TARIKU ACHAMYELEH ASRESS

MECHANICAL STRENGTH VARIABILITY OF DEFORMED REINFORCING STEEL BARS FOR CONCRETE STRUCTURES IN ETHIOPIA

PhD THESIS

2022

NEAR EAST UNIVERSITY

INSTITUTE OF GRADUATE STUDIES

DEPARTMENT OF MECHANICAL ENGINEERING

MECHANICAL STRENGTH VARIABILITY ANALYSIS OF DEFORMED REINFORCEMENT STEEL BARS FOR CONCRETE STRUCTURES IN ETHIOPIA

Ph.D. THESIS

Tariku Achamyeleh ASRESS

Nicosia

June, 2022

NEAR EAST UNIVERSITY
INSTITUTE OF GRADUATE STUDIES
DEPARTMENT OF MECHANICAL ENGINEERING

MECHANICAL STRENGTH VARIABILITY ANALYSIS OF DEFORMED REINFORCING STEEL BARS FOR CONCRETE STRUCTURES IN ETHIOPIA

Ph.D. THESIS

Tariku Achamyeleh ASRESS

Supervisors

Assoc. Prof. Dr. HÜSEYIN ÇAMUR
Prof. Dr. Mahmut A. SAVAŞ

Nicosia

June, 2022

Approval

We certify that we have read the thesis submitted by Ahmed Muayad Rashid AL-ANI titled **"MECHANICAL STRENGTH VARIABILITY ANALYSIS OF DEFORMED REINFORCING STEEL BARS FOR CONCRETE STRUCTURES IN ETHIOPIA"** and that in our combined opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Doctor of Mechanical Engineering.

Examining Committee	Name-Surname	Signature
Head of the Committee:	Assist. Prof. Dr. Ali ŞEFIK	
Committee Member:	Prof. Dr. Hasan HACIŞEVKI	
Committee Member:	Assoc. Prof. Dr. Kamil DIMILILER	
Committee Member:	Assoc. Prof. Dr. Youssef KASSEM	
Committee Member:	Assist. Prof. Dr. Metin BILIN	
Supervisor:	Assoc. Prof. Dr. Hüseyin ÇAMUR	
Co-Supervisor:	Prof. Dr. Mahmut A. SAVAŞ	

Approved by the Head of the Department

09/06/2022

Assoc. Prof. Dr. Hüseyin ÇAMUR

Head of Department

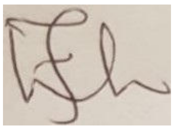
Approved by the Institute of Graduate Studies

…../…../2022

Prof. Dr. Kemal Hüsnü Can Başer

Declaration

I hereby declare that all information, documents, analysis and results in this thesis have been collected and presented according to the academic rules and ethical guidelines of Institute of Graduate Studies, Near East University. I also declare that as required by these rules and conduct, I have fully cited and referenced information and data that are not original to this study.



Tariku Achamyeleh Asress

09/06/2022

Acknowledgments

I am very much grateful to my supervisors Assoc. Prof. Dr. Hüseyin ÇAMUR and Prof. Dr. Mahmut A. SAVAŞ for the unconditional and unwavering support and guidance they have given me through my study in general and this thesis in particular.

I am also so thankful to all Mechanical Engineering Department staff for considering me as a colleague by providing me research assistantship position and course delivering role. Prof. Dr. Yusuf Sahin, Assoc. Prof. Dr. Ali Evcil, and Engin Esenel should also be thanked for their valuable time during my stay at NEU. I need to extend my gratitude to the members of the examining committee who have contributed their share during the monitoring process.

I would also like to thank my colleagues in the Department of Mechanical Engineering at Debre Tabor University, Ethiopia for their continuous support during laboratory experimental works.

I am grateful to the Betre-Science scholarship program designers and organizers at the then Ministry of Science & Technology (MoST) and later Ministry of Science & Higher Education (MoSHE) and Ministry of Education (MoE). I am thankful to the staff at Ethiopian Embassy - Ankara who have contributed their share in facilitating the stipend and other payments. Friends under the Betre-Science scholarship program at NEU, I am grateful for our time together as it was enjoyable and fruitful above all.

Special thanks go to my wife Mrs. Mehret Belete and my children Mariamawit and Leul for always never giving up on me on those days they were yearning for me during my study years away from home. Your devotion and strength have paid off well.

THANK YOU!

Tariku Achamyeleh ASRESS

Abstract

Mechanical Strength Variability Analysis of Deformed Reinforcing Steel Bars for Concrete Structures in Ethiopia

Asress, Tariku Achamyeleh
Ph.D., Department of Mechanical Engineering
Advisors: Assoc. Prof. Dr. Hüseyin ÇAMUR and Prof. Dr. Mahmut A. SAVAŞ
June 09, 2022 (118) pages

The requirement in terms of conformity and quality for concrete reinforced structures has widely become the center of interest in finding the optimum mechanical strength behaviors and linear density properties of reinforcement steel bars used in building and construction projects of all sorts. The mechanical strength and linear density variability analysis were studied in this research. The fact that use of substandard reinforcement steel bars in the Ethiopian construction industry has led to the failure of concrete reinforced structures and the collapse of buildings at large.

This study presents the statistical variability analysis of grade 60 deformed reinforcement steel bars considering mechanical strength behaviors and linear density properties. The investigation surveyed more than 450 samples of reinforcement steel bars from construction sites with nominal bar diameters covering 6 mm to 32 mm. The work was focused on 8, 10, 12, and 16 mm nominal bar diameters as these are the reinforcement steel bars that are widely used in the Ethiopian construction market, i.e. accounting for about 70%. The tests covered from the year 2015 to 2020. The four various bar diameter bars were grouped into two larger groups of lots upon the year the test was conducted. Lot 1 was for experimental tests conducted between 2015 and 2017 and Lot 2 between 2018 and 2020.

Yield strength (YS), tensile strength (TS), elongation, mass-per-length (M/L), and the characteristic ratio of tensile strength-per-yield strength were studied for the reinforcement bars those were identified in the initial survey. Mechanical and linear density behaviors were analyzed for statistical variability against statistical parameters such as the maximum, minimum, range, mean, standard deviation (SD),

coefficient of variance (CoV), skewness, and kurtosis based on the recorded experimental results. Furthermore, the results of YS, TS, EL, and TS/YS were analyzed independently by the one-way one-level analysis of variance (ANOVA) method in both of the lots.

It is found that the mean results of YS, TS, EL, and TS/YS ratio for Lots 1 and 2 were 593.1 MPa, 701.1 MPa, 14.8%, and 1.182; and 572 MPa, 674 MPa, 15.5%, and 1.177, respectively. The maximum experimental values of the aforementioned mechanical and density properties in the given order in Lots 1 and 2 were 857 MPa, 990 MPa, 28%, 1.96; and 766 MPa, 828 MPa, 27%, 1.91, respectively whereas the minimum values in Lot 1 and 2 were 354 MPa, 487 MPa, 6%, 1.03; and 332 MPa, 483 MPa, 5%, 1.02, respectively. The coefficient of variance values of TS, YS, EL and TS/YS in Lots 1 and 2 were 14.5%, 9.7%, 26.8%, 10.3%; and 14.2%, 9.6%, 23.7%, 9.5%, respectively. Furthermore, the one-level one-way ANOVA, with a confidence interval of 95%, indicated that the aggregate data of all the sample bars in both lots showed significant variability. The contribution percentage of the ANOVA analysis for YS, TS, EL and TS/YS in Lot 1 and Lot 2 were 70.4%, 58.5%, 67.8%, 16.5%; and 65.7%, 40.9%, 75.7%, 22.8%, respectively.

The normality test and goodness-of-fit analysis for YS, TS, EL, and TS/YS indicated that there were no distribution models that best fit the data. Thus, the transformation of the data was applied using a transformation technique called Box-Cox Transformation. The transformation in all mechanical strength parameters demonstrated that reinforcement steel bars used in the Ethiopian construction market were lacking process capability.

Despite a decrement in mean values of yield and tensile strength and a slight increment of elongation percentage from Lot 1 to Lot 2, all the mean values of YS, TS, and EL in both Lots 1 and 2 fulfilled the minimum recommended sets of values by the ASTM A615 standard. This could justify that the class of steel reinforcement bars used in the Ethiopian construction industry could commonly be used for common structural applications. The class of steels considered in this experimental work prevailed that it is not advisable to use the bars in the seismic prone areas such as the earthquake regions, as the bars could easily fail in post elastic loading conditions.

It appears that the regulatory governmental entities in Ethiopia such as the Ethiopian Standards Institute (ESI), and also the federal and regional design and supervision organizations and clients should put effort into strengthening the quality control practices and customs for the conformity of the rebars with the international and national standards.

Following the present work, additional studies would be conducted on the variability of material compositions and their effect on strength characteristics. The source of the reinforcement bars should also be considered to avoid the wrong generalization. Moreover, the effects of chemical composition, microalloying, and corrosion on mechanical and linear density behavior of deformed reinforcement steel bars should be investigated further in the future.

***Keywords*:** reinforcement steel; grade 60; yield strength; tensile strength; percent elongation

Özet

Etiyopya'da Beton Yapilar İçin Deforme Edilmiş Destek Çeliklerinin Mekanik Mukavemet Varyasyon Analizi

Asress, Tariku Achamyeleh
Doktora Tezi, Makina Mühendisliği Bölümü
Danışmanlar: Doç. Dr. Hüseyin ÇAMUR ve Prof. Dr. Mahmut A. SAVAŞ
09 Haziran 2022, (118) sayfa

Betonarme yapılar için uygunluk ve kalite gereksinimi, her türden inşaat projelerinde kullanılan donatı çelik çubuklarının optimum mekanik ve doğrusal yoğunluk davranışlarını bulmada geniş çapta ilgi odağı haline gelmiştir. Bu araştırmada mekanik dayanım ve lineer yoğunluk değişkenlik analizi çalışılmıştır. Etiyopya inşaat endüstrisinde standart altı çelik donatı çubuklarının kullanılması, betonarme yapıların başarısız olmasına ve genel olarak binaların çökmesine yol açmıştır. Bu çalışmada, deforme olmuş 60. Sınıf çelik çubukların mekanik mukavemet ve doğrusal yoğunluk davranışlarının değişkenliğinin istatistiksel analizini incelendi. Bu nedenle, 6 mm ila 32 mm arasında değişen çubuk çaplarına sahip şantiyelerden alınan 450'den fazla çelik takviye çubuğu örneği toplandı. Çalışmalar, Etiyopya inşaat pazarında yaygın olarak kullanılan takviye çelik çubukları, yani ~%70 olduğundan, 8, 10, 12 ve 16 mm'lik çubuk çaplarına odaklandı. 2015'ten 2020'ye kadar olan bir süreç göz önüne alındı. Dört farklı çaplı çubuk, test yıllarına göre iki partiye ayrıldı. Lot 1, 2015 ile 2017 arasında ve Lot 2, 2018 ile 2020 arasında gerçekleştirilen deneysel testler kapsamında değerlendirildi. İlk etütte tanımlanan donatı çubukları için akma dayanımı (YS), çekme dayanımı (TS), uzama, uzunluk başına kütle ve çekme dayanımının akma dayanımına karakteristik oranı incelenmiştir. Mekanik ve doğrusal yoğunluk davranışları, kaydedilen deneysel değerlere bağlı olarak maksimum, minimum, aralık, ortalama, standart sapma (SD), varyans katsayısı (CoV), çarpıklık ve basıklık gibi istatistiksel parametrelere karşı istatistiksel değişkenlik açısından analiz edilmiştir. Ayrıca, akma mukavemeti, çekme mukavemeti, uzama yüzdesi ve akma başına çekme mukavemeti sonuçları, her iki partide de tek seviyeli ve tek yönlü varyans analizi (ANOVA) yöntemiyle

bağımsız olarak irdelenmiştir. Lot 1 ve Lot 2 için çekme dayanımı, akma dayanımı, uzama yüzdesi, çekme-akma dayanımı oranı ortalama değerlerinin 593.1 MPa, 701.1 MPa, %14.8; ve sırasıyla 572 MPa, 674 MPa, %15.5 olduğu görülmüştür. Lot 1 ve 2'deki yukarıda bahsedilen mekanik ve yoğunluk özelliklerinin maksimum deneysel değerleri 857 MPa, 990 MPa, %28, 1.96; ve 766 MPa, 828 MPa, %27, 1.91, Lot 1 ve 2'deki minimum değerler ise 354 MPa, 487 MPa, %6, 1.03; ve sırasıyla 332 MPa, 483 MPa, %5, 1.02 olarak tesbit edilmiştir. Lot 1 ve 2'deki TS, YS, EL ve TS/YS'nin varyans değerleri katsayısı %14.5, %9.7, %26.8, %10.3; ve sırasıyla %14.2, %9.6, %23.7, %9.5 olarak bulunmuştur. Ek olarak, %95 güven aralığına sahip tek seviyeli ve tek yönlü ANOVA, her iki lottaki tüm çubukların toplu verilerinin önemli değişkenlik gösterdiğini ortaya koymuştur. Lot 1 ve Lot 2'de YS, TS, EL ve TS/YS için ANOVA analizinin katkı yüzdesi %70.4, %58.5, %67.8, %16.5; ve sırasıyla %65.7, %40.9, %75.7, ve %22.8 seviyesindedir.

YS, TS, EL ve TS/YS için normallik testi ve uyum iyiliği analizi, verilere en uygun dağılım modelinin olmadığını göstermiştir. Böylece verilerin dönüştürülmesi, Box-Cox Dönüşümü adı verilen bir dönüşüm tekniği kullanılarak uygulandı. Tüm mekanik dayanım parametrelerindeki dönüşüm, Etiyopya inşaat pazarında kullanılan çelik donatı çubuklarının proses kabiliyetinden yoksun olduğunu gösterdi.

Lot 1'den Lot 2'ye akma ve çekme mukavemeti değerlerindeki azalmaya ve uzama yüzdesindeki hafif artışa rağmen, Lot 1 ve Lot 2'deki YS, TS ve EL'nin ortalama değerleri, ASTM A615 standartı tarafından önerilen minimum değer setlerini karşıladığı anlaşıldı. Bu veriler, Etiyopya inşaat endüstrisinde kullanılan çelik takviye çubukları sınıfının genel yapısal uygulamalar için yaygın olarak kullanılabileceğini mümkün gösterebilir. Buradaki deneysel çalışmada incelenen çelik sınıfı, çubuklar elastik sonrası yükleme koşullarında kolayca bozulabileceğinden, yer sarsıntısı gibi sismik eğilimli alanlarda kullanılmaları sakıncalı olabilir.

Etiyopya Standartları Enstitüsü (ESI) gibi Etiyopya'daki düzenleyici devlet kurumları ile federal ve bölgesel tasarım ve denetim kuruluşları ve müşteriler, inşaat demirlerinin uluslararası ve ulusal standartlara uygunluğu için kalite kontrol uygulamalarının ve gümrüklerin güçlendirilmesi için çaba göstermelerinin gerektiği anlaşılmaktadır.

Burada verilen çalışmanın ardından malzeme bileşimlerinin değişkenliği ve bunların mukavemet özellikleri üzerindeki etkileri hakkında ek çalışmalar yapılması önerilebilir. Yanlış genellemelerden kaçınmak için donatı çubuklarının kaynağı da dikkate alınmalıdır. Ayrıca, kimyasal bileşimin, mikro alaşımlamanın ve korozyonun deforme olmuş takviye çelik çubuklarının mekanik ve doğrusal yoğunluk davranışı üzerindeki etkisi daha detaylı araştırılmalıdır.

Anahtar kelimeler: takviye çeliği; 60 derece; akma dayanımı; gerilme direnci; uzama yüzdesi

Table of Contents

Approval 2

Declaration 3

Acknowledgments 4

Abstract 5

Table of Contents 11

List of Tables 15

List of Figures 16

List of Abbreviations 18

CHAPTER I

Introduction 19

Statement of the Problem 20

Purpose of the Study 22

Research Questions / Hypotheses 22

Questions 22

Answers 22

Significance of the Study 23

Limitations 23

Definition of Terms 24

Lower yield strength 24

Luder strain 24

Strain Hardening 25

Tensile Strength 25

Elongation at fracture 25

CHAPTER II

Literature Review 26

General Introduction.. 26

Carbon Content.. 26

Production of Steel 27

Steel Production from Iron Ore 29

Types of Steel... 29

Carbon Steel.. 30

Alloy Steel 30

Stainless Steel 30

Tool Steel.. 30

High-Carbon Steel 30

Mild Steel.. 31

Medium Carbon Steel 31

Stainless Steel 31

High-Speed Steel 31

Cobalt Steel.. 31

Nickel Chromium Steel 31

Aluminum Steel 31

Chromium Steel 31

Corrosion and Reinforcement Steel Bars 31

Corrosion Process 32

Mass Loss 33

Effect of Corrosion on Monotonic and Variable Loading 34

Compressive Strength... 34

Tensile Strength... 34

CHAPTER III

Methodology... 37

Survey.. 37

Types and Sample Size of Reinforcement Bars 37
Materials 38
Tensile Test 39
Variability Analysis 39
Goodness-of-fit 41
Process Capability 41
Error Analysis 42
Error in Addition 42
Error in Subtraction 42
Error in a Product 43
Error in a Division 43
CHAPTER IV
Findings and Discussion 44
Distribution of Reinforcement Steel Bars 44
Distribution for 8 mm Diameter 44
Distribution for 10 mm Diameter 50
Distribution for 12 mm Diameter 57
Distribution for 16 mm Diameter 63
Distribution for the Lot Aggregate Data 70
Summary for the Total Aggregate Data 76
Distribution of Mechanical Strengths 76
Statistical Summary 79
Goodness-of-fit Test 80
Error Analysis 84
CHAPTER V
Discussion 86
Mechanical Strength Characteristics 86

Variability Analysis 86

Goodness-of-fit and Process Capability Analysis 89

CHAPTER VI

Conclusion and Recommendations 90

Conclusion 90

Recommendation 91

Future Work 92

References 93

Appendices 102

Appendix A F-Table & $F_{.05}$ (f_1, f_2), 95% Confidence Interval (Roy, 2010) 102

Appendix B ASTM A615/A615M -15a 104

Appendix C ACI 318 -11 107

Appendix D Plagiarism Report 110

Appendix E Curriculum Vitae 111

List of Tables

Page

Table 1. Percentage of Utilization of Rebars in the Ethiopian Market 37
Table 2. Generalized Analysis of Variance Table 40
Table 3. Statistical Summary of 8 mm Diameter in Lot 1 48
Table 4. Statistical Summary of 8 mm Diameter in Lot 2 48
Table 5. ANOVA of 8 mm Diameter in Lot 1 49
Table 6. ANOVA of 8 mm Diameter in Lot 2 50
Table 7. Statistical Summary of 10 mm Diameter in Lot 1 54
Table 8. Statistical Summary of 10 mm Diameter in Lot 2 55
Table 9. ANOVA Summary of 10 mm Diameter in Lot 1... 55
Table 10. ANOVA Summary of 10 mm Diameter in Lot 2....................................... 56
Table 11. Statistical Summary of 12 mm Diameter in Lot 1 61
Table 12. Statistical Summary of 12 mm Diameter in Lot 2 61
Table 13. ANOVA Summary of 12 mm Diameter in Lot 1....................................... 62
Table 14. ANOVA Summary of 12 mm Diameter in Lot 2....................................... 63
Table 15. Statistical Summary of 16 mm Diameter in Lot 1 67
Table 16. Statistical Summary of 16 mm Diameter in Lot 2 68
Table 17. ANOVA Summary of 16 mm Diameter in Lot 1....................................... 68
Table 18. ANOVA Summary of 16 mm Diameter in Lot 2....................................... 69
Table 19. Statistical Summary of the Aggregate Data in Lot 1 73
Table 20. Statistical Summary of the Aggregate Data in Lot 2 74
Table 21. Statistical Summary of the Aggregate Data in Lot 1 74
Table 22. ANOVA Summary of the Aggregate Data in Lot 2.................................. 75
Table 23. Statistical Summary of the Total Aggregate Data 79
Table 24. ANOVA Summary of the Total Aggregate Data....................................... 79
Table 25. Summary of Goodness-of-fit Test... 80
Table 26. Summary of Absolute and Relative Error Values...................................... 85
Table 27. Results From Previous Studies in Ethiopia and Other Countries 87

List of Figures

Page

Figure 1. Schematic Stress-strain Curve for a Structural Grade Steel 24
Figure 2. Steel Production Share of Different Methods.. 28
Figure 3. Process Stages for Iron Production.. 29
Figure 4. Scheme of the Accelerated Corrosion Process 33
Figure 5. Effect of Corrosion on Strength of Reinforcements Bars........................... 36
Figure 6. Representative Photos of Test Specimens and Tensile Test Setup............. 39
Figure 7. Distribution of YS for 8 mm in Lot 1 and Lot 2... 44
Figure 8. Distribution of TS for 8 mm in Lot 1 and Lot 2 45
Figure 9. Distribution of Elongation Percentage for 8 mm in Lot 1 and Lot 2.......... 46
Figure 10. Distribution of Mass-per-length for 8 mm in Lot 1 and Lot 2 46
Figure 11. Distribution of TS/YS for 8 mm in Lot 1 and Lot 2................................. 47
Figure 12. Scatterplot of TS/YS vs YS of Respective Lots for 8 mm Bars............... 47
Figure 13. Distribution of YS for 10 mm in Lot 1 and Lot 2..................................... 51
Figure 14. Distribution of TS for 10 mm in Lot 1 and Lot 2 51
Figure 15. Distribution of Elongation for 10 mm in Lot 1 and Lot 2 52
Figure 16. Distribution of Mass-per-length for 10 mm in Lot 1 and Lot 2 53
Figure 17. Distribution of TS/YS for 10 mm in Lot 1 and Lot 2............................... 53
Figure 18. Scatterplot of TS/YS vs YS of Respective Lots for 10 mm Bars............. 54
Figure 19. Distribution of YS for 12 mm in Lot 1 and Lot 2..................................... 57
Figure 20. Distribution of TS for 12 mm in Lot 1 and Lot 2 58
Figure 21. Distribution of Elongation for 12 mm in Lot 1 and Lot 2 58
Figure 22. Distribution of Mass-per-length for 12 mm in Lot 1 and Lot 2 59
Figure 23. Distribution of TS/YS for 12 mm in Lot 1 and Lot 2............................... 60
Figure 24. Scatterplot of TS/YS vs YS of Respective Lots for 12 mm Bars............. 60
Figure 25. Distribution of YS for 16 mm in Lot 1 and Lot 2..................................... 64
Figure 26. Distribution of TS for 16 mm in Lot 1 and Lot 2 65
Figure 27. Distribution of Elongation for 16 mm in Lot 1 and Lot 2 65
Figure 28. Distribution of Mass-per-length for 16 mm in Lot 1 and Lot 2 66
Figure 29. Distribution of TS/YS for 16 mm in Lot 1 and Lot 2............................... 66
Figure 30. Scatterplot of TS/YS vs YS of Respective Lots for 16 mm Bars............. 67

Figure 31. Distribution of YS for the Aggregate data in Lot 1 and Lot 2 70
Figure 32. Distribution of TS for the Aggregate data in Lot 1 and Lot 2 71
Figure 33. Distribution of Elongation for the Aggregate Data in Lots 1 and 2 72
Figure 34. Distribution of TS/YS for the Aggregate Data in Lot 1 and Lot 2 72
Figure 35. Scatterplot of TS/YS vs YS of Respective Lots for the Aggregate 73
Figure 36. Distribution and Normality Test of YS for the Total Aggregate 76
Figure 37. Distribution and Normality Test of TS for the Total Aggregate 77
Figure 38. Distribution and Normality Test of EL for the Total Aggregate 77
Figure 39. Distribution and Normality TS/YS for the Total Aggregate 78
Figure 40. Scatterplot of TS/YS vs YS of the Total Aggregate Data 78

List of Abbreviations

ACI:	American Concrete Institute
AD:	Anderson-Darling
ASTM:	American Standards for Testing Materials
BCT:	Box-Cox Transformation
BOF:	Basic Oxygen Furnace
CoV:	Coefficient of Variance
c_p/ c_{pk}:	Process Capability Indices (Sample)
EAF:	Electric Arc Furnace
EL:	Elongation Percentage
ESI:	Ethiopian Standards Institute
GDP:	Growth Domestic Product
LSL:	Lower Specification Limit
OHF:	Open-Hearth Furnace
p_p/ p_{pk}:	Overall Process Performance Indices (Population)
PPM:	Parts per Million
RC:	Reinforced Concrete
Rebar:	Reinforcement bar
SD:	Standard Deviation
TS:	Tensile Strength
USL:	Upper Specification Limit
UTM:	Universal Testing Machine
YS:	Yield Strength

CHAPTER I

Introduction

Concrete is relatively stronger for compressive than tension loadings. In reinforced concrete (RC) structure, reinforcement steel which shows equal strength for compressive and tensile load is used to have combined improved quality of the concrete to withstand tensile force on the concrete structure. The steel bars employed for the provision of reinforcement in concrete structures are termed reinforcing or in other words reinforcement steel bars shortly rebars. The mechanical behaviors of rebars play a greater role in the improvement of the service life of construction buildings and structures like bridges and skyscrapers. Moreover, in places where the earthquake is inevitable, the concrete structure is prone to fatigue failure in that reinforcement steel bars play important role in withstanding loads at post elastic conditions. Under the circumstances, the rebars give the reinforced concrete structure to use its strength and dissipation of energy characteristics. This phenomenon relies greatly on the ductile behavior of the structure beyond the elastic proportional region. In general, the strength and durability of RC structures depend largely on the extent of certain properties of the rebars such as yield, tensile strength, fatigue, and bending strengths. Ductility and weldability index, and are also properties governing the strength of steel in RC members.

Steel exhibits a wide range of mechanical behaviors from which the factor of strength is the predominant characteristic. The mechanical strength of engineering materials is assessed concerning yield strength, tensile strengths, elasticity modulus, percentage of elongation, and so forth. Any increase in these properties of steel will enrich the durability, reliability, and availability of the structures the steel is used.

In the design of structures, uncertainties in loading, design, and construction make it possible for the effect of the load to be lower or higher than the estimated value the structure is expected to resist. Possible causes of these uncertainties take account of unanticipated load settings, varying constructional tolerances and loadings, and material property variations. For this reason, building design codes and specifications demand the factor of design to be greater than unity maximizing the probability of reliability to an acceptably high level in other words failure will be the least possible.

Under the category of material property variations, the variability of mechanical strength and linear density properties of reinforcement steel bars influence the overall performance of reinforced concrete structures.

In the United States of America (US) and Great Britain, the material properties have specified requirements as detailed by ASTM A 615, A 706, and BS 4449 standards (ASTM A 615, 2015; ASTM A706, 2001).

This study is conducted to analyze the variability of the mechanical strength and linear density behaviors of reinforcement steel bars used in construction projects throughout Ethiopia and to evaluate the degree to which reinforcement steel bars in the Ethiopian market satisfy the minimum requirements set by ASTM and other related standards (ACI, 2011). These tests measure the yield strength, tensile strength, percentage of elongation, and mass-per-length of the reinforcement steel bars.

Statement of the Problem

Variation is common for products under manufacturing processes. The variation can be within the product itself, or product to product generally due to manufacturing inconsistencies. The way the product is transported and stored can also be a source of variation. A well-established understanding of the variability of steel properties is advantageous in the development and advancement of statistically-based analysis and expressions for concrete member strength that is used in the further establishment of reliability-based strength-reduction factors in the design and building codes. For these reasons, it is useful to analyze the actual experimental values of the mechanical strength and linear density behaviors of the reinforcement steel bars as compared to those used in design and construction.

The mechanical strength and linear density behaviors of reinforcement steel bars are controllable at the manufacturing stage, but the variations from piece to piece, from batch to batch and from industry to industry are difficult to control influenced by factors such as loading rate, variation in material composition, and nominal bar cross-section.

For these reasons, all manufacturing firms conduct tests on their steel bar products as per their quality controlling policy to verify that their bars conform to certain international standards and accepted requirements. These tests are performed to measure the yield strength, tensile strength, elongation percentage, and mass-per-length (or percent of nominal weight) of the reinforcement steel bars.

In the case of Ethiopia, the construction sector is growing annually with an average of 12.43% and its contribution to the Growth Domestic Product (GDP) is 5.3%. One of the common building materials in the construction industry is steel (Awonchefew, 2018). The demand for reinforcement steel bars in the Ethiopian market is fulfilled from two sources, i.e. local production and importation of reinforcement bars with a 57.51% share of imported steel bars (Tariku, 2020). The production of reinforcement bars in Ethiopian industries largely depends on the usage of recycled metal scraps that, according to research, show a great variation in mechanical properties due to scrap feed inconsistency and impurities in the scraps. This led to the hasty generalization that the reinforcement bars produced locally are mostly substandard ones which in turn is highly affecting consumers purchasing behavior (Tariku, 2020).

Moreover, global and local market dynamics greatly affect the supply of reinforcement steel bars to construction projects. The past few years have demonstrated that the turbulent market dynamics impacted the construction industry. Gashahun, (2020) assessed how Covid-19 impacted the industry. Furthermore, in the case of Ethiopia, nationwide protests underwent since 2016. The government had imposed a repeated state of emergencies as a cracking down mechanism for upheavals (Jayapregasham et al., 2018). The construction industry as the backbone of the country's economy faced a headwind from both global and national social, political and economic grievances. Commonly, the void in the reinforcement steel bar market is filled with either locally produced bars or substandard ones left for years due to lack of conformity.

Despite the extensive efforts made in the construction industry that have been taking place in the country; no documented detailed studies have been done on the quantification of such variability and its possible source. The present research work was designed to explore the characterization and variability study of mechanical strength behaviors of rebars used in the Ethiopian market and to identify the possible source of variation with some suggestions.

Purpose of the Study

The general purpose/objective of this study is to investigate the mechanical strength characteristic of grade 60 reinforcement steel bars used in the Ethiopian construction market in the years 2015 - 2020.

Specifically, the study had the following four purposes;

i. To survey and identify the most used bar sizes in the Ethiopian construction market.

ii. To evaluate the mechanical and linear density properties of the identified bar sizes.

iii. To methodize a classification approach to assess the effect of usage time on mechanical strength and linear density properties.

iv. To analyze statistical variability of the bars using mechanical strength and linear density parameters.

Research Questions / Hypotheses

Questions

I. What are the most utilized reinforcement steel bars grade and size i.e. nominal diameter?

II. How can we classify the experimental work?

III. What are the parameters that well describe the mechanical and linear density properties?

IV. What are the test methods to find out the required properties?

V. What are the statistical tools to examine the variability of mechanical strengths?

Answers

Hypothesis (Alternate Hypothesis): Grade 60 reinforcement steel bars are widely used for general civil structures.

I. The most utilized grade in the Ethiopian construction market has to be identified to give due consideration to the appropriate grade and sizes used at most (Achamyeleh & Şahin, 2019).

II. The situation analysis in the construction market is turbulent due to numerous global and national dynamics (Gashahun, 2020). The paper will follow the grouping of the experimental run based on the test period to show how the test periods can affect the variability of the mechanical strength properties.

