
BOS	Basic Oxygen Steel Making
BS	British Standard
CE	Carbon Equivalent
C.I.	Confidence Interval
CONSC	Construction Company
CoV	Coefficient of Variability
CR	Cooling Rate
CTD	Cold Twisted Deformed
DF	Degree of Freedom
EAF	Electric Arc Furnace
EL	Elongation
FCC	Face Centered Cubic
HolT	Holding Time
HR	Heating Rate
Hv	Vickers hardness number
ISO	International Standard Organization
KEBS	Kenya Bureau of Standards

KS	Kenyan Standard
PDF	Probability Density Function
QST	Quenched self Tempered
RA	Relative Accuracy
RBS	Rwanda Bureau of Standards
Rebar	Reinforcing bar
RM	Rolling Mill
SD	Standard Deviation of a sample
TMT	Thermo Mechanical Treatment
UTM	Universal Testing Machine
UTS	Ultimate tensile strength
YS	Yield strength
α	Probability for a result to fall in the rejection area
$\mathbf{A}_{gt}$	Elongation at maximum load
$\mathbf{D}_{12-20}$	Ribbed bar with nominal diameter varying from 12 to 20 mm
K	Strain hardening ratio
R	Regression Coefficient
$\mathbf{R}_{e}$	Alternative notation for yield strength
$\mathbf{R}_{P_{0.2}}$	Proof stress
$\mathbf{Y}_{12-20}$	Twisted bar with nominal diameter varying from 12 to 20 mm

ABSTRACT

The quality requirements for concrete reinforcement have increased interest in optimizing the mechanical properties of reinforcing bars used for the construction of all types of structures such as buildings, piers and hydraulic jibs. The variability of mechanical properties of reinforcing steel bars manufactured from scrap metals by local manufacturers in Kenya have been investigated in this research. This was motivated by the fact that it has been noticed that the use of the substandard reinforcing bars in construction industry could lead to collapse of the structures reinforced with these bars in many developing countries.

Therefore a complete understanding and knowledge of the extent of variability of mechanical properties and the real behavior of these construction materials was of prime importance for the proper behavior and integrity of the building structures. To address the above problem, a survey was carried out on a sample of manufacturers of reinforcing steel bars, construction companies and main distributors of steel bars in the country.

Some bars were randomly selected from hardwares, rolling mills and other from outside the country and a few samples from construction sites. Laboratory tensile tests, chemical composition analysis, microstructure examination, micro hardness tests and heat treatment were carried out on a set of the bars. The heat treatment behavior of reinforcing steel bars was investigated in this study and the results were evaluated using the microvickers hardness tests.

The results were compared with the existing set standards for specified class of reinforcing steel bars and a statistical model on the variability of the mechanical properties of these bars was established and possible sources of the variation was identified. The yield strength of the bars sampled from the rolling mills complied with standards except in one case.

The result show that the yield strength of 69% of reinforcing steel bars collected from distributors failed in yield strength because the mean value for YS was below the BS 4449 standard value of 460 N/mm^2. The possible cause of variability was the inconsistence in chemical composition. It was found that the twisted bars exhibited higher value of yield strength than self tempered ribbed bars. It was also found that the grain size have high influence on the tensile properties of the bars. It was observed that the yield strength of bars tested decreased with an increase of grain size. Grain size greater than 28μm resulted in yield strength less than the standard value.

CHAPTER 1

INTRODUCTION

1.1 Background

The mechanical properties of reinforcing steel bars play an important role in the service life of building structures such as skyscrapers and bridges. The strength and durability of reinforced concrete structures depend to a large extent on certain properties of reinforcing bars such as tensile strength, bendability, fatigue, weldability and ductility [1].

Steel exhibits a wide range of mechanical characteristics of which the strength factor is the dominant property. Engineering strength is evaluated in terms of yield strength YS, ultimate tensile strength UTS, modulus of elasticity (E), percentage elongation and impact strength. Thus, any increase in strength characteristics of steel will enhance the reliability and durability of the structure in which it is used. Low strength characteristics often result in short life span of the structure, undesirable deflection and even collapse. The ductile behavior of reinforced concrete structures are strongly influenced by the mechanical characteristics of the steel used for their reinforcement. In particular, the total elongation at maximum force A_{gt}, and the strain hardening ratio, K (defined as the ratio between the tensile strength and the 0.2 proof strength) of the steel play a decisive role in determining dissipative capacity of reinforced concrete sections and structural members [2].

The bars are manufactured by casting and/or rolling from billets or ingots in mills by smelting iron ore or steel scraps. The bars are subsequently ribbed in hot form or twisted in cold form. The two common methods of production of reinforcing steel bars are: Microalloying and cold twisting methods. Microalloying method consists of adding a small percentage of alloying element in the molten metal during production process of steel. This method of produces bars with high yield strength but its drawback is that the process is costly because of the high cost of microalloying elements such as vanadium, niobium and titanium. On the other hand, the cold twisting method consists of twisting the bars after being cooled to room temperature. This method is less expensive and produces bars with high yield strength but with low ductility. A Thermo Mechanical Treatment (TMT) process, commonly known as TEMPCORE process, can replace the above methods due to its advantages of producing bars with high yield strength accompanied by a high ductility. In this process, the ribbed bar is produced in the final pass of the rolling mill and followed by a water spray resulting in a bar having a ductile ferrite−pearlite core and a hard tempered martensite case [3,4]. The standards for reinforcing bars are set by International Standard Organization (ISO) and local statutory bodies. The manufacturing process has an effect on the mechanical properties of reinforcing steels. If the alloying elements are not well controlled, they can have a severe effect on the quality of the bar resulting in a substandard reinforcing steel. Also the cold working by twisting the bar increases the strength of the bar but reduces its ductility [5]. Hence the anticipated variability on the mechanical properties of the steel could possibly be dependent on steel manufacturing process. A statistical study on the mechanical properties of reinforcing bars conducted in Canada by Allen [1] showed that, the variation in tensile properties could be noticed from the same batch of reinforcing steels bars and a slight variability along the same bar. This information was obtained from two sources: one, a small sample of bars tested at the National Research Council of Canada; the other a larger sample of 132 test results obtained from a Canadian manufacturing plant. The overall CoV for all batches tested was of the order of 7 to 8% which was considerably greater than variation within a single heat. However, the source of this great variability was not identified, and neither was it accounted for. In the Eastern African region, it is noted that there has been a rapid expansion in building industry and consequently an increase in consumption of reinforcing bars that are either sourced from local mills or overseas sources or a combination of both. While variation in properties of the reinforcing bars is known to exist, attempt to formally compile the information is not there. Not much study has been carried out on the characterization and variability of mechanical properties of reinforcing steels used in the region as it has been done overseas. Although investigations on the variability of mechanical properties of reinforcing steels have been carried out in a number of countries [1,6–8], the cause of this variability has received little attention. Therefore the main objective of this research was to investigate on the characterization and variability of mechanical properties of the reinforcing steel bars from locally produced stocks.

1.2 Statement of the problem

Manufacturing process of common reinforcing steel bars largely relies on recycling of scrap metal as the raw material. Furthermore research has shown that due to variation in scrap feeds and impurities present in scraps, the mechanical properties may vary and contribute to a substandard reinforcing bar. Recently, the Kenya Association of Manufacturers (KAM) reported that local steel mills have been making substandard steel bars because of the price of raw materials in the international market. Also in a notice to manufacturers, the Kenya Bureau of Standards (KEBS) highlighted that weak steel reinforcing bars have largely contributed to the collapse of buildings in the country, as reported by Jim Onyango [9] on October 29, 2007. Preliminary investigations conducted at the KEBS, at the Material Branch of the Ministry of Roads and Public Works (MRPW) in Kenya and survey in Rwanda confirmed existence of variation in the mechanical properties of reinforcing steel bars. High variability of mechanical properties of the reinforcing bars from the standard value can have severe effects on the building structure. In spite of the widespread construction work that has been taking place in the country, no recorded studies have been done on the quantification of such variability and its possible source. The present work was aimed at investigating the characterization and variability of mechanical properties of reinforcing bars made from scraps and identifying the possible source of that variability.

1.3 Objectives of the study

1.3.1 Main objective

The primary objective was to determine the extent of variability of mechanical properties in reinforcing steel bars used in the construction industry and identify the possible causes of that variability.

1.3.2 Specific objectives

In order to achieve the primary objective, the research was sub-divided into the following tasks:

- Carrying out a survey of manufacturers and end users of reinforcing steel bars
- Determining the effect of chemical composition on the mechanical properties of reinforcing steel bars
- Determining the effect of microstructure on the mechanical properties of the reinforcing steel bars
- Determining the effect of heat treatment on the mechanical properties of reinforcing steel bars

1.4 Scope of the research

The research was carried out on reinforcing steel bars of 12, 16 and 20 mm nominal diameter. Two types of steels were examined. These are hot-rolled / Self Tempered (ribbed) and Work-hardened (square twisted) reinforcing steel bars made from scrap.

1.5 Justification of the Study

The significance of this study is to provide information to the rolling mills, statutory bodies and end users of reinforcing steel bars about the possible causes of variability of mechanical properties of reinforcing steel bars and provide alternative ways of improving on the quality of the bars made from scrap.

1.6 Hypothesis

Testing the reinforcing steel bars made from scrap to determine whether their chemical composition and microstructures have influence on their mechanical properties.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

Steel has a large field of application ranging from small appliances to big construction industries. Most steels have a crystalline structure and consist of a basic iron-carbon system. Relatively small changes in the carbon content and/or other alloys result in significant changes in the mechanical behavior of the resultant steel. The mechanical properties of steel that are of interest to the design engineer are the stress-strain curve; the yield strength; the amount of strain at yield, the percentage elongation at failure, or ductility; the amount and rate of strain hardening; and the ultimate tensile strength [10] .While the mechanical behavior of a particular steel is significantly influenced by its carbon content, other factors that influence its properties are the chemical composition and the method used to shape the ingot into the final form as steel bar. The mechanical properties of steel are mainly affected by the following parameters:

(i) Chemical Composition
    - Carbon content
    - Presence of alloying elements such as manganese, silicon, chromium, vanadium and copper

(ii) Physical Condition

- Slow cooling from the molten state or quenching
- Annealing
- Hardening characteristics
- Shaping operation (e.g. cold working)
- Weldability

Carbon is the most important element that governs the mechanical properties of steel and most heat treatments of steel are based primarily on controlling the distribution of carbon. Low and medium carbon steels are used extensively for construction of buildings, in most cases as reinforcing bars in concrete. Previous research have been conducted to provide detailed information on the strength and ductility properties of reinforcing bars that are manufactured from scrap metals in developing countries. Typical examples are the cases of Ghana and Nigeria [11, 12]. From the statistical analysis, these steel bars exhibited significant variability in yield strength. From the same study it was observed that the chemical composition in these steel bars could not meet the standard requirement for the limit of carbon content and other associated elements such as silicon, sulfur, phosphorus and manganese present in the steel bars. The final product was a bar with high tensile strength with low % elongation.

The grades of the reinforcing bars are set by the well known standards such as ISO, ASTM, BS and KS. Low alloy steel of grade 60 or 500MPa (ASTM A706) is useful for application of reinforcing steel bars that involve both welding and bending. The carbon content of these steels is approximately 0.25% .

The grades are designated by the specified minimum yield strength. For example Grade 460 denotes the minimum yield strength of 460N/mm^2 as per BS4449:1997, Grade 500 denotes the minimum yield strength of 500N/mm^2 as per ASTM A 706 or BS4449:2005 for both twisted and ribbed bars [13,14]. ISO 6935-2:2007 covers ten steel grades not intended for welding and eleven steel grades intended for welding (see Table E.1 in Appendix E).

The designation of common carbon and low alloy steels are shown in Table E.2. Steel derives its mechanical properties from a combination of chemical composition, heat treatment and manufacturing processes [15]. In the normalized condition, steel exhibits maximum toughness but a lower strength as compared to oil quenched conditions. The strength of steel may be improved by oil quenching as well as water quenching followed by tempering at 300 ^{o}C and 400^{o}C with some compromise on toughness [16].

There is a considerable effect of the processes of steel making on the quality of concrete reinforcement [17]. It is important that quality norms are exercised in the case of reinforcing bars which should invariably have been rolled from billets of known composition . Reinforcing steel bars have remarkable benefits in the concrete because besides the increased strength, the bars can reduce or control crack width of the concrete and help maintain aggregate interlock. The change in strength is such that even the smallest cross-sectional area of steel wire will increase the value by 16% or more [18]. Reinforcing steel bars also contribute considerably to earthquake resistance. Under the action of loads, they act together as a frame transferring forces from one to another. With the use of longitudinal bar (large diameter), and vertical stirrup (smaller diameter bar) a beam can withstand the seismic damage [19]. However reinforced steel bars of high tensile strength and high ductility are required. Research [1] has shown that for the same manufacturer of reinforcing steels the Coefficient of Variability (CoV), which is the ratio of standard deviation of the tensile strength to the mean value of the same for a number of samples, could be noticed from the same batch and a slight variability along the same bar. Constructional bars of a given nominal type may display variation in strength from piece to piece even when made by a controlled standardized process. Investigation by Clifton F. [6] on structural material showed that noticeable variation of mechanical properties not only occurs between one batch and another but also within the same batch. Later Mirza S.A. [7] found out that there is variation in yield strength for reinforcing steel bar of Grades 40 and 60 with CoV of 10.7% and 9.3% respectively.

2.2 Overview of the methods of production of reinforcing steel bars

Steel is used in two different ways in concrete steel structures; these are reinforcing or prestressing steel. Prestressing steels are tendons (generally of high tension cable or rod) used to provide clamping load. Reinforcing steel is placed in the form prior to casting of concrete. Stresses in the reinforcing steel are caused by the loads on the structure. The most common types of reinforcing steel are in the form of bars. These are commonly classified according to the methods of production (hot rolled or cold worked), surface characteristics (plain or deformed), strength grade (medium-tensile strength or high-tensile strength), or weldability [20]. Figure 2.1 shows the general classification of various metal alloys from which the reinforcing bars can fall under the category of low-carbon high strength, low alloy steel [21]. Figure 2.2 shows the classification of various ferrous alloys by commercial name and structure [22].

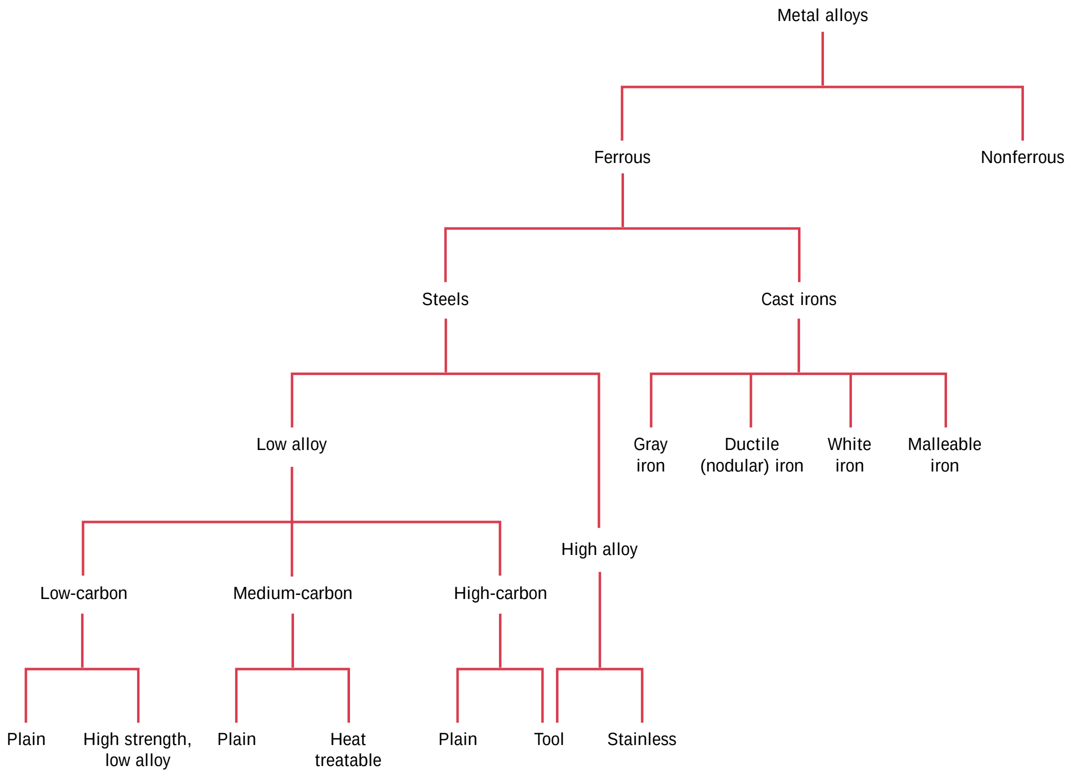


Figure 2.1: **Classification of metal alloys** [21]

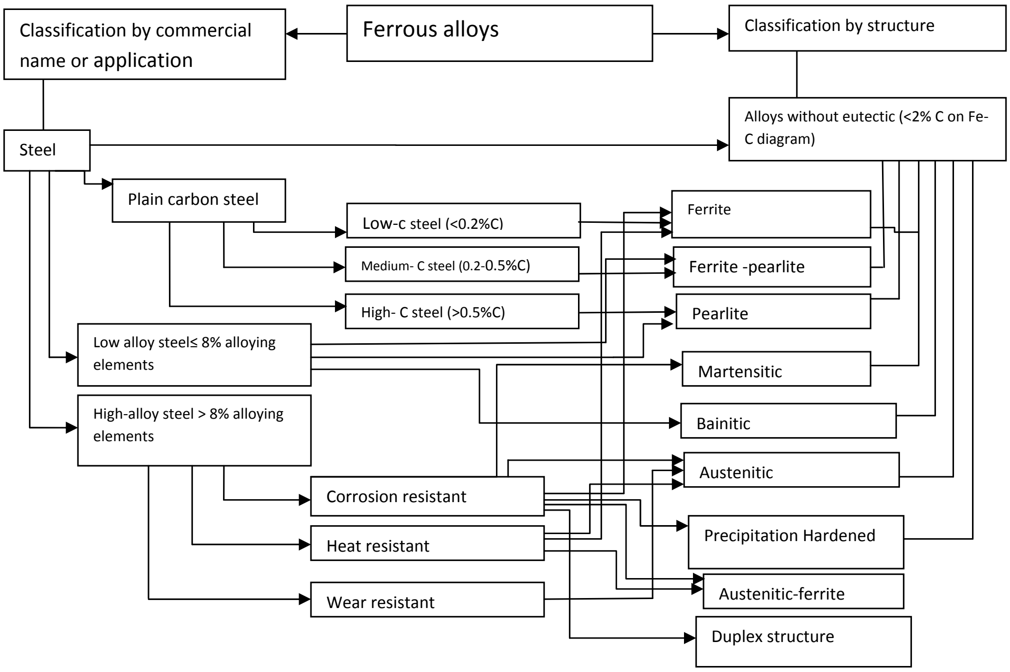


Figure 2.2: **Classification of ferrous alloys by commercial name and structure** [22]

Production of steel is preceded by production of iron through the blast furnace process [23]. The iron produced is then further processed in a steelmaking furnace to make the steel for the desired product. In a typical process, iron ore, coke and flux (limestone, silica and dolomite) are charged into the top of a large refractory-lined fabricated-steel furnace. The common steel making furnaces are: Basic Oxygen Steelmaking (BOS) and the Electric-Arc Furnace (EAF). In the BOS process, molten iron is first produced by smelting iron ore in a blast furnace. This pig iron is then transferred to a steel making vessel called converter. Some scrap steel up to 30% of the charge may be added. Reinforcing bars are made by rolling steel billets from mills or ingot from scrap metals. The EAF process normally uses 100% scrap metal as the raw material. Scrap metal is charged into the furnace and heat is applied by means of electrical discharge from carbon electrodes, thus melting the scrap.

Table 2.1 shows the typical chemical composition found in a reinforcing steel bar. Reinforcing bars are made by rolling steel billet from mills or ingot from scrap metals.

Table 2.1: **Typical chemical composition (% weight) found in a reinforcing steel bar** [24]

Manufacturing Process	**C**	**Mn**	**Si**	**S**	**P**	**Cu**	**Ni**	**Cr**	**Mo**	**Sn**	**N**
BOS	0.20	0.80	0.15	0.01	0.05	0.03	0.02	0.02	0.01	0.01	0.006
EAF	0.20	0.80	0.15	0.15	0.03	0.02	0.15	0.15	0.05	0.025	0.010

2.2.1 Reinforcing steel bar from scrap

The process consists of collecting scrap metals, sorting them, melting in a furnace, mixing with ingredients (additives), cast the molten metal into moulds for making the ingots. After the ingots solidify, the moulds are stripped. Before rolling of each stock, the ingot is placed in a soaking pit for heating to ensure that the entire cross-section is uniform. The rolled bar is normally cooled in air. To increase the strength of the bar, cold working by twisting is performed and finally the bar is inspected and stored.

The production of reinforcing steel bars from scrap metals has raised interest of researchers [25] who tried to classify the scrap metal commonly used in three categories (home scrap, process scrap and obsolete scrap) according to the place of generation, chemical composition or physical properties. Obsolete scrap causes the biggest trouble for steel maker, because its recovery is difficult, and this type of scrap is often mixed or coated with other materials such as copper, grass, plastic, zinc, tin etc. The chemical composition of obsolete scrap fluctuates widely depending on its origin and can affect the mechanical properties of the reinforcing bars.

A complete understanding and knowledge of the real behaviour of construction materials is of prime importance for the proper behaviour of engineered structures. The physical properties of structural materials are expected to meet the demand of the fundamental assumptions underlying structural codes of practice on which designs are based. Locally manufactured reinforcing steel bars from scrap metal are typical examples. In developing countries such as Kenya where imported steel is very expensive, milling companies have taken up the challenge to re-cycle obsolete vehicle and machine metal parts for the production of structural and reinforcing steel bars. The study in Ghana by Charles K. Kankam and Mark Adom-Asamoah [11] on Strength and ductility characteristics of reinforcing steel bars milled from scrap metals, showed that reinforcing bars did not meet the BS4449 maximum limit of 0.25% for carbon requirements for mild steel. The phosphorus and sulfur impurities in the steel bars from three companies exceeded the preferred limit of 0.05% for phosphorus and 0.01% for sulfur. These excess carbon, sulphur and phosphorus contents increase the strength and hardness of the steels, and at the same time decrease their ductility, making them brittle.

The British Standard BS 4449: 2005 defines the characteristic strength of steel reinforcement as that value of the yield stress below which not more than 5% of the test material should fall. The presence of variation in the strength of bars is as a result of such factors as variation in the chemical composition and heat treatment. With regard to quality control of chemical properties, steel manufacturers must give the results of analysis for carbon (C), manganese (Mn), silicon (Si), sulphur (S) and phosphorus (P) for all steels. The KS 573 and BS 4449:2005 give maximum percentage composition of mild steel as S 0.06% , P 0.06% , C 0.25% , Mn 0.65% and Si 0.25% . The different elements have varying effects on the behaviour of mild steel. The carbon level affects the strength and hardening properties of steel. Higher carbon contents increase strength but reduce ductility. Excessive levels of phosphorus and sulphur, which are non metallic impurities reduce fracture toughness. For modern steel-making practice, sulphur and phosphorus are preferably maintained at less than 0.01% . Steel grades with a high level of dissolved gases, particularly oxygen and nitrogen, can behave in a brittle manner, if not controlled by addition of small elements with a particular affinity for them to float out in the liquid steel at high temperature. Manganese, chromium, molybdenum, nickel and copper also affect the strength to a lesser extent than carbon, although their sole effect is on the microstructure of the steel. Research by Shunichi and Morifumi [26] showed that addition of alloying elements such as Niobium and Vanadium was effective to increase strength of reinforcing steel bars.

2.2.2 Production of high strength reinforcing steel bars

The production of quality high-yield reinforcing steel bars continues to receive attention from researchers across the globe. The process of production of reinforcing steel bars is described in detail in the literature (for example, see [17, 27–29]).

Generally the methods of producing high quality reinforcing steel bars can be classified into three (3) distinct categories [5]:

- Reinforcing steel bars produced by micro alloying technique. For these bars, the yield strength can be increased by modifying the chemical composition. These are generally ribbed bars.
- Reinforcing twisted bars subjected to strain hardening after hot-rolling, for instance by cold deformation. This method enables the production of high strength weldable reinforcing bars from low carbon and manganese steels, but it leads to a decrease of ductility and stress-strain diagram with no yield plateau.
- Reinforcing steel bars produced by Thermo-Mechanical Treatment (TMT) technique commonly known as Self Tempered steel bars. These are generally ribbed bars

Research [3] has revealed that the first above two widely used conventional processes present some drawbacks of having low ductility in case of twisted bars and the cost of micro-alloy addition in case of ribbed bars. These drawbacks are overcome by the Thermo Mechanical Treatment (TMT)process, commonly known as TEMPCORE process, which is the fabrication process of quenched and self-tempered steel. The TMT process involves cooling the reinforcing steel bar by pressurized water as it emerges from the finishing stand at a cooling rate higher than 200^{o}C/s inside a Thermex water cooling installation so that a thin layer of martensite about 4 mm thick forms on the surface of a 32mm bar diameter while the core of the bar is still austenite [3, 4].

On emergence out of the Thermex unit, the bar is allowed to cool in the still air as shown in Figure 2.3.

The TEMPCORE process has gained wide acceptance as it has the ability of imparting the required mechanical properties to steel product in as rolled condition and therefore eliminates the costs associated with twisting or micro-alloy addition. This process results in reinforcing steel that fulfills the required characteristics, i.e., high strength with a yielding plateau, good weldability, bendability and ductility.

It has been shown by many researchers [31] that rolled wires and reinforcing steel bars after cooling have martensite structure on the outer surface and pearlite-ferrite in the core.

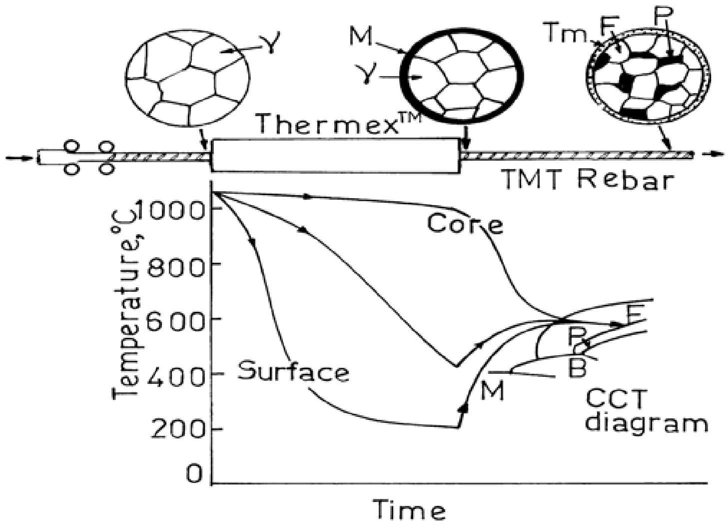
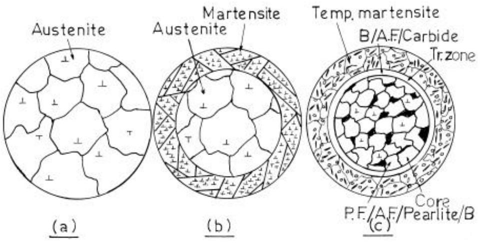
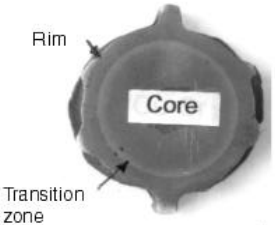


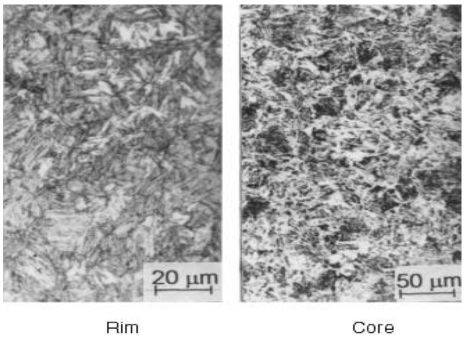
Figure 2.3: **Schematic diagram of TMT process of reinforcing steel bars [4]**



i. Evolution of microstructure in a Self Tempered reinforcing steel bar



ii. macrostructure in a Self Tempered reinforcing steel bar



iii. Microstructures of the rim and core in a Self Tempered reinforcing steel bar

Figure 2.4: **Microstructure evolution of a self tempered reinforcing steel bar [30]**

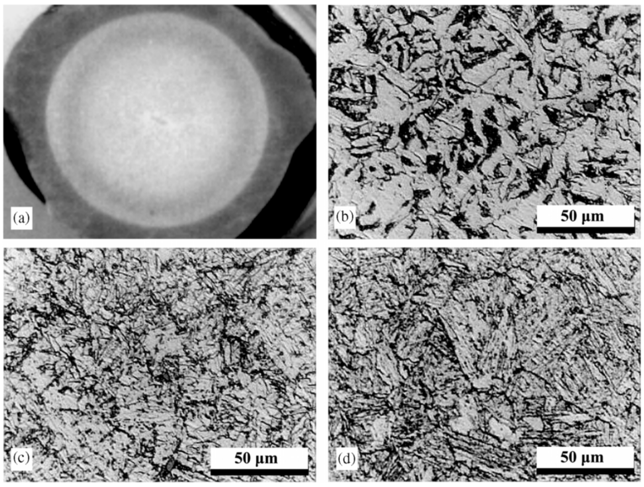


Figure 2.5: **(a) Typical cross-section of a Tempcore bar and optical micrographs of the (b) core, (c) intermediate layer and (d) outer hardened self tempered layer [30]**

In a typical crosssection of the bars, three main zones are observed as shown on the macrograph of Figure 2.5. A study by Nikolaou and Papadimitriou [30] showed that the tempcore process leads to reinforcing bars that exhibit a composite microstructure. They found that the microstructural changes during heating of the steel bar were mainly localized in the outer layer of the cross section, where tempering phenomena of martensite were pronounced.

2.3 Effect of alloying elements on the mechanical properties of reinforcing steel bars

The alloying elements in steel have been proved to have effect on the mechanical properties of steel. Shunichi and Morifumi [26] investigated the effects of microalloying elements on mechanical properties of reinforcing bars and found that with

0.05% Nb and 0.05 % V addition to 0.25 C- 0.5 Si -1.2Mn steel (% weight) led to an effective increase in strength.

Weiguo et al [28] have carried a research on production of high strength hot rolled ribbed steel bar BS G460 and found that vanadium addition results in a bar with stable mechanical properties and good uniformity.

With increasing carbon content, from near 0% the ferrite phase decreases with a corresponding increase in pearlite phase and about 0.8% carbon, there would be pearlite phase alone. It has been established that with the increase of pearlite phase, tensile strength of steel increases while elongation property, i.e., ductility reduces. The maximum tensile strength is attained at about 100% pearlite phase but the ductility will then be near zero, i.e., the steel would be brittle. Thus, the mechanical properties of steel are related to the carbon content [20, 24]. It has been shown that the hardening capacity of a steel depends mainly on its carbon content and to a lesser extent on its content of alloying elements and the grain size of austenite grains [32].

To have a reinforcing steel bar of desirable properties, the carbon content is controlled and is usually found to lie in a narrow range of 0.15% to 0.25% . The low carbon level is chosen for preventing embrittlement of the bar during strain hardening and the development of undesirable microstructure in the heat-affected zone of such bar during welding [12]. However alloying elements used in the manufacture of steel modify the phase diagram so that the point at which the maximum pearlite phase forms is at a different percentage of carbon. An index called Carbon Equivalent(CE) has been established to convert the amount of these alloying elements into the equivalent percentage of carbon. The alloying elements have effect on the mechanical properties of steels. Table 2.2 shows the elements commonly used in manufacture of steels in general and their effects on the properties of the steel. These include: Manganese(Mn), Silicon (Si),Copper(Cu), Nickel(Ni), Chromium(Cr), Molybdenum (Mo), Vanadium(V), Columbium(Co), Titanium(Ti), and Zirconium(Zi) [33].

The alloying elements, which increase hardenability, include Carbon (C), Manganese (Mn), Molybdenum (Mo), Chromium (Cr), Silicon (Si) and Nickel (Ni).

The BS4449 international specification limits the Carbon Equivalent (CE) value and Carbon content to 0.51% and 0.25% respectively. The formula used to calculate CE is given by:

$$CE = C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15} \tag{2.1}$$

The reinforcing steel bar is considered to be weldable without preheating, if CE is less than 0.51% otherwise the bar is non-weldable [14].

2.4 Mechanical properties of reinforcing steel bars

Although the tensile strength of the steel bar is regarded as the most specified property, it is one in an array of properties that determine the ability of the steel to be

Table 2.2: **Effect of alloying elements on the mechanical properties of steels** [33]

Elements	**Effect**
Carbon (C)	Increase hardness and tensile strength but reduces ductility
Manganese (Mn)	Improves hardenability, ductility and wear resistance. Mn eliminates formation of harmful iron sulfides, increasing strength at high temperatures
Nickel (Ni)	Increases strength, impact strength and toughness, impart corrosion resistance in combination with other elements.
Chromium (Cr)	Improves hardenability, strength and wear resistance, sharply increases corrosion resistance at high concentrations (> 12%).
Tungsten (W)	Increases hardness particularly at elevated temperatures due to stable carbides, refines grain size.
Vanadium (V)	Increases strength, hardness, creep resistance and impact resistance due to formation of hard vanadium carbides, limits grain size
Molybdenum (Mo)	Increases hardenability and strength particularly at high temperatures and under dynamic conditions.
Silicon (Si)	Improves strength, elasticity, acid resistance and promotes large grain sizes, which cause increasing magnetic permeability.
Titanium (Ti)	Improves strength and corrosion resistance, limits austenite grain size
Cobalt (Co)	Improves strength at high temperatures and magnetic permeability
Zirconium (Zr)	Increases strength and limits grain sizes
Boron (B)	Highly effective hardenability agent, improves deformability and machinablilty
Copper (Cu)	Improves corrosion resistance
Aluminum (Al)	Deoxidizer, limits austenite grains growth

used effectively and safely under all conditions. In addition to tensile strength which imparts strength to the reinforced concrete structure, other important properties include [20]:

- *Bond performance*: To enable the concrete unit to possess tensile properties. Since unreinforced concrete is generally brittle the presence of steel in the concrete will enhance the tensile properties.

- *Ductility and Formability*: To provide structural integrity in the presence of cracking and to enable the steel to bend on small radii with a precise response.
- *Fatigue performance*: To enable the structure to endure cyclical loading from cause such a wind and earthquake
- *Weldability*: To permit joining of bars

2.4.1 Tensile strength of reinforcing steel bars

The two important characteristics which determine the character of reinforcement are the yield point and the Modulus of Elasticity of the reinforcing steel bars. Generally, the Modulus of Elasticity of the steel is taken as equal to 200kN/mm^2. In addition, the shape of the stress-strain curve of tensile test of steel has significant influence on the performance of reinforced concrete members [20].

The stress-strain relationship is linear up to the yield point (see Figure 2.6) for self tempered reinforcing steel bars where Re and R$_{P_{0.2}}$ are yield and proof stress respectively.

The process of cold working involves stretching and twisting of mild steel beyond its yield plateau, and subsequently releasing the load as indicated by the thin line in Figure 2.7. The end product is the familiar cold twisted deformed (CTD) bar. Although stretching and cold twisting results in a residual strain in the steel, it also results in an increased proof strength. Upon reloading, the steel follows a linear elastic path (with the same modulus of elasticity, E$_s$ as the original mild steel) up

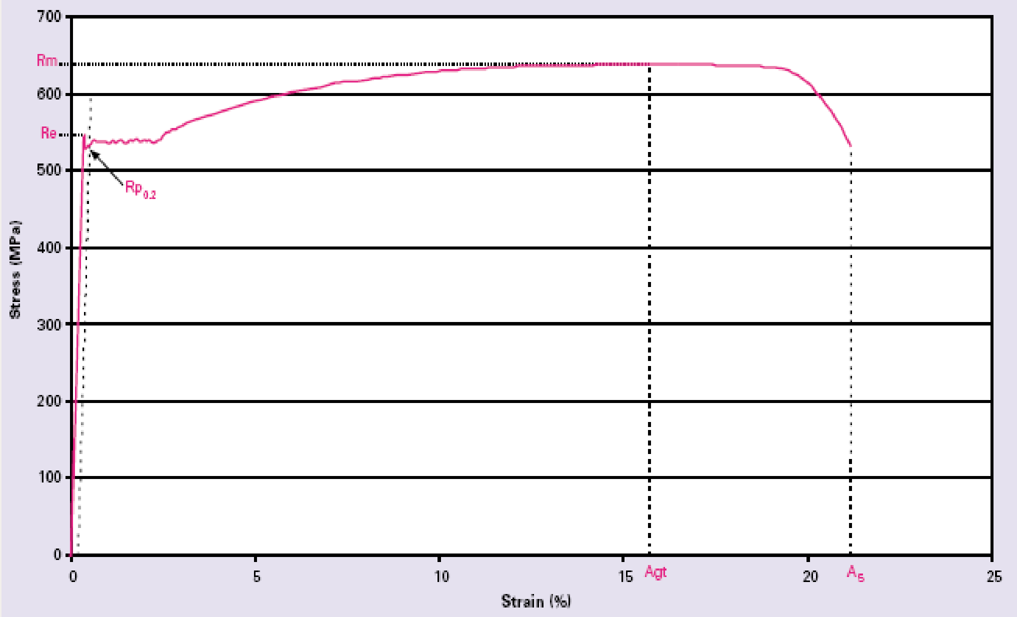


Figure 2.6: **Stress-strain curve of a ribbed reinforcing steel bar** [34]

to the point where the unloading started (the new raised yield point). This point of yielding is not likely to be well defined if the point of unloading lies beyond the yield plateau of the mild steel bar. After the yield point, as can be seen from Figure 2.7, the material enters the strain hardening range following the path indicated by the thick line in Figure 2.7. It should be noted that although the process of cold working effectively increases the proof strength of the steel, it also reduces the ductility in the material [17].

After undergoing twisting operation, the bar will behave as shown in Figure 2.8 and it has no yield plateau as compared to self tempered / ribbed reinforcing steel bar [17, 35].

