Evaluation of Surface Geometries and Physical Properties of Concrete Reinforcement Steel Rods Rolled in Nigeria

Article *in* Case Studies in Construction Materials · December 2017

DOI: 10.1016/j.cscm.2017.12.003

3 authors:

Oluwafemi Leramo
Covenant University
39 PUBLICATIONS **687** CITATIONS

L.O. Adekoya
Obafemi Awolowo University
27 PUBLICATIONS **538** CITATIONS

Cleophas Loto
Covenant University
244 PUBLICATIONS **4,119** CITATIONS

Case Studies in Construction Materials 8 (2018) 150–159

Contents lists available at ScienceDirect

Case Studies in Construction Materials

journal homepage: www.elsevier.com/locate/cscm

Case study

Evaluation of surface geometries and physical properties of concrete reinforcement steel rods rolled in Nigeria

Richard O. Leramo[a,*], Lawson O. Adekoya[b], Cleophas A. Loto[a]

[a] The Energy and Environment Research Group (TEERG), Mechanical Engineering Department, Covenant University, Ogun State, Nigeria
[b] Mechanical Engineering Department, Obafemi Awolowo University, Ile-Ife, Osun State, Nigeria

ARTICLE INFO

Keywords:
Surface geometries
Thermo-Mechanically Treated
Scraps
Billets

ABSTRACT

The objective of this research was to evaluate the surface geometries and physical properties of locally-rolled steel rods made from billets that are produced from locally-sourced scraps and three available imported rebars in Nigeria. The database of test results obtained were compared with specifications in NIS 117:2004 (local) and BS 4449:2005 and ISO 6935-2: 2007 (international) standards. There are 26 indigenous rolled samples that are available in Nigeria of which two samples were from imported billets but rolled locally, five (5) were Thermo-Mechanically Treated (TMT) and the remaining 19 were ordinary rods (without any form of heat treatment). The average measurements of fifteen samples selected at random from each brand were taken. Their measurements were taken and computed for full length, nominal diameter, cross-sectional area, mass per length, rib height, transverse rib inclination, rib spacing, rib flank inclination, relative area, longitudinal height and rib base width. These data were systematically documented to study their qualities. Findings showed that none of brands fully conformed to the three standards in terms of diameter and cross-section area. Out of the ordinary locally-rolled rods, Brands 7, 10, 16 and 18 were the best in terms of conformity. Among the TMTs, Brand 6 B was the best in performance. The two selected rods, Brands 20 B and 21 (locally-rolled from imported billets) performed well by meeting four (4) of the specifications for surface geometries and physical properties. Among the imported steel rods, Brand 24 gave the best performance in specifications for surface geometries and physical properties.

1. Introduction

The quality of a reinforcement bar can be represented by its geometrical rib features (i.e. surface geometries including shape, width, height, spacing and inclination with respect to the surface of the rods) and physical properties in terms of length of the rods and nominal diameter, area of the ribs and rods, mass and density of the rebars. The prime reason for having ribs at the outer surface of the rods is to improve bonding of reinforcement steel rods with concrete by mechanical interlocking. Bond strength is usually affected by many factors such as rib surface geometry, concrete strength, concrete cover, chemical adhesion, surface condition of rebars and location of the bars during casting, etc. From all indications of the reviewed papers, rib geometry has the greatest effect in terms of bonding of reinforcement steel to the concrete. Proper geometrical configuration of ribs can as well prevent failure due to cyclic loadings (fatigue). The ribs can be longitudinal or transverse and are shaped, spaced and inclined according to the specification requirements from adopted standards. Many researchers have contributed immensely to the study of reinforced concrete. Darwin and Graham [1] stated that there is broadly inconsistent suggestion on the effect of rib geometry on the bond strength between concrete

---

[*] Corresponding author.
E-mail address: richard.leramo@covenantuniversity.edu.ng (R.O. Leramo).

https://doi.org/10.1016/j.cscm.2017.12.003
Received 24 August 2017; Received in revised form 7 December 2017; Accepted 11 December 2017

and reinforcing rods. Some researchers suggested that some rib geometries have strong significant influence on bond strength, while others recommended little significant influence; it was also found to be possible for rebars with different surface geometry to give results that are almost the same with bond strength and split resistance from the concrete. It was observed by Clark [2,3] through an overview of some of the past work on surface geometry, that the greater the transverse-rib flank inclination, the greater the slip for a given force. His studies also recommended that the ratio of shearing area to the rib bearing area may be limited to a maximum of 10. He also opined that for a bar with nominal diameter smaller than 13, the average spacing between two consecutive ribs and the ribs height should be equal to 70% and 4% of the diameter respectively. The studies of Rehm [4,5] suggested that if the ratio of rib spacing to rib height is less than 7, and if that of rib flank inclination is greater than 40°, the bond strength will not improve and it is most likely that the concrete adjacent to the ribs undergoes gradual crushing which might lead to a pull-out failure.

Lutz and Gergely [6] advocated that if the rib flank inclination angle is between 30° and 40°, rather than acts as a wedge, it may favour slipping of reinforcement bar with respect to the concrete which may result into crushing effect of the concreate that is adjacent the ribs. Lutz and Gergely [6] emphasized that a rib flank inclination angle less than 30° may weaken the load-slip effect of the rebar and concrete. Soretz and Holzenbein [7] realized that rib inclination is a relatively small parameter when compared to rib bearing area; however, the work supported the finding in the work of Lutz and Gergely [6] that ribs of a lower transverse-rib flank inclination exhibit more slip, but deliver the same bond strength with equal rib heights and steeper face rib flank inclination. They further suggested in their work that the minimum requirement for rib flank inclination angle is not essential. Skorobogatov and Edwards [8] studied rebars of rib flank inclination angles of 48.5° and 57.8° and concluded that the rib flank inclination angles do not affects bond strength.

