Comprehensive characterization of reinforcement steel bars from different steel plants

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Abstract
Both Local manufacturing and the global market meet the need for reinforced steel bars. But without good cause, the majority of consumers don't trust local items. This study characterized produced rebars from six factories (brands A-F) with varying diameters against NIS 117, BS 4449, and ASTM standards, focusing on yield strength, ultimate tensile strength (UTS), elongation, hardness, chemical composition, and microstructure. The samples were subjected to tensile testing on a 1000 kN Universal Motion Incorporated machine, hardness testing via Digital Micro Vickers Hardness Tester (HVS-1000Z, 4.904 N load), chemical analysis with Spectromaxx Metal Analyzer (MAXxLMF14) at DICON Laboratory, Kaduna, and microstructural examination using JEOL JSM 7600F scanning electron microscope. Statistical analysis employed IBM SPSS 27 for Mann-Whitney U tests and Python 3.13 for multi-linear regression. All samples met ASTM A706 and NIS 117 standards. For BS 4449, there was conformity except for A10 (10mm, UTS 595.036 MPa) and A20 (20mm, UTS 574.512 MPa). Tensile stress showed significant differences across brands ($p < 0.05$), except for 16mm diameter ($p=1.000$). Hardness varied significantly except for 20mm brands ($p=0.151$). A 3D regression surface and scatter plot yielded $R^2=0.793$, indicating a strong predictive model. Brand A rebars maintained optimal carbon levels per standards. Lastly, rebars (A,B, C, D, E, and F) were subjected to microstructural analysis using a JEOL JSM 7600F scan electron microscopy machine with a model. Additionally, their morphology was shown, indicating that C12, B16, D16, and A25 had less inclusions and flaws than E20 and F25.

1. Introduction

Steel is a mechanically and economically advantageous engineering material [1]; [2]. Steel's relative ease of manufacture and its availability in the earth's crust have given it an economic edge [2]; [3]; [4]. The material's strong strength to support a variety of loads and its good formability because of its flexibility are what provide it mechanical benefits. Steel may be made from secondary resources using electric furnaces or from virgin iron ore using the basic oxygen furnace (BOF) method. Steel product utilized as the primary building material for infrastructure setup and residential building construction is reinforced steel bar for concrete buildings [1]; [5]. By taking in the tensile pressures utilized in the structure, the reinforcement steel bars inserted in reinforced concrete (RC) constructions increase the concrete's tensile strength [6]; [7]; [8]; [9]; [10]. Among many other industries, steel products are used for mining, oil and gas, building and construction, telecommunication, likewise in the automotive sector [3]; [7]. According to national and international standards, rebar comes in a variety of grades that are utilized in the building sector [27]; [29]; [30]; [31].

The rapid urbanization and infrastructural expansion have greatly raised the demand for reinforced concrete [11]; [12]. Anecdotal evidence and empirical studies show that poor steel materials are commonly used in construction projects, causing structural failures, financial losses, and safety hazards [13]. The quality of rebar in Nigeria has been negatively impacted by the growing use of scraps as feedstock for steel rolling mill companies' manufacturing of reinforcing steel bars [14]. The collapse of buildings and infrastructures which results in the loss of lives and properties have boost researchers' interests in assessing the fundamental characteristics of reinforcing steel bars in Nigerian markets, given that local markets are a significant source of supply for the steels used in building and structural development [3]; [15].

Reinforcement steel bars' mechanical characterization and microstructural analysis in the Osun State construction sector [16]. Only Sample B fulfilled the NIS 117 standard, whereas Samples A, C, and D failed ASTM A706, according to the mechanical examination of reinforcement steel bar samples (A, B, C, and D) from Osun State markets. The rebar made locally according to Ethiopian standards [1]; [28]. One sample from B400BWR failed to meet the CES 101, 2017 minimum yield strength requirement of 400 MPa. B500BWR samples satisfied all condition outlined in the standard. The quality variations of reinforced steel bars gathered from various building sites in various regions to determine the mechanical parameters by the National Annex of Cameroon to Eurocode 2 [17]. In addition, there was a determination that reinforcing bars without markings did not meet the

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minimal criterion [17]. The mechanical characteristics comprising native and foreign steel bars measuring 10, 12, 14, 18, and 20 mm used in building construction in Aden, Yemen [6]. Yield strengths for 10, 12, 14, 18, and 20 mm bars (318-444.8 MPa) were below the 460 MPa limit, but 16 mm bars above it (463.62-466.36 MPa). Only 16 mm bars met the 600 MPa ultimate tensile strength requirement (BS 4449:1997), ranging from 602.12 to 637 MPa. The mechanical and chemical properties of reinforcing bars made in Nigerian steel factories using scrap metal [3]. The reinforcing steel bars were related to both National and Global standards to be sure of their conformity for building applications by carrying out hardness tests, tension tests, and chemical composition analysis. The physical and geometric parameters of reinforced steel bars utilized in Ghana's building sector [18]. They concluded that local and imported rebars differed in diameter and rib height. The impact of final rolling temperature and chemical composition on the mechanical characteristics of locally produced reinforcing bars made in Pakistan from unseparated scrap metal, and they provided suggestions to remove mechanical property variances [4]. Philosophy of positivism, a logical methodology, as well as a survey technique to assess the typical steel reinforced bar diameters utilized in Ghana's building industry [19].