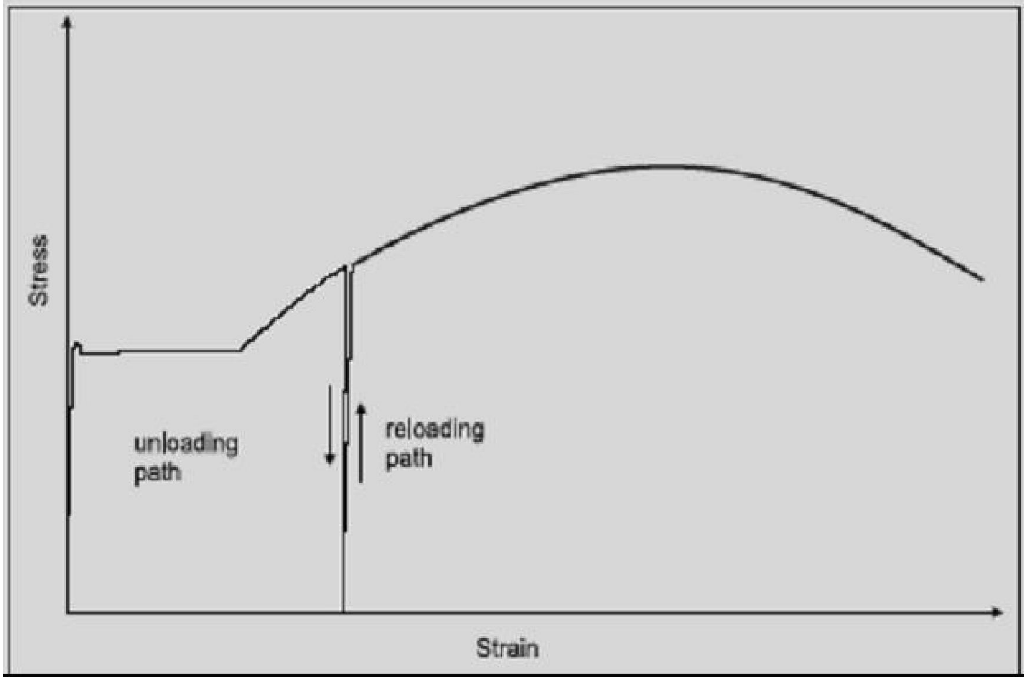


Figure 2.7: **Effect of cold working on reinforcing steel bar [17]**

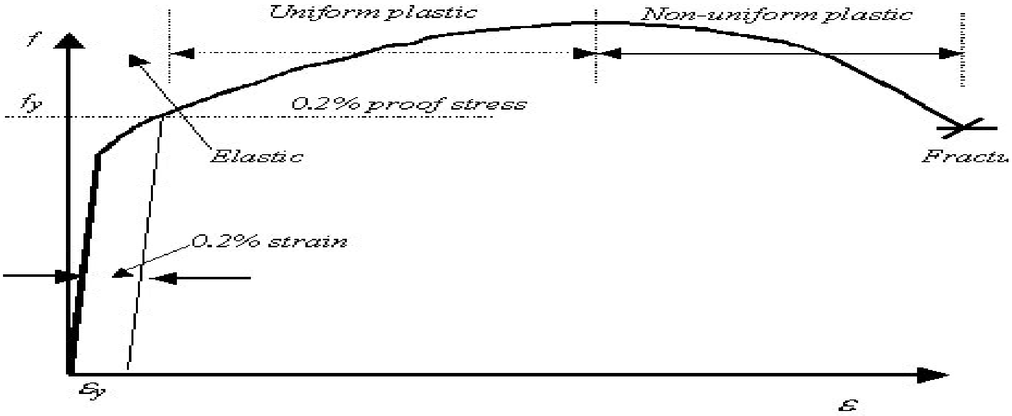


Figure 2.8: **Stress-strain curve of a twisted reinforcing steel bar [17]**

2.4.2 Ductility of reinforcing steel bars

Ductility can be determined by a tensile or bending test; the higher the percentage of elongation the more the material becomes ductile. Research [1] has shown that the service life, strength and ductility of concrete structures depend to a large extent on certain properties of reinforcing bars such as Modulus of Elasticity, Yield Stress, Ultimate Stress and Elongation. The values are controlled in practice by the international standards specifications such as American Society of Testing Materials (ASTM). Most reinforcing steel will require bending before being installed into a concrete structure. Because they are relatively high strength steels, and because the ribs on the bar surface act as stress concentrators, reinforcing steels may fracture on bending if the radius of bend is too tight [24]. The presence of crack in bending test reveals that the material is brittle hence the ductility is low. The bending test predicts the ductility of the reinforcing steel bar. The specimen is subjected to the prescribed sequence of operations and should not show any sign of crack or fracture. Table 2.3 shows the requirement for bending tests.

Table 2.3: **Recommended mandrel diameter for bars to be used in bending test [36]**

Nominal diameter(d) of the bar (mm)	**Former/mandrel diameter (mm)**
≤ 16	3d
16<d≤32	6d
32<d≤ 50	7d

2.4.3 Fatigue properties of reinforcing steel bars

A component or structure which survives a single application of load may fracture if the application is repeated a large number of times. This would be fatigue failure. Fatigue failure can be defined as the number of cycles and hence the time taken to reach a predefined failure criterion [37, 38]. There are two basic approaches for the assessment of fatigue life of structural components. The first method which is currently in general use relies on empirically derived relationships between applied stress ranges and fatigue life commonly called S-N approach. The second, based on fracture mechanics, considers the growth rate of an existing defect at each stage in its propagation [37]. The ISO6935-2:2007 as well as the BS 4449:2005 require that fatigue properties for steel bars for concrete reinforcement be established. In fatigue test, the bars are deemed defective or non-defective depending upon their ability to endure five (5) million of cycles of stress at the specified stress range given the relevant bar size. Table 2.4 shows typical fatigue test values and conditions on reinforcing steel bars [36]. It has been proved [38] that the fatigue failure of a ribbed bar is very much different from that of a plain bar. In spite of the increase in yield strength of high strength deformed bars, a corresponding increase in fatigue strength does not take place. This is caused by the junctions of the longitudinal and transverse ribs with the body of the bar from region of stress concentration inducing ”notch effect” that results in premature brittle failure.

Table 2.4: **Recommended applied stress and specific nominal sizes of bars in fatigue test [36]**

Bar diameter d(mm)	**Stress (MPa)**
≤ 16	200
<16≤20	185
>20,≤25	170
>25, ≤ 32	160
>32	150

2.5 Phase transformation and microstructure of steel

As molten steel cools, grains known as austenite are formed; this is essentially a solution of carbon elements in iron. If the temperature of the steel decreases slowly, the austenite undergoes a transformation in the temperature range of 700-540 ^{o}C to ferrite, which has a more limited solubility of carbon. To accommodate this limited solubility, the carbon precipitates as iron islands. The alternating mixture of ferrite and iron carbide are known as pearlite. Ferrite is ductile but has low tensile strength. Thus the steel becomes a mixture of a soft ferrite matrix and a hard pearlite matrix [4,30]. Examples of constructional steels having ferrite-pearlite microstructure are the common carbon (mild) steel, and various high-strength low-alloy steels. If the steel is cooled rapidly, the transformation of austenite to ferrite and pearlite is suppressed and, instead, very hard needle-like microstructures known as martensite and bainite are formed. Bainite forms in transformations below about

450^oC and above 230^oC . Martensite starts to form below about 260^oC with the transformation occurring almost instantly during rapid cooling. To develop useful product, these microstructures must be tempered by reheating the steel and slowly cooling, thus improving toughness and ductility [3].

The addition of carbon to the pure iron results in a considerable difference in the structure (as shown in Figure 2.9) which consists of two constituents, one being the ferrite, and the other parts representing the constituent containing the carbon, the amount of which is therefore an index of the quantity of carbon in the steel.

The structure of the reinforcing steel bar is a combination of ferrite and pearlite (the structure on the bottom left of Figure 2.9).

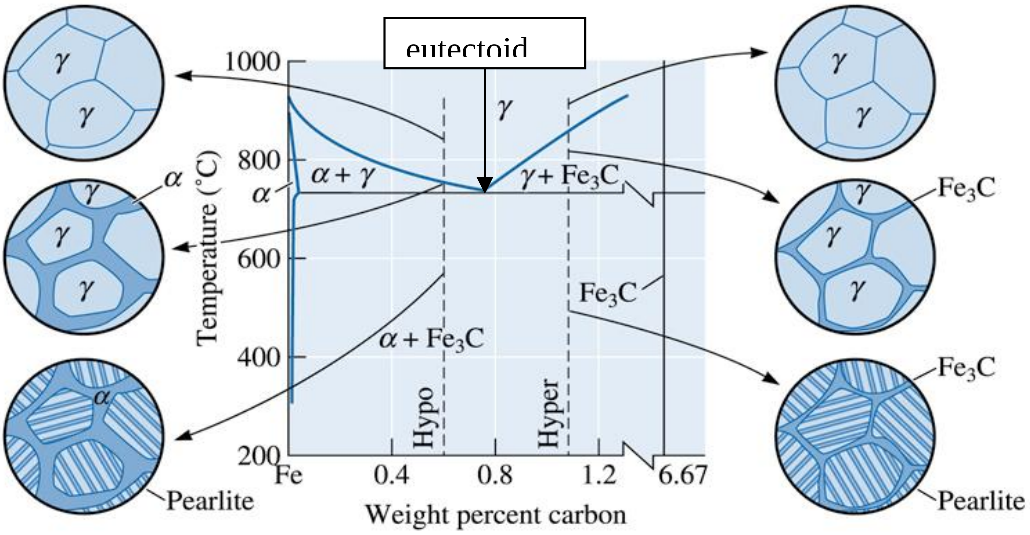


Figure 2.9: **Iron-carbon phase diagram showing the variations of the microstructures of the steel as function of temperature and carbon content [39]**

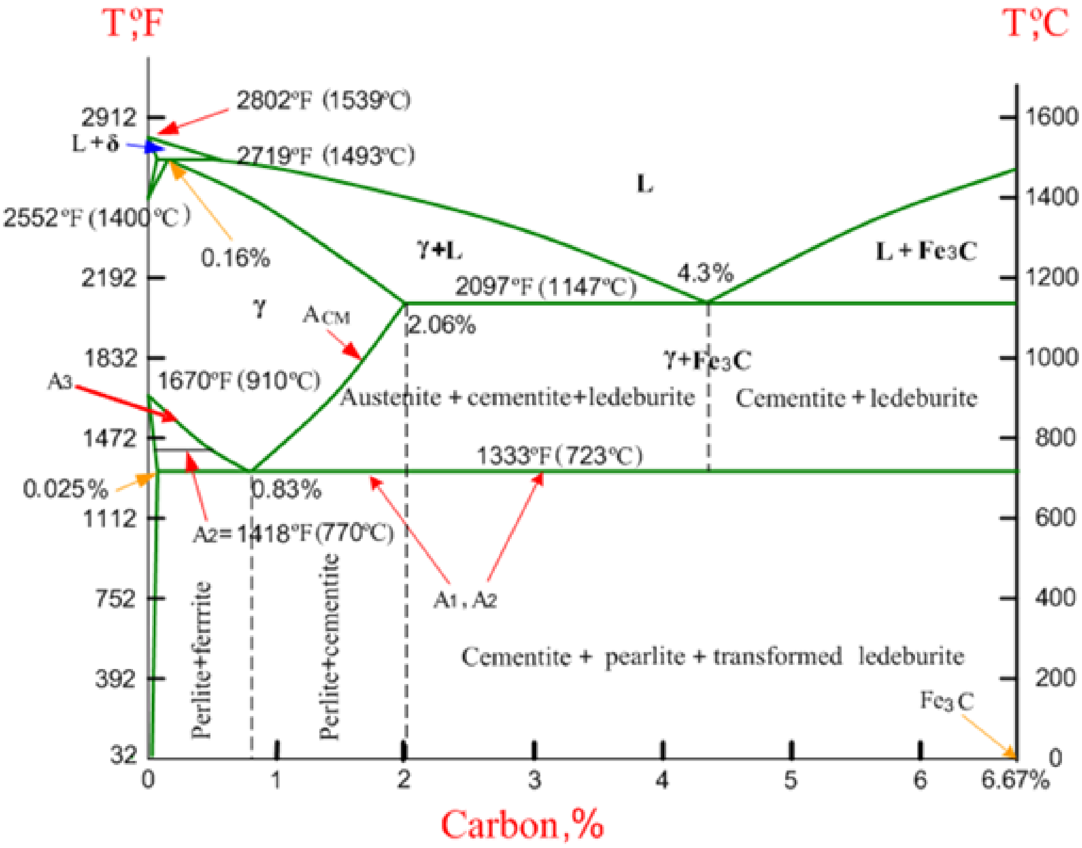


Figure 2.10: **Iron - carbon phase diagram showing different phase transformations in steel [39]**

Research [40–42] has revealed that the yield strength (YS) increases with the grain size because the grain boundaries hinder the movement of dislocation produced by cold deformation of metals according to the Hall-Petch equation:

$$YS = R_o + kd^{\frac{-1}{2}} \tag{2.2}$$

With: R_o is a constant depending on the chemical and phase composition of the steel and k is a constant characteristic for the effect of linear grain size (d).

For steels having an essentially ferritic microstructure the following relations were developed for the yield stress [41]:

$$YS = 104.1 + 32.6(\%Mn) + 84(\%Si) + 17.5d^{\frac{-1}{2}} \tag{2.3}$$

From the work of Gladshtein [43] it was found that most structural steels have a structure of equiaxed grains of ferrite and pearlite with sizes of 5 - 100 μm. He carried out experimental work on carbon steels, High Strength Low alloy steel and fine-grained high-stregth (FGHS) steel hardened with nitrides and found that the amount of pearlite was varying from 15 to 30 volume% and the respective guaranteed yield strengths ranged from 23 to 50 kg/mm^2. The author focused his work on the main characteristics of the material, the resistance to plastic deformation and the cold resistance in relation to grain size and found that the mechanical properties of steel depend on the structure and especially the ferrite grain size. Later Cota et al [44] investigated the properties of a microalloyed steel, with niobium and vanadium in its composition and found that the microstructure of the sample consisted of ferrite and pearlite and the Vickers hardness (Hv) was Hv 205 ±1 , for a pearlite volume fraction of 24.4% , and ferrite average grain size of 6.9 μm.

Shunichi and Fragiel [26, 45] found that micro-alloyed elements such as Niobium (Nb), Vanadium (V) and Titanium (Ti) contribute to grain refinement process of High Strength Low Alloy steel (HSLA).

Pang et al [46] investigated the relationship of microstructure and mechanical properties of Niobium microalloyed high strength rebar steel and found that it was composed of a complex ferrite+bainite+pearlite+martensite structure and martensite existing in the microstructure had a close relationship with the continuous tensile stress-strain curve that lacked marked yield point. The above authors found that the average grain sizes of the three steels investigated were comparatively small; and the grain size (diameter) values for specimens were 12.1μm, 13.8μm, and 12.6 μm respectively corresponding to ASTM grain No. G 9.7, 9.3, and 9.5 respectively. They concluded that the contents of major alloy elements as Carbon, Manganese, Silicon and Niobium have substantial influences on the microstructure formation. That is, all these factors including steel chemistry and steel rolling practice have to be carefully adjusted and controlled in order to obtain satisfactory microstructure and mechanical properties of reinforcing steel bars.

2.6 Heat treatment of steel

A typical heat treatment usually starts with an austenitization treatment where the ferrite (α Fe, BCC) phase transforms to the austenite (γFe, FCC) and all carbides are dissolved in the austenite. Slow cooling to below the eutectoid temperature results in the formation of ferrite and cementite (Fe_3C). This might appear as a lamellar ferrite/cementite structure called pearlite depending on the carbon content of the steel and the cooling rate [47]. It has been shown that for applications that require adequate mechanical properties, high temperature thermo-mechanically treated low alloy steel should be employed [48]. Steel responds to a variety of heat treatments [23] that can be used to obtain desirable characteristics. These heat treatments can be divided into slow cooling treatment and rapid cooling treatment. Slow cooling consists of Annealing, Normalizing and Stress relieving and rapid cooling consists of Quenching-and-Tempering. In their findings, Bello et Al [49], it was shown that tempered dual phase (Ferrite-Martensite) micro-alloyed steels significantly exhibited mechanical properties with higher tensile strength, ductility and impact toughness. To improve the quality of low carbon reinforcing steels, a rapid heat treatment [50] was found to be efficient in terms of improving the mechanical properties.

It was observed by Muhamad et al [51] that, austenitizing a low carbon steel at 910^{o}C for a short period and then water quenching results in an increase of tensile strength and hardness while the elongation decreases. The microstructure resulting from this heat treatment is a mixture of martensite and finer pearlite. This is a hard microstructure that increases the tensile strength and reduces the ductility of the material.

2.7 Standard specification of reinforcing steel bars

The common type of reinforcing steel is in the form of bars/wires. These are classified according to the methods of production (hot rolled or cold worked), surface characteristics (plain or deformed), strength grade and weldability. Hot rolled bars are normally deformed with ribs at the surface. Cold worked bars are square twisted. The International Standards Organization ISO 6935-2:2007(E) has defined the required standards for the reinforcing bars used in concrete.

Table 2.5 shows the dimensions, mass/unit length and permissible deviations for different bar sizes, twisted and ribbed bars [36]. The ISO 6935-2:2007(E) and BS4449:1997, 2005 have specified the standards requirement for yield strength for most of the reinforcing bars. The minimum yield strength is 460MPa (BS4449:1997), 500MPa (BS4449:2005) for high tensile deformed bars and 250MPa (BS4449:1997) for mild steel round bars. The tensile strength should exceed the yield strength by 10 to 15% and the minimum % Elongation should be 14% for Grade 460-500 and 22% for Grade 250. Kenya Bureau of Standards (KEBS) follows the BS4449:1997 to certify the reinforcing bars from local and overseas source [52].

Table 2.5: **Dimensions and mass/unit length of reinforcing steel bars** [36]

Nominal diameter d(mm)	Nominal cross-section A(mm^2)	Mass/ unit length (kg/m)	
		Requirement	Permissible deviation %
6	28.3	0.222	±8
8	50.3	0.395	±8
10	78.5	0.617	±6
12	113	0.888	±6
14	154	1.210	±5
16	201	1.580	±5
20	314	2.470	±5
25	491	3.850	±4
28	616	4.840	±4
32	804	6.310	±4

2.8 Microstructure and grain size determination in steel

A direct correlation exists between steel's microstructures and its mechanical properties. Therefore, the development of a relevant structure - property model in steel is one of the effective method of improving its mechanical properties [30].

The grain size of steel is revealed by microscopic examination of a polished section on the specimen prepared by an appropriate method for the type of steel and for the information sought [53]. The individual metal crystals are called grains and their size can influence a number of physical and mechanical properties. Until the field of stereology was established the techniques used to measure the grain size were different as the people who did the measurements used different approaches. The results were not very consistent nor were they reproducible. Obviously, there was a need for a reliable, accurate method of making grain size measurements. This leads to the establishment of several standard methods. The most widely used method is the mean lineal intercept, or Heyn's technique. The mean lineal intercept length is the average length of a line segment that crosses a sufficiently large number of grains. It is proportional to the equivalent diameter of a spherical grain . The Microstructural quantity known as micro grain size number, G, is defined by the following relationship [53, 54]

$$G = 6.643856 log_{10} N_L - 3.288 \tag{2.4}$$

Where N_L is the number of grain boundary intercepts per test line. The number of grains per $1mm^2$, m, is given by:

$$m = 8 \times 2^G \tag{2.5}$$

The area of grain in mm^2, is given by:

$$a = \frac{1}{m} \tag{2.6}$$

and the mean diameter of the grain, d, is given by:

$$d = \frac{1}{\sqrt{m}} \tag{2.7}$$

Grain size is a very important factor in relation to the various physical properties of steel and is of prime importance in the behavior of metals under different loads. Narula and Gupta [55] in their work have found that the increase in grain size in steel has the following effect:

(i) Improves strength of steel after heat treatment

(ii) Improves machinability

(iii) Improves the mechanical properties such as tensile strength,

(iv) Quenching cracks and distortion are reduced in fine-grained steel, creep strength and hardenability are increased

Fine-grained steel may be heated to higher temperature without the fear of over heating. The following factors govern the grain size:

(i) Nature and amount of deoxidizers

    The tendency towards grain growth is determined by the method of deoxidation of the steel and deoxidizers used. A deoxidizer is added to molten steel to eliminate trapped gases and to reduce the iron oxide. Steel is deoxidized either by Ferro-manganese or Ferro-silicon.

(ii) Composition of steel

(iii) Metallic and non-metallic inclusions

(iv) Mechanical working processes like rolling, forging, etc.

(v) Heat treatment processes

(vi) Time of heating and cooling

Abdalla et al [56] showed that there is the relationship between grain size and mechanical properties of steel. They found the ASTM grain size below G-7.5 could result in a decrease in the UTS and YS with a corresponding increase in % Elongation.

2.9 Vickers hardness test

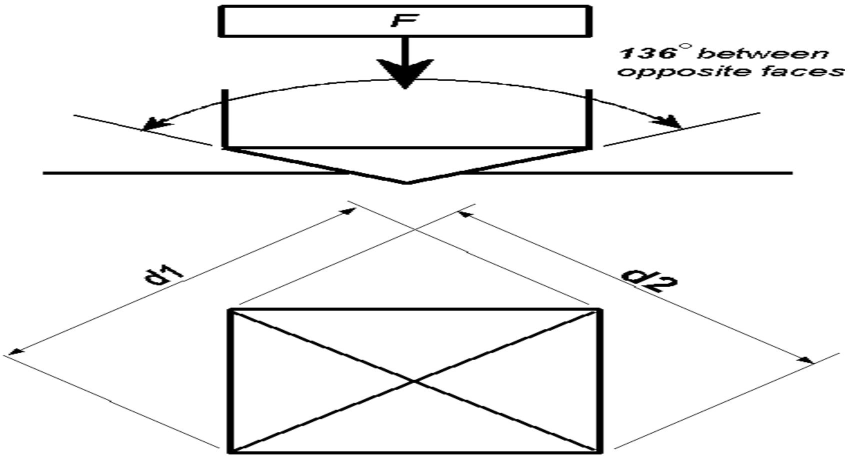
This method was introduced in England in 1925 by R. Smith and G. Sandland [57] as an alternative to the Brinell method to measure the hardness of materials. The Vickers hardness test method consists of indenting the test material with a diamond indenter, in the form of a right pyramid as shown in Figure 2.11 with a square base and an angle of 136^0 between opposite faces subjected to a load ranging from 25 gf to 200 gf. Microvickers hardness was used to calculate the strain hardening exponent from the Meyer's relation. Eugene Meyer of the Materials Testing Laboratory at the Imperial School of Technology (Germany) made intensive study of Brinell method and published the results in 1908. His work showed that resistance to penetration by a ball varies with the degree of penetration as follows:

$$F = ad^m \tag{2.8}$$

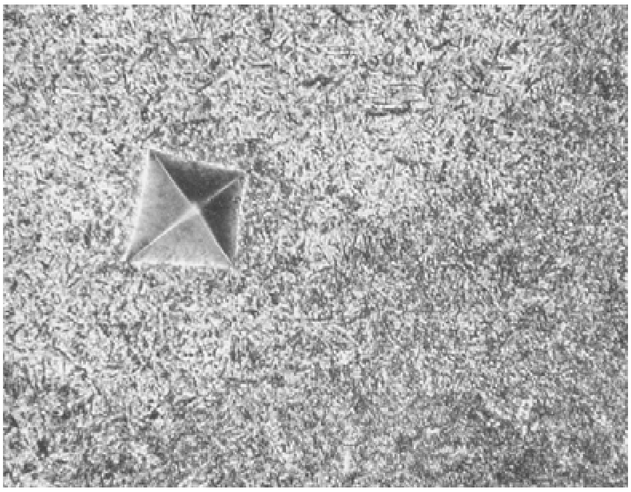
where: F is the load, d is diameter of indentation, a is resistance of the material to initial penetration, and m measures the effect of deformation on the hardness of the metal [58].

The slope of the linear portion of the log-log plot of load F vs indentor diameter,d, gave the Meyer's index, m, and to a good approximation equals to the reciprocal of the strain hardening exponent [59]. The Vickers hardness (Hv) is the quotient obtained by dividing the load (F) by the area of indentation and is given by:

$$Hv = \frac{2FSin\frac{136^o}{2}}{d^2} \tag{2.9}$$



(a) Vickers test scheme



(b) An indentation left after a Vickers hardness test

Figure 2.11: **Flow pattern during Vickers indentation of a material** [58]

CHAPTER 3

METHODOLOGY

3.1 Introduction

The present study was carried out on reinforcing steel bars of 12, 16 and 20 mm nominal diameters. The steel bars used in the present investigation were obtained directly from two (2) steel rolling mills in Kenya , six (6) hardware stores / distributors, two (2) construction sites and samples from outside the country (Rwanda and Democratic Republic of Congo). Rwanda relies solely on imported steel bars since there is no rolling mill operating in the country. Two types of reinforcing steel bars were examined; namely ribbed bars and twisted bars. The samples were given a specific code for identification and confidentiality purposes. The experimental design plan is shown in Figure 3.1.

The properties were confined to yield stress, ultimate tensile strength and elongation. A comparative study was conducted on various grades of reinforcing steel bars. Also a survey on bars from construction sites was carried out and tensile tests were performed on sampled bars. Bars tested were randomly sampled from local rolling mills and hardware stores in the country. In this study, two types of reinforcing steels were investigated. These are cold-worked square twisted bars and hot-rolled ribbed bars. Chemical composition analysis, microstructure examination and the effect of heat treatment on the mechanical properties of reinforcing steel bars were studied.

To familiarize with the production process of reinforcing steel bars, ample time was spent in one of the rolling mills in Kenya for a period of one month. The rolling mill manufactures ribbed and twisted bars from scrap metal. Besides learning about the production of the bars, the experience included the use of facilities in the steel plant for controlling the quality of steel ingot and determining the mechanical properties of the bars. A two week period was spent at the Ministry of Road and Public Work (Materials Branch) in Kenya on the methods of testing the reinforcing steel bars.

The following equipments were used in carrying out the various experiments in the present work.

(i) Universal Testing Machines: one UTM from Steelmakers Ltd (maximum capacity 600kN) and two from Jomo Kenyatta University of Agriculture and Technology of 300 kN and 1000 kN respectively.

(ii) Universal Surface Grinder

(iii) Optical Metallurgical Microscope (40X magnification), from the University of Nairobi

(iv) Atomic Emission Spectrometer (METAVISION-108)

(v) Electric muffle furnace (with Maximum Temperature of 1200 ^{O}C)

(vi) Micro vickers hardness tester (10X magnification)

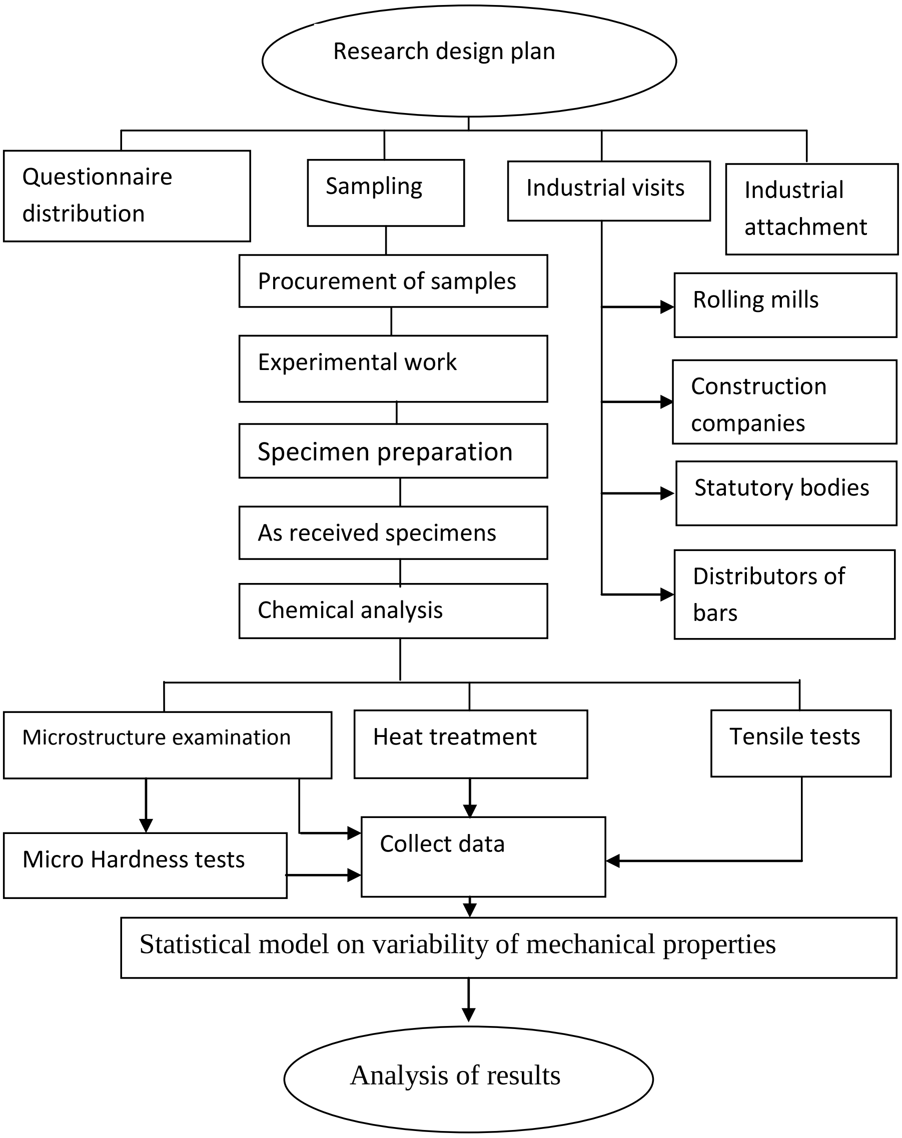


Figure 3.1: **Conceptual Framework**

Tensile test specimens were prepared from the as rolled bars according to BS 4449 (2005) standard and the values for ultimate tensile strength, yield strength and percent elongation of the as rolled specimens were determined. Heat treatment regimes were performed on the specimens and finally tensile tests, microstructure examination and micro hardness tests were carried on them after various heat treatment conditions. The grain size was determined by a linear intercept method, using a test pattern consisting of three concentric and equally spaced circles (Figure 3.2) having a total circumference of 500 mm.

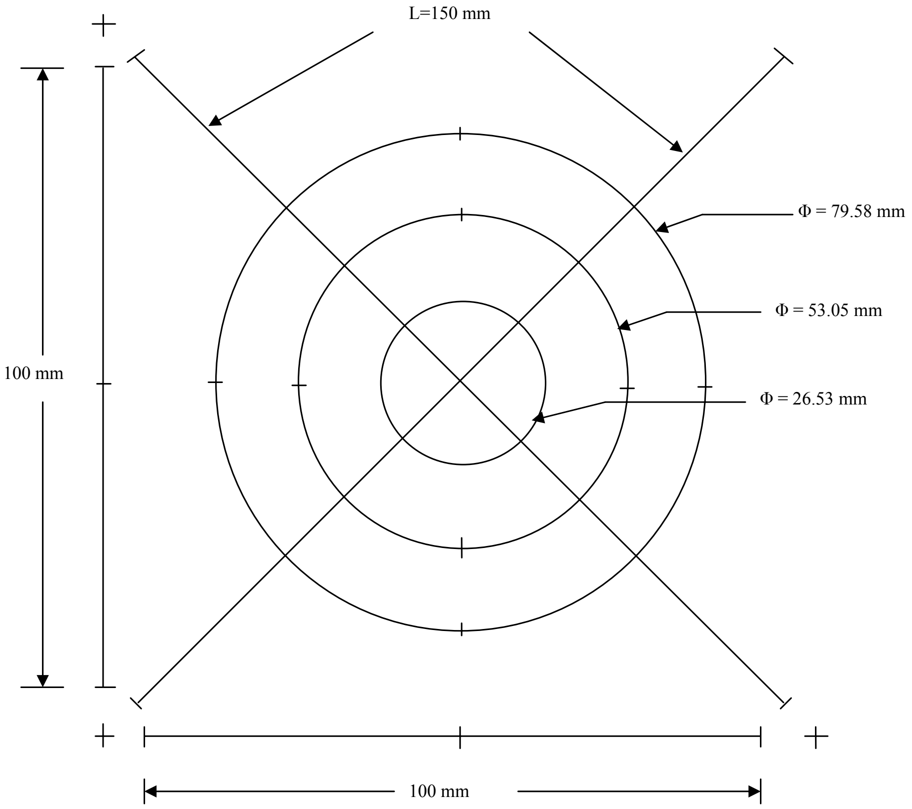


Figure 3.2: **Test pattern used for grain size determination** [54]

3.2 Survey

The survey comprised of a structured questionnaire and visits to steel rolling mills, main distributors (hardwares) and to construction industry in the country (Kenya). The purpose of the survey was to obtain information that would reveal the quality control methods and the methods of production of the bars used in building industry. In case of production, ample time was spent on the shop floor to learn about the rolling of the bars, and subsequently sampled some from identified heats. The experience included the casting of the ingot from scrap metal.

3.3 Experimental work

The experimental work involved the following: chemical analysis, tensile tests, microstructure examination, micro hardness tests and heat treatment of reinforcing steel bars. Twenty three (23) bars from the first rolling mill identified as (RM1), forty seven (47) bars from the second rolling mill identified as (RM2), and thirteen (13) bars randomly collected from six hardwares (identified by A,B,C,D,E and F) were investigated. Tests for tensile properties from twenty seven (27) bars from construction Company (identified by CONSC1) and three (3)bars from another construction site (identified by CONSC2) were carried out.

3.3.1 Chemical composition analysis

A chemical analysis on the steel was carried out using an Atomic Emission Spectrometer (AES) METAVISION-108 (see Figure 3.3) located at Steel Makers Ltd. By means of regression analysis, the results were then used to establish the effect of chemical composition on the tensile properties. A sample of specimens from two rolling mills, six distributors of reinforcing steel bars and some from construction sites were analyzed chemically.

The tabulated results are given in Table A.1 to Table A.4 in Appendix A. Atomic emission spectrometer determines the element concentration via a quantitative measurement of the optical emission from excited atoms. Analyte atoms in solution are aspirated into the excitation region where they are desolved, vaporized, and atomized by a flame, discharge, or plasma.

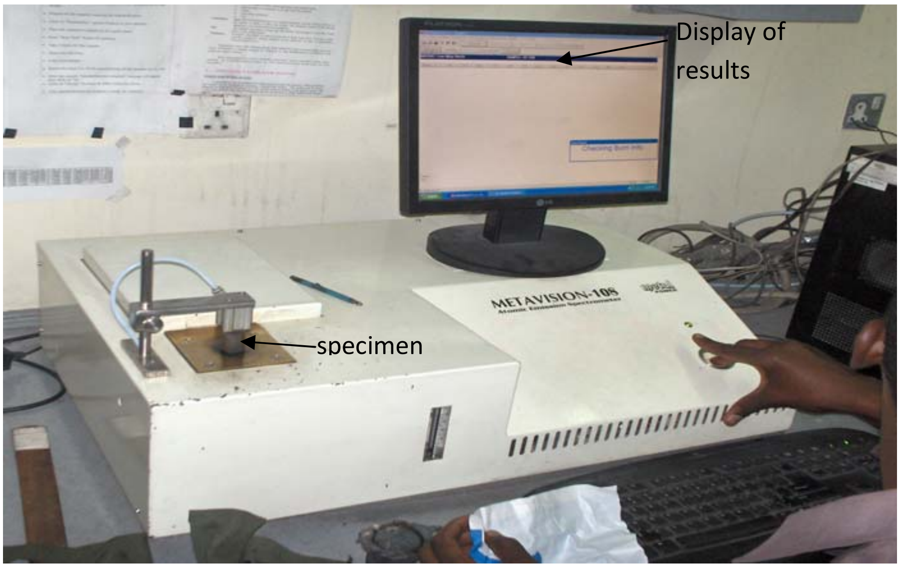


Figure 3.3: **Chemical analysis using an atomic emission spectrometer (METAVISION-108) at Steel Makers Ltd**

The fundamental characteristic of this process is that each element emits energy at specific wavelengths peculiar to its atomic character. The intensity of the energy emitted at the chosen wavelength is proportional to the amount (concentration) of that element in the sample being analyzed. Thus, by determining which wavelengths are emitted by a sample and by determining their intensities, the analyst can qualitatively and quantitatively find the elements from the given sample relative to a reference standard.

The wavelengths used in AES ranges from the upper part of the vacuum ultraviolet (160 nm) to the limit of visible light (800 nm). As borosilicate glass absorbs light below 310 nm and oxygen in air absorbs light below 200 nm, optical lenses and prisms are generally fabricated from quartz glass and optical paths are evacuated or filled by a non absorbing gas such as Argon. Figure 3.4 shows a schematic diagram of the working principle of an Atomic Emission Spectrometer [60].

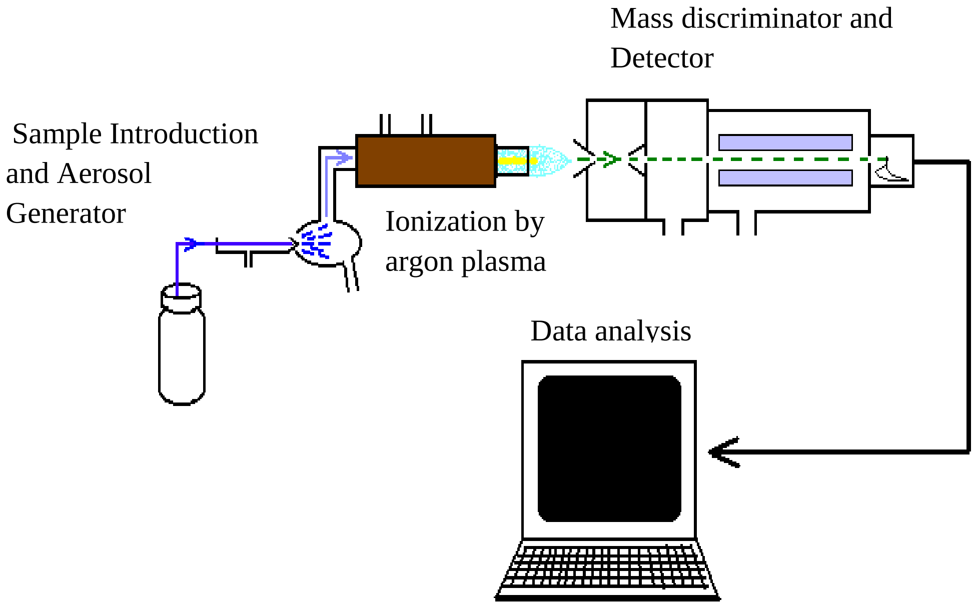


Figure 3.4: **Schematic diagram of the working principle of Atomic Emission Spectrometer (AES)** [60]

3.3.2 Regression analysis

Regression analysis can be defined as a statistical technique used to find relationships between variables for the purpose of predicting future values. Since the mechanical properties, namely yield strength, ultimate tensile strength and % Elongation of a particular reinforcing steel bar are functions of chemical compositions in the bar, the regression analysis was used to estimate the yield strength, tensile strength and % Elongation of the bars at a specific percentage of Carbon, Silicon and Manganese. The multiple regression equation was developed using the Microsoft excel 2007 Package using LINEST Function [61]. The equation

$$y = mx + b \tag{3.1}$$

algebraically describes a straight line for a set of data with one independent variable where x is the independent variable, y is the dependent variable, m represents the slope of the line, and b represents the y-intercept. If a line represents a number of independent variables in a multiple regression analysis to an expected result, the equation of the regression line takes the form

$$y = m_1x_1 + m_2x_2 + ... + m_nx_n + b \tag{3.2}$$

in which y is the dependent variable, x_1 through x_n are n independent variables, m_1 through m_n are the coefficients of each independent variable, and b is a constant.