Losberg and Olsson [9] stated that as the rib inclination angle is closer to 90° with respect to longitudinal axis, the slip effect is reducing thereby increasing in bond strength. This assertion is favourably supported by Soretz and Holzenbein [7] that stated that the more perpendicular the rib to the longitudinal axis, the higher the bond strength. Losberg and Olsson [9] also tested specimens with different rib bar spacing, it was found that split strength was not being affected by the rib spacing and concluded that the bond strength decreases when rib spacing is becoming closer than two-third of the nominal diameter. Soretz and Holzenbein [7] investigated into random combination of rib height, spacing and transverse rib-inclination. Part of their observation was that the higher the ribs height, the more splitting it initiated; also their observation confirmed that it is not the peak geometry of dimension: rib spacing 7.6 mm of bar diameter and rib height of 0.76 mm bar diameter, that gave best combination of increased bond strength and low splitting as suggested by Losberg and Olsson in [9]. Furthermore, many authors like Clark [2,3], Soretz and Holzenbein [7], Losberg and Olsson [9] and Kimura and Jirsa [10] agreed that at least under some conditions, an increase in relative rib area will increase bond strength. However, Losberg and Olsson [9] opined that under some other conditions, the relative rib area may not have significant effect on bond strength, especially when the ribs are more perpendicular to the longitudinal axis, which implies that the effect of the relative rib area is relatively insignificant.

In addition, Darwin and Graham [1] researched into the effect of deformation height and spacing on bond strength of reinforcement bars; the experimental programme consist of 156 test specimens. Some of their submissions agreed with some past work and they also concluded that the bond load-slip response of tested rebars was a function of relative rib area, and independent of the specific combination of rib spacing and height; they further established that the increase in bond strength is proportional to increase in relative rib area, which is contrary to the assertion in the work of Losberg and Olsson [9]. Regarding the work of Hamad [11], who studied the effects of rib spacing ranging from 35 to 65% of rebar diameter, rib height of 5 and 12.5% of the diameter and 30° and 90° of rib inclination angle, he submitted that the best in terms of bond strength quality was the rib inclination of 60°, rib spacing of 50% and rib height of 10% of the reinforcement diameter. Lorrain, et al., [12] evaluated some factors that influenced geometric properties of the bar on bond strength through pull-out test. It was resolved in the work that rib inclination and rib face angle did not significantly affect the bonding performance, for the combination of rib height ranging from 0.64 to 0.97, rib spacing of 7.25 to 9.12, transverse-rib flank inclination angle of 146° to 159° and rib inclination from 50° to 59° of all tested specimens. Also rib height and rib spacing were found to be the most influential parameters for bond performance.

In this work, the surface geometry and physical properties of the steel bars for the reinforcement of concrete were evaluated in accordance with local and international standards but not on bond strength from a pull-out test. Reinforcement rods of 12 mm diameter of all available brands in Nigeria were intended to be used for this research work. In few cases where 12 mm diameter rods were not available locally (in the market or produced by a particular company), other diameters were utilized. Standard specifications were adapted for each brand according to the dimension of the diameters.

2. Materials and methods

The reinforcement steel rods utilized for the experiment consists of 29 samples including local and imported categories and analysed using varied standard documents [13–15]. These three standard specifications were chosen to examine the compliance of steel brands available in Nigeria with both local and international standards.

Plate 1 shows the selected rebars for this study. The full lengths of the 15 rods of each brand were measured using a tape rule (Crocodile Best Quality 7.5 m of model SX200), after which their averages were computed. The nominal diameters were measured with the aid of digital electronic caliper (Mitutoyo of Stainless steel and hardened, model DXC 5342); the cross-sectional areas of the rods were thus calculated from diameter obtained. In calculating the mass per length, the mass of each rod was first measured with a

Plate 1. Physical Brand pictures of all the selected steel rods with identification mark.

digital weighing balance (Camry digital weighing balance: model ACS-30-ZC41) having the maximum and minimum readings of 30 kg and 200 g respectively. The length was measured using the tape rule and average masses were then divided by the corresponding average length measured for each mass.

The ribbed heights (a) were also measured with the aid of digital electronic caliper. The average heights of the ribs were determined as the mean value of measurements made at the centers of not less than three typical transverse ribs for each row of the ribs as specified by those standards. The height of the rib was computed by dividing the difference of nominal diameter and total height of

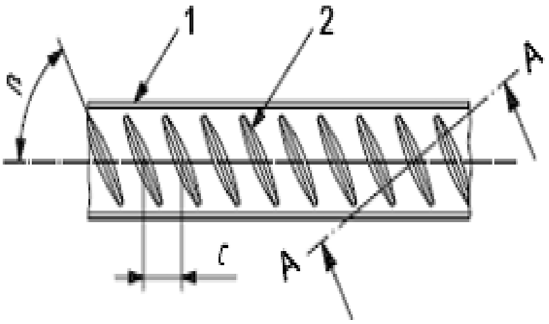

Fig. 1. Ribbed bar – Definition of geometry [15].
Key: 1–longitudinal rib, 2–transverse rib, β – the angle between the axis of transverse rib and bar axis, C – transverse rib spacing, A–A – section of the bar detailed.

