The Effect of the Carbon Content on the Ductile Behavior of Reinforcing Steel

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ABSTRACT

This study investigates the influence of the raw materials on the ductility of four threaded reinforcing steel commonly used in Indonesia, with the aim of ensuring compliance with the applicable standard (SNI 2052:2024). The chemical composition and mechanical properties of the threaded reinforcing steel were analyzed using Optical Emission Spectroscopy (OES) and the Universal Testing Machine (UTM), respectively. The chemical test results showed that sample S1 likely originated from cleaner raw materials than samples S2, S3, and S4, as indicated by the former's simpler alloy content. Samples S1, S2, and S3 met the standard criteria for the maximum carbon content according to SNI 2052:2024, while sample S4 exceeded the standard carbon content limit. Additionally, the Carbon equivalent (C_{eq}) values of samples S1, S2, and S3 confirmed the standard requirements, specifically regarding the strength and toughness aspects. However, sample S4 showed a C_{eq} value of 0.7, which exceeded the standard limit. The mechanical analysis demonstrated Yield Strength (YS) and Ultimate Tensile Strength (UTS) values ranging from 431.2 MPa to 505.4 MPa and 614 MPa to 673 MPa, respectively. The average UTS/YS ratio was above 1.25, which is the minimum limit. All reinforcing steels studied in this paper met the mechanical property requirements.

Keywords-reinforcing steel; carbon content; mechanical properties; SNI 2052:2024 standard

I. INTRODUCTION

Indonesia is highly prone to earthquakes due to its position on the Pacific Ring of Fire, experiencing annual seismic events with magnitudes of up to 6 on the Richter scale. The earthquakes in Cianjur (2022) and Sumedang (2023) caused structural damage to thousands of houses, with inadequate construction organization identified as a contributing factor. Reinforced concrete construction requires reinforcing steel that meets the established standards (SNI 2052:2024) to ensure the structural safety [1].

Steel is a crystalline alloy composed of iron, carbon, and small amounts of other elements [2]. The manufacturing process has a significant impact on its properties, including the percentage of various constituent elements, and the cooling rate in the production process [3-5]. Several researchers have studied the chemical and mechanical properties of reinforcing steel in counties like Nigeria, Saudi Arabia, Ethiopia, Senegal, United Kingdom, Colombia, and the United States, reporting that it is important to evaluate the quality of commercially available reinforcing steel to determine its compliance with the applicable standards as well as its structural applications [6-15].

The selection of the optimal material composition for smelting remains a major challenge faced by producers in the scrap steel recycling industry. One of the difficulties during the recycling process is controlling the level of unwanted residual elements, such as Cu, Ni, Sn, As, Cr, Mo, and Pb, which are commonly present in scrap. These impurities can adversely affect the YS and elongation of the bar [16]. In [17], the effect of carbon on the stress-strain behavior of plain carbon steel under Zener-Hollomon conditions was investigated, with the results demonstrating that the carbon effect appeared only in steels with a carbon content greater than 0.4%. On the other hand, authors in [18] examined the mechanical properties of medium carbon steel with a carbon content between 0.30 and 0.55% by weight through tensile and microhardness tests at room temperature. The findings revealed that an increase in the carbon content could led to higher yield stress and maximum tensile stress, while the tensile elongation remained almost constant. This means that the carbon content had little to no effect on the tensile elongation of steel at room temperature.

This study analyzed the chemical composition and mechanical properties of reinforcing steel from several Indonesian manufacturers to ensure compliance with the required standards.

II. MATERIALS AND METHODS

A. Materials

This research examined four brands of threaded reinforcing steel bars, each with a diameter of 16 mm, denoted as S1, S2, S3, and S4.

B. Methods

The chemical composition testing was conducted using OES techniques. The mechanical properties were evaluated with a UTM, while the microstructural characteristics were examined through Scanning Electron Microscopy - Energy Dispersion Spectroscopy (SEM-EDS) analysis. All reinforcing steel specimens were prepared according to ASTM E8 [19], as presented in Figure 1 and Table I.

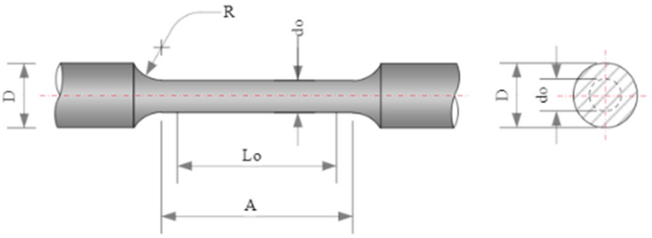

Fig. 1. Reinforcing steel specimen (top view only - modified per reviewer requirements).