The LINEST function uses this more general equation (Eq 3.2) to return the values of m_1 through m_n and the value of b, given a known set of values for y and a known set of values for each independent variable. This function takes the form LINEST(known y's, known x's, const, stats).

Table 3.1: **Inputs of independent variables used to generate the multiple regression equations**

x_n	X_{n-1}	……..	X_2	X_1	intercept
m_n	m_{n-1}	…….	m_2	m_1	b
se_n	se_{n-1}	…	se_2	se_1	se_b
r^2	Se_y				
F	D_f				
ss_{reg}	Ss_{resid}				

Table 3.2: **Designation of the statistical parameters**

se_1 through se_n	Standard error values for each coefficient
Se_b	Standard error value for the constant b
R^2	Coefficient of determination
Se_y	Standard error value for **y**
F	F statistic
Df	Degrees of freedom
Ss_{reg}	Regression sum of squares
Ss_{resid}	Residual sum of squares

3.3.3 Tensile test

The tensile test specimens were prepared as follows: All bars were cut into length of 600 mm each. The specimens were tested without any machining operation according to BS4449 (2005) standard using the Universal Testing Machine (UTM) with a capacity of 600 KN (Type: FIE Make Universal Testing Machine, UTN/E-60) at a rate of 8 mm/minute. The gauge length (L_O) was calculated using the standard formula.

$$L_o = 5.65\sqrt{A_o} \tag{3.3}$$

where A_o is the nominal cross-section area of the bar given by:

$$A_o = \frac{\text{Mass per meter run}}{\text{Density of Steel}(\rho = 0.00785 \text{ g/mm}^3)} \tag{3.4}$$

Figure 3.5 and Figure 3.6 show the specimen dimensioning and the set up for tensile test.

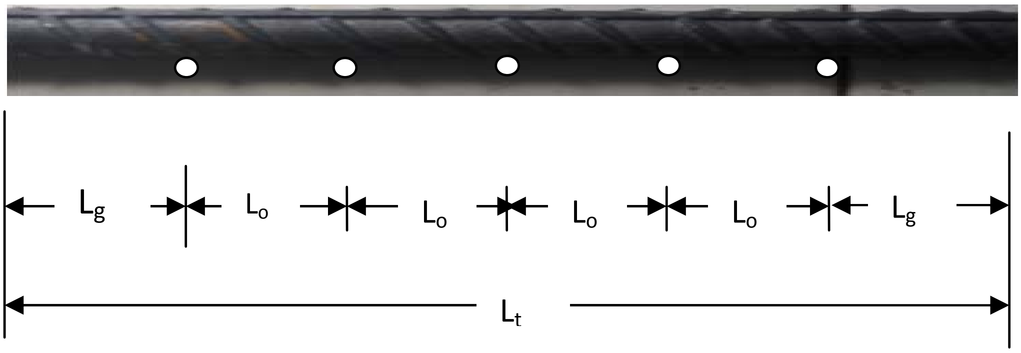


Figure 3.5: **Specimen dimensioning**

Data for Yield strength, Ultimate tensile strength and the percentage elongation were computed and tabulated. The Yield strength was calculated from the 0.2% strain. From the data, the CoV was calculated for all sampled bars.

Figure 3.6: **Tensile test set up**

3.3.4 Microstructure examination

The microstructural characterization was done on samples cut from the as-received and from the heat treated reinforcing steel bars using an optical microscope. The preparation of a specimen to reveal its microstructure involved:

- Sawing the section to be examined
- Manual filing of the section to be examined
- Surface grinding using the Universal surface grinder
- Mounting the specimen in resins (for small samples)
- Grinding the specimen on progressively finer SiC waterproof papers

- Polishing the specimen using 6 and 1μm granulation diamond paste on a rotating wheel
- Etching in dilute acid (2% Nital)
- Washing in alcohol and drying

The specimen was first surface ground-using a precision surface grinder (Figure 3.7) available in the machine shop at JKUAT then wet ground on progressively finer SiC waterproof papers to produce a reasonably flat surface.

Figure 3.7: **Surface grinding of metallographic specimen**

The sample was moved forward and backward on the paper until the whole surface was covered with unidirectional scratches (Figure 3.8). It was then washed with running water to remove debris associated with the grade of paper used. It was thereafter ground on the next finer paper such that the scratches produced are at right angles to those formed by the previous paper. This was achieved by rotating the specimen 90^o between grinding steps (Figure 3.9). This procedure was repeated through the range of SiC waterproof papers (220, 320, 400 and 600 grit). Subsequently, the ground sample was polished on a rotating wheel using 6 μm diamond paste. Fine polishing to a perfect mirror-like finish of the surface was achieved by using 1 micron diamond paste. The polished sample was then etched using a 2% Nital solution (a reagent that is a solution mixture of 2 ml of Nitric Acid (HNO_3), 98 ml of Ethanol (CH_3CH_2OH)).

After etching, the sample was flooded with a stream of water followed by a jet of Acetone (CH_3COCH_3) and finally dried quickly in a stream of warm dry air to prevent corrosion.

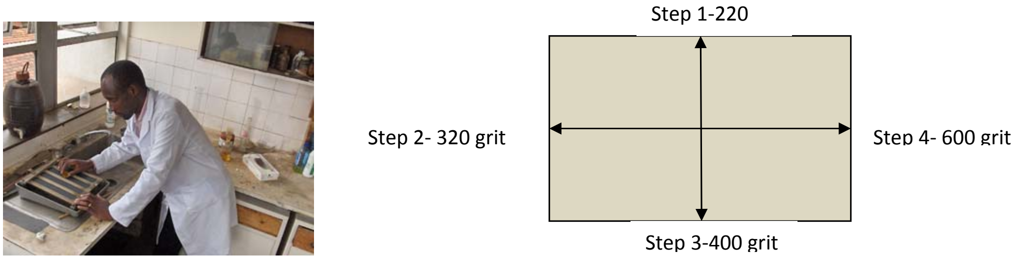


Figure 3.8: **Grinding sequences on silicon carbide papers**

The etched surface of the polished samples was finally observed in an optical microscope with an in-built camera (Figure 3.10) at a magnification of 544X i.e. the product of 40X for the objective lens, 8X for the eye piece and 1.7X for resolution of the microscope used. Phases in each specimen were analyzed and compared with

Figure 3.9: **Polishing operation with diamond paste on a rotating wheel polishing machine**

the expected phases in the reinforcing steel bars.

Figure 3.10: **Microstructure examination**

3.3.5 Grain size determination

The grain size of sampled bars was computed using the intercept method described in ASTM standard E112-96 (2004) [54], where a pattern of three concentric circles of total circumferential length 500 mm as shown in Figure 3.11 was successively applied to five randomly selected and widely spaced fields. The accuracy was determined by computing the relative accuracy at 95% Confidence Interval (CI).

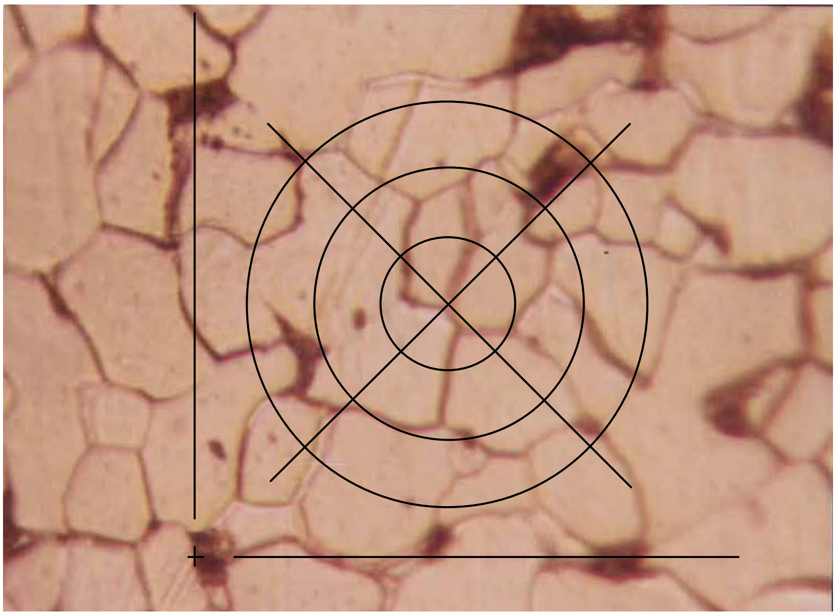


Figure 3.11: **Test pattern for intercept counting placed on a micrograph**

The following steps were followed in order to determine the ASTM grain size:

(a) Place three concentric circles of diameter 79.59, 53.05 and 26.53 mm respectively on a single field of view as shown in Figure 3.11

(b) Count the total number of intercepts, N, between the test pattern and the grain boundaries, triple junctions count as 1.5

(c) Divide the number of intercepts, N, by the total length L

(d) Repeat(a-c) for 2 to 4 additional fields of view

(e) Obtain N_L as the average of results from (c) for all fields of view

(f) Calculate the ASTM grain size number, G

No determination of average grain size can be an exact measurement. Thus, no determination is complete without also calculating the precision within which the determined size may, with normal confidence, be considered to represent the actual average grain size of the specimen examined. Many specimens vary measurably in grain size from one field of view to another, this variation being responsible for a major portion of the uncertainty.

After the desired numbers of fields have been identified, the mean value of N number of intercepts has been calculated according to:

$$\overline{X} = \frac{\sum X_i}{n} \tag{3.5}$$

Where X_i represents an individual value and n is the number of measurements (see Table 3.3).

Table 3.3: **Computation of mean value from a set of measurements**

Field No.	1	2	3	…	n	$\overline{X}$
Individual measurements X_i	X_1	X_2	X_3	…	X_n	$\frac{\sum_{i=1}^{n} X_i}{n}$

X_i can be either the number of grains intercepted by the test line pattern, the ASTM grain size number or average grain size.

The standard deviation (SD) of the individual measurements was calculated according to the equation:

$$SD = \sqrt{\frac{\sum (X_i - \overline{X})^2}{n-1}} \tag{3.6}$$

The percent relative accuracy % RA of the measurements was calculated at 95% confidence level from the equation:

$$\%\ RA = \frac{95\%\ CI.100}{\overline{X}} \tag{3.7}$$

Where 95% CI is the 95% confidence interval measured according to:

$$95\%\ CI = \frac{t.SD}{\sqrt{n}} \tag{3.8}$$

Where t is the 95% confidence internal multiplier (student t-Test) read from the standard table.

3.4 Heat treatment

The Electrical Muffle Furnace (1200^{o}C maximum capacity) shown in Figure 3.12 was used to heat treat the specimens and the iron - carbon phase diagram (Figure 3.13) was used to determine the required temperature for each heat treatment condition. Four heat treatments were carried out in this work in accordance with Figure 3.14 to 3.16 namely Annealing, Normalizing, Quenching and Tempering.

3.4.1 Quenching and tempering

Specimens from three (3) heats of known chemical composition were austenitized at 900^{o}C in an electric muffle furnace for 30 minutes, quenched in ice and finally tempered at 400 ^{o}C, 500 ^{o}C and 600 ^{o}C for 60 minutes (Figure 3.14).

Note: HR is the heating rate, CR is the cooling rate and HolT is the holding time.

Figure 3.12: **Electrical Muffle Furnace used for heat treatment (1200 ^{o}C Maximum capacity) at JKUAT, Structural and Materials Engineering lab**

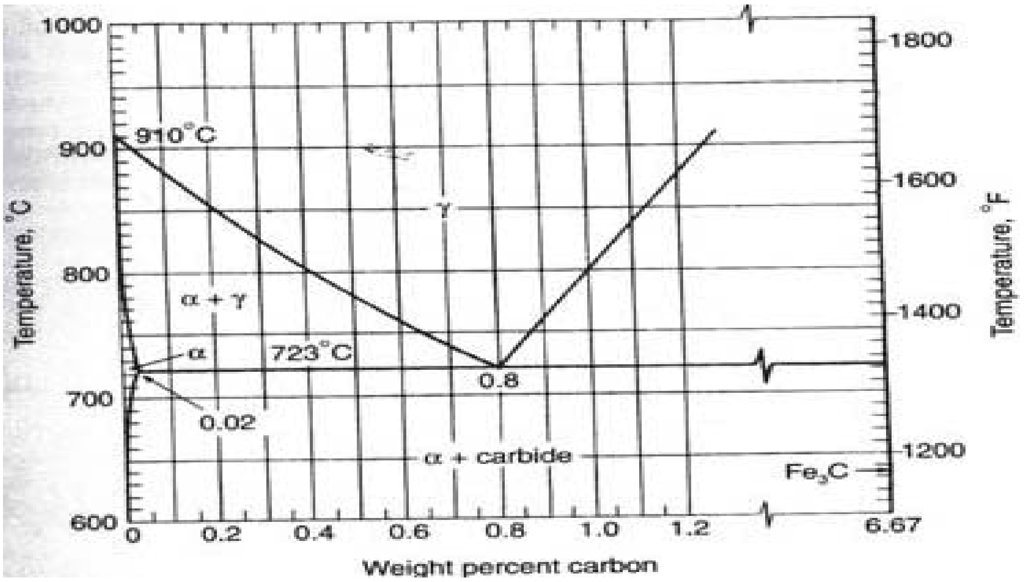


Figure 3.13: **Iron-carbon phase diagram** [62]

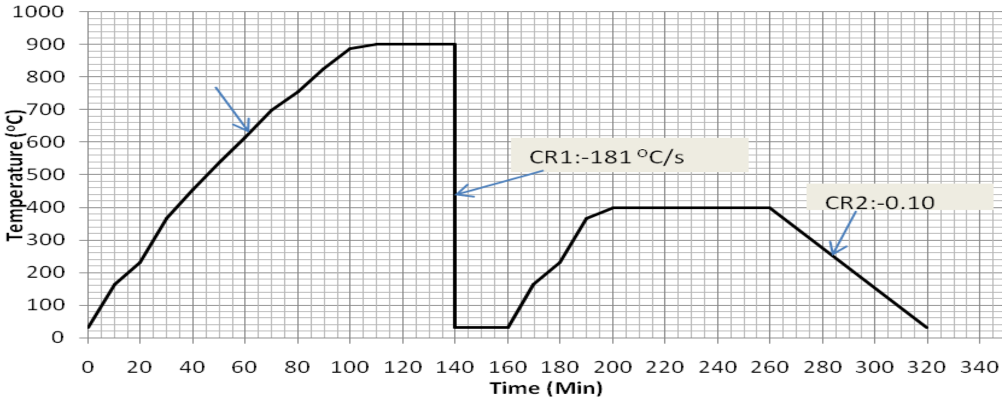


Figure 3.14: **Temperature Time (TT) diagram for Quenching and Tempering**

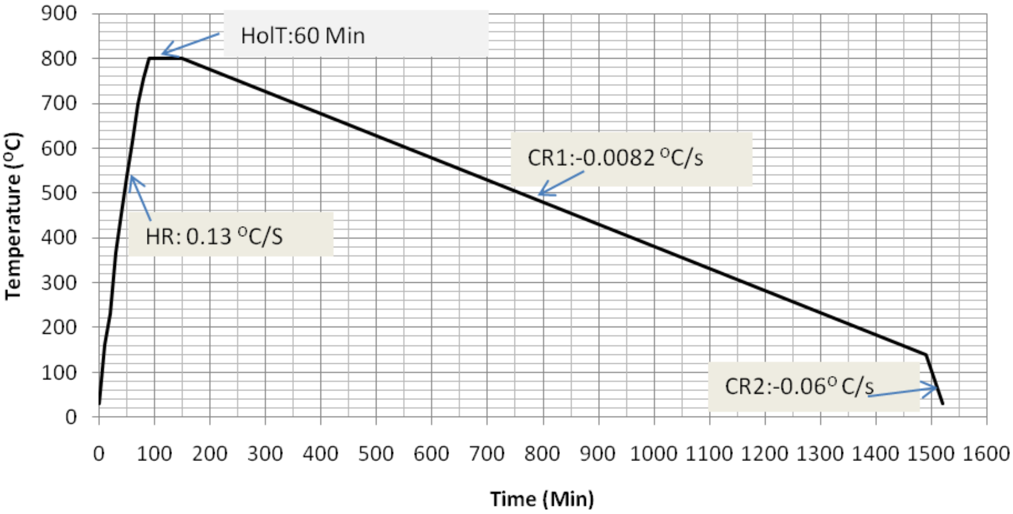


Figure 3.15: **TT diagram for Annealing**

3.4.2 Annealing

Specimens from three (3) heats were intercritically annealed at the inter critical temperatures of 730, 750 and 800^o C, for the following holding times: 30, 60 and 90 minutes and cooled at a low rate in the furnace (Figure 3.15).

3.4.3 Normalizing

Specimens from three (3) heats were austenitized at 900^{o}C, soaked for 60 minutes and then cooled in still air (Figure 3.16).

After each heat treatment, the sampled specimens were prepared for microstructure examination. An optical metallurgical microscope was used to view the microstructure of the polished specimens.

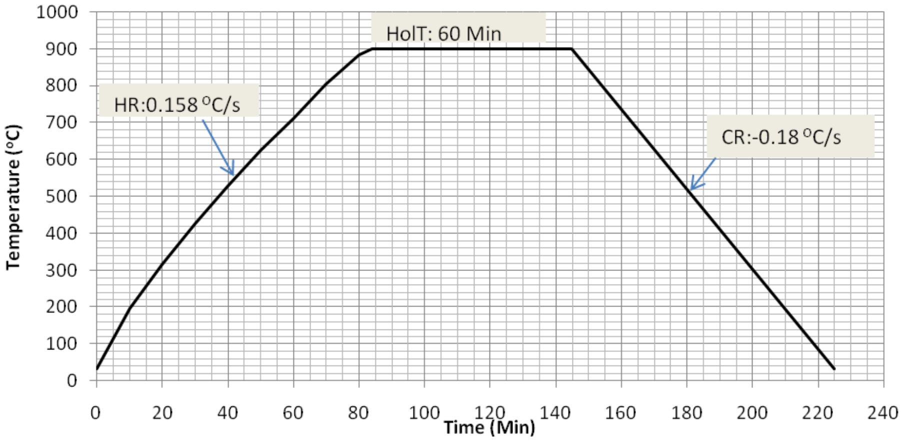


Figure 3.16: **TT diagram for Normalizing**

3.5 Micro-Vickers hardness test

The micro hardness test was performed on the specimens in the as received and heat treated conditions using a micro hardness tester in the materials laboratory at the Jomo Kenyatta University of Agriculture and Technology. The time for the initial application of a force of 200 gf was 5 s to 8 s, and the test force was maintained for 10 s. The two diagonals of the indentation left on the surface of the material after removal of the load were measured using a micrometer incorporated into the eye piece of the Microvickers hardness tester (Figure 3.17) and their average value was calculated. At least six indents were made across the polished surface of a test specimen and tensile properties were related to microhardness of the bars.

Figure 3.17: **Microvickers hardness tester used in determination of hardness, a) specimen under load, b) reading of imprint indentation**

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

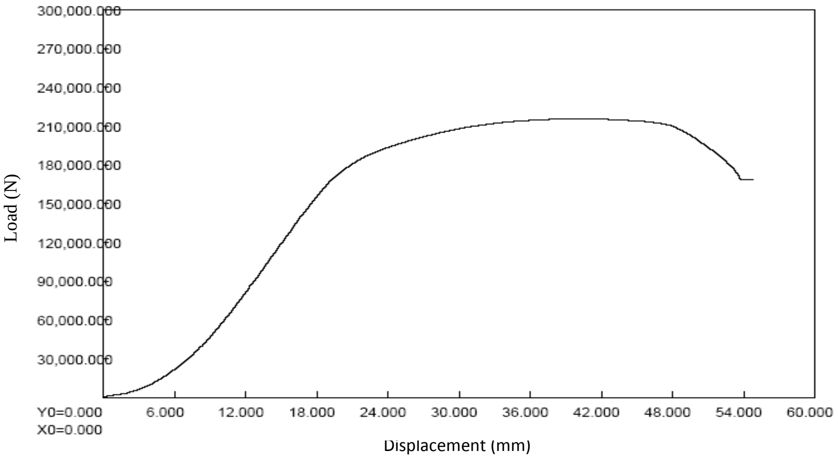
The results from the present work are grouped into two sections namely: Result from the experimental work and results from a survey. The experimental part includes tensile test, chemical analysis, microstructure examination, microhardness test and heat treatment. This chapter highlights also the main differences between the mechanical properties of self tempered and work hardened reinforcing steel bars used in building industry in Kenya.

4.2 Behavior of self tempered and work hardened reinforcing steel bars

The graphs in Figure 4.1 show the comparisons between the load- displacement curves of a self tempered and work hardened reinforcing steel bar. From the figure it can be seen that the self tempered reinforcing steel bar has a distinct yield point. That is, the yield plateau is distinct for self tempered reinforcing steel bars while the work hardened does not have a yield plateau. More graphs are shown in Appendix B.

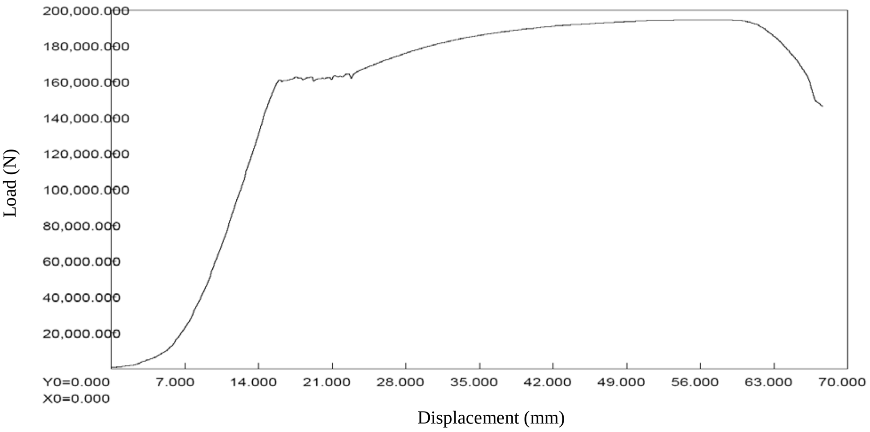
Figure 4.2 shows a comparison between the tensile properties of both ribbed self tempered and twisted bars. From the figure, it is seen that the work-hardened reinforcing bars exhibit higher yield strength as compared to their counterparts (self tempered bars). The higher value could be due to the work hardening phenomenon during twisting operation. Further comparison of the experimental data is shown in Figure 4.3. The difference is also evident in Figures 4.4 and 4.5 showing the hardness values of both types of steels investigated. The difference is also found in the microstructures of both steels. The microstructure of a self tempered reinforcing steel bars is characterized by a clear difference between the core and the rim part of the bar cross section. The rim is a complete martensite phase, while the core is a combination of ferrite/pearlite phase which is a soft structure. On the other hand, the microstructure of work hardened reinforcing bars showed a mixture of ferrite/pearlite phase (refer to Figure 4.21). It was observed that the volume fraction of ferrite increased with a corresponding decrease in carbon content (refer to Table A.1 - A.4 in Appendix A).

From the same tables, the results show that for the sample of eighteen bars, which were chemically analyzed from rolling mill RM2, only two were not weldable. All bars sampled from RM1 for chemical analysis were found to be weldable since none had a CE value greater than 0.51 as recommended by the BS 4449:2005 standard. Three out of eight bars sampled from hardware stores were not weldable. It was observed that the weldability of the bar is independent on the production process since non weldable bars were found in both types of bars i.e., self tempered and work hardened reinforcing steel bars.



(a) Load vs Displacement graph of a work hardened (Twisted bar No.VII Y20 from RM1)

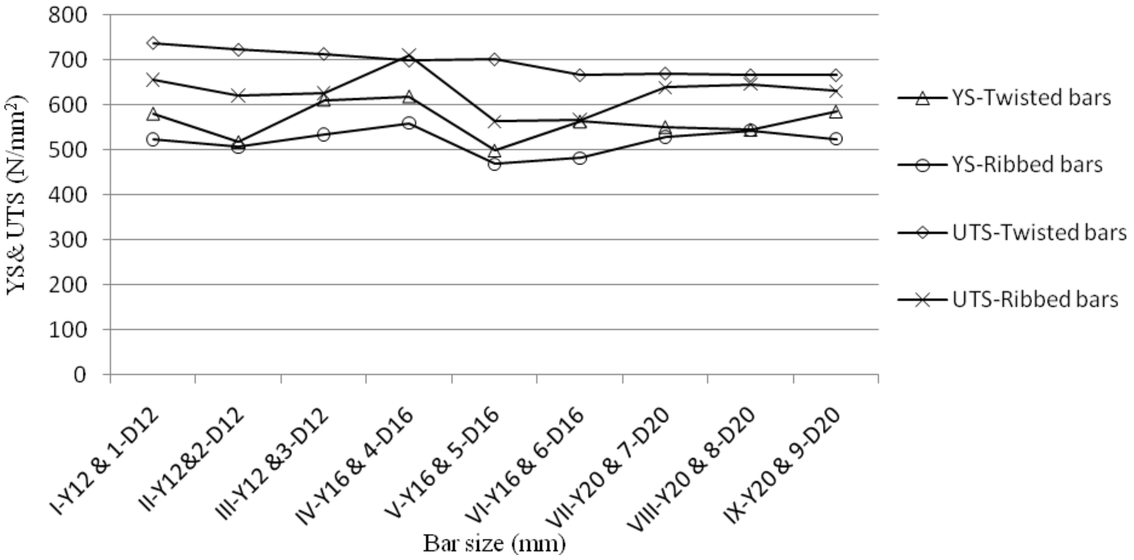
Results: YS = 552.204 N/mm², UTS = 671.615 N/mm², % El = 15.5



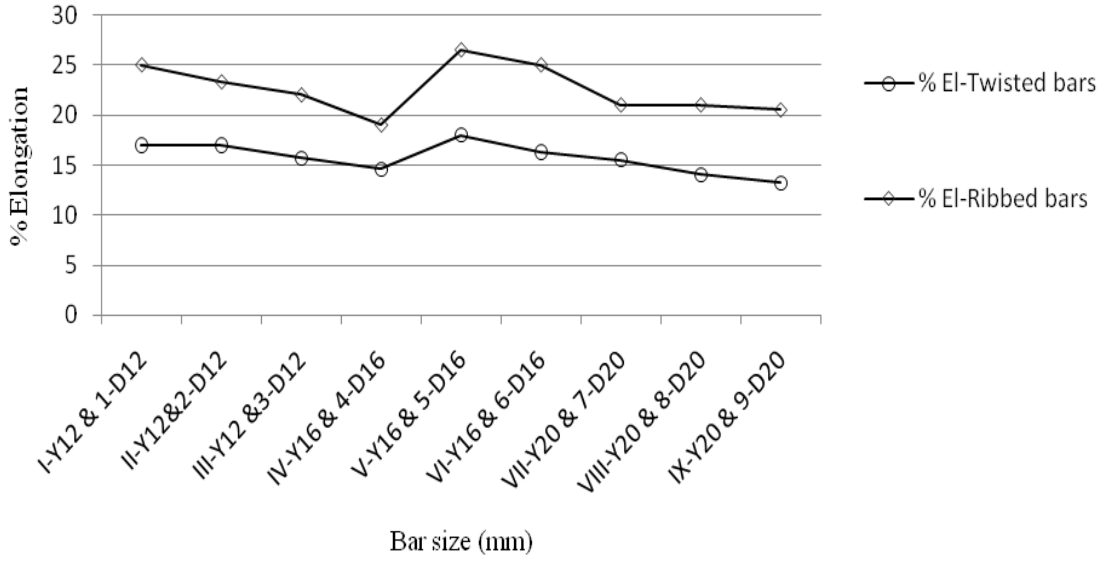
(b) Load vs Displacement graph of a Self Tempered (Ribbed bar No.7D20 from RM1)

Results: YS = 528.482 N/mm², UTS = 639.721 N/mm², % El = 21

Figure 4.1: **Load vs displacement curves: Comparison between twisted and ribbed self tempered reinforcing steel bars**



(a) Comparison between YS & UTS of Twisted and Ribbed bars



(b) Comparison between the % Elongation of Twisted and Ribbed bars

Figure 4.2: **Tensile properties of a set of ribbed and twisted bars**

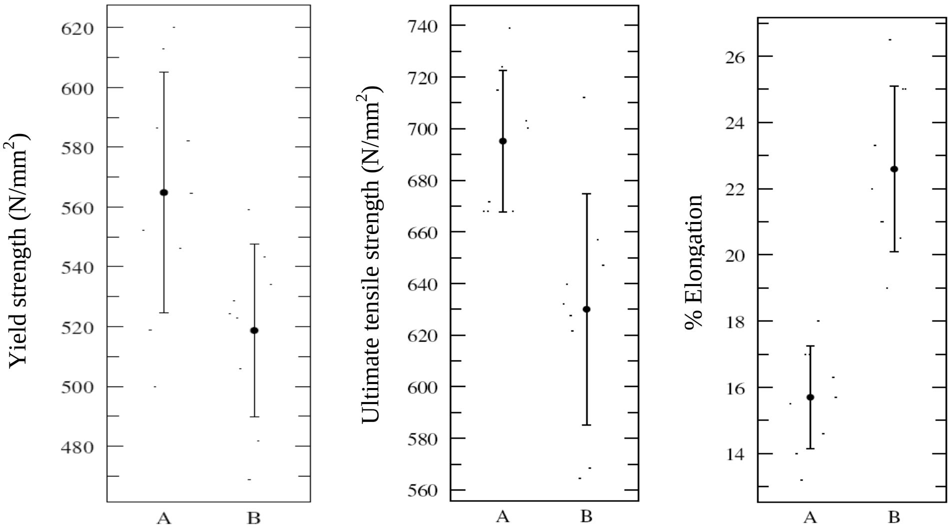


Figure 4.3: **Statistical parameters showing comparison between the tensile properties of work hardened (Group A) and self tempered (Group B)reinforcing steel bars**

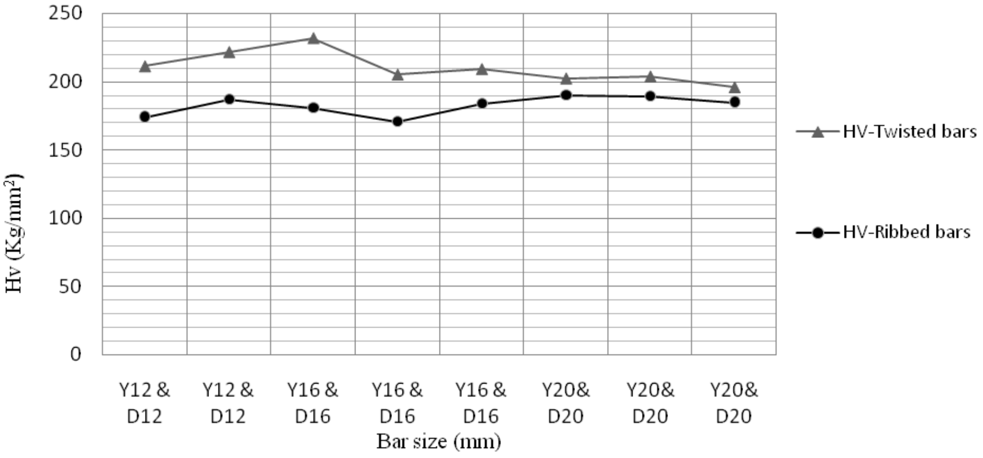


Figure 4.4: **Hardness of self tempered and work hardened reinforcing steel bars**

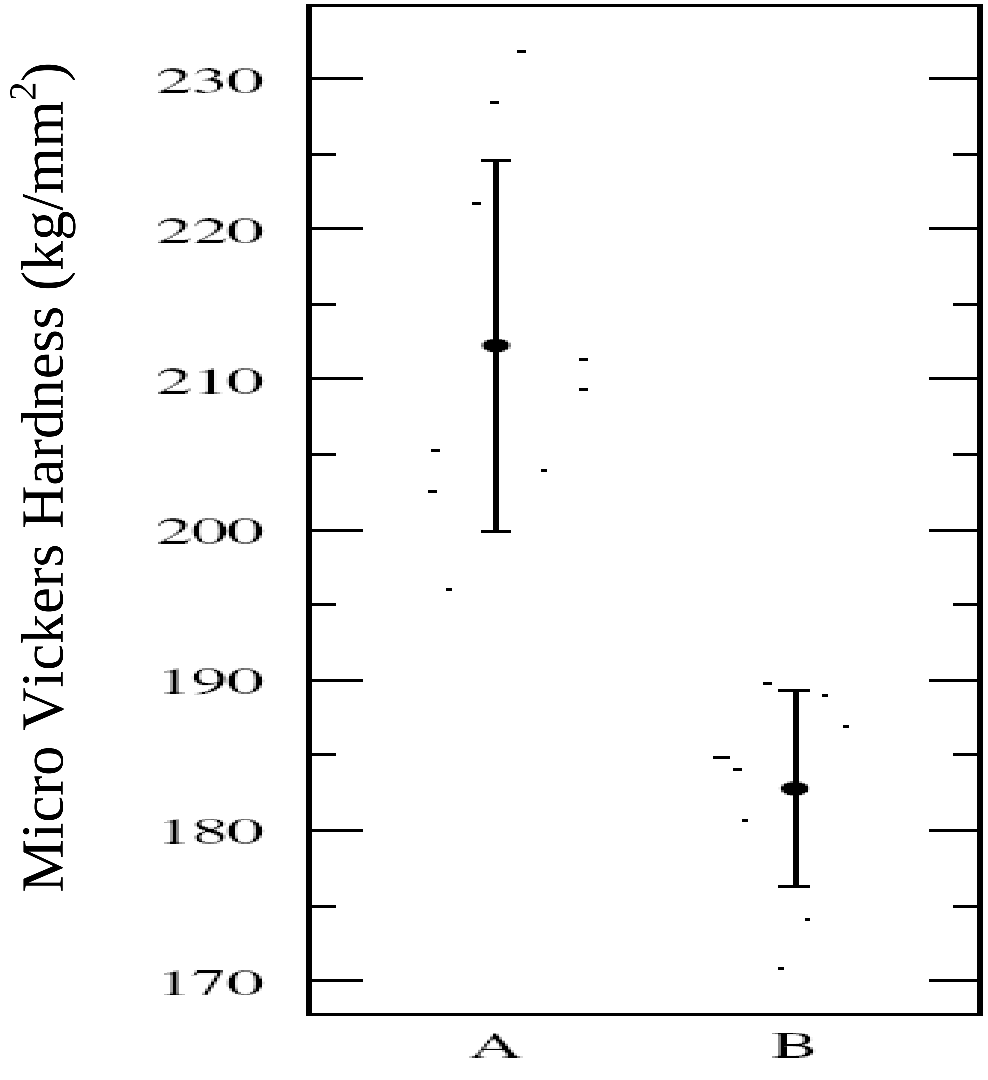


Figure 4.5: **Statistical parameters showing comparison between the hardness of work hardened (Group A) and self tempered (Group B) reinforcing steel bars**

4.3 Histogram of mechanical properties of bars investigated

This section is a compilation of results of mechanical properties of bars from two rolling mills in Kenya, bars from six distributors of reinforcing steel bars and data from one construction company in the country. Figure 4.6 to Figure 4.12 show the histograms and normal probability plots for Yield strength, Ultimate tensile strength and % Elongation of bars from rolling mills RM1 and RM2, various hardwares/distributors and one construction company (CONSC1). From these Figures, it was found that the bars investigated exhibited variability in mechanical properties. All the twenty three (23) bars from rolling mill RM1 had the mean yield strength greater than 460 N/mm^2 accompanied by an acceptable % elongation. They all have the % Elongation greater than 14% as per the requirement of BS44498:2005 standards (see Figure 4.6 and 4.7).

Seven (7) bars from a sample of forty seven (47) bars (i.e. 14.6%) from rolling mill RM2, exhibited a yield strength which is below the value specified by the BS44498:2005 standard (that is 460 N/mm^2). Three(3) bars (i.e.6% of bar from RM2) exhibited a percentage elongation less than 14% (refer to Figure 4.8 and 4.9).

On the other hand, Figure 4.10 and Figure 4.11 show that 54 % (seven out of thirteen) of reinforcing steel bars randomly sampled from hardwares failed to meet the minimum YS requirement of 460 N/mm^2, a standard requirement for reinforcing steel bars used for concrete reinforcement. Bars from hardwares and their corresponding tensile properties are shown in Table B.3 of Appendix B.

The failure of bars from hardwares was mainly due to low carbon contents as shown in Table A.3 in Appendix A.