Between the required quenching conditions, reinforcing bar strength, and volume of a martensite ring represented as a portion of the region of the bar section [20]. The mechanical, chemical as well as geometric qualities of native bars for reinforcement in Ghana [21]. The local bars' actual diameters were much less than their stated sizes, but the imported bars precisely matched their declared dimensions. Both a light microscope and a SEM to examine the dual-phase microstructure of a specifically manufactured rebar sample that had been etched with etchant of lepera and natal [22]. Quasi-static testing to determine the impact of strain rate on steel rebar's tensile strength with the lowest yield strengths of 235, 335, 400, and 500 MPa [23]. The mechanical characteristics of rebar made from scrap. They focused on composition of chemicals, microstructure and distribution of phases over the sectional area. The mechanical properties and microstructure of TRIP steel made of medium Mn produced via both hot and cold rolling [24]. They also compared Austenite consistency, work hardening properties, and fracture morphology. The strength of RMSRBs produced in Ghana using scrap metal [25]. Specimens underwent tensile, chemical, micro-hardness, and microstructure testing. The tensile strength varied from 576.00 to 768.40 N/mm^2, above the ASTM E8/E8M-16a requirement of 250 N. The mechanical and chemical qualities of reinforcing bars in Lubumbashi, such as those brought in from South Africa (FA) and Zambia (FZ) [26]. They all fulfilled ISO 6898 mechanical norms. Chemically, they were consistent with ISO 9001 with the exception of Mo, Ni, and Cu.

This study goal is to carry out comprehensive characterization of reinforcing bars (rebars) manufactured by different steels manufacturers in Nigeria. This is critical to establishing confidence with clients, particularly consultants and contractors who have expressed worries about the constancy of quality in locally made rebars. There is a significant void in extensive examinations into the most regularly utilized diameters in Nigeria (10 mm, 12 mm, 16 mm, 20 mm, and 25 mm). In this work, the mechanical characteristics of these locally made rebars are examined in relation to their hardness, especially yield strength, ultimate tensile strength (UTS), and ductility (as determined by the UTS/YS ratio and elongation). This study seeks to give precise and accurate data that will help enhance quality control and increase acceptability of locally made rebars in the building sector.

2. Materials and Method

Reinforcement Steel Bars from Six distinct steel factories in Nigeria provided steel bars measuring 10, 12, 16, 20, and 25 mm. These bars were selected at random from various temperatures for characterizations. Factory designations are A, B, C, D, E, and F for secrecy reasons. Samples from plant A (A10, A20 and A25) with heat numbers of 23060255, 23060257 and 23080313 respectively were sourced for the experiment likewise samples from plant B (B10, B12 and B16) with heat numbers of 230705121, 230705123 and 23040615 respectively. C12, D16, E20, and F25 were gotten from Kenyetta building material market, Enugu State, Nigeria.

2.1. Tension test

Three replicates of a tensile test experiment were conducted on various brands of chosen rebar samples, and the average result were calculated. Each of the tension test specimens was cut to a length of 500 mm. Peiris and Coorey's formulae were used to calculate the gauge length for the samples can be seen in Equation (1) [36]; [41]. The test was conducted in the University of Nigeria, Nsukka's Mechanical Engineering Workshop using the Universal Motion Incorporated Tensile Testing Machine, MUTC 100, which has a 1000 KN capability. In the tension test, elongation, yield strength, and ultimate tensile strength were all carefully evaluated from the UTM (Figure 1). Each sample was represented using its nominal dimensions and alphabets.

$$\text{Gauge Length } Lo = 5.65\sqrt{A} \quad (1)$$

Where A is the Cross-Sectional Area of the rebars

2.2. Hardness Test

The Digital Micro Vickers Hardness Tester was used to conduct the Vickers hardness test, Model: HVS-1000Z, as illustrated in Figure 4, in accordance with the ASTM test standard. The hardness test also employed

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samples cut from tension-tested rebar that were 10 mm high (see Figure 5). The bar brands (A, B, C, D, E, and F) of the reinforcement steel bars utilized for structural examination were measured for scratch utilizing a Vickers hardness tester to determine hardness in this study. The indents were spaced 0.5 mm apart. At the Defense Industry Corporation of Nigeria (DICON) Laboratory in Kaduna State, a spherical steel rod was subjected to the Vickers hardness test with a test load of 4.904 N. Three measurement points were recorded, as indicated in Figure 2, to assess the hardness of the rebar from its perimeter to its center. Vickers hardness (HV) ratings were derived from the test's diagonal indentation results. Micro-hardness was assessed using 3 kgf and a 15-s dwell time utilizing a Vickers hardness tester machine, which can calculate the Vickers hardness number based on the approximate area of the indent and the applied force at the cross section of the samples Erisir [1]. Cleaning, grinding, and polishing are the procedures that were used. Diagram of vickers hardness testing indentation diagonals can be seen in Figure 3.