III. Steel products can best be explained by how they perform on certain mechanical strength behaviors. Finding parametric values such as yield strength (Bournonville et al., 2004; Perera & Guluwita, 2018), tensile strength, elongation percentage at fracture (Carrillo et al., 2021), mass-per-length (Carrillo et al., 2021; Djavanroodi & Salman, 2017) and tensile to yield strength ratio (Djavanroodi & Salman, 2017; Tavio, Retno, Raka, & Agustiar, 2018) values of the reinforcement steels bars generally depicts the overall performance of the bar in general structural applications and seismic-prone areas.

IV. Tensile tests for the elongation percentage and yield and tensile strengths, direct measurement, and weighing of the reinforcement bar for estimating the mass-per-length values for each specimen are the common test methods in characterizing reinforcement steel bars.

V. Real mechanical behaviors of the reinforcement steels bars enable evaluating the anticipated reinforce concrete (RC) structure performance variability performance which in turn cut the uncertainty (Carrillo et al., 2021).

Significance of the Study

The significance of the study is to provide information to manufacturing industries, governing bodies, and end-users of reinforcement steel bars on the possible causes of variability of mechanical properties and provide alternative ways of improving the quality of the bars in the Ethiopian construction market.

Limitations

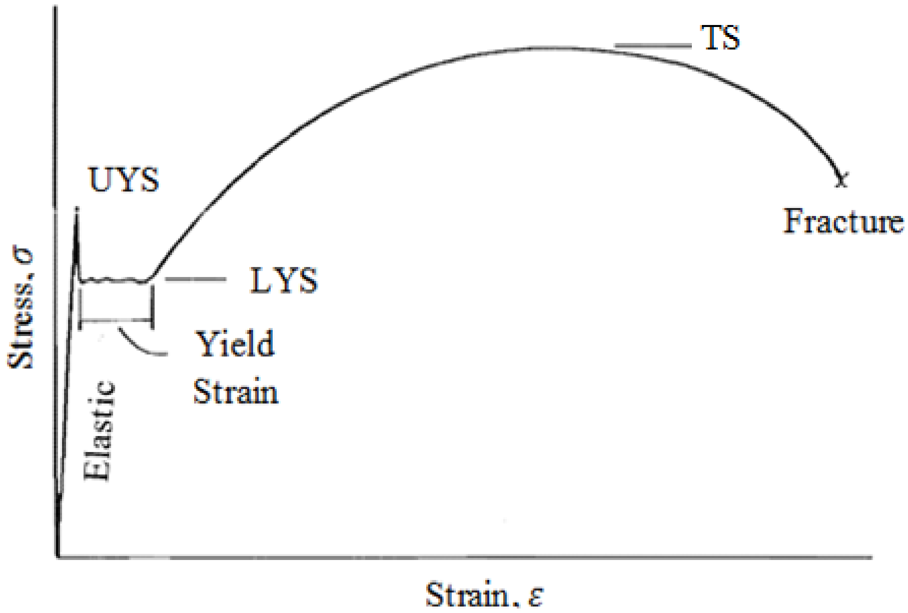
This study is limited to grade 60 reinforcement steel bars of nominal diameters of 8 mm, 10 mm, 12 mm, and 16 mm. Mechanical strength characteristics particularly yield strength, tensile strength, percentage of elongation; and linear density property i.e., mass-per-length are the main parameters of interest studied in this paper. Reinforcement steel bar sources, the effect of chemical composition, and corrosion are not part of this research work.

Definition of Terms

A typical stress-strain relationship for reinforcement steel bars used in RC members is presented in Figure 1. The corresponding mechanical strength properties and their derivatives are investigated using the diagram. For this, the terms and definitions that are used throughout this study are presented in this section.

Figure 1.

Schematic Stress-strain Curve for a Structural Grade Steel (Tat, 1991)



Lower yield strength

As indicated in the stress-strain curve, it indicated an initial linearly proportional elastic region up to a point. A sudden load drop happens when the elastic proportionality limit is attained. The point at which this phenomenon occurs is termed the upper yield point and that is the amount of stress sufficiently initiating plastic deformation. Following the sudden drop, fluctuation of the load is exhibited for about a nearly constant stress value dwelling Luder ensembles form and disperse throughout the specimen's gauge length. The lowest recorded point value is referred to as the lower yield. The stress at that point is termed the lower yield point or lower yield strength.

Luder strain

Luder strain which is termed yield point elongation denotes the elongation that befalls at the lower yield point stress. At this point, the strain increases without further increase in stress. The overall tensile strength of steel generally depends on the nature of the Luder strain. The higher the carbon content the shorter the Luder strain. This region of the Luder strains adds benefit to the concrete structure in conditions when the structure is loaded with a seismic environment. The reinforcement steel bar in this loading condition will give extra strength in withstanding post elastic deformation which is expected at plastic joints.

Strain Hardening

This section in the stress-strain curve usually starts when there is an increase in the stress immediately after the Luder strain region. When this phenomenon in steel is exhibited, additional force increment in the loading is expected so that the deformation may progress. The rate by which the stress increases over the even strain hardening section is controlled by the rated strain is hardening which is considered a material property of the steel.

Tensile Strength

Metals usually of having ductile property, when they are stressed with a stress value higher than the elastic proportion limit, will follow plastic deformation. The strain hardening phenomenon prior to this region will have an increasing force application which leads to further deformation. Consequently, the highest maximum force will be recorded resulting from plastic deformation instability. Following this point, the amount of load or force applied will be reduced up to a point at which fracture or rupture of the material occurs. The tensile strength is determined in the process as the largest recorded load divided by the original cross-sectional area of the specimen. The tensile strength is one of the reinforcement steel properties used to determine the flexure overstrength factor in the analysis.

Elongation at fracture

The elongation percentage is usually measured over the gauge length at fracture as a percentage of the original gauge length. It is used to show the nature of ductility of the steel as ductility, similar to Luder strain, is a function of the strength of steel.

CHAPTER II

Literature Review

General Introduction

Steel has an enormous area of applications going from simple small tools to huge building and construction projects. The atomic structure of most steels is crystalline and involves a basic iron-carbon phase system. Changes in carbon content and its alloying elements in the smallest amount can have a significant mechanical strength property of the resulting steel. The mechanical strength behaviors of steel that are of great concern to the design and material engineer are the stress-strain graph which vividly indicates the yield strength, the yielding strain, the percentage of elongation, the tensile strength, and a few additional characteristics (Munyazikwiye, 2010). The mechanical behaviors of steel are mainly affected by the amount and variety of certain parameters such as the chemical composition of the steel is consisting of and the physical condition of the steel structure. Carbon content and the presence of alloying elements constitute the chemical composition while heat treatment conditions, shaping operation, and environmental effects such as corrosion determine the physical condition of the steel.

This section will mainly focus on the effect of carbon content and corrosion on the mechanical behavior of reinforcement steel.

Carbon Content

The most critical element by which the mechanical strength behavior of the steel, in general, is influenced by Carbon. The distribution of carbon within the steel is commonly controlled by heat treatment processes. The reinforcement steel bars in concrete structures are of low and medium carbon steel for building construction. Previously, various researchers have assessed the effect of carbon and other alloying elements for providing detailed characteristics when it comes to the strength and ductile behavior of the reinforcement bars mainly manufactured from scraps (Joshua et al., 2019; Kankam, 2004; Kankam & Adom-Asamoah, 2002; Munyazikwiye, 2010).

Reinforcement bars, besides the increased tensile strength, have outstanding benefits for the concrete structure in reducing or controlling crack propagation and maintaining interlock of aggregate. It is indicated that the slightest increase in the area of cross-section of reinforcement steel bar can increase the value of strength by more than 16% (Munyazikwiye, 2010). Reinforcement steel bars also give considerable benefit to the concrete structure in resisting seismic loads. Under the action of such loads, reinforcement bars perform collectively as a frame which enables them to transfer the force from one to the other. With the use of a longitudinal large diameter bar, and a vertical smaller diameter stirrup the concrete structure can withstand the seismic effect [19].

However, reinforcement steel bars with higher tensile strength and ductility are required. Allen, (1972) showed that for the same manufacturer of reinforcement steel bars the Coefficient of Variance (CoV) could be observed from the same batch and a minor variability along with the same bar size. Reinforcement steel bars used for building construction of a given nominal class type and size may exhibit variability in mechanical strength values from piece to piece even when the steel is produced by a controlled standardized process. This was also affirmed by an investigation by Clifton (1971) on structural material that noticeable variation of mechanical properties not only occurs between one batch and another but also within the same batch. Later, Mirza & MacGregor (1979) investigated variation in yield strength for reinforcement steel bars of grades 40 and 60 and found the CoV as 10.7% and 9.3% respectively.

It is equally significant that quality standards and practices are implemented for reinforcement bars that should have been consistently produced from billets of accepted chemical composition.

The quality and variability of reinforcement bars are considerably affected by the processes followed in the steel-making stages (Djavanroodi & Salman, 2017; Singh & Kaushik, 2002).

Production of Steel

While steel was manufactured in bloomery reactors for millennials, allow usage grew widely after more effective manufacturing techniques for blister steel and then cauldron steel was invented in the 17th century (Liu et al., 2015). The modern age of mass-produced steel began with the creation of the Bessemer progression in the middle of the 19th century. It was tailed by the process Siemens-Martin and then the process Gilchrist-Thomas which improved the steel value. Upon the start of modern manufacturing technology, wrought iron was substituted by mild steel.

Further process refining, such as Basic Oxygen Steelmaking (BOS), effectively displaced previous processes by furthest reducing manufacturing costs and enhancing metal consistency. Steel today is one of the biggest and most popular products, processing more than 1.3 billion tons per annum (Liu et al., 2015). Based on figures from "The 1992 Industrial Census," there are 1,118 facilities for steel production in the United States of America, 40 of which remain. Steel manufacturing is an industry worth over $9 billion and involves about 241,000 people in the US.

Iron and alloy are made from bauxite as well as scrap in various separate manufacturing operations. A steel production process includes five fundamental phases according to the Organization for Economic Co-operation and Development / International Energy Agency (OECD / IEA): (1) handling of raw input materials, (2) processing of alloy, (3) processing of iron, (4) casting and (5) shaping and finishing; steel-production (stage 2) is the most energy-intensive phase which typically occurs in the blast reactor cycle, with bauxite and coke as the main constituents. Various alloys are also generated by a direct decreasing progression, in which instance the main inputs are iron ore and natural gas (Liu et al., 2015). The different methods along with their share are presented in Figure 2.

Figure 2.

Steel Production Share of Different Methods (Dragna et al., 2018)

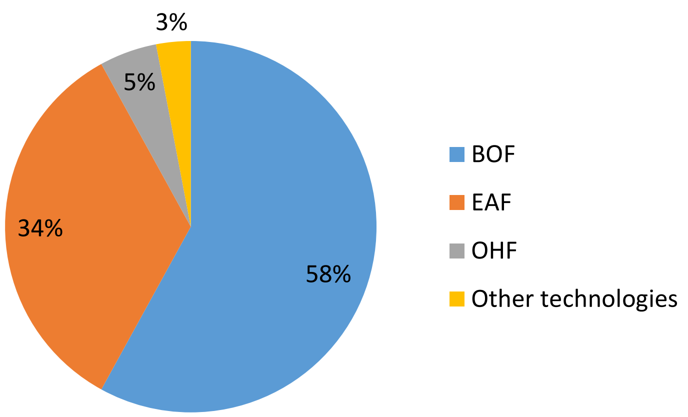
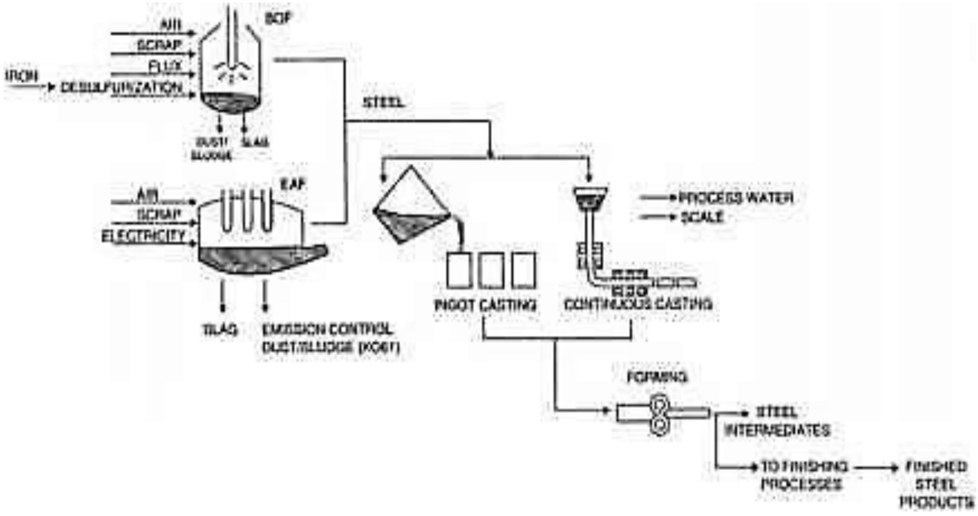


Figure 3.

Process Stages for Iron Production (Liu et al., 2015).



Steel manufacturing processes that regulate (phase 3) are the basic oxygen furnace (BOF) and the electric arc furnace (EAF). The open-hearth furnace (OHF) has also gained a substantial bazaar stake until lately, however owing to its poor service, it has now faded out entirely in many other countries. For some nations, several novel systems (e.g. the Corex progression) were added. Generally, the simple oxygen furnace accounts for approximately 60% of the overall steel output, while the electric arc reactor amounts to 34%.

Steel Production from Iron Ore

In an automated steel plant steelmaking requires three basic phases. Firstly, it provides the source of heat needed to melt iron ore. The bauxite is then heated in a reactor. The melted iron is eventually analyzed into alloy manufacture. Such three phases could be carried out at one plant; nevertheless, the fuel supply is mostly obtained from suppliers outside the plant (Holappa, 2010).

Types of Steel

Steel is an alloy composed of carbon as well as iron. There are many different steel classes which had distinctive chemical components, depending on the particular percentage of extra carbon as well as alloys. When selecting the amount of iron you choose to purchase, it is vital to recognize that there could be four major categories of metal categorized according to their chemical structure and physical characteristics: carbon, alloy, stainless, and tool steels (Baddoo, 2018).

Carbon Steel

Carbon steel tends to be rusty and polished and is prone to rust. Carbon fiber could also include other steels such as manganese, silicon, and copper. There seem to be three major types of carbon steel: truncated carbon steel, moderate carbon steel, as well as heavy carbon steel. Low carbon alloy is the most frequent and usually has a carbon content of less than 30 percent. Moderate carbon alloy produces up to 60 percent carbon and also manganese, and medium carbon steel is much larger. High carbon alloy produces up to 1.5 tons of carbon alloy and is the toughest of the classes. and could also be challenging to deal with (Odusote & Adeleke, 2012).

Alloy Steel

Alloy steels are a multi-metal blend comprising nickel, copper, and aluminum. Alloy steels incline to be lower and are utilized in engineering, automotive parts, conduits, as well as engines. The intensity and characteristics of alloy steels depend on the attentiveness of their components (Crook, 1927).

Stainless Steel

Stainless steels are light, sturdy to rust, and utilized in numerous merchandise, such as household equipment, backsplashes, as well as utensils for cooking. It has a truncated carbon footprint Stainless steel uses chromium in the metal, which could also have nickel or molybdenum. Stainless steel is powerful and could stand great temperatures. There are additional 100 kinds of stainless steel, building a highly flexible material that could be tailored to your needs (Baddoo, 2018).

Tool Steel

Tool steels are thermal as well as scraps resistant and robust. They are called tool steels since they are mostly utilized to manufacture power tools, along with tools for marking, grinding, and form castings. Tool steels consist of varying concentrations of vanadium, cobalt, molybdenum, and tungsten which enhance their toughness and resistance to heat. They too are widely utilized for producing hammers. There are various grades of alloy that could be utilized for different usage (Baddoo, 2018).

High-Carbon Steel

It is also used in the making of axes, swords, scissors, and other cutting (Magasdi et al, 2010).

Mild Steel

This steel is utilized to make the roofs for vehicle frames, panels, boxes, cases, and sheet metal. It is now utilized as a substitute for wrought iron in the production of railroad rails (Magasdi et al., 2010).

Medium Carbon Steel

They are used in the building of tool frames and springs (Baddoo, 2018).

Stainless Steel

This steel is used in the building of crockery, wrist watches, kitchen utensils, cutlery, and surgical equipment (Baddoo, 2018).

High-Speed Steel

Basically, this steel is used in the making of tools that cut other metals (Baddoo, 2018).

Cobalt Steel

It is too like the high-speed steel is used for drilling purposes

Nickel Chromium Steel

It is commonly used as an armor plate

Aluminum Steel

It is used in the making of furniture.

Chromium Steel

They are used in the making of Automobile and airplane parts.

Corrosion and Reinforcement Steel Bars

The corrosion of steel reinforcement bars in concrete structures is taken to be one of the main reasons for the strength degradation in several existing reinforced concrete structures which appear to aggravate the premature failure of structures due to an aggressive environment (Apostolopoulos & Matikas, 2016) or even to moderately aggressive environments (Imperatore & Rinaldi, 2019).

Many researchers have studied corrosion and shown its effect on mechanical strength deterioration of reinforcement steel bars. Reinforcement steel bars were investigated as bare bars; semi-embedded bars, and embedded in reinforced concrete members. Under all conditions, very few papers tried to demonstrate the effect of corrosion on tensile strength while many gave much more detailed analysis of compressive and low cycle fatigue analysis. Even though the effects of corrosion on mechanical strength were extensively studied, proposing mathematical models was so limited and shallow. The effect of corrosion tensile strength and high cycle fatigue behaviors were hardly investigated. A lack of procedures and standards was observed in many of the papers and it is hardly reliable to deduce the research findings as acceptable in the scientific world. On the other hand, the experimental work is greatly based on accelerated artificial corrosion processes with completely different corrosion rates, under which circumstances the corroded specimens are considerably different than those developed under natural conditions (Lin et al., 2019).

Corrosion Process

Naturally corroded specimens give the perfect impression in investigating the corrosion and its impact on mechanical properties as corrosion morphology and localized chloride attack may take place. This process demands such a long time that mimicking the natural corrosion phenomenon with an accelerated corrosion process is technically vital.

It is more convenient to use the reinforcement bar embedded in the concrete as this method almost fully represents the corrosion phenomenon close to the natural process caused by chloride attack. While, the impressed current method, on the other hand, is used more on bare bars to appropriately represent the corrosion due to carbonation (Hu et al., 2019).

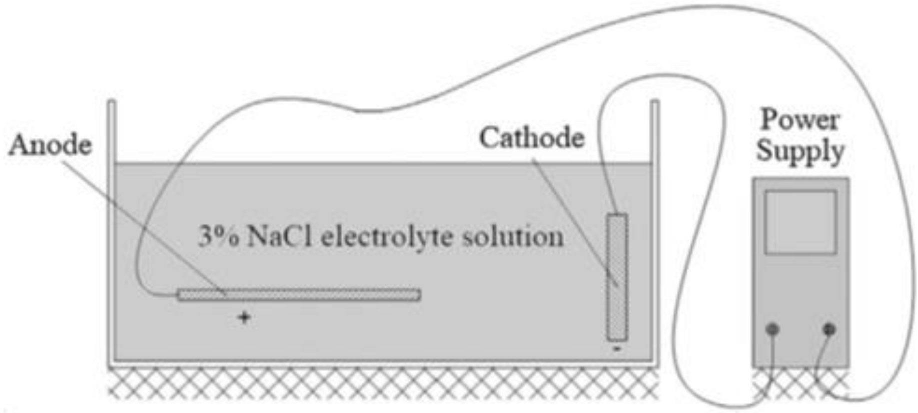
Different corrosion levels can be attained by applying Faraday's Law:

$$T = \frac{M_{loss} * n * C_F}{I * M_{specimen}} \qquad (1)$$

where T is time, M_{loss} is the required mass loss due to corrosion, n is the valence of the specimen (n = 2 for steel), C_F is the Faraday constant (C_F = 96480), I is the average electrical current, $M_{specimen}$ is the molar mass of steel.

Figure 4.

Scheme of the Accelerated Corrosion Process. (Imperatore & Rinaldi, 2019)



The NaCl electrolyte solution used for corroding the reinforcing rebars by different researchers ranges between 3-5% (Abouhussien & Hassan, 2014; A. Apostolopoulos & Matikas, 2016; Apostolopoulos & Papadakis, 2008; Apostolopoulos, 2007; Castro et al., 2003; Chen et al., 2018; Fernandez et al., 2015; Guo et al., 2015; Imperatore & Rinaldi, 2019; Imperatore et al., 2017; Li & Wang, 2013; Ponjayanthi D., 2016; Sanchez et al., 2017; Sun et al., 2018; Wang, 2012; Wu et al., 2019; Zhang et al., 2016; Zhou et al., 2015; Zhu, 2011; Zhu & Francois, 2013). A strong concentration of sulfuric acid and nitric acid solutions could also be used in corroding the reinforcing steel bars (Hawileh et al., 2011).

Once the desired corrosion is achieved, cleaning of the specimens for the intended mechanical tests is done by mechanical brush (Apostolopoulos et al., 2017; Bazán et al., 2019; Imperatore & Rinaldi, 2019), Clark's solution (Almusallam, 2001; Zhang et al., 2012; Zhu & Francois, 2013), pressure sand cleaning and blasting (Fernandez et al., 2015; Fernandez & Berrocal, 2019), use of cleaning solution like hydrochloric acid and hexamethylenetetramine (Chen et al., 2018; Deb, 2012; Imperatore et al., 2017; Sun et al., 2018; Yan et al., 2017).

Mass Loss

Uniform mass loss is assumed through the corrosion process that the mass loss of the corroded specimen is estimated involving the mass-per-unit length of the original steel bar, and the final mass-per-unit length of the original steel bar after removal of the corrosion by-products. The generalized mass loss in percentage is computed using the following equation.

$$\varphi = 100\left(\frac{m_o - m}{m_o}\right) \qquad (2)$$

where φ is mass loss in percentage, m_o is mass-per-length of the original test specimen, and m is mass-per-length of the corroded specimen after the removal of corrosion additives.

Effect of Corrosion on Monotonic and Variable Loading

The mechanical strength of the reinforced steel bar is greatly affected by availability and level of corrosion. Monotonic loading such as compressive and tensile loadings are studied by many researchers.

Compressive Strength

Imperatore & Rinaldi (2019) experimentally investigated and analytically modeled corroded steel bars under corrosion. The corrosion was artificially created with a 3% NaCl electrolyte solution while the corrosion level was varied based on the duration of the samples dipped under this solution. The paper further studied the effect of slenderness ratio coupled with corrosion under compressive strength to analytically model for buckling. The study showed that corrosion affected the compressive strength of reinforced steel bars. Furthermore, steel bars with a slenderness ratio higher than 5 underwent buckling. Kashani et al. (2012) also experimentally proved that steel bars with a slenderness ratio lower than 5 were not prone to buckling. However, the buckling phenomenon was not analytically modeled.

Tensile Strength

Hawileh et al. (2011) investigated the effect of tensile strength grade B500B reinforcing steel bars due to corrosion. The corrosion process was according to ASTM G1-03 standard which recommends 10% strong solutions of nitric and sulfuric acids. Four mass loss percentages were identified i.e. 0%, 9.54%, 13.38% and 19.60% as different corrosion rate levels. The mass loss percentage for these corrosion levels was estimated using equation (2). For the corrosion levels indicated from 0% to 19.60%, the test result indicated that there was a decrement in yield strength, tensile strength, percentage of elongation at ultimate stress, and elongation percentage at fracture. When the bars were corroded to a level of 19.6% mass loss, the yielding and tensile strength of the rebars exhibited a reduction of about 26%.

Moreover, corrosion had a significant effect on the percentage of elongation reduction at ultimate strength by 76.6% and at fracture by 38.74%.

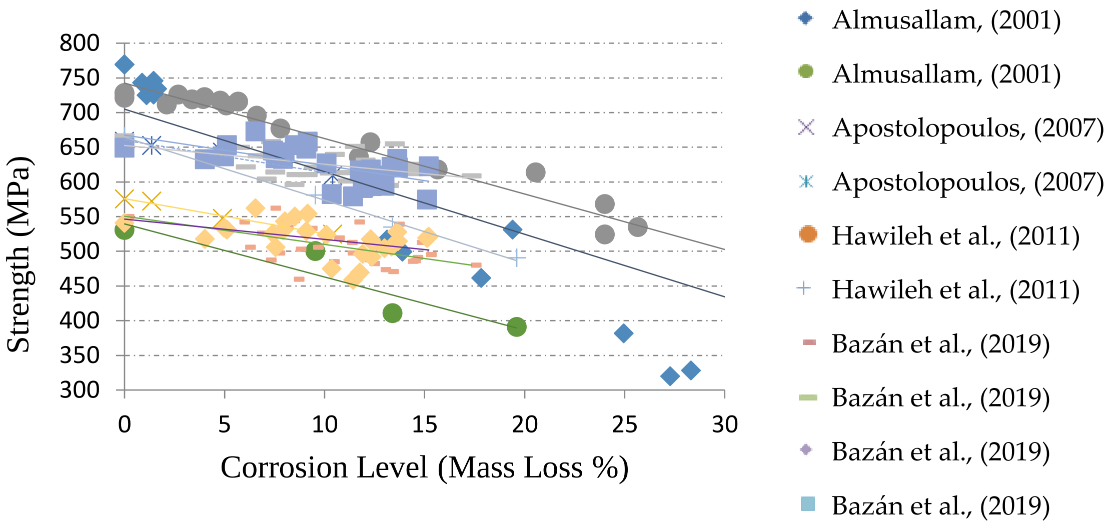
Imperatore et al., (2017) studied corrosion and its effect on tensile strength behaviors of reinforcement steel bars of the radius of diameters 8 mm, 12 mm, 16 mm, and 20mm. 65 corrosion levels were produced upon mass loss estimation ranging from 0 to 53.21% mass loss. Yielding strength, tensile strength, and elongation percentage against corrosion degree were compared. The result showed that corrosion damage had a significant reduction in ductility of the reinforcement bars. Bar with 8mm diameter was greatly affected than the other bars for the reason that the lower the diameter of bars, the lower the martensitic formed as martensitic cortex facilitates the creation of cavities which quickly interrupts – under a corrosion attack.

Kashani et al., (2012) studied the response of the stress-strain curve to corrosion. The specimens with 8 mm and 12 mm diameter were cast in reinforced concrete and were corroded by an electrolytic process. Six mass loss percentages were created as corrosion levels and stress-strain diagrams were plotted under the tensile test. The result showed that corrosion degrees up to 15% didn’t show a significant influence on the nature of the stress-strain curve whereas for corrosion levels beyond 15% significant drop in plastic deformation was recorded.

Apostolopoulos, (2007) investigated the tensile strength property of S500 temp core reinforcing steel bar under corrosion damage. The corrosion levels varied based on the duration of salt spray corrosion exposure time up to 90 days. The paper showed that there was a significant reduction in yield strength, tensile strength, and elongation percentage at fracture by 9.65%, 8.09%, and 43.43%, respectively, due to the bar being exposed to salt spray for 90 days.

Figure 5.

Effect of Corrosion on Strength of Reinforcements Bars



CHAPTER III

Methodology

Survey

The purpose of the survey was to gather the information that would reveal the number of steel bars of various diameters used in Ethiopian construction projects. Steel bars of 6 to 32 mm nominal diameters were utilized directly in the construction of different structures in different proportions. According to the survey, the most utilized kinds of steel reinforcement bars were found to be 10 mm, 12 mm, 8 mm, and 16 mm nominal diameters in the given order (Achamyeleh & Şahin, 2019). The percentage of utilization by the construction market of each designated diameter is presented in Table 1.

Table 1.

Percentage of Utilization of Rebars in the Construction Market

ameters	**ercentage of the Rebars**
10	19.64
12	17.86
8	16.52
16	13.84
14	11.61
20	10.71
32	3.57
24	3.13
30	3.00
6	1.79

Types and Sample Size of Reinforcement Bars

The study was carried out on 8, 10, 12, and 16 mm nominal diameters of grade 60 ribbed reinforcement steel bars. The steel bars used in the present study were collected randomly from Ethiopian steel markets irrespective of their place of origin.

Ethiopia solely relied on both imported and locally produced steel bars with an almost equal share in the market.

The mechanical properties of interest in the tensile test were yielding strength (YS), tensile strengths (TS), elongation percentages (EL), and mass-per-lengths. One derivative characteristic was also investigated by considering the ratio of YS and TS.

The following materials, tools, and equipment were directly used to conduct various experiments in this research.

Materials

- Grade 60 ribbed reinforcement steel bars
- beam balance (±5x10^{-5}kg)
- Steel rule (±5x10^{-4}m)
- Vernier caliper (±1x10^{-5}m)
- cutter machine
- Universal Testing Machine manufactured by MATEST, Model C140-09/ZG/002. The machine is calibrated by the National Metrology Institute of Ethiopia with certificate number OF-012. The maximum capacity of the UTM is 300kN with an accuracy of 0.062% of the load.

Specimens for the tensile test were prepared according to the ASTM A615 standard and the values for YS, TS, EL, and mass-per-length were determined.

Experimental Work

The experimental work involved tensile tests and mass-per-length investigation of the reinforcement steel bars. A total of 329 specimens were investigated for tensile and mass-per-length tests.

The tensile strength values from the test are based on the mathematical formulas presented below (Achamyeleh & Şahin, 2019).

The yielding stress (YS),

$$\mathrm{YS} = \frac{\text{Yielding Load}}{\text{Nominal Area}}, \dots \quad \dots \quad \dots \quad \dots \quad \dots (3)$$

The tensile stress (TS),

$$\mathrm{TS} = \frac{\text{Maximum Load}}{\text{Nominal Area}}, \dots \quad \dots \quad \dots \quad \dots \quad \dots (4)$$

The elongation percentage at fracture (EL),

$$\mathrm{EL} = \left(\frac{l_u - l_o}{l_o}\right) x100\% \dots \quad \dots \quad \dots \quad \dots \quad \dots (5)$$

where l_o and l_u are original gauge length and ultimate length at fracture, respectively, while *EL* is the percentage elongation of the specimen at fracture.

Tensile Test

All the test specimens were prepared into a total length of 400 mm for tensile testing without additional machining operation and tested at room temperature with no effect of humidity. According to ASTM A615, the gauge length should be 8 in or 200 mm. The initial diameters and initial gauge lengths of all the specimens were recorded before the monotonic tension test was conducted. A photograph of tensile test specimens and test setup is presented in Figure 6. The remaining portion at both ends was used for fixing the specimen onto the UTM (Achamyeleh et al., 2022; Achamyeleh & Şahin, 2019). The tensile tests were conducted at a rate of 1 mm/minute.