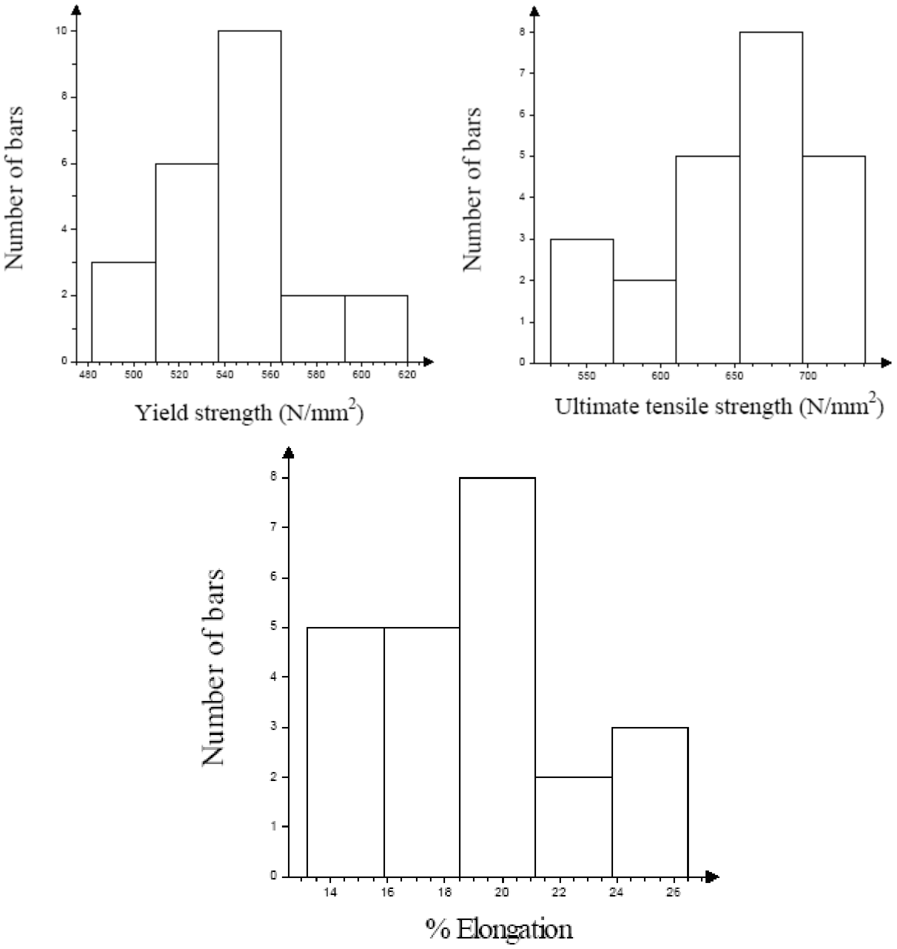


Figure 4.6: **Histograms of mechanical properties of bars investigated from rolling mill RM1**

Bars from two rolling mills meet the minimum required yield strength except five bars from RM2, which did not pass the test as shown in Table B.2 and Figure 4.8. Data in the normal probability plots in Figures 4.7, 4.9, 4.11 and 4.13 show that the data for yield strength, ultimate tensile strength and elongation were normally

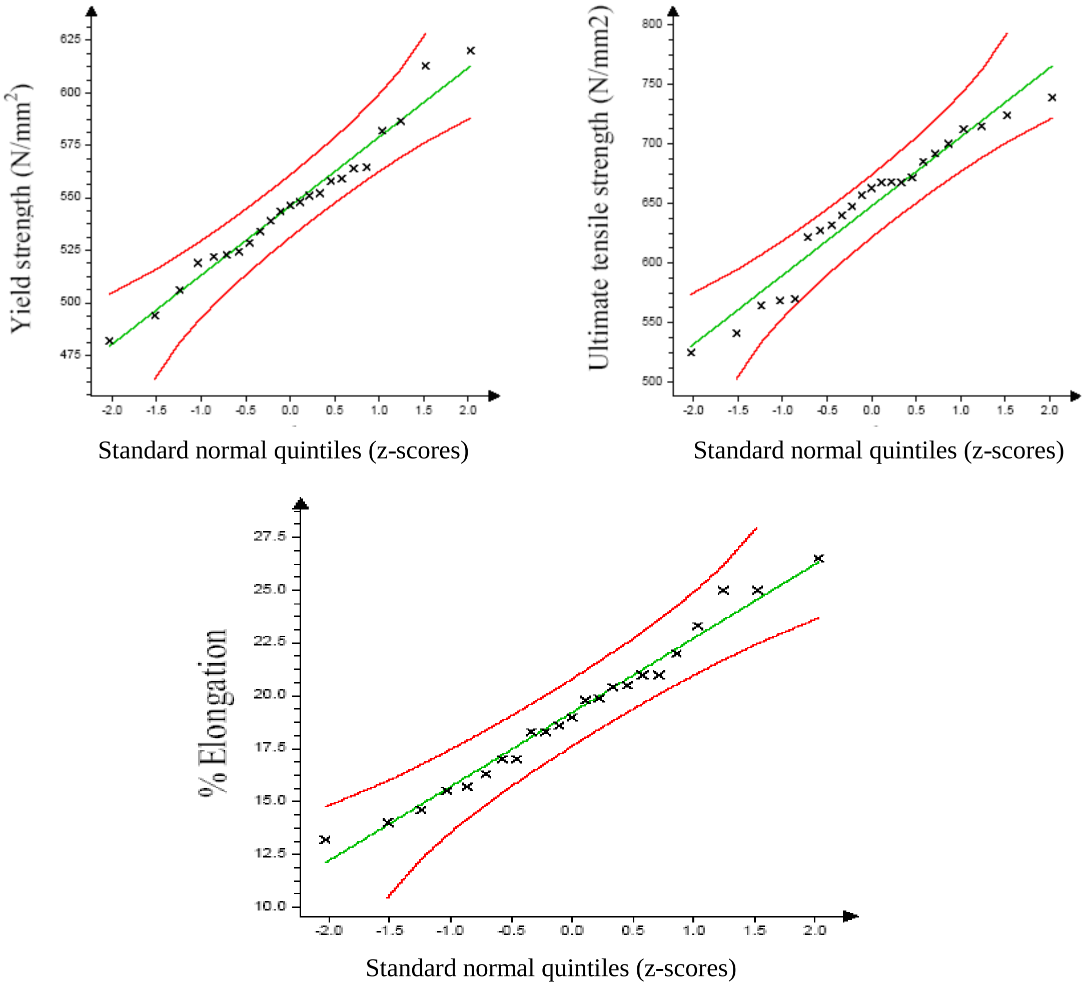


Figure 4.7: **Variability of mechanical properties of bars from rolling mill RM1**

distributed because all values were within the boundary lines (the red curved lines in the normal probability plots) except a few data for the ultimate tensile strength of bars from CONSC1, which deviated from the boundary lines. The mean characteristic value (that is yield strength) of these bars was above the minimum standard value of yield strength (i.e.460N/mm^2). The mean yield strength of bars from RM1 was 546.1 N/mm^2 and that of bars from RM2 was 523.5 N/mm^2. This was also

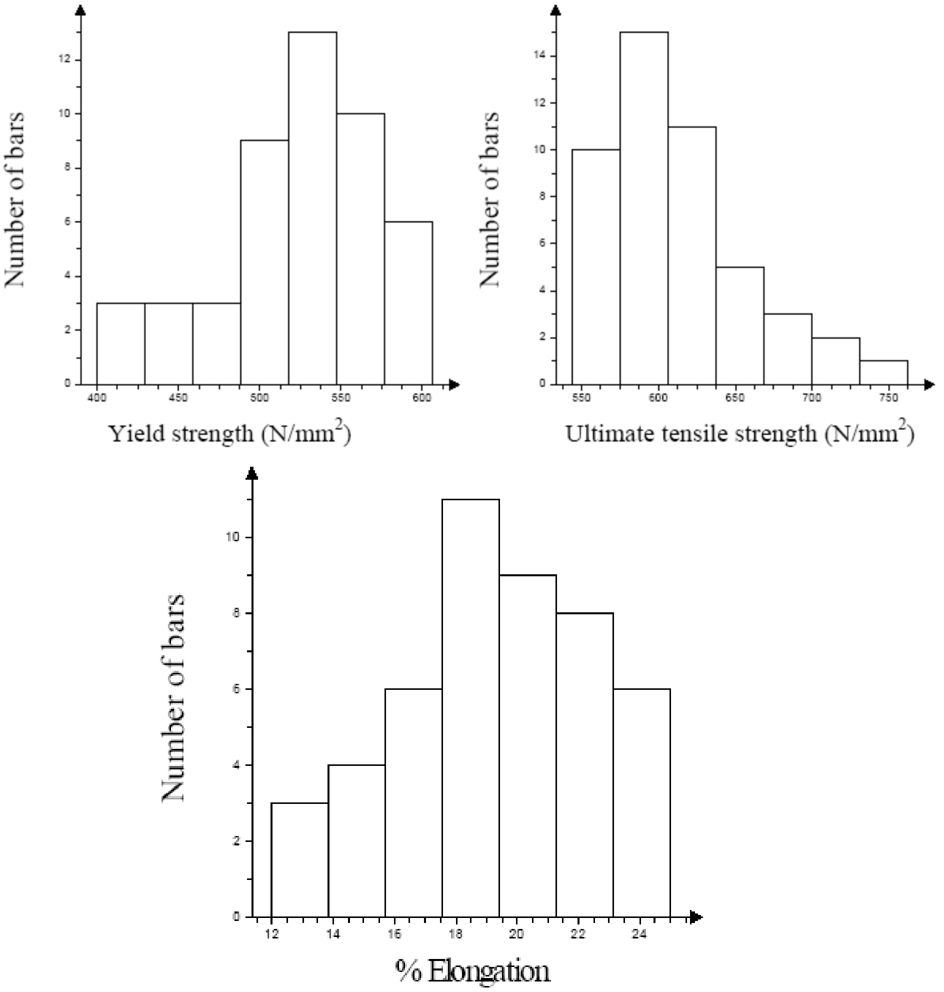


Figure 4.8: **Histograms of mechanical properties of bars investigated from rolling mill RM2**

proved by their low coefficient of variability (6.2% for bars from RM1 and 9.5% for bars from RM2 (refer to Appendix C.1.11 and C.1.12)). These values are presented in Table 4.1, 4.2 and 4.3.

This was also observed from the microstructure of the bars characterized by relatively fine grain size. A typical example of the microstructure of bars collected from rolling mill RM2 is shown in Figure 4.23.

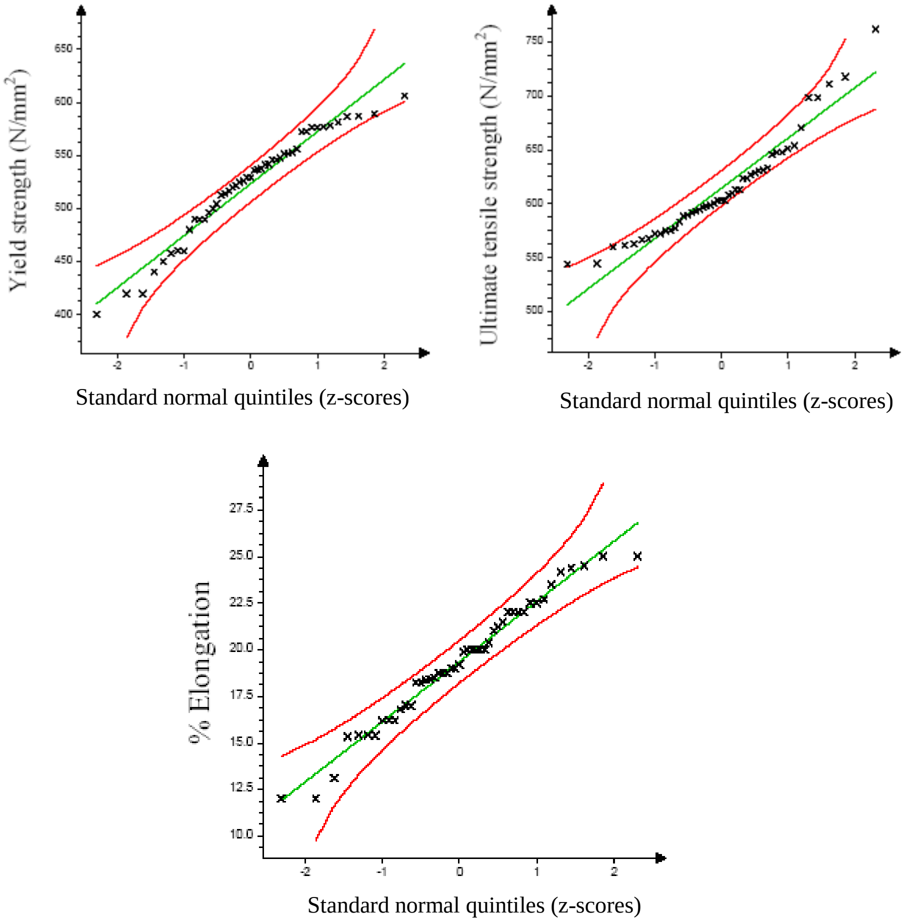


Figure 4.9: **Variability of mechanical properties of bars from rolling mill RM2**

A variability in mechanical properties of reinforcing steel bars is also observed on bars from a typical construction company (CONSC1). The results show that six (6) out of twenty seven (27) bars from a typical construction company have yield strength which is below the standard requirements and seven (7) bars failed in % Elongation (see Table B.4, Figure 4.12 and 4.13). The mean value of yield strength of bars from the data collected from CONSC1 was 472.9 N/mm^2 and the coefficient of variability was 6.2% (refer to Appendix C.1.9). On the other hand, bars collected

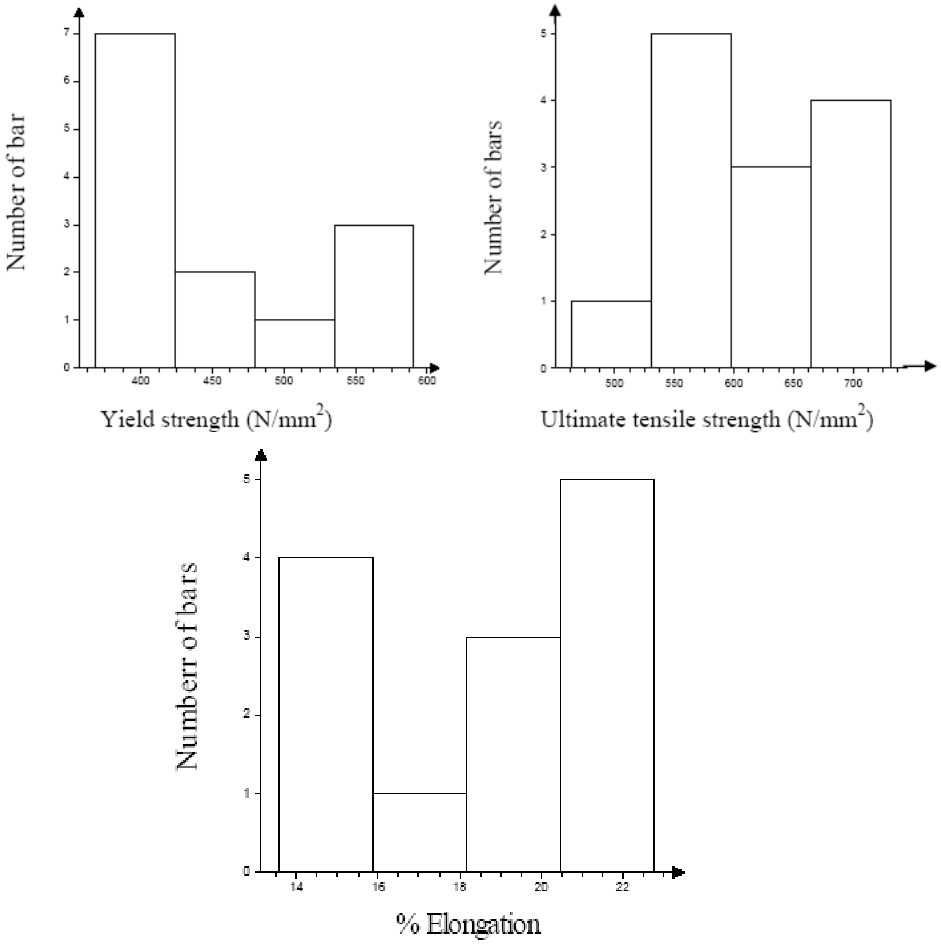


Figure 4.10: **Histograms of mechanical properties of bars investigated from hardwares**

from hardwares did not meet the minimum requirement of yield strength because the mean value of yield strength of these bars was below 460N/mm^2, that is 452.7 N/mm^2 and the COV was very high (16.7%). These values are reproduced in Table 4.3 and Figure 4.17.

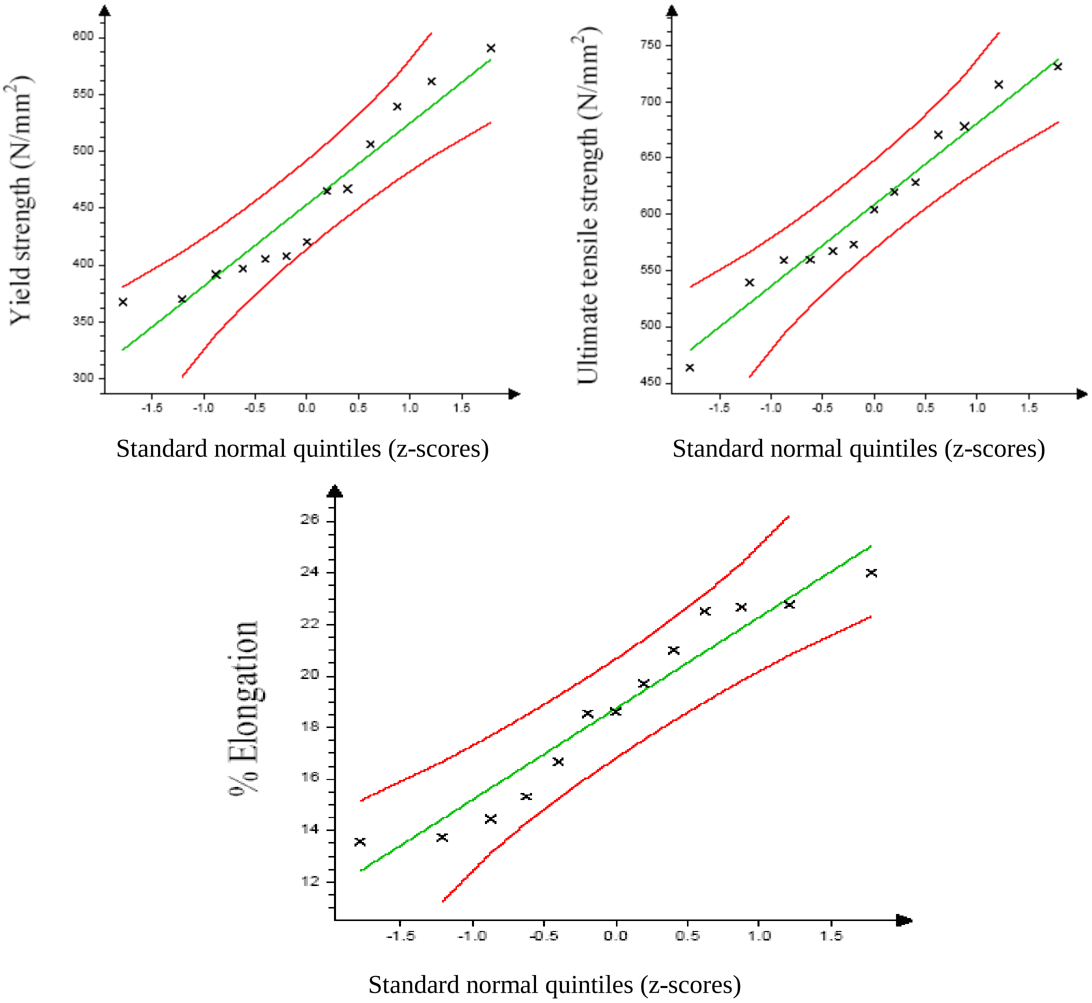


Figure 4.11: **Variability of mechanical properties of bars from hardwares**

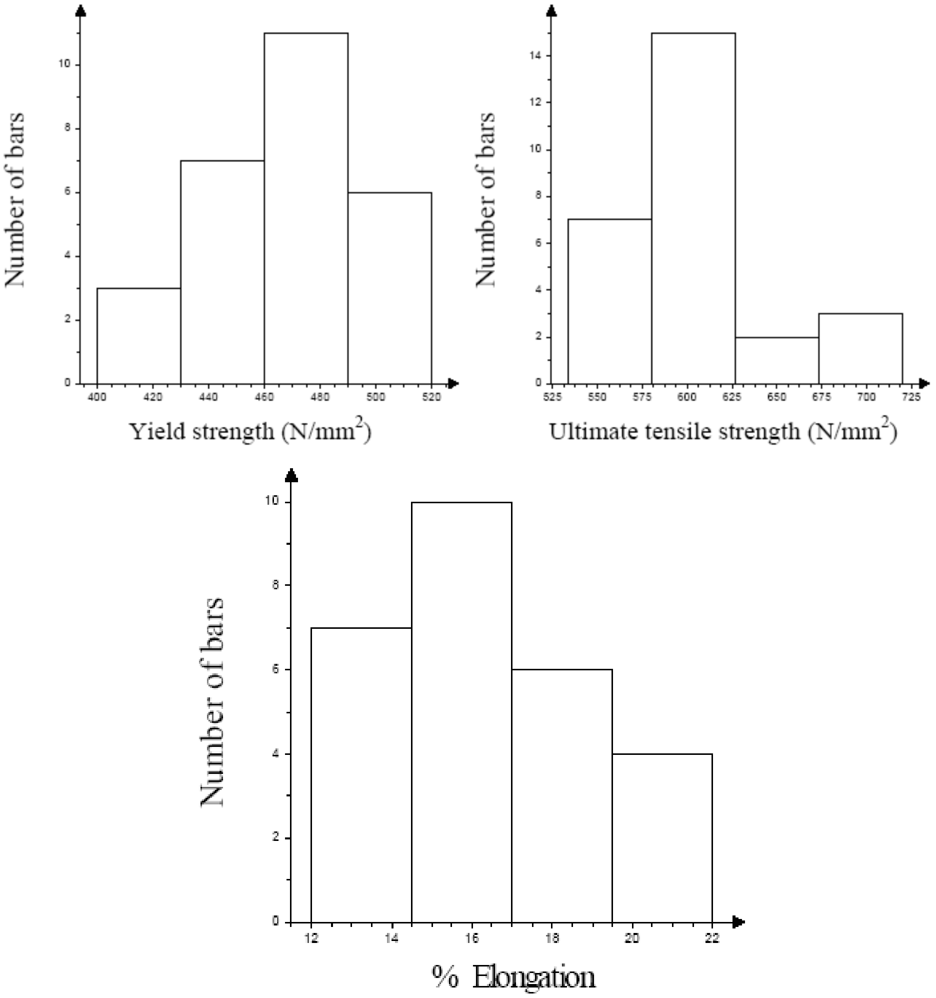


Figure 4.12: **Histograms of mechanical properties of bars investigated from a building construction company (CONSC1)**

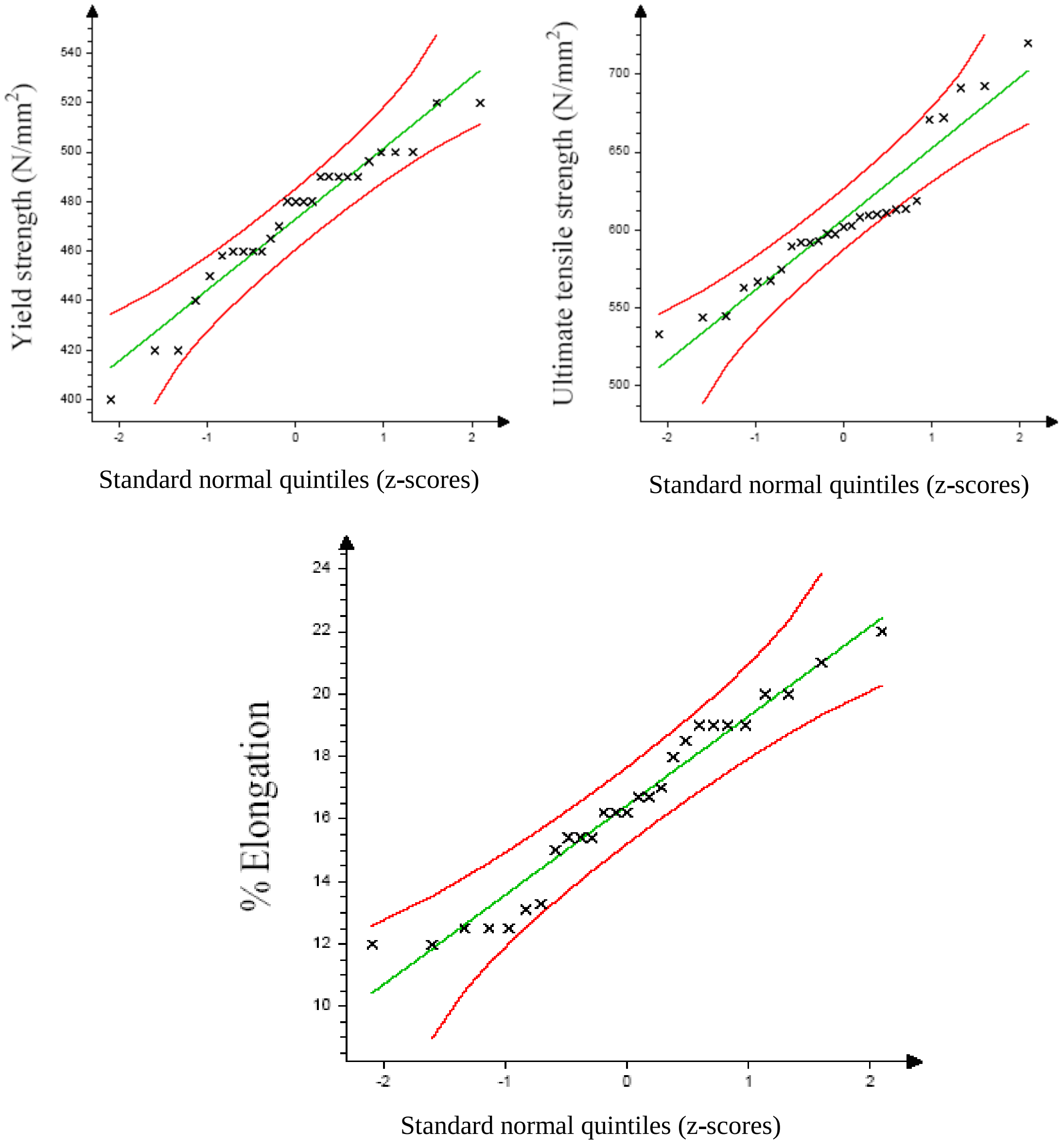


Figure 4.13: **Variability of mechanical properties of bars from a building construction company (CONSC1)**

4.4 Correlation between hardness and tensile properties of bars investigated

From the microvikers hardness test, it can be observed from Figure 4.14 that there is a correlation between hardness and tensile properties of reinforcing steel bars. Experiment shows that bars sampled for microhardness test have a hardness value in the range of Hv 150 to Hv 200. It can be inferred from the figure that yield strength gets higher as the hardness exceeds Hv 190. The correlation equations for yield strength, tensile strength and % elongation are as shown in Figure 4.14, where y is the characteristic parameter (either YS, UTS or % EL), x is the corresponding hardness value of the specimen and R is the regression coefficient.

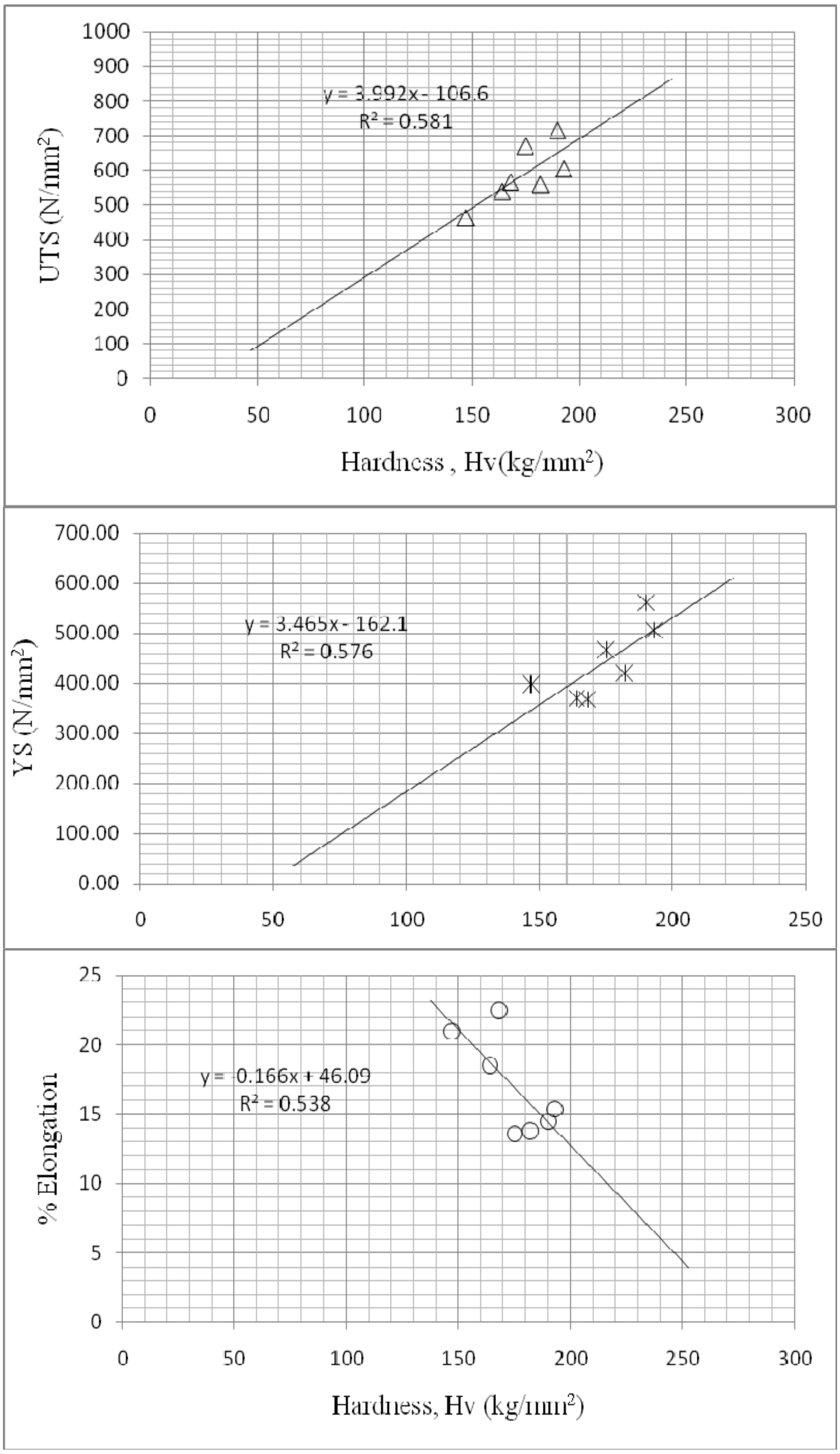


Figure 4.14: **Correlation between hardness and tensile properties of bars sampled from hardwares**

4.5 Statistical model of mechanical properties of reinforcing steel bars

Figure 4.15 and Table 4.1 show that the tensile properties of bars from typical rolling mills (Group A) are significantly different from tensile properties of bars collected from hardware stores (Group B). The 95% C.I. of yield strength for bars in Group B is out of the standard range.

It can be inferred from Table 4.1 that bars with low yield strength (Group B) have a coefficient of variability (COV) greater than 10% which can have a severe effect on the structure in which these bars are used for concrete reinforcement.

The student t-test shows that there is a big difference between the yield strength of bars from typical rolling mills and yield strength of bars randomly sampled from hardware stores. The t-calculated (t-stat) was equal to 3.812 (see Table C.2 in Appendix C) while comparing the yield strength of bars from rolling mills and those from hardware stores. This value is far much greater than the t-tabulated value of 1.998 and falls in the rejection area on the t-distribution curve at 95% C.I. with a degree of freedom (DF) of 64. This implies that there is high variability of yield strength of bars investigated.

The t-test shows that the ultimate tensile strength and the % elongation of bars from Group A and Group B, are not statistically significant since the t-stat for UTS was 1.073 and the t-stat for % elongation 0.198. These values are less than the critical values of t (refer Table C.2 in Appendix C). Comparing the results of tensile properties of bars from any rolling mill and bars from hardwares, it was proved statistically that bars collected from either rolling mill surpassed those from hardware stores in terms of yield strength.

Form Table 4.2 the coefficients of variability for yield strength, ultimate tensile strength and % elongation of bars from rolling mill RM2 are 0.095, 0.077 and 0.169 respectively, whereas the coefficients of variability of the same properties of bars from hardware stores are high (i.e. 0.167, 0.125 and 0.199 for yield strength, ultimate tensile strength and % elongation respectively). Statistical comparison is shown in Figure 4.16.

Similar comparisons between rolling mill RM1 and Hardware stores are shown in Table 4.3 whereby the Coefficients of variability for yield strength, ultimate tensile strength and % elongation are 0.062, 0.092 and 0.188 respectively. Graphical comparisons are also shown in Figure 4.17.