Figure 1. Plate 1: Universal Tensile Machine (UTM)

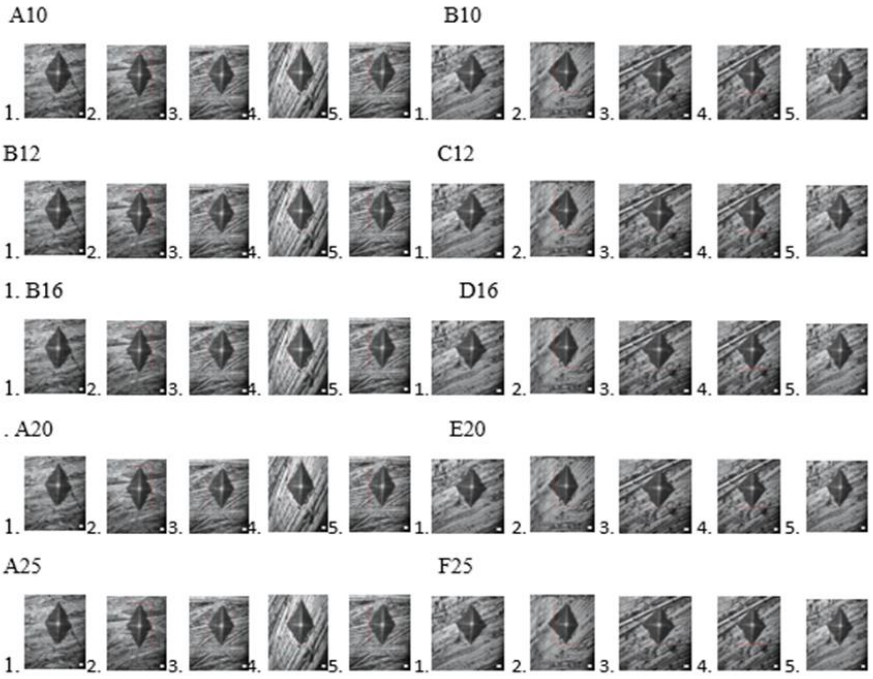

Figure 2. Plate 2: Measurement Points

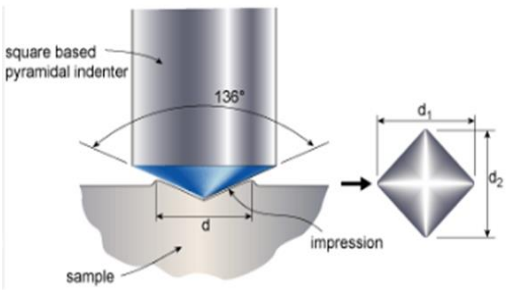

Figure 3. Plate 3: A Diagram of Vickers Hardness Testing Indentation Diagonals

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Figure 4. Plate 4: Digital Micro Vickers Hardness Tester

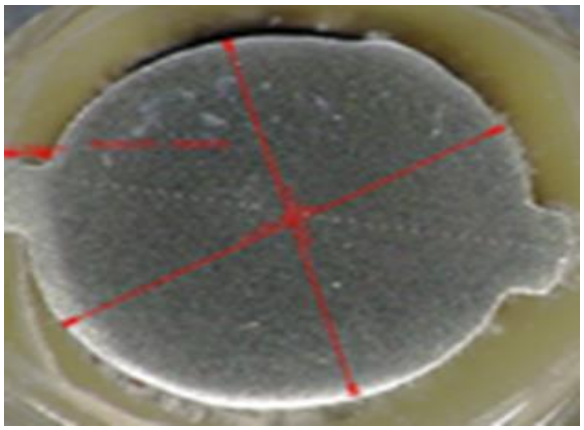

Figure 5. Plate 5: Brand indented by hardness test

2.3. Mann Whitney U Test

The Non-Parametric Test known as Mann Whitney U Test were used to determine the In-depth Statistical Analysis for Tensile Strength and Hardness Values (HV) in order to unveil the Underlying trend. IBM SPSS Statistics 27 were used in the analysis.

2.4. Multi-Linear Regression Model

Python 3.13 were used to develop a Non-Linear Regression model for Tensile Test prediction using the strain and Yield Stress. 3-D Regression Surface Visualization tool were developed which captured the Non-linear Relationship that exists between the strain and Yield Stress that gives rise to the Resulting Tensile Stress. Likewise, scattered plot was developed which shows the model's fitness. A non-linear regression model is formulated in Equation (2).

$$T = B_0 + B_1 S + B_2 Y + B_3 S^2 + B_4 Y^2 \quad (2)$$

Where T is Tensile Strength, S is Strain and Y is Yield Strength can shown in Equation (3).

$$S = \frac{\Delta GL}{GL_o} \quad (3)$$

ΔGL is change in Gauge length = Final gauge length – Original gauge length
GL_o is Original gauge length

The relationship is expressed in Equation (4)

$$Y = \frac{WpL}{M} \quad (4)$$

Where w is Yield load, p is density, L is length and M is mass.