Variability Analysis

Statistical parameters such as means, standard deviations (SD), and coefficient of variance (CoV), were computed for mechanical strength variables of YS, TS, and EL; linear density property i.e. M/L; and the characteristic ratio of TS to YS values. Means, standard deviations, and coefficient of variance were computed using the following procedure.

$$\overline{\mathrm{X}} = \frac{\sum \mathrm{X_i}}{\mathrm{n}} \dots \dots \dots \dots \dots (6)$$

The SD and CoV of each measurement were computed based on the equations:

$$\mathrm{SD} = \sqrt{\frac{\sum(\mathrm{X_i} - \overline{\mathrm{X}})^2}{\mathrm{n} - 1}} \dots \dots \dots \dots \dots (7)$$

$$\mathrm{CoV} = \frac{\mathrm{SD}}{\overline{\mathrm{X}}} \qquad \dots \dots \dots \dots \dots (8)$$

where X_i stands for an individual value and *n* is the number of total tests.

Microsoft Excel 2010 and Minitab 16 were used to conduct the statistical variability analyses in this study.

Figure 6.

Representative Photos of Test Specimens and Tensile Test Setup

Analysis of variance (ANOVA) was also used to show the variability of tested tensile parameters. One-factor, one-level test type of one-way analysis of variance (ANOVA) was formulated in which YS, TS, EL, and TS/YS were analyzed using an ANOVA table (Achamyeleh et al., 2022; Achamyeleh & Şahin, 2019; Roy, 2010) as presented in Table 2.

Table 2.

Generalized Analysis of Variance Table

ource of ariation	S	V	·cal	Pure SS	P
m		S_m/f_m	V_m/V_e	$S_m - V_e$	S'_m/S_T
e		S_e/f_e	-	'e $= S_m + V_e$	S'_e/S_T
T					

m = Mean; e = Errors; T = Total; n = Total results number; f = Degree of freedom; SS = Squares Sum; f_T = Total degree of freedom = n – 1; $\bar{Y}$ = Mean values of the results = $\sum_{i=1}^{n} Y_i/n$; Y_0 = Target value; S_T = Total's squares sum = $\sum_{i=1}^{n}(Y_i - Y_0)^2$; F-cal = Variance Ratio; S_m = Mean's square sum = $n(\bar{Y} - Y_0)^2$; S_e = Errors' square sum = $S_T - S_m$; V_T = Total Variance = S_T/f_T; V_m= Variance for mean = S_m/f_m; V_e= Variance for errors = S_e / f_e; F_m= Variance ratio of the mean =V_m/V_e; S'_m = Pure Sum of Squares for the mean = $S_m - V_e$; S'_e = Pure Sum of Squares for the errors = $S_m + V_e$; P = Percent contribution.

Goodness-of-fit

Testing of goodness-of-fit of distributions to data helps find the distribution type (normal, logistic, lognormal, Weibull, etc) and the parametric values of the mean, variance, etc. that return the maximum probability of generating the observed data. Statistical software such as Minitab can be used to test for goodness-of-fit based on the null hypothesis.

The hypotheses for Anderson-Darling test are:

H_0: the data follows a normal distribution.

H_1: the data do not follow a normal distribution.

According to the null hypothesis, the samples are normally distributed when the p-value is greater than the selected significance level, for this study 5%.

Process Capability

Process capability is a measurement of the consistency of a quality parameter of interest which is described by the total variation which occurs as a result of all common variation causes that exist in the system. It involves determining the mean values of the sample data and the standard deviation of the quality characteristics.

A common index for relating the potential of a process to meet design or requirement specifications is the process capability, C_p *Index*.

It is used to relate the process spread with the specification spread, assuming specification limits on both sides to the mean. It is given by:

$$C_p = \frac{USL - LSL}{6\sigma} \dots \dots \dots \dots \dots (9)$$

where, USL and LSL are upper and lower specification limits, respectively, and σ is the sample standard deviation.

It is not only process variability that characterizes the influence of the process's ability whether it yields conforming items or not but also the process means position can determine process capability. C_{pk} index is a measure of the position of the sample mean. It is used when the process means are shifted or not equally positioned from the upper and lower specifications. The assumption in the previous index is that the process mean is halfway between design specification limits. The process capability index, in this case, is given by:

$$C_{pk} = \min\left\{\frac{USL - \mu}{3\sigma}, \frac{\mu - LSL}{3\sigma}\right\} \dots \dots \dots \dots \dots (10)$$

Desirable values are $C_{pk} \geq 1.33$ (Litteral & Rudisill, 2008).

Error Analysis

Errors in measurement systems often arise from various sources and must be aggregated correctly to obtain a prediction of the total likely error in output reading from the measurement system. When a measurement is affected by systematic and random errors, means of expressing the combined effect are required. Moreover, a measurement system often comprises several distinct components, each of which is subject to errors.

Error in Addition

For two separate components, *y* and *z* with maximum errors *ay* and *bz*, respectively, the sum of the probable maximum error, *e*, in the system, *S*, is calculated as:

$$e = \sqrt{(ay)^2 + (bz)^2} \dots \dots \dots \dots \dots (11)$$

Thus, $S = (y + z) \pm e$ *or* $S = (y + z)(1 \pm f)$ where $f = e/(y + z)$.

Error in Subtraction

The maximum probable error in the system can be estimated using equation 9.

$$S = (y - z) \pm e \text{ or } S = (y - z)(1 \pm f) \dots \dots \dots \dots \dots (12)$$

where $f = e/(y - z)$.

Error in a Product

$$e = \sqrt{a^2 + b^2} \dots \quad \dots \quad \dots \quad \dots \quad \dots (13)$$

Error in a Division

$$e = \sqrt{a^2 + b^2} \dots \quad \dots \quad \dots \quad \dots \quad \dots (14)$$

In general, in the case of a large number of variables, absolute errors must be compensated for errors with different signs using equation 15 (Graba, 2021).

$$\Delta W = \sqrt{(\frac{\partial W}{\partial W_1}\Delta W_1)^2 + (\frac{\partial W}{\partial W_2}\Delta W_2)^2 + \cdots + (\frac{\partial W}{\partial W_n}\Delta W_n)^2} \dots \quad \dots \quad \dots (15)$$

where ΔW is the uncertainty of the measured value of a parameter.

CHAPTER IV
Findings and Discussion

Distribution of Reinforcement Steel Bars

Mechanical properties of Grade 60 steel bars were studied for statistical parameters extensively based on measured data.

For the two lots of reinforcement steel bars, the distribution of YS, TS EL, and mass-per-length were determined. Additionally, the characteristic ratio of TS to YS was also studied statistically in both lots.

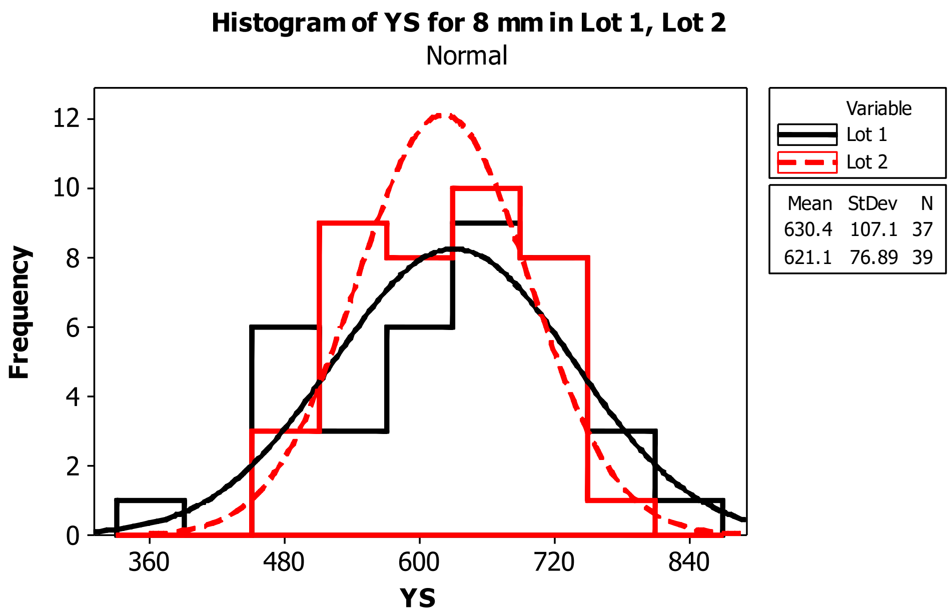
Distribution for 8 mm Diameter

It is demonstrated that the reinforcement steel bars that are studied under this category exhibited variability in all parameters. The total bars investigated in Lots 1 and 2 were 37 and 39, respectively.

Yield Strength. According to ASTM A615 standard, it is found that 1 bar out of 37 in Lot 1 failed to fulfill the requirement. In lot 2, all the reinforcement steel bars in the sample fulfilled the minimum YS value. The distribution for YS of both lots is presented in Figure 7.

Figure 7.

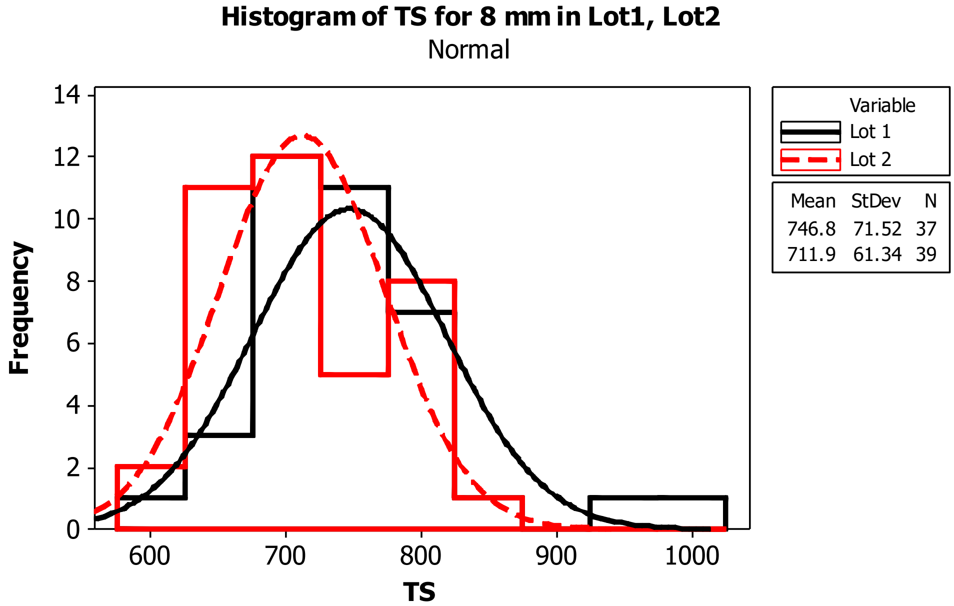
Distribution of YS for 8 mm in Lot 1 and Lot 2



Tensile Strength. Like the yield strength results, according to ASTM A615 standard, it is found that 1 bar out of 37 in Lot 1 failed to fulfill the requirement. In lot 2, samples fulfilled the minimum TS value. The distribution for tensile strength of both Lots 1 and 2 are presented in Figure

Figure 8.

Distribution of TS for 8 mm in Lot 1 and Lot 2



Elongation Percentage. It is noted that the EL test values showed significant statistical variability in both lots. The average EL in Lot 1 was found to be 13.6 while in Lot 2 it was 12.9. The ASTM standard doesn't set a minimum requirement for elongation percentage for 8 mm bar size. The distribution of elongation percentage is shown in Figure 9.

Mass-per-Length. All bars in Lot 1 surpassed the minimum requirement set for bar size and class under investigation. But, in Lot 2, 3 bars (7.69% of the sample) failed to fulfill the minimum requirement for M/L. Lots 1 and 2 exhibited mean M/L values of 0.3896 and 0.3817, respectively. The distribution of M/L is shown in Figure 10.

TS/YS. The TS/YS values showed a decrement trend with an increase in the YS values. This is evidence that ductility decreases as the yield strength tends to get higher. The mean characteristics ratio of TS to YS were 1.2085 and 1.1546, respectively. 68% of the test results in Lot 1 and 82 % in Lot 2 failed to exhibit the minimum requirement set by ACI. The histogram and normal distribution graphical representation of the characteristic ratio is presented in Figure 11.

Figure 9.

Distribution of Elongation Percentage for 8 mm in Lot 1 and Lot 2

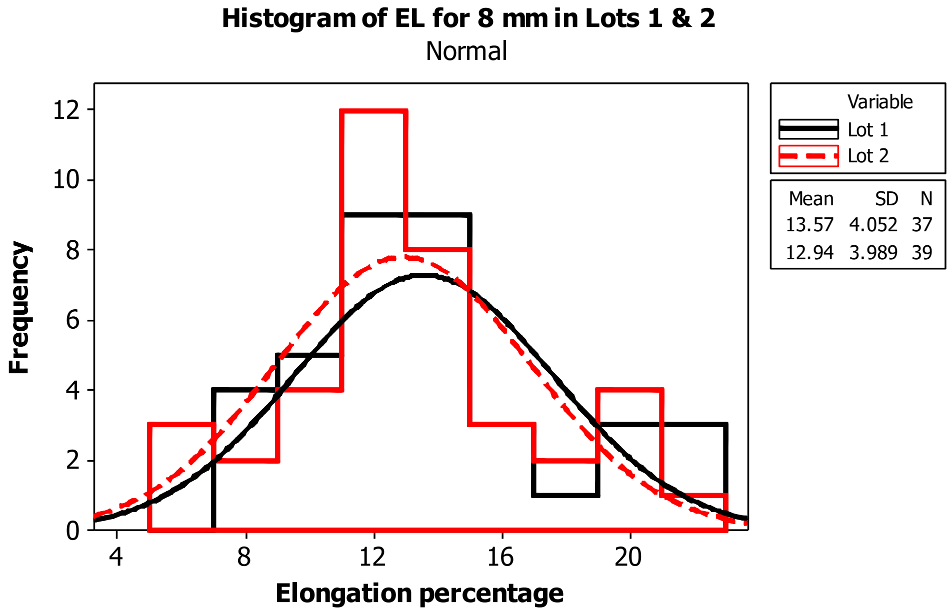


Figure 10.

Distribution of Mass-per-length for 8 mm in Lot 1 and Lot 2

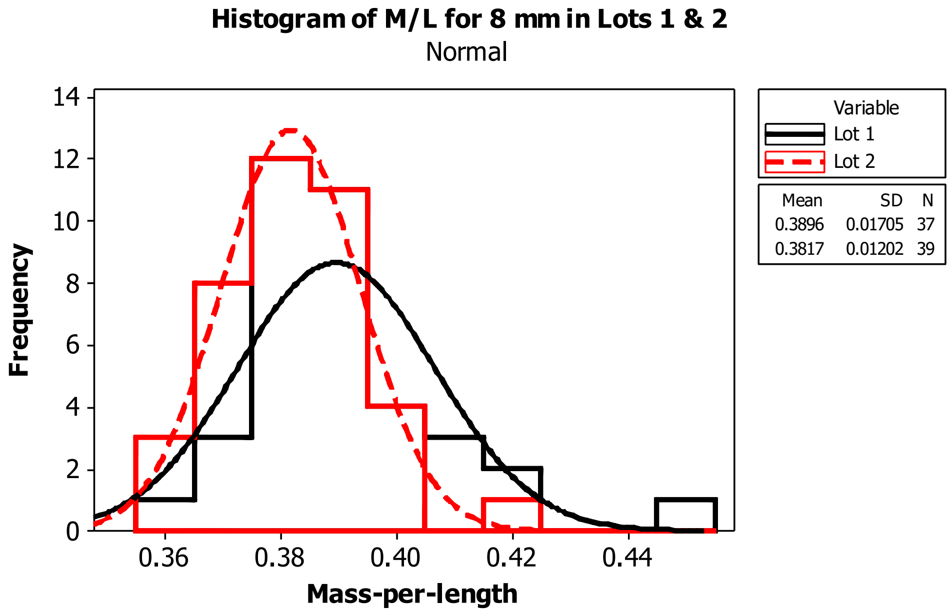
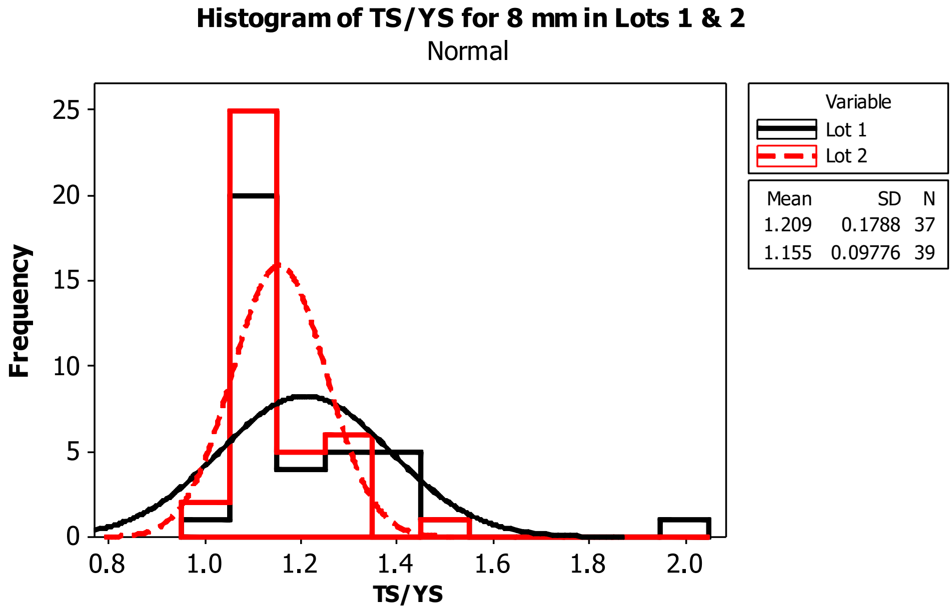


Figure 11.

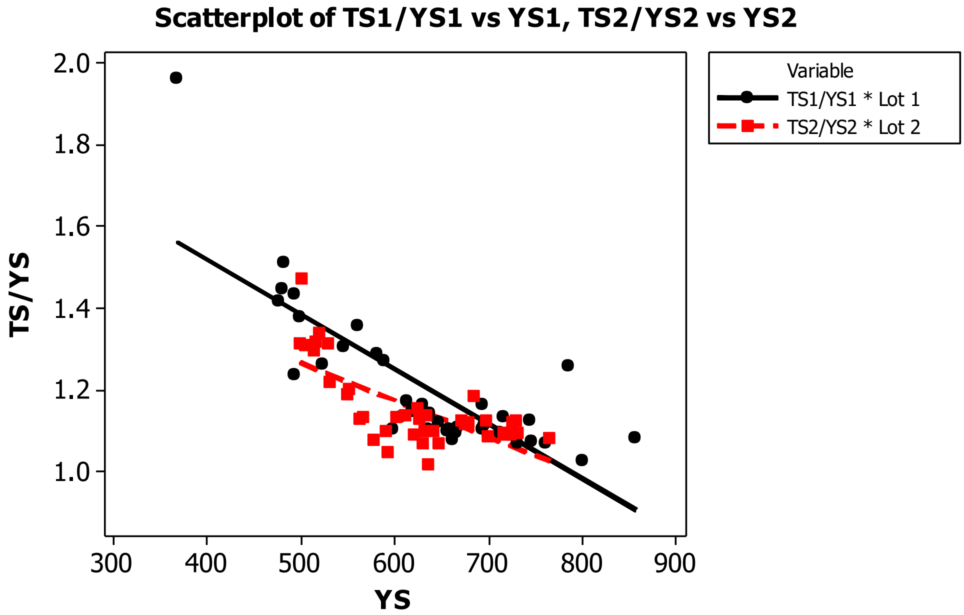
Distribution of TS/YS for 8 mm in Lot 1 and Lot 2



The scatter plot of TS/YS vs. YS is presented in Figure to show the trend of the decrement of the characteristic ratio over increasing YS.

Figure 12.

Scatterplot of TS/YS vs YS of Respective Lots for 8 mm Diameter Bars



Statistical Analysis. The statistical analysis which included the results of parameters like minimum, maximum, range, mean, variance, SD, CoV, kurtosis, and skewness are evaluated for all variables. The analysis is summarized in Table 3.

Table 3.

Statistical Summary of 8 mm Diameter in Lot 1

Parameters	YS	TS	EL	M/L	TS/YS
Min	368.00	609.67	7.20	0.3640	1.0257
Max	857.30	990.00	22.30	0.4550	1.9620
Range	489.30	380.33	15.10	0.0910	0.9362
Mean	630.37	746.85	13.57	0.3896	1.2085
Variance	11470.67	5114.53	16.42	0.0003	0.0320
Std. Dev.	107.10	71.52	4.05	0.0171	0.1788
CoV	16.99%	9.58%	29.85%	4.38%	14.79%
Skewness	-0.2264	1.3635	0.6419	1.7598	2.3940
Kurtosis	-0.1346	3.2830	-0.2629	4.9964	7.7723

Table 4.

Statistical Summary of 8 mm Diameter in Lot 2

Parameters	YS	TS	EL	M/L	TS/YS
Min	499.00	621.00	5.00	0.3600	1.0189
Max	766.00	828.00	21.50	0.4190	1.4711
Range	267.00	207.00	16.50	0.0590	0.4522
Mean	621.05	711.90	12.94	0.3817	1.1547
Variance	5912.1	3762.1	15.9	0.0	0.0
Std. Dev.	76.89	61.34	3.99	0.01	0.10
CoV	12.38%	8.62%	30.83%	3.15%	8.47%
Skewness	0.0005	0.4095	0.3135	0.4572	1.4536
Kurtosis	-1.0999	-1.0876	-0.0432	1.1296	1.7863

One-way and one-level ANOVA is analyzed for all mechanical and linear density properties are summarized in Tables 5 and 6 for Lots 1 and 2, respectively.

Table 5.

ANOVA of 8 mm Diameter in Lot 1

Source	DOF	SS	Variance	F	Pure SS	P
			Yield Strength			
Mean	1	1637523.4	1637523	142.8	1626053	0.793016
Errors	36	412943.9	11470.67	1	424414.6	0.206984
Total	37	2050467.4	55418.04			
			Tensile Strength			
Mean	1	773.747027	773.747	47.1	757.3269	0.555
Errors	36	591.124173	16.42012	1	607.5443	0.445
Total	37	1364.8712	36.88841			
			Elongation			
Mean	1	773.747	773.747	47.1	757.3269	0.555
Errors	36	591.124	16.42012	1	607.5443	0.445
Total	37	1364.871	36.88841			
			Mass-per-length			
Mean	1	0.02534	0.025343	87.16	0.025053	0.700
Errors	36	0.010466	0.000291	1	0.010758	0.300
Total	37	0.0358	0.000968			
			TS/YS			
Mean	1	0.0637	0.063709	1.99	0.031746	0.026
Errors	36	1.1506	0.031962	1	1.182604	0.974
Total	37	1.2144	0.03282			

Table 6.

ANOVA of 8 mm Diameter in Lot 2

Source	DOF	SS	Variance	F	Pure SS	P
			Yield Strength			
Mean	1	1576443.1	1576443.1	266.6	1570531	0.872
Errors	38	224659.9	5912.1	1	230572	0.128
Total	39	1801103.0	46182.1			
			Tensile Strength			
Mean	1	329360.4	329360.4	87.54709	325598.3	0.689
Errors	38	142959.6	3762.094	1	146721.7	0.311
Total	39	472320	12110.77			
			Elongation			
Mean	1	604.1603	604.1603	37.97301	588.25	0.487
Errors	38	604.5897	15.91026	1	620.5	0.513
Total	39	1208.75	30.99359			
			Mass-per-length			
Mean	1	0.013128	0.013128	90.80832	0.012983	0.697
Errors	38	0.005494	0.000145	1	0.005638	0.303
Total	39	0.018622	0.000477			
			TS/YS			
Mean	1	0.354538	0.354538	37.09541	0.344981	0.481
Errors	38	0.363184	0.009557	1	0.372741	0.519
Total	39	0.717722	0.018403			

Distribution for 10 mm Diameter

The total bars investigated in Lots 1 and 2 are 44 and 27, respectively.

Yield Strength. According to ASTM A615 standard, it is found that 1 bar out of 44 in Lot 1 failed to fulfill the requirement. In lot 2, all the 27 sample bars fulfilled the minimum YS value. The distribution for YS of both Lots is presented in Figure 13.

Tensile Strength. Based on the ASTM standard, it is found that 4 bars out of 44 in Lot 1 failed to fulfill the requirement while in lot 2, all the 27 sample bars fulfilled the minimum requirement for TS. The distribution for tensile strength of both Lot 1 and 2 are presented in Figure 14.

Figure 13.

Distribution of YS for 10 mm in Lot 1 and Lot 2

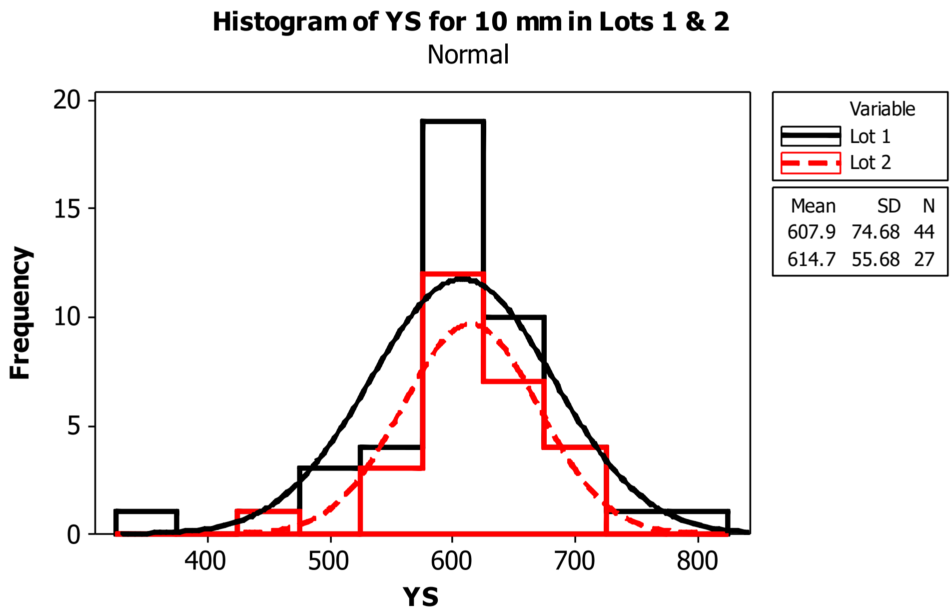
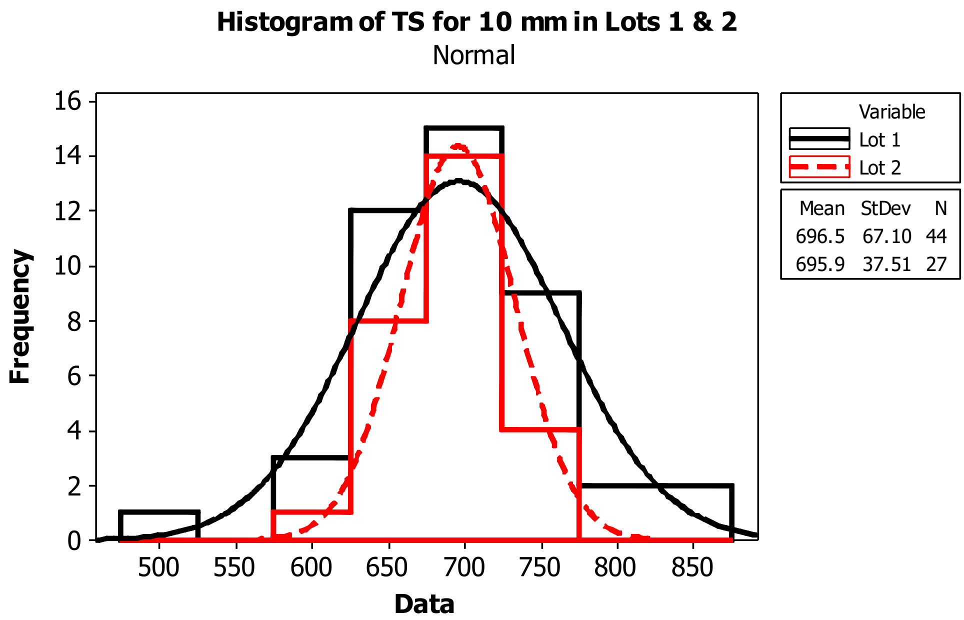


Figure 14.

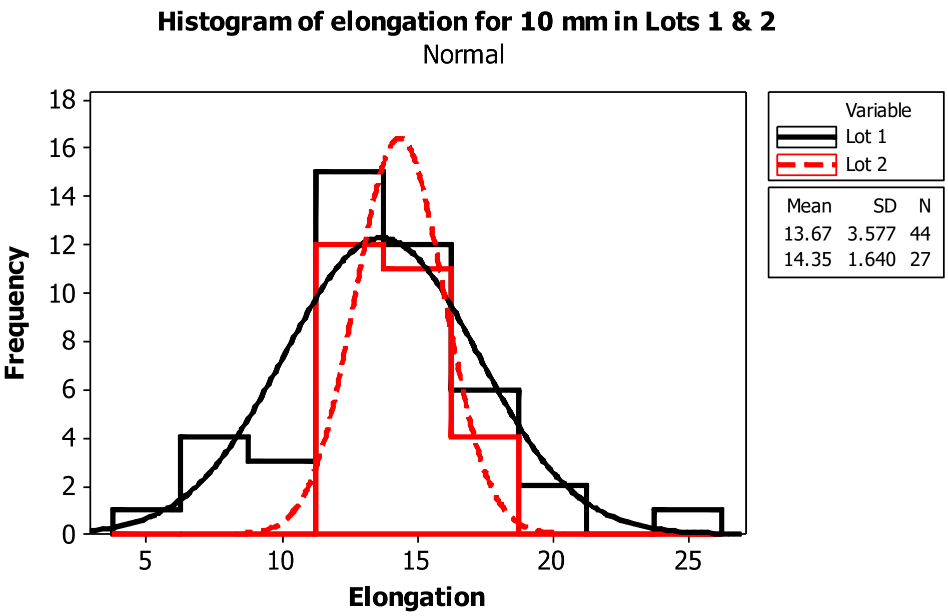
Distribution of TS for 10 mm in Lot 1 and Lot 2



Elongation Percentage. The average EL of the samples in Lot 1 was found to be 13.67 while in Lot 2 it was 14.35. Five bars in Lot 1 didn't fulfill the requirement set by ASTM while all the sample bars in Lot 2 surpassed the minimum requirement set for EL The distribution of EL is shown in Figure 15.

Figure 15.