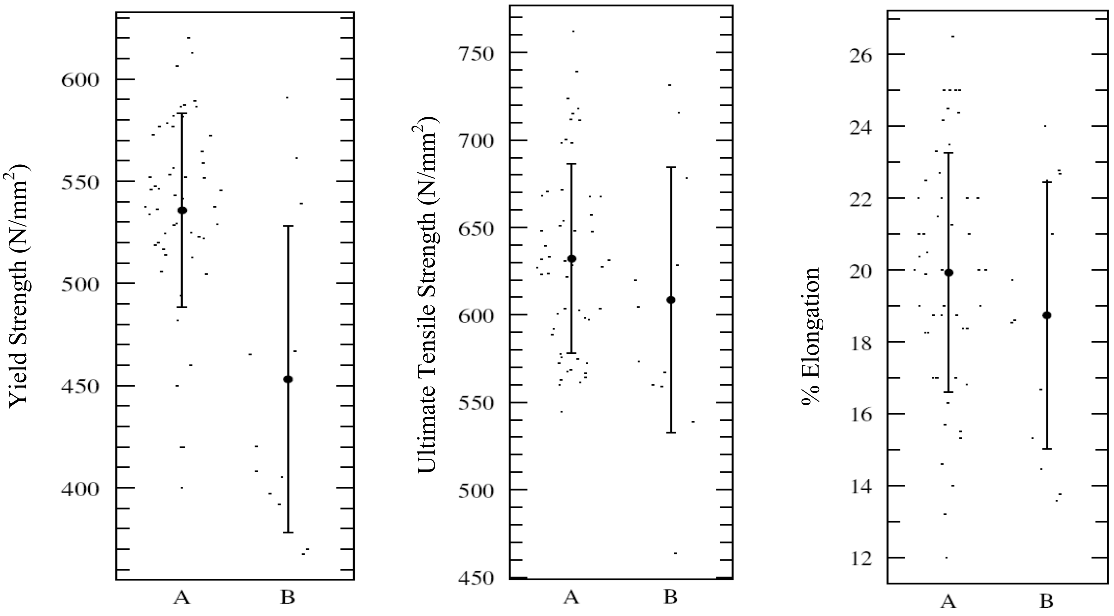


Figure 4.15: **Comparison between the mechanical properties of bars from rolling mills (Group A) and hardwares (Group B)**

Table 4.1: **Statistical parameters of the mechanical properties of bars from rolling mills and hardwares**

Statistical Parameters	Results from Rolling Mills (Group A)			Results from Distributors (Group B)		
	Number of specimens : 53			Number of specimens : 13		
	YS (N/mm^2)	UTS (N/mm^2)	% Elongation	YS (N/mm^2)	UTS (N/mm^2)	% Elongation
Mean	536	632	19.9	453	609	18.7
Min	400	545	12.0	368	464	13.6
Max	620	762	26.5	591	731	24
Median	542	628.	20	420	604	18.6
95 % CI	520.9 -550.5	616.0 - 648.3	18.99 - 20.86	423.2 - 482.9	576.0 - 641.2	16.85 - 20.63
SD	47.5	54.1	3.33	75.1	76	3.71
COV	0.088	0.085	0.167	0.166	0.125	0.198

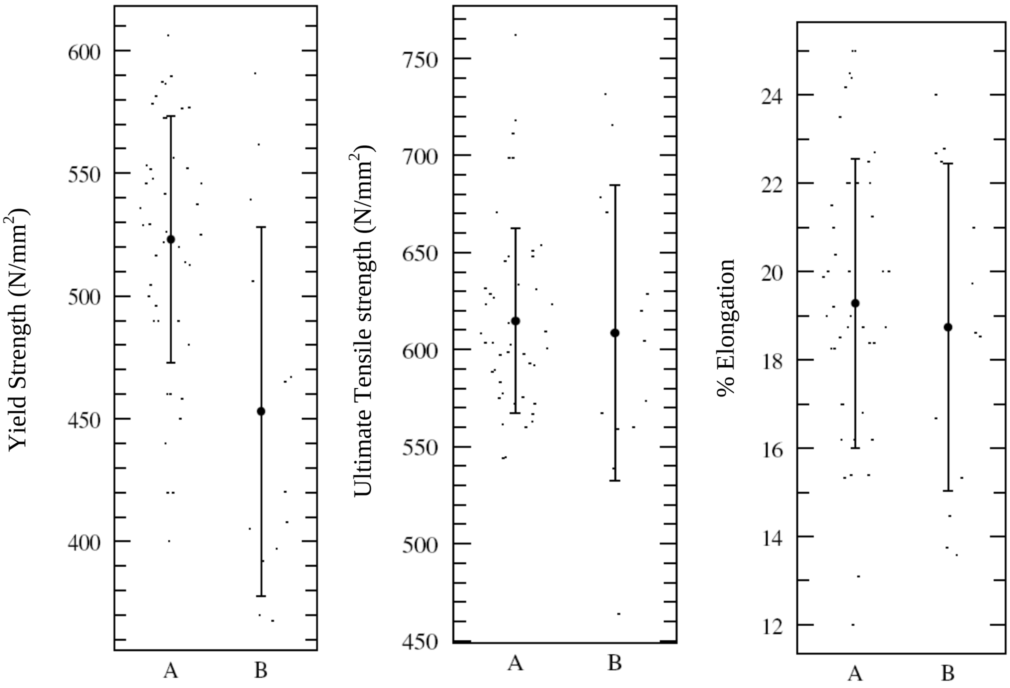


Figure 4.16: **Comparison between the mechanical properties of bars from rolling mill RM2 (Group A) and hardwares (Group B)**

Table 4.2: **Statistical parameters of the mechanical properties of bars from rolling mill RM2 and hardwares**

Statistical Parameters	Results from rolling mill RM2 (Group A)			Results from distributors (Group B)		
	Number of items: 47			Number of items: 13		
	YS(N/mm^2)	UTS (N/mm^2)	% Elongation	YS(N/mm^2)	UTS (N/mm^2)	% Elongation
Mean	523.5	614.3	19.35	452.7	608.6	18.7
Min	400	544	12.0	367.7	461.6	13.58
Max	606.3	762.1	25.0	590.8	731.4	24.0
Median	529.2	603.3	19.2	420.1	607.6	18.61
95% CI	506 - 540	598.5 - 630.9	18.29 - 20.28	421.7 - 484.4	578.1 - 639.0	16.87- 20.61
SD	±49.8	±47.2	±3.27	±75.1	±76.4	±3.74
CoV	0.095	0.077	0.169	0.167	0.125	0.199

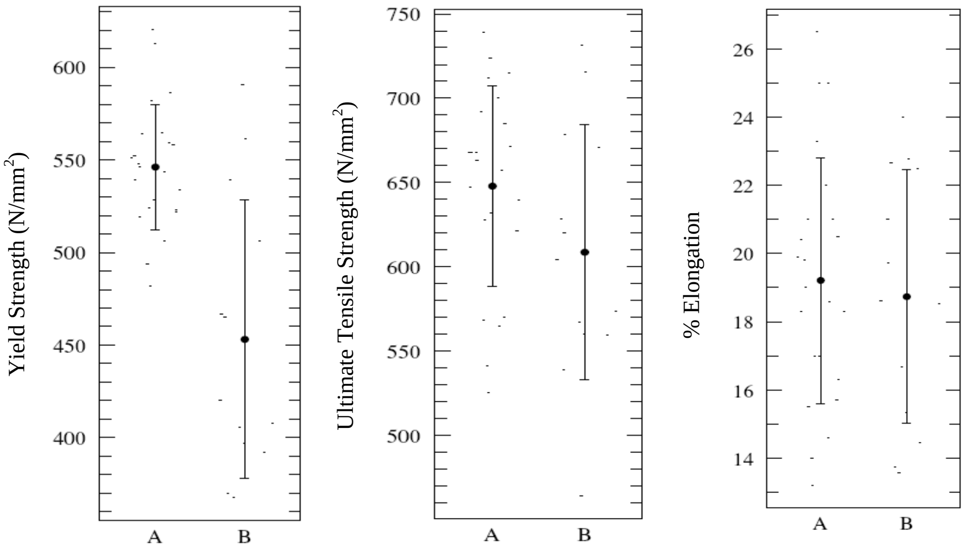


Figure 4.17: **Comparison between the mechanical properties of bars from rolling mill RM1 (Group A) and hardwares (Group B)**

Table 4.3: **Statistical parameters of the mechanical properties of bars from rolling mill RM1 and hardwares**

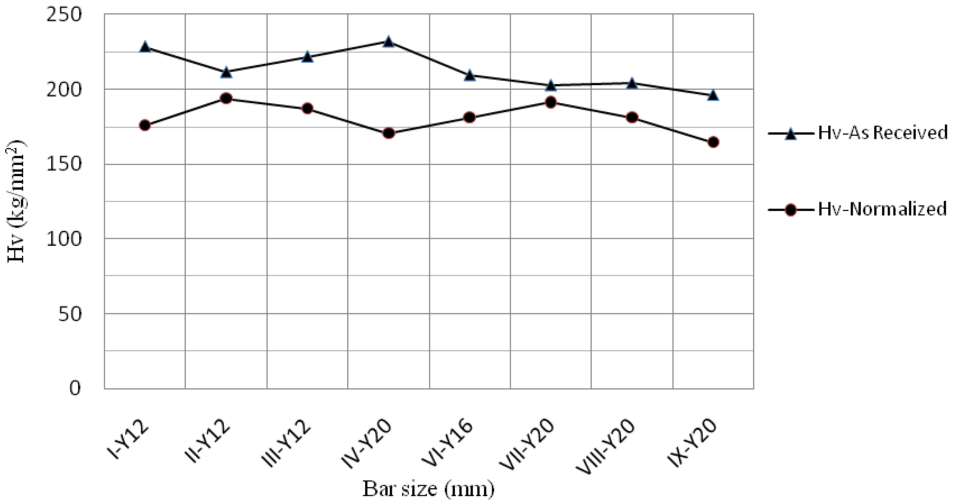
Statistical Parameters	Results from Rolling mill RM1 (Group A)			Results from Distributors (Group B)		
	Number of items: 23			Number of items: 13		
	YS(N/mm^2)	UTS (N/mm^2)	% Elongation	YS(N/mm^2)	UTS (N/mm^2)	% Elongation
Mean	546	648	19.2	453	609	18.7
Min	482	525	13.2	368	464	13.6
Max	620	739	26.5	591	731	24.0
Median	546	663	19.0	420	604	18.6
95% CI	523.9 - 568.2	619.9 - 675.7	17.67 - 20.76	423.6 - 482.5	571.4 - 645.7	16.69 - 20.79
SD	±33.8	±59.6	±3.61	±75.1	±76.0	±3.71
CoV	0.062	0.092	0.188	0.166	0.125	0.198

4.6 Effect of heat treatment on mechanical properties of reinforcing steel bars

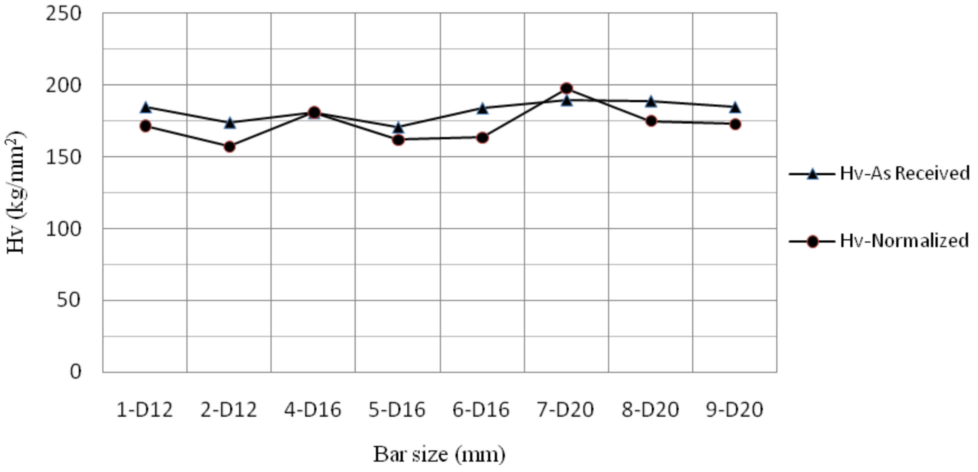
The effect of heat treatment was investigated on bars from rolling mill RM1. It was observed from the experimental work that the yield strength of bars investigated decreased by subjecting them to various heat treatment. This can be attributed to the absence of grain refiners in all bars tested.

The only grain refiner element traced from the chemical analysis was vanadium and its content was negligible (less than 0.01%) . It has been found from the literatures that grain refiner elements like vanadium, niobium and titanium have high potential in grain size refinement of steel at high temperature and enhance the yield strength of steel. Figures 4.18 and 4.20 show the effect of normalizing and annealing on the hardness of reinforcing bars investigated.

The experiment shows that the hardness of both types of steel decreases after heat treatment and the value of hardness was found to be in the range of Hv 150 to Hv 200 for work (strain) hardened / twisted bar and between Hv 150 and Hv 155 for self tempered/ ribbed bars. The comparison is presented in Figure 4.19. The high value of Hv for twisted bar can be attributed to the strain hardening phenomenon in twisted bars. On the other hand, low Hv in the ribbed bars is attributed to the extensive softening of the outer hard layer at high temperature. Annealing of reinforcing bars resulted in low values of hardness with an increase in temperature as shown in Figure 4.20. This can be attributed to high cooling rate for the annealing process, which generally results in coarse grains of the bars as the annealing temperature increases.



(a) Effect of normalizing on hardness of work hardened (twisted) reinforcing steel bars



(b) Effect of normalizing on hardness of self tempered (ribbed) reinforcing steel bars

Figure 4.18: **Effect of normalizing on mechanical properties of reinforcing steel bars**

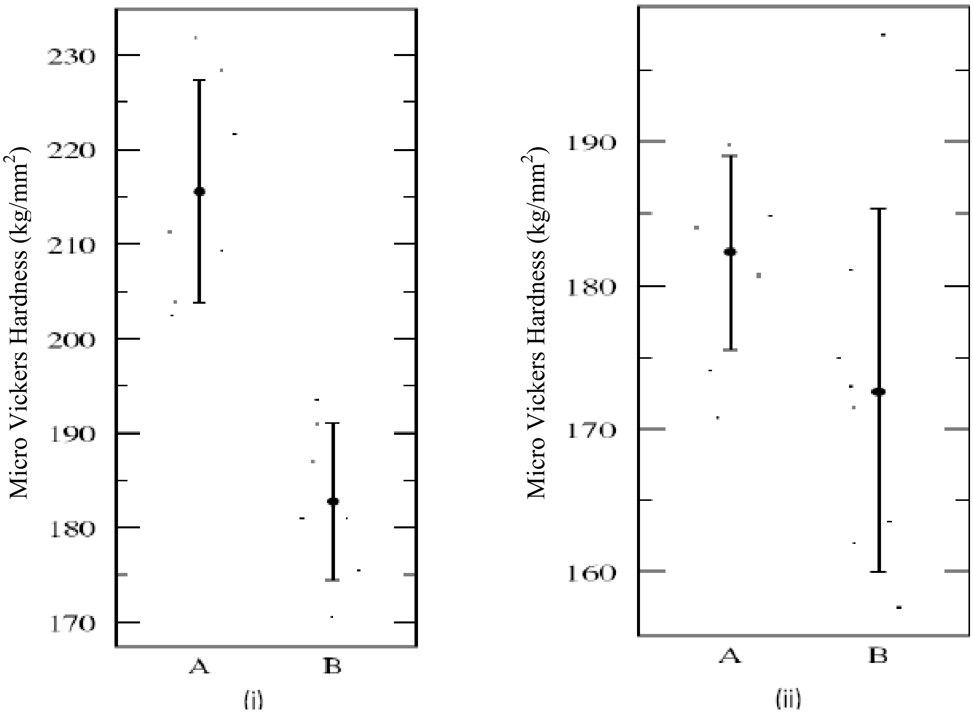


Figure 4.19: **Statistical parameters showing the effect of normalizing on the hardness of (i)Work hardened and (ii)Self tempered reinforcing steel bars. Group A: As received bars, Group B: Normalized bars**

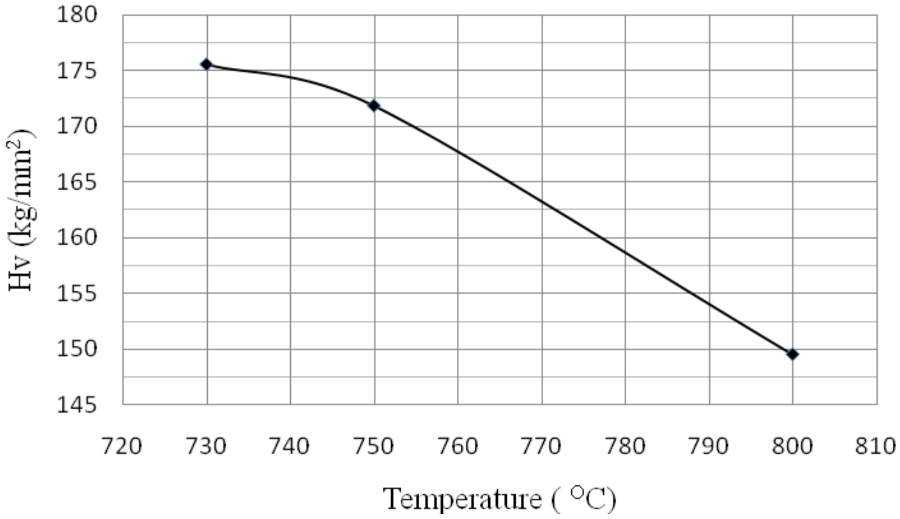
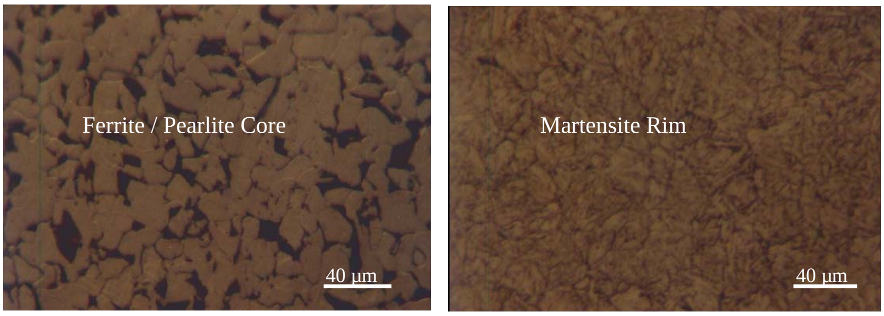


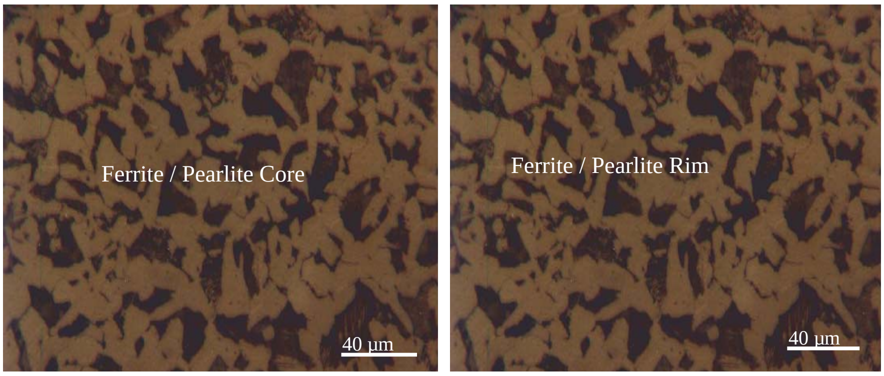
Figure 4.20: **Effect of annealing temperature on hardness of reinforcing steel bars**

4.7 Effect of microstructure on mechanical properties of reinforcing steel bars

The results show that the microstructure of Quenched Self Tempered (QST) bars is different from that of Cold Twisted Deformed (CTD) bar. From Figure 4.21 it is observed that CTD bars have a dual-phase micro structure of ferrite-pearlite throughout its cross section (i.e. no difference between the core and the rim) but the QST bars are characterized by a microstructure with a tempered martensite rim and ferrite-pearlite core. The optical microstructures of the sampled steels exhibited the ferrite structure (Figure 4.22) and typical ferrite-pearlite duplex structures (Figure 4.23 and 4.24) and a martensite structure (Figure 4.25). Bars with structure dominated by ferrite phase were proved to have low YS and UTS as compared to those with structure dominated by pearlite phase. It can be inferred from these micrographs that the cause of differences in structures of bars is the carbon content present in these bars. The higher the carbon content is, the higher the volume fraction of pearlite and consequently the higher the Yield strength and Ultimate tensile strength become.



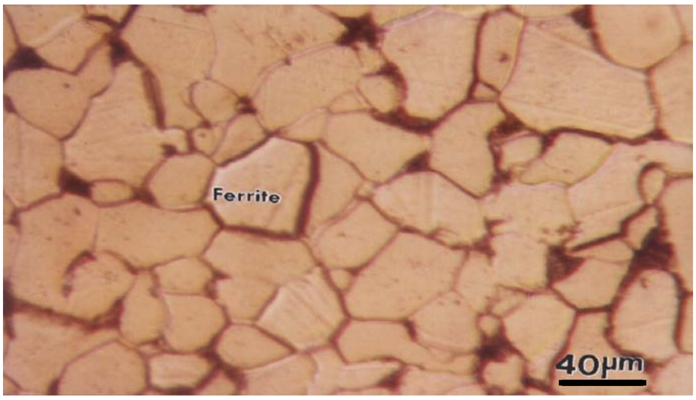
a. Micrograph of a self tempered / ribbed reinforcing steel bar



b. Micrograph of a cold twisted reinforcing steel bar

Figure 4.21: **Comparison between microstructures of self tempered and work hardened reinforcing steel bars**

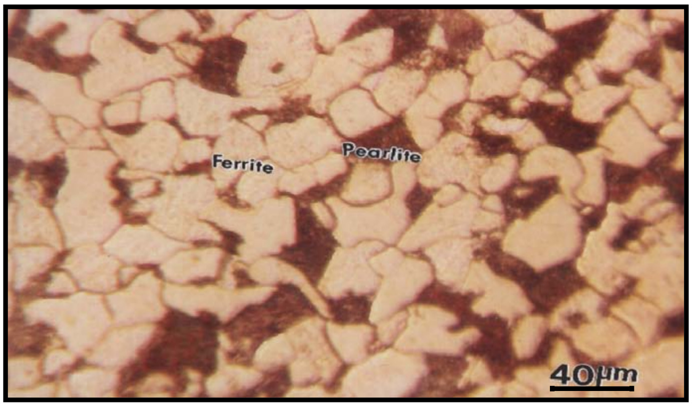
It can be inferred from the microstructure of bars investigated that the structure of the steel has a direct relationship with the mechanical properties. Steel represented by micrograph (Figure 4.23) has low YS and high % elongation. The bar characterized by the micrograph in Figure 4.25 has a high YS and a low % elongation.



Magnification 544X, % C: 0.0599, YS: 432 N/ mm^2, UTS: 524 N/mm^2, % Elongation:20

Source: Building construction site No.1

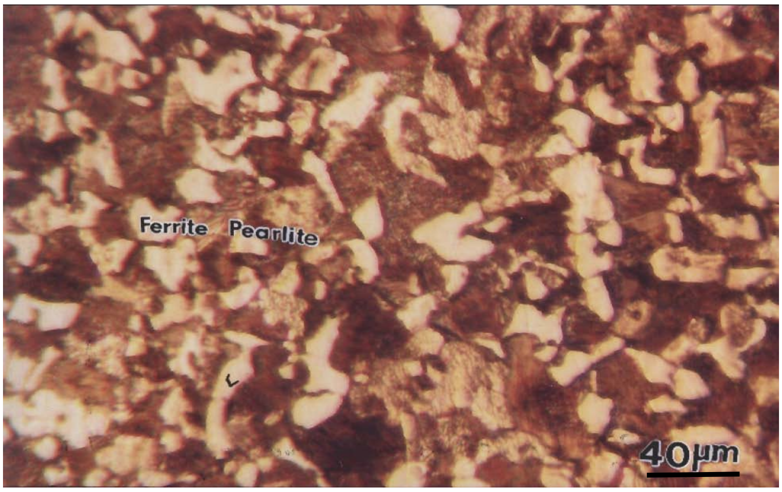
Figure 4.22: **Micrograph of a ferrite phase of a bar collected from one construction site No.1**



Magnification 544X, % C: 0.1928, YS: 552 N/mm^2, UTS: 672 N/mm^2, %Elongation: 15.5

Source: Rolling mill 2

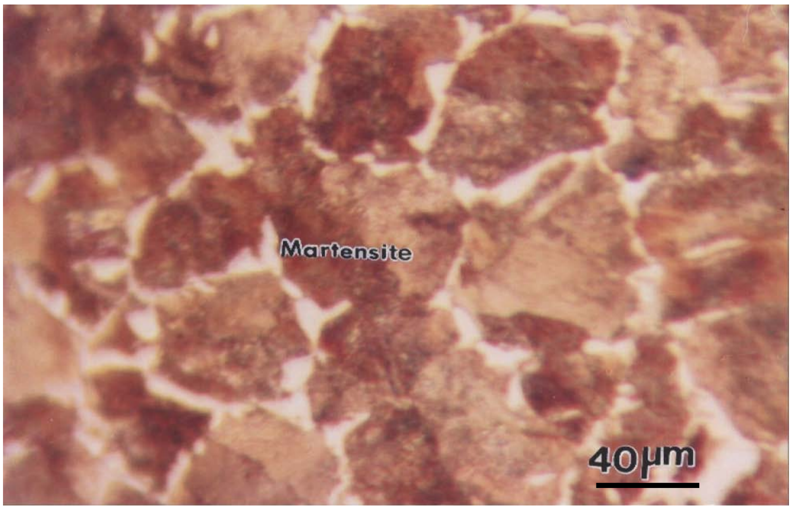
Figure 4.23: **Micrograph of a combined ferrite/pearlite structure from a rolling mill**



Magnification 544X, % C: 0.2829, YS: 606 N/mm^2, UTS: 698 N/mm^2, % Elongation: 19.8

Source: Building Construction site No.2

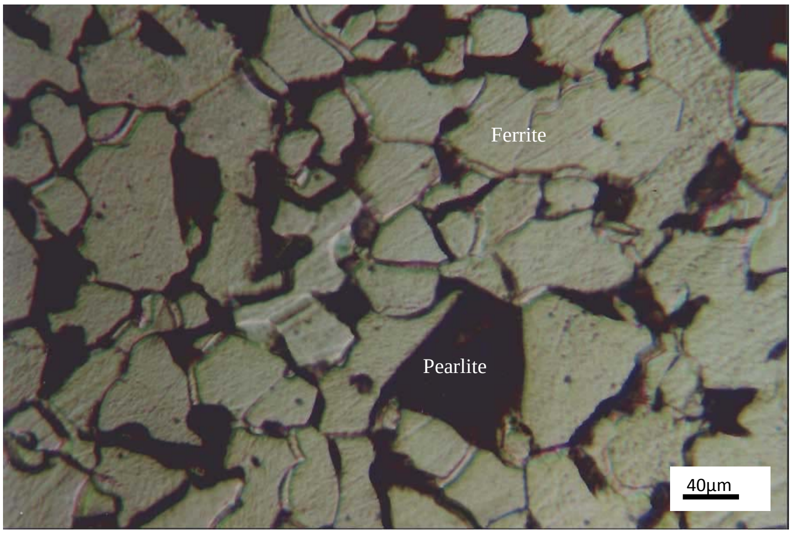
Figure 4.24: **Micrograph of a ferrite/pearlite phase of a bar collected from one construction site No.2**



Magnification 544X, % C: 0.4048, YS: 684N/mm^2, UTS: 828 N/mm^2, %Elongation: 5%

Source: Overseas

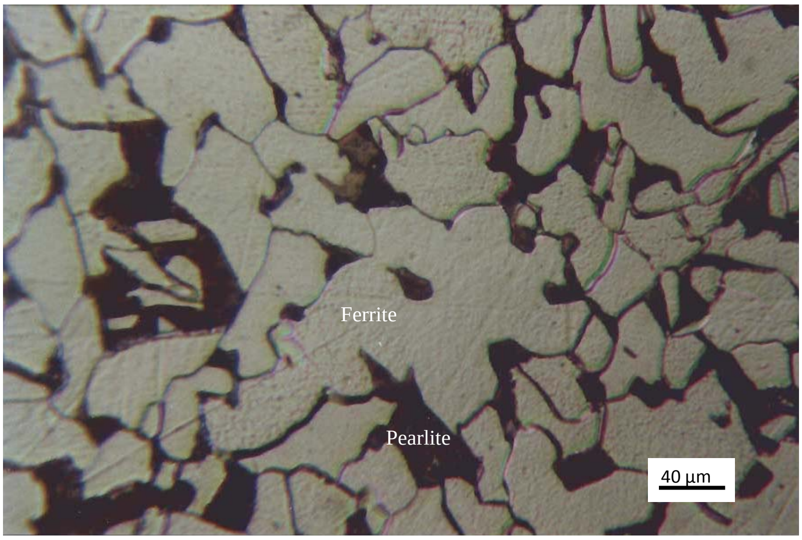
Figure 4.25: **Micrograph of a martensite phase of a bar collected from an overseas source**



Magnification: 544 X, % C: 0.0989, YS: 397.5 N/mm^2, UTS: 463.84 N/mm^2, % Elongation: 21

Source: Hardware C

Figure 4.26: **Micrograph of a ferrite/pearlite phase of a bar collected from Hardware C**



Magnification: 544X, % C: 0.1497, YS: 370.5 N/mm^2, UTS: 539 N/mm^2, % Elongation: 18.54

Source: Hardware E

Figure 4.27: **Micrograph of a ferrite/pearlite phase of a bar collected from Hardware E**

4.8 Correlation between chemical composition and mechanical properties of reinforcing steel bars

To establish the correlation between the chemical composition and the mechanical properties of bars investigated, data for tensile tests and chemical composition of sixteen bars (eight bars from RM1 and eight bars from hardwares) as shown in Table 4.4 were used.

Table 4.4: **Tensile properties and chemical composition of bars from different sources**

S/N	Specimen code	Mechanical properties			Chemical composition		
		YS	UTS	%EL	C	Si	Mn
1	7-D20	528.5	639.7	21	0.1278	0.2122	0.5969
2	8-D20	543.3	647.4	21	0.1307	0.2073	0.607
3	9-D20	524.3	632	20.5	0.1273	0.2175	0.591
4	IV-Y16-SB-1	620.169	700.221	14.6	0.1996	0.2375	0.5883
5	VI-Y16	564.571	668.036	16.3	0.2329	0.2543	0.6001
6	VII-Y20	552.2	671.6	15.5	0.1928	0.2199	0.6033
7	VIII-Y20	546.3	667.9	14	0.2008	0.2259	0.6111
8	IX-Y20	586.5	667.9	13.2	0.2038	0.2298	0.6091
9	A3-Y20	506.07	604.39	15	0.153	0.2106	0.5123
10	B2-Y16	391.88	559.19	24	0.1198	0.1689	0.5364
11	A2-Y16	367.71	567.14	22.5	0.104	0.08	0.415
12	C3-Y20	397.05	463.84	20	0.0989	0.2004	0.6531
13	C2-Y16	561.60	715.43	14.46	0.1627	0.2061	0.5072
14	D2-Y16	420.11	559.99	13.75	0.1573	0.189	0.4523
15	E2-Y16	370.00	539	18.54	0.1497	0.2019	0.5116
16	F1-Y20	466.98	670.65	13.58	0.2288	0.2247	0.4891

The multiple regression analysis showed that the yield strength, tensile strength and the % Elongation were correlated with the chemical composition by equations (4.1) to (4.3). From the regression analysis using excel spread sheet, empirical equations were developed.

Table 4.5 shows the developed equations for yield strength, ultimate tensile strength and % Elongation respectively. The main chemical elements that were significantly contributing to the strength of the bars were carbon, silicon and manganese. From the test, the other chemical components were not significant in contributing to the strength of the bars hence eliminated from the regression equation.

The generalized equations are:

$$YS = k_{ys} + a_{ys}(\%\ C) + b_{ys}(\%\ Si) + c_{ys}(\%\ Mn) \tag{4.1}$$

$$UTS = k_{uts} + a_{uts}(\%\ C) + b_{uts}(\%\ Si) + c_{uts}(\%\ Mn) \tag{4.2}$$

$$\%\ El = k_{el} - a_{el}(\%\ C) - b_{el}(\%\ Si) + c_{el}(\%\ Mn) \tag{4.3}$$

where a,b,c are coefficient constants for carbon, silicon and manganese respectively, k is the intercept between the Y-axis (tensile properties) and the X-axis (alloying elements).

Two statistical packages, namely Microsoft Excel and Genstat were used to assess whether the difference of mean values from tensile test and Correlation Equation were statistically significant. The comparison was carried out using the student's t-test. To test or check the accuracy of the correlation equation, the tensile properties were verified on a sample of thirty six bars from different sources (specimen No. 1

Table 4.5: **Results from multiple regression analysis**

YS	Mn	Si	C	Intercept
	423.8443	438.7805	777.8756	45.33997
	358.7916	825.681	572.4572	146.4069
	0.568168	60.60242	#N/A	#N/A
	5.262863	12	#N/A	#N/A
	57986.01	44071.84	#N/A	#N/A

YS=45.33997+777.8756(%C)+438.7805(%Si)+423.8443(%Mn)

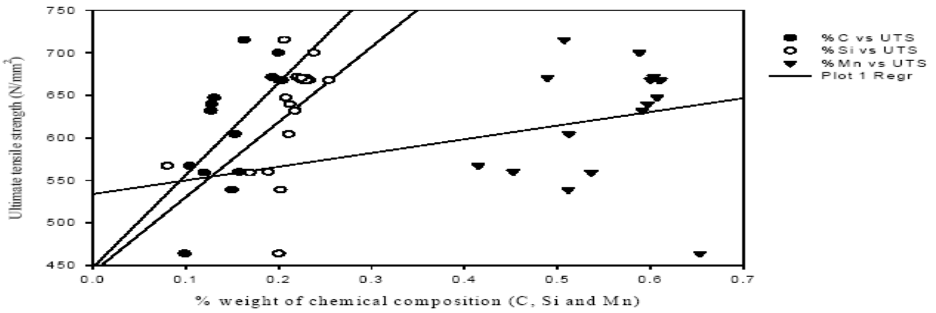
UTS	Mn	Si	C	Intercept
	52.62834	54.0036	1044.634	413.9934
	327.6523	754.0207	522.774	133.7003
	0.475307	55.34278	#N/A	#N/A
	3.623509	12	#N/A	#N/A
	33294.51	36753.88	#N/A	#N/A

UTS=413.9934+1044.634(%C) +54.0036(Si) +52.62834(Mn)

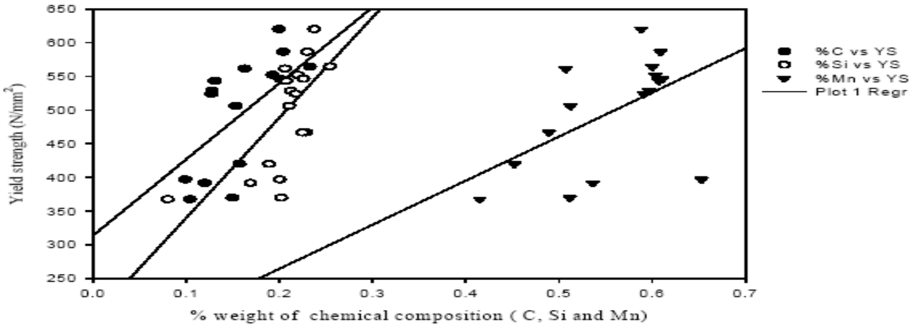
%EL	Mn	Si	C	Intercept
	19.66843	-40.6978	-46.6584	22.35926
	13.30766	30.62469	21.23256	5.430263
	0.6927	2.247757	#N/A	#N/A
	9.016615	12	#N/A	#N/A
	136.667	60.62895	#N/A	#N/A

%El= 22.35926-46.6584 (%C)-40.6978 (%Si) +19.66843 (%Mn

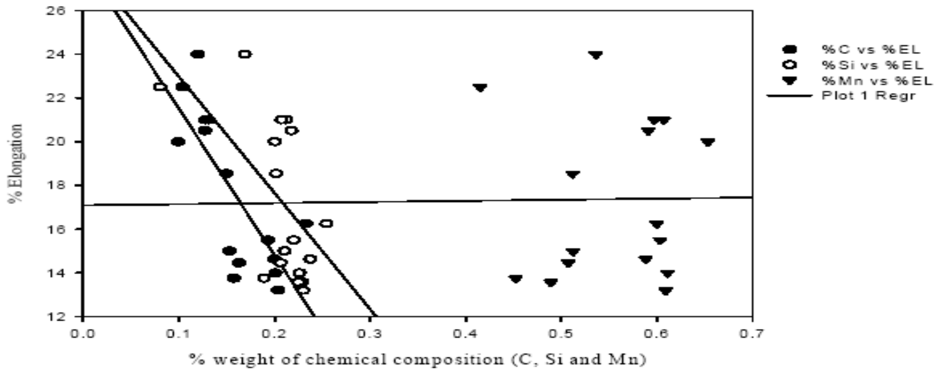
to No. 9 are from RM1, specimen No. 10 is from an overseas source , specimen No. 11 to 18 are from hardwares and specimen No. 19 to 36 are from RM2.).



(a) Influence of chemical composition on tensile strength of reinforcing steel bars



(b) Influence of chemical composition on yield strength of reinforcing steel bars



(c) Influence of chemical composition on % elongation of reinforcing steel bars

Figure 4.28: **Influence of chemical composition on tensile properties of bar investigated**

It has been found from the present work that three elements had a significant influence on the strength of the reinforcing steel bars. These elements are: Carbon, Silicon and Manganese (Figure 4.28). From the figure, it is shown that for carbon

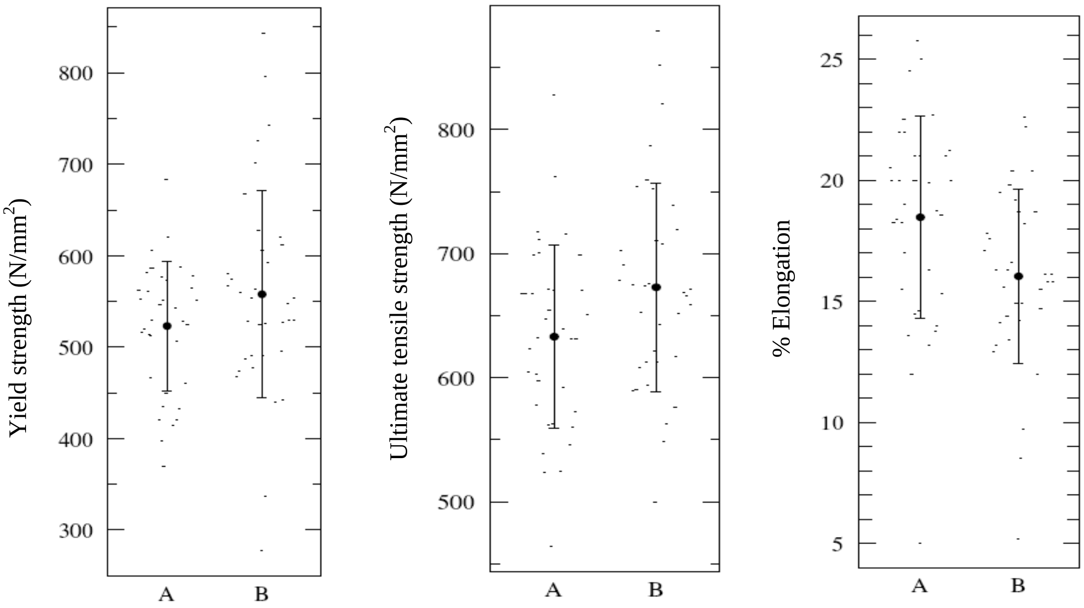


Figure 4.29: **Comparison between results from tensile test (Group A) and correlation equation (Group B)**

content greater than 0.16 % the yield strength of the bar complied with the standard requirement. But this was accompanied by a decrease in the % Elongation. From the same Figure 4.28 c, only carbon and silicon significantly affected the ductility of the bars. Figure 4.29 shows the the standard deviations from the means of results from tensile test and the correlation equation.

While comparing the yield strength from tensile test and correlation equation it was found that the t calculated (t-stat) was -1.557 (see Table C.1 of Appendix C) and was within the acceptable area on the t-distribution curve shown in Figure I.1 in Appendix I. This value was less than the t tabulated 1.994 at 95% C.I. with DF of 70 on the t-distribution curve. Therefore, it implies that the correlation equation

Table 4.6: **Results from tensile tests and correlation equations**

S/N	SPECIMEN CODE	YS-from tensile test	YS-from Correlation Equation	UTS-from tensile test	UTS-from Correlation Equation	% EL-from tensile test	% EL-from Correlation Equation	Chemical composition		
								C	Si	Mn
1	7-D20	528.5	490.85	639.7	590.37	21	19.5	0.1278	0.2122	0.5969
2	8-D20	543.3	495.24	647.4	593.67	21	19.8	0.1307	0.2073	0.607
3	9-D20	524.3	490.29	632	589.82	20.5	19.2	0.1273	0.2175	0.591
4	IV-Y16-SB-1	620.169	554.16	700.221	666.29	14.6	14.9	0.1996	0.2375	0.5883
5	VI-Y16	564.571	592.44	668.036	702.60	16.3	12.9	0.2329	0.2543	0.6001
6	VII-Y20	552.2	547.51	671.6	659.02	15.5	16.3	0.1928	0.2199	0.6033
7	VIII-Y20	546.3	559.67	667.9	668.12	14	15.8	0.2008	0.2259	0.6111
8	IX-Y20	586.5	562.87	667.9	671.36	13.2	15.5	0.2038	0.2298	0.6091
9	X-Y20	432.3	277.34	523.7	499.53	20	20.4	0.0599	0.123	0.3101
10	XI-Y16-SA-1-DRC	683.627	702.12	828.201	879.20	5.0	5.2	0.4048	0.2286	0.57
11	A3-Y20	506.07	473.90	604.39	612.16	15.33	16.6	0.153	0.2106	0.5123
12	B2-Y16	435.294	439.99	524.263	576.49	25.75	20.4	0.1198	0.1689	0.5364
13	A2-Y16	414.541	337.24	545.698	548.80	21.25	22.2	0.104	0.08	0.415
14	C3-Y20	397.5	487.02	463.84	562.50	21	22.6	0.0989	0.2004	0.6531
15	C2-Y16	561.60	477.31	715.43	621.78	14.46	16.3	0.1627	0.2061	0.5072
16	D2-Y16	420.11	442.33	559.99	612.32	13.75	16.1	0.1573	0.189	0.4523
17	E2-Y16	370.00	467.22	539	608.20	18.54	17.1	0.1497	0.2019	0.5116
18	F1-Y16	466.98	529.21	670.65	690.88	13.58	12.0	0.2288	0.2247	0.4891
19	**HTD20-7367**	450	526.74	592	673.90	19	15.6	0.2112	0.1895	0.552
20	**HTD20-7364**	420	525.14	563	616.90	17	18.7	0.1513	0.2198	0.6268
21	**HTD20-7371**	520	529.57	670.6	642.31	20	18.7	0.1775	0.1874	0.6227
22	**HTD20-7361**	460	528.04	602.8	651.60	12	18.2	0.1875	0.1801	0.6083
23	**D20-7362**	513.903	573.85	577.494	652.88	22.0	14.9	0.1829	0.277	0.6245
24	**HTD20-7375**	516.583	605.46	561.576	707.46	22.0	15.8	0.2363	0.2139	0.6664
25	**HTD20-7366**	512.533	581.05	572.205	678.56	22.7	17.8	0.209	0.2003	0.673
26	D16-6932	551.796	795.72	711.168	786.56	20	9.7	0.2949	0.3828	0.8329
27	D16-6925	581.452	620.00	762.114	852.20	18.75	14.2	0.3345	0.4343	1.2412
28	D16-6940	529.25	843.00	698.622	820.93	20	16.1	0.3249	0.275	1.001
29	D16-7422	551.973	627.76	597.069	710.24	25	17.6	0.2363	0.2029	0.7304
30	D16-7445	606.256	668.05	698.576	759.40	19.875	13.4	0.2829	0.2381	0.7035
31	D16-7439	586.5	612.21	717.9	675.88	18.25	18.7	0.2021	0.2197	0.7391
32	Y16-7382	576.6	725.39	630.884	754.08	20	14.7	0.2698	0.2812	0.8182
33	Y16-7379	562.122	742.93	623.284	752.51	22.5	8.5	0.2659	0.3991	0.7447
34	Y16-7512	572.635	526.35	631.355	674.89	24.5	14.1	0.2123	0.2113	0.5265
35	Y16-7520	587.219	567.32	650.91	719.14	18.25	14.4	0.2536	0.1817	0.578
36	Y16-7552	578.3	553.62	654	738.97	18.375	13.2	0.2763	0.1595	0.527

developed can be used to estimate the yield strength of reinforcing steel bars since both means of yield strength from experiment and correlation equation are not statistically significant as proved by the student's t-test.