TABLE I. DIMENSIONS OF ASTM E8 TENSILE TEST SPECIMENS

Parameters	Dimensions				
	Standard specimen diameter (mm)	**Small specimen diameter (mm)**			
	12.5	9	6	4	2.5
L_o	62.5 ± 0.1	45 ± 0.1	30 ± 0.1	20 ± 0.1	12.5 ± 0.5
D_o	12.5 ± 0.2	9 ± 0.1	6 ± 0.1	4 ± 0.1	2.5 ± 0.1
R	10	8	6	4	2
A	75	54	36	24	20

The detailed dimensions of the tensile test specimens are displayed in Table I, where the gauge length (L_o), specimen diameter (D_o), radius (R), and overall length (A), or different specimen sizes are specified.

The specimens were machined to ensure that fracture occurred within the designated gauge length, defined as four times the bar diameter (*4d*), as illustrated in Figure 2. The primary purpose of reducing the diameter of the gauge length section during tensile testing was to localize the deformation in that area. By reducing the cross-sectional area, stress was concentrated in this region, ensuring that elongation and fracture occurred in a controlled and localized manner. For specimens with a reduced diameter, the stress accounted for the reduced cross-sectional area is calculated using:

$$\sigma = \frac{P}{A_{reduced}} \quad (1)$$

where $A_{reduced}$ is the cross-sectional area of the machined gauge section, not the original bar area. This ensures accurate stress values despite the geometric modification.

Fig. 2. Samples of 16 mm diameter threaded reinforcing steel.

Tensile testing was performed using a UTM machine at the laboratory of Structures and Materials in the department of Civil Engineering, Hasanuddin University (Figure 3). The tensile load was applied at a controlled loading rate of 0.5

mm/min to ensure consistent testing conditions. The machine recorded real-time load and strain data throughout the testing process.

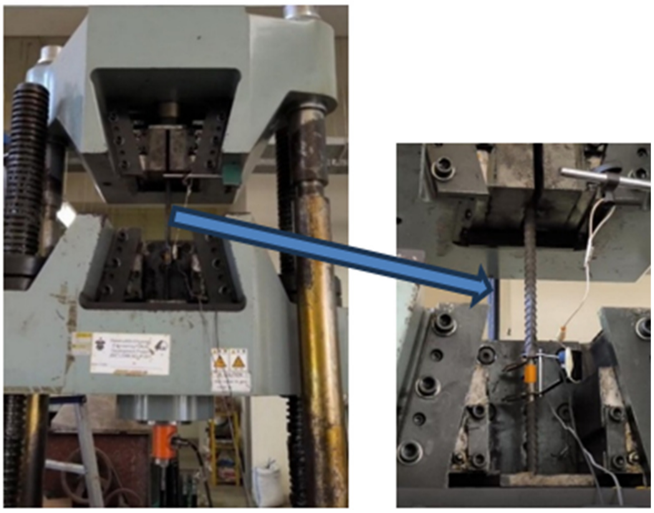

Fig. 3. Tensile test set up.

The OES test was performed using Atomic Spark Spectrometer Bruker Q4 Tasman and Handheld XRF Analyzer S1 TITAN (Figure 4). It was conducted at Detech Material Testing Laboratory, which holds ISO/IEC 17025:2017 accreditation.

Fig. 4. OES test equipment.

III. RESULTS AND DISCUSSION

A. Chemical Composition Analysis

The Carbon Equivalent (C_{eq}) value was calculated using:

$$C_{eq} = C + \frac{Mn}{6} + \frac{Cu}{40} + \frac{Ni}{20} + \frac{Cr}{10} + \frac{Mo}{50} + \frac{V}{10} \quad (2)$$

where C_{eq} is the carbon equivalent.

Table II summarizes the chemical composition of the tested sample, while Figure 5 compared the carbon content of the tested samples with the SNI values. Samples S1, S2, and S3 exhibited C_{eq} values within the standard limits, indicating better weldability and a lower risk of cracking. Sample S4 showed the highest C_{eq} value, exceeding the standard limits.