Distribution of Elongation for 10 mm in Lot 1 and Lot 2

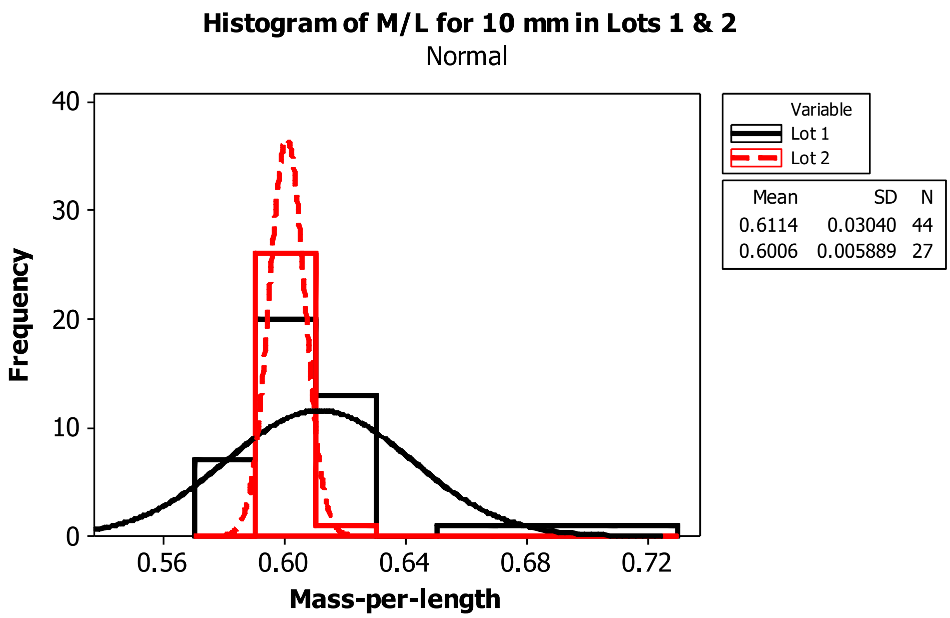


Mass-per-Length. For Lot 1 and Lot 2, the mean M/L values were 0.6113 and 0.6006, respectively. All the sample bars in Lots 1 and 2 were within the range of standard values. The distribution of mass-per-length is shown in Figure 16.

TS/YS. The TS/YS values showed a decrement trend with an increase in the YS values. The mean characteristics ratio of TS to YS were 1.1515 and 1.1368, respectively. 93% of the test results in Lot 1 and 96 % in Lot 2 failed to surpass the minimum set value required by ACI.

Figure 16.

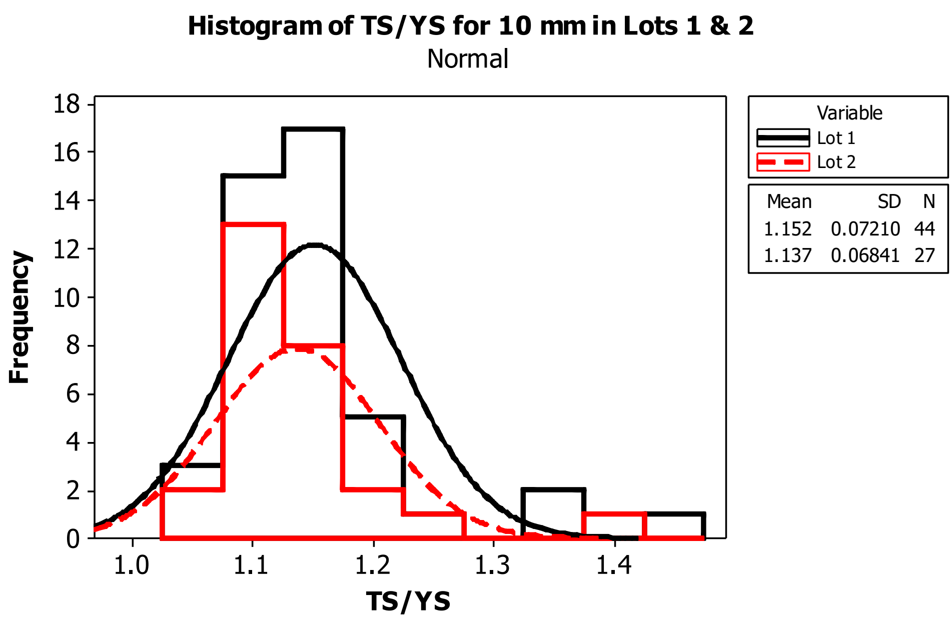
Distribution of Mass-per-length for 10 mm in Lot 1 and Lot 2



Histogram and normal distribution graphical representation of the characteristic ratio for 10 mm nominal diameter steel bars is presented in Figure 17.

Figure 17.

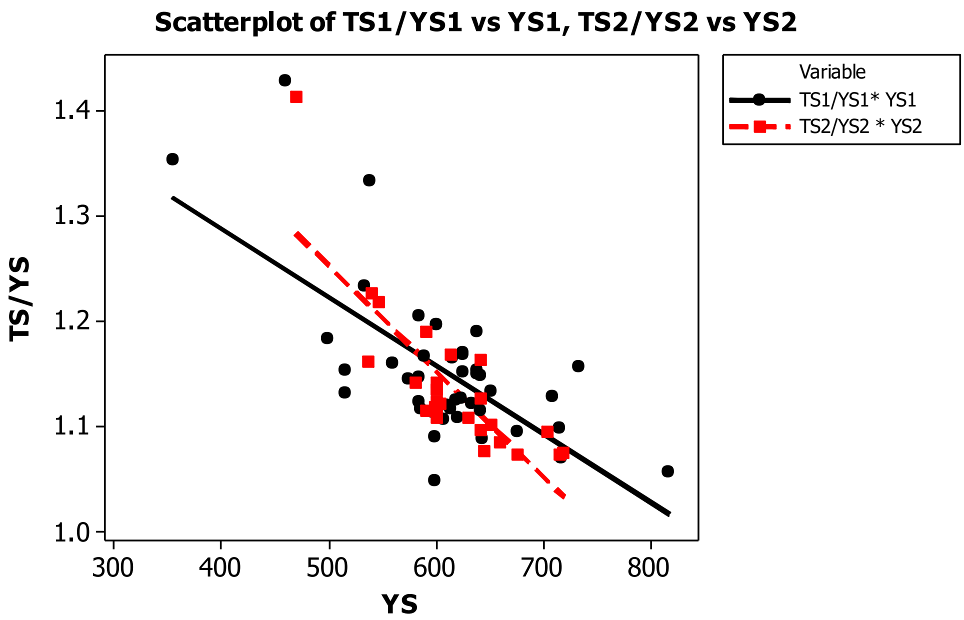
Distribution of TS/YS for 10 mm in Lot 1 and Lot 2



The scatterplot of the characteristic ratio against yield strength is plotted to show the trend of TS/YS in increasing YS.

Figure 18.

Scatterplot of TS/YS vs YS of Respective Lots for 10 mm Diameter Bars



Statistical Analysis. The statistical analysis of parameters were evaluated for all variables and summarized in Tables 7 and 8. ANOVA table is also summarized in Tables 9 and 10.

Table 7.

Statistical Summary of 10 mm Diameter in Lot 1

Parameters	YS	TS	EL	M/L	TS/YS
Min	354.00	478.67	6.00	0.5740	1.0485
Max	816.67	862.67	24.50	0.7260	1.4275
Range	462.67	384.00	18.50	0.1520	0.3791
Mean	607.93	696.50	13.67	0.6114	1.1515
Variance	5576.43	4502.49	12.79	0.0009	0.0052
Std. Dev.	74.68	67.10	3.58	0.0304	0.0721
CoV	12.28%	9.63%	26.16%	4.97%	6.26%
Skewness	-0.4809	-0.3386	0.3560	2.2653	2.0859
Kurtosis	3.2606	2.3376	1.2777	5.9098	5.5742

Table 8.

Statistical Summary of 10 mm Diameter in Lot 2

Parameters	YS	TS	EL	M/L	TS/YS
Min	469.00	623.00	11.50	0.5910	1.0726
Max	719.00	773.00	17.00	0.6163	1.4115
Range	250.00	150.00	5.50	0.0253	0.3389
Mean	614.74	695.85	14.35	0.6006	1.1368
Variance	3100.58	1407.05	2.69	0.0000	0.0047
Std. Dev.	55.68	37.51	1.64	0.0059	0.0684
CoV	9.06%	5.39%	11.43%	0.98%	6.02%
Skewness	-0.2608	0.5926	0.0439	0.5785	2.6938
Kurtosis	0.8875	-0.0384	-1.4550	0.3221	9.6485

Table 9.

ANOVA Summary of 10 mm Diameter in Lot 1

Source	DOF	SS	Variance	F	Pure SS	P
			Yield Strength			
Mean	1	1554030.8	1554030.8	278.7	1548454.3	0.863
Errors	43	239786.7	5576.4	1.0	245363.1	0.137
Total	44	1793817.5	40768.6			
			Tensile Strength			
Mean	1	257515.8303	257515.83	57.2	253013.3	0.561
Errors	43	193607.2832	4502.49496	1	198109.8	0.439
Total	44	451123.1135	10252.798			
			Elongation			
Mean	1	961.2	961.236	75.1	948.44	0.627
Errors	43	550.0	12.791		562.82	0.372
Total	44	1511.3	34.346			
			Mass-per-length			
Mean	1	0.043	0.0433	46.9	0.0424	0.510
Errors	43	0.039	0.0009	1	0.0406	0.489
Total	44	0.083	0.0018			

Table 9 (Continued).

			TS/YS			
Mean	1	0.426	0.426	82.08	0.421	0.648
Errors	43	0.223	0.005	1	0.2287	0.351
Total	44	0.650	0.014			

Table 10.

ANOVA Summary of 10 mm Diameter in Lot 2

Source	DOF	SS	Variance	F	Pure SS	P
			Yield strength			
Mean	1	1023946.8	1023946.8	330.2	1020846.2	0.924
Errors	26	80615.2	3100.6	1.0	83715.8	0.076
Total	27	1104562.0	40909.7			
			Tensile strength			
Mean	1	155344.6	155344.6	110.4041	153937.5	0.802
Errors	26	36583.41	1407.054	1	37990.46	0.198
Total	27	191928	7108.444			
			Elongation			
Mean	1	773.34	773.3426	287.622	770.65	0.913
Errors	26	69.90741	2.688746	1	72.596	0.086
Total	27	843.25	31.23148			
			Mass-per-length			
Mean	1	0.011516	0.011516	332.0768	0.01148	0.924
Errors	26	0.000902	3.47E-05	1	0.00093	0.075
Total	27	0.012417	0.00046			
			TS/YS			
Mean	1	0.345935	0.345935	73.91185	0.341254	0.729
Errors	26	0.12169	0.00468	1	0.12637	0.270
Total	27	0.467624	0.017319			

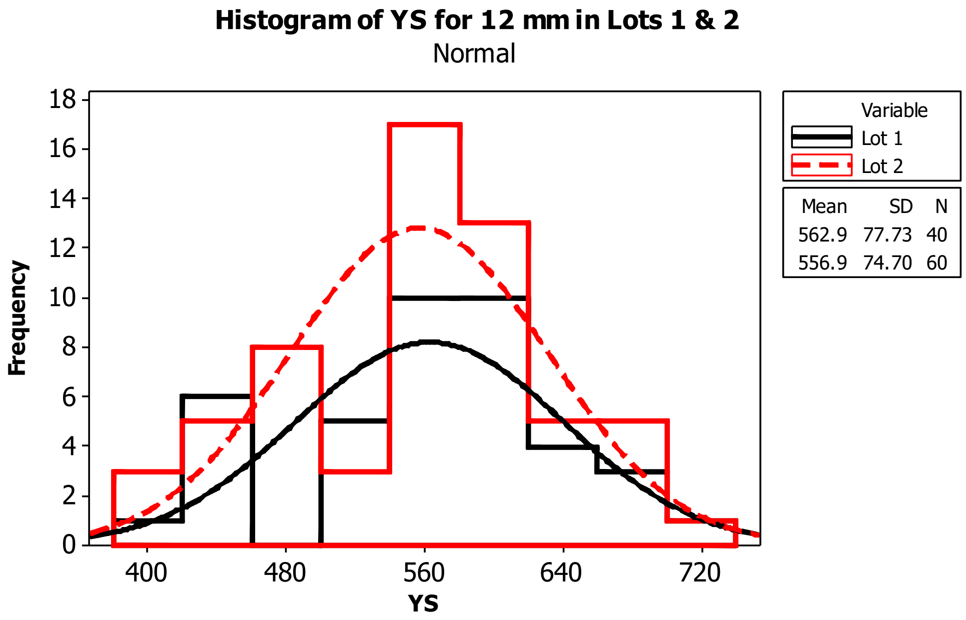
Distribution for 12 mm Diameter

The total sample bars investigated in Lots 1 and 2 were 40 and 60, respectively.

Yield Strength. According to the ASTM A615 standard, it is found that 1 bar out of 40 samples in Lot 1 and 3 bars out of 60 samples failed to fulfill the requirement. The distribution for yield strength of both Lot 1 and 2 are presented in Figure 19.

Figure 19.

Distribution of YS for 12 mm in Lot 1 and Lot 2



Tensile Strength. It is found that 3 bars out of 40 in Lot 1 and 14 bars out of 60 samples failed to fulfill the minimum requirement. The distribution for tensile strength of both Lot 1 and 2 are presented in Figure 20.

Elongation Percentage. The average EL in Lot 1 was found to be 15.93 while in Lot 2 it was 15.75. All the tested bars in both lots fulfilled the minimum ASTM requirement for EL. The distribution of EL is shown in Figure 21.

Mass-per-Length. The mean M/L values in Lots 1 2 were 0.8768 and 0.8580, respectively. All the sample bars in Lots 1 and 2 were within the range of standard values. The distribution of M/L is presented in Figure 22.

Figure 20.

Distribution of TS for 12 mm in Lot 1 and Lot 2

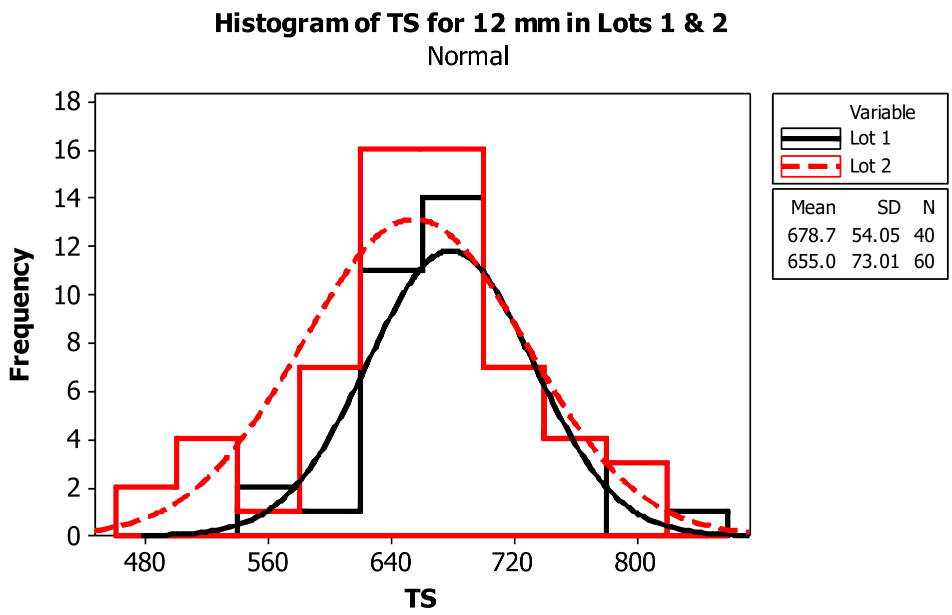


Figure 21.

Distribution of Elongation for 12 mm in Lot 1 and Lot 2

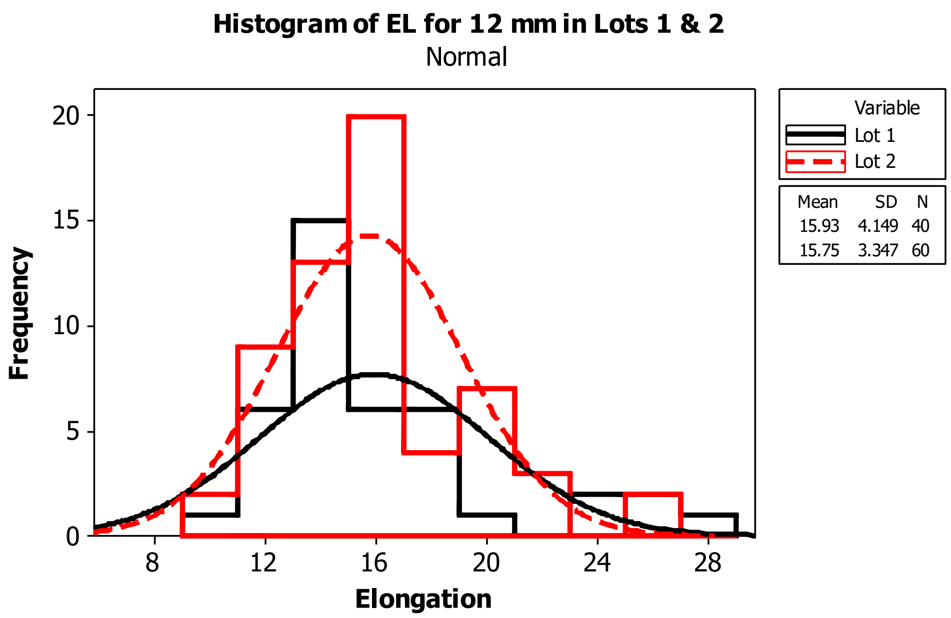
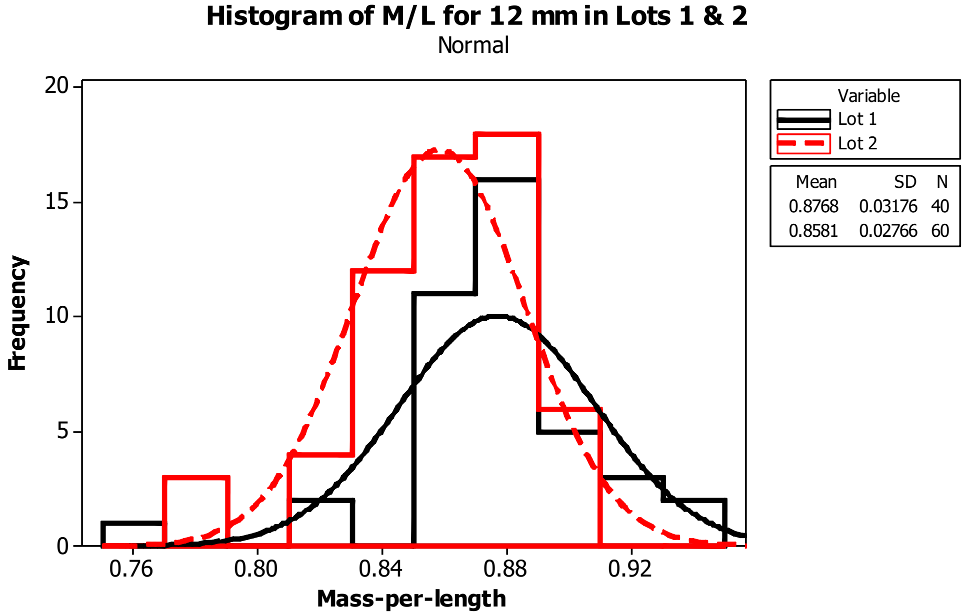


Figure 22.

Distribution of Mass-per-length for 12 mm in Lot 1 and Lot 2



TS/YS. The mean characteristics ratio of TS to YS were 1.2192 and 1.1820, respectively. 75% of the test results in Lot 1 and 90 % in Lot 2 failed to surpass the minimum set value required by ACI. Histogram and normal distribution graphical representation of the characteristic ratio for 12 mm nominal diameter steel bars is presented in Figure 23. The decrement trend of TS/YS versus respective YS values is plotted in Figure 24.

Statistical Analysis. The statistical analysis for all parameters was evaluated for all variables and summarized in Tables 11 and 12. Moreover, one way ANOVA table is summarized in Tables 13 and 14.

Figure 23.

Distribution of TS/YS for 12 mm in Lot 1 and Lot 2

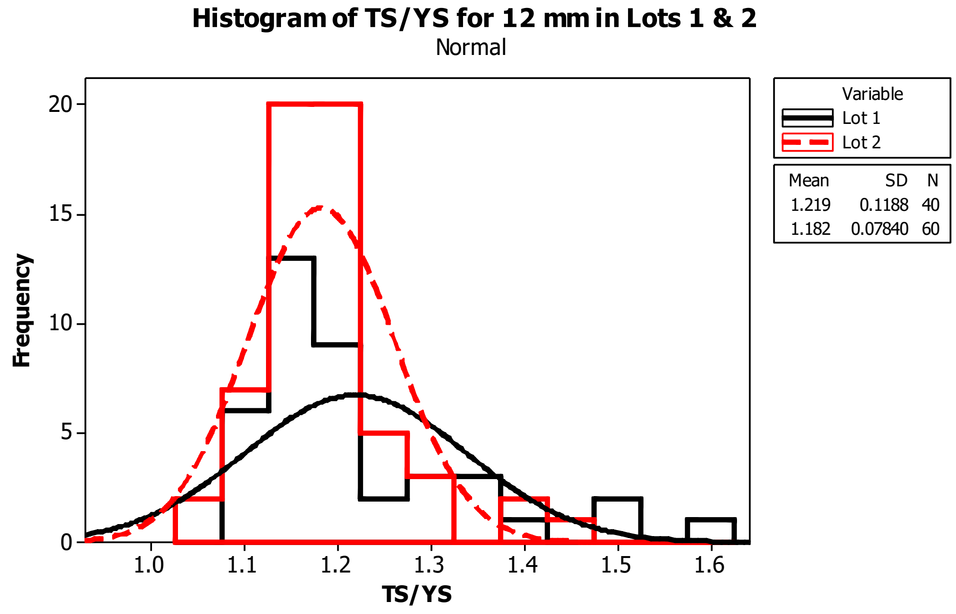


Figure 24.

Scatterplot of TS/YS vs YS of Respective Lots for 12 mm Diameter Bars

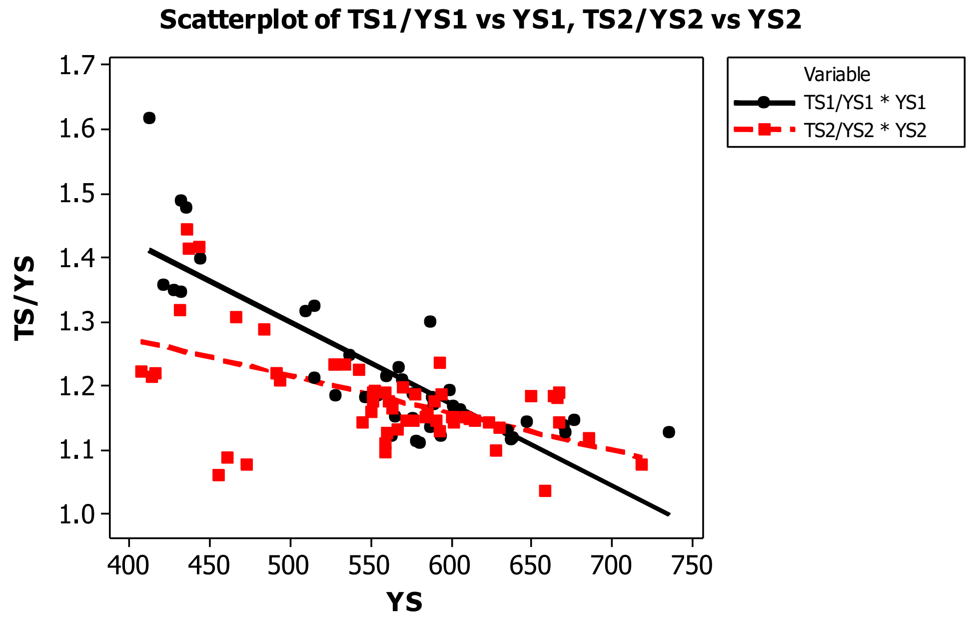


Table 11.

Statistical Summary of 12 mm Diameter in Lot 1

Parameters	YS	TS	EL	M/L	TS/YS
Min	412.30	570.30	10.67	0.7630	1.1109
Max	735.50	828.00	28.20	0.9470	1.6161
Range	323.20	257.70	17.53	0.1840	0.5051
Mean	562.86	678.70	15.93	0.8768	1.2192
Variance	6041.79	2921.08	17.21	0.0010	0.0141
Std. Dev.	77.73	54.05	4.15	0.0318	0.1188
CoV	13.81%	7.96%	26.05%	3.62%	9.75%
Skewness	-0.3492	0.3640	1.5455	-0.8728	1.6305
Kurtosis	-0.1277	0.6689	1.8970	3.6686	2.4184

Table 12.

Statistical Summary of 12 mm Diameter in Lot 2

Parameters	YS	TS	EL	M/L	TS/YS
Min	407.00	483.00	10.00	0.7730	1.0365
Max	718.00	794.00	25.00	0.8970	1.4437
Range	311.00	311.00	15.00	0.1240	0.4072
Mean	556.85	655.03	15.75	0.8581	1.1820
Variance	5579.96	5330.37	11.20	0.0008	0.0061
Std. Dev.	74.70	73.01	3.35	0.0277	0.0784
CoV	13.41%	11.15%	21.25%	3.22%	6.63%
Skewness	-0.2348	-0.4480	0.8126	-1.1662	1.3965
Kurtosis	-0.4981	0.3993	0.5377	1.6154	3.0106

Table 13.

ANOVA Summary of 12 mm Diameter in Lot 1

Source	DOF	SS	Variance	F	Pure SS	P
			Yield Strength			
Mean	1	816373.5	816373.5	135.1	810331.7	0.770
Errors	39	235629.8	6041.8	1	241671.6	0.230
Total	40	1052003.3	26300.1			
			Tensile strength			
Mean	1	137808.81	137808.81	47.17	134887.7	0.536
Errors	39	113922.13	2921.0802	1	116843.2	0.464
Total	40	251730.95	6293.2736			
			Elongation			
Mean	1	1918.9175	1918.91756	111.48	1901.706	0.734
Errors	39	671.26253	17.211859	1	688.4744	0.266
Total	40	2590.1801	64.754502			
			Mass-per-length			
Mean	1	0.0709469	0.0709469	70.35	0.069938	0.634
Errors	39	0.0393314	0.0010085	1	0.04034	0.366
Total	40	0.1103	0.0027569			
			TS/YS			
Mean	1	0.0380389	0.0380389	2.69	0.023921	0.040
Errors	39	0.5506174	0.0141184	1	0.564736	0.960
Total	40	0.5887	0.0147164			

Table 14.

ANOVA Summary of 12 mm Diameter in Lot 2

Source	DOF	SS	Variance	F	Pure SS	P
			Yield strength			
Mean	1	1123675.4	1123675.4	201.4	1118095.4	0.770
Errors	59	329217.6	5580.0	1.0	334797.6	0.230
Total	60	1452893.0	24214.9			
			Tensile strength			
Mean	1	73640.07	73640.07	13.81518	68309.69	0.176
Errors	59	314491.9	5330.372	1	319822.3	0.824
Total	60	388132	6468.867			
			Elongation			
Mean	1	2733.75	2733.75	244.1033	2722.551	0.802
Errors	59	660.75	11.19915	1	671.9492	0.198
Total	60	3394.5	56.575			
			Mass-per-length			
Mean	1	0.032763	0.032763	42.83615	0.031998	0.411
Errors	59	0.045126	0.000765	1	0.045891	0.589
Total	60	0.077889	0.001298			
			TS/YS			
Mean	1	0.277144	0.277144	45.08905	0.270997	0.424
Errors	59	0.362648	0.006147	1	0.368795	0.576
Total	60	0.639792	0.010663			

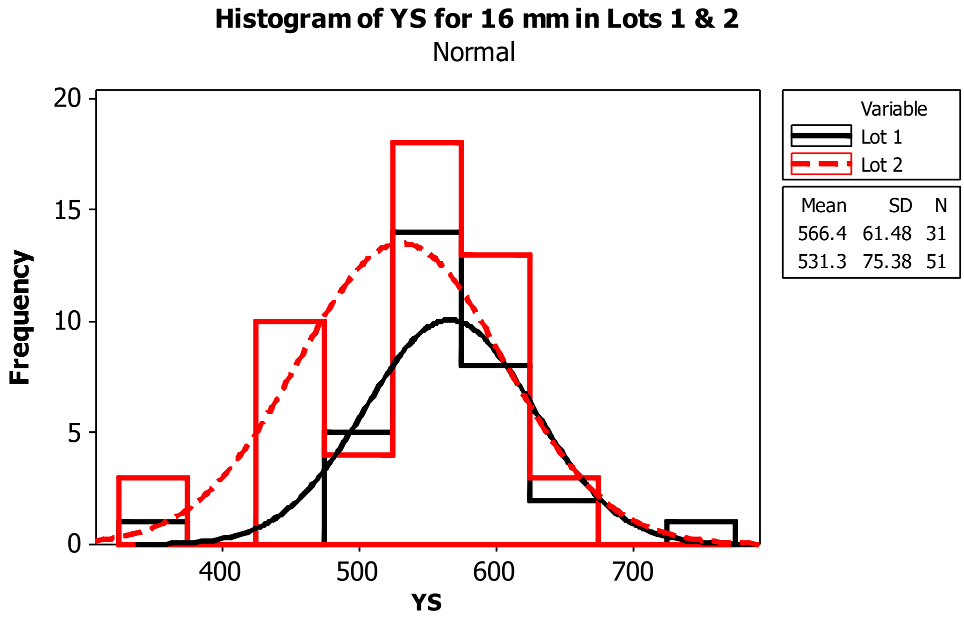
Distribution for 16 mm Diameter

The total bars investigated in Lots 1 and 2 are 31 and 51, respectively.

Yield Strength. It is found that 1 bar out of 31 in Lot 1 and 3 bars out of 51 samples failed to fulfill the requirement set by ASTM for yield strength. The distribution for yield strength of both Lots is presented in Figure 25.

Figure 25.

Distribution of YS for 16 mm in Lot 1 and Lot 2



Tensile Strength. Like the yield strength, according to ASTM A615 standard, it is found that 2 bars out of 31 in Lot 1and 6 bars out of 51 samples in Lot 2 failed to fulfill the requirement for minimum tensile strength. The distribution for tensile strength of both lots is presented in Figure 26.

Elongation Percentage. The average elongation percentage in Lot 1 was found to be 16.29 while in Lot 2 it was 17.68. The distribution of elongation percentage is shown in Figure 27.

Mass-per-Length. The mean M/L values of the samples in Lots 1 and 2 were 1.554 and 1.524, respectively. EL results of all the samples in Lots 1 and 2 were within the range of the M/L requirement. The distribution of mass-per-length is shown in Figure 28.

TS/YS. The mean characteristics ratio of TS to YS were 1.2099 and 1.2501, respectively. 71% of the test results in Lot 1 and 75 % in Lot 2 failed to surpass the minimum set value required by ACI. Histogram and normal distribution graphical representation of the characteristic ratio for 16 mm nominal diameter steel bars is presented in Figure 29. The trend of TS/YS versus respective YS values of both lots is plotted in Figure 30.

Figure 26.