The results from the developed empirical formulae are not statistically significant different from the experimental values in Table 4.6 since the t-stat is less than the t-critical as shown in Table C.1 of Appendix C.

Knowing the chemical composition of the molten steel, Eqns 4.1 - 4.3 can be used by reinforcing steel bar manufacturers in order to estimate the mechanical properties of the final product prior to the rolling operation.

Not only will the mechanical properties of the bars will be estimated, but also the production output of the company will increase because defective bars will be avoided at the initial stage of production process.

4.9 Effect of grain size on mechanical properties of reinforcing steel bars

The mechanical properties of steel are generally affected by their grain size. When the grain undergoes deformation, its initial structure gets dislocation and hence resistance to plastic deformation increases. This phenomenon causes the yield strength of the steel to increase. The grain size of reinforcing bars investigated in the present study varied from 22 μm to 38 μm. Table 4.7 shows examples of grain size determination procedure whereby the average grain size of three samples from different sources are calculated. Their respective values are 37 μm, 32 μm and 25 μm.

In this Table, M denotes the magnification, L is the total length of the circle test pattern, N is the number of grains intercepted by the test circles and N_L is the number of intercepts per unit length of test line. The % RA, of the measurements was calculated at 95% C.I. and was less that 10 % as recommended by the ASTM 112-98. The results show that for bars with grain sizes greater than 28 μm, the YS was lower than the standard value as shown in Figure 4.30.

Table 4.7: **Grain size determination**

BAR CODE: E2-from Hardware

Field of View	M	L	N	N_L	ASTM, G	m	a	d
1	544	500	28	30.46	6.63007	792.3899	0.001262	0.036
2	544	500	28	30.46	6.63007	792.3899	0.001262	0.036
3	544	500	24	26.11	6.18528	582.164	0.001718	0.041
4	544	500	31	33.73	6.92375	971.284	0.00103	0.032
5	544	500	25	27.20	6.30307	631.6884	0.001583	0.040
		mean	27.2	29.5936	6.53445	753.9832	0.001371	0.037
		SD	2.7749	3.01907747	0.29381	153.8243	0.000276	0.004
		COV	0.102	0.10201792	0.04496	0.204016	0.201604	0.101
		95% CI	2.4323	2.64628946	0.25753	134.8305	0.000242	0.003278
		%RA	8.9421	8.94210052	3.94112	17.88242	17.67101	8.889952

BAR CODE: X-JKUAT

Field of View	M	L	N	N_L	ASTM, G	m	a	d
1	544	500	33	35.90	7.10415	1100.654	0.000909	0.030
2	544	500	30	32.64	6.82914	909.6313	0.001099	0.033
3	544	500	29	31.55	6.73132	849.9999	0.001176	0.034
4	544	500	31	33.73	6.92375	971.284	0.00103	0.032
5	544	500	33	35.90	7.10415	1100.654	0.000909	0.030
		mean	31.2	33.9456	6.9385	986.4446	0.001024	0.032
		SD	1.7889	1.94627357	0.16581	112.7329	0.000118	0.002
		COV	0.0573	0.05733508	0.0239	0.114282	0.115091	0.058
		95% CI	1.568	1.70595265	0.14534	98.81289	0.000103	0.001612
		%RA	5.0255	5.02554868	2.0947	10.01707	10.08796	5.043241

BAR CODE: VII-APEX

Field of View	M	L	N	N_L	ASTM, G	m	a	d
1	544	500	44	47.87	7.93422	1956.718	0.000511	0.023
2	544	500	35	38.08	7.27392	1238.109	0.000808	0.028
3	544	500	39	42.43	7.58616	1537.277	0.000651	0.026
4	544	500	45	48.96	7.99906	2046.67	0.000489	0.022
5	544	500	38	41.34	7.51121	1459.453	0.000685	0.026
		mean	40.2	43.7376	7.66092	1647.645	0.000629	0.025
		SD	4.2071	4.57736483	0.30282	342.8061	0.000131	0.003
		COV	0.1047	0.10465514	0.03953	0.208058	0.209193	0.105
		95% CI	3.6877	4.01216345	0.26543	300.4773	0.000115	0.002296
		%RA	9.1733	9.17325928	3.46472	18.23677	18.33621	9.196761

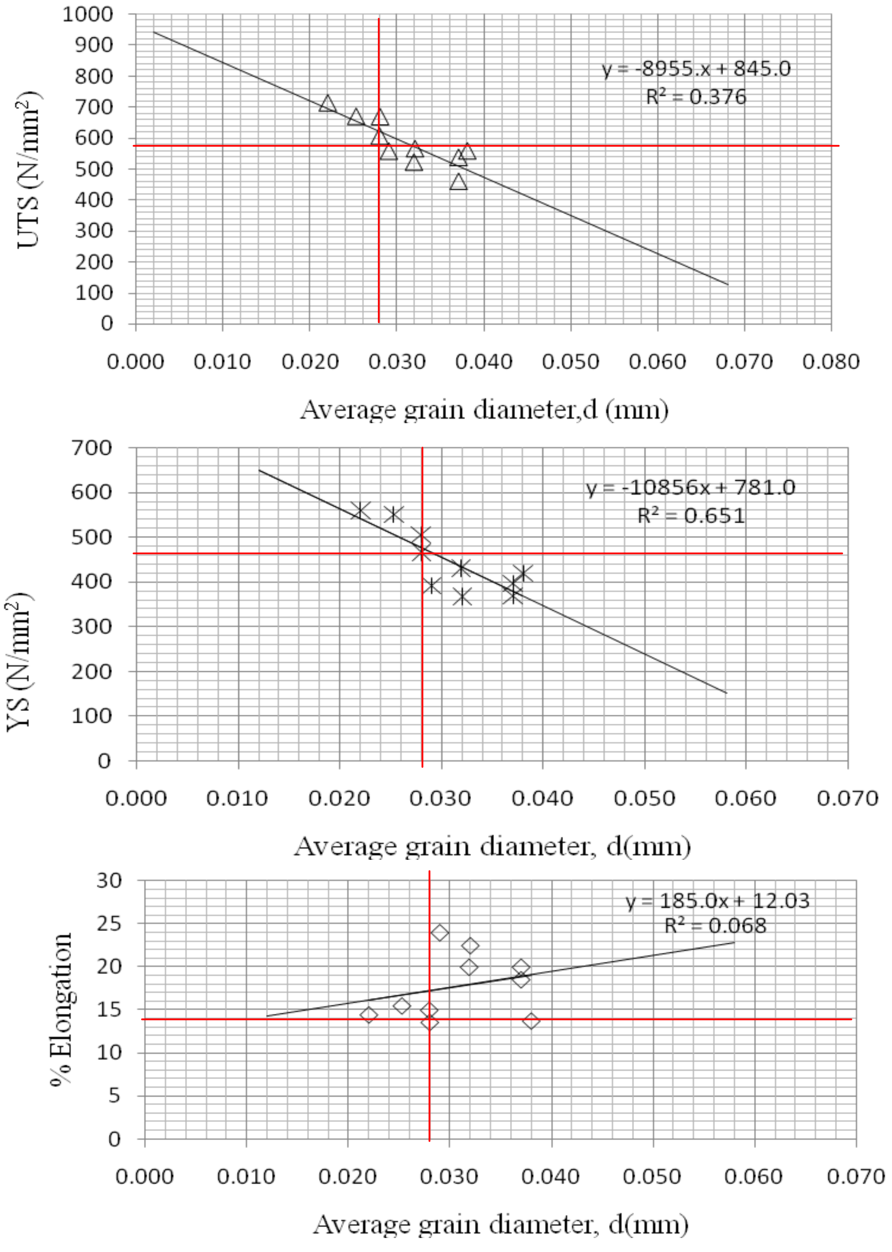


Figure 4.30: **Effect of grain size**

4.10 Results from Survey

The survey was conducted in various areas involved in the quality and the application of reinforcing steel bars.

A structured questionnaire was distributed to Kenya Bureau of Standards, Rwanda Bureau of Standards, Material Branch-Ministry of Roads and Public works in Kenya, six rolling mills of which two rolling mills responded to the questionnaire, ten construction companies of which five responded and six distributors (hardware stores) of reinforcing steel bars of which four responded. A list of companies of interest is shown in Table G.1 in APPENDIX G.

Summaries of response to the questionnaires used to carry the survey are shown in Table G.2- G.6. The cross sign indicates the response to the question asked by the researcher to the party involved. The challenge faced was the low response noticed during the survey especially from rolling mills. The author recommends that future researchers should expound more on this part of the survey.

4.10.1 Results from statutory bodies

The results from a survey at Kenya Bureau of Standards (KEBS) show that not all steel bars manufacturers comply with the set standards. 5% of steel plants have been reported not to comply with the standards.

Tensile and bending tests and chemical composition analysis are the main quality control methods performed by the above statutory body.

The minimum characteristic strength (yield strength) specified by statutory bodies is between 450 to 460 N/mm^2 .

On the other hand the results show that the Rwanda Bureau of Standards (RBS) has no bank of data on the mechanical properties of reinforcing steel bars because no testing policy has yet been implemented in the country. The quality control on the mechanical properties of reinforcing bars is done by subcontracting with other laboratories in the East African region. This can contribute to the infiltration of substandard reinforcing bars on the Rwandan construction market.

4.10.2 Results from construction companies

As far as the application of reinforcing bars is concerned, construction companies interviewed reported that 80% of reinforcing steel bars used for construction are twisted bars while the other 20 % are ribbed bars. Results from the survey to construction companies show that two out of five respondents encountered failure of bars . The main cause of the failure was the low yield strength and poor bending response.

4.10.3 Results from rolling mills

Three rolling mills have been visited and the production processes used by these rolling mills were studied. One rolling mill designated as RM1 uses two methods of production of reinforcing steel bars namely the Tempcore process and Cold Twisting process. The first process (Tempcore) is new in Kenya. Therefore an intensive research needs to be carried out on the bars produced by this process with the aim of producing competitive reinforcing bars on the international market. A sample of bars was collected from this company (RM1) and tested. The results are shown in Table B.1. Two other rolling mills (RM2 and RM3) use the cold twisting method for achieving the high tensile properties (i.e. yield strength, tensile strength and % Elongation). A sample of bars were tested as the bars were produced. The results show that bars from RM2 comply with the standard requirement as presented in Table B.2 in Appendix B, except a few bars which did not meet the minimum required yield strength (460 N/mm^2). These are four bars designated by their heat numbers (D20-7367, D20-7378, D20-7336 and D20-7364). No sample was collected from RM2.

The quality control consisted of carrying out the chemical analysis using atomic emission spectrometer or wet lab technique before casting of ingot. Also tensile tests were carried out on the bars in the as rolled condition.

4.10.4 Industrial attachment

For a period four weeks, an industrial attachment to rolling mill RM2 was carried out. Ample time was spent on the production of reinforcing bars and the quality control of the bars. Before rolling the ingot into bars, a sample was collected from each heat and chemically analyzed. The main elements which were controlled are: Carbon, Silicon and Manganese. Other elements were also traced from the sample of the molten steel. These included Sulfur (Si), Phosphorus (P), Aluminium (Al), Vanadium (V), Chromium (Cr), Molybdenum (Mo), Boron (B), Copper (Cu), Nickel (Ni) and Iron (Fe). The mechanical properties of bars from this company comply with the standard requirement of bars used for concrete reinforcement. The quality compliance of the bars from this company is due to their policy of quality assurance and the facility in the premisses to carry out inspection at every step of the process. The equipment includes: An atomic emission spectometer and a Universal Testing Machine. The company also has a lab for wet analysis especially for carbon and sulphur analysis. A short description of the production of reinforcing steel bar is given in Appendix H.

4.10.5 Results from hardware

The result from the survey to hardwares shows that bars available on the market are from local manufacturers. Most of rolling mills in the country produce twisted bars and these are cheaper than the ribbed bars, reason why twisted bars were available in every hardware investigated.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

The results from the experiments and the analysis are recounted for the two types of bars, namely the work-hardened (twisted bars) and self tempered (ribbed bars). Further information was collected from two rolling mills, construction sites and hardware stores. The experimental work consisted of tensile tests, chemical analysis, hardness tests and heat treatment. The bars fell under two categories: Category 1 that exhibited low-yield strength and category 2 that complied with the standards, especially bars from the two rolling mills because of having elaborate procedures for determining the quality of the metal and the bars during the production process. However, 69% of bars from hardware stores failed the test. Also, the survey revealed that the major weakness in bars that contractors have been using was in low yield strength. The possible causes of variability of mechanical properties of reinforcing steel bars were:

- The inconsistence in chemical composition, mainly the carbon content followed by silicon and manganese, whereby bars with less than 0.15 % C, 0.5% Mn and 0.2% Si exhibited yield strength less than standard value of 460 N/mm^2.
- The variation in microstructure and grain size, whereby bars which exhibited low yield strength had microstructures mostly dominated by ferrite phases

with the ferrite volume fraction grater than 80% and the average grain size greater than 28 μm.

The Kenya Bureau of Standards reported that 5% of rolling mills operating in the country are not certified. This could be the reason for failure of bars collected from hardware stores/distributors of reinforcing steel bars reported in this work.

5.2 RECOMMENDATIONS

Based on the results from the present work, recommendations are addressed to manufacturers and end users of reinforcing steel bars.

To manufacturers, it is recommended to control the carbon content during the production process and maintain its content in the range of 0.15 - 0.25 % C. Use of micro alloying elements such as vanadium, niobium and titanium would be important in order to limit the grain growth and improve the characteristic strength (yield strength) of the reinforcing steel bars manufactured in Kenya.

To the end users of the bars, care should be taken while using the bars for construction of buildings. It is recommended that before using the bars, tensile tests should be carried out on a sample of bars regardless of the mill certificate. This will contribute to the integrity of building structures and prevent any incident that may occur due to the infiltration of sub standard reinforcing bar on the building construction market. This study focused on the tensile properties of reinforcing steel bars. The tensile properties are not the only mechanical properties to be investigated. A number of further investigations, not reported in this work, can be carried out in the following areas for the safety of building structures such as storey building, bridges and hydraulic power plant, which use reinforcing steel bars in concrete reinforcement. The following studies will be of much interest in guaranteeing the integrity of building structures:

i. Investigation on fatigue behavior and toughness properties of reinforcing steel bars.

ii. Improvement of the mechanical properties of low carbon reinforcing steel bars by micro alloying.

iii. Simulation of production process of reinforcing steel bars for optimization purposes, using Computer Aided Manufacturing (CAM) softwares.

iv. Further microstructure examination on reinforcing steel bars using image analysis technique.

v. Further investigation on bars from hardwares including data on their sources. Such research should focus mainly on quality control practices by manufacturers of reinforcing bars.

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APPENDIX A

CHEMICAL ANALYSIS

Table A.1: **Chemical composition on deformed/ribbed bars D20 from RM2**

Alloying elements	Heat No.						
	HTD20-7367	**HTD20-7364**	**HTD20-7371**	**HTD20-7361**	**D20-7362**	**HTD20-7375**	**HTD20-7366**
C	0.2112	0.1513	0.1775	0.1875	0.1829	0.2363	0.209
Si	0.1895	0.2198	0.1874	0.1801	0.277	0.2139	0.2003
Mn	0.552	0.6268	0.6227	0.6083	0.6245	0.6664	0.673
P	0.0915	0.0679	0.0674	0.0646	0.0847	0.0679	0.0599
S	0.0452	0.0508	0.0297	0.0534	0.0635	0.0356	0.0387
Cr	0.0743	0.0721	0.0666	0.0628	0.0728	0.0824	0.0692
Mo	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Ni	0.099	0.089	0.1143	0.0888	0.077	0.11	0.0801
Al	<0.0100	0.0178	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100
Cu	0.3975	0.2478	0.2383	0.2259	0.2519	0.2492	0.2192
V	0.01	0.01	0.01	0.01	0.01	0.01	0.01
B	<0.0050	<0.0050	<0.0050	<0.0050	<0.0050	<0.0500	<0.0500
Fe	98.347	98.4377	98.5003	98.5765	98.3445	98.311	98.439
Results for CE, %Ferrite, %Pearlite, YS (N/mm^2), UTS (N/mm^2) and %EL							
CE	0.357	0.299	0.324	0.328	0.329	0.394	0.361
%Ferrite	73.6	81.0875	77.8125	76.5625	77.1375	70.4625	73.875
%Pearlite	26.4	18.9125	22.1875	23.4375	22.8625	29.5375	26.125
YS (N/mm^2)	450	420	520	460	513.903	516.583	512.533
UTS (N/mm^2)	592	563	670.6	602.8	577.494	561.576	572.205
%EL	19	17	20	12	22.0	22.0	22.7

Table A.2: **Chemical composition on deformed / ribbed bars D16 and Y16 from RM2**

Alloying elements	Heat No.					
	D16-6932	**D16-6925**	**D16-6940**	**D16-7422**	**D16-7445**	**D16-7439**
C	0.2949	0.3345	0.3249	0.2363	0.2829	0.2021
Si	0.3828	0.4343	0.275	0.2029	0.2381	0.2197
Mn	0.8329	1.2412	1.001	0.7304	0.7035	0.7391
P	0.09	0.0465	0.0722	0.0679	0.0733	0.0673
S	0.0847	0.0558	0.0601	0.0276	0.0278	0.0258
Cr	0.0966	0.0847	0.0864	0.0719	0.1278	0.0687
Mo	0.02	0.02	0.033	0.02	0.02	0.02
Ni	0.1249	0.079	0.1798	0.0892	0.0471	0.021
Al	<0.0100	<0.0100	<0.0100	<0.0100	0.0129	<0.0100
Cu	0.3232	0.2407	0.3052	0.2313	0.03433	0.1729
V	0.0826	0.0493	0.0143	0.01	0.01	0.01
B	0.006	<0.0050	<0.0050	<0.0500	<0.0500	<0.0500
Fe	97.6665	97.4237	97.6461	98.325	98.085	98.47
Results for CE, %Ferrite, %Pearlite, YS (N/mm^2), UTS (N/mm^2) and %EL						
CE	0.503	0.593	0.551	0.400	0.437	0.358
%Ferrite	63.1375	58.1875	59.3875	70.4625	64.6375	74.7375
%Pearlite	36.8625	41.8125	40.6125	29.5375	35.3625	25.2625
YS (N/mm^2)	551.796	581.452	529.25	551.973	606.256	586.5
UTS (N/mm^2)	711.168	762.114	698.622	597.069	698.576	717.9
%El	20	18.75	20	25	19.875	18.25

Alloying elements	Heat No.				
	Y16-7382	**Y16-7379**	**Y16-7512**	**Y16-7520**	**Y16-7552**
C	0.2698	0.2659	0.2123	0.2536	0.2763
Si	0.2812	0.3991	0.2113	0.1817	0.1595
Mn	0.8182	0.7447	0.5265	0.578	0.527
P	0.0823	0.0919	0.0684	0.0566	0.0671
S	0.0439	0.0531	0.0448	0.026	0.0321
Cr	0.1008	0.1576	0.1076	0.0769	0.0763
Mo	0.02	0.0309	0.0207	0.02	0.02
Ni	0.1088	0.1193	0.0425	0.0372	0.0466
Al	<0.0100	0.0441	0.0217	<0.0100	0.0321
Cu	0.1804	0.388	0.288	0.1772	0.3265
V	0.01	0.01	0.01	0.01	0.01
B	<0.0050	<0.0050	<0.0500	<0.0500	<0.0500
Fe	98.0409	97.6011	98.454	98.595	98.439
Results for CE, %Ferrite, %Pearlite, YS (N/mm^2), UTS (N/mm^2) and %EL					
CE	0.452	0.464	0.350	0.386	0.410
%Ferrite	66.275	66.7625	73.4625	68.3	65.4625
%Pearlite	33.725	33.2375	26.5375	31.7	34.5375
YS (N/mm^2)	576.6	562.122	572.635	587.219	578.3
UTS (N/mm^2)	630.884	623.284	631.355	650.91	654
%EL	20	22.5	24.5	18.25	18.375

Table A.3: **Chemical composition on twisted / work hardened bars from hardwares**

Alloying elements	**Specimen No.**							
	A3-Y20	**B2-Y16**	**A2-Y16**	**C3-Y20**	**C2-Y16**	**D2-Y16**	**E2-Y16**	**F1-Y16**
C	0.153	0.1198	0.104	0.0989	0.1627	0.1573	0.1497	0.2288
Si	0.2106	0.1689	0.08	0.2004	0.2061	0.189	0.2019	0.2247
Mn	0.5123	0.5364	0.415	0.6531	0.5072	0.4523	0.5116	0.4891
P	0.0374	0.0403	0.024	0.0205	0.0198	0.019	0.0145	0.0557
S	0.0316	0.0189	0.02	<0.0100	<0.0100	<0.0100	<0.0100	0.0404
Cr	0.0788	0.0582	0.05	0.02	0.02	0.02	0.02	0.0829
Mo	0.002	0.002	0.02	0.02	0.02	0.02	0.02	0.02
Ni	0.0367	0.0244	0.043	0.02	0.02	0.02	0.02	0.1106
Al	0.0184	<0.0100	0.012	<0.0100	<0.0100	<0.0100	<0.0100	0.0755
Cu	0.2703	0.2113	0.21	0.02	0.02	0.02	0.02	0.4601
V	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
B	<0.0050	<0.0050	<0.0050	<0.0050	<0.0050	<0.0050	<0.0050	<0.0050
Fe	98.6309	98.8074	99.04	99.0163	99.1	99.1693	99.1116	98.2141
Results for CE, %Ferrite, %Pearlite, YS (N/mm^2), UTS (N/mm^2) and %EL								
CE	0.27701	0.238953	0.206033	0.220417	0.2599	0.24535	0.247633	0.370943
% Ferrite	80.88	85.03	87.00	87.64	79.66	80.34	81.29	71.40
% Pearlite	19.13	14.98	13.00	12.36	20.34	19.66	18.71	28.60
YS (N/mm^2)	506.07	435.294	414.541	397.5	561.60	420.11	370.00	466.98
UTS (N/mm^2)	604.39	524.263	545.698	463.84	715.43	559.99	539	670.65
%ELONGATION	15.33	25.75	21.25	21	14.46	13.75	18.54	13.58

Table A.4: **Chemical composition on rolling mill RM1**

Alloying elements	**Specimen No.**									
	7-D20	**8-D20**	**9-D20**	**IV-Y16**	**VI-Y16**	**VII-Y20**	**VIII-Y20**	**IX-Y20-J**	**X-Y20-JKUAT**	**XI-Y16-DRC**
C	0.1278	0.1307	0.1273	0.1996	0.2329	0.1928	0.2008	0.2038	0.0599	0.4048
Si	0.2122	0.2073	0.2175	0.2375	0.2543	0.2199	0.2259	0.2298	0.123	0.2286
Mn	0.5969	0.607	0.591	0.5883	0.6001	0.6033	0.6111	0.6091	0.3101	0.57
P	0.0484	0.0493	0.0479	0.0502	0.0436	0.0409	0.035	0.045	0.0418	0.0729
S	0.0153	0.0136	0.0182	0.0192	0.0256	0.0188	0.0205	0.0198	0.011	0.0249
Cr	0.1046	0.0998	0.1118	0.0827	0.0915	0.127	0.1291	0.133	0.0217	0.00706
Mo	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Ni	0.033	0.0314	0.0314	0.02	0.0584	0.0432	0.0523	0.0489	0.02	0.0385
Al	0.0128	0.01	0.01	<0.0100	0.0113	0.01	0.01	<0.0100	<0.0100	<0.0100
Cu	0.1659	0.158	0.1803	0.1478	0.2022	0.1327	0.139	0.1453	0.0601	0.2281
V	0.005	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
B	<.0050	<.0050	<.0050	<0.0050	<0.0050	<.0050	<0.0050	<.0050	<0.0050	<0.0050
Fe	98.6783	98.6929	98.6573	98.6399	98.4618	98.6034	98.5729	98.5519	99.3689	98.2141
Results for CE, %Ferrite, %Pearlite, YS (N/mm^2), UTS (N/mm^2) and %EL										
CE	0.266	0.270	0.268	0.331	0.375	0.336	0.347	0.351	0.127	0.525
%Ferrite	84.025	83.6625	84.0875	75.05	70.8875	75.9	74.9	74.525	92.5125	49.4
%Pearlite	15.975	16.3375	15.9125	24.95	29.1125	24.1	25.1	25.475	7.4875	50.6
YS (N/mm^2)	528.5	543.3	524.3	620.169	564.571	552.2	546.3	586.5	432.3	683.627
UTS (N/mm^2)	639.7	647.4	632	700.221	668.036	671.6	667.9	667.9	523.7	828.201
%EL	21	21	20.5	14.6	16.3	15.5	14	13.2	20	5.0

APPENDIX B

TENSILE TESTS

Table B.1: **Mechanical properties of bars from RM1**

S/N	Specimen code	Mechanical properties			Remarks
		YS	**UTS**	**% EL**	
1	I-Y12,VI	582	739	17	Pass
2	II-Y12	519	724	17	Pass
3	III-Y12	612.8	715	15.7	Pass
4	IV-Y16	620.169	700.221	14.6	Pass
5	VI-Y16	564.571	668.036	16.3	Pass
6	VII-Y20	552.2	671.6	15.5	Pass
7	VIII-Y20	546.3	667.9	14	Pass
8	IX-Y20	586.5	667.9	13.2	Fails in % EL
9	1-D12	523	657.1	25	Pass
10	2-D12	506	621.5	23.3	Pass
11	3-D12	534	627.5	22	Pass
12	4-D16	559	712	19	Pass
13	5-D16	494	564.5	26.5	Pass
14	6-D16	481.7	568.4	25	Pass
15	7-D20	528.5	639.7	21	Pass
16	8-D20	543.3	647.4	21	Pass
17	9-D20	524.3	632	20.5	Pass
18	A-Y12	522	525	19.9	Pass
19	B-Y16	539	541	18.3	Pass
20	C-Y20	564	570	18.3	Pass
21	A-D12	548	663	20.4	Pass
22	B-D16	551	692	18.6	Pass
23	C-D20	558	685	19.8	Pass

Table B.2: **Mechanical properties of bars from RM2**

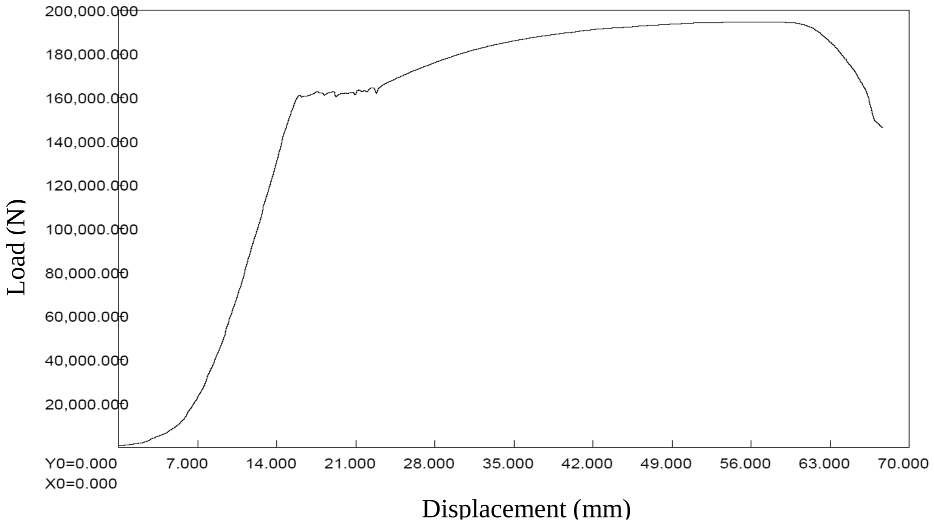
S/N	Heat No./code	Mechanical properties			Remarks
		YS	UTS	% EL	
1	D20-7367	450	592	19	Pass
2	D20-7378	400	567.5	22	Fails in YS
3	D20-7336	420	574.8	19	Fails in YS
4	D20-7376	460	566.7	21	Pass
5	D20-7364	420	563	17	Fails in YS
6	D20-7371	520	670.6	20	Pass
7	D20-7361	460	602.8	12	Fails in % EL
8	D20-7362	513.903	577.494	22.0	Pass
9	D20-7375	516.583	561.576	22.0	Pass
10	D20-7366	512.533	572.205	22.7	Pass
11	D25-7355	490	597.5	15.4	Pass
12	D25-7356	480	589.5	18.5	Pass
13	D25-7359	440	544	16.2	Fails in YS
14	D25-7358	490	592.9	16.2	Pass
15	D25-7338	490	608.2	13.1	Pass
16	D25-7353	496.2	609.4	15.4	Pass
17	D25-7324	458.1	613.4	15.4	Fails in YS
18	D25-7370	500	613	16.2	Pass
19	D25-7334	526.205	583.127	19.2	Pass
20	D25-7310	576.754	645.772	12	Pass
21	D25-7327	536.034	603.41	16.8	Pass
22	HTD16-7439-1	589.4	633.4	18.75	Pass
23	HTD16-7440	545.7	598.5	24.375	Pass
24	HTD16-7442	553.1	626.8	21.25	Pass
25	HTD16-7422	551.973	597.069	25	Pass
26	HTD16-7445	606.256	698.576	19.875	Pass
27	HTD16-7439-4	586.5	717.9	18.25	Pass
28	D16-6932	551.796	711.168	20	Pass
29	D16-6925	581.452	762.114	18.75	Pass
30	D16-6940	529.25	698.622	20	Pass
31	Y16-7545	576.6	628.5	17	Pass
32	Y16-7530	541.5	594.3	22.5	Pass
33	Y16-7547	572.4	648.1	18.375	Pass
34	Y16-7552	578.3	654	18.375	Pass
35	Y16-7540	556.347	648	20.375	Pass
36	Y16-7512	572.635	631.355	24.5	Pass
37	Y16-7520	587.219	650.91	18.25	Pass
38	Y16-7396	546.014	623.44	18.75	Pass
39	Y16-7382	576.6	630.884	20	Pass
40	Y16-7379	541.5	623.284	22.5	Pass
41	D12-7760	537.6	572.2	22	Pass
42	D12-7761	547.8	600.6	23.5	Pass
43	D12-7763	522.0	603.3	25	Pass
44	D12-7766	504.4	544.7	20	Pass
45	D12-7768	537.3	575.6	21.5	Pass
46	D12-7770	529.0	560.1	15.333	Pass
47	D12-7777	524.9	588.5	24.167	Pass

Table B.3: **Mechanical properties of bars from distributors/hardwares**

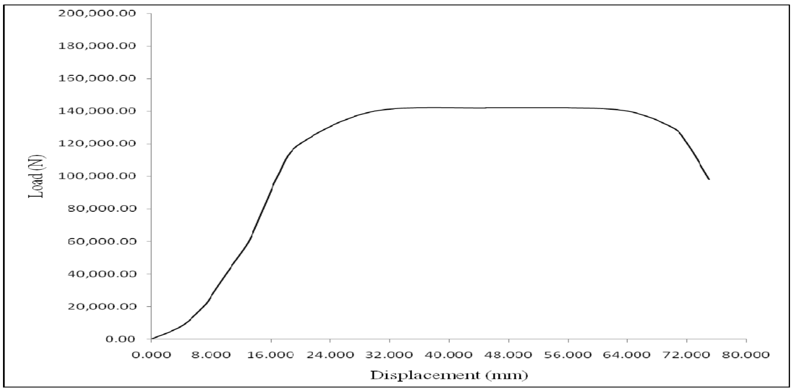
Hardware Code	**S/N**	**Specimen code**	**Mechanical Properties**			**Remarks**
			YS	**UTS**	**% EL**	
A	1	A1-Y12	407.93	573.45	22.78	Fails in YS
	2	A2-Y16	367.71	567.14	22.5	Fails in YS
	3	A3-Y20	508.69	607.59	15	Pass
B	4	B1-Y12	405.37	628.52	16.67	Fails in YS
	5	B2-Y16	391.88	559.19	24	Fails in YS and UTS
C	6	C1-Y12	590.77	731.41	22.67	Pass
	7	C2-Y16	561.6	715.43	14.46	Pass
	8	C3-Y20	390.094	461.604	21	Fails in YS and UTS
D	9	D1-Y12	539.16	678.38	18.61	Pass
	10	D2-Y16	420.11	559.99	13.75	Fails in YS and UTS
E	11	E1-Y12	465.1	620.02	19.72	Pass
	12	E2-Y16	370	539	18.54	Fails in YS and UTS
F	13	F1-Y16	466.98	670.65	13.58	Pass

Table B.4: **Mechanical properties of bars from an identified construction company**

S/N	**Heat No. / code**	**Mechanical properties**			**Remarks**
		YS	**UTS**	**% EL**	
1	HTD20-7367	450	592	19	Fails in YS
2	HTD20-7378	400	567.5	22	Fails in YS
3	HTD20-7336	420	574.8	19	Fails in YS
4	HTD20-7376	460	566.7	21	Pass
5	HTD20-7364	420	563	17	Fails in YS
6	HTD20-7371	520	670.6	20	Pass
7	HTD20-7361	460	602.8	12	Fails in % EL
8	D20-SMLA 001	460	544.7	15	Pass
9	HTD20-7867	465	592	19	Pass
10	HTD20-7375	490	618.7	19	Pass
11	D20-01	500	720	12	Fails in % EL
12	D16 -7530	480	692.6	12.5	Fails in % EL
13	D16 -7530	500	672	12.5	Fails in % EL
14	D16 -7530	520	691	12.5	Fails in % EL
15	D12-7573	470	611	16.7	Pass
16	D12 -7573	480	610	16.7	Pass
17	D12 -7573	480	602	13.3	Fails in % EL
18	D12 - 8056-B1	460	533.5	20	Pass
19	HTD25-7355	490	597.5	15.4	Pass
20	HTD25-7356	480	589.5	18.5	Pass
21	HTD25-7359	440	544	16.2	Fails in YS
22	HTD25-7358	490	592.9	16.2	Pass
23	HTD25-7338	490	608.2	13.1	Fails in % EL
24	HTD25-7353	496.2	609.4	15.4	Pass
25	HTD25-7324	458.1	613.4	15.4	Fails in YS
26	HTD25-7370	500	613	16.2	Pass
27	HTD25-7356	490	597.5	18	Pass



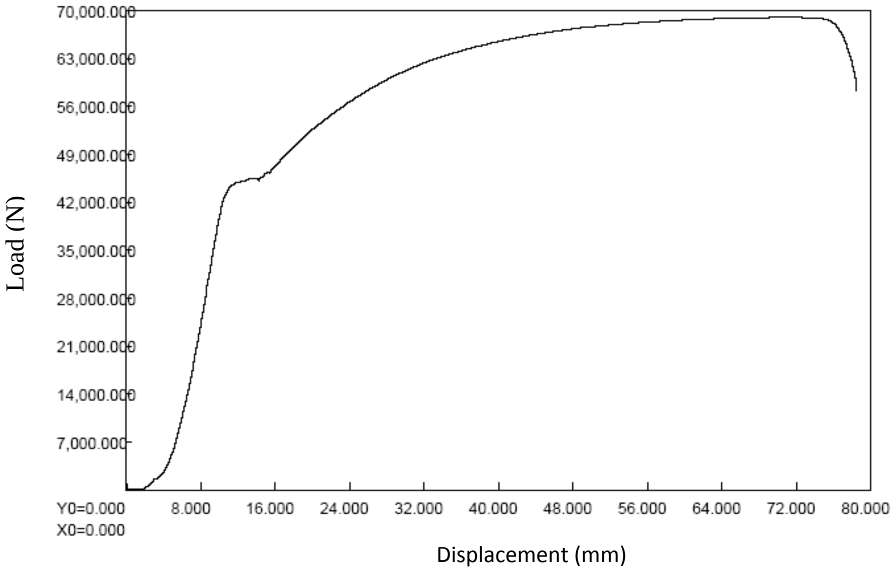
(a) Self Tempered/ribbed bar, D20, from RM1, Cross-section area: 304.211 mm², YS: 528.482 N/mm², UTS: 639.721 N/mm², %El: 21



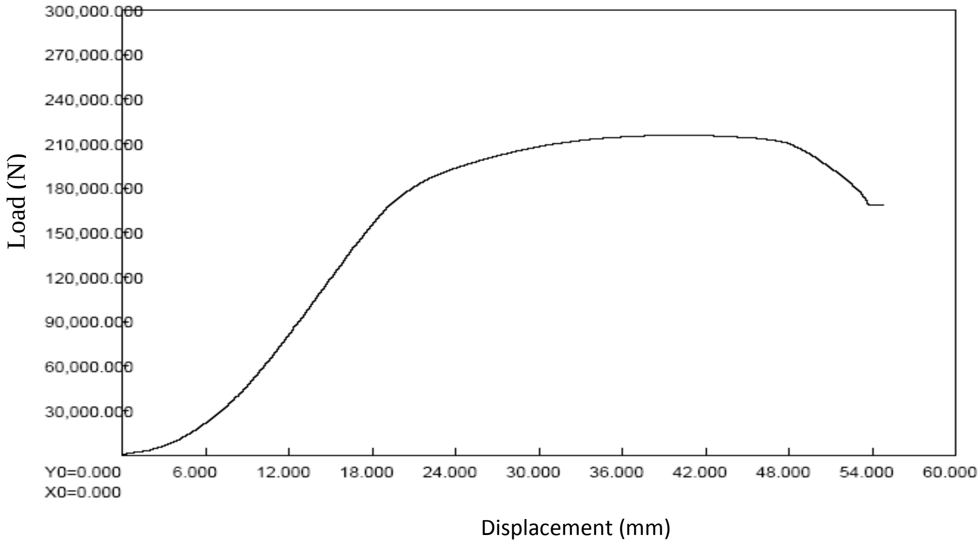
(b) Work- hardened / twisted barY20, from Hardwar C, Cross-section area= 307.926 mm^2,

