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Variability of Mechanical Properties and Reliability of Thermo Mechanically Treated Reinforcements in Nigeria

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Abstract

Thermo Mechanically Treated (TMT) reinforcements from different manufacturers in Nigeria were subjected to tensile strength tests to determine the variability of their yield strength, ultimate tensile strength, and ductility. For the 70 samples tested, 91.5% met the required characteristic strength of 500 MPa, and the percentage elongation at fracture satisfied all the requirements of BS 4449:2005. The probability distribution of the yield strength of the TMT reinforcements were found to conform better to normal distribution with a Chi-Square value (X^2) *of 4.342 against lognormal and Weibull distribution, with Chi-Square values of 4.80 and 6.536 respectively. The mean yield strength of the samples was found to be 532.8 MPa with a standard deviation of 24.926 MPa, and coefficient of variation of 4.678%. The probability of the samples tested falling below the yield strength of 500 MPa was found to be 9.4% with a reliability index of 1.316. The ultimate tensile strength to yield strength ratio* (R_m/R_e) *was found to be averagely high (with a mean of 1.356 and a standard deviation of 0.095) when compared to the requirements of BS 4449:2005 and test results from other parts of the world. This was the major source of non-conformity to the requirements of BS 4449:2005.*

1.Introduction

Reinforced concrete is the most popular construction material in Nigeria, accounting for about 90% of buildings erected in the country. In reinforced concrete construction, steel is mainly used to resist tensile and flexural stresses, and in some cases assist in resisting compressive stresses. As a result, the cost of reinforcement is of paramount importance to contractors, builders, and intending home owners.

Nigeria's steel market is usually categorised into 'local' and 'foreign' reinforcements which are priced differently in the market. Local reinforcements are manufactured indigenously in the country, while foreign reinforcements are imported into the country, usually from Germany, Ukraine, and Russia [1,2,3]. In the middle of local and foreign reinforcements are the thermo mechanically treated (TMT) reinforcements. TMT reinforcements are currently produced worldwide on a large scale for high strength steel [4]. In Uganda, recycled metal scraps are used in the production of TMT reinforcements, and this helps immensely in solving environmental problems [5]. Despite the presence of locally manufactured TMT reinforcements in Nigeria, they have not received much attention from researchers in order to evaluate their performance, characteristics, and applicability in the construction industry. Also, while most researches on local and foreign reinforcements have been focused on conformity to earlier versions of BS 4449 [6], few attempts have been made to relate Nigerian steel with conformity to the Eurocodes specifications and more recent versions of

BS 4449 [7,8]. The Nigerian Institution of Structural Engineers (NIStructE) and construction control agencies approve the use of BS 8110-1:1992 [9] and EN 1992-1-1:2004 [10] for structural design of buildings in Nigeria. As a result it is important to evaluate how TMT reinforcements in Nigeria conform to the requirements of the Eurocodes.

TMT reinforcements are characterised by their softer inner core, and hardened outer core, and are manufactured by a process called thermo mechanical treatment. Thermo mechanical treatment combines plastic deformation processes such as forging, rolling, etc with thermal processes like heat treatment, water quenching, heating, and cooling at various rates into a single process [11]. During the cooling process of TMT reinforcements, the inner core remains red hot, while the cooled outer surface gets auto tempered due to heat flow from the core to the surface, and turns the outer surface into a hardened martensitic layer [5,4,12] as shown in Figure 1. This gives TMT reinforcements unique microstructure (hard surface and soft core) which helps in providing the much needed surface hardness and ductility needed for reinforcements [13]. TMT reinforcements are characterised by their high strength, ductility, more resistance to corrosion, and general improved performance [12, 14].

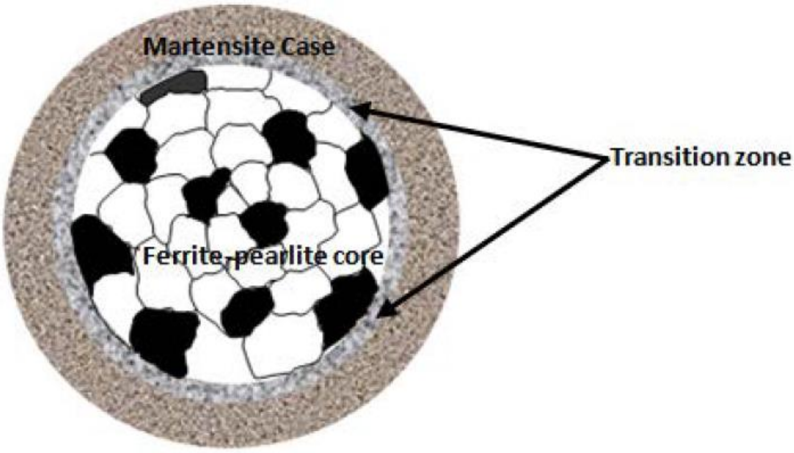

Figure 1: Cross-section of multi-layered Microstructures of TMT Bars [4]