Distribution of TS for 16 mm in Lot 1 and Lot 2

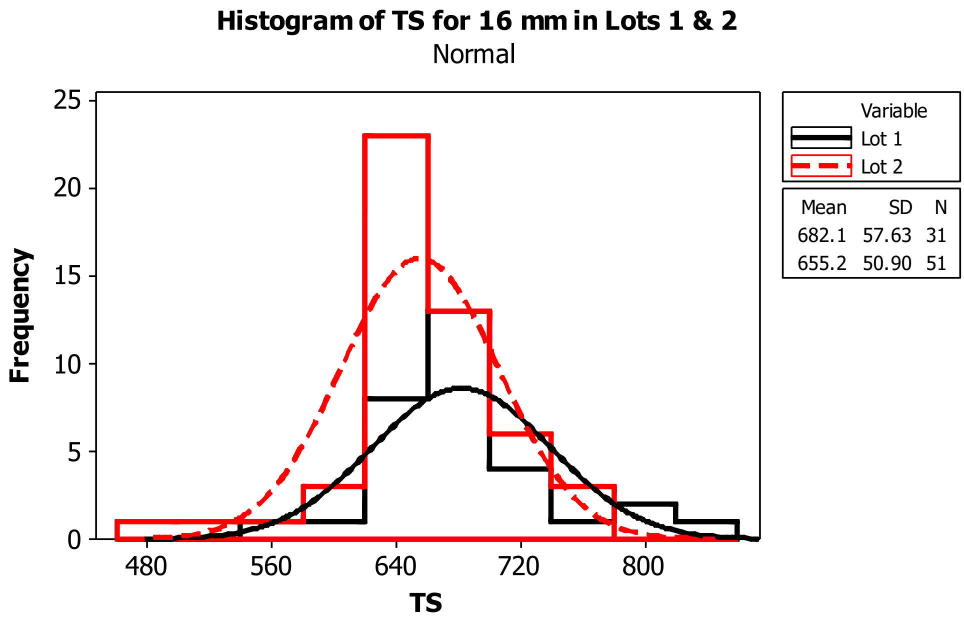
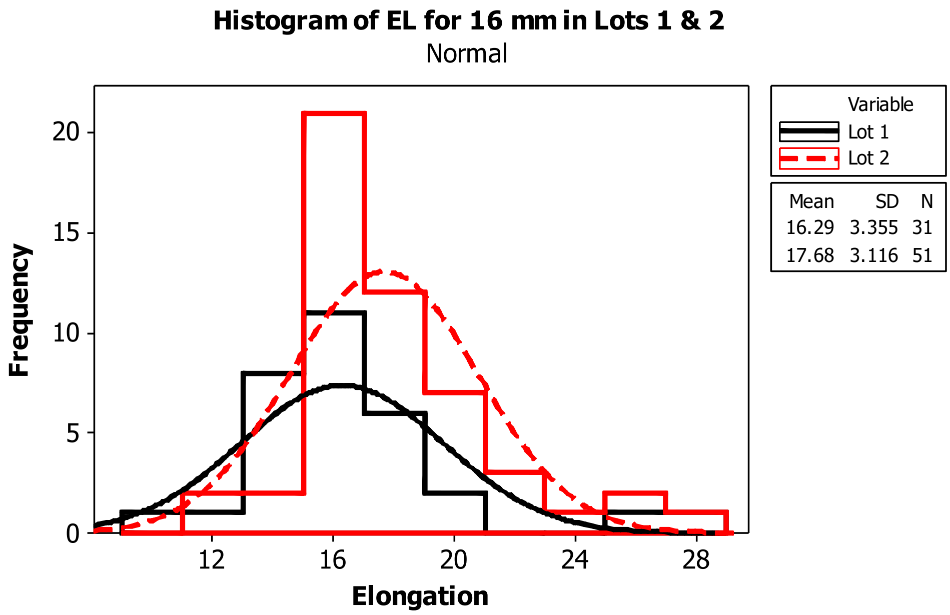


Figure 27.

Distribution of Elongation for 16 mm in Lot 1 and Lot 2



Statistical Analysis. The summary of statistical analysis is summarized in Tables 15 and 16. Moreover, one way ANOVA table is summarized as in Tables 17 and 18.

Figure 28.

Distribution of Mass-per-length for 16 mm in Lot 1 and Lot 2

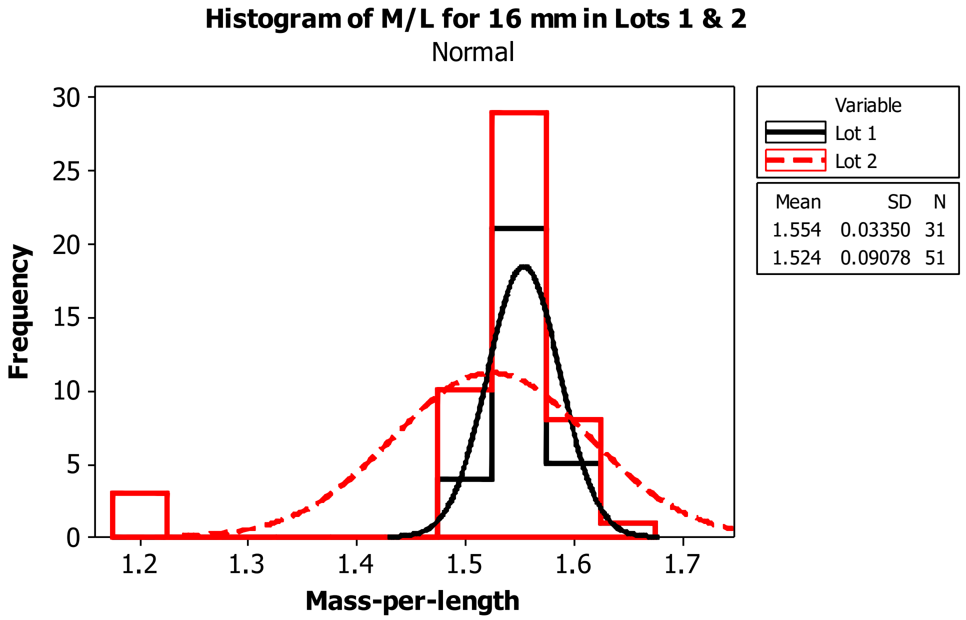


Figure 29.

Distribution of TS/YS for 16 mm in Lot 1 and Lot 2

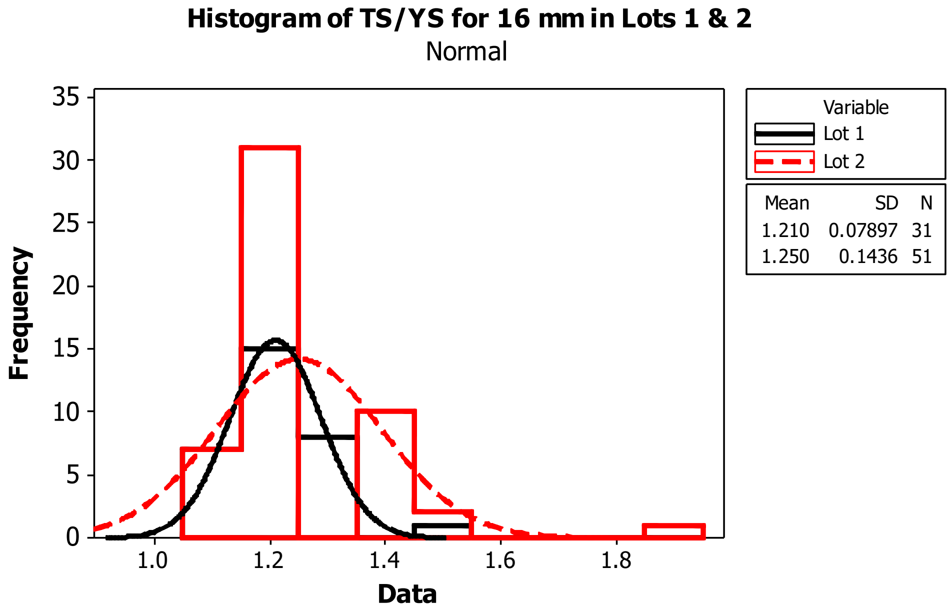


Figure 30.

Scatterplot of TS/YS vs YS of Respective Lots for 16 mm Diameter Bars

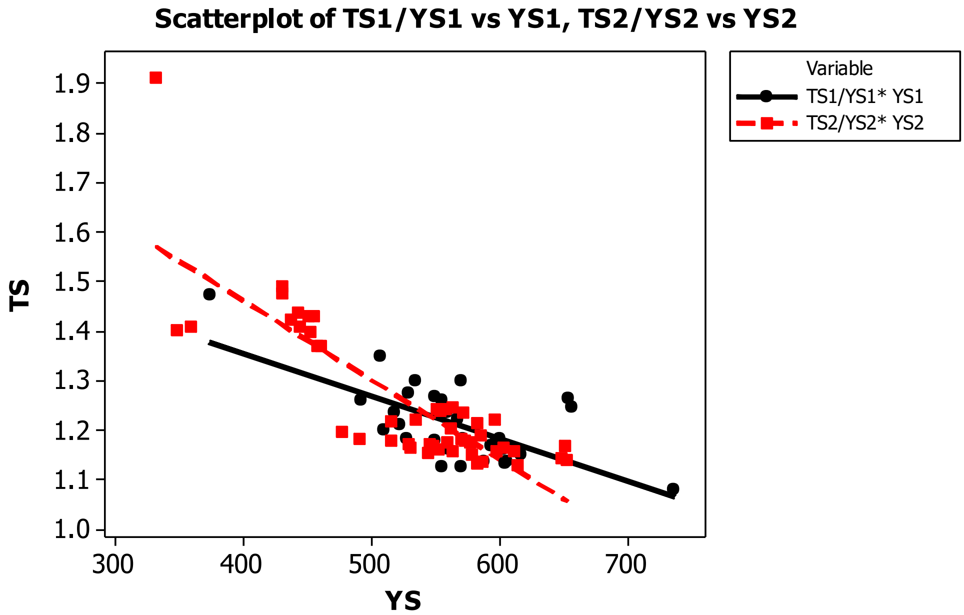


Table 15.

Statistical Summary of 16 mm Diameter in Lot 1

Parameters	YS	TS	EL	M/L	TS/YS
Min	373.67	550.00	10.83	1.4900	1.0769
Max	736.67	825.67	27.80	1.6280	1.4719
Range	363.00	275.67	16.97	0.1380	0.3950
Mean	566.37	682.13	16.29	1.5541	1.2099
Variance	3779.91	3321.71	11.26	0.0011	0.0062
Std. Dev.	61.48	57.63	3.36	0.0335	0.0790
CoV	10.86%	8.45%	20.60%	2.16%	6.53%
Skewness	-0.2381	0.6323	1.7666	0.2582	1.2297
Kurtosis	3.5941	1.4930	4.7705	0.3374	2.7299

Table 16.

Statistical Summary of 16 mm Diameter in Lot 2

Parameters	YS	TS	EL	M/L	TS/YS
Min	332.00	487.00	12.00	1.1760	1.1270
Max	653.00	759.00	27.00	1.6300	1.9127
Range	321.00	272.00	15.00	0.4540	0.7856
Mean	531.27	655.24	17.68	1.5244	1.2501
Variance	5682.76	2590.90	9.71	0.0082	0.0206
Std. Dev.	75.38	50.90	3.12	0.0908	0.1436
CoV	14.19%	7.77%	17.63%	5.96%	11.49%
Skewness	-0.8405	-0.9174	1.2924	-3.2391	2.3552
Kurtosis	0.3077	2.5054	1.9690	10.5545	7.8050

Table 17.

ANOVA Summary of 16 mm Diameter in Lot 1

Source	DOF	SS	Variance	F	Pure SS	P
			Yield strength			
Mean	1	664129.0	664129.0	175.7	660349.1	0.849
Errors	30	113397.3	3779.9	1.0	117177.2	0.151
Total	31	777526.3	25081.5			
			Tensile strength			
Mean	1	119655.546	119655.546	36.0	116333.8	0.530
Errors	30	99651.3853	3321.71284	1	102973.1	0.470
Total	31	219306.9312	7074.41714			
			Elongation			
Mean	1	1646.15516	1646.15516	146.2	1634.899	0.824
Errors	30	337.688239	11.2562746	1	348.9445	0.176
Total	31	1983.8434	63.9949484			

			Mass-per-length			
Mean	1	0.0937541	0.0937541	83.5	0.092632	0.727
Errors	30	0.03366979	0.00112233	1	0.034792	0.273
Total	31	0.1274	0.00411045			

Table (Continued)

			TS/YS			
Mean	1	0.0497297	0.0497297	7.97	0.043493	0.184
Errors	30	0.18710912	0.00623697	1	0.193346	0.816
Total	31	0.2368	0.00763996			

Table 18.

ANOVA Summary of 16 mm Diameter in Lot 2

Source	DOF	SS	Variance	F	Pure SS	P
			Yield strength			
Mean	1	631482.8	631482.8	111.1	625800.1	0.683
Errors	50	284138.2	5682.8	1	289820.9	0.317
Total	51	915621.0	17953.4			
			Tensile strength			
Mean	1	63317.82353	63317.824	24.4	60726.92	0.315
Errors	50	129545.1765	2590.9035	1	132136.1	0.685
Total	51	192863.000	3781.6275			
			Elongation			
Mean	1	3839.338235	3839.3382	395.5	3829.63	0.886
Errors	50	485.4117647	9.7082353	1	495.12	0.114
Total	51	4324.750	84.79902			
			Mass-per-length			
Mean	1	0.032523263	0.0325233	3.9	0.024282	0.055
Errors	50	0.412039647	0.0082408	1	0.42028	0.945
Total	51	0.445	0.0087169			
			TS/YS			
Mean	1	6.97838E-07	6.978E-07	<1	-0.02063	-0.020

Errors	50	1.031440224	0.0206288	1	1.052069	1.020
Total	51	1.031440922	0.0202243			

Distribution for the Lot Aggregate Data

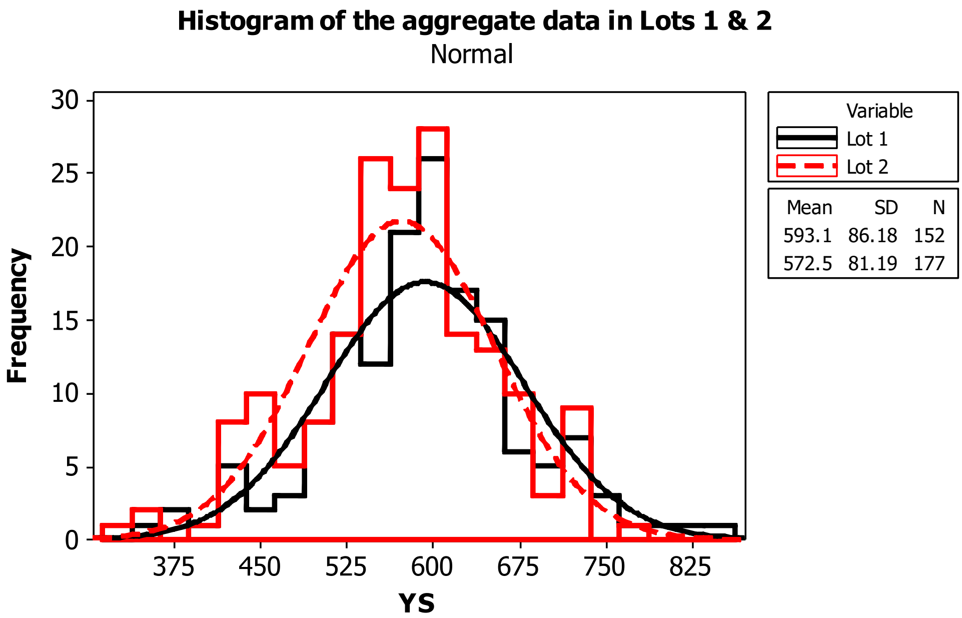
As aggregate data, the total bars investigated in Lots 1 and 2 were 152 and 177, respectively. Mechanical strength properties were studied for the aggregate data. As the values of M/L for different nominal diameters were varying, the M/L analysis is skipped from the aggregate data evaluation.

Yield Strength. It is found that 4 bars out of 152 (i.e. 2.63%) in Lot 1 failed to fulfill the requirement. In lot 2, 6 bars out of 177 (i.e. 3.39%) failed to fulfill the minimum yield strength value. The distribution for yield strength of both Lot 1 and 2 are presented in Figure 31.

Tensile Strength. According to the ASTM A615 standard, it is found that 10 bars (i.e. 6.58%) failed to fulfill the requirement. In lot 2, 20 bars (i.e. 11.30%) failed to fulfill the minimum tensile strength value set by ASTM. The distribution for the aggregate tensile strength in both lots is presented in Figure 32.

Figure 31.

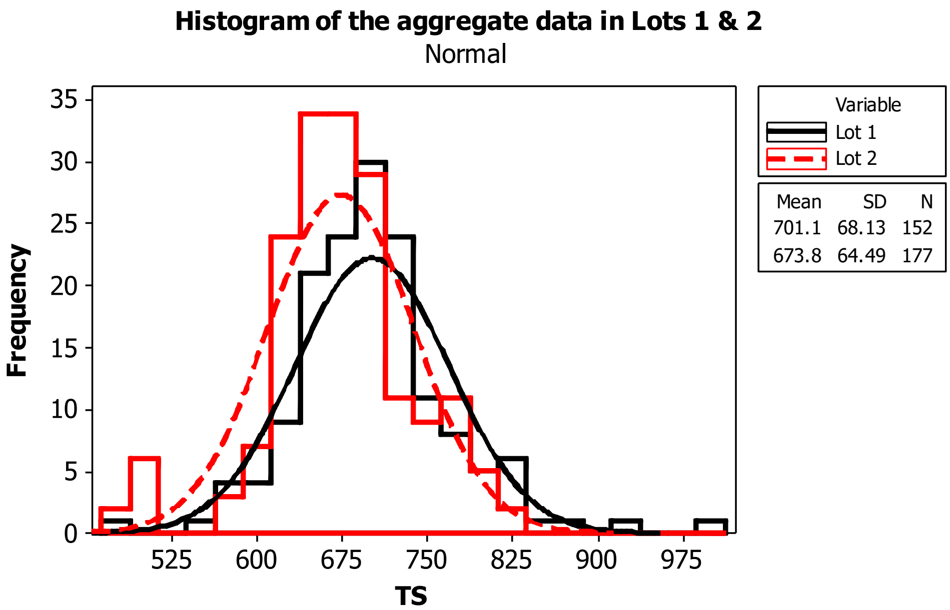
Distribution of YS for the Aggregate Data in Lot 1 and Lot 2



Elongation Percentage. It is noted that the EL exhibited significant statistical variability for the aggregate data in both lots. According to the ASTM A615 standard, it is found that 9 bars i.e. 5.62% in Lot 1 and 5 bars i.e. 2.82% failed to fulfill the minimum requirement. The average EL in Lot 1 was found to be 14.77 while in Lot 2 it was 15.47. The aggregate data analysis for elongation percentage didn't look into 8 mm diameter bars as ASTM standard doesn't set a minimum requirement for elongation percentage. The distribution of EL for the aggregate is presented in Figure 33.

Figure 32.

Distribution of TS for the Aggregate Data in Lot 1 and Lot 2



TS/YS. The TS/YS values showed a descending trend with the increase in the YS values for the aggregate data. The mean characteristics ratio of TS to YS were 1.1822 and 1.1771, respectively. 78% of the test results in Lot 1 and 85 % in Lot 2 failed to surpass the set value required by ACI. The histogram and normal distribution graphical representation of the characteristic ratio for the aggregate data is presented in Figure 34. The trend of TS/YS versus respective YS values of both lots is plotted in Figure 35.

Statistical Analysis. The analysis which included statistical parameters such as minimum, maximum, range, mean, variance, SD, CoV, kurtosis, and skewness is done for all variables. The analysis of the aggregate data is summarized in Tables 19 and 20. Moreover, one way ANOVA table is summarized as in Tables 21 and 22.

Figure 33.

Distribution of Elongation for the Aggregate Data in Lot 1 and Lot 2

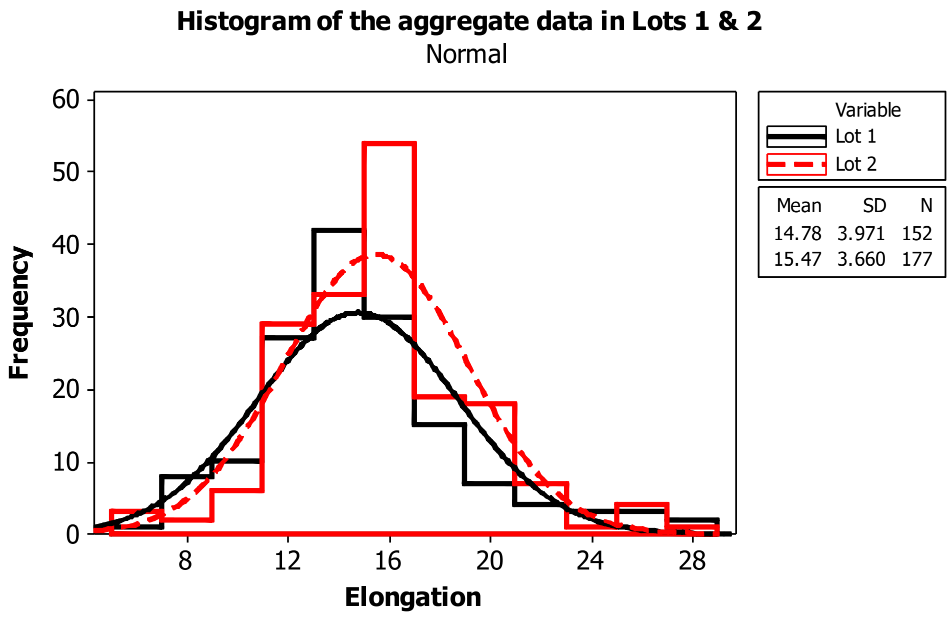


Figure 34.

Distribution of TS/YS for the Aggregate Data in Lot 1 and Lot 2

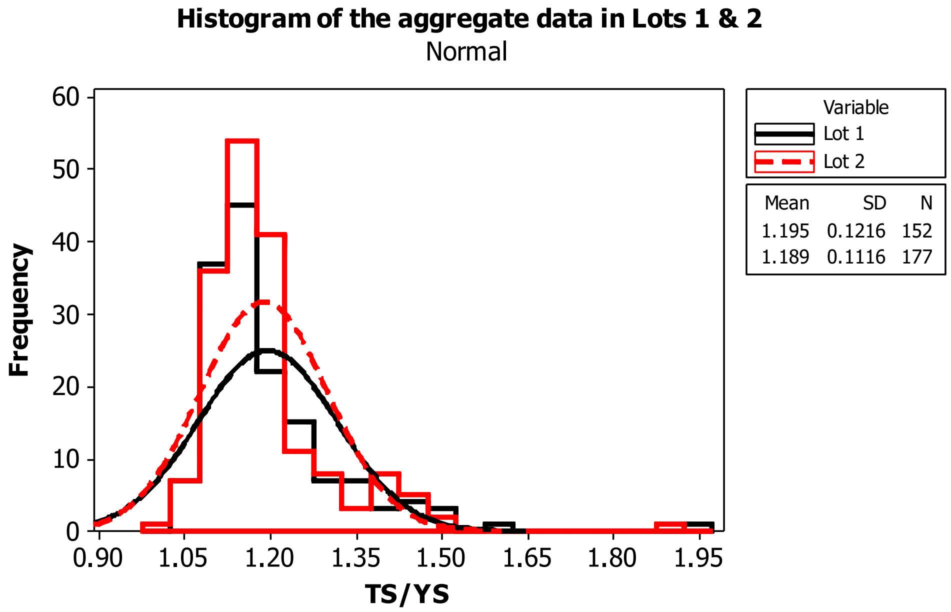


Figure 35.

Scatterplot of TS/YS vs YS of Respective Lots for the Aggregate Data

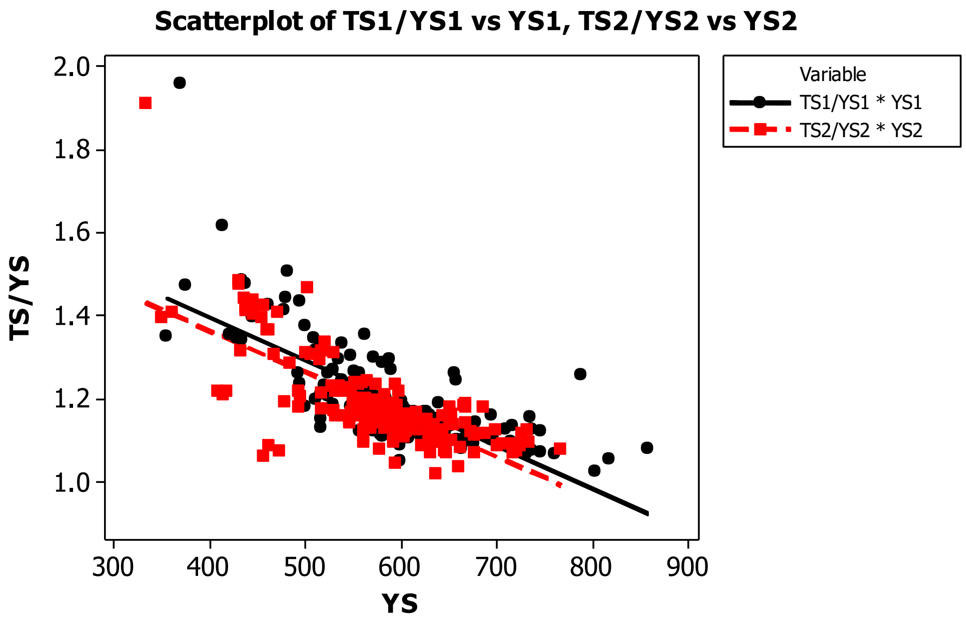


Table 19.

Statistical Summary of the Aggregate Data in Lot 1

Parameters	YS	TS	EL	TS/YS
Min	354.00	478.67	6.00	1.03
Max	857.30	990.00	28.20	1.96
Range	503.30	511.33	22.20	0.94
Mean	593.06	701.14	14.78	1.18
Variance	7427.64	4641.75	15.77	0.01
Std. Dev.	86.18	68.13	3.97	0.12
CoV	14.53%	9.72%	26.87%	10.28%
Skewness	0.0164	0.6446	0.8608	2.5333
Kurtosis	0.8105	2.5876	1.5969	10.5721

Table 20.

Statistical Summary of the Aggregate Data in Lot 2

Parameters	YS	TS	EL	TS/YS
Min	332.00	483.00	5.00	1.02
Max	766.00	828.00	27.00	1.91
Range	434.00	345.00	22.00	0.89
Mean	572.46	673.85	15.47	1.18
Variance	6591.53	4159.22	13.40	0.01
Std. Dev.	81.19	64.49	3.66	0.11
CoV	14.18%	9.57%	23.66%	9.48%
Skewness	-0.3090	-0.3457	0.3678	2.3835
Kurtosis	0.1415	1.1506	1.0520	9.8319

Table 21.

Statistical Summary of the Aggregate Data in Lot 1

Source	DOF	SS	Variance	F	Pure SS	P

Yield strength						
Mean	1	4552240.5	4552240.5	612.9	4544812.9	0.801
Errors	151	1121574.0	7427.6	1	1129001.6	0.199
Total	152	5673814.5	37327.7			
Tensile strength						
Mean	1	1000721	1000721	215.6	996079	0.585
Errors	151	700904.5	4641.752	1	705546.3	0.415
Total	152	1701625	11194.9			
Elongation						
Mean	1	5069.4	5069.364	321.5	5053.597	0.678
Errors	151	2380.8	15.76686	1	2396.563	0.322
Total	152	7450.2	49.01421			
TS/YS						
Mean	1	0.5	0.458003	30.9	0.44322	0.165
Errors	151	2.2	0.014782	1	2.246914	0.835
Total	152	2.7	0.017698			

Table 22.

ANOVA Summary of the Aggregate Data in Lot 2

Source	DOF	SS	Variance	F	Pure SS	P
Yield strength						
Mean	1	4114069.1	4114069.1	624.1	4107477.5	0.779
Errors	176	1160109.9	6591.5	1.0	1166701.5	0.221
Total	177	5274179.0	29797.6			
Tensile strength						
Mean	1	513220.1	513220.1	123.3933	509060.9	0.409
Errors	176	732022.9	4159.2	1	736182.1	0.591
Total	177	1245243	7035.3			
Elongation						
Mean	1	7413.391	7413.4	553.3651	7399.994	0.757
Errors	176	2357.859	13.4	1	2371.256	0.243
Total	177	9771.25	55.2			

TS/YS						
Mean	1	0.66467	0.665	53.36986	0.652216	0.228
Errors	176	2.191909	0.012	1	2.204363	0.772
Total	177	2.856579	0.016			

Summary for the Total Aggregate Data

Distribution of Mechanical Strengths

Similar to the lot aggregates, the variability of mechanical and linear density behaviors of the total tests in this study is summarized. The total bars investigated were 329 samples. The distribution along with the normality test result of yield strength, tensile strength, elongation percentage, and tensile-to-yield strength ratio are presented in Figures 36, 37, 38, and 39. Similarly, the trend of TS/YS versus respective YS values of both lots is plotted in Figure 40.

Figure 36.

Distribution and Normality Test of Yield Strength for the Total Aggregate

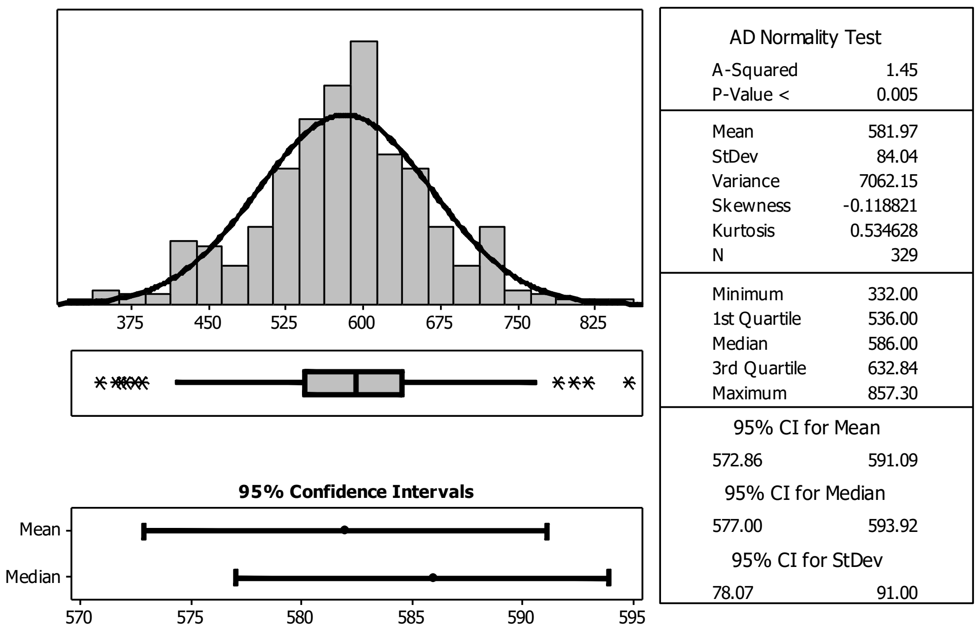


Figure 37.