TABLE II. CHEMICAL COMPOSITION ANALYSIS RESULTS

Chemical composition	S1	S2	S3	S4	SNI standard
C	0.318	0.333	0.302	0.411	0.320
Si	0.200	0,.00	0.220	0.280	0.550
Mn	0.800	0.470	0.560	1.210	1.650
P	0.020	0.020	0.018	0.030	0.050
Si	0.010	0.020	0.019	0.050	0.050
Cr	0.050	0.400	0.352	0.080	-
Mo	0.001	0.010	0.001	0.001	-
Ni	0.010	0.060	0.038	0.060	-
Cu	0.010	0.100	0.099	0.300	-
Al	0.000	0.000	0.000	0.000	-
As	0.004	0.005	0.006	0.010	-
B	0.000	0.002	0.002	0.001	-
Bi	0.003	0.003	0.003	0.003	-
Ce	0.002	0.002	0.002	0.002	-
Co	0.002	0.006	0.006	0.010	-
Mg	0.001	0.002	0.002	0.002	-
Nb	0.005	0.007	0.008	0.006	-
Pb	0.002	0.002	0.002	0.002	-
Sb	0.003	0.003	0.003	0.005	-
Sn	0.000	0.006	0.016	0.010	-
Ta	0.020	0.020	0.020	0.020	-
La	-	0.001	0.000	0.001	-
Ti	-	0.002	0.002	0.002	-
V	-	0.006	0.009	0.005	-
W	-	0.031	0.031	0.040	-
Zn	-	0.030	0.030	0.060	-
Zr	-	0.009	0.010	0.013	-
Se	-	0.003	0.003	0.004	-
N	0.020	0.038	0.017	0.020	-
Ca	0.000	0.000	0.000	0.001	-
Te	0.007	0.003	0.011	0.010	-
Fe	98.44	98.21	98.20	97.480	-
C_{eq}*	0.46	0.48	0.46	0.700	0.6

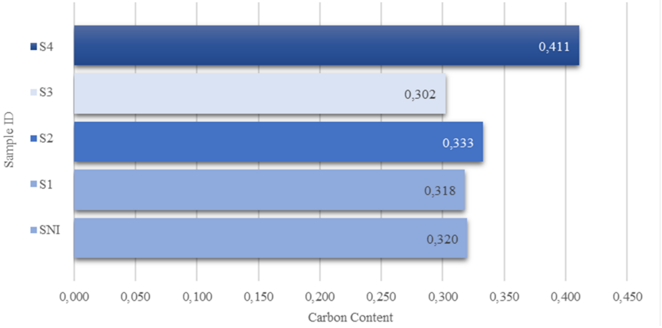

Fig. 5. Comparison of carbon content across samples.

B. Mechanical Properties Analysis

The strain was calculated as the change in length per unit initial length

$$\varepsilon = \frac{(L_u - L_o)}{L_o} \quad (3)$$

where L_u and L_o are the final and initial length, respectively.

The modulus of elasticity was defined as the ratio between the stress and strain within the elastic region :

$$E = \frac{(\sigma_2 - \sigma_1)}{(\varepsilon_2 - \varepsilon_1)} \quad (4)$$

where E is the modulus of elasticity, σ_2 is the stress at strain ε_2 (taken at a certain percentage of the maximum stress, e.g., 40%

Fu), σ_1 is the stress at strain ε_1 (taken at a very small strain, e.g., 50 microstrain), ε_2 is the strain at the time of stress σ_2, and ε_1 is the strain at stress σ_1.

Table II outlines the tensile strength test results for all samples. The key parameters included the yield load, ultimate load, YS, UTS, strain, the UTS/YS ratio, and Young's modulus (E).

TABLE III. TENSILE TEST ANALYSIS RESULTS

Sample	**Load (N)**		**Stress (MPa)**		**Strain (με)**	**UTS/YS ratio**	***E* (GPa)**
	Yield	**Ultimate**	**YS**	**UTS**			
S1a	58.510	78.502	472.2	633.6	45,215.3	1.34	232.7
S1b	55.980	80.770	466.5	673.2	63,100.5	1.44	240.6
S2a	52.580	79.430	431.2	651.5	73,645.9	1.51	224.7
S2b	53.110	79.435	434.2	649.4	96,679.4	1.50	257.6
S3a	38.000	43.150	546.4	620.5	16,245.9	1.14	144.2
S3b	36.300	46.400	480.3	613.9	117,593.0	1.28	235.6
S4a	54.780	83.970	473.5	725.7	113,943.0	1.53	203.3
S4b	53.250	87.630	460.2	757.7	117,100.0	1.65	153.5

C. Correlation Analysis

Figures 6 - 11 illustrate the relationship between the chemical composition, mechanical properties, and microstructural characteristics of the tested reinforcing steel samples.