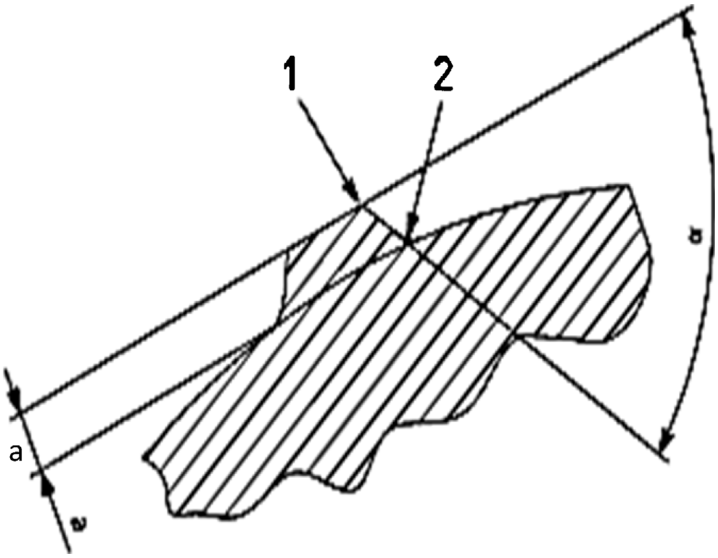

Fig. 2. Section A–A of the Rib flank inclination, α and rib height, a [15].
Key: 1–rib, 2–rounded transition, a – maximum height of the transverse rib, α – transverse rib flank inclination.

the rib by 2. The ribbed bars used for this research have both transverse and longitudinal ribs. The definition of geometry of the ribbed bar and section A–A of the rib flank inclination and rib height are indicated as shown in Fig. 1 and Fig. 2 respectively.

The rib spacing (c) was determined by the average spacing of transverse ribs by dividing the distance between centers of at least eleven ribs on any one side of the bar by the number of intervening intervals as stated by the standards. The spacing is measured with the aid of stainless meter ruler (model ZWY 201). Transverse inclination angle (β) was measured by HP bevel protractor (Model No 5001); average of eleven transverse inclination angles were thus computed. Rib flank inclination (α) was calculated using approximation method while first assuming that rib is triangular in nature. The rib base width was then measured with the aid of digital electronic caliper.

According to Lutz et al., [16] the rib inclination angle can be calculated by arc tangent of average height over half of the average base width of the ribs.

According to EURO [17] the relative rib area is defined by the following expression in Eq. (1):

$$f_R = \frac{1}{\pi d}\sum_{i=1}^{n}\frac{\frac{1}{m}\sum_{j=1}^{m} F_{R,i,j}\sin\beta_{i,j}}{C_i} + \frac{1}{p}\sum_{k=i}^{q} a'_k \tag{1}$$

where n = number of rows of transverse ribs on the circumference, m = number of different transverse rib inclinations per row, q = number of longitudinal ribs for cold-twisted bar. According to Darwin and Graham [1], the relative rib area, R_r, can also be computed from Eq. (2) as:

$$R_r = \frac{projected\ \ rib\ \ area\ \ normal\ \ to\ \ bar\ \ axis}{nominal\ \ bar\ \ perimeter \times center - to - center\ \ ribs\ \ pacing(c)} \tag{2}$$

Eq. (2) was used in this study to determine relative rib area of samples selected. The projected rib area normal to the bar axis can be calculated using half of π (Pi) multiplied by products of ‘a’, and ‘b’, where, a, is base width and b is the height of the rib [3]. The nominal bar perimeter = $2 * \pi r$ (r is the radius of the bar in question).

3. Results and discussion

The summary of standard specifications for surface geometries and physical properties of hot deformed worked steel rods is shown in Table A1 in the Appendix A. Table A2 in Appendix A shows the compliance of designated rebar brands with selected three standards in terms of surface geometries and physical properties. It can be observed from Table A2 in Appendix A, that Brands 6A, 7, 8 and 16 conformed to NIS 117:2004, ISO 6935-2:2007 and BS 4449:2004 specified standards, in average length, among all the Brands; Brand 10 did not comply with any of the standards because its average length exceeded the required specification requirement for length ranges from 12 to 12.05 m while that of ISO and BS are between 12 and 12.10 m [13]. This non-compliance may be attributed to poor quality control management of products from the manufacturers.

However, with the average diameter (Table A2), none of the steel Brands meets the specification, since there is none within the permissible range of deviation specified by the selected standards. It can be seen from the table that among 24 samples that are meant to be 12 mm in diameter, the steel rods ranged in diameter from 9.90 to 11.80 mm (58.3% of samples fall between 11 and 11.80 mm while 41.7% exist between 9.90 and 11.00 mm) (Table A2). There were three samples for the 16 mm steel rods with diameters ranging from 13.00 to 15.00 mm. The only steel rod that was specified to be 20.00 mm in diameter was measured at 18.50 mm. In the same vein, the steel rod that was expected to be 25.00 mm in diameter was measured to be 23.40 mm.

The nominal cross-sectional area for the 12, 16, 20 and 25 mm reinforcement steel rods are 113.14, 210.14, 314.29 and 491.07 mm^2 respectively, according to the NIS 117:2004, ISO 6935-2:2007 and BS 4449:2004 standards. It was observed that only NIS 117:2004 standard has tolerance specification for cross sectional area, as shown in Table A1. For 12 mm steel rods, the tolerance for cross-section area is 106.69 to 119.59 mm^2, whereas for 16 mm and 20 mm steel rods, the tolerance for cross-sectional areas are supposed to be 185.86–216.43 mm^2 and 284.11–344.46 mm^2 respectively according to NIS 117:2004. It can be concluded from Table A2 that none of the rods that have diameters 12, 16 and 20 mm, comply with the standard. For Brand 23, only steel rod with diameter of 25 mm, falls between the specified tolerances of $393.84 - 588.30\ \text{mm}^2$ and therefore is compliant with NIS 117:2004.