Distribution and Normality Test of Tensile Strength for the Total Aggregate

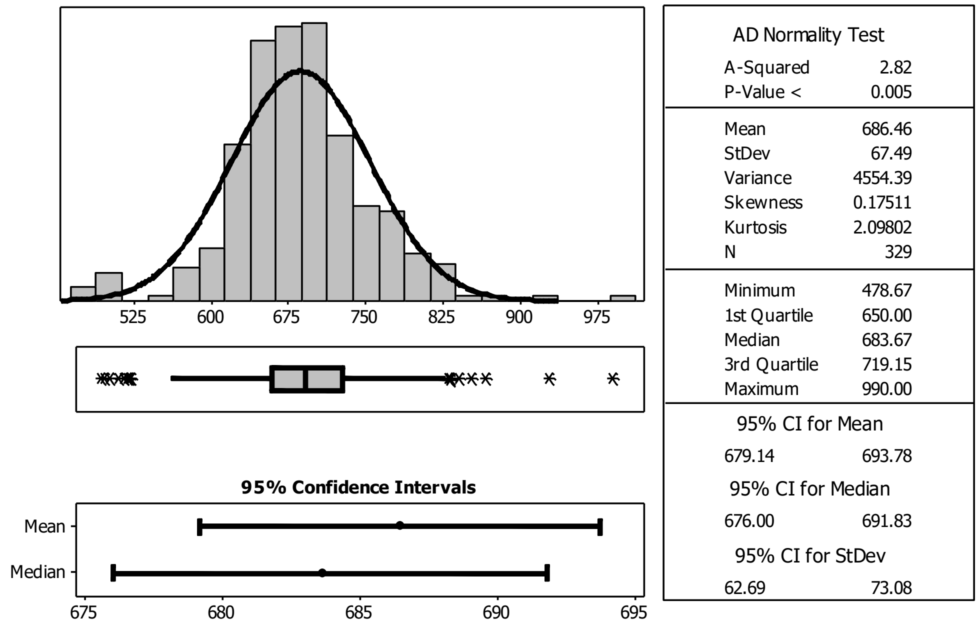


Figure 38.

Distribution and Normality of Elongation Percentage for the Total Aggregate

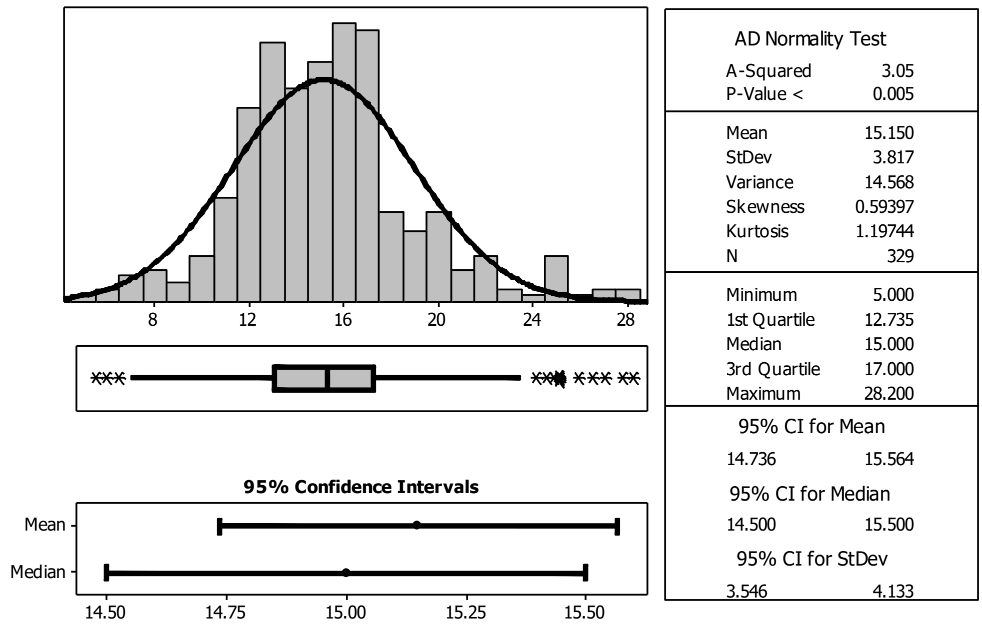


Figure 39.

Distribution and Normality TS/YS for the Total Aggregate

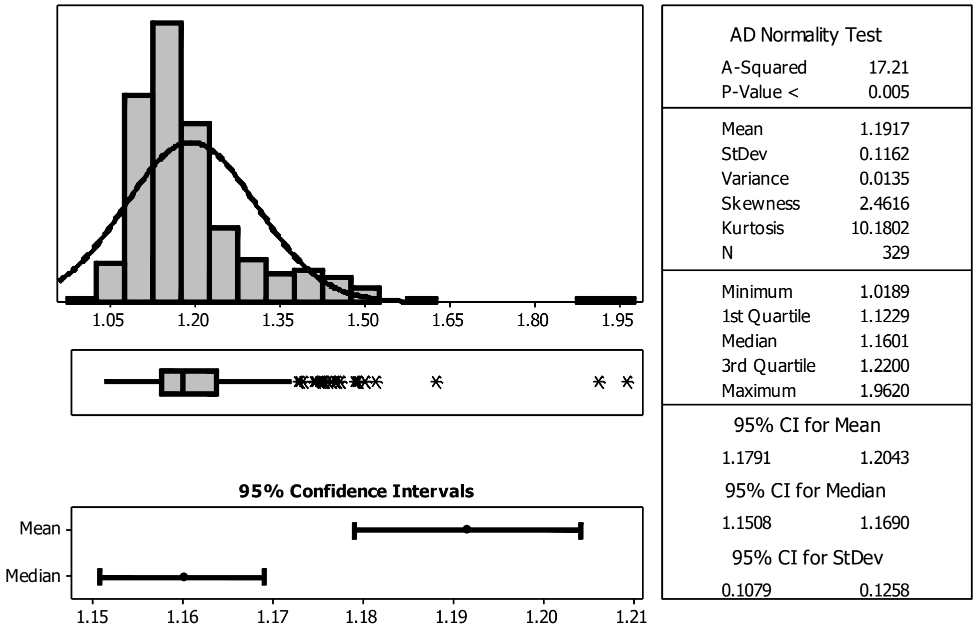
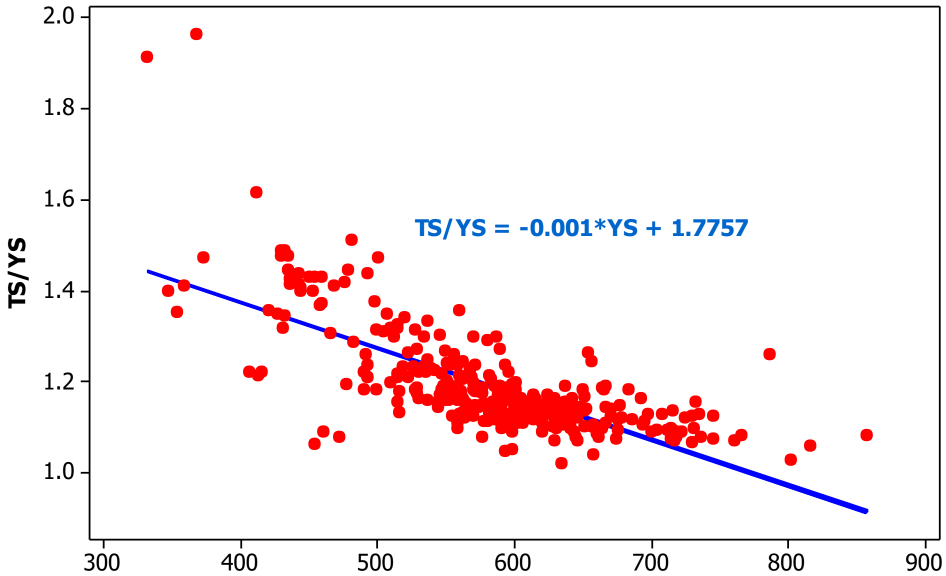


Figure 40.

Scatterplot of TS/YS vs YS of the Total Aggregate Data



Statistical Summary

Table 23 summarizes the statistical parameters used in this study for the mechanical strength properties.

Table 23.

Statistical Summary of the Total Aggregate Data

Parameters	YS	TS	EL	TS/YS
Min	332.00	478.67	5.00	1.019
Max	857.30	990.00	28.20	1.962
Range	525.30	511.33	23.20	0.94
Mean	581.97	686.46	15.15	1.192
Variance	7062.15	4554.39	14.57	0.01
Std. Dev.	84.04	67.49	3.82	0.12
COV	14.44%	9.83%	25.19%	9.75%
Skewness	-0.1188	0.1751	0.5940	2.4616
Kurtosis	0.5346	2.0980	1.1974	10.1802

One-way one-level ANOVA table is summarized for the total aggregate data as presented in Table 24.

Table 24.

ANOVA Summary of the Total Aggregate Data

Source	DOF	SS	Variance	F	Pure SS	P
Yield Strength						
Mean	1	8631607.4	8631607.4	1222.2	8624545.3	0.788
Errors	328	2316386.0	7062.2	1.0	2323448.2	0.212
Total	329	10947993.5	33276.6			
Tensile Strength						
Mean	1	1453028.3	1453028.3	319.0	1448473.9	0.492
Errors	328	1493840.0	4554.4	1.0	1498394.4	0.508
Total	329	2946868.2	8957.0			
Elongation Percentage						
Mean	1	12443.1	12443.1	854.1	12428.5	0.722
Errors	328	4778.3	14.6	1.0	4792.9	0.278

Total	329	17221.4	52.3			
			TS/YS			
Mean	1	1.1	1.1	82.9	1.1	0.199
Errors	328	4.4	0.0	1.0	4.4	0.801
Total	329	5.5	0.0			

Goodness-of-fit Test

As it is indicated in Figures 36 - 39, the normality of the total data was evaluated using the Anderson-Darling normality test method (Anderson & Darling, 1952) as it produces a normal probability plot and makes a hypothesis test to check whether or not the observations follow a normal distribution. When the p-value is more than 0.05, the assumption to reject the null hypothesis at the alpha = 0.05 significance level fails and the conclusion is the data follow a normal distribution. When the p-value is less than 0.05 the null hypothesis will be rejected that the data follow the non-normal distribution. In that case, testing of goodness-of-test will be conducted to establish a useful model that fits the data.

Goodness-of-fit of the parameters is evaluated for various distributions. The summary of this result is presented in Table 25.

Table 25.

Summary of Goodness-of-fit Test

	p-values			
Distribution	YS	TS	EL	TS/YS
N	<0.005	<0.005	<0.005	<0.005
BCT	<0.005	<0.005	<0.005	<0.005
LN	<0.005	<0.005	<0.005	<0.005
3PLN	*	*	*	*
E	<0.003	<0.003	<0.003	<0.003
2PE	<0.010	<0.010	<0.010	<0.010
W	<0.010	<0.010	<0.010	<0.010
3PW	<0.005	<0.005	<0.005	<0.005
SEV	<0.010	<0.010	<0.010	<0.010

LEV	<0.010	<0.010	<0.010	<0.010
G	<0.005	<0.005	<0.005	<0.005
3PG	*	*	*	*
L	0.047	<0.005	<0.005	<0.005
LL	<0.005	0.017	0.017	<0.005
3PLL	*	*	*	*
JT	0.301	0.502	0.128	0.345

where, N = Normal; BCT = Box-Cox Transformation; LN = Lognormal; 3PLN = 3-Parameter Lognormal; E = Exponential; 2PE = 2-Parameter Exponential; W = Weibull; 3PW = 3-Parameter Weibull; SEV = Smallest Extreme Value; G = Gamma; 3PG = 3-Parameter Gamma; LEV = Largest Extreme Value; L = Logistic; LL = Loglogistic; 3PLL = 3-Parameter Loglogistic; JT = Johnson Transformation

When the data fail to fit all the possible distribution types, a remedial transformation action to make the data fit normal transformed data should be taken. Box-Cox transformation is one of these remedial actions used to make data normal. The transformed data and respective process capability indices are presented in Figures 41, 42, 43, and 44 for YS, TS, EL, and TS/YS, respectively.

Figure 41

Process Capability of Yield Strength

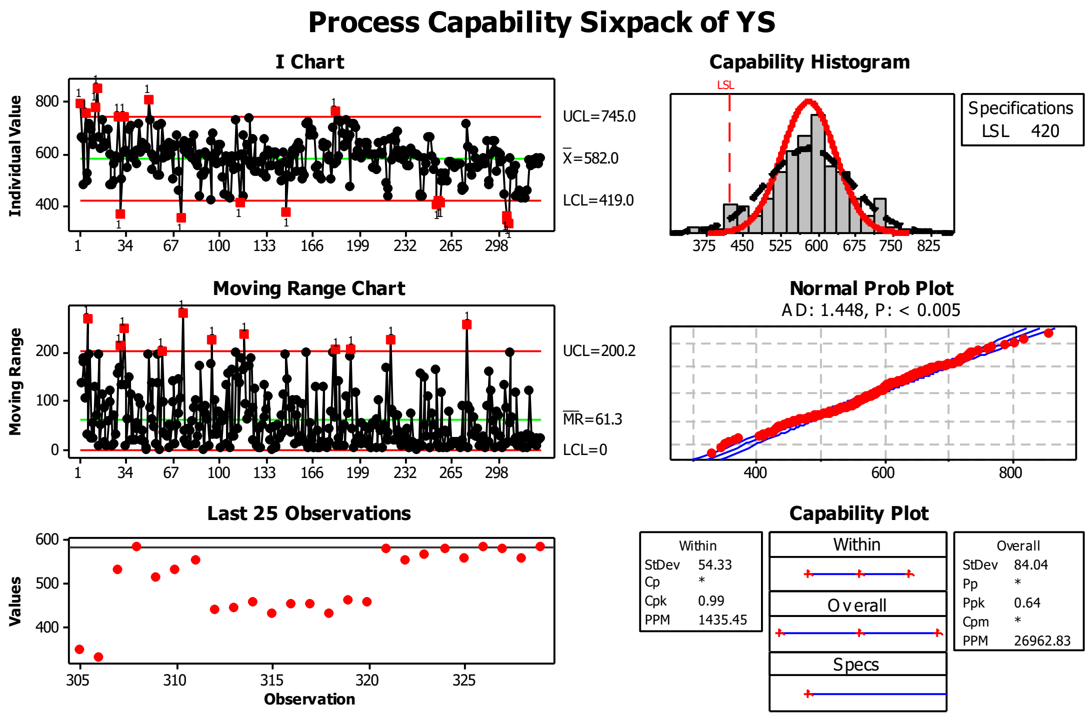


Figure 42

Process Capability of Tensile Strength

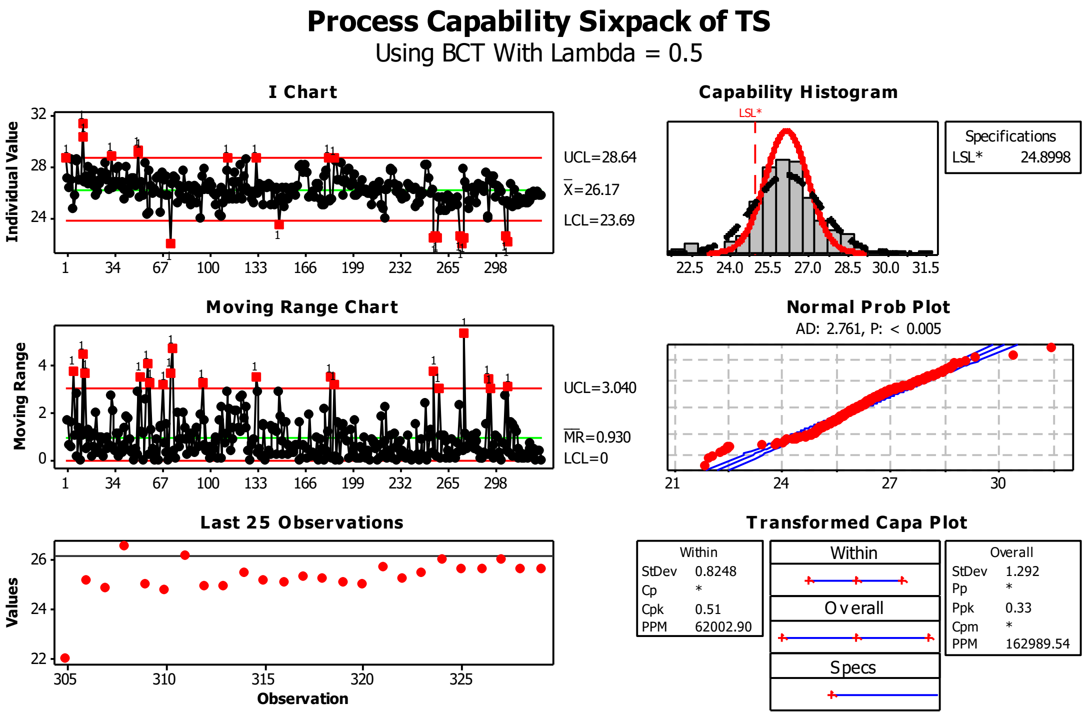


Figure 43

Process Capability of Elongation Percentage

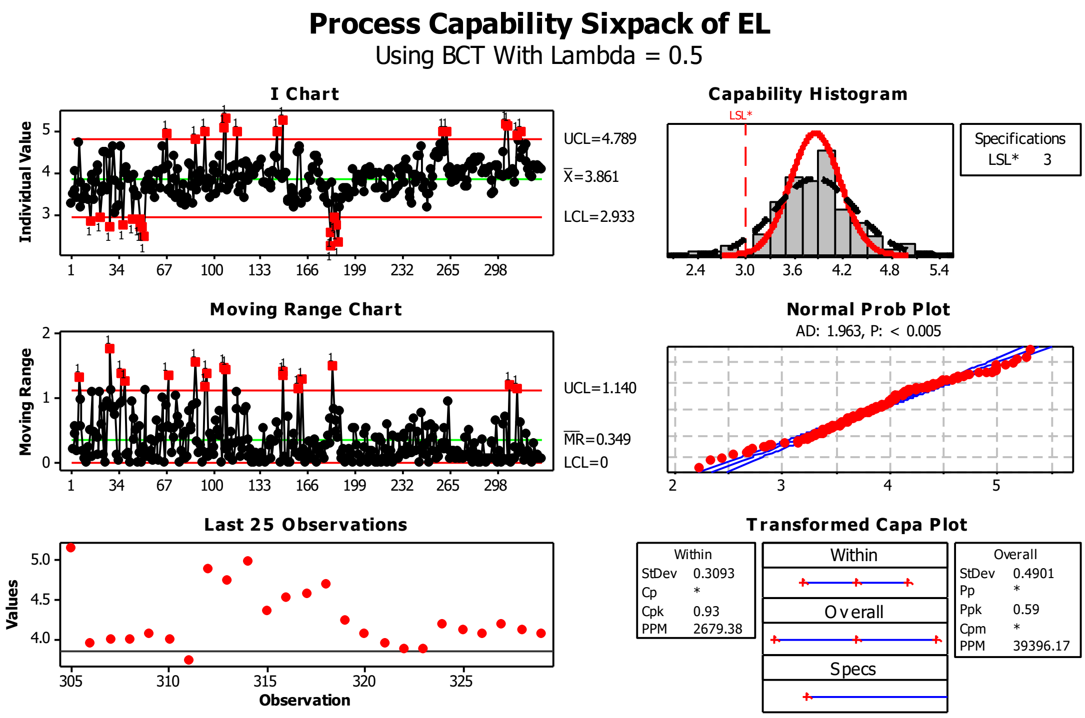
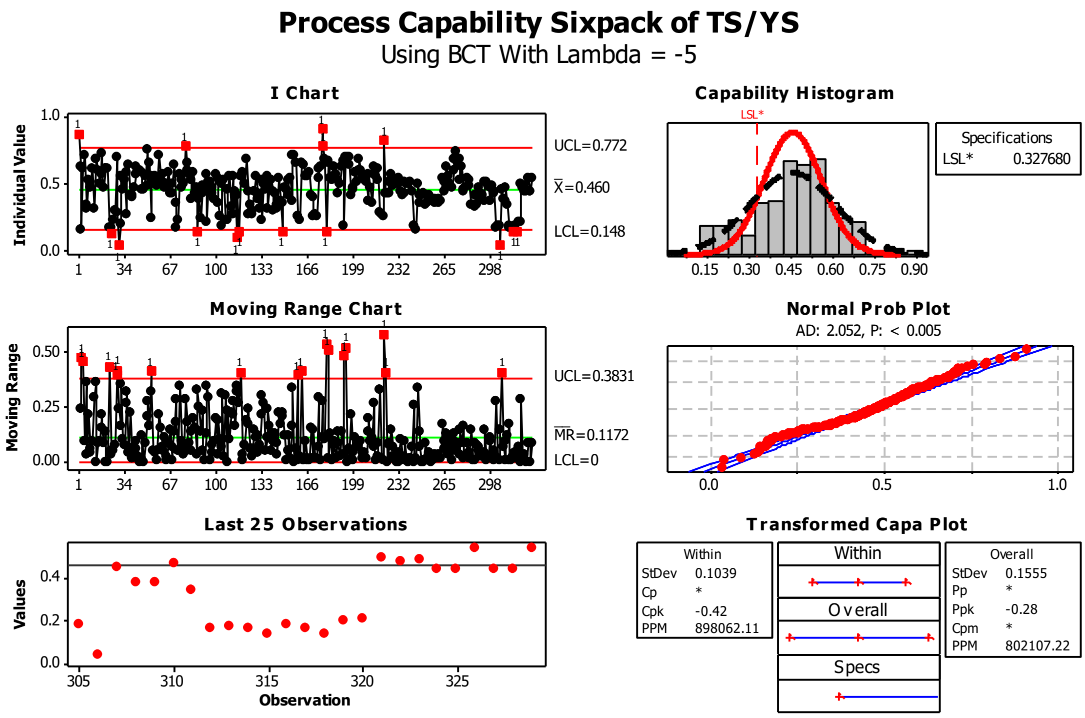


Figure 44

Process Capability of Tensile-to-Yield Strength Ratio



Error Analysis

Uncertainty of the performed measurements was calculated using equations 11 – 15 discussed in Chapter 3. The basic equation for stress and elongation analysis discussed as equations 3 – 5 were also used for the error estimation. For calculations, the following measurement accuracies were adopted: $\Delta d = 0.01mm$, $\Delta l = 0.5mm$, $\Delta m = 0.5g$, and $\Delta F = 0.00062N$.

For both yield and tensile stresses, the absolute error analysis will take the form,

$$\Delta\sigma = \sqrt{(\frac{\partial\sigma}{\partial F}\Delta F)^2 + (\frac{\partial\sigma}{\partial D}\Delta D)^2}$$

where,

$$\sigma = \frac{4F}{\pi D^2}, \frac{\partial\sigma}{\partial F} = \frac{4}{\pi D^2} \text{ and } \frac{\partial\sigma}{\partial D} = -\frac{4F}{3\pi D^3}$$

The absolute error estimation of elongation percentage involves the combined consideration of equations 12 and 14. Hence,

$$\Delta EL = \sqrt{(\Delta l)^2 + \left(\sqrt{(L_f\Delta l)^2 + (L_o\Delta l)^2}\right)^2}$$

The absolute error of mass-per-length is estimated using equation 14.

$$\Delta\left(\frac{M}{L}\right) = \sqrt{(\Delta m)^2 + (\Delta l)^2}$$

The absolute and relative errors of the measured results are presented in Table 26. In spite of the poor accuracy of the measuring tools used in this study, the calculated errors are found to be acceptable. Environmental effects such as temperature, pressure, humidity, etc. can affect the experimental result and can be reflected in cumulative errors in the reading scale. It is explained in the methods and materials section that the experimental runs were conducted at room temperature, with no effect from humidity and pressure. Hence, it’s assumed the reading was not affected by environmental effects in general.

Table 26.

Summary of Absolute and Relative Error Values

	Bar sizes (mm)			
Mean Measured Value	8	10	12	16
σ_y (MPa)	625.59	610.52	559.25	544.54
$\Delta\sigma_y$ (MPa)	0.00026	0.00020	0.00016	0.00011
$\delta\sigma_y$ (%)	0.000042	0.00003	0.00003	0.00002
σ_u (MPa)	728.91	696.25	664.49	665.40
$\Delta\sigma_u$ (MPa)	0.00030	0.00023	0.00018	0.00014
$\delta\sigma_u$ (%)	0.000042	0.00003	0.00003	0.00002
EL (%)	13.246	13.93	15.82	17.15
ΔEL (%)	2.020	0.1516	0.153	0.154
δEL (%)	1.14	1.088	0.967	0.898
M/L (kg/m)	0.3856	0.6073	0.8656	0.6142
$\Delta\ (M/L)$ (kg/m)	0.0005	0.0005	0.0005	0.0005
$\delta\ (M/L)$ (%)	0.130	0.0827	0.058	0.0327

CHAPTER V

Discussion

In this study, the experimental work included tensile tests in a way mechanical strength characteristic values are recorded for further variability analysis. Thus, the discussion here is grouped under two main subsections; namely mechanical strength values and variability results. This section below mainly focused on comparing the results of the aggregate data with similar works reported in the literature.

Mechanical Strength Characteristics

The total experiments covered in this study were 329 of which 76, 71, 100, and 82 tests were analyzed for 8, 10, 12, and 16 mm diameter bars, respectively. The mean and CoV values of the tested parameters for all four bar sizes are discussed in detail in comparison to other similar studies.

10 bars out of 329 samples failed to meet the minimum requirement for yield strength by ASTM i.e. 420 MPa. 30 bars i.e. 9.12% of the total samples exhibited a tensile strength value which is below ASTM A615 requirement for tensile strength i.e. 620 MPa. 14 bars (i.e. 4.26% of the total samples) exhibited elongation percentage less than 9%. 268 bars (i.e. 81.46% of the total samples) failed to meet the tensile to yield strength ratio requirement by the ACI (ACI, 2011) standard i.e. 1.25.

The mean yield strength, tensile strength, elongation percentage, and tensile-to-yield strength ratio values for the total tests were 581.97 MPa, 686.5 MPa, 15.15%, and 1.192, respectively. The minimum YS, TS, EL, and TS/YS in the total tests conducted were 332 MPa, 478.8 MPa, 5%, and 1.019 while the maximum values were 857.3 MPa, 990 MPa, 28.2%, and 1.962, respectively, as it is presented in Figures 36, 37, 38 and 39 in Chapter IV.

Variability Analysis

Mean, SD, variance, CoV, minimum, maximum, range, skewness, and kurtosis were used for analyzing the variability of the data for different mechanical strength properties. This paper considered CoV (%) values and comparisons of these values of YS, TS, EL, and TS/YS were made with similar studies as presented in

Table 26. The CoV found for YS, TS, EL, and TS/YS were 14.44, 9.83, 25.2, and 9.75%, respectively.

It can be noted that the mean yield and tensile strength values are higher than the findings from similar studies (Ajagbe et al., 2019; Carrillo et al., 2021; Djavanroodi & Salman, 2017; Ede et al., 2014; Firat, 2016; Kankam & Adom-Asamoah, 2002; Odusote et al., 2019; Rafi et al., 2014). The mean elongation percentage is close to the findings from a few studies (Carrillo et al., 2021; Djavanroodi & Salman, 2017) but less than the findings from other studies (Firat, 2016; Odusote et al., 2019; Taher et al., 2013). The summary of statics for mechanical properties of reinforcement steel bars is presented in Table 27.

Table 27.

Results From Previous Studies in Ethiopia and Other Countries

Author/ Country	Diameter	Statistical Parameter	YS (MPa)	TS (MPa)	EL (%)	M/L (Kg/m)	TS/YS (-)
(Carrillo et al., 2021)/ Colombia	N3 to N8	Mean	443.0	635.8	13.5	-	1.44
		CoV (%)	5.2	4.9	-	-	5.9
(Bournonville et al., 2004)/ US	N3	Mean	510.4	685.6	14.8	-	-
		CoV (%)	4.2	4.4	0.9	-	-
	N4	Mean	471.9	648.2	15.4	-	-
		CoV (%)	5.4	5.7	1.4	-	-
	N5	Mean	472.9	647.9	15.5	-	-
		CoV (%)	5.4	5.4	1.6	-	-
	N6	Mean	477.7	655.9	15.2	-	-
		CoV (%)	4.7	5.0	1.9	-	-
	N7	Mean	480.0	664.1	15.2	-	-
		CoV (%)	4.8	4.6	2.3	-	-
	N8	Mean	475.0	659.6	15.6	-	-
		CoV (%)	4.8	4.6	2.0	-	
(Djavanroodi & Salman, 2017)/ Saudi Arabia	NA	Mean	540.87	675.99	14.67	-	-
		CoV (%)	9.6	3.2	14.4	-	-
(Alo et al., 2017)/Nigeria	16 mm	Mean	501.25	647.9	26.4	-	-
		CoV (%)	-	-	-	-	-

Table (Continued).

(Munyazikwiye, 2010)/Kenya	16 mm, & 20 mm	Mean	496.7	623.4	17.3	-	-
		CoV (%)	6.2-16.7	7.7-9.9	16.9-18.8	-	-
(Adeleke et al., 2018)	10, 12 & 16 mm	Mean	446.1	584.5	-	-	-
		CoV (%)	-	-	-	-	-
(Tavio et al., 2018)/India	NA	Mean	494.6	636.6	-	-	1.29
(Ede et al., 2014)/Nigeria	12 mm	Mean	457	-	-	-	-
	16 mm	Mean	459	-	-	-	-
(Firat, 2016)/Turkey	8 – 32 mm	Mean	488.78	610.82	22.97	-	1.25
		CoV (%)	36	33	12.7	-	2.5
(Kankam & Adom-Asamoah, 2002)/Ghana	NA	Mean	400	536.67	10.67	-	-
(Awofadeju et al., 2014)/Nigeria	12 mm	NA	382.9-469.6	520.2-738.46	10.8-22.2	-	1.36-1.68
	16 mm	NA	400-551.7	550.4-918.82	8.3-14.53	-	1.17-1.83
(Alabi et al., 2016)/Nigeria	10 mm	Mean	410.73	667.73	27.11	-	-
	12 mm	Mean	404.64	544.8	31.54	-	-
	16 mm	Mean	373.14	556.14	30.42	-	-
(Nkubana, 2018)/Rwanda	10 mm	Mean	449.03	546.89	20.84	0.585	1.229
	12 mm	Mean	507.91	628.87	20.38	0.823	1.257
(Mander & Matamoros, 2019)/US	NA	Mean	482.7	655.0	16.0	-	1.36
		CoV	5.0	5.0	13.8	-	4.0
(Dey et al., 2021)/India	8 , 12 & 16 mm	Mean	409	470	29.0	-	1.15
(Joseph, 2013)/Nigeria	10 mm	Mean	347	460.75	11.53	-	1.303
	12 mm	Mean	373.5	491	10.78	-	1.31
	16 mm	Mean	451.25	592	9.03	-	1.313
	20 mm	Mean	452.5	604.5	8.65	-	1.335
(Nwakonobi & Umar, 2015)/Nigeria	12 mm (Local)	Mean	438.24	632.37	30.02	-	-
	12 mm (Imported)	Mean	656.62	766.29	20.81	-	-
(Lourenço, 2012)/Portugal	16	Mean	527.17	656.03	25.52	-	-
	20	Mean	530.60	652.93	24.28	-	-

Goodness-of-fit and Process Capability Analysis

The normality test values showed that all the mechanical strength characteristics were not fit for normal distribution as all the P-values were less than 0.05. Individual distribution identification was done using Minitab 16 capabilities and the results suggested that there were no adequate distributions found that best model the data thus the transformation of the data was applied using BCT. The transformation resulted in P_{pk}, C_{pk}, and PPM values with various lambdas for YS, TS, EL, and TS/YS. The C_{pk} values for YS, TS, EL, and TS/YS were 0.99, 0.51, and 0.93, -0.42, respectively. All these values were less than the expected value for a process that is capable i.e. C_{pk} = 1.33.