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2.5. Testing for Chemical Composition

The Spectromaxx Metal Analyzer, model number MAXxLMF14, serial number 09001204, were used in the Defence Industry Corporation of Nigeria (DICON) Laboratory in Kaduna State to determine the rebars' percentage chemical composition. In the examination, the percentage composition of the primary chemical constituents C, Mn, Si, S, P, Cr, Cu, N, Ni, and Mo was examined. The tungsten carbide disks were put on the machine after the samples with diameters of 25 mm, 20 mm, and 16 mm were made to fit into their matching standard orifices. The monitor and argon gas were turned on during setup. Tungsten carbide disks with holes that were the proper size (10 mm and 12 mm) were utilized for the smaller 10 mm and 12 mm samples. Prior to installation, every sample was cleaned, smoothed, and leveled by grinding and polishing. The average elemental composition by weight (wt%) was shown on the attached monitor, and the test was carried out in compliance with the guidelines provided by NIS 117 (2004). The experimental set up can be seen in Figure 6.



Figure 6. Plate 6: The Experimental Set up

2.6. The analysis of microstructures

The steel brands A, B, C, D, E, and F, which had sizes of 12 mm, 16 mm, 20 mm, and 25 mm and were designated C12, B16, D16, E20, F25, and A25, were examined for surface imperfections, roughness, micro-voids, inclusions and fracture properties using a scanning electron microscope (SEM) machine with a model called the JEOL JSM 7600F. The University of Ibadan's Material and Metallurgical Engineering Workshop was the place for the experiment.

2.7. Sem sample preparation

As shown in Figure 7a, samples were obtained from several steel factories (A–F). They were then cut into 10mm lengths before being ground (see Figure 7b), and lastly, they were sent to the SEM machine (Figure 7c). Every sample was the right size to fit inside the specimen chamber, and they are often fixed firmly on a specimen holder known as a specimen stub. Many SEM models are capable of examining any part of a 6-inch (15 cm) semiconductor wafer, and some of them can tilt an object of that size to 450 degrees. The samples were coated with the electrically conductive platinum using either low-vacuum sputter coating or high-vacuum evaporation. SEM equipment places the specimen in a relatively high-pressure chamber with a short working distance and a differentially pumped electron optical column in order to maintain a low enough vacuum at the electron gun. The high-pressure region surrounding the sample neutralizes charge and amplifies the secondary electron signal in the Electron SEM. An FEG-SEM is ideal for low-voltage SEM because the field emission guns (FEG) provides tiny spots and high primary electron brightness at low accelerating potentials.



(a) (b) (c)

Figure 7. Plate 7: Steel bars and Preparations for SEM Experimental Set up

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3. Results and Discussion

The mechanical properties of the selected reinforcement steel bars, including yield stress, ultimate tensile stress, and strain, are summarized in Table 1.

Table 1. Mechanical Properties of Selected Reinforcement Steel bars

Brand	Yield Stress (MPa)	Ultimate Tensile Stress (MPa)	Strain (%)	Reference
A10	517.72	593.11	29.22	Present Study
B10	634.99	791.43	16.66	Present Study
B12	532.53	706.88	22.47	Present Study
C12	430.82	613.37	41.31	Present Study
B16	420.83	583.49	20.88	Present Study
D16	423.36	580.11	29.11	Present Study
A20	484.74	573.82	22.47	Present Study
E20	509.50	603.30	24.20	Present Study
A25	360.96	641.23	21.83	Present Study
F25	418.50	703.46	20.88	Present Study
EC	473.00	626.00	24.70	[45]
IC	641.00	753.00	19.00	[45]
SC	582.00	727.00	21.30	[45]
SF	597.00	707.00	20.30	[45]
US	566.00	713.80	10.03	[16]
NS	401.75	582.20	18.31	[16]
AS	500.00	624.00	13.02	[16]
BS	400.00	693.60	18.00	[44]
IG	450.00	652.00	28.00	[44]
IS	400.00	611.00	28.00	[44]
GS	325.00	660.00	25.00	[44]

The samples of reinforcing steel bars' mechanical properties are detailed in Table 1. ASTM A706, BS 4449, and NIS 117 all specify that reinforcing steel bars must have a minimum yield strength of 415, 500, and 420 MPa, respectively. ASTM A706, BS 4449, and NIS 117 criteria are all exceeded by reinforcing steel bars A10, B10, B12, and E20. NIS 117 and ASTM A706 criteria are exceeded by C12, D16, A20, and F25. Despite having yield strengths of 420.83 and 360.96, respectively, B16 and A25 were unable to fulfill ASTM A706, BS 4449, and NIS 117 criteria. Due to the large number of leftover pieces, the sources of this pattern cannot be identified. This is one disadvantage of using scraps as the main raw material to make reinforcing steel bars [3]; [32]; [33]. The minimum Tensile Strength required by ASTM A706, BS 4449, and NIS 117 is 590, 600, and 500 Mpa, respectively. Steel samples from the several factories under examination that have the following UTS values; 593.11, 583.49, 580.11, and 573.82, respectively exceed all requirements except for A10, B16, D16, and A20. A10 surpasses ASTM A706 and N1S 117 specifications. Additionally, all of the research's samples surpass the NIS 117 criteria. The strains in every sample used in the experiment are over the recommended thresholds (ASTM, BS 4449, and N1S 117). The yield strength and ultimate tensile strength of the current investigation are higher than those of [16] et al.'s results (2024]. Except for B10, which has yield stress and UTS of 634.98 and 791.43, respectively, the yield strength and UTS of higher than those of the current study [1]. Every sample reported by met all of the recommended specifications [34]. This study makes it evident that the samples have a high level of ductility. Summary of tensile strength results can be seen in Table 2.