The nominal mass per length according to NIS 117:2004, ISO 6935-2:2007 and BS 4449:2004 are 0.888 kg/m, 1.579 kg/m, 2.466 kg/m and 3.854 kg/m for the 12 mm, 16 mm, 20 mm and 25 mm reinforcement steel rods respectively. For 12 mm diameter rods, the permissible deviation (minimum and maximum tolerance values) from nominal mass/length based on NIS 117:2004 and BS 4449:2004 standards is ± 4.5% (i.e. 0.848 and 0.928 kg/m respectively) as shown in Table A2. It was found that only 41.7% of the 12 mm diameter steel samples (which included two imported types i.e. Brands 22 and 24) complied with their permissible deviation based on the NIS 117:2004 and BS 4449:2004; with the ISO 6935-2:2007 standard, the permissible deviation for the 12 mm diameter rods is ± 6% (i.e. 0.835 and 0.941 kg/m for the minimum and maximum tolerance values respectively), about 41.7% of the samples agreed with this standard. In addition, the minimum and maximum values of permissible deviation for the 16 mm sample are 1.509 kg/m and 1.651 kg/m based on NIS 117:2004 and BS 4449:2004; only Brand 16 out of the 3 samples of 16 mm diameter had full compliance with specified standard. Steel rods having 20 mm diameter (Brand 13B) and 25 mm diameter (Brand 23), did not comply with NIS 117:2004, and BS 4449:2004 range of 2.359 to 2.581 kg/m and 3.677 to 4.023 kg/m respectively. The permissible deviation with ISO 6935-2:2007 for the 16, 20 and 25 mm steel rods are ± 5, ± 5 and ± 4% respectively; among the three (3) Brands of 16 mm diameter, only Brand 16 is in agreement with the permissible minimum and maximum tolerance (1.501 and 1.659 kg/m). However, the 20 and 25 mm diameter steel rods did not comply with the specified deviation ranges of 2.347 to 2.594 kg/m and 3.696 to 4.004 kg/m respectively.

The transverse and longitudinal values of ribs of the different Brands of steel rebars and the permissible deviation from various standards NIS 117:2004, ISO 6935-2:2007 of the rebars in reinforced concrete are also shown in Table A1. As indicated in Table A2, for 12 mm diameter steel rebars to meet compliance standards employed in this research work, the transverse rib height must be: ≥ 0.84 mm (NIS), ≥ 0.6 mm (ISO) and 0.36 mm < rib height < 1.8 mm (BS). In addition, the transverse rib height needed for the 16 mm steel rebars to meet the standards include: ≥ 1.12 mm (NIS), ≥ 0.8 mm (ISO) and BS within range 0.48 mm < rib height < 2.4 mm (BS). It was observed that out of the 24 steel rebars of 12 mm diameter, 37.5% of the samples did not comply with NIS standard, and 20.8% fell below ISO standard, while about 4.1% deviated from BS standard; with the three rebars having 16 mm diameter, Brand 16 did not comply with NIS specification, while Brand 6A and 17 B agreed with NIS, ISO and BS standards. The 20 mm rebar conformed to the BS specification but deviated from the NIS and ISO standards, whereas the 25 mm diameter rebar (Brand 23) is in agreement with the adopted standards (NIS, ISO and BS).

The average transverse-rib inclination is shown in Table A2. The transverse-rib inclination angle (β°) is either $\beta^\circ \geq 45^\circ$ or $\beta^\circ \geq 60^\circ$ for NIS specification, $35^\circ \leq \beta^\circ \leq 90^\circ$ for ISO standard, and $35^\circ \leq \beta^\circ \leq 75^\circ$ for the BS standard. It was deduced from Table A1, that about 62.5% and 8.3% of the 12 mm steel rebars are within acceptable limits of $\beta^\circ \geq 45^\circ$ and $\beta^\circ \geq 60^\circ$ respectively, for the NIS standard; with the ISO standard, about 70.8% of 12 mm rebars were found to be within acceptable limits. Concerning the 16 mm rebar, Brand 6A was found to meet the two conditions from NIS standard whereas Brands 13A and 23 complied with NIS standard at $\beta^\circ \geq 60^\circ$; for the ISO standard, Brand 6A among the three (3) Brands with 16 mm diameter, was not within the acceptable limits. The 20 and 25 mm diameters were within the required range of ISO specification. Similar pattern of results found with ISO standard, were observed when the steel rebars were compared with the BS standard.

The transverse-rib spacing (c) is either c ≤ 8.8 mm for spacing greater than 45° or c ≤ 7.2 mm for transverse-rib spacing greater than 60° for the 12 mm steel rebar using the NIS standard. Among the 12 mm samples, 50% conform to c ≤ 8.8 while 4.2% comply with c ≤ 7.2. For the ISO standard, 37.5% of the 12 mm diameter exist within the allowable limits while all the 12 mm samples conform to the BS standard; with the 16 mm steel rebar, c ≤ 11.7 mm or c ≤ 9.6 mm for transverse-rib spacing greater than 45° or 60° respectively for NIS standard. Only Brand 16 of the 16 mm rod, was found to fall within the tolerance limits of both c ≤ 11.7 and c ≤ 9.6 mm (NIS) and 8 ≤ c ≤ 11.2 mm of the ISO standard. All the 16 mm rebars exist within the limits for the BS standard. The 20 mm diameter rebar made the allowable tolerance limits with BS standard but failed to comply with NIS and ISO standards (Table A1). The 25 mm sample complied with NIS specification (c ≤ 14.6 mm) and also fell within tolerable limits of BS standard (10 ≤ c ≤ 30) as shown in Table A1.

Specified tolerance limits exist for the BS and ISO as BS ≥ 45° and ISO ≥ 45° for all diameters for the average transverse-rib flank inclination (α°). With the 12 mm sample, 25% of the samples conform to both BS and ISO standards while for 16 mm steel bars, only Brand 19 among the three (3) Brands conformed to BS and ISO standards. Both the 20 mm and 25 mm steel rods failed to meet the terms of the two standards (BS and ISO).

Out of the three standards employed in this research, only BS 4449:2005 has specification for transverse-relative rib area for steel bars needed for the reinforcement of concrete. For the 12 mm rebars, 70.8% fulfilled the requirement specification, while only Brand 17 B complied with BS standard. Steel bar Brands of 20 mm and 25 mm diameters failed to satisfy the BS condition for transverse-relative rib area as shown in Table A1.