To the best of the authors' review, no published literature was seen on assessment and evaluation of TMT reinforcements in Nigeria. However, the performance of local and imported steel reinforcements have been extensively studied by researchers in Nigeria [1, 3, 15, 16, 17]. In the work of Ejeh and Jibrin [16], 60% of locally manufactured reinforcements were found to have fallen below the standard requirement of BS 8110-1:1997 [9] based on yield strength and elongation considerations. In another study by Ede et al. [2], 70% of 1325 samples of locally made reinforcements tested in Lagos state were found to have met the specifications of BS 8110-1:1997 [9] based on characteristic yield strength and elongation. Osarenmwida and Amuchi [18] compared the performance of locally made ϕ10 mm and ϕ12 mm steel bars with imported equivalent steel size from China, and discovered that the yield strength of reinforcements tested exceeded the recommended minimum value of 414 MPa based on ASTM A706 [19]. However, an objective review of the results showed that imported steel from China had average yield strength of 469 MPa for ϕ12mm bars, while local reinforcements had average yield strengths of 399 MPa and 449 MPa for Kogi and Lagos steel bars respectively. This showed that technically, the locally manufactured reinforcements tested failed to meet the required characteristic strength for reinforced concrete construction, based on BS 4449:1997 [6] and BS 8110-1:1997 [9].

Due to the problems of quality assurance of reinforcements in Nigeria, most structural engineers in Nigeria resolve to the use of yield strength of 410 MPa in reinforced concrete design [3, 20]. BS 8110-1:1997 [9] however specified minimum tensile strength of 425 MPa for deformed hot-rolled high-yield bar (conforming to BS 4449:1997[6]) with diameter less than 16 mm, and 460 MPa for bars with diameter greater than 16 mm. By implication, the use of yield strength of 410 MPa in design means non-conformity to the code of practice, but it is usually justified as an error on the safe side due to the poor performance of local reinforcements when tested in the laboratories. EN 1992-1-1:2004 [10] however supports the use of yield strength ranging from 400 to 600 MPa, with characteristic strength of 500 MPa adopted for design purposes in the UK [21]. The new reinforcement specification can be found in the documents BS 4449:2005+A3:2016 [8] and BS EN 10080:2005 [22]. However, design engineers must specify the ductility class of the reinforcement in their detailing.

BS 4449:2005 [7] was the first document that incorporated the full revision of reinforcement specification by upgrading the yield strength of reinforcement to 500 MPa, and added a third ductility class of reinforcements according to EN 10080:2005 [22]. While BS 4449:1997 [6] described elongation at fracture and at maximum load, BS 4449:2005 [7] defined only elongation at maximum load. Furthermore, EN 10080:2005 [22] did not define steel grades expressly, but recommended that technical classes be assessed from the yield strength (R_e), ratio of tensile strength to the yield strength (R_m/R_e), and the percentage elongation at maximum force (A_{gt}). R_m/R_e is a measure of steel's ability to work harden prior to fracture, and it is used as a measure of ductility [23]. These three steel grades conform to the ductility classes of reinforcements defined in EN 1992-1-1:2004. The steel classes are given in Table 1 while the absolute values of reinforcement tensile properties are as given in Table 2.

Table 1: Steel reinforcement ductility classes

Grade	$(R_m/R_e)_k$	A_{gt}
B500A	≥ 1.05	≥ 2.5%
B500B	≥ 1.08	≥ 5.0%
B500C	≥ 1.15 < 1.35	≥ 7.5%

Source: Table 4, BS 4449:2005 + A2:2009 [7]

Table 2: Absolute maximum and minimum values of reinforcement tensile properties

Characteristic performance	**Minimum Value**			**Maximum Value**		
	B500A	**B500B**	**B500C**	**B500A**	**B500B**	**B500C**
R_e, MPa	485	485	485	650	650	650
R_m/R_e	1.03^a	1.06	1.13	N/A	N/A	1.38
A_{gt}, %	2.0^b	4.0	6.0	N/A	N/A	N/A

Source: Table 10, BS 4449:2005 + A2:2009 [7]

This objective of this paper is to evaluate the tensile strength properties of four different brands of locally manufactured TMT reinforcements in Nigeria to determine their conformity, ductility classes, and variability with respect to the Eurocodes specification.