Table 2. Summary of Tensile Strength Results

S/N	Brand	Mean ± SE	*U*	*p*-value
1	A10	593.1074 ± 1.63	25.000	0.008*
	B10	791.4275 ± 1.18		
2	B12	706.8827 ± 10.69	0.000	0.008*
	C12	613.3673 ± 14.20		
3	B16	583.4897 ± 2.32	13.000	1.000
	D16	580.1097 ± 5.78		
4	A20	573.8208 ± 3.44	25.000	0.008*
	E20	599.9870 ± 5.85		
5	A25	641.2273 ± 0.83	25.000	0.008*
	F25	703.4585 ± 5.50		

[1]All values expressed as mean ± standard error (±SE).
[2]Probabilty values are significant at p < 0.05 using Mann-Whitney U test.

Table 2 shows the mean differences in values of the studied brands. There were significant ($p < 0.05$) differences for all the brands compared, except for Brands B16 and D16 which showed non-significant ($p = 1.000$) differences in their mean values. It was observed that Brands B10, B12, E20 and F25 were significantly ($p = 0.008$) higher than their counterparts A10, C12, A20 and A25, respectively. 3-D regression surface for tensile stress prediction using strain and yield stress can be seen in Figure 8.

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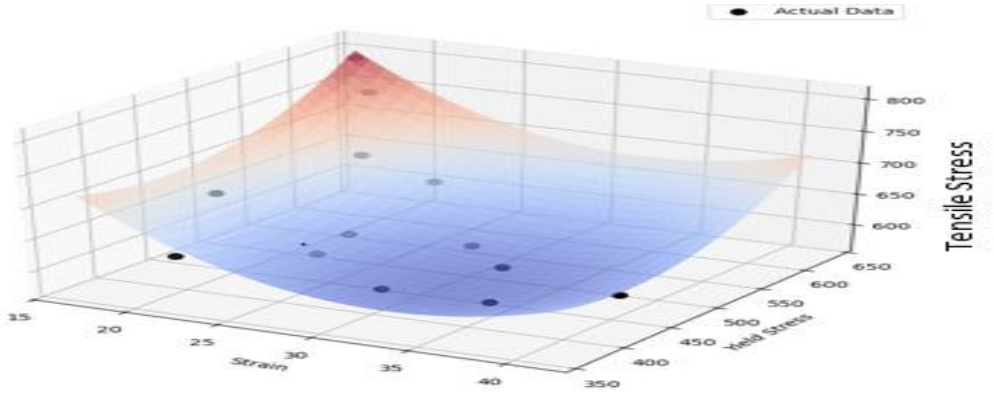

Figure 8. 3-D Regression Surface for Tensile Stress Prediction using strain and Yield Stress

Figure 8 displays a regression surface used to predict Tensile Stress based on two independent variables: Strain and Yield Stress. This type of model is often created using a form of multiple linear regression or polynomial regression where two predictor variables are used to describe the response variable, tensile stress. The red orange background describes the areas of higher predicted Tensile Stress (around 700-800Mpa) while the blue background describes Areas of lower predicted Tensile Stress (around 500-600Mpa). This 3D regression surface is a powerful visualization tool to understand the complex, non-linear relationship between Strain, Yield Stress, and the resulting Tensile Stress. It allows engineers or material scientists to visualize the predicted material behavior and identify combinations of Strain and Yield Stress that lead to desired (or undesired) Tensile Stress values. The Tensile Stress increases significantly towards the edges of the plot (high Strain, low Yield Stress or vice versa, and very high values for both). Figure 9 displays a scatter plot titled "Actual versus Predicted Tensile Strength

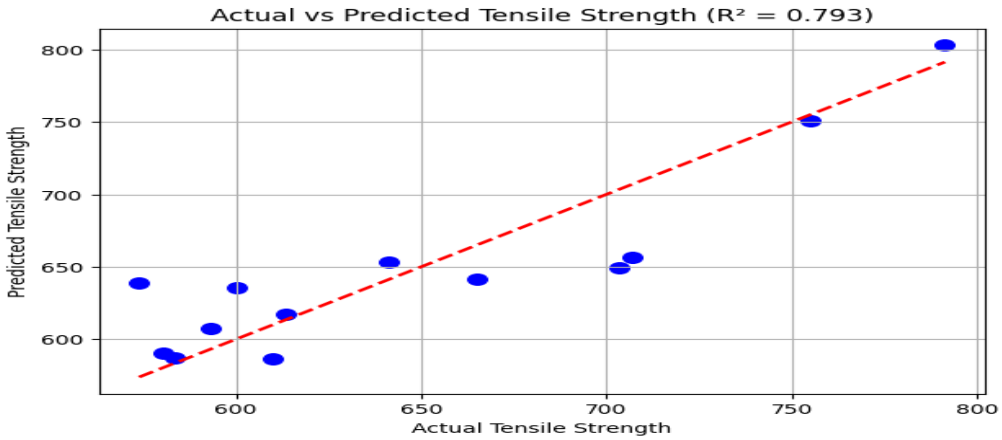

Figure 9. Plot of Predicted Tensile Strength versus Actual Tensile Strength

The scatter plot visually confirms that the regression model for Tensile Strength performs reasonably well, with the predicted values closely tracking the actual values. The R^2 value of 0.793 quantitatively supports this assessment, indicating that the model captures a substantial amount of the underlying relationship. This is generally considered a good fit in many engineering or materials science applications which suggests that the model is useful for prediction. Hardness values can be seen in Table 3.