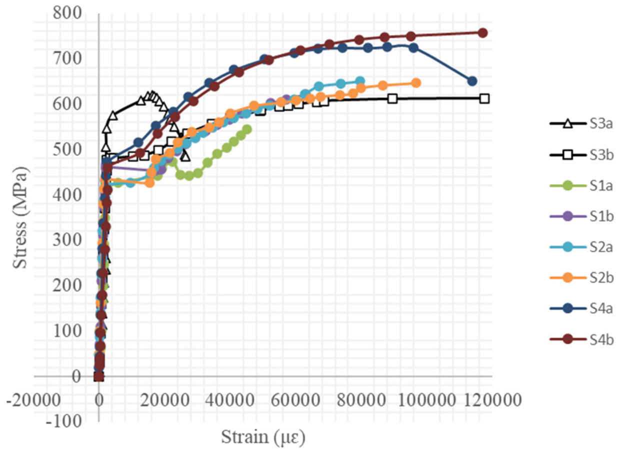

Fig. 6. Stress - strain curve.

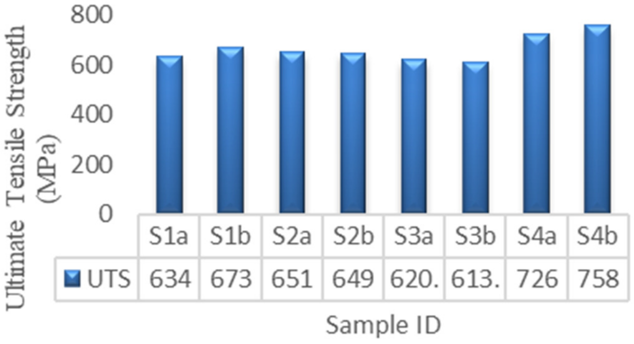

Fig. 7. UTS value.

Sample S4 exhibited the highest carbon content (0.411%) and achieved the highest UTS values (726 - 758 MPa). Despite its elevated carbon content, S4 also showed high strain values (113,943 - 117,100 με) and the greatest UTS/YS ratio (1.53 - 1.65), indicating good ductility. This suggests that factors other than carbon content, such as alloying elements or process factors, also affect the steel ductility. Specifically, the high manganese content of S4 steel (1.210% wt) combined with high carbon contributed to its strength. The UTS/YS ratio, an important indicator of steel ductility, met the minimum criterion of 1.25 in all samples except S3a.

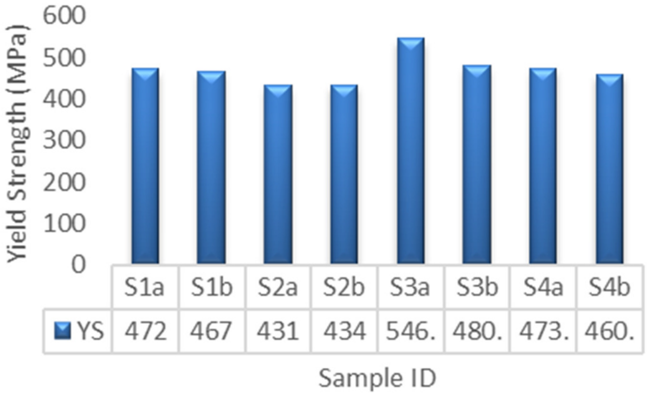

Fig. 8. YS value.

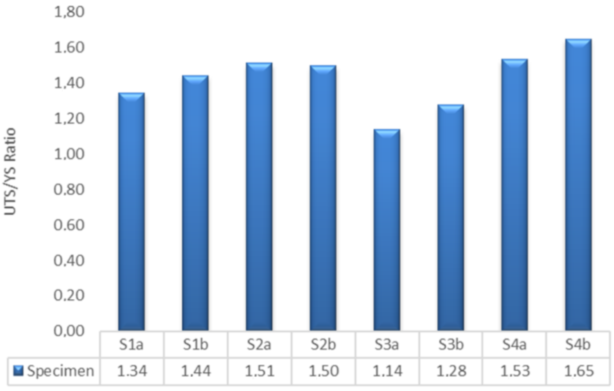

Fig. 9. UTS / YS ratio.