2. Methodology

70 samples of TMT reinforcements consisting of 10 mm, 12 mm, 16 mm, 20 mm, and 25 mm bars were collected randomly across different construction sites in Nigeria, and were cut to a length of

600 mm for the purpose of determining their tensile strength properties. The samples distribution is shown in Table 3, and the rib pattern of some of the samples is shown in Figure 2.

Table 3: Sample size of the different bar reinforcements

Diameter of bar	Number of samples collected
10 mm	12
12 mm	18
16 mm	18
20 mm	15
25mm	7
Total	**70**

Figure 2: Rib pattern of some of the studied TMT reinforcements in Nigeria

The samples were selected across four different brands of TMT reinforcements in Nigeria namely Tiger TMT, TMT Shield, Rock TMT, and Real TMT. These samples were collected from construction sites in Lagos (Ebute-Metta and Ikeja), Onitsha, and Abuja. The selected brands were labelled A, B, C, and D in no respective order for the purpose of this research. The tensile strength test was carried out using Servo Computerised UTM Machine. Each sample was tested within one week after delivery to site.

Clause 8.1.3 of BS 4449:2005+A2:2009 [7] specified procedures for evaluation of tensile strength results. When the characteristic value C_v specified is a lower limit, the sample is deemed to conform to standard when all the values are equal to or greater than the specified characteristic strength, or when it conforms to Equation (1);

$$\bar{x} \geq C_v + \alpha_1 \tag{1}$$

Where $\bar{x}$ is the mean characteristic value of the parameter tested, and α_1 = 10 MPa for R_e, 0 for R_m/R_e and 0% for A_{gt} with all individual samples greater than the minimum values of the parameters provided in Table 10 of BS 4449:2005+A2:2009 [7] (see Table 2).

After evaluation of the tensile properties in the laboratory, the strength parameters were subjected to statistical test to determine their variability and probability distribution curve using MS Excel and MATLAB software. For material strength, it is usually recommended that normal, lognormal, and Weibull distributions be considered for distribution curve [24], and these distributions were all investigated in this study. The goodness of fit of each distribution was evaluated using Chi-square (X^2) at 95% confidence level. The probability of the samples falling below the yield strength of 500 MPa and the associated reliability index was evaluated based on the most fitting distribution curve.

For the evaluation of the probability of failure of reinforcements, it was assumed to be a fundamental case of one random variable where a specific value of performance was taken as non-random (deterministic). In this research work, the yield strength of 500 MPa was taken as a fixed value that defines acceptability. With that, F_y = 500 MPa with a mean (μ_{Fy}) of 500 MPa and standard deviation $\sigma_{Fy} = 0$. The probability of failure p_f (i.e. reinforcement yield stress R_e falling below 500 Mpa) was determined from the distribution function described by [25] which is given in Equation (2);

$$p_f = p(R_e < F_y) = \Phi_R(F_y) \tag{2}$$

Where the value of the distribution $\Phi_R(F_y)$ can be obtained from standardised tables for which the value μ_0 corresponding to F_y is computed from the general transformation formula given in Equation (3);

$$\mu_0 = (F_y - \sigma_{Re})/\sigma_{Re} \tag{3}$$

The probability of failure is then given as Equation (4) as described in [25];

$$p_f = p(R_e < F_y) = \Phi_R(F_y) = \Phi_U(\mu_0) \tag{4}$$

Where $\Phi_U(\mu_0)$ is the value of the distribution function of a standardised random variable using the appropriate distribution. The value $-\mu_0$ represents the margin between the fixed value of 500 MPa from the mean of the values of the yield stress obtained for all the samples expressed in the units of standard deviation. If the distribution is normal, this margin is called the reliability index (β) which is given by Equation (5);

$$\beta = (\mu_{Re} - F_y)/\sigma_{Re} \tag{5}$$

The probability of failure was then expressed as Equation (6);

$$p_f = p(R_e < F_y) = \Phi_U(-\beta) \tag{6}$$

Reliability index (β) is the negative value of the standardised normal variable corresponding to the probability of failure, and it is normally used as a measure of structural reliability as given in Equation (7);

$$\beta = -\Phi_U^{-1}(p_f) \tag{7}$$

3. Results and Discussion

The tensile strength results of the diameter ϕ10mm bars tested are shown in Table 4 while the descriptive statistics are shown in Table 5.