Table 3. Hardness Values (HV, HRA, HRD, HRC)

Brand	HV	HRA	HRD	HRC
A10	227.50	54.90	37.70	20.90
B10	262.40	63.40	43.50	24.10
B12	240.60	58.10	39.90	22.10
C12	258.00	62.30	42.80	23.70
B16	236.40	61.10	40.30	20.40
D16	228.70	60.30	39.20	18.90
A20	219.00	57.70	37.50	18.10
E20	225.50	59.90	38.80	18.20
A25	210.30	58.30	36.20	14.80
F25	238.60	60.60	40.20	20.10

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Table 3 displayed The Hardness values for C12, B16, D16, E20, A25, and F25. Representatives from HRD, HRC, HRA, and HV were present. For 10mm reinforcing steel, the hardness values range from 13.47 to 18.01HRC, which is somewhat lower [15]. In Bangedesh, 20mm rods had hardness values of 29.5 and 32 HRC for samples 1 and 2, respectively [35]. Comparatively speaking, this is less than the figures in Table 2. The hardness of 8mm to 16mm reinforcing steel bars was evaluated in Ethiopia who discovered that the lowest overall value was 153HV and the maximum was 336HV [1]. Vickers Hardness Value also varied, ranging from 255.76 to 295.38HV [25]. The hardness values were quite high due to the high carbon content of the steel samples. The amount of carbon in steel affects its hardness [35]. The numbers that come after the letters (A–F) represent the nominal dimensions. It is clear that the hardness value and the diameter of the reinforcing steel bars are inversely related. The A25 of 210.3 is actually the lowest when compared to the other samples. This suggests that smaller indentations yield more benefit. The hardness Value of F is 238.6. Despite having the same nominal diameter, F's higher hardness rating makes it more abrasion-resistant than A's. Together with the HV values, Table 4 displays the corresponding Rockwell hardness conversions that were obtained.

Table 4. Summary of Hardness Test Results

S/N	Brand	Mean ± SE	*U*	*p*-value
1	A10	227.50 ± 0.10	25.000	0.008*
	B10	262.38 ± 0.45		
2	B12	240.58 ± 0.27	25.000	0.008*
	C12	257.98 ± 0.80		
3	B16	236.38 ± 0.54	0.000	0.008*
	D16	228.72 ± 0.54		
4	A20	219.00 ± 3.29	20.000	0.151
	E20	225.52 ± 0.44		
5	A25	210.30 ± 2.35	25.000	0.008*
	F25	238.90 ± 1.96		

[1]All values expressed as mean ± standard error (±SE).
[2]Probabilty values are significant at $p < 0.05$ using Mann-Whitney U test.

Table 4 shows the mean differences in values of the studied brands. There were significant ($p < 0.05$) differences for all the brands compared, except for Brands A20 and E20 which showed non-significant ($p = 0.151$) differences in their mean values. It was observed that Brands B10, C12, B16 and F25 were significantly ($p = 0.008$) higher than their counterparts A10, B12, D16 and A25, respectively. Carbon and other major residual elements in the reinforcement steel bars compared with Various studies and standards can be seen in Table 5.

Table 5. Carbon and other major residual elements in the reinforcement steel bars compared with Various studies and standards

Samples	% C	% Mn	% Si	% S	% P	% Cr	% Mo	% Cu	% Ni	References
A25	0.132	1.000	0.220	0.025	<0.0000	0.401	0.022	0.430	0.046	Present Research
F25	0.700	2.020	0.300	0.051	<0.010	0.57	0.059	0.66	0.091	Present Research
A20	0.059	0.910	0.162	0.021	0.0049	0.298	0.015	0.350	0.060	Present Research
E20	0.850	0.373	0.125	0.193	0.017	0.093	0.298	0.196	0.148	Present Research
B16	1.010	3.090	3.520	0.183	0.025	0.65	0.073	1.21	7.41	Present Research
D16	0.890	>4.6	0.590	0.134	0.025	0.79	0.060	0.111	0.149	Present Research
B12	0.367	0.520	0.223	0.029	0.014	0.174	0.016	0.175	0.095	Present Research
C12	0.358	0.680	0.291	0.002	0.0096	0.218	0.013	0.284	0.093	Present Research
A10	0.107	0.990	0.162	0.034	0.016	0.470	0.0072	0.52	0.087	Present Research
B10	0.310	0.900	0.201	0.026	0.0089	0.344	<0.000	0.425	0.072	Present Research
AR	0.200	0.850	0.240	0.060	0.030	0.200	0.020	0.220	0.130	[3]
BR	0.220	0.660	0.100	0.060	0.020	0.320	0.020	0.480	0.210	[3]
CR	0.190	0.360	0.120	0.050	0.030	0.320	0.020	0.380	0.150	[3]
A	0.126	0.507	0.126	0.030	0.055	0.210	0.078	0.188	0.097	[25]
B	0.192	0.277	0.116	0.025	0.036	0.240	0.082	0.207	0.102	[25]
C	0.176	0.478	0.168	0.024	0.037	0.173	0.093	0.258	0.102	[25]
NIS 117	0.300	1.200	0.300	0.040	0.040	...	...	...	...	[31]
BS4449	0.250	1.000	0.400	0.050	0.050	...	...	...	...	[29]
ASTM A706	0.300	1.500	0.500	0.045	0.035	...	...	...	...	[28]