The microstructure of S1 steel displayed the presence of round and irregularly shaped particles scattered across the surface. A prominently large irregular particle was clearly visible. The particle sizes varied, with some having a clear round shape. The S2 microstructure demonstrated a combination of large irregular particles and a collection of smaller, finer particles. Additionally, the S3 microstructure showed a more homogeneous surface with fewer large particles compared to the other samples. There were elongated micro-cracks or fissures visible within the structure. Secondary particles appeared to be concentrated along the fissures with a relatively finer underlying matrix. With the lowest carbon content (0.302%), the S3 microstructure showed different characteristics. A more homogeneous surface aligned with the lower carbon content, while the presence of micro-cracks may have been caused by the influence of the production process or the applied heat treatment. The S4 microstructure exhibited highly distinctive characteristics, with the surface displaying numerous round to oval-shaped particles of varying sizes. The particle concentration was significantly higher compared to the other samples, while the underlying matrix structure demonstrated a more textured and complex morphology.

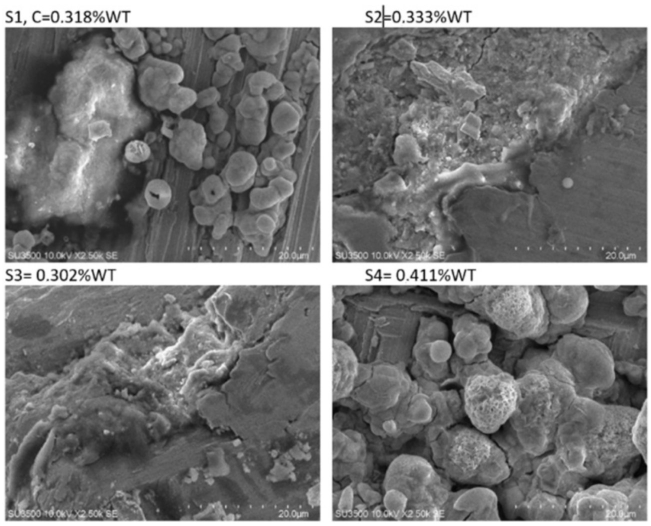

Fig. 10. Microstructur analysis of steel samples using SEM-EDS.

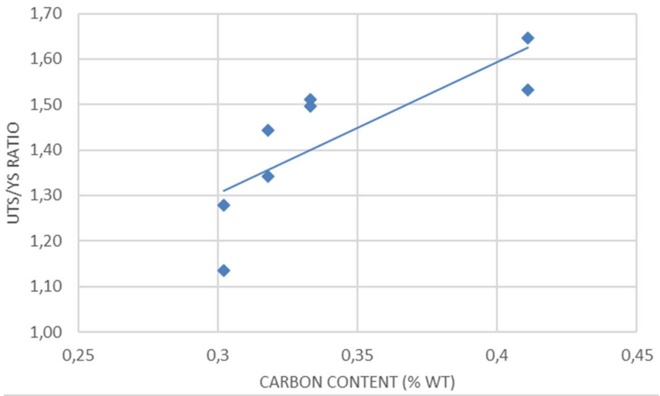

Fig. 11. Relationship between carbon content and UTS/YS ratio demonstrating the effect of carbon on steel ductility.

IV. CONCLUSION

This study evaluated the chemical composition and mechanical properties of four 16 mm diameter threaded reinforcing steel from several Indonesian manufacturers. The Optical Emmision Spectroscopy (OES) and the Universal Testing Machine (UTM) tensile tests were used, as well as the Scanning Electron Microscopy - Energy Dispersion Spectroscopy (SEM- EDS) was utilized for microstructural analysis. Based on the results, several key findings were revealed:

- This study challenged the conventional assumption that a higher carbon content always decreases ductility. S4 steel with the highest carbon content (0.411%) exhibited the optimum ductility (UTS/YS ratio = 1.65), suggesting an optimal balance between carbon and manganese (1.210%) in S4, which demonstrated synergistic effects in creating favorable microstructures.
- The elastic modulus showed significant variations (144.17 - 257.57 GPa) with no direct correlation to the ductility strength, indicating that this parameter should not be the primary criterion for evaluating the reinforcing steel quality. The microstructural morphology and phase distribution had more significant influence on the UTS/YS ratio compared to the chemical composition alone.
- All samples met the minimum UTS/YS ratio requirement of 1.25, except S3a, indicating adequate ductility for structural applications. The finding suggest that ductility should be prioritized over the elastic modulus in selecting reinforcing steel for earthquake-resistant structures.

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