Table 4: Tensile strength results of ϕ10mm bars

S/N	SAMPLE LABEL	YIELD		ULTIMATE		A_{gt} (%)	R_e/R_m	Remarks/ Classification
		Load (kN)	Stress (MPa)	Load (kN)	Stress (MPa)			
1	B_{10A1}	41.93	534.14	55.91	712.19	12.57	1.33	Class C
2	B_{10A2}	42.35	539.48	56.47	719.31	12.70	1.33	Class C
3	B_{10A3}	41.83	532.88	55.77	710.50	12.54	1.33	Class C
4	B_{10A4}	40.34	513.91	52.79	685.21	13.97	1.33	Class C
5	B_{10A5}	40.77	519.37	54.36	692.49	14.12	1.33	Class C
6	B_{10A6}	40.45	515.30	53.93	687.07	14.10	1.33	Class C
7	B_{10A7}	42.31	533.11	54.56	685.42	13.00	1.29	Class C
8	B_{10A8}	41.45	520.41	51.00	647.34	11.50	1.24	Class C

9	B_{10A9}	41.22	520.41	52.67	660.04	12.50	1.27	Class C
10	B_{10B1}	41.10	523.53	54.80	698.04	13.70	1.33	Class C
11	B_{10B2}	40.47	515.54	53.96	687.39	13.49	1.33	Class C
12	B_{10B3}	40.65	517.90	54.21	690.53	13.55	1.33	Class C

For the 12 sample sizes of ϕ10mm tested as shown in Table 4, all the reinforcements were found to conform to the requirements of EN 10080:2005 [23] and BS 4449:2005+A2:2009 [7], and can be classified as ductility class C (B500C) based on R_e/R_m, and A_{gt}. It could also be seen that none of the individual samples fell below the specified characteristic strength of 500 MPa, and non exceeded 650 MPa. The average yield strength of 523.831 MPa was found to be greater than $C_v + \alpha_1$ (500 + 10 = 510 MPa) which shows general good performance of the entire ϕ10 mm samples tested.

Table 5: Descriptive statistics of the ϕ10mm bars

Statistical Parameters	Yield Stress (MPa)	Ultimate Stress (MPa)	Elongation (%)
Mean ($\bar{x}$)	523.831	689.627	13.145
Median (M_d)	520.42	688.627	13.245
Variance (s^2)	76.151	419.816	0.652
Standard Deviation (s)	8.726	20.489	0.807
Skewness (k)	0.644	-0.689	-0.536
Coefficient of variation (δ)	1.665	2.971	6.142
Maximum value (*Max*)	539.48	719.31	14.12
Minimum value (*Min*)	513.91	647.34	11.50

The tensile strength results of the diameter ϕ12mm bars are shown in Table 6, while the descriptive statistics are shown in Table 7.

Table 6: Tensile strength results of ϕ12mm bars

S/N	SAMPLE LABEL	YIELD		ULTIMATE		A_{gt} (%)	R_e/R_m	Remarks/ Classification
		Load (kN)	Stress (MPa)	Load (kN)	Stress (MPa)			
1	B_{12A1}	61.48	543.56	81.97	724.75	18.44	1.33	Class C
2	B_{12A2}	62.08	548.86	82.77	731.81	18.62	1.33	Class C
3	B_{12A3}	63.18	558.66	84.25	744.88	18.92	1.33	Class C
4	B_{12A4}	60.55	535.35	80.73	713.79	15.73	1.33	Class C
5	B_{12A5}	61.11	540.33	81.48	720.44	15.87	1.33	Class C
6	B_{12A6}	60.90	538.43	81.20	717.91	15.82	1.33	Class C
7	B_{12A7}	64.87	563.84	74.00	651.94	15.00	1.16	Class C
8	B_{12A8}	59.90	519.79	70.87	616.70	16.50	1.19	Class C
9	B_{12A9}	60.34	528.60	72.33	634.32	12.50	1.20	Class C
10	B_{12B1}	60.30	533.15	80.40	710.86	18.09	1.42	N/C
11	B_{12B2}	60.87	538.16	81.15	717.55	18.26	1.48	N/C
12	B_{12B3}	60.37	533.75	80.49	711.66	18.11	1.48	N/C
13	B_{12C1}	53.78	475.49	80.26	709.66	13.96	1.49	N/C
14	B_{12C2}	53.86	476.20	80.38	710.74	13.98	1.49	N/C
15	B_{12C3}	54.35	480.52	81.11	717.19	14.12	1.49	N/C
16	B_{12D1}	55.87	493.97	74.49	658.63	14.51	1.33	Class C
17	B_{12D2}	55.06	486.80	73.41	649.07	14.30	1.33	Class C
18	B_{12D3}	55.40	489.86	73.87	653.14	14.38	1.33	Class C