The longitudinal rib height surface geometry requirements for hot deformed bars are only being specified by NIS and BS standards and not the ISO standard as shown in Table A1. For the 12 mm diameter steel bar, 45.8% of the samples complied with NIS requirement of rib height ≥ 1.2, while 58.3% complied with BS standard of rib height ≤ 1.2. Brand 6A and 17B agreed with tolerance limits while Brand 16 did not exist within the limits with NIS standard for the 16 mm diameter steel bars. However, for BS specification, only Brand 16 complied while Brand 6A and 17B did not meet limits of BS standard. Brand 13B having diameter of 20 mm exist within the tolerance limit of NIS specification but not with BS, whereas Brand 23 (25 mm diameter) complied favourably with BS standard but deviated from NIS requirement. Both BS and ISO specifications stated clearly, that it is not compulsory for steel bars to have longitudinal ribs.

From Table A2, only NIS has standard for longitudinal rib base width. The width is preferred if it is wider, because it will assist in sharing or distribution of stresses and in torsional force resistance of the rebars [18]. There was 100% compliance with longitudinal rib base width ≥ 1.2, for the 12 mm diameter rebar. Concerning the 16 mm steel bar, all the three Brand samples complied with the requirement of ≥ 1.6. The 20 mm diameter also met the NIS standard requirement of ≥2.0. In this category of longitudinal rib base width, only 25 mm rebar conformed to NIS standard.

4. Conclusions

Evaluation of surface geometries and physical properties of locally-rolled steel rods made from billets that were produced from locally-sourced scraps, two locally-rolled steel rods from imported billets and three available imported (Ukrainian, Brazilian and Turkish) rebars in Nigeria was carried out. The results obtained from tests conducted on the adopted Brands were compared with the NIS 117:2004 (local) and BS 4449:2005 and ISO 6935-2: 2007 (international) standards. The following were deduced:

- None of the selected brands was found to comply with the three standards (NIS, ISO and BS) in terms of the diameter and cross section area.
- Ordinary locally-rolled rods of Brands 7, 10, 16 and 18 were the best in terms of conformity. Among the TMT brands, Brand 6 B gave the best performance.
- The two selected rods, Brands 20 B and 21 that are locally-rolled from imported billets performed excellently well by meeting four (4) of the specifications in surface geometries and physical properties.
- Among the imported steel rods, Brand 24 gave the best performance in specifications based on the surface geometries and physical properties.

Acknowledgments

The first author is grateful to Professor Adekoya L. O. of Department of Mechanical Engineering, Obafemi Awolowo University, Ile-Ife, Osun State and Professor Loto C. A. of Department of Mechanical Engineering, Covenant University, Ota, Ogun State, who were his Ph.D supervisors. He also wishes to thank the Management of Covenant University for providing platform for his Ph.D and financial support during his Ph.D programme.

Appendix A

Table A1
Summary of standard specifications for surface geometries and physical properties of the hot deformed worked steel bars.

Nominal Diameter	Average Full Length (m)	Actual Average Diameter (mm)	Actual Average Cross-Sectional Area (mm^2)	Actual Average Mass/Length (Kg/m)	Transverse Rib					Longitudinal Rib	
					Average Rib Height (mm)	Average Transverse-rib inclination (β^0)	Average Rib Spacing (c) (mm)	Average Transverse-rib flank inclination (α^0)	Average Relative Rib Area	Average Height (mm)	Average Rib Base Width (mm)
12 mm	NIS^{+50mm}_{-0mm} ISO^{+100mm}_{0mm} BS^{+100mm}_{0mm}	No permissible deviation given	NIS ± 5.7% ISO ± nill BS ± nill	NIS ± 4.5% ISO ± 6% BS ± 4.5%	NIS ≥ 0.84 ISO ≥ 0.6 BS: 0.36–1.8	NIS: 45° or 60^0 ISO: $35° \leq \beta \leq 90°$ BS: $35° \leq \beta \leq 75°$	NIS: c ≤ 8.8 or c ≤ 7.2 ISO: 6 ≤ c ≤ 8.4 BS: 4.8 ≤ c ≤ 14.4	NIS: nill BS ≥ 45° ISO ≥ 45°	NIS: nill ISO: nill BS 0.04	NIS ≥ 1.2 ISO: nill BS ≤ 1.2	NIS ≥ 1.2 ISO: nill BS: nill
16 mm			NIS ± 7.6% ISO ± nill BS ± nill	NIS ± 4.5% ISO ± 5% BS ± 4.5%	NIS ≥ 1.12 ISO ≥ 0.8 BS: 0.48–2.4		NIS: if $\beta° \geq 45° \therefore c \leq$- 8.8 or if $\beta° \geq 60° \therefore c \leq$- 7.5 ISO: 8 ≤ c ≤ 11.2 BS: 6.4 ≤ c ≤ 19.2		NIS: nill ISO: nill BS: 0.056	NIS ≥ 1.6 ISO: nill BS ≤ 1.6	NIS ≥ 1.6 ISO: nill BS: nill
20 mm			NIS ± 9.6% ISO ± nill BS ± nill	NIS ± 4.5% ISO ± 5% BS ± 4.5%	NIS ≥ 1.40 ISO ≥ 1 BS:0.6–3		NIS: c ≤ 14.6 or c ≤ 12.0 ISO: 10 ≤ c ≤ 14 BS: 8 ≤ c ≤ 24		NIS: nill ISO: nill BS: 0.056	NIS ≥ 2.0 ISO: nill BS ≤ 2.0	NIS ≥ 2.0 ISO: nill BS: nill
25 mm			NIS ± 19.8% ISO ± nill BS ± nill	NIS ± 4.5% ISO ± 4% BS ± 4.5%	NIS ≥ 1.75 ISO ≥ 1.5 BS: 0.75–3.75		NIS: c ≤ 18.3 or c ≤ 15.0 ISO: 12.5 ≤ c ≤ 17.5 BS: 10 ≤ c ≤ 30		NIS: nill ISO: nill BS: 0.056	NIS ≥ 2.5 ISO: nill BS ≤ 2.5	NIS ≥ 2.5 ISO: nill BS: nill

Notes: NIS = NIS 117: 2004 (Specification for Steel Bars for Reinforcement of Concrete), ISO = ISO 6935-2:2007 (Steel for the Reinforcement of Concrete, Part 2: Ribbed Bars. International Standard Organization), BS = BS 4449:2005 (Steel for the reinforcement of concrete − weldable reinforcing steel bar, coil and de-coiled product Specification).