CHAPTER VI

Conclusion and Recommendations

Conclusion

The current work analyzed essentially the mechanical strength characteristics and the variability of these characteristics of the reinforcement steel bars in the Ethiopian construction market.

The survey comprised reinforcement bars with bar diameters ranging from 6 to 32 mm irrespective of the source of origin, chemical composition, and effect of corrosion. The study covered more than 400 data from rebars used from the years 2015 to 2020. Rebars with nominal diameters of 6, 14, 20, 24, 300, and 32 mm were not studied as they were least utilized by the Ethiopian construction market.

International standards including ASTM A 615 and ACI were followed to compare tensile test results and the characteristic ratio of tensile-to-yield strength, respectively.

The study revealed that the mean values of yield strength, tensile strength, elongation, and mass-per-length values passed the minimum ASTM requirement. However, the mean characteristic ratio of tensile-to-yield strength values for all bar sizes and lots were below the ACI requirement. Additional categorization of the test results was created based on the test period to show the trends in quality characteristics of interest. According to the lot grouping, the mean YS value showed a decrement from 593.1 MPa to 572.5 MPa. Similarly, mean TS showed a decrement from 701.1 to 673.8 MPa. On the contrary, the elongation percentage showed an increment from 14.77 to 15.47%. The mean characteristic ratio of tensile-to-yield strength showed a slight decrement from 1.182 to 1.177.

One-way one-level ANOVA analysis exhibited that, with 95% CI, the data for YS, TS, and EL were dissimilar with respective variability contributions in both lots. For all YS, TS, and EL, the calculated fisher values, i.e. F_{cal}, were higher than *F-tables*. These demonstrated that the apparent data spread contribution percentages were high enough to indicate dissimilarity. The data for TS/YS was found to be with less F_{cal} values than F-table for the 95% CI.

The total aggregate data were further investigated for the normality test in addition to all the statistical analyses conducted for each bar size and lot. All YS, TS, EL, and TS/YS failed the Anderson-Darling normality test with a CI of 95%. Moreover, goodness-of-fit tests were assessed to identify the right distribution which adequately models for the data spread. All the data for YS, TS, EL, and TS/YS didn't fit any of the distributions. As a result, the transformation of the data using the Box-Cox transformation method was employed. The transformation resulted in process capability index values that were found to be below the accepted sets of values.

Recommendation

In general, the current work revealed that the reinforcement steel bars used in the Ethiopian market can be used for general structural applications but are not recommended in regions where seismic effects are a common phenomenon. Since all the rebars showed poor quality in the characteristic ratio of TS to YS, the rebars exhibit poor post-elastic properties that would cause a collapse of structures in seismic-prone areas.

Even though all the mechanical strength values seemed to be stable, the normality test values and the process capability indices confirmed that the reinforcement steel bars currently used in the Ethiopian market are collected from sources that had incapable process lucking consistent distribution. In this regard, it’s recommended to manufacturers that they should instate proper quality controlling and monitoring procedures. Moreover, in the case where scrap metals are used for reinforcement steel bar production, manufacturers should control and maintain the right ranges of carbon content and alloying elements that yields higher mechanical strength values. Furthermore, importers in the sector should have proper sampling techniques in place to accept/reject the rebars before distributing the rebars to the market. Contractors should follow ethical procedures in the designing and selection of the right bar sizes and classes. End-users of the reinforcement bars should be acquainted with the necessary knowledge of the quality parameters and give sufficient care to the proper testing. Above all, government institutions in the Ethiopian government such as the Ethiopian Standards Institute (ESI), and regional design and supervision agencies should strengthen the controlling mechanisms in checking for the conformance of the rebars.

Future Work

Many investigations that are not addressed in this research work can further be examined in a future study. The following study areas could be of much interest in addressing the quality issues related to reinforcement steel bars in a full-fledged manner:

- Investigation of mechanical characteristics considering data of the sources of rebars.
- Investigation of cyclic load and bending behaviors of rebars.
- Investigation of effects of chemical composition and micro-alloying on mechanical strength behavior improvement.
- Investigation of the effect of corrosion on mechanical properties of rebars.
- Identification and applications of artificial intelligence-based models for mechanical strength prediction particularly, when actual testing is not practical.

References

A, Mander T, M. (2019). Constitutive Modeling and Overstrength Factors for Reinforcing Steel. *ACI Structural Journal*, *116*(3). https://doi.org/10.14359/51713320

Abouhussien, A. A., & Hassan, A. A. A. (2014). Experimental and empirical time to corrosion of reinforced concrete structures under different curing conditions. *Advances in Civil Engineering*, *2014*. https://doi.org/10.1155/2014/595743

Achamyeleh, T., Çamur, H., Savaş, M. A., & Evcil, A. (2022). Mechanical strength variability of deformed reinforcing steel bars for concrete structures in Ethiopia. *Scientific Reports*, *12*(1), 1–10. https://doi.org/10.1038/s41598-022-06654-1

Achamyeleh, T., & Şahin, Y. (2019). Investigation of Mechanical Properties of Ribbed Reinforcement Steel Bars: A Case Study on Ethiopian Construction Industry. *International Journal of Steel Structures*, *19*(5), 1682–1693. https://doi.org/10.1007/s13296-019-00236-0

ACI, C. (2011). *Building Code Requirements for Structural Concrete (ACI 318-11)*. American Concrete Institute.

Adeleke, A. A., Odusote, J. K., Ikubanni, P. P., & Lasode, O. A. (2018). Dataset on the evaluation of chemical and mechanical properties of steel rods from local steel plants and collapsed building sites. *Data in Brief*, *21*, 1552–1557. https://doi.org/10.1016/j.dib.2018.10.162

Ajagbe, W., Ganiyu, A., Adegbite, A., & Akodu, O. (2019). Investigations on the chemical composition and tensile strength of steel bars in the Nigerian construction industry. *IOP Conference Series: Materials Science and Engineering*, *513*(1). https://doi.org/10.1088/1757-899X/513/1/012026

Alabi, A. G. F., Ayoade, A. O., Odusote, J. K., & Akanni, A. A. (2016). Assessment of Suitability of Nigerian Made Steel Bars for Structural Applications. *The Journal of the Association of Professional Engineers of Trinidad and Tobago*, *44*(2), 17–23.

Allen, D. E. (1972). Statistical study of the mechanical properties of reinforcing bars. *Building Research Note; No. BRN-85*. https://doi.org/10.4224/40000624

Almusallam, A. A. (2001). Effect of degree of corrosion on the properties of reinforcing steel bars. *CONSTRUCTION & BUILDING MATERIALS*, *15*, 361–368.

Alo, F. I., Atanda, P. O., Daniyan, A. A., Abodunrin, O. W., & Oluwasegun, K. M. (2017). An Assessment of Imported and Local Constructional Steel in Nigeria: Analysis by One-Way ANOVA . *International Journal of Materials Engineering*, *7*(3), 45–51. https://doi.org/10.5923/j.ijme.20170703.01

Anderson, T. W., & Darling, D. A. (1952). Asymptotic Theory of Certain "Goodness of Fit" Criteria Based on Stochastic Processes. *The Annals of Mathematical Statistics*, *23*(2), 193–212. https://doi.org/10.1214/aoms/1177729437

Apostolopoulos, A., & Matikas, T. E. (2016). Corrosion of bare and embedded in concrete steel bar-impact on mechanical behavior. *International Journal of Structural Integrity*, *7*(2), 240–259. https://doi.org/10.1108/IJSI-09-2014-0047

Apostolopoulos, C. A., & Papadakis, V. G. (2008). Consequences of steel corrosion on the ductility properties of reinforcement bar. *Construction and Building Materials*, *22*(12), 2316–2324. https://doi.org/10.1016/j.conbuildmat.2007.10.006

Apostolopoulos, C., Drakakaki, A., Apostolopoulos, A., Matikas, T., Rudskoi, A. I., & Kodzhaspirov, G. (2017). Characteristic defects-corrosion damage and mechanical behavior of dual phase rebar. *Materials Physics and Mechanics*, *30*(1), 1–19.

Apostolopoulos, Ch Alk. (2007). Mechanical behavior of corroded reinforcing steel bars S500s tempcore under low cycle fatigue. *Construction and Building Materials*, *21*(7), 1447–1456. https://doi.org/10.1016/j.conbuildmat.2006.07.008

Arinaitwe, Nkubana, D. (2018). Quality Assessment and Control of Steel Reinforcing Bars Used in Rwandan Construcion Industry. *International Journal of Innovative Research in Science, Engineering and Technology*, *7*(6), 6723–6735. https://doi.org/10.15680/IJIRSET.2018.0706053

ASTM A 615. (2015). Standard Specification for Deformed and Plain Billet-Steel

Carbon Steel Bars for. *ASTM A615*, 1–8. https://doi.org/10.1520/A0615

ASTM A706. (2001). American Society for Testing and Materials Information Handling Services. *ASTM A706*.

Awofadeju, A. S., Adekiigbe, A., Akanni, A. O., & Adeyemo, B. G. (2014). Evaluation of Locally Produced and Imported Reinforced Steel Rods for Structural Purposes in Nigerian Market. *International Journal of Recent Development in Engineering and Technology Website: Www.Ijrdet.Com*, *3*(8), 1–4. Retrieved from www.ijrdet.com

Awonchefew, R. (2018). *Analysis of supply chain of domestic steel reinforcement bar for the construction projects in Addis Ababa* (Addis Ababa University). Retrieved from http://etd.aau.edu.et/handle/123456789/15773

Baddoo, N. (2018). Foreword: Recent research into structural stainless steel. *Journal of Constructional Steel Research*, *150*, 541. https://doi.org/10.1016/J.JCSR.2018.08.034

Bazán, A. M., de las Nieves González, M., Alberti, M. G., & Gálvez, J. C. (2019). Influence of the loading speed on the ductility properties of corroded reinforcing bars in concrete. *Materials*, *16*(6), 1–17. https://doi.org/10.3390/ma12060965

Bournonville, M., Dahnke, J., & Darwin, D. (2004). *Statistical analysis of the mechanical properties and weight of reinforcing bars*.

Carrillo, J., Lozano, H., & Arteta, C. (2021). Mechanical properties of steel reinforcing bars for concrete structures in central Colombia. *Journal of Building Engineering*, *33*(September 2020), 101858. https://doi.org/10.1016/j.jobe.2020.101858

Castro, H., Rodriguez, C., Belzunce, F. J., & Canteli, A. F. (2003). Mechanical properties and corrosion behaviour of stainless steel reinforcing bars. *Journal of Materials Processing Technology*, *143–144*(1), 134–137. https://doi.org/10.1016/S0924-0136(03)00393-5

Chen, H., Zhang, J., Yang, J., & Ye, F. (2018). Experimental Investigation into Corrosion Effect on Mechanical Properties of High Strength Steel Bars under Dynamic Loadings. *International Journal of Corrosion*, *2018*.

https://doi.org/10.1155/2018/7169681

Clifton, F. (1971). Strength Variability in Structural Materials Strength Variability in Structural Materials. *Aeronautical Research Council Reports and Memoranda*, (3654).

Crook, W. J. (1927). Alloy steels and their uses. *Journal of Chemical Education*, *4*(5), 583. https://doi.org/10.1021/ed004p583

Deb, S. (2012). Accelerated Short-Term Techniques to Evaluate Corrosion in Reinforced Concrete Structures. *The Masterbuilder*, (July 2012), 248–255.

Demissew Gashahun, A. (2020). Assessment on Impact of Covid-19 on Ethiopian Construction Industry. *Ijesc*, (July). Retrieved from http://ijesc.org/

Dey, I., Manna, P., Yadav, M., Kumar Tewary, N., Kumar Saha, J., & Kumar Ghosh, S. (2021). Study on the Perspective of Mechanical Properties and Corrosion Behaviour of Stainless Steel, Plain and TMT Rebars. In *Stainless Steels [Working Title]* (pp. 1–22). https://doi.org/10.5772/intechopen.101388

Djavanroodi, F., & Salman, A. (2017). Variability of Mechanical Properties and Weight for Reinforcing Bar Produced in Saudi Arabia. *IOP Conference Series: Materials Science and Engineering*, *230*(1). https://doi.org/10.1088/1757-899X/230/1/012002

Dragna, E. C., Ioana, A., & Constantin, N. (2018). Methods of steel manufacturing - The electric arc furnace. *IOP Conference Series: Materials Science and Engineering*, *294*(1). https://doi.org/10.1088/1757-899X/294/1/012017

Ede, A., Olofinnade, O., & Joshua, O. (2014). Experimental Investigation of Yield Strengths of Steel Reinforcing Bars Used in Nigerian Concrete Structures. *Experimental Investigation of Yield Strengths of Steel Reinforcing Bars Used in Nigerian Concrete Structures*, *5*(4), 76–83.

Fernandez, I., Bairán, J. M., & Marí, A. R. (2015). Corrosion effects on the mechanical properties of reinforcing steel bars . Fatigue and r – e behavior. *CONSTRUCTION & BUILDING MATERIALS*, *101*, 772–783. https://doi.org/10.1016/j.conbuildmat.2015.10.139

Fernandez, I., & Berrocal, C. G. (2019). Mechanical Properties of 30 Year ‐ Old Naturally Corroded Steel Reinforcing Bars. *International Journal of Concrete Structures and Materials*. https://doi.org/10.1186/s40069-018-0308-x

Firat, F. K. (2016). *Mechanical Properties of Reinforcing Steel in R / C : Uncertainty Analysis and Proposal of a New Material Factor*. 4019–4028. https://doi.org/10.1007/s13369-016-2077-7

Graba, M. (2021). *Evaluation of measurement uncertainty in a static tensile test*. 709–722.

Guo, A., Li, H., Ba, X., Guan, X., & Li, H. (2015). Experimental investigation on the cyclic performance of reinforced concrete piers with chloride-induced corrosion in marine environment. *Engineering Structures*, *105*, 1–11. https://doi.org/10.1016/j.engstruct.2015.09.031

Hawileh, R. A., Abdalla, J. A., Al Tamimi, A., Abdelrahman, K., & Oudah, F. (2011). Behavior of corroded steel reinforcing bars under monotonic and cyclic loadings. *Mechanics of Advanced Materials and Structures*, *18*(3), 218–224. https://doi.org/10.1080/15376494.2010.499023

Holappa, L. (2010). On Physico-Chemical and Technical Limits in Clean Steel Production. *Steel Research International*, *81*(10), 869–874. https://doi.org/https://doi.org/10.1002/srin.201000203

Hu, M., Han, Q., Xu, K., & Du, X. (2019). Impact of corrosion on cyclic behaviors of ultra-high-strength reinforcing bars. *Construction and Building Materials*, *209*, 606–618. https://doi.org/10.1016/j.conbuildmat.2019.03.182

Imperatore, S., & Rinaldi, Z. (2019). Experimental behavior and analytical modeling of corroded steel rebars under compression. *Construction and Building Materials*, *226*, 126–138. https://doi.org/10.1016/j.conbuildmat.2019.07.109

Imperatore, S., Rinaldi, Z., & Drago, C. (2017). Degradation relationships for the mechanical properties of corroded steel rebars. *Construction and Building Materials*, *148*, 219–230. https://doi.org/10.1016/j.conbuildmat.2017.04.209

Jayapregasham, S., & Tjon-a-meeuw, R. (2018). Evaluating Ethiopia's Development Progress. *Undergraduate Economic Review*, *15*(1).

Joseph, A. A. (2013). *Assessment Of Mechanical Properties Of Reinforcing Steel Used In Construction Works At F.C.T, Abuja*. *2*(6), 2346–2358.

Joshua, O., Olusola, K. O., Oyeyemi, K. D., Hawileh, R. A., Abdalla, J. A., Oudah, F., … Zhu, W. (2019). Experimental investigation on the cyclic performance of reinforced concrete piers with chloride-induced corrosion in marine environment. *Construction and Building Materials*, *22*(3), 1–9. https://doi.org/10.1051/e3sconf/20183401024

Kankam, C. K. (2004). Bond strength of reinforcing steel bars milled from scrap metals. *Materials and Design*, *25*(3), 231–238. https://doi.org/10.1016/j.matdes.2003.09.011

Kankam, C. K., & Adom-Asamoah, M. (2002). Strength and ductility characteristics of reinforcing steel bars milled from scrap metals. *Materials and Design*, *23*(6), 537–545. https://doi.org/10.1016/s0261-3069(02)00028-6

Kashani, M. M., Crewe, A. J., & Alexander, N. A. (2012). Stress-strain response of corroded reinforcing bars under monotonic and cyclic loading. *15th World Conference on Earthquake Engineering (15WCEE)*, 1–9.

Li, P., & Wang, Y. (2013). Effect of Corrosion on Mechanical Properties of Rebar HRB400. *Advanced Materials Research*, *807–809*, 2735–2738. https://doi.org/10.4028/www.scientific.net/amr.807-809.2735

Lin, H., Zhao, Y., Feng, P., Ye, H., Ozbolt, J., Jiang, C., & Yang, J. (2019). State-of-the-art review on the bond properties of corroded reinforcing steel bar. *Construction and Building Materials*, *213*, 216–233. https://doi.org/10.1016/j.conbuildmat.2019.04.077

Litteral, L., & Rudisill, F. (2008). Capability ratios: Comparison and interpretation of short-term and overall indices. *International Journal of Quality and Standards*, *2*(1), 67.

Liu, Q., Wang, B., Wang, Z., Wang, B., Xie, F., & Chang, J. (2015). Fine production in steelmaking plants. *Materials Today: Proceedings*, *2*, S348–S357. https://doi.org/10.1016/j.matpr.2015.05.049

Lourenço, J. P. F. (2012). *Study of steel bars for use in reinforced concrete produced* *by the _ Tempcore@_ process*.

Magasdi, A., Ginsztler, J., & Dobránszky, J. (2010). Fatigue of Laserbeam Welded Joints of High-Carbon Steel Strips. *Materials Science, Testing and Informatics V*, *659*, 61–66. https://doi.org/10.4028/www.scientific.net/MSF.659.61

Mirza, S. A., & MacGregor, J. G. (1979). VARIABILITY OF MECHANICAL PROPERTIES OF REINFORCING BARS. *ASCE J Struct Div*.

Munyazikwiye, B. B. (2010). *Investigation on Characterization and Variability of Mechanical Properties of Reinforcing Steel Bars made from Scrap* (Jomo Kenyatta University of Agriculture and Technology). Retrieved from http://journals.jkuat.ac.ke/index.php/pgthesis_abs/article/view/405

Nwakonobi, T., & Umar, S. (2015). Comparative Study on the Strength Characteristics of Reinforcement Bars from Local Industries and Imported Sources. *International Journal of Scientific & Engineering Research6*, (5), 1011–1015. Retrieved from http://www.ijser.org/researchpaper%5CComparative-Study-on-the-Strength-Characteristics-of-Reinforcement-Bars-from-Local-Industries-and-Imported-Sources.pdf

Odusote, J. K., & Adeleke, A. A. (2012). Analysis of Properties of Reinforcing Steel Bars: Case Study of Collapsed Building in Lagos, Nigeria. *Progress in Industrial and Civil Engineering*, *204*, 3052–3056. https://doi.org/10.4028/www.scientific.net/AMM.204-208.3052

Odusote, J. K., Shittu, W., Adeleke, A. A., Ikubanni, P. P., & Adeyemo, O. (2019). Chemical and Mechanical Properties of Reinforcing Steel Bars from Local Steel Plants. *Journal of Failure Analysis and Prevention*, *19*(4), 1067–1076. https://doi.org/10.1007/s11668-019-00695-x

Perera, K. P. A. S., & Guluwita, S. P. (2018). Study of Yield Strength and Elongation Variations of Reinforcement Steel Bars (TMT bars) Manufactured Using Local Ingots. *Engineer: Journal of the Institution of Engineers, Sri Lanka*, *51*(2), 7. https://doi.org/10.4038/engineer.v51i2.7290

Ponjayanthi D., V. (2016). Effect of Corrosion on the Mechanical Properties of Steel

Reinforcement. *International Journal of Current Research and Review*, *8*(12), 14–20.

Rafi, M. M., Lodi, S. H., & Nizam, A. (2014). Chemical and Mechanical Properties of Steel Rebars Manufactured in Pakistan and Their Design Implications. *Journal of Materials in Civil Engineering*, *26*(2), 338–348. https://doi.org/10.1061/(asce)mt.1943-5533.0000812

Roy , R. K. (2010). *A primer on the Taguchi method*. Retrieved from https://search.ebscohost.com/login.aspx?direct=true&scope=site&db=nlebk&db=nlabk&AN=860349

Sanchez, J., Fullea, J., & Andrade, C. (2017). Corrosion-induced brittle failure in reinforcing steel. *Theoretical and Applied Fracture Mechanics*, *92*(August), 229–232. https://doi.org/10.1016/j.tafmec.2017.08.006

Singh, B., & Kaushik, S. K. (2002). Influence of steel-making processes on the quality of reinforcement. *Indian Concrete Journal*, *76*(7), 407–412.

Sun, X., Kong, H., Wang, H., & Zhang, Z. (2018). Evaluation of corrosion characteristics and corrosion e ff ects on the mechanical properties of reinforcing steel bars based on three-dimensional scanning. *Corrosion Science*, *142*(November 2017), 284–294. https://doi.org/10.1016/j.corsci.2018.07.030

Taher, L. S. Ben, Abmdas, M. S., & Elmazoghi, H. G. (2013). Variability in Yield Strength and Elongation of Reinforcing Steel Bars. *The Twelfth Arab Conference on Structural Engineering*, 547–557. Libya: University of Tripoli.

Tariku, A. (2020). *Investigating the Factors Influencing Reinforcement Bar Consumers Shifting from Local to Imported and its Improvement* (Addis Ababa University). Retrieved from http://etd.aau.edu.et/handle/123456789/23579

Tat, L. W. (1991). *Statistical Analysis of Reinforcing Steel Properties*. (June).

Tavio, Retno, A., Raka, G. P., & Agustiar. (2018). Tensile strength/yield strength (TS/YS) ratios of high-strength steel (HSS) reinforcing bars. *AIP Conference Proceedings 1964*. https://doi.org/https://doi.org/10.1063/1.5038318

Wang, Y. (2012). Effect of Corrosion on Mechanical Properties of Reinforcing Bar

HPB235. *Advanced Materials Research*, *450–451*, 201–204. https://doi.org/10.4028/www.scientific.net/amr.450-451.201

Wu, X., Chen, L., Li, H., & Xu, J. (2019). Experimental study of the mechanical properties of reinforced concrete compression members under the combined action of sustained load and corrosion. *Construction and Building Materials*, *202*, 11–22. https://doi.org/10.1016/j.conbuildmat.2018.12.156

Yan, X., Di, W., Yingfeng, T., Minqiu, H., & Hai, S. (2017). Experimental studies on mechanical properties of corroded steel bars after elevated temperature. *Procedia Engineering*, *210*, 622–629. https://doi.org/10.1016/j.proeng.2017.11.122

Zhang, W., Song, X., Gu, X., & Li, S. (2012). Tensile and fatigue behavior of corroded rebars. *Construction and Building Materials*, *34*, 409–417. https://doi.org/10.1016/j.conbuildmat.2012.02.071

Zhang, X., Liang, X., Wang, Z., Huang, H., & Zhou, H. (2016). An experimental study on effect of steel corrosion on the bond-slip performance of reinforced concrete. *International Conference on Durability of Concrete Structures, ICDCS 2016*, (Figure 2), 290–295.

Zhou, H., Lu, J., Xv, X., Dong, B., & Xing, F. (2015). Effects of stirrup corrosion on bond-slip performance of reinforcing steel in concrete: An experimental study. *Construction and Building Materials*, *93*, 257–266. https://doi.org/10.1016/j.conbuildmat.2015.05.122

Zhu, W. (2011). *Effect of corrosion on the mechanical properties of the corroded reinforcement and the residual structural performance of the corroded beams*. 0–151.

Zhu, W., & Francois, R. (2013). Effect of corrosion pattern on the ductility of tensile reinforcement extracted from a 26-year-old corroded beam. *Advances in Concrete Construction*, *1*(2), 121–136. https://doi.org/10.12989/acc2013.01.2.121

Appendices

Appendix A

F-Table & $F_{.05}$ (f_1, f_2), 95% Confidence Interval (Roy, 2010)

f_1 = Number of degrees of freedom of the numerator

f_2 = Number of degrees of freedom of the denominator

	f₁								
f₂	1	2	3	4	5	6	7	10	…
1	161.4	199.5	215.7	224.5	230.2	233.9	236.7	241.8	…
2	18.5	19.0	19.61	19.2	19.3	19.33	19.35	19.39	
3	10.10	9.55	9.27	9.11	9.01	8.94	8.88	8.78	
4	7.70	6.94	6.59	6.38	625	6.16	6.09	5.96	
5	6.60	5.78	5.40	5.19	5.05	4.95	4.87	4.73	
6	5.98	5.14	4.75	4.53	4.38	4.28	4.20	4.06	
7	5.59	4.73	4.34	4.12	3.97	3.86	3.78	3.63	
8	5.31	4.46	4.06	3.83	3.68	3.58	3.50	3.34	
9	5.11	4.25	3.86	3.63	3.48	3.37	3.29	3.13	
10	4.96	4.10	3.70	3.47	3.32	3.21	3.13	2.91	
11	4.84	3.98	3.58	3.35	3.20	3.09	3.01	2.78	
12	4.77	3.88	3.49	3.25	3.10	2.99	2.91	2.68	
13	4.66	3.80	3.41	3.17	3.02	2.91	2.83	2.60	
14	4.60	3.73	3.34	3.11	2.95	2.84	2.76	2.60	
15	4.54	3.68	3.28	3.04	2.90	2.79	2.70	2.54	
16	4.49	3.63	3.23	3.00	2.85	2.74	2.65	2.49	
17	4.45	3.59	3.19	2.94	2.81	2.60	2.61	2.44	
18	4.41	3.55	3.15	2.92	2.77	2.66	2.57	2.41	
19	4.38	3.52	3.12	2.89	2.74	2.62	2.54	2.37	
20	4.35	3.49	3.09	2.86	2.71	2.60	2.51	2.34	
21	4.32	3.46	3.07	2.84	2.68	2.57	2.42	2.32	
22	4.30	3.44	3.04	2.81	2.66	2.55	2.46	2.29	
23	4.27	3.42	3.02	2.79	2.64	2.52	2.44	2.27	
24	4.25	3.40	3.00	2.77	2.62	2.50	2.42	2.25	

25	4.24	3.38	2.99	2.75	2.60	2.49	2.40	2.23	
26	4.22	3.36	2.97	2.74	2.58	2.47	2.38	2.22	
27	4.21	3.35	2.96	2.72	2.57	2.45	2.37	2.20	
28	4.19	3.34	2.94	2.71	2.55	2.44	2.39	2.19	
29	4.18	3.32	2.93	2.70	2.54	2.43	2.34	2.17	
30	4.17	3.31	2.92	2.68	2.53	2.42	2.33	2.16	
40	4.05	3.21	2.83	2.60	2.44	2.33	2.24	2.07	
100	4.00	3.15	2.75	2.52	2.36	2.25	2.16	1.91	
150	3.84	2.99	2.60	2.37	2.21	2.09	2.00	1.83	

Appendix B

ASTM A615/A615M -15a

Designation: A615/A615M – 15a$^{\varepsilon 1}$

American Association State Highway and Transportation Officials Standard
AASHTO No.: M 31

Standard Specification for Deformed and Plain Carbon-Steel Bars for Concrete Reinforcement[1]

This standard is issued under the fixed designation A615/A615M; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

This standard has been approved for use by agencies of the U.S. Department of Defense.

ε[1] NOTE—Editorial corrections were made to Section 4 in August 2015.

1. Scope*

1.1 This specification covers deformed and plain carbon-steel bars in cut lengths and coils for concrete reinforcement. Steel bars containing alloy additions, such as with the Association for Iron and Steel Technology and the Society of Automotive Engineers series of alloy steels, are permitted if the resulting product meets all the other requirements of this specification. The standard sizes and dimensions of deformed bars and their number designations are given in Table 1.

1.2 Bars are of five minimum yield strength levels: namely, 40 000 psi [280 MPa], 60 000 psi [420 MPa], 75 000 psi [520 MPa], 80 000 psi [550 MPa], and 100 000 psi [690 MPa], designated as Grade 40 [280], Grade 60 [420], Grade 75 [520], Grade 80 [550], and Grade 100 [690], respectively.

NOTE 1—Grade 100 [690] reinforcing bars were introduced in this specification in 2015. In contrast to the lower grades, which have ratios of specified tensile strength to specified yield strength that range from 1.31 to 1.5, Grade 100 [690] reinforcing bars have a ratio of specified tensile strength to specified yield strength of 1.15. Designers should be aware that there will, therefore, be a lower margin of safety and reduced warning of failure following yielding when Grade 100 [690] bars are used in structural members where strength is governed by the tensile strength of the reinforcement, primarily in beams and slabs. If this is of concern, the purchaser has the option of specifying a minimum ratio of tensile strength to actual yield strength. Consensus design codes and specifications such as "Building Code Requirements for Structural Concrete (ACI 318)" may not recognize Grade 100 [690] reinforcing bars: therefore the 125 % of specified yield strength requirements in tension and compression are not applicable. Mechanical and welded splices should meet a minimum specified tensile strength of 115 000 psi [790 MPa].

NOTE 2—Designers need to be aware that design standards do not recognize the use of the No. 20 [64] bar, the largest bar included in this specification. Structural members reinforced with No. 20 [64] bars may require approval of the building official or other appropriate authority and require special detailing to ensure adequate performance at service and factored loads.

1.3 Plain bars, in sizes up to and including 2½ in. [63.5 mm] in diameter in coils or cut lengths, when ordered shall be furnished under this specification in Grade 40 [280], Grade 60 [420], Grade 75 [520], Grade 80 [550], and Grade 100 [690]. For ductility properties (elongation and bending), test provisions of the nearest smaller nominal diameter deformed bar size shall apply. Requirements providing for deformations and marking shall not be applicable.