N/C: Non-conforming

For ϕ12mm bars, 3 samples from brand *C* (B_{12C1}, B_{12C2}, and B_{12C3}) were found to fall below the individual minimum acceptable yield strength of 485 MPa, with the R_e/R_m ratios exceeding the maximum acceptable value of 1.38. Three samples from brand *B* were also found to exceed the work hardening ratio (R_e/R_m) of 1.38, but generally the elongation values were acceptable. Considering the general overview of the results, the mean yield strength exceeded the specified characteristic strength and satisfied Equation (1). Therefore, the totality of the ϕ12 mm bars tested cannot be said to satisfy the requirements of the code, except on brand by brand basis, of which brand *A* performed satisfactorily.

Table 7: Descriptive statistics of the ϕ12mm bars

Statistical Parameters	Yield Stress (MPa)	Ultimate Stress (MPa)	Elongation (%)
Mean ($\bar{x}$)	521.406	694.169	15.950
Median (M_d)	533.450	711.260	15.775
Variance (s^2)	862.926	1475.595	4.021
Standard Deviation (s)	29.375	38.413	2.00531
Skewness (k)	-0.440	-0.777	0.148
Coefficient of variation (δ)	5.633	5.533	12.572
Maximum value (*Max*)	563.84	744.88	18.92
Minimum value (*Min*)	475.490	616.70	12.50

The tensile strength results of the diameter ϕ16mm bars are shown in Table 8 while the descriptive statistics are shown in Table 9.

Table 8: Tensile strength results of ϕ16mm bars

S/N	SAMPLE LABEL	YIELD		ULTIMATE		A_{gt} (%)	R_e/R_m	Remarks/ Classification
		Load (kN)	Stress (MPa)	Load (kN)	Stress (MPa)			
1	B_{16A1}	113.32	563.51	151.10	751.35	16.99	1.33	Class C
2	B_{16A2}	114.27	568.21	152.36	757.61	17.14	1.33	Class C
3	B_{16A3}	115.34	573.54	153.79	764.72	17.30	1.33	Class C
4	B_{16A4}	109.25	543.24	145.66	724.32	14.19	1.33	Class C
5	B_{16A5}	111.25	553.19	148.33	737.58	14.45	1.33	Class C
6	B_{16A6}	110.20	548.00	146.94	730.66	14.31	1.33	Class C
7	B_{16A7}	108.80	535.14	128.33	634.24	14.0	1.19	Class C
8	B_{16A8}	114.67	564.87	130.67	644.15	12.50	1.14	Class C
9	B_{16A9}	113.56	559.92	72.33	659.02	13.00	1.18	Class C
10	B_{16B1}	163.71	521.05	244.35	777.69	14.17	1.49	N/C
11	B_{16B2}	163.80	521.32	244.48	778.09	14.18	1.49	N/C
12	B_{16B3}	163.31	519.77	243.75	775.09	14.18	1.49	N/C
13	B_{16C1}	100.83	501.41	150.50	712.53	13.16	1.42	N/C
14	B_{16C2}	101.38	504.11	151.31	748.38	13.26	1.48	N/C
15	B_{16C3}	163.31	519.77	243.75	775.09	14.18	1.49	N/C
16	B_{16D1}	101.67	505.56	145.24	722.23	10.59	1.42	N/C
17	B_{16D2}	101.37	504.10	144.82	720.14	10.56	1.42	N/C
18	B_{16D3}	101.55	505.00	145.07	721.38	10.25	1.43	N/C