Table A2
Compliance of designated rebar brands with selected three standards in terms of surface geometries and physical properties.

Brand Category	Structural Name	Average Full Length (m)	Actual Average Diameter (mm)	Actual Average Cross-Sectional Area (mm^2)	Actual Average Mass/Length (Kg/m)	Transverse Rib					Longitudinal Rib	
						Average Rib Height (mm)	Average Transverse-rib inclination (β^0)	Average Rib Spacing (c) (mm)	Average Transverse-rib flank inclination (α^0)	Average Relative Rib Area	Average Height (mm)	Average Rib Base Width (mm)
Ordinary steels												
Brand 1	Y12	11.67 (NC, NC, NC)	10.30 (NC, NC, NC)	83.36 (NC, NA, NA)	0.723 (NC, NC, NC)	0.85 (C, C, C)	55.1 (C, C, C)	10.2 (NC, NC, C)	40.3 (NA, NC, NC)	0.042 (NA, NA, C)	1.45 (C, NA, NC)	2.75 (C, NA, NA)
Brand 2	Y12	11.62 (NC, NC, NC)	10.50 (NC, NC, NC)	86.63 (NC, NA, NA)	0.781 (NC, NC, NC)	0.55 (NC, NC, C)	51.5 (C, C, C)	7.5 (C, C, C)	31.4 (NA, NC, NC)	0.037 (NA, NA, NA)	0.90 (NC, NA, C)	3.00 (C, NA, NA)
Brand 3	Y12	11.63 (NC, NC, NC)	10.50 (NC, NC, NC)	86.63 (NC, NA, NA)	0.748 (NC, NC, NC)	0.55 (NC, NC, C)	30.0 (NC, NC, NC)	13.6 (NC, NC, C)	28.8 (NA, NC, NC)	0.020 (NA, NA, NA)	1.00 (NC, NA, C)	1.50 (C, NA, NA)
Brand 4	Y12	11.95 (NC, NC, NC)	10.75 (NC, NC, NC)	90.80 (NC, NA, NA)	0.786 (NC, NC, NC)	0.73 (NC, C, C)	45.0 (C, C, C)	8.0 (C, C, C)	44.0 (NA, NC, NC)	0.045 (NA, NA, C)	0.95 (NC, NA, C)	1.40 (C, NA, NA)
Brand 5	Y12	11.95 (NC, NC, NC)	11.00 (NC, NC, NC)	95.07 (NC, NA, NA)	0.861 (C, C, C)	1.00 (C, C, C)	43.0 (NC, C, C)	12.4 (NC, NC, C)	38.6 (NA, NC, NC)	0.040 (NA, NA, C)	1.95 (C, NA, NC)	3.00 (C, NA, NA)
Brand 6A	Y16	12.05 (C, C, C)	13.00 (NC, NC, NC)	132.79 (NC, NA, NA)	1.269 (NC, NC, NC)	1.35 (C, C, C)	33.0 (NC, NC, NC)	13.4 (NC, NC, C)	42.0 (NA, NC, NC)	0.050 (NA, NA, NA)	3.90 (C, NA, NC)	2.55 (C, NA, NA)
Brand 7	Y12	12.02 (C, C, C)	10.50 (NC, NC, NC)	86.63 (NC, NA, NA)	0.794 (NC, NC, NC)	1.75 (C, C, C)	57.0 (C, C, C)	8.5 (NC, NC, C)	49.4 (NA, C, C)	0.103 (NA, NA, NA)	3.50 (C, NA, NC)	2.00 (C, NA, NA)
Brand 8	Y12	12.00 (C, C, C)	11.60 (NC, NC, NC)	105.73 (NC, NA, NA)	0.862 (C, C, C)	0.45 (NC, NC, C)	28.0 (NC, NC, NC)	12.9 (NC, NC, C)	24.2 (NA, NC, NC)	0.017 (NA, NA, NA)	0.40 (NC, NA, C)	2.60 (C, NA, NA)
Brand 9	Y12	11.70 (NC, NC, NC)	10.00 (NC, NC, NC)	78.57 (NC, NA, NA)	0.788 (NC, NC, NC)	1.50 (C, C, C)	30.0 (NC, NC, NC)	12.0 (NC, NC, C)	63.4 (NA, C, C)	0.063 (NA, NA, C)	2.80 (C, NA, NC)	2.00 (C, NA, NA)
Brand 10	Y12	12.22 (NC, NC, NC)	10.60 (NC, NC, NC)	88.28 (NC, NA, NA)	0.829 (NC, NC, NC)	1.10 (C, C, C)	51.0 (C, C, C)	7.6 (C, C, C)	47.7 (NA, C, C)	0.072 (NA, NA, C)	0.90 (NC, NA, C)	2.65 (C, NA, NA)
Brand 11A	Y12	11.92 (NC, NC, NC)	11.00 (NC, NC, NC)	95.07 (NC, NA, NA)	0.746 (NC, NC, NC)	0.50 (NC, NC, C)	30.0 (NC, NC, NC)	13.0 (NC, NC, C)	26.6 (NA, NC, NC)	0.019 (NA, NA, NA)	0.00 (NC, NA, C)	1.35 (C, NA, NA)
Brand 12	Y12	11.92 (NC, NC, NC)	10.00 (NC, NC, NC)	78.57 (NC, NA, NA)	0.707 (NC, NC, NC)	0.90 (C, C, C)	30.0 (NC, NC, NC)	10.1 (NC, NC, C)	38.0 (NA, NC, NC)	0.045 (NA, NA, C)	1.40 (C, NA, NC)	2.20 (C, NA, NA)
Brand 13A	Y12	11.99 (NC, NC, NC)	11.00 (NC, NC, NC)	95.07 (NC, NA, NA)	0.728 (NC, NC, NC)	1.00 (C, C, C)	50.0 (C, C, C)	11.1 (NC, NC, C)	45.0 (NA, C, C)	0.045 (NA, NA, C)	0.10 (NC, NA, C)	2.15 (C, NA, NA)
Brand 14	Y12	11.90 (NC, NC, NC)	11.50 (NC, NC, NC)	103.91 (NC, NA, NA)	0.741 (NC, NC, NC)	0.25 (NC, NC, NC)	39.0 (NC, C, NC)	8.0 (NC, C, C)	18.4 (NA, NC, NC)	0.016 (NA, NA, NA)	0.50 (NC, NA, C)	1.40 (C, NA, NA)
Brand 15	Y12	11.74 (NC, NC, NC)	10.00 (NC, NC, NC)	78.57 (NC, NA, NA)	0.746 (NC, NC, NC)	1.10 (C, C, C)	34.5 (NC, NC, NC)	11.1 (NC, NC, C)	41.3 (NA, NC, NC)	0.050 (NA, NA, C)	3.55 (C, NA, NC)	1.60 (C, NA, NA)
Brand 16	Y16	12.04 (C, C, C)	15.00 (NC, NC, NC)	176.79 (NC, NA, NA)	1.543 (C, C, C)	0.95 (NC, C, C)	67.0 (C, C, C)	9.3 (C, C, C)	28.5 (NA, NC, NC)	0.051 (NA, NA, C)	1.40 (NC, NA, C)	2.05 (C, NA, NA)
Brand 17A	Y12	11.96 (NC, NC, NC)	11.30 (NC, NC, NC)	100.33 (NC, NA, NA)	0.759 (NC, NC, NC)	0.75 (NC, C, C)	54.0 (C, C, C)	7.5 (C, C, C)	36.9 (NA, NC, NC)	0.050 (NA, NA, C)	0.10 (NC, NA, C)	2.90 (C, NA, NA)
Brand 18	Y12	11.97 (NC, NC, NC)	11.00 (NC, NC, NC)	95.07 (NC, NA, NA)	0.861 (C, C, C)	1.00 (C, C, C)	53.0 (C, C, C)	9.0 (NC, NC, C)	33.7 (NA, NC, NC)	0.056 (NA, NA, C)	0.95 (NC, NA, C)	3.10 (C, NA, NA)
Brand 19	Y12	11.97 (NC, NC, NC)	9.90 (NC, NC, NC)	77.01 (NC, NA, NA)	0.717 (NC, NC, NC)	0.95 (C, C, C)	30.0 (NC, NC, NC)	11.4 (NC, NC, C)	28.5 (NA, NC, NC)	0.042 (NA, NA, C)	2.45 (C, NA, NC)	2.10 (C, NA, NA)