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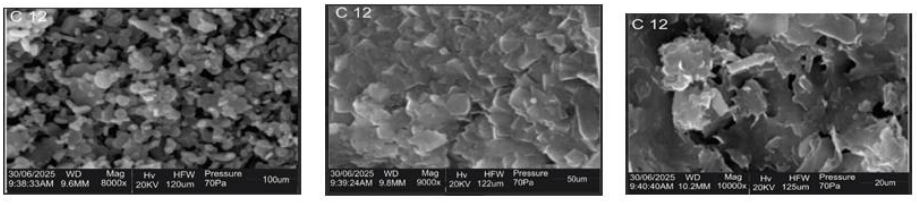
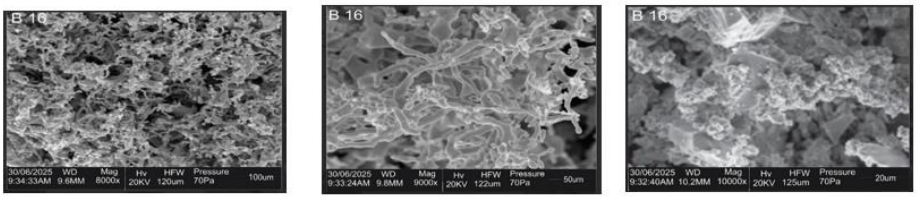
Carbon and other significant residual components in the reinforcing steel bars are described in Table 5 along with comparisons to other research and standards. With the exception of brands A25, A20, and A10, which had percentage compositions of 0.132%, 0.059%, and 0.107%, respectively, none of the brands satisfied the standard carbon standards (NIS, BS4449, and ASTM). The lowest carbon percentage is found in plant A20, which indicates 20mm rebar. At 1.010%, D16 has the greatest carbon concentration. The rebars used in this study have phosphorus (P) and sulfur (S) levels that vary from 0.0000 to 0.025% and 0.0022 to 0.193%, respectively. With the exception of E20, B16, and D16, which had percentage compositions of %0.193, %0.183, and %0.134 respectively. All of the brands complied with the Recommended NIS 117, BS4449, and ASTM Standards [12–18]. Every sample maintains the necessary phosphorus content level as advised by the standards. Brand D16's reinforcing bars contain the greatest percentage of magnesium (>4.640%), followed by B16 (3.090%) and F25 (2.020%). The negative consequences of using scraps in the manufacturing of steel are demonstrated by the deviation in the carbon and sulfur concentrations from the norms. As shown in Table 4, the findings of this study were contrasted with those of earlier research [3]; [25]. The standard levels of carbon, sulfur, and phosphorus are maintained by the findings [25]; [3]. Even though the phosphorus and sulfur contents varied, most of the brands still satisfied the minimal yield and tensile strength requirements for use as reinforcing materials. This performance might be attributed to the combined action of other remaining elements, particularly silicon and manganese, which efficiently deoxidize steel and enhance its mechanical properties [3]; [34]; [36]. Moreover, the inclusion of carbon, nickel, copper, and chromium may have affected the strength levels that satisfied the relevant standards [37]. Figure 10 shown a micrograph (a) is X8000, micrograph (b) is X9000 and micrograph (c) is X10000.



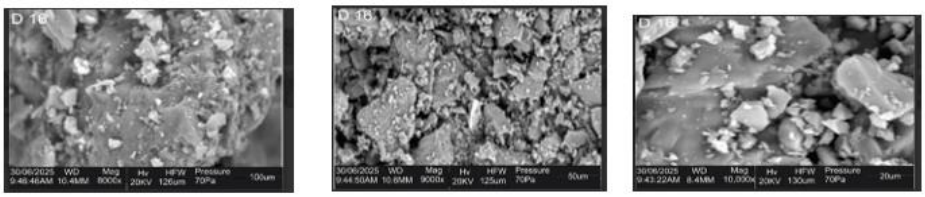
(a) (b) (c)

Plate 8



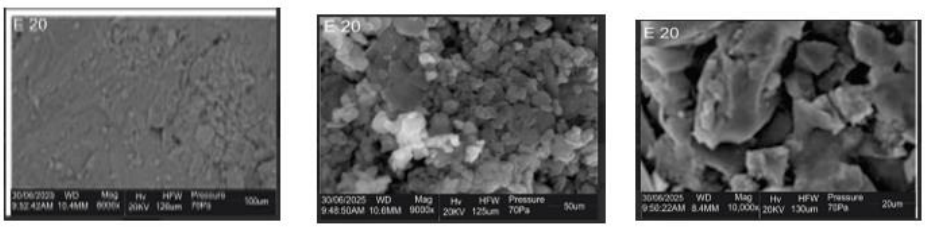
(a) (b) (c)