N/C: Non-conforming

Table 9: Descriptive statistics of the ϕ16mm bars

Statistical Parameters	Yield Stress (MPa)	Ultimate Stress (MPa)	Elongation (%)
Mean ($\bar{x}$)	533.989	729.682	13.800
Median (M_d)	528.230	734.120	14.175
Variance (s^2)	653.714	1977.554	4.204
Standard Deviation (s)	25.567	44.469	2.050
Skewness (k)	0.159	-1.025	-0.140
Coefficient of variation (δ)	4.787	6.094	14.855
Maximum value (*Max*)	573.54	778.09	17.30
Minimum value (*Min*)	501.41	634.24	10.25

All the individual ϕ16mm bars were found to satisfy the requirements of yield stress and elongation with none of the samples falling below the specified characteristic value. However, 9 out of the 18 samples tested exceeded the maximum R_m/R_e value of 1.35. Also, the lowest values of elongation were observed in brand *D*.

The tensile strength results of the diameter ϕ20mm bars are shown in Table 10, while the descriptive statistics are shown in Table 11.

Table 10: Tensile strength results of ϕ20 mm bars

S/N	**SAMPLE LABEL**	**YIELD**		**ULTIMATE**		**A_{gt} (%)**	**R_e/R_m**	**Remarks/ Classification**
		Load (kN)	**Stress (MPa)**	**Load**	**Stress (MPa)**			
1	B_{20A1}	172.08	547.69	245.83	782.41	17.20	1.43	N/C
2	B_{20A2}	171.64	546.28	245.20	780.40	17.16	1.43	N/C
3	B_{20A3}	173.59	552.47	247.98	789.24	17.35	1.43	N/C
4	B_{20A4}	177.95	566.37	237.27	755.16	15.41	1.33	Class C
5	B_{20A5}	176.53	561.84	235.37	749.12	15.28	1.33	Class C
6	B_{20A6}	177.60	565.26	236.81	753.68	15.37	1.33	Class C
7	B_{20A7}	171.23	542.24	218.34	691.28	15.00	1.27	Class C
8	B_{20A8}	172.89	545.41	215.21	681.77	13.00	1.25	Class C
9	B_{20A9}	165.56	523.22	212.22	672.25	16.00	1.28	Class C
10	B_{20B1}	163.71	521.05	244.35	777.69	14.17	1.49	N/C
11	B_{20B2}	163.80	521.32	244.48	778.09	14.18	1.49	N/C
12	B_{20B3}	163.31	519.77	243.75	775.09	14.18	1.49	N/C
13	B_{20D1}	165.59	527.02	236.56	752.89	9.12	1.43	N/C
14	B_{20D2}	168.30	535.65	240.43	765.21	10.6	1.43	N/C
15	B_{20D3}	167.84	539.90	242.34	771.29	8.58	1.43	N/C

N/C: Non-conforming

Table 11: Descriptive statistics of the ϕ20 mm bars

Statistical Parameters	**Yield Stress (MPa)**	**Ultimate Stress (MPa)**	**Elongation (%)**
Mean ($\bar{x}$)	541.032	751.705	14.173
Median (M_d)	542.240	765.210	15.00
Variance (s^2)	262.077	1467.028	7.668
Standard Deviation (s)	16.188	38.301	2.769
Skewness (k)	0.150	-1.320	-0.983
Coefficient of variation (δ)	2.992	5.095	0.195
Maximum value (*Max*)	566.37	789.24	17.35
Minimum value (*Min*)	519.77	672.25	8.58

Diameter ϕ20mm bars had average yield strength of 541.032 MPa, with none of the reinforcements falling below the yield strength of 500 MPa. Low elongation values were observed in brand *D*, while the highest elongation values were observed in brand *A*. It was also observed that 60% of the samples exceeded the recommended maximum R_m/R_e value of 1.38. However for the ϕ25mm bars tested, all the samples exceeded the defined characteristic yield strength of 500 MPa, with good elongation values (see Table 12). It could also be seen that 3 out of the 7 samples tested exceeded the recommended maximum R_m/R_e value of 1.38. The ϕ25mm bars tested performed well with minimum yield strength of 529.83 MPa, and minimum elongation of 13.5% (see Table 13).