(*continued on next page*)

Table A2 (*continued*)

Brand Category	Structural Name	Average Full Length (m)	Actual Average Diameter (mm)	Actual Average Cross-Sectional Area (mm^2)	Actual Average Mass/Length (Kg/m)	Transverse Rib					Longitudinal Rib	
						Average Rib Height (mm)	Average Transverse-rib inclination (β^0)	Average Rib Spacing (c) (mm)	Average Transverse-rib flank inclination (α^0)	Average Relative Rib Area	Average Height (mm)	Average Rib Base Width (mm)
TMT steels												
Brand 6B	Y12	11.96 (NC, NC, NC)	11.80 (NC, NC, NC)	109.40 (NC, NA, NA)	0.869 (C, C, C)	0.85 (C, C, C)	(75.0)(45.0)(75.0) (C, C, C)	(8.8) (14.8)(14.8) (C, NC, C)	40.3 (NA, NC, NC)	0.048 (NA, NA, C)	1.20 (C, NA, C)	2.70 (C, NA, NA)
Brand 11B	Y12	11.89 (NC, NC, NC)	11.50 (NC, NC, NC)	103.91 (NC, NA, NA)	0.862 (C, C, C)	0.75 (NC, C, C)	76.5 (C, C, C)	11.0 (NC, NC, C)	39.8 (NA, NC, NC)	0.034 (NA, NA, NA)	0.90 (NC, NA, C)	2.05 (C, NA, NA)
Brand 13B	Y20	11.97 (NC, NC, NC)	18.50 (NC, NC, NC)	268.91 (NC, NA, NA)	2.264 (NC, NC, NC)	0.75 (NC, NC, C)	51.5 (C, C, C)	14.7 (NC, NC, C)	31.0 (NA, NC, NC)	0.026 (NA, NA, NA)	2.20 (C, NA, NC)	2.00 (C, NA, NA)
Brand 20A	Y12	11.93 (NC, NC, NC)	11.00 (NC, NC, NC)	95.07 (NC, NA, NA)	0.850 (C, C, C)	1.00 (NC, C, C)	49.0 (C, C, C)	6.9 (C, C, C)	53.1 (NA, C, C)	0.072 (NA, NA, C)	1.60 (C, NA, NC)	2.00 (C, NA, NA)
Brand 17B	Y16	11.95 (NC, NC, NC)	14.00 (NC, NC, NC)	154.00 (NC, NA, NA)	1.470 (NC, NC, NC)	1.75 (C, C, C)	(53.0)(166.0) (C, C, C)	15.1 (NC, C, C)	49.4 (NA, C, C)	0.058 (NA, NA, C)	1.90 (C, NA, NC)	2.60 (C, NA, NA)
Locally-rolled from imported billets												
Brand 20B	Y12	11.97 (NC, NC, NC)	11.40 (NC, NC, NC)	102.11 (NC, NA, NA)	0.859 (C, C, C)	0.80 (C, C, C)	47.5 (C, C, C)	7.6 (C, C, C)	38.6 (NC, NC, NC)	0.053 (NA, NA, C)	0.25 (NC, NA, C)	2.30 (C, NA, NA)
Brand 21	Y12	11.95 (NC, NC, NC)	11.00 (NC, NC, NC)	95.07 (NC, NA, NA)	0.884 (C, C, C)	1.25 (C, C, C)	(55.9)(56.0)(40.0) (C, C, C)	(8.1)(15.3)(15.3) (C, C, C)	51.3 (NC, C, C)	0.077 (NA, NA, C)	2.30 (C, NA, NC)	2.45 (C, NA, NA)
Imported rebars												
Brand 22	Y12	11.94 (NC, NC, NC)	11.80 (NC, NC, NC)	109.40 (NC, NA, NA)	0.882 (C, C, C)	0.60 (NC, C, C)	61.0 (C, C, C)	8.0 (NC, C, C)	38.6 (NC, NC, NC)	0.038 (NA, NA, NA)	0.50 (NC, NA, C)	1.40 (C, NA, NA)
Brand 23	Y25	11.62 (NC, NC, NC)	23.40 (NC, NC, NC)	430.23 (C, NA, NA)	3.568 (NC, NC, NC)	1.80 (C, C, C)	57.5 (C, C, C)	16.6 (C, C, C)	38.6 (NC, NC, NC)	0.054 (NA, NA, C)	2.40 (C, NA, NC)	2.10 (NC, NA, NA)
Brand 24	Y12	11.89 (NC, NC, NC)	11.30 (NC, NC, NC)	100.33 (NC, NA, NA)	0.896 (C, C, C)	0.95 (C, C, C)	56.0 (C, C, C)	6.3 (C, C, C)	43.5 (NC, NC, NC)	0.075 (NA, NA, C)	1.60 (C, NA, NC)	1.70 (C, NA, NA)