YS= 390.094 N/mm^2, UTS= 461.604 N/mm^2, % El= 20

Figure B.1: **Graphical result for typical tensile test of a reinforcing bar from RM1 and hardware C**



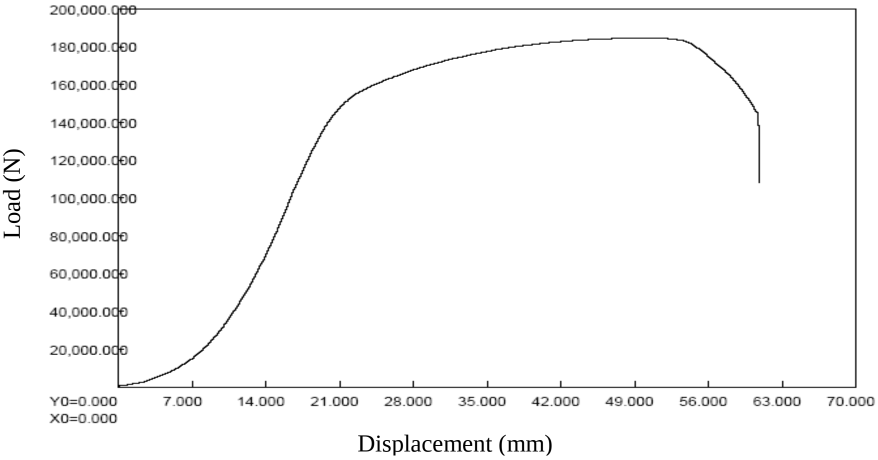
(a) Ribbed bar, D12 from Rwanda. Cross-section area: 109.190 mm², YS: 396.465 N/mm², UTS: 632.201 N/mm², %El: 24



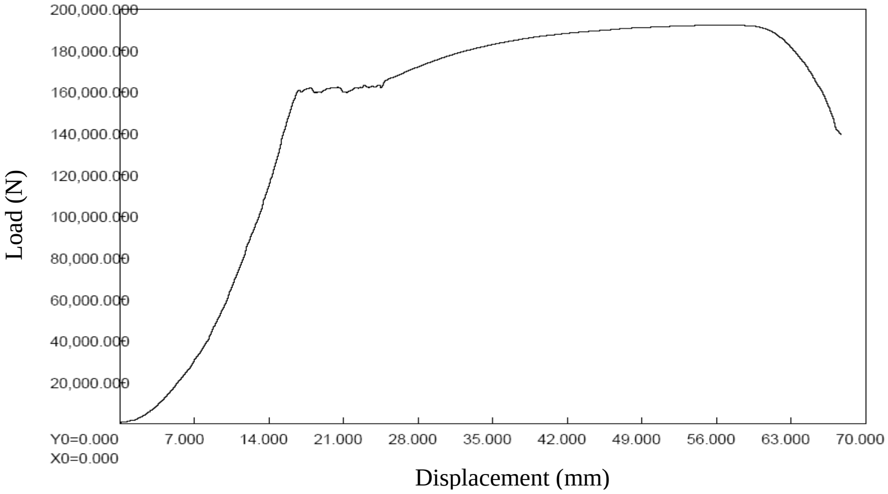
(b) Work- hardened / twisted bar Y20, specimen No.VII, Cross-section area: 321.077 mm^2,

YS: 552.204 N/mm², UTS: 671.615 N/mm², % El: 15.5

Figure B.2: **Graphical result for typical tensile test of reinforcing bar from Rwanda and RM1**

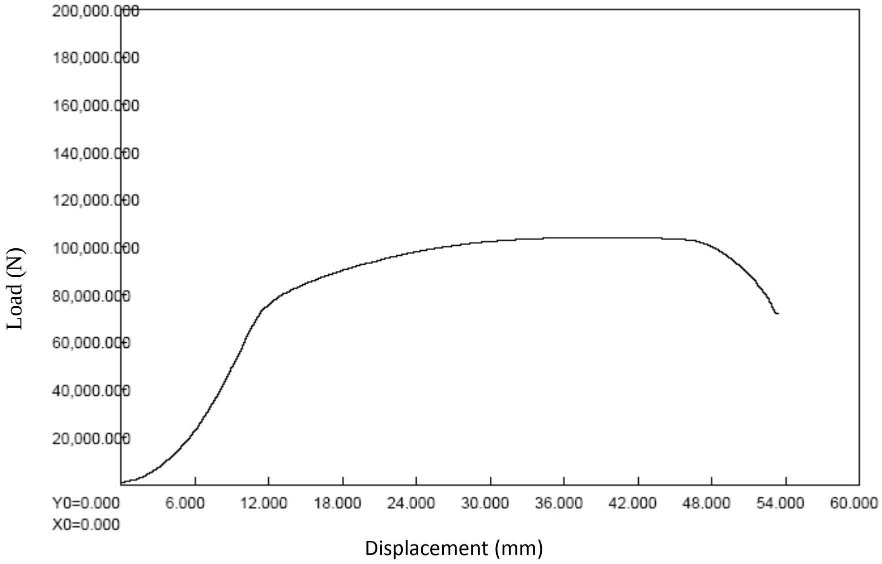


(a) Work- hardened / twisted bar, Y20 from hardware B, Cross-section area = 303.957 mm², YS: 508.690 N/mm², UTS: 607.586 N/mm², % El: 15

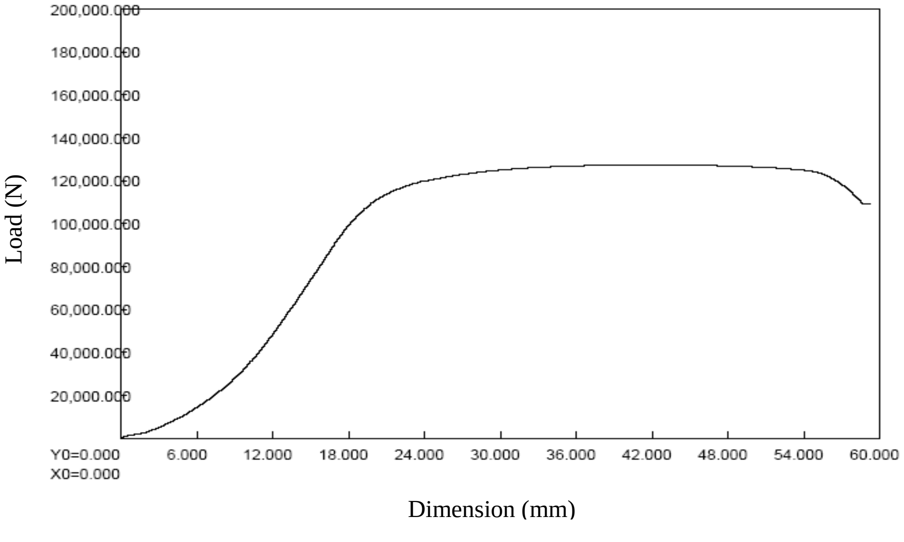


(b) Self tempered / ribbed bar, D20,specimen No.9 from rolling mill RM1, Cross-section area = 304.211 mm², YS: 524.340N/mm², UTS: 632.028 N/mm², % El: 20.5

Figure B.3: **Graphical result for typical tensile test of a reinforcing bar from hardware B and rolling mill RM1**

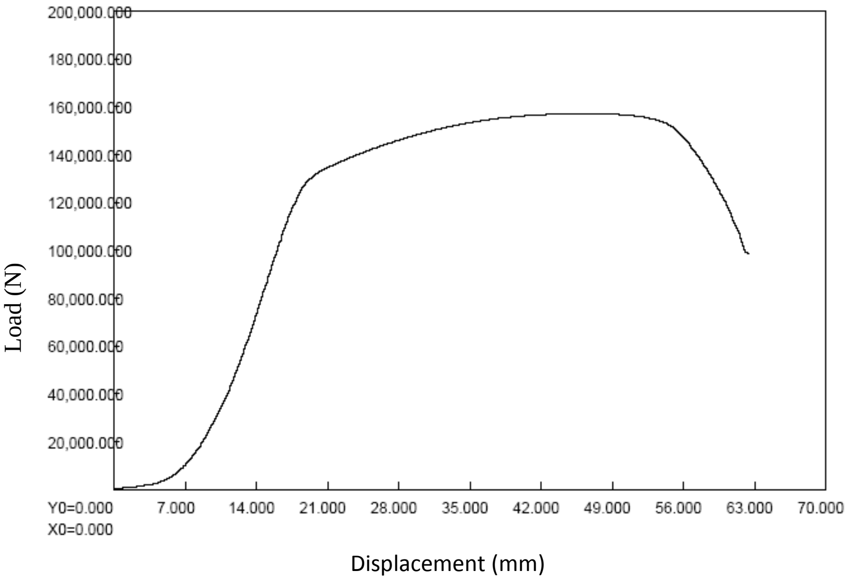


(a) Work-hardened / twisted bar, Y16 from hardware A, Cross-section area = 190.765 mm², YS: 414.541 N/mm^2, UTS: 545.698 N/mm², %El: 21.25

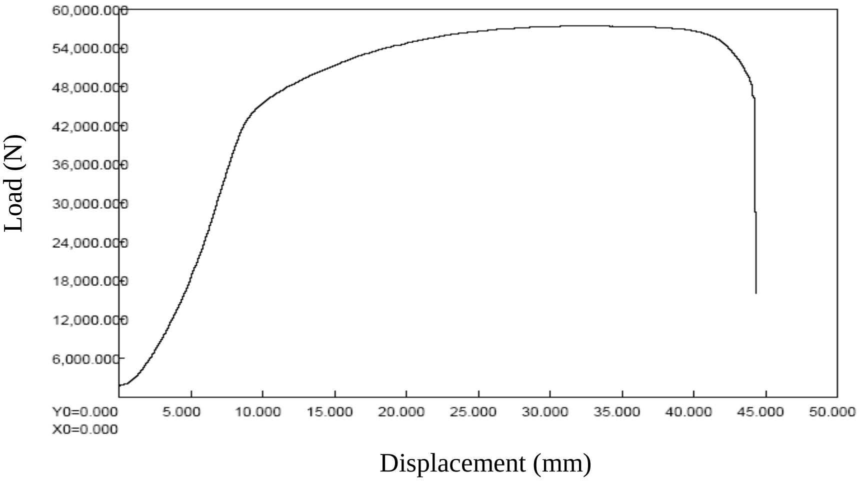


(b) Work-hardened / twisted bar, Y16 from rolling mill RM2, Cross-section area = 201.804 mm², YS: 572.635 N/mm^2, UTS: 631.355 N/mm², %El: 24.5

Figure B.4: **Graphical result for typical tensile test of a reinforcing bars from hardware A and Rolling mill RM2**

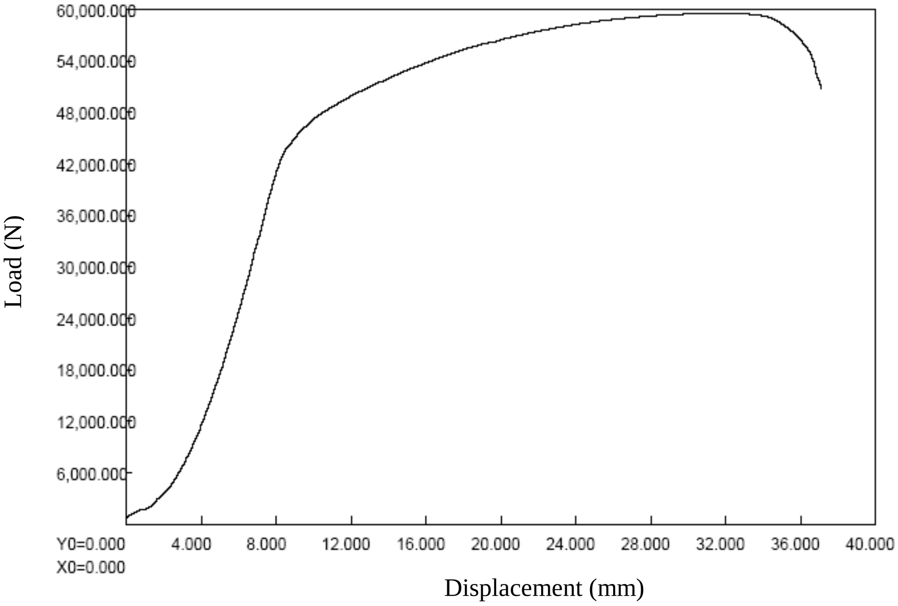


(a) Work-hardened/ twisted bar, Y20 from JKUAT, Cross-section area: 299.979 mm²
YS: 432.330 N/mm², UTS: 523.737 N/mm², %El: 20

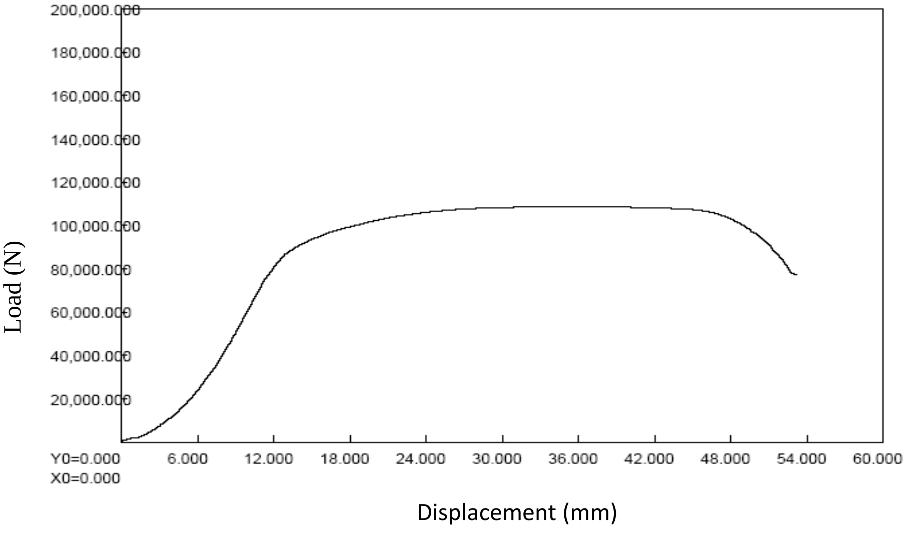


(b) Work-hardened/ twisted bar, Y12 from Hardware A, Cross-section area = 106.157 mm ²
YS: 427.574 N/mm², UTS: 540.897 N/mm², %El: 25

Figure B.5: **Graphical result for typical tensile test of a reinforcing bar from JKUAT and hardware A**



(a) Work-hardened / twisted bar, Y12 from hardware B, Cross-section area = 97.991 mm², YS: 457.389 N/mm², UTS: 608.015 N/mm², %El: 16.667



(b) Work-hardened / twisted bar, Y16 from hardware B, Cross-section area = 207.377 mm², YS: 435.294 N/mm² UTS: 524.263 N/mm², % El: 25.75

Figure B.6: **Graphical result for typical tensile test of reinforcing bars from hardware B**

APPENDIX C

STUDENT T TEST

Table C.1: **t-Test for comparing tensile properties of bars from tensile test and correlation equation**

	YS from tensile test	*YS from correlation equation*
Mean	523.082	557.747
Minimum _Maximum	370 _ 664	277 _ 843
Standard deviation	70.805	113.297
Coefficient of variability	0.135	0.203
95% C.I.	491.7 _ 554.4	526.3 _ 589.2
Observations	36	36
Hypothesized Mean Difference	0	
DF	70	
t Stat	-1.557	
P(T<=t) one-tail	0.062	
t Critical one-tail	1.671	
P(T<=t) two-tail	0.125	
t Critical two-tail	1.994	
	UTS from tensile test	*UTS from correlation equation*
Mean	632.930	672.821
Minimum _Maximum	464 _ 828	500 _ 879
Standard deviation	74.213	83.934
Coefficient of variability	0.117	0.125
95% C.I.	606.6 _ 659.3	646.5 _ 699.2
Observations	36	36
Hypothesized Mean Difference	0	
DF	70	
t Stat	-2.136	
P(T<=t) one-tail	0.018	
t Critical one-tail	1.667	
P(T<=t) two-tail	0.036	
t Critical two-tail	1.994	
	% EL from tensile test	*% EL from correlation equation*
Mean	18.470	16.031
Minimum _Maximum	5 _ 25.8	5.2 _ 22.6
Standard deviation	4.175	3.621
Coefficient of variability	0.226	0.226
95% C.I.	17.17 _ 19.77	14.73 _ 17.33
Observations	36	36
Hypothesized Mean Difference	0	
DF	70	
t Stat	2.649	
P(T<=t) one-tail	0.005	
t Critical one-tail	1.667	
P(T<=t) two-tail	0.010	
t Critical two-tail	1.994	

Table C.2: **t-Test for comparing tensile properties of bars from rolling mills and hardwares**

	YS of bars from rolling mills	*YS of bars from hardwares*
Mean	536.371	453.056
Minimum _Maximum	400 _ 620	368 _ 591
Standard deviation	47.859	75.148
Coefficient of variability	0.089	0.166
95% C.I.	520.9 _ 550.5	423.2 _ 482.9
Observations	53	13
Hypothesized Mean Difference	0	
DF	64	
t Stat	3.812	
P(T<=t) one-tail	0.001	
t Critical one-tail	1.761	
P(T<=t) two-tail	0.002	
t Critical two-tail	1.998	
	UTS of bars from rolling mills	*UTS of bars from hardwares*
Mean	632.565	608.570
Minimum _Maximum	545 _ 762	464 _ 731
Standard deviation	54.131	76.003
Coefficient of variability	0.086	0.125
95% C.I.	616.0 _ 648.3	576.0 _ 641.2
Observations	53	13
Hypothesized Mean Difference	0	
DF	64	
t Stat	1.073	
P(T<=t) one-tail	0.150	
t Critical one-tail	1.753	
P(T<=t) two-tail	0.300	
t Critical two-tail	1.998	
	% EL of bars from rolling mills	*% EL of bars from hardwares*
Mean	19.726	18.739
Minimum _Maximum	12 _ 26.5	13.6 _ 24.0
Standard deviation	3.485	3.713
Coefficient of variability	0.177	0.198
95% C.I.	18.99 _ 20.86	16.85 _ 20.63
Observations	53	13
Hypothesized Mean Difference	0	
DF	64	
t Stat	0.869	
P(T<=t) one-tail	0.198	
t Critical one-tail	1.734	
P(T<=t) two-tail	0.396	
t Critical two-tail	1.998	

C.1 Summary statistics

C.1.1 Summary statistics for % Elongation of bars from CONSC1

Number of values = 47

Number of observations = 27

Number of missing values = 20

Mean = 16.43

Median = 16.20

Minimum = 12.00

Maximum = 22.00

Range = 10.00

Lower quartile = 13.73

Upper quartile = 19.00

Standard deviation = 2.93

Standard error of mean = 0.56

Variance = 8.57

Coefficient of variation = 17.82

C.1.2 Summary statistics for % Elongation of bars from hardwares

Number of values = 47

Number of observations = 13

Number of missing values = 34

Mean = 18.71

Median = 18.61

Minimum = 13.58

Maximum = 24.00

Range = 10.42

Lower quartile = 14.87

Upper quartile = 22.54

Standard deviation = 3.74

Standard error of mean = 1.04

Variance = 13.98

Coefficient of variation = 19.98

C.1.3 Summary statistics for % Elongation of bars from RM1

Number of values = 47

Number of observations = 23

Number of missing values = 24

Mean = 19.21

Median = 19.00

Minimum = 13.20

Maximum = 26.50

Range = 13.30

Lower quartile = 16.48

Upper quartile = 21.00

Standard deviation = 3.61

Standard error of mean = 0.75

Variance = 13.00

Coefficient of variation = 18.76

C.1.4 Summary statistics for % Elongation of bars from RM2

Number of values = 47

Number of observations = 47

Number of missing values = 0

Mean = 19.35

Median = 19.20

Minimum = 12.00

Maximum = 25.00

Range = 13.00

Lower quartile = 17.00

Upper quartile = 22.00

Standard deviation = 3.27

Standard error of mean = 0.48

Variance = 10.73

Coefficient of variation = 16.92

C.1.5 Summary statistics for UTS of bars from CONSC1

Number of values = 47

Number of observations = 27

Number of missing values = 20

Mean = 607.0

Median = 602.0

Minimum = 533.5

Maximum = 720.0

Range = 186.5

Lower quartile = 578.5

Upper quartile = 613.3

Standard deviation = 46.5

Standard error of mean = 9.0

Variance = 2163.7

Coefficient of variation = 7.7

C.1.6 Summary statistics for UTS of bars from hardwares

Number of values = 47

Number of observations = 13

Number of missing values = 34

Mean = 608.6

Median = 607.6

Minimum = 461.6

Maximum = 731.4

Range = 269.8

Lower quartile = 559.8

Upper quartile = 672.6

Standard deviation = 76.4

Standard error of mean = 21.2

Variance = 5829.4

Coefficient of variation = 12.5

C.1.7 Summary statistics for UTS of bars from RM1

Number of values = 47

Number of observations = 23

Number of missing values = 24

Mean = 647.8

Median = 663.0

Minimum = 525.0

Maximum = 739.0

Range = 214.0

Lower quartile = 623.0

Upper quartile = 690.2

Standard deviation = 59.6

Standard error of mean = 12.4

Variance = 3552.3

Coefficient of variation = 9.2

C.1.8 Summary statistics for UTS of bars from RM2

Number of values = 47

Number of observations = 47

Number of missing values = 0

Mean = 614.3

Median = 603.3

Minimum = 544.0

Maximum = 762.1

Range = 218.1

Lower quartile = 578.9

Upper quartile = 632.9

Standard deviation = 47.2

Standard error of mean = 6.9

Variance = 2230.3

Coefficient of variation = 7.7

C.1.9 Summary statistics for YS of bars from CONSC1

Number of values = 47

Number of observations = 27

Number of missing values = 20

Mean = 472.9

Median = 480.0

Minimum = 400.0

Maximum = 520.0

Range = 120.0

Lower quartile = 460.0

Upper quartile = 490.0

Standard deviation = 29.3

Standard error of mean = 5.6

Variance = 858.5

Coefficient of variation = 6.2

C.1.10 Summary statistics for YS of bars from hardwares

Number of values = 47

Number of observations = 13

Number of missing values = 34

Mean = 452.7

Median = 420.1

Minimum = 367.7

Maximum = 590.8

Range = 223.1

Lower quartile = 391.4

Upper quartile = 516.3

Standard deviation = 75.8

Standard error of mean = 21.0

Variance = 5739.8

Coefficient of variation = 16.7

C.1.11 Summary statistics for YS of bars from RM1

Number of values = 47

Number of observations = 23

Number of missing values = 24

Mean = 546.1

Median = 546.3

Minimum = 481.7

Maximum = 620.2

Range = 138.5

Lower quartile = 523.3

Upper quartile = 562.8

Standard deviation = 33.8

Standard error of mean = 7.1

Variance = 1145.4

Coefficient of variation = 6.2

C.1.12 Summary statistics for YS of bars from RM2

Number of values = 47

Number of observations = 47

Number of missing values = 0

Mean = 523.5

Median = 529.2

Minimum = 400.0

Maximum = 606.3

Range = 206.3

Lower quartile = 491.6

Upper quartile = 555.5

Standard deviation = 49.8

Standard error of mean = 7.3

Variance = 2475.5

Coefficient of variation = 9.5

APPENDIX D

DETERMINATION OF GRAIN SIZE OF STEEL

The following procedure has been followed for determining the average grain size of the specimens:

i Select the field locations (one in the center of the specimen and four clause to the edges of the specimen)

ii Take the micro-photo of the selected fields at a given magnification

iii Draw a three concentric test line pattern on each field

iv Count the average number (N_A) of intercepts covered by the pattern

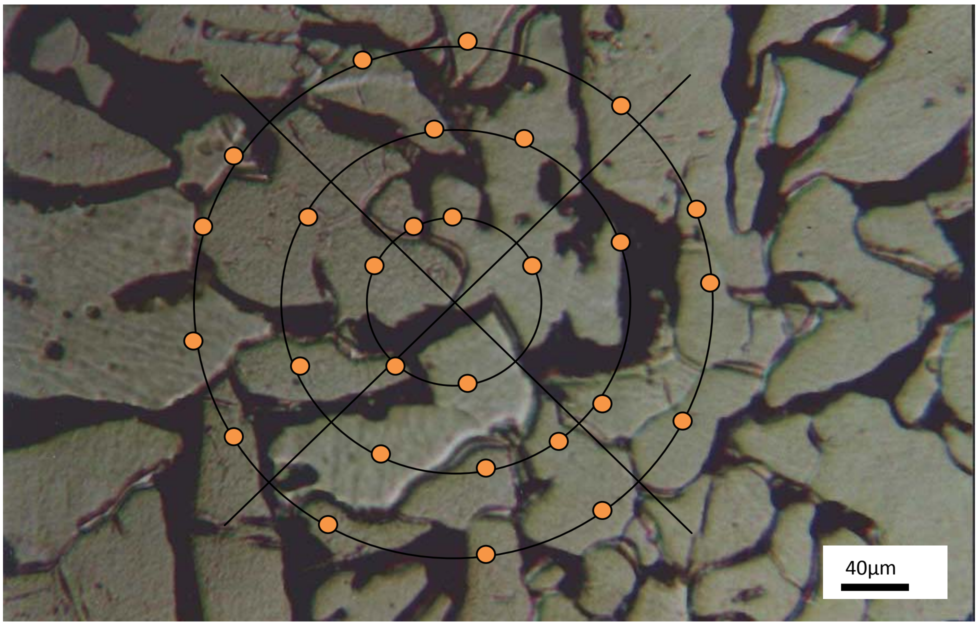
v Calculate the number of intercepts per unit length (N_L)

vi Calculate the ASTM grain size number, G.

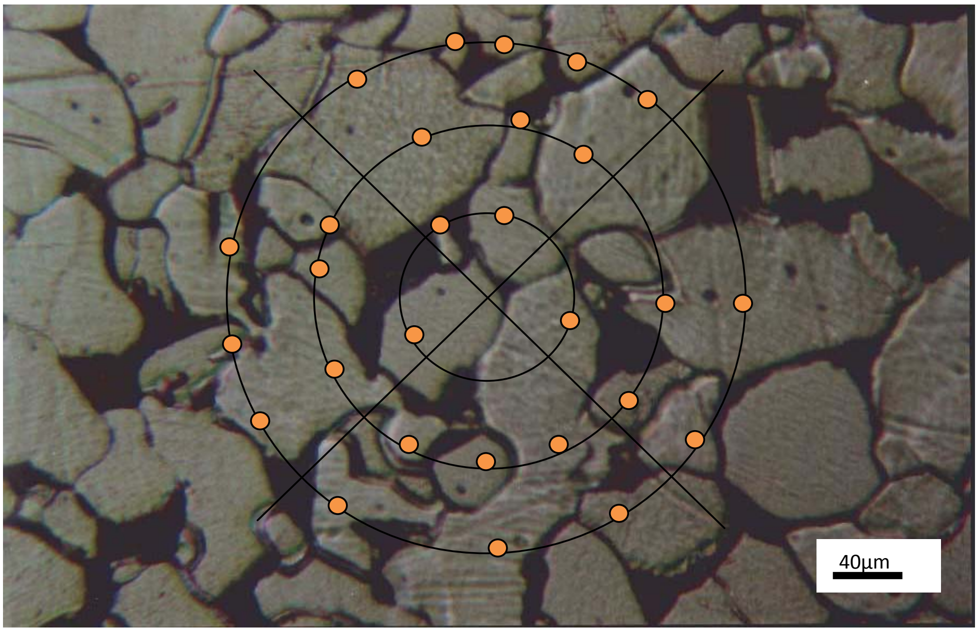
vii Calculate the number of grain per 1 mm^2

viii Calculate the average grain diameter

ix Calculate the % Relative Accuracy (% RA)

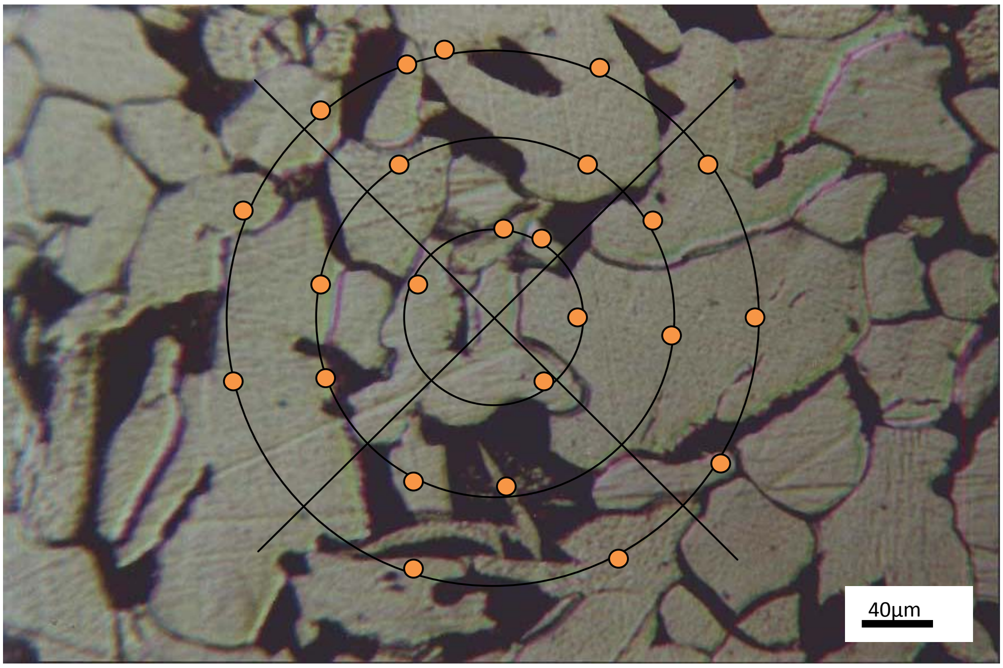


N=28

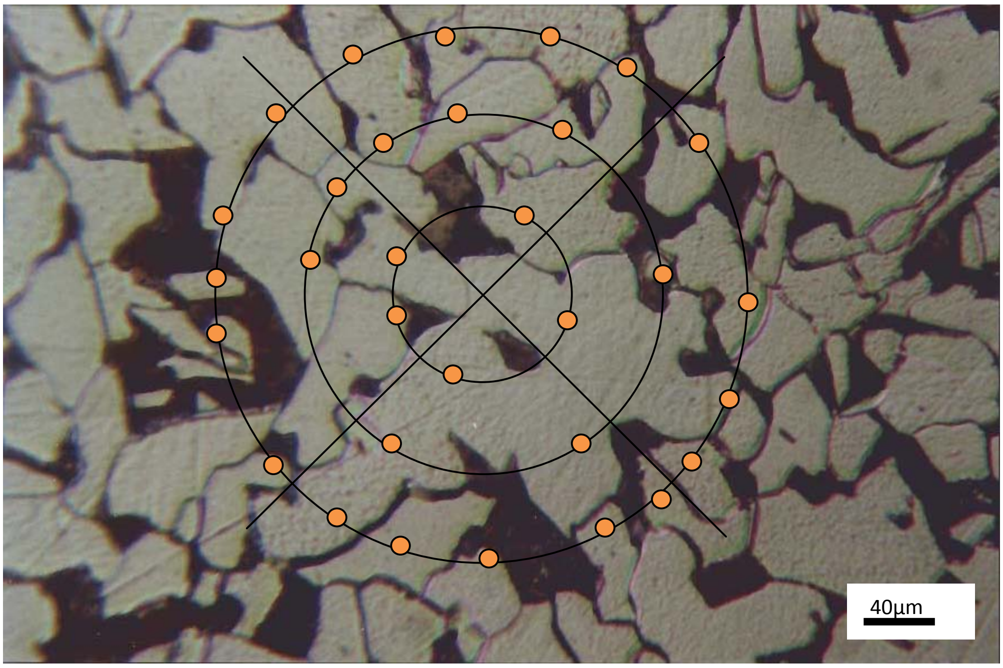


N=28

Figure D.1: **Intercept method for grain size determination, Field 1 and 2**

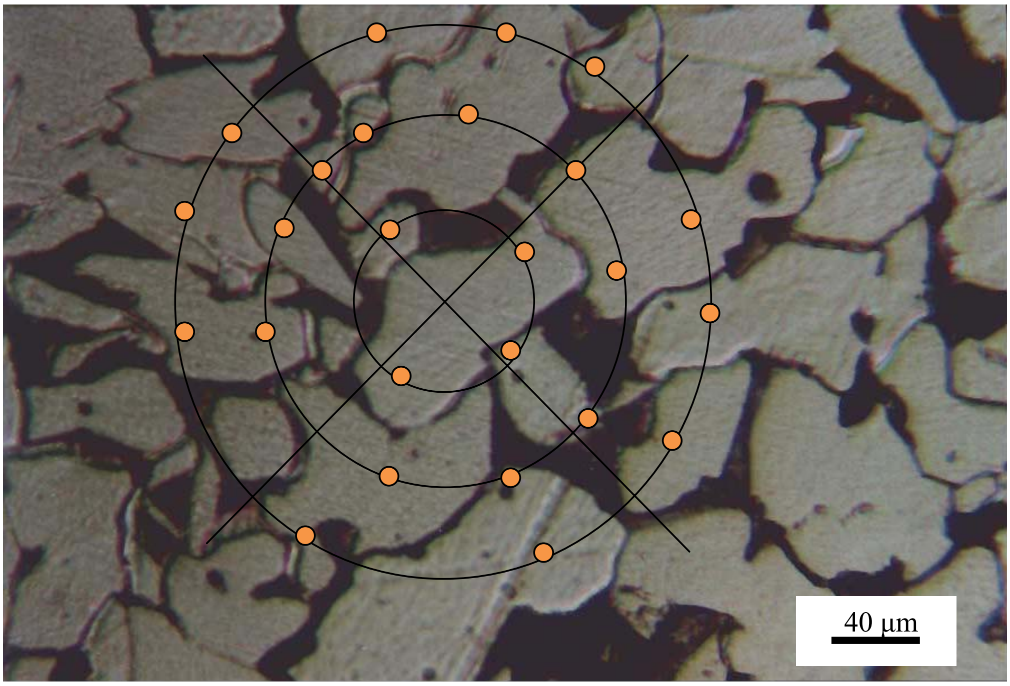


N=24



N=31

Figure D.2: **Intercept method for grain size determination, Field 3 and 4**



N=25

NA= 27.2 ,NL=29.6, G=6.5, d=0.037mm = 37 µm

Figure D.3: **Intercept method for grain size determination, Field 5**

APPENDIX E

GRADES AND DESIGNATIONS OF STEELS

Table E.1: **Steel Grades**

ISO 6935-2:2007, STEEL GRADES FOR CONCRETE REINFORCEMENT

B300A-R
B300B-R
B300C-R
B300D-R
B400A-R
B400B-R
B400C-R
B500A-R
B500B-R
B500C-R

B300DWR
B350DWR
B400BWR
B400CWR
B400DWR
B420 DWR
B500AWR
B500BWR
B500CWR
B500DWR

Note:

- ‘B’ stands for reinforcing steel for concrete
- The next 3 digits represent the specified characteristic value of upper yield strength
- The 5th symbol stands for ductility class
- The sixth symbol relates to welding;
  ”-“means not intended for welding and
  “W” means intended for welding.
- The last “R” stands for ribbed bar

Table E.2: **Steel Designations [63]**

Designation	Approximate alloy content,%
Carbon steels	
10xx	Plain carbon
11xx	Resulfurized
12xx	Resulfurized and rephosphorized
Manganese steels	
13xx	Mn 1.75
Nickel steels	
23xx	Ni 3.5
25xx	Ni 5.0
Nickel Chromium Steels	
31xx	Ni 1.25,Cr 0.65-0.80
32xx	Ni 1.75,Cr 1.07
33xx	Ni 3.50,Cr 1.50-1.57
34xx	Ni 3.00,Cr 0.77
Nickel Chromium Molybdenum Steels	
43xx	Ni 1.82,Cr 0.50, Mo 0.25
47xx	Ni 1.45,Cr 0.45, Mo 0.20-0.35
81xx	Ni 0.30,Cr0.40, Mo 0.12
86xx	Ni 0.55,Cr 0.50, Mo 0.20
87xx	Ni 0.55,Cr 0.50, Mo 0.25
94xx	Ni 0.45,Cr 0.40, Mo 0.12
Nickel Molybdenum Steels	
46xx	Ni 0.85-1.82, Mo 0.20
48xx	Ni 3.50,Mo 0.25
Chromium steels	
50xx	Cr 0.27 -0.65
51xx	Cr 0.80-1.05

APPENDIX F

MICROGRAIN SIZE RELATIONSHIPS

Table F.1: **Micro grain size relationships computed for uniform Randomly oriented Equiaxed Grains [54]**

ASTM Micro-Grain Size Number G	"Diameter" of Average Grain Section[A]		Average Intercept Distance[B] $\bar{l}$, mm	Intercept Count, n/l per mm	Area of Average Grain Section, $\bar{a}$, mm^2	Calculated Number of Grains per mm^3, n/v[C]	Average	
	Nominal d_n, mm	Feret's d_f, mm					Grains per mm^2 at 1×,[D] n/a	Grains per in.^{2} at 100×, n/a
00[E]	0.51	0.570	0.453	2.210	0.258	6.11	3.88	0.250
0	0.36	0.403	0.320	3.125	0.129	17.3	7.75	0.500
0.5	0.30	0.339	0.269	3.716	0.0912	29.0	11.0	0.707
1.0	0.25	0.285	0.226	4.42	0.0645	48.8	15.50	1.000
1.5	0.21	0.240	0.190	5.26	0.0456	82	21.9	1.414
(1.7)[F]	0.200	0.226	0.177	5.64	0.0400	100	25.0	1.613
2.0	0.18	0.202	0.160	6.25	0.0323	138	31.0	2.000
2.5	0.15	0.170	0.135	7.43	0.0228	232	43.8	2.828
	µm	µm	µm		mm^2 × 10^{-3}			
3.0	125	143	113	8.84	16.1	391	62.0	4.000
(3.2)[F]	120	135	106	9.41	14.4	463	69.4	4.480
3.5	105	120	95	10.51	11.4	657	87.7	5.657
(3.7)[F]	100	113	89	11.29	10.0	800	100	6.452
4.0	90	101	80.0	12.5	8.07	1105	124	8.000
4.5	75	85	67.3	14.9	5.70	1859	175	11.31
(4.7)[F]	70	79	62.0	16.1	4.90	2331	204	13.17
5.0	65	71	56.6	17.7	4.03	3126	248	16.00
(5.2)[F]	60	68	53.2	18.8	3.60	3708	278	17.92
5.5	55	60	47.6	21.0	2.85	5258	351	22.63
(5.7)[F]	50	56	44.3	22.6	2.50	6400	400	25.81
6.0	45	50	40.0	25.0	2.02	8842	496	32.00
(6.4)[F]	40	45	35.4	28.2	1.60	12 500	625	40.32
6.5	38	42	33.6	29.7	1.43	14 871	701	45.25
(6.7)[F]	35	39	31.0	32.2	1.23	18 659	816	52.67
7.0	32	36	28.3	35.4	1.008	25 010	992	64.00
(7.2)[F]	30	34	26.6	37.6	0.900	29 630	1111	71.68
7.5	27	30	23.8	42.0	0.713	41 061	1403	90.51
(7.7)[F]	25	28	22.2	45.1	0.625	51 200	1600	103.23
	µm	µm	µm		mm^2 × 10^{-6}	×10^6	×10^3	
8.0	22	25	20.0	50.0	504	0.0707	1.98	128.0
(8.4)[F]	20	23	17.7	56.4	400	0.1000	2.50	161.3
8.5	19	21	16.8	59.5	356	0.1190	2.81	181.0
9.0	16	18	14.1	70.7	252	0.200	3.97	256.0
(9.2)[F]	15	17	13.3	75.2	225	0.237	4.44	286.7
9.5	13	15	11.9	84.1	178	0.336	5.61	362.0
10.0	11	13	10.0	100	126	0.566	7.94	512.0
(10.3)[F]	10	11.3	8.86	113	100	0.800	10.00	645.2
10.5	9.4	10.6	8.41	119	89.1	0.952	11.22	724.1
(10.7)[F]	9.0	10.2	7.98	125	81.0	1.097	12.35	796.5
11.0	8	8.9	7.07	141	63.0	1.600	15.87	1024
(11.4)[F]	7.0	7.9	6.20	161	49.0	2.332	20.41	1317
11.5	6.7	7.5	5.95	168	44.6	2.692	22.45	1448
(11.8)[F]	6.0	6.8	5.32	188	36.0	3.704	27.78	1792
12.0	5.6	6.3	5.00	200	31.5	4.527	31.7	2048
(12.3)[F]	5.0	5.6	4.43	226	25.0	6.40	40.0	2581
12.5	4.7	5.3	4.20	238	22.3	7.61	44.9	2896
13.0	4.0	4.5	3.54	283	15.8	12.80	63.5	4096
13.5	3.3	3.7	2.97	336	11.1	21.54	89.8	5793
(13.8)[F]	3.0	3.4	2.66	376	9.0	29.6	111.1	7168
14.0	2.8	3.2	2.50	400	7.88	36.2	127	8192
(14.3)[F]	2.5	2.8	2.22	451	6.25	51.2	160	10323

[A] Feret's diameter = height between tangents; $d_f = \bar{a}/\bar{l}$. Values of d_n and d_f rounded to digits shown.