Table 12: Tensile strength results of ϕ25mm bars

S/N	**SAMPLE LABEL**	**YIELD**		**ULTIMATE**		**Agt (%)**	**R_e/R_m**	**Remarks/ Classification**
		Load (kN)	**Stress (MPa)**	**Load (kN)**	**Stress (MPa)**			
1	B_{25A1}	278.59	567.52	397.99	810.74	18.33	1.43	N/C
2	B_{25A2}	278.91	568.16	398.44	811.65	17.43	1.43	N/C
3	B_{25A3}	261.55	529.83	320.00	649.60	14.0	1.23	Class C
4	B_{25A4}	264.21	535.92	320.00	649.60	13.5	1.21	Class C

5	B_{25A5}	262.55	531.86	323.00	655.69	16.0	1.23	Class C
6	B_{25B1}	276.01	562.25	411.95	839.18	17.92	1.49	N/C
7	B_{25C1}	295.90	602.77	394.53	803.69	15.37	1.33	Class C

N/C: Non-conforming

Table 13: Descriptive statistics of the ϕ25mm bars

Statistical Parameters	Yield Stress (Mpa)	Ultimate Stress (Mpa)	Elongation (%)
Mean ($\bar{x}$)	556.901	745.735	16.078
Median (M_d)	562.250	803.690	16.000
Variance (s^2)	695.366	7875.528	3.627
Standard Deviation (s)	26.369	88.744	1.904
Skewness (k)	0.694	-0.312	-0.215
Coefficient of variation (δ)	4.735	11.900	11.842
Maximum value (*Max*)	602.77	839.18	18.330
Minimum value (*Min*)	529.830	649.60	13.500

Descriptive statistics was also carried out on all the 70 samples combined with an aim of having a general overview of all the TMT bars tested. The results of the descriptive statistics are given in Table 14.

Table 14: Descriptive statistics of all the 70 samples

Statistical Parameters	Yield Stress (MPa)	Ultimate Stress (MPa)	Elongation (%)
Mean ($\bar{x}$)	532.812	720.008	14.548
Median (M_d)	533.450	718.61	14.18
Variance (s^2)	621.327	2544.85	5.270
Standard Deviation (s)	24.926	50.446	2.295
Skewness (k)	-0.0815	0.0301	-0.1688
Coefficient of variation (δ)	4.678	7.006	15.775
Maximum value (*Max*)	602.77	839.18	18.92
Minimum value (*Min*)	475.490	6I6.7	8.58

3.1 Yield strength description of all samples

Generally, the mean yield strength of all the 70 samples tested was found to be 532.812 MPa, with a standard deviation of 24.926 MPa. The frequency distribution of the samples using different curve fittings is shown in Figure 3.

From the data obtained from the laboratory, the goodness of fit of each distribution was evaluated using Chi-Square at 5% significance level. The data was categorised into 6 bins, thereby giving a degree of freedom of 5. From table of Chi-Square distribution (p = 0.05), the critical X^2 value of 11.07 was obtained.