Notes: Abbreviations in the bracket represent as follows: C = Compliant, NC = Not compliant, NA = Not applicable and are in this order (NIS 117: 2004, ISO 6935-2:2007, BS 4449:2005) respectively.

References

[1] D. Darwin, E.K. Graham, Effect of Deformation Height and Spacing on Bond Strength of Reinforcement Bars, (1993).
[2] A.P. Clark, Comparative bond efficiency of deformed concrete reinforcement bars, ACI Struct. J. 43 (1946) 381–400.
[3] A.P. Clark, Bond of concrete reinforcing bars, ACI Struct. J. 46 (1949) 161–184.
[4] G. Rehm, The fundamental law of bond, Symp Bond Crack Form. Reinf. Concr., Tekniska Hogskolans Rotaprinttrychkeri, Stockholm, RILEM Paris, 1957.
[5] G. Rehm, Uber die grunlagen des verbundes zwischen stahl und beton, Dtsch. Ausschuss Fur Stahlbet. (1961) 59.
[6] L.A. Lutz, P. Gergely, Mechanics of bond and slip of deformed bars in concrete, ACI Struct. J. 64 (1967) 711–721.
[7] S. Soretz, H. Holzenbein, Influence of rib dimensions of reinforcing bars on bond and Bendability, ACI Struct. J. 76 (1979) 111–128.
[8] S.M. Skorobogatov, A.D. Edwards, The influence of the geometry of deformed steel bars on their bond strength in concrete, Inst. Civ. Eng, The Institute of Civil Engineers, 1979, 2017, pp. 327–339.
[9] A. Losberg, P.-A. Olsson, Bond failure of deformed reinforcing bars based on the longitudinal splitting effect of the bars, ACI Struct. J. 76 (1979) 5–18.
[10] H. Kimura, J.O. Jirsa, Effects of Bar Deformation and Concrete Strength on Bond of Reinforcing Steel to Concrete, (1992).
[11] B.S. Hamad, Bond strength improvement of reinforcing bars with specially designed rib geometries, ACI Struct. J. 92 (1995) 3–13.
[12] M.S. Lorrain, L.F. Caetano, S.B. Vale, L.E.S. Gomes, M.P. Barbosa, L.C.P. Silva Filho, Bond strength and rib geometry: a comparative study of the influence of deformation patterns on anchorage bond strength, PCI Annu. Conv. 3rd Int. FIB Congr. Washington, DC, 2010, 2010, pp. 4374–4385.
[13] SON, NIS 117:2004, Specification for Steel Bars for the Reinforcement of Concrete, (2004).
[14] BSI, BS 4449:2005, Steel for the Reinforcement of Concrete–Weldable Reinforcing Steel ?Bar, Coil and Decoiled Product–Specification, British Standard, (2005).
[15] ISO, ISO 6935-2:2007, Steel for the Reinforcement of Concrete–Part 2: Ribbed Bars, International Standard, (2007).
[16] L.A. Lutz, P. Gergely, G. Winter, The Mechanics of Bond and Slip of Deformed Reinforced Bars in Concrete, (1966) (Ithaca, N.Y.).
[17] EURO, BS EN ISO 15630-1:2002, Steel for the Reinforcement and Prestressing of Concrete–Test Methods–Part 1: Reinforcing Bars, Wire Rod and Wire, British Standard, (2002).
[18] M. Kokubu, H. Okamura, Use of large-Sized deformed bars in reinforced concrete, J. Fac. Eng. Univ. Tokyo 31 (1972) 87.