[B] Value of Heyn intercept or mean free path.

[C] Computation of n/v based on grains averaging to spherical shape for which $n/v = 0.5659\ (n/l)^3$.

[D] To obtain grains per mm^2 at 100×, multiply by 10^{-4}.

[E] The use of "00" is recommended instead of "minus 1" to avoid confusion.

[F] The G values shown in parentheses are calculated to one decimal place and correspond to some of the nominal "diameter" sizes, (d_n) customarily used in reporting ge grain size by the copper and brass industry.

APPENDIX G

SUMMARIES OF THE QUESTIONNAIRES

Table G.1: **List of companies surveyed**

S/N	Name of the company	Location / Address	Date of visit	Responded (Yes or No)
	A. Hardware stores			
1	Mateko Hardware	P.O.Box 570 Kigali-Rwanda	19/12/2008	Yes
2	Tumaine Timber & Hardware ltd	P.O.Box 430 Kalimini (Juja)-Kenya	22/7/2009	Yes
3	Ndiikoma Merchants Hardware	P.O.Box 294 Kalimoni (Juja)-Kenya	22/7/2009	Yes
4	Jama Corner Hardware	P.O.Box 1018 Ruiru-Kenya	23/7/2009	Yes
5	Kens Metal Ltd	P.O.Box 45726-00100 Nairobi-Kenya, Industrial Area	05/8/2009	Yes
6	Central Auto and Hardware ltd	Industrial Area Nairobi-Kenya	10/8/2009	No
7	Joska Hardware	Ruiru-Kenya	10/8/2009	No
8	Ruiru Hardware	Ruiru-Kenya	10/8/2009	No
	B. Construction companies			
1	N.K.Brothers	P.O.Box 10709 Nairobi- Kenya Industrial Area	28/7/2009	Yes
2	Model Builders	P.O.Box 3415-00506 Nairobi- Kenya, Industrial Area	28/7/2009	Yes
3	H.Young	P.O.Box 30118-00100 Nairobi- Kenya, Industrial Area	28/7/2009	Yes
4	Maridadi Building Contractor Ltd	P.O.Box 43518 Nairobi- Kenya Industrial Area	28/7/2009	Yes
5	Sumitomo Mitsui Construction Co Ltd	P.O.Box 60487-00200 Nairobi-Kenya, Ngong Road	10/7/2009	Yes
6	Kirinyaga Construction (K) ltd	P.O.Box 48632-00100 Nairobi	07/7/2009	No
7	Landmark Holdings Ltd	P.O.Box 66537-00800 Westland	10/7/2009	No
8	Mellech Engineering & Construction Ltd	P.O.Box 45770-00100 Nairobi	10/7/2009	No
9	Intex Construction Ltd	P.0.Box 60293-00100 Nairobi	11/7/2009	No
10	Samani Construction Ltd	P.O.Box 1036-00100 Nairobi	10/7/2009	No
11	Mugoya Construction & Engineering Ltd	P.O.Box 47011-00100 Nairobi	10/7/2009	No
	C. Statutory bodies			
1	Kenya Bureau of Standards	P.O.Box 5497-00200 Nairobi, Kapiti Road	08/12/2008	Yes
2	Ministry of Road and Public Works, Material Branch	P.O.Box 11873-00400 Nairobi	05/02/2009	Yes
3	Rwanda Bureau of Standards	P.O.Box 7099 Kigali-Rwanda	18/12/2008	Yes
	D. Rolling mills			
1	Apex Steel Ltd-Rolling mill division	P.O.Box 18441-00500 Nairobi, Athi River	11/03/2008	Yes
2	Steel Makers Ltd	P.O.Box 44574-00100 Nairobi, Athi River	18/03/2008	Yes
3	Insteel Ltd	P.O.Box 78161-Nairobi	01/11/2008	No
4	Mabati Rolling Mills Ltd	P.O.Box 87547-80100 Mombasa	11/11/2008	No
5	Athi River Steel Plant Ltd	P.O.Box 45574-00100 Nairobi	03/11/2008	No
6	Morris & Co Ltd	P.O.Box 18310-00500 Nairobi	1/11/2008	No

Table G.2: **Summary of questionnaire to construction companies**

VARIABLES		RESPONDENTS				
		CONS1	CONS2	CONS3	CONS4	CONS5
1	Working Experience					
i	Less than ten (10) years	x				
ii	More than ten (10) years		x	x	x	x
2	Source of bars					
i	Direct from local rolling mills			x	x	x
ii	Imported				x	x
iii	From main distributors	x	x	x		
iv	From hardware stores	x	x			
3	Case of failure of bars (Yes or No)					
i	Yes				x	x
ii	No	x	x	x		
4	Failure in:					
i	Yield Strength				x	x
ii	Ultimate tensile strength					
iii	Bending				x	
iv	Elongation					
5	Does the company have quality control?					
i	Yes		x	x	x	x
ii	No	x				
6	Types of bars most used					
i	Twisted	x	x	x	x	x
ii	Ribbed				x	x

Table G.3: **Summary of questionnaire to statutory bodies**

VARIABLES		RESPONDENTS		
		KEBS	RBS	MRPW
1	Types of tests carried out			
i	Tensile test	x		x
ii	Microstructure examination	x		
iii	Chemical analysis	x		x
2	Has the company have data bank of test carried out (Yes or No)			
i	Yes	x		x
ii	No		x	
3	How often does the company carry out routine inspection?			
i	Monthly			
ii	Quarterly	x		
iii	Yearly			
iv	Randomly			x
4	What minimum yield strength of the bar does the company specify?			
i	450	x	x	
ii	460			x
iii	500			
iv	No specification			
5	What minimum % Elongation of the bar does the company specify?			
i	10			
ii	12	x	x	
iii	14			x
iv	20			
6	What is the percentage of certified rolling mills in the country	95%	-	-
7	Who are the main importers of reinforcing steel bar in the country			
i	Building contractors			
ii	Hardware stores			
iii	Main distributors			
iv	All the above	x	x	

Table G.4: **Summary of questionnaire to hardware stores**

VARIABLES		RESPONDENTS (HARDWARE STORES)					
		A	B	C	D	E	F
1	Main customers						
i	Building contractors	x	x		x		
ii	Individual people	x	x	x			
2	Types of bars the company sales						
i	Twisted bars	x	x	x	x		
ii	Ribbed bars				x		
3	For what reason the above is mostly preferred?						
i	Is most manufactured in the country	x	x	x	x		
ii	Is cheap	x	x				
4	Source of reinforcing steel bars						
i	Local steel bars manufacturers	x	x	x			
ii	Overseas /imported						
5	Main suppliers/local manufacturers of bars in Kenya						
i	Devki Steel Plant Ltd	x		x	x		
ii	Athi River Steel Plant Ltd	x	x				
iii	Rolmill Kenya	x					
iv	Apex Steel Ltd		x				
v	Steelmakers Ltd						
vi	Prime Steel Kitengela Ltd	x					

Table G.5: **Summary of questionnaire to rolling mills**

VARIABLES		RESPONDENTS	
		RM1	RM2
1	Does the firm use scrap metal to manufacture reinforcing steel bars? (Yes or No)		
	Yes	x	x
	No		
2	If Yes How the firm sort out scrap?		
	Visual inspection	x	x
	Use of magnets		
	Conducting chemical analysis		x
3	How often do you carry out chemical composition analysis		
	Daily	x	x
	Weekly		
	Other , specify		
4	Which furnace do you use for smelting the scraps		
	Induction furnace	x	x
	Electrical Arc Furnace		
	Basic Oxygen Furnace		
5	At what temperature do you smelt the scrap?		
	1350 °C		
	1470 °C		
	1480 °C		
	Other , specify	1560 °C to 1600 °C	1580 °C
5	What temperature required for rolling the ingot into bars?		
	1000 °C		
	1050 °C		x
	1100 °C		x
	1200 °C	x	
	Other , specify		
6	Do you carry out any quality control of the product? (Yes or No)		
	Yes	x	x
	No		

Table G.6: **Summary of questionnaire to rolling mills cont'd**

7	If yes what tests do you carry out?		
	Tensile test	x	x
	Impact test	x	
	Bending test		x
	Chemical analysis	x	x
8	What is the minimum yield strength expected by carrying out tensile test?		
	250 N/mm^2		
	350 N/mm^2		
	460 N/mm^2	x	x
	Other specify		
9	What is the minimum % Elongation expected by carrying out tensile test?		
	10		
	12		
	14	x	x
	Other specify		
10	Do you carry out any heat treatment on the reinforcing bars? (Yes or No)		
	Yes		
	No	x	x
11	If yes, what type of heat treatment carried out?		
	Normalizing		
	Quenching and Tempering		
	Any other, specify		

APPENDIX H

SUMMARY OF WORK DONE AT STEEL MAKERS LTD

(Attachment for one month, from 7th April to 7th May 2009)

H.1 Introduction

Steel Makers Ltd processes bars from scrap metal. Steel processed from scrap metal is the most efficient method of producing steel because of less energy requirement as compared to steel processed from iron ore. The scrap consisted of a variety of metals that had be sorted before being charged into the furnace.

The sorting consisted of separating light metal and heavy metals. Care was taken not to charge dangerous material such as enclosed pipes, perfumed cans and gas containers since they could explode and cause serious damages to the staff as well as to the entire plant. After sorting the scrap, the next step was to charge the scrap into the furnace for smelting. The furnace used in production of steel was the induction furnace. A typical furnace used for smelting the scrap had a charging capacity of six tons from which sixty ingots were cast for the production of reinforcing steel bars. After cooling the ingots, they were reheated into a reheating furnace before rolling them into reinforcing bars of different shapes. Figure H.1 shows the flow chart followed to produce reinforcing steel bars.

The production process of reinforcing steel bars consisted of the following steps:

(i) Collecting and sorting of scrap steels

(ii) Pre-heating the furnace and charging the scrap metal in the furnace

(iii) Smelting the scraps into the furnace and prepare the moulds

(iv) Taking a small sample of the molten steel for chemical analysis before casting

(v) Casting of steel into the moulds (making ingots)

(vi) Removing ingots from the moulds after solidification

(vii) Cooling the ingots in still air

(viii) Reheating the ingots in the reheating furnace to the recrystallization temperature 100^{o}C - 1200^{o}C

(ix) Roughing operation

(x) Rolling the bars in three consecutive stands

(xi) Cooling the final product on the cooling bed

(xii) Cold twisting operation to increase the yield strength of the bars

Note: Ribbed bars do not necessary need the cold twisting operation. Ribs are formed on the bar as it passes through the last stand of the rolling mill where the bar is continuously deformed between two rollers. It is this deformation which imparts high strength to the bar. On the other hand twisted bars gain the high strength through cold twisting operation where the bar is strain hardened and hence results in an increase of yield strength accompanied by a decrease in ductility i.e. % Elongation.

H.2 Control of chemical composition during melting process

In the process of refining the molten steel, the sulphur and phosphorus had to be eliminated as far as possible, while carbon, silicon, and manganese were reduced to the percentage required in the finished steel. The removal of impurities was effected by means of oxidation, part of oxygen being supplied from the scale formed during melting-down period (i.e. time taken in the furnace), and the balance from ore additions to the molten slag or by introducing oxidizing agent such as rusted mild steel. The oxide of carbon being a gas, escaped in bubbles. The oxide of manganese, silicon and phosphorus on the other hand, passed into the slag, in which they were held. The process was controlled throughout by chemical analysis of small spoonful samples of the molten steel drawn off at intervals, and the carbon was reduced to the amount required in the finished steel. When the furnace was tapped the metal and slag were poured into the ladle, from which the molten steel was subsequently cast into the ingot moulds through a specially prepared nozzle fitted into the base of the ladle. Separation of slag from metal, took place in the ladle; the lighter slag, floating on the metal, protected it from oxidation and loss of heat.

The principal agents (alloying elements) used in the deoxidation of steel were manganese, silicon and aluminium; aluminium being the most powerful deoxidizer used in steel making. Aluminium was used in conjunction with silicon.

Besides acting as a deoxidizer, manganese played an important part in counteracting the harmful effect of sulphur, which could not be entirely removed in the refining process. In the absence of manganese, when the percent content of sulphur is high, sulphur combines with some of iron to form iron sulphide, which forms a very brittle membrane around the boundaries of the crystal grains.

H.3 Production of ingot

The moulds used for casting the ingots were cast iron with high interior surface finish to allow a corresponding surface finish of the cast (ingot). The specifications of the ingots produced are shown in Figure H.2. Ingot moulds were made of cast iron, having considerable wall thickness in order to withstand the severe conditions of service. To enable the ingot to be stripped from the mould after solidification, the mould was made open at both ends and was tapered in section as shown in Figure H.2. When casting, the bottom of the mould was sealed by simply placing it on a cast-iron base plate as shown in Figure H.3.

The following conditions are generally observed in casting of ingot:

(i) The temperature of the metal, the range of which is limited by the fact that if it is too high the ingots are liable to develop cracks in the working, and if it is too low the metal is so sluggish that the ingot has a very uneven skin. With proper melting conditions in the furnace there should never be any lack of heat for casting.

(ii) Another equally important factor in casting is the prevention of "splash", that is the metal splashing on to the sides of the mould.

Considering the pressure head of molten steel in the ladle and the height at which the stream of molten steel has to fall into the mould, it will be easily understood that to overcome splashing is by no means an easy matter, especially at the base end of an ingot when the stream strikes the bottom of the mould. Splashed metal immediately solidifies on the cool mould walls and becomes coated with a film of scale which prevents it from becoming properly fused into the main body of rising metal. This gives rise to surface defects in the ingot, which are often found later in the finished section of the ingot.

The type of mould casting used by Steel Makers Ltd is the bottom casting.

In this type of casting the molten metal is poured through a system of refractory runners into the base of the mould as shown in Figure H.3. This method has many advantages. In the first place it eliminates splash, and secondly the method is suitable for the simultaneous casting of a group of ingots from the one ladle stream. The finer and more uniform the stream the better will be the resulting ingots.

H.4 Rolling Process

The ingot after stripping from the mould was cooled and then transferred to a reheating furnace where it was reheated to a temperature from 1000^{o}C to 1250^{o}C. When soaked at these high temperatures, the ingot could be readily worked to any desired shape. The ductility increases with increase in temperature, and for this reason it was necessary for the temperature of ingot to be uniform throughout. Ribbed Bars were produced by mills with grooves, or passes cut in the rolls. The bar was drawn through these grooves by the rotation of the rolls, and by a series of such passes the bar reduced to the required section. A typical roll train illustrating successive passes is shown in Figure H.4.

The design of the grooves in the rolls is of the utmost importance, because bad design leads to defects in the finished product. 1^{st} and 2^{nd} passes remove taper in ingot and make it of uniform cross-sectional area. At the exit of the last stand the bar was cooled on the cooling bed and finally twisted.

H.5 Production of a specific bar size (e.g.Y16)

Consider a billet or ingot of weight *Wi*. To estimate the length of a square bar having a nominal diameter equivalent to the diameter of a round bar of 16mm, the following relation applies.

$$\text{Weight of the ingot } (W_i) = \text{Weight of the bar } (W_b) \tag{H.1}$$

$$W_b = x^2 \times \rho_s \times l_b \tag{H.2}$$

$$\text{Therefore}, x^2 \times \rho_b \times l_b = W_i \tag{H.3}$$

Where x: is the size of the square bar, ρ_s is the density of steel, l_b is the length of the bar. The size of the bar is given by the following expression.

$$\frac{\Pi d^2}{4} \times \rho_s = x^2 \times \rho_s \tag{H.4}$$

$$x = \sqrt{\frac{\Pi d^2}{4}} \tag{H.5}$$

Where d is the diameter of a round bar. Therefore the length of the square bar is given by:

$$l_b = \frac{W_i}{x^2 \times \rho_s} \tag{H.6}$$

For billet;

$$l_b = \frac{4 \times s^2 \times \rho_s \times l_i}{\Pi d^2 \times \rho_s} \tag{H.7}$$

Where: s is the size of the billet in mm li is length of the billet in mm.

If s= 100mm, li=6000mm and d=16mm

$$l_b = \frac{4 \times 100^2 \times 6000}{\Pi \times 16^2} = 29841.5mm \approx 298m \tag{H.8}$$

Therefore, ignoring cutting losses, 24 bars of 12 m long each can be produced from one single billet of 6 m long and 100x100 mm cross section.

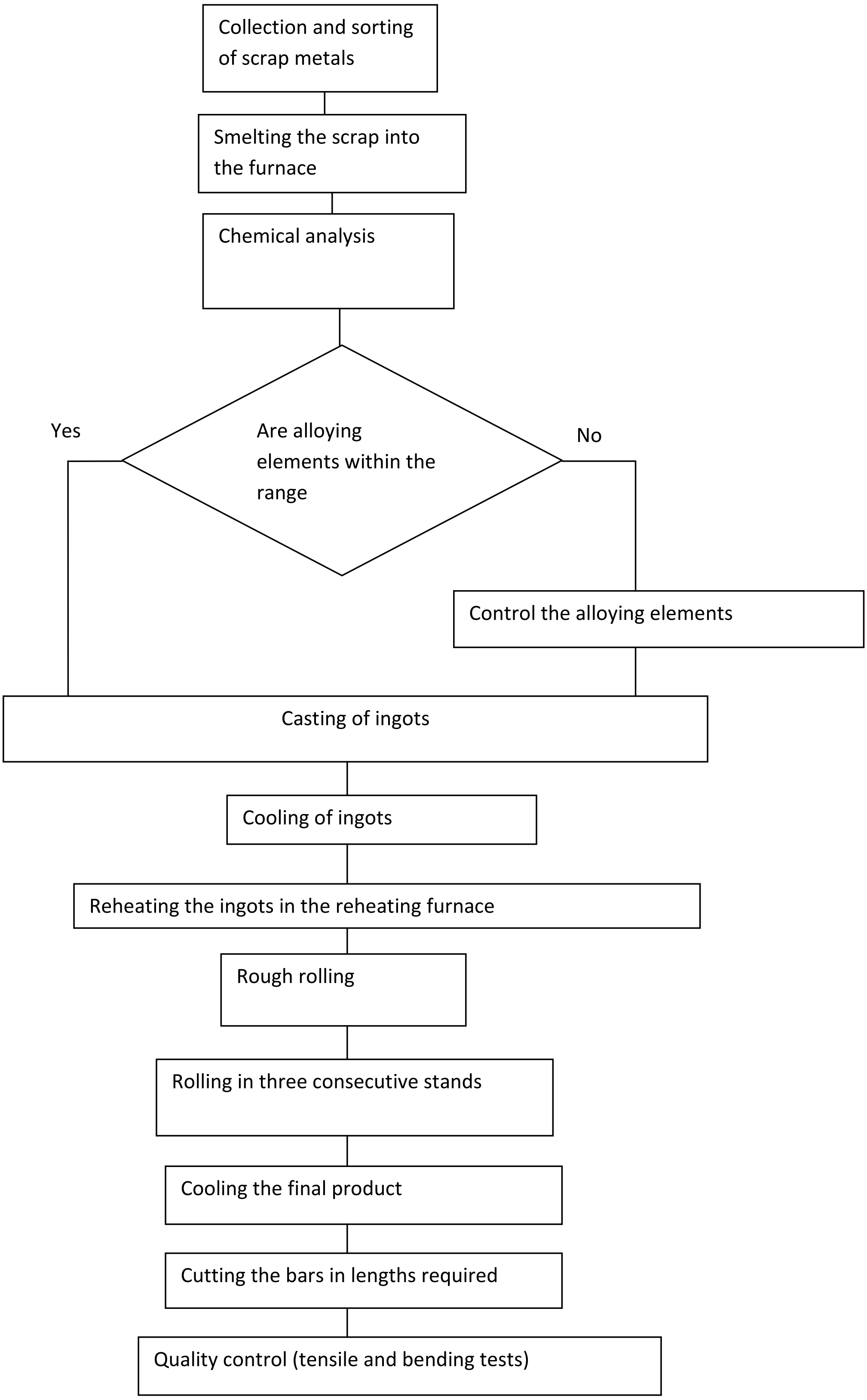


Figure H.1: **Flow chart of production process of reinforcing steel bars** a= 5 inch (127 mm)

b= 4 inch (101.6 mm)

L= 60 inch (1524 mm)

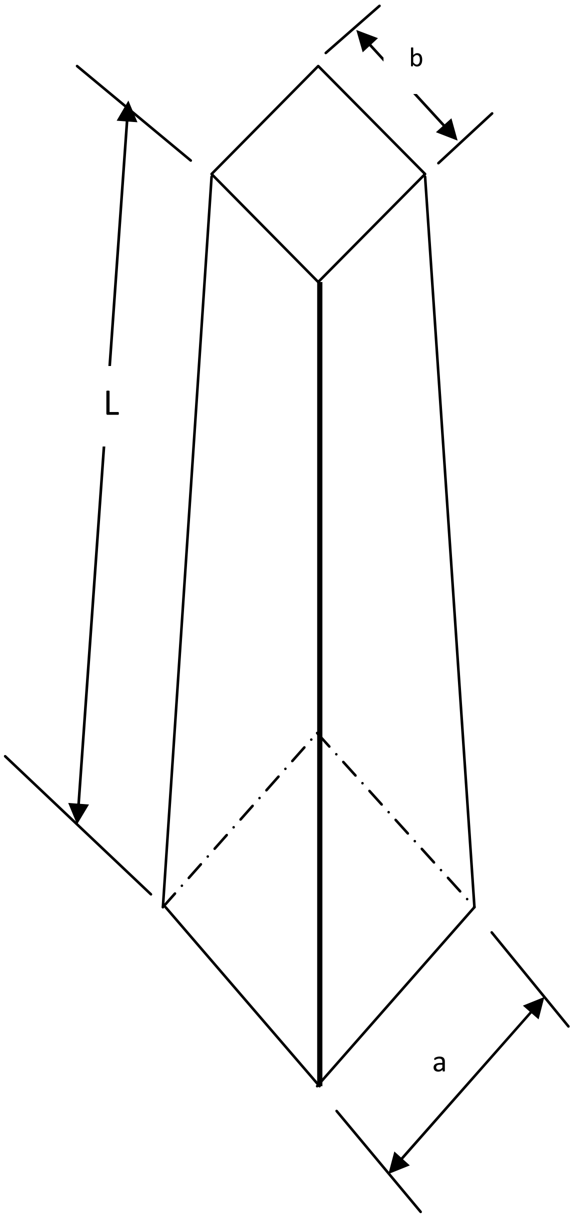


Figure H.2: **Dimensions of Ingot**

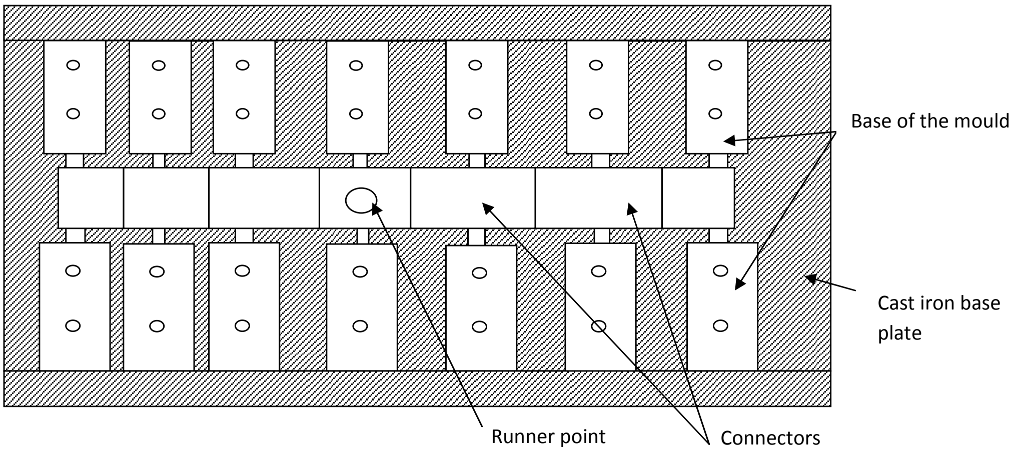


Figure H.3: **Top view of ingot moulds set on top of a cast- iron base plate**

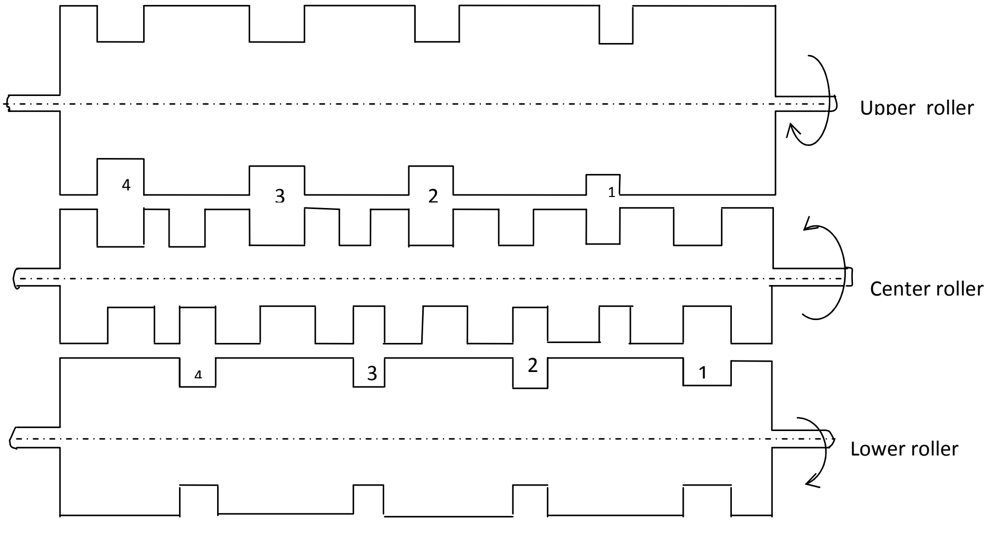


Figure H.4: **Alignment of Rollers in Roughing stands**

APPENDIX I

PROBABILITY DENSITY FUNCTION (PDF) AND STUDENT T-TABLE

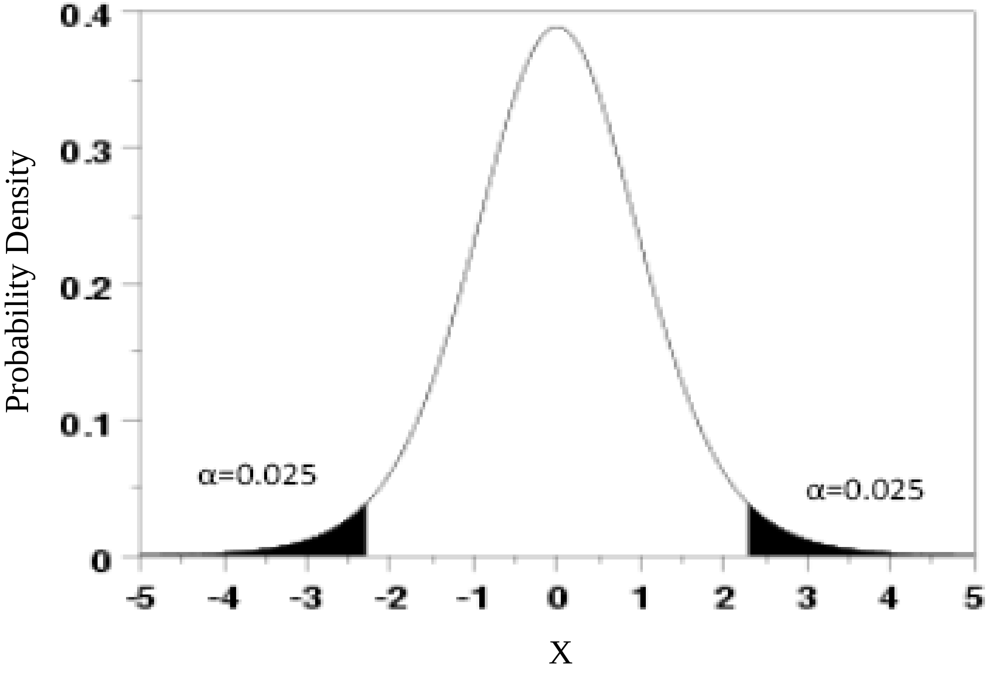


Figure I.1: **t-Probability Density Function (PDF)(Two-sided test at 95% C.I or $\alpha = 0.05$) [64]**

Table I.1: **Student's t- Table [64]**

ν	0.10	0.05	0.025	0.01	0.005	0.001
1.	3.078	6.314	12.706	31.821	63.657	318.313
2.	1.886	2.920	4.303	6.965	9.925	22.327
3.	1.638	2.353	3.182	4.541	5.841	10.215
4.	1.533	2.132	2.776	3.747	4.604	7.173
5.	1.476	2.015	2.571	3.365	4.032	5.893
6.	1.440	1.943	2.447	3.143	3.707	5.208
7.	1.415	1.895	2.365	2.998	3.499	4.782
8.	1.397	1.860	2.306	2.896	3.355	4.499
9.	1.383	1.833	2.262	2.821	3.250	4.296
10.	1.372	1.812	2.228	2.764	3.169	4.143
11.	1.363	1.796	2.201	2.718	3.106	4.024
12.	1.356	1.782	2.179	2.681	3.055	3.929
13.	1.350	1.771	2.160	2.650	3.012	3.852
14.	1.345	1.761	2.145	2.624	2.977	3.787
15.	1.341	1.753	2.131	2.602	2.947	3.733
16.	1.337	1.746	2.120	2.583	2.921	3.686
17.	1.333	1.740	2.110	2.567	2.898	3.646
18.	1.330	1.734	2.101	2.552	2.878	3.610
19.	1.328	1.729	2.093	2.539	2.861	3.579
20.	1.325	1.725	2.086	2.528	2.845	3.552
21.	1.323	1.721	2.080	2.518	2.831	3.527
22.	1.321	1.717	2.074	2.508	2.819	3.505
23.	1.319	1.714	2.069	2.500	2.807	3.485
24.	1.318	1.711	2.064	2.492	2.797	3.467
25.	1.316	1.708	2.060	2.485	2.787	3.450
26.	1.315	1.706	2.056	2.479	2.779	3.435
27.	1.314	1.703	2.052	2.473	2.771	3.421
28.	1.313	1.701	2.048	2.467	2.763	3.408
29.	1.311	1.699	2.045	2.462	2.756	3.396
30.	1.310	1.697	2.042	2.457	2.750	3.385
31.	1.309	1.696	2.040	2.453	2.744	3.375
32.	1.309	1.694	2.037	2.449	2.738	3.365
33.	1.308	1.692	2.035	2.445	2.733	3.356
34.	1.307	1.691	2.032	2.441	2.728	3.348
35.	1.306	1.690	2.030	2.438	2.724	3.340

Table I.2: Student's t- Table Cont'd

36.	1.306	1.688	2.028	2.434	2.719	3.333
37.	1.305	1.687	2.026	2.431	2.715	3.326
38.	1.304	1.686	2.024	2.429	2.712	3.319
39.	1.304	1.685	2.023	2.426	2.708	3.313
40.	1.303	1.684	2.021	2.423	2.704	3.307
41.	1.303	1.683	2.020	2.421	2.701	3.301
42.	1.302	1.682	2.018	2.418	2.698	3.296
43.	1.302	1.681	2.017	2.416	2.695	3.291
44.	1.301	1.680	2.015	2.414	2.692	3.286
45.	1.301	1.679	2.014	2.412	2.690	3.281
46.	1.300	1.679	2.013	2.410	2.687	3.277
47.	1.300	1.678	2.012	2.408	2.685	3.273
48.	1.299	1.677	2.011	2.407	2.682	3.269
49.	1.299	1.677	2.010	2.405	2.680	3.265
50.	1.299	1.676	2.009	2.403	2.678	3.261
51.	1.298	1.675	2.008	2.402	2.676	3.258
52.	1.298	1.675	2.007	2.400	2.674	3.255
53.	1.298	1.674	2.006	2.399	2.672	3.251
54.	1.297	1.674	2.005	2.397	2.670	3.248
55.	1.297	1.673	2.004	2.396	2.668	3.245
56.	1.297	1.673	2.003	2.395	2.667	3.242
57.	1.297	1.672	2.002	2.394	2.665	3.239
58.	1.296	1.672	2.002	2.392	2.663	3.237
59.	1.296	1.671	2.001	2.391	2.662	3.234
60.	1.296	1.671	2.000	2.390	2.660	3.232
61.	1.296	1.670	2.000	2.389	2.659	3.229
62.	1.295	1.670	1.999	2.388	2.657	3.227
63.	1.295	1.669	1.998	2.387	2.656	3.225
64.	1.295	1.669	1.998	2.386	2.655	3.223
65.	1.295	1.669	1.997	2.385	2.654	3.220
66.	1.295	1.668	1.997	2.384	2.652	3.218
67.	1.294	1.668	1.996	2.383	2.651	3.216
68.	1.294	1.668	1.995	2.382	2.650	3.214
69.	1.294	1.667	1.995	2.382	2.649	3.213
70.	1.294	1.667	1.994	2.381	2.648	3.211
71.	1.294	1.667	1.994	2.380	2.647	3.209
72.	1.293	1.666	1.993	2.379	2.646	3.207
73.	1.293	1.666	1.993	2.379	2.645	3.206
74.	1.293	1.666	1.993	2.378	2.644	3.204

Table I.3: Student's t- Table Cont'd

75.	1.293	1.665	1.992	2.377	2.643	3.202
76.	1.293	1.665	1.992	2.376	2.642	3.201
77.	1.293	1.665	1.991	2.376	2.641	3.199
78.	1.292	1.665	1.991	2.375	2.640	3.198
79.	1.292	1.664	1.990	2.374	2.640	3.197
80.	1.292	1.664	1.990	2.374	2.639	3.195
81.	1.292	1.664	1.990	2.373	2.638	3.194
82.	1.292	1.664	1.989	2.373	2.637	3.193
83.	1.292	1.663	1.989	2.372	2.636	3.191
84.	1.292	1.663	1.989	2.372	2.636	3.190
85.	1.292	1.663	1.988	2.371	2.635	3.189
86.	1.291	1.663	1.988	2.370	2.634	3.188
87.	1.291	1.663	1.988	2.370	2.634	3.187
88.	1.291	1.662	1.987	2.369	2.633	3.185
89.	1.291	1.662	1.987	2.369	2.632	3.184
90.	1.291	1.662	1.987	2.368	2.632	3.183
91.	1.291	1.662	1.986	2.368	2.631	3.182
92.	1.291	1.662	1.986	2.368	2.630	3.181
93.	1.291	1.661	1.986	2.367	2.630	3.180
94.	1.291	1.661	1.986	2.367	2.629	3.179
95.	1.291	1.661	1.985	2.366	2.629	3.178
96.	1.290	1.661	1.985	2.366	2.628	3.177
97.	1.290	1.661	1.985	2.365	2.627	3.176
98.	1.290	1.661	1.984	2.365	2.627	3.175
99.	1.290	1.660	1.984	2.365	2.626	3.175
100.	1.290	1.660	1.984	2.364	2.626	3.174
∞	1.282	1.645	1.960	2.326	2.576	3.090