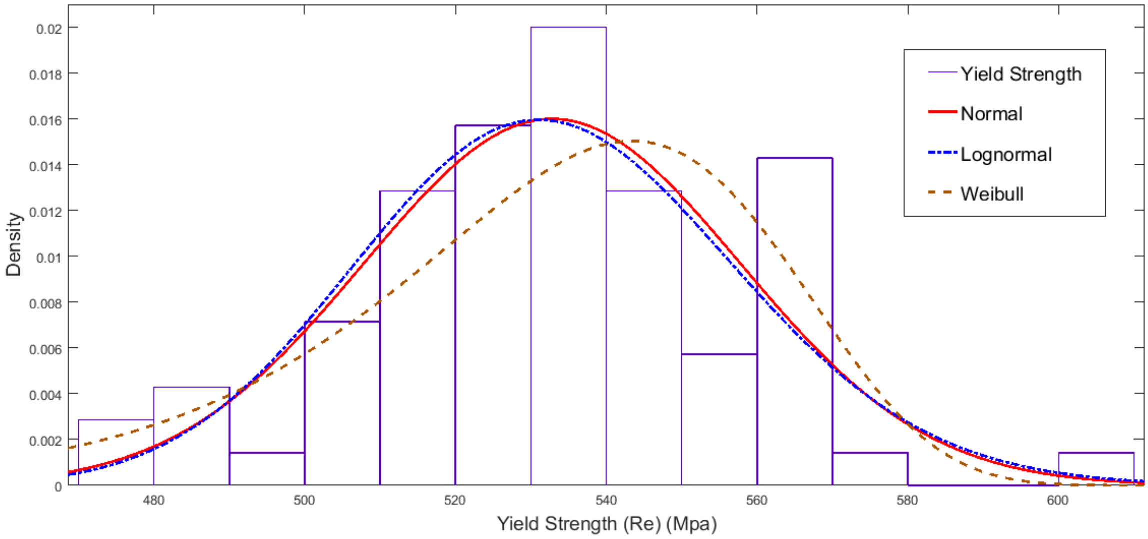

Figure 3: Yield strength distribution of all the 70 samples tested

For normal distribution, $X^2 = 4.342 < 11.07$ Ok
For lognormal distribution, $X^2 = 4.8039 < 11.07$ Ok
For Weibull distribution, $X^2 = 6.5366 < 11.07$ Ok

From the values of X^2, it can be observed that normal distribution gave the closest prediction of the data by having the least value. For a perfect fit, $X^2 = 0$.

Using normal distribution, the reliability index is therefore given by;

$\beta = (\mu_{Re} - F_y)/\sigma_{Re} = (532.812 – 500)/24.926 = 1.316$

Hence the probability of failure;

$p_f = p(R_e < 500) = \Phi_U(-1.316) = 0.094$ (9.4% probability of the sample falling below 500 MPa)

On the other hand, the probability of the samples falling below the individual minimum acceptable yield strength value of 485 MPa is 0.027 (2.7%) with a reliability index of 1.918.

3.2 Ductility description of all samples

Elongation (A_{gt}) and work hardening ratio (R_m/R_e) values are normally used to define the ductility characteristics of reinforcements. In the samples tested, the minimum value of elongation obtained for all the samples was 8.58%, and the mean was 14.458% with a standard deviation of 2.295%. The minimum value is greater than the minimum characteristic value of 7.5% specified for grade C reinforcements in BS 4449:2005.

On the other hand, high values of R_m/R_e were obtained with an average of 1.356, which is higher than the value of 1.35 specified in Table 4 of BS 4449:2005. This high value of R_m/R_e has also been reported in studies carried out on other reinforcements in Nigeria [1, 16, 17]. Bachmann [26] has earlier reported very low ductility values of steel reinforcements produced in Europe. In Sri Lanka, quenched and self-tempered steel (QST) studied by Bandara et al. [27] showed R_m/R_e values ranging from 1.15 to 1.24. According to [28], low values of R_m/R_e leads to high concentration of strains and subsequent failure before the ultimate stress is reached, which means failure will likely be brittle. However, high values of R_m/R_e imparts the ductility of the structure by assuring that significant energy absorption and dissipation occur during inelastic deformation, and guaranteeing that plastic hinge develops at the intended location. However, if the value of R_m/R_e is too high, then there is no certainty on the amount of strain hardening and flexural over-strength that may be generated [29]. According to [16], high values of R_m/R_e is not good for ductility and might indicate high carbon content in the reinforcement.

4 Conclusion

From the study on the variability of mechanical properties of TMT reinforcements in Nigeria, it could be seen that 91.4% of the samples tested surpassed the characteristic yield strength of 500 MPa. The lower values of yield strength were only discovered in ϕ12 mm bars. The lower yield strength values observed in ϕ12mm bars of brand *C* and *D* could possibly arise from production processes of the batch of reinforcement tested. Design engineers are however free to decide on the characteristic value of yield strength to use for design, since Eurocodes permits the use of yield strength ranging from 400 – 600 MPa. Manufacturers should however follow the recommendations in clause 8.2.2 of [7] for assessment of long-term quality level of their characteristic strength. Also, none of the samples exceeded the maximum recommended yield strength of 650 MPa, and only 3 out of the 70 samples tested failed to attain the minimum individual characteristic yield strength of 485 MPa. 42.85% of the samples exceeded the absolute maximum permissible R_m/R_e value of 1.38, and this was the major source of deviation from the requirements of the code, but none of the samples fell below the minimum requirement. Lack of balance in the ratio of the ferrite-pearlite core (soft core) to the martensite case (hard surface) of TMT bars produced in Nigeria could also be a possible cause of high R_m/R_e value. Future work should involve extensive testing of the chemical properties of TMT reinforcements produced in Nigeria, to see how they impart on the mechanical properties. Subsequently, reinforced concrete designers in Nigeria can confidently use f_{yk} = 500 MPa, and a material factor of safety of 1.15 at ultimate limit state (design strength = $0.87f_{yk}$ = 435 MPa) provided TMT reinforcements have been specified.

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