NOTE 3—Welding of the material in this specification should be approached with caution since no specific provisions have been included to enhance its weldability. When this steel is to be welded, a welding procedure suitable for the chemical composition and intended use or service should be used. The use of the latest edition of AWS D1.4/D1.4M is recommended. The AWS D1.4/D1.4M Welding Code describes the proper selection of the filler metals and preheat/interpass temperatures, as well as performance and procedure qualification requirements.

1.4 Requirements for alternate bar sizes are presented in Annex A1. The requirements in Annex A1 only apply when specified by the purchaser (see 4.2.4).

1.5 The text of this specification references notes and footnotes which provide explanatory material. These notes and footnotes (excluding those in tables) shall not be considered as requirements of the specification.

1.6 This specification is applicable for orders in either inch-pound units (as Specification A615) or in SI units (as Specification A615M).

1.7 The values stated in either inch-pound units or SI units are to be regarded separately as standard. Within the text, the SI units are shown in brackets. The values stated in each system may not be exact equivalents; therefore, each system shall be used independently of the other. Combining values from the two systems may result in non-conformance with the specification.

1.8 *This specification does not purport to address all of the safety concerns, if any, associated with its use. It is the*

[1] This specification is under the jurisdiction of ASTM Committee A01 on Steel, Stainless Steel and Related Alloys and is the direct responsibility of Subcommittee A01.05 on Steel Reinforcement.

Current edition approved July 1, 2015. Published July 2015. Originally approved in 1968. Last previous edition approved in 2015 as A615/A615M – 15. DOI: 10.1520/A0615_A0615M-15AE01.

TABLE 1 Deformed Bar Designation Numbers, Nominal Weights [Masses], Nominal Dimensions, and Deformation Requirements

Bar Designation No.	Nominal Weight, lb/ft [Nominal Mass, kg/m]	Nominal Dimensions[A]			Deformation Requirements, in. [mm]		
		Diameter, in. [mm]	Cross-Sectional Area, in.^{2} [mm^2]	Perimeter, in. [mm]	Maximum Average Spacing	Minimum Average Height	Maximum Gap (Chord of 12.5 % of Nominal Perimeter)
3 [10]	0.376 [0.560]	0.375 [9.5]	0.11 [71]	1.178 [29.9]	0.262 [6.7]	0.015 [0.38]	0.143 [3.6]
4 [13]	0.668 [0.994]	0.500 [12.7]	0.20 [129]	1.571 [39.9]	0.350 [8.9]	0.020 [0.51]	0.191 [4.9]
5 [16]	1.043 [1.552]	0.625 [15.9]	0.31 [199]	1.963 [49.9]	0.437 [11.1]	0.028 [0.71]	0.239 [6.1]
6 [19]	1.502 [2.235]	0.750 [19.1]	0.44 [284]	2.356 [59.8]	0.525 [13.3]	0.038 [0.97]	0.286 [7.3]
7 [22]	2.044 [3.042]	0.875 [22.2]	0.60 [387]	2.749 [69.8]	0.612 [15.5]	0.044 [1.12]	0.334 [8.5]
8 [25]	2.670 [3.973]	1.000 [25.4]	0.79 [510]	3.142 [79.8]	0.700 [17.8]	0.050 [1.27]	0.383 [9.7]
9 [29]	3.400 [5.060]	1.128 [28.7]	1.00 [645]	3.544 [90.0]	0.790 [20.1]	0.056 [1.42]	0.431 [10.9]
10 [32]	4.303 [6.404]	1.270 [32.3]	1.27 [819]	3.990 [101.3]	0.889 [22.6]	0.064 [1.63]	0.487 [12.4]
11 [36]	5.313 [7.907]	1.410 [35.8]	1.56 [1006]	4.430 [112.5]	0.987 [25.1]	0.071 [1.80]	0.540 [13.7]
14 [43]	7.65 [11.38]	1.693 [43.0]	2.25 [1452]	5.32 [135.1]	1.185 [30.1]	0.085 [2.16]	0.648 [16.5]
18 [57]	13.60 [20.24]	2.257 [57.3]	4.00 [2581]	7.09 [180.1]	1.58 [40.1]	0.102 [2.59]	0.864 [21.9]
20 [64][B]	16.69 [24.84]	2.500 [63.5]	4.91 [3167]	7.85 [199.5]	1.75 [44.5]	0.113 [2.86]	0.957 [24.3]

[A] The nominal dimensions of a deformed bar are equivalent to those of a plain round bar having the same weight [mass] per foot [metre] as the deformed bar.
[B] Refer to Note 2.

responsibility of the user of this specification to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

2. Referenced Documents

2.1 *ASTM Standards:*[2]

A6/A6M Specification for General Requirements for Rolled Structural Steel Bars, Plates, Shapes, and Sheet Piling
A370 Test Methods and Definitions for Mechanical Testing of Steel Products
A510/A510M Specification for General Requirements for Wire Rods and Coarse Round Wire, Carbon Steel, and Alloy Steel
A700 Guide for Packaging, Marking, and Loading Methods for Steel Products for Shipment
A706/A706M Specification for Deformed and Plain Low-Alloy Steel Bars for Concrete Reinforcement
A751 Test Methods, Practices, and Terminology for Chemical Analysis of Steel Products
E29 Practice for Using Significant Digits in Test Data to Determine Conformance with Specifications
E290 Test Methods for Bend Testing of Material for Ductility

2.2 *ACI Standard:*[3]

ACI 318 Building Code Requirements for Structural Concrete

2.3 *AWS Standard:*[4]

AWS D1.4/D1.4M Structural Welding Code—Reinforcing Steel

2.4 *U.S. Military Standard:*[5]

MIL-STD-129 Marking for Shipment and Storage

2.5 *U.S. Federal Standard:*[5]

Fed. Std. No. 123 Marking for Shipment (Civil Agencies)

3. Terminology

3.1 *Definitions of Terms Specific to This Specification:*

3.1.1 *deformations, n*—transverse protrusions on a deformed bar.

3.1.2 *deformed bar, n*—steel bar with protrusions; a bar that is intended for use as reinforcement in reinforced concrete construction.

3.1.2.1 *Discussion*—The surface of the bar is provided with protrusions that inhibit longitudinal movement of the bar relative to the concrete surrounding the bar in such construction. The protrusions conform to the provisions of this specification.

3.1.3 *plain bar, n*—steel bar without protrusions.

3.1.4 *rib, n*—longitudinal protrusion on a deformed bar.

4. Ordering Information

4.1 Orders for carbon-steel bars for concrete reinforcement under this specification shall contain the following information:

4.1.1 Quantity (weight) [mass],
4.1.2 Deformed or plain,
4.1.3 Bar designation number (size) of deformed bars, or nominal diameter (size) of plain bars
4.1.4 Cut lengths or coils,
4.1.5 Grade, and
4.1.6 ASTM designation and year of issue.

4.2 The purchaser shall have the option to specify additional requirements, including but not limited to, the following:

4.2.1 Require bars in each bundle to be supplied from a single heat (19.1),
4.2.2 Special package marking requirements (20.2),
4.2.3 Other special requirements, if any, and
4.2.4 Optional requirements of Annex A1.

5. Material and Manufacture

5.1 The bars shall be rolled from properly identified heats of mold-cast or strand-cast steel. The steel shall be made by any commercially accepted process.

[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.
[3] Available from American Concrete Institute (ACI), P.O. Box 9094, Farmington Hills, MI 48333-9094, http://www.concrete.org.
[4] Available from American Welding Society (AWS), 8669 NW 36 Street, #130, Miami, FL 33166-6672, http://www.aws.org.
[5] Available from Standardization Documents Order Desk, DODSSP, Bldg. 4, Section D, 700 Robbins Ave., Philadelphia, PA 19111-5098, http://www.dodssp.daps.mil.

6. Chemical Composition

6.1 The chemical analysis of each heat of steel shall be determined in accordance with Test Methods, Practices, and Terminology A751. The manufacturer shall make the analysis on test samples taken preferably during the pouring of the heat. The percentages of carbon, manganese, phosphorus, and sulfur shall be determined. The phosphorus content thus determined shall not exceed 0.06 %.

6.2 A product check, for phosphorus, made by the purchaser shall not exceed that specified in 6.1 by more than 25 %.

7. Requirements for Deformations

7.1 Deformations shall be spaced along the bar at substantially uniform distances. The deformations on opposite sides of the bar shall be similar in size, shape, and pattern.

7.2 The deformations shall be placed with respect to the axis of the bar so that the included angle is not less than 45°. Where the line of deformations forms an included angle with the axis of the bar from 45 to 70° inclusive, the deformations shall alternately reverse in direction on each side, or those on one side shall be reversed in direction from those on the opposite side. Where the line of deformations is over 70°, a reversal in direction shall not be required.

7.3 The average spacing or distance between deformations on each side of the bar shall not exceed seven tenths of the nominal diameter of the bar.

7.4 The overall length of deformations shall be such that the gap (measured as a chord) between the ends of the deformations shall not exceed 12.5 % of the nominal perimeter of the bar. Where the ends terminate in a rib, the width of the rib shall be considered as the gap between these ends. The summation of the gaps shall not exceed 25 % of the nominal perimeter of the bar. The nominal perimeter of the bar shall be 3.1416 times the nominal diameter.

7.5 The spacing, height, and gap of deformations shall conform to the requirements prescribed in Table 1.

8. Measurements of Deformations

8.1 The average spacing of deformations shall be determined by measuring the length of a minimum of ten spaces and dividing that length by the number of spaces included in the measurement. The measurement shall begin from a point on a deformation at the beginning of the first space to a corresponding point on a deformation after the last included space. Spacing measurements shall not be made over a bar area containing bar marking symbols involving letters or numbers.

8.2 The average height of deformations shall be determined from measurements made on not less than two typical deformations. Determinations shall be based on three measurements per deformation, one at the center of the overall length and the other two at the quarter points of the overall length.

8.3 Insufficient height, insufficient circumferential coverage, or excessive spacing of deformations shall not constitute cause for rejection unless it has been clearly established by determinations on each lot (Note 4) tested that typical deformation height, gap, or spacing do not conform to the minimum requirements prescribed in Section 7. No rejection shall be made on the basis of measurements if fewer than ten adjacent deformations on each side of the bar are measured.

NOTE 4—As used within the intent of 8.3, the term "lot" shall mean all the bars of one bar size and pattern of deformations contained in an individual shipping release or shipping order.

9. Tensile Requirements

9.1 The material, as represented by the test specimens, shall conform to the requirements for tensile properties prescribed in Table 2.

9.2 The yield point or yield strength shall be determined by one of the following methods:

9.2.1 The yield point shall be determined by the drop or halt of the gauge of the tensile testing machine, where the steel tested has a sharp-kneed or well-defined yield point.

9.2.2 Where the steel tested does not have a well-defined yield point, the yield strength shall be determined by the offset method (0.2 % offset), as described in Test Methods and Definitions A370.

9.3 When material is furnished in coils, the test specimen shall be taken from the coil and straightened prior to placing it in the jaws of the tensile testing machine. (See Note 5.)

NOTE 5—Straighten the test specimen to avoid formation of local sharp bends and to minimize cold work. Insufficient straightening prior to attaching the extensometer can result in lower-than-actual yield strength readings.

9.3.1 Test specimens taken from post-fabricated material shall not be used to determine conformance to this specification. (See Note 6.)

TABLE 2 Tensile Requirements

	Grade 40 [280][A]	Grade 60 [420]	Grade 75 [520]	Grade 80 [550]	Grade 100 [690]
Tensile strength, min, psi [MPa]	60 000 [420]	90 000 [620]	100 000 [690]	105 000 [725]	115 000 [790]
Yield strength, min, psi [MPa]	40 000 [280]	60 000 [420]	75 000 [520]	80 000 [550]	100 000 [690]
Elongation in 8 in. [200 mm], min, %					
Bar Designation No.					
3 [10]	11	9	7	7	7
4, 5 [13, 16]	12	9	7	7	7
6 [19]	12	9	7	7	7
7, 8 [22, 25]	...	8	7	7	7
9, 10, 11 [29, 32, 36]	...	7	6	6	6
14, 18, 20 [43, 57, 64]	...	7	6	6	6

[A] Grade 40 [280] bars are furnished only in sizes 3 through 6 [10 through 19].

Appendix C

ACI 318 -11

BUILDING CODE REQUIREMENTS FOR STRUCTURAL CONCRETE (ACI 318-11) AND COMMENTARY

REPORTED BY ACI COMMITTEE 318

PREFACE

The "Building Code Requirements for Structural Concrete" ("Code") covers the materials, design, and construction of structural concrete used in buildings and where applicable in nonbuilding structures. The Code also covers the strength evaluation of existing concrete structures.

Among the subjects covered are: contract documents; inspection; materials; durability requirements; concrete quality, mixing, and placing; formwork; embedded pipes; construction joints; reinforcement details; analysis and design; strength and serviceability; flexural and axial loads; shear and torsion; development and splices of reinforcement; slab systems; walls; footings; precast concrete; composite flexural members; prestressed concrete; shells and folded plate members; strength evaluation of existing structures; provisions for seismic design; structural plain concrete; strut-and-tie modeling in Appendix A; alternative design provisions in Appendix B; alternative load and strength reduction factors in Appendix C; and anchoring to concrete in Appendix D.

The quality and testing of materials used in construction are covered by reference to the appropriate ASTM standard specifications. Welding of reinforcement is covered by reference to the appropriate American Welding Society (AWS) standard.

Uses of the Code include adoption by reference in general building codes, and earlier editions have been widely used in this manner. The Code is written in a format that allows such reference without change to its language. Therefore, background details or suggestions for carrying out the requirements or intent of the Code portion cannot be included. The Commentary is provided for this purpose. Some of the considerations of the committee in developing the Code portion are discussed within the Commentary, with emphasis given to the explanation of new or revised provisions. Much of the research data referenced in preparing the Code is cited for the user desiring to study individual questions in greater detail. Other documents that provide suggestions for carrying out the requirements of the Code are also cited.

Keywords: admixtures; aggregates; anchorage (structural); beam-column frame; beams (supports); **building codes**; cements; cold weather construction; columns (supports); combined stress; composite construction (concrete and steel); composite construction (concrete to concrete); compressive strength; **concrete construction**; concrete slabs; **concretes**; construction joints; continuity (structural); contract documents; contraction joints; cover; curing; deep beams; deflections; earthquake-resistant structures; embedded service ducts; flexural strength; floors; folded plates; footings; formwork (construction); frames; hot weather construction; inspection; isolation joints; joints (junctions); joists; lightweight concretes; load tests (structural); loads (forces); materials; mixing; mixture proportioning; modulus of elasticity; moments; pipe columns; pipes (tubing); placing; plain concrete; precast concrete; prestressed concrete; prestressing steels; quality control; **reinforced concrete**; reinforcing steels; roofs; serviceability; shear strength; shear walls; shells (structural forms); spans; splicing; strength; strength analysis; stresses; **structural analysis**; **structural concrete**; **structural design**; structural integrity; T-beams; torsion; walls; water; welded wire reinforcement.

ACI 318-11 was adopted as a standard of the American Concrete Institute May 24, 2011, to supersede ACI 318-08 in accordance with the Institute's standardization procedure and was published August 2011.

A complete metric companion to ACI 318 has been developed, 318M; metric equivalents are provided only in Appendix F of this document.

BUILDING CODE REQUIREMENTS FOR STRUCTURAL CONCRETE (ACI 318-11) AND COMMENTARY

REPORTED BY ACI COMMITTEE 318

ACI Committee 318
Structural Building Code

Voting Main Committee Members

Randall W. Poston
Chair

Basile G. Rabbat
Secretary

Sergio M. Alcocer
Neal S. Anderson
Florian G. Barth
Roger J. Becker
Kenneth B. Bondy
Dean A. Browning
James R. Cagley
Ned M. Cleland
W. Gene Corley
Charles W. Dolan
Anthony E. Fiorato
Catherine E. French
Robert J. Frosch
Luis E. Garcia
Satyendra Ghosh
Harry A. Gleich
David P. Gustafson
James R. Harris
Terence C. Holland
Shyh-Jiann Hwang
James O. Jirsa
Dominic J. Kelly
Gary J. Klein
Ronald Klemencic
Cary S. Kopczynski
Colin L. Lobo
Paul F. Mlakar
Jack P. Moehle
Gustavo J. Parra-Montesinos
Julio A. Ramirez
David M. Rogowsky
David H. Sanders
Guillermo Santana
Thomas C. Schaeffer
Stephen J. Seguirant
Andrew W. Taylor
Eric M. Tolles
James K. Wight
Sharon L. Wood
Loring A. Wyllie Jr.

Voting Subcommittee Members

F. Michael Bartlett
Raul D. Bertero
Allan P. Bommer
JoAnn P. Browning
Nicholas J. Carino
Ronald A. Cook
David Darwin
Lisa R. Feldman
Kevin J. Folliard
H. R. Trey Hamilton III
R. Doug Hooton
Kenneth C. Hover
Steven H. Kosmatka
Michael E. Kreger
Jason J. Krohn
Daniel A. Kuchma
Andres Lepage
Raymond Lui
LeRoy A. Lutz
Joseph Maffei
Donald F. Meinheit
Fred Meyer
Denis Mitchell
Theodore A. Mize
Suzanne Dow Nakaki
Theodore L. Neff
Lawrence C. Novak
Viral B. Patel
Conrad Paulson
Jose A. Pincheira
Mario E. Rodriguez
Bruce W. Russell
M. Saiid Saiidi
Andrea J. Schokker
John F. Stanton
Roberto Stark
John W. Wallace

International Liaison Members

Mathias Brewer
Josef Farbiarz
Luis B. Fargier-Gabaldon
Alberto Giovambattista
Hector D. Hernandez
Angel E. Herrera
Hector Monzon-Despang
Enrique Pasquel
Patricio A. Placencia
Oscar M. Ramirez
Fernando Reboucas Stucchi
Fernando Yañez

Consulting Members

John E. Breen
Neil M. Hawkins
H. S. Lew
James G. MacGregor
Robert F. Mast
Charles G. Salmon

CODE

members made with that lightweight concrete provide strength and toughness equal to or exceeding those of comparable members made with normalweight concrete of the same strength. Modification factor λ for lightweight concrete in this Chapter shall be in accordance with 8.6.1 unless specifically noted otherwise.

21.1.5 — Reinforcement in special moment frames and special structural walls

21.1.5.1 — Requirements of 21.1.5 apply to special moment frames, special structural walls, and all components of special structural walls including coupling beams and wall piers.

21.1.5.2 — Deformed reinforcement resisting earthquake-induced flexure, axial force, or both, shall comply with ASTM A706, Grade 60. ASTM A615 Grades 40 and 60 reinforcement shall be permitted if:

(a) The actual yield strength based on mill tests does not exceed f_y by more than 18,000 psi; and

(b) The ratio of the actual tensile strength to the actual yield strength is not less than 1.25.

21.1.5.3 — Prestressing steel resisting earthquake-induced flexural and axial loads in frame members and in precast structural walls shall comply with ASTM A416 or A722.

21.1.5.4 — The value of f_{yt} used to compute the amount of confinement reinforcement in 21.6.4.4 shall not exceed 100,000 psi.

21.1.5.5 — The values of f_y and f_{yt} used in design of shear reinforcement shall conform to 11.4.2.

COMMENTARY

R21.1.5 — Reinforcement in special moment frames and special structural walls

Use of longitudinal reinforcement with strength substantially higher than that assumed in design will lead to higher shear and bond stresses at the time of development of yield moments. These conditions may lead to brittle failures in shear or bond and should be avoided even if such failures may occur at higher loads than those anticipated in design. Therefore, a ceiling is placed on the actual yield strength of the steel [see 21.1.5.2(a)]. ASTM A706 for low-alloy steel reinforcing bars now includes both Grade 60 (442) and Grade 80 (550); however, only Grade 60 is generally permitted because of insufficient data to confirm applicability of existing code provisions for structures using the higher grade. Section 21.1.1.8 permits alternative material such as ASTM A706 Grade 80 if results of tests and analytical studies are presented in support of its use.

The requirement for a tensile strength larger than the yield strength of the reinforcement [21.1.5.2(b)] is based on the assumption that the capability of a structural member to develop inelastic rotation capacity is a function of the length of the yield region along the axis of the member. In interpreting experimental results, the length of the yield region has been related to the relative magnitudes of nominal and yield moments.[21.8] According to this interpretation, the larger the ratio of nominal to yield moment, the longer the yield region. Chapter 21 requires that the ratio of actual tensile strength to actual yield strength is not less than 1.25. Members with reinforcement not satisfying this condition can also develop inelastic rotation, but their behavior is sufficiently different to exclude them from direct consideration on the basis of rules derived from experience with members reinforced with strain-hardening steel.

The restrictions on the values of f_y and f_{yt} apply to all types of transverse reinforcement, including spirals, circular hoops, rectilinear hoops, and crossties. The restrictions on the values of f_y and f_{yt} in 11.4.2 for computing nominal shear strength are intended to limit the width of shear cracks. Research results[21.9-21.11] indicate that higher yield strengths can be used effectively as confinement reinforcement as specified in 21.6.4.4.

Appendix D

Plagiarism Report

AUTHOR	TITLE	SIMILARITY	GRADE	RESPONSE	FILE	PAPER ID	DATE
Tariku Achamyeleh As...	Conclusion	0%	--	--		1859495426	19-Jun-2022
Tariku Achamyeleh As...	Introduction	3%	--	--		1859495390	19-Jun-2022
Tariku Achamyeleh As...	Abstract	4%	--	--		1859495381	19-Jun-2022
Tariku Achamyeleh As...	Literature Review	6%	--	--		1859495402	19-Jun-2022
Tariku Achamyeleh As...	Discussion	7%	--	--		1859495417	19-Jun-2022
Tariku Achamyeleh As...	Findings and Results	8%	--	--		1859495430	19-Jun-2022
Tariku Achamyeleh As...	Methodology	11%	--	--		1859495409	19-Jun-2022
Tariku Achamyeleh As...	Full Report	12%	--	--		1859495440	19-Jun-2022

Appendix E

Curriculum Vitae

Personal Information	
First Name(s)/Surname(s)	Tariku Achamyeleh/Asress
Address(es)	Near East University, TRNC Mersin 10, 99138, Turkey
Telephone(s)	Office: -
	Mobile: +251911067173 /// +905338596814
E-mail:	tarikuachamyeleh.asress@neu.edu.tr /// tariku.achamyeleh@mu.edu.et /// tariach@dtu.edu.et /// tarenku@gmail.com
Nationality	Ethiopian
Place of Birth	Debre Markos
Date of birth	10 August, 1985 G.C
Gender	Male
Employment/Occupational Field	Mechanical /Industrial Engineering
Work Experience	
Name and Address of Employer	Near East University
	99138, K.K.T.C., Via Mersin 10, Turkey
Type of Business or Sector	Higher Educational Institute
Date	October 2017 – January 2022
Occupation or Position Held	Research Assistant

Main Activities and Responsibilities:	- Teach courses for UG and assist PG programs
	- Participate in project and research works
Name and Address of Employer	Debre Tabor University
	P.O. Box 272, Debre Tabor, Ethiopia
Type of Business or Sector	Governmental (Higher Educational Institute)
Date	December 2016– September 2017
Occupation or Position Held	Head, Department of Mechanical Engineering
Main Activities and Responsibilities	- Direct and administer the teaching-learning, research, and community support services of the department.
	- Plan, execute/and administer the teaching-learning, research, and community service of the department.
	- Manage the overall administrative and financial activities of the department;
	- Have the mandate to solicit funding for the department;
	- Have the mandate to initiate, develop and manage external relations regarding the department;
	- Evaluate and monitor the quality of the teaching-learning, research, and community service activity;
	- Organize and mobilize resources to support the programs within the department.
	- Maintain the balance between the teaching-learning, research, and community service assignments of academic staff in consultation with respective course/research team leaders;
Date	November 2015 – November 2016
Occupation or Position Held	University-Industry Linkage Coordinator
Main Activities and	- Establish a sustainable structure for a qualified internship system

Responsibilities	- Link the university to industry for mutual benefit through MoU
	- Obtain Support from the industry for university programs and projects
	- Obtain opportunities in the industry for practical experience for DTU students
	- Organize seminars/workshops/visits for university-industry relationship
	- Building and providing sufficient support for a community of innovative researchers
	- Transferring knowledge to society through outreach and technology transfer
Date	September 2015 – September 2017
Occupation or Position Held	Lecturer
Main Activities and Responsibilities	- Teaching and researching
	- Preparing laboratory equipment specification for purchase
	- Preparing laboratory manuals
	- Advising and mentoring students' projects in different factories
Name and Address of Employer	Mekelle University
	P.O. Box 231, Mekelle, Ethiopia
Type of Business or Sector	Governmental (Higher Educational Institute)
Date	October 2010 - August 2015
Occupation or Position Held	Lecturer
Main Activities and Responsibilities	- Teaching
	- Researching
	- Advising and mentoring students' projects
Name and Address of Employer	East Gojjam Zone Water Development Office, P.O.Box 341

Type of Business or Sector	Governmental
Date	October 2009 – September 2010
Occupation or position held	Water Quality Expert
Main Activities and Responsibilities	- Identify problems related to water quality and devise a mechanism for prevention and control.
	- Conduct water quality experiments (Bacteriological, Physical and Chemical tests) of new deep wells to approve their quality for drinking.
	- Capacitate Wereda Staffs on inclusive water usage and management, water treatment and disinfection, and water sanitary inspection.
	- Work with UNICEF and WB Water Supply, Sanitation, and Hygiene Programs regarding water quality.
	- Follow up on water supply construction projects as vice water supply process coordinator.
	- Facilitate training on community water and hygiene matters
Name and Address of Employer	Aneded Wereda Education Head Office
Type of Business or Sector	Governmental
Date	November 2007 – September 2009
Occupation or Position Held	Office Vice Head
Main Activities and Responsibilities	- Plan, organize, and manage activities and manpower for the development of the sector.
	- Strengthen school administration.
	- Follow up School Improvement and Teachers Professional Development Programs

	- Mobilize community participation towards the success of Millennium Development Goals in education.
Education and Training	
Date	2017- 2022
Title of Qualification Awarded	PhD in Mechanical Engineering
Principal Subjects/Occupational	Advanced Materials Engineering, Advanced Metadata Analysis, Advanced Heat Treatment, Experimental Design and Analysis, Mechanical Behaviors of Composite Materials
Name of university	Near East University
Date	2012 – 2015
Title of Qualification Awarded	MSc. in Product Design and Development (Mechanical Engineering)
Principal Subjects/occupational	Product Design and Development I and II, Solid Modeling and Simulation, Design for Manufacturing, Advanced Finite Element Methods, Quality and Project Management, CAD/CAM, Advanced Manufacturing Processes, Experimental Measurement and Analysis, Introduction to Fracture Mechanics, Reliability and Maintenance.
Thesis	Design and Optimization of NACA64A410 Blade Aerofoil for Small Wind Turbine Application.
Name of University	Mekelle University, Ethiopia
Date	2003 – 2007
Title of Qualification Awarded	B.Sc. in Industrial Engineering

Principal Subjects/occupational	Thermodynamics, Material Science, Machine Design, Machine Elements, Introduction to Mechatronics, Strength of Materials, Machine Design, Machine Drawing, Numerical Methods, Applied Mathematics(I-III), Project Management, Manufacturing (I- III), Production Engineering, Operation Research, Operation Management I-II, Computer Integrated Manufacturing and High Volume Production, Maintenance, Innovation & Entrepreneurship, etc.			
Name of university	Mekelle University, Ethiopia			
Personal Skills and Competence				
Mother Tongue	Amharic			
Other Languages	English			
	Listening	Reading	Speaking	Writing
	Excellent	Excellent	Excellent	Excellent
Social Skills and Competence	Good in teamwork			
Computer Skills and Competence	- competent with Microsoft Office programs			
	- different programming languages and application packages such as AutoCAD, CATIA, ANSYS, C++, Matlab, MINITAB			
Additional Information				
Personal Interests	Playing football, athletics and listening to music, watching movies.			
Articles and Proceedings	1. Mechanical strength variability of deformed reinforcing steel bars for concrete structures in Ethiopia. Sci Rep 12, 2600 (2022). https://doi.org/10.1038/s41598-022-06654-1			
	2. Investigation of Mechanical Properties of Ribbed Reinforcement Steel Bars: A Case Study on			

	Ethiopian Construction Industry International Journal of Steel Structures (2019) 19(5):1682–1693, https://doi.org/10.1007/s13296-019-00236-0
	3. Experimental Comparison of Solar Cooker Using Black Coated and Aluminum Coated Box International Journal of Mechanical Engineering (IIJME) ISSN: 2321-6441 Volume 5, Issue 4, April 2017
	4. Experimental Investigation of Mechanical Properties for Tamarind Shell Particles as Filler in Epoxy Composite International Journal of Engineering Research And Advanced Technology (IJERAT) ISSN:2454-6135 Volume 03, Issue 3, March–2017
	5. Experimental Analysis of Solar Cooker Using Black Coated Box: Review Comparisons of Optimizing Measurements SSRG International Journal of Mechanical Engineering (SSRG-IJME) ISSN: 2348 – 8360, Volume 4 Issue 2–February 2017
	6. Analysis of Steam Turbine Casing International journal of applied research in science and engineering E-ISSN:2456-124x, Vol. 1 Issue 10, March 2017
	7. Crash Analysis of a Bumper with Outer Frame of Car Chassis International Journal of Modern Trends in Engineering and Research DOI: 10.21884/IJMTER.2017.4004.WCCCH, Vol. 4 Issue1, January 2017

	8. Design of Exhaust Silencer Muffler for Transmission Losses with the Performance of a Four Stroke Diesel Engine with and without Muffler Section International Journal of Mechanical Engineering and Technology (IJMET) ISSN Print: 0976-6340 and ISSN Online: 0976-6359, Vol. 8 Issue1, January 2017
	9. Aerodynamic Optimization of NACA64A410 Blade Aerofoil for Small Wind Turbine Application with ANSYS Fluent Proceedings - International Conference on Industrial Engineering and Operations Management, Kuala Lumpur, Malaysia, March 8-10, 2016
References:	1. Assoc. Prof. Dr. Huseyin Camur, Chair, Department of Mechanical Engineering, Faculty of Engineering, Near East University, Lefkosa, TRNC, Turkey Email: huseyin.camur@neu.edu.tr
	2. Prof. Dr. Mahmut A. Savas Professor, Department of Mechanical Engineering, Faculty of Engineering, Near East University, Lefkosa, TRNC, Turkey Email: mahmut.savas@neu.edu.tr
	3. Prof. Dr. Yusuf SAHIN Nişantaşı Üniversitesi, Turkey Email: yusuf.sahin@nisantasi.edu.tr
	4. Mulu Bayray, Ph.D. (Associate Professor, Mekelle University) Mekelle University, Mekelle, Ethiopia Mobile: +251-09-14-30-16-83(cell) Email: mul_at@yahoo.com