Plate 9



(a) (b) (c)

Plate 10



(a) (b) (c)

Plate 11

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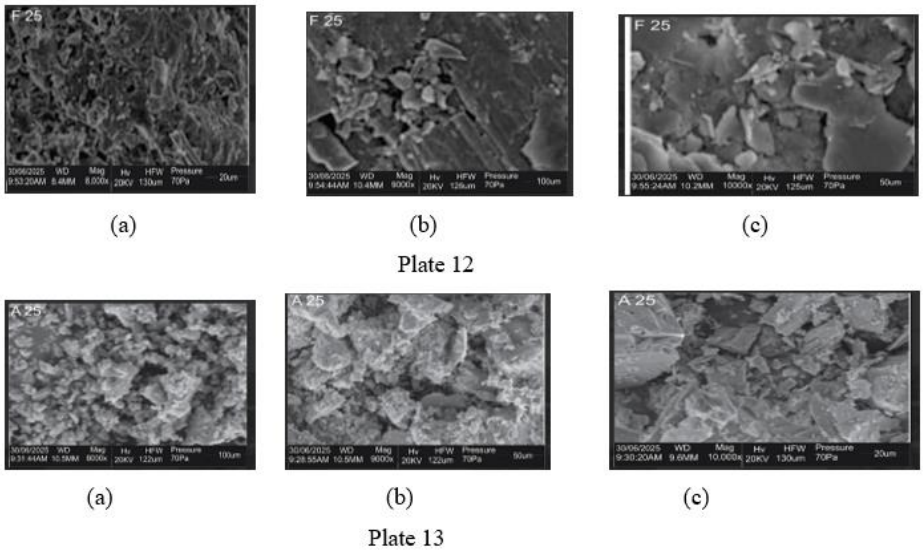

Figure 10. Micrograph (a) is X8000, micrograph (b) is X9000 and micrograph (c) is X10000

Plates 8 through 13 displays Scanning Electron Microscope (SEM) micrographs of Brands A, B, C, D, E, and F with the corresponding labels C12, B16, D16, E20, F25, and A25. Important characteristics including working distance (WD), horizontal field width (HFW), accelerating voltage (HV), scale bars, and pressure were captured in the pictures. Three magnifications were used to analyze the samples: X8000, X9000, and X10000. SEM experiments were conducted at magnification levels of X500, X1000, and X1500, and X5000 [1]; [37]. The microstructures are viewed in more detail than in previously published research. Pearlite (dark areas), a ferritic matrix (bright areas), and defect-like structures are visible in the SEM morphology. Higgins (1985) claims that when the carbon content of simple carbon steel rises, the pearlite areas expand and the microstructure becomes darker. More flaws, like internal fractures that could have been added during manufacture, become apparent at greater magnifications. Samples C12, B16, D16, and A25 (see Plates 8a, 8b, 8c; 9a, 9b, 9c; and 13a, 13b, 13c) had fewer inclusions and faults than samples E20 and F25 (see Plates 11a, 11b, 11c and 12a, 12b, 12c). Stress concentrators can be defects such as segregations, pinholes, and inclusions that are frequently caused by liquid steel production methods. By encouraging early fracture initiation, these flaws decrease ductility under load or deformation, which lowers the yield strength and ultimate tensile strength (UTS) [16]; [37]; [38]; [39]; [40].

4. Conclusion

This study examined the mechanical properties and hardness ratings of steel bars used for reinforcement from various steel mills. We collected reinforcing steel bars from many steel factories that belonged to different companies. They were tested for microstructural, tensile, hardness, and % chemical composition using scan electron microscopy (SEM). All the samples of steel bars from different plants met NIS 117 and ASTM A706 requirements. The same is true for the BS 4449 standard, with the exception of A10 (10mm) and A20 (20mm), which have UTS values of 595.036 and 574.512 Mpa, respectively. The hardness test results demonstrate that the spherical steel samples' surface hardness is consistent and reliable. There was statistically significant difference among the Tensile Stress Results of the steel brands except for B16 and D16 with a p-value of 1.000. There was also statistically significant difference among the Hardness Tests Results for the same brands except for A20 and E20 with a p-value of 0.151. 3-D Regression Surface is a powerful visualization tool to understand the non-linear correlation between the strain, Yield Stress and the resulting Tensile Stress. The scatter plot with R2 value of 0.7933 indicates that the model captures a substantial amount of the underlying relation which indicates that the model is a good fit for prediction. Some of the Reinforcement Steel Bar brands did not fulfill the required standards for their Percentage Chemical Composition. Compared to E20 and F25, SEM showed that C12, B16, D16, and A25 had less inclusions and defects.

Author Contributions

All authors have equal contributions to the paper. All the authors have read and approved the final manuscript.

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Declaration of Conflicting Interests

The author declared no potential conflicts of interest with respect to the research, authorship, and/ or publication of this article.

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Data Availability

The datasets generated during and/ or analysed during the current study are available from the corresponding author on reasonable request.

Declaration on AI Use

The authors declare that no artificial intelligence (AI) or AI-assisted tools were used in the preparation of this manuscript.

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