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PROPERTIES OF SPINNED STEEL AND BOND WITHIN CONCRETE

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Abstract: Ductility of reinforced concrete sections is of paramount importance in Construction engineering applications, especially in the areas associated with seismic and impact loading. The presented paper aims to evaluate the effectiveness of Spinned steel bars used as reinforcement bars. An experimental program was performed to evaluate the bond strength of these bars within concrete and their ductility, strengths and toughness of Spinned steel bars. Several tests were initially conducted on the Spinned bars (tension, bending and scanning electron microscopy) to assess their properties and present its potential to be used in reinforced concrete elements. The experimental investigation results reveal that Spinned steel bars have higher bond strength with concrete compared to regular steel reinforcement. Nevertheless, Spinned steel bars showed tendency for higher energy absorption, which can suggest its future use in design of structures subjected to dynamic loading.

1 INTRODUCTION

Reinforcement is an essential element for structures that are subjected to tensile stresses, where concrete have a strong resistance to compression, but weak resistance in tension; therefore, reinforced concrete is used as a composite material composed of both steel and concrete to resist both compressive and tensile stresses applied on structures. It is of paramount importance of reinforcement to have a high bond strength interlocking with concrete for the reinforcement to be fully subjected to tensile stresses without slippage from concrete; nevertheless, high resistance to tensile stresses for long lasting durable structures. As ductility is an essential parameter for structures subjected to dynamic actions such as seismic forces, wind and impact, design for such loads have been increasingly dependent on ductility enhancement (Tedesco et al, 1999). In the past years new methods of reinforcements, like prestressed reinforcement, began to arise through the process of twisting reinforced steel strands to obtain higher resistance to loads. As described in the patent presented by (Schmidt, 1940) who first published and presented the idea of twisting two reinforced steel bars together adopted the idea of twisting two bars together in a cold state from iron. Schmidt presented that the strength of rolled iron may be increased through the process of twisting in a cold state. Schmidt also claimed an increase in bonding capacity, accompanied by little or no increase of the elastic limit, and has no practical advantages. However, Schmidt did not mention a range for the number of pitches per unit length. If the number of pitches increased dramatically, it weakens the resistance of the twisted reinforcement to carry a higher load. Unlike what Schmidt stated, this paper presents a different perspective towards the modulus of toughness and ductility with different values that could lead to future benefits and usage. Another patent was presented by Dow and Ellis (2005) in which they discussed the idea of serpentines reinforcement, in which the shape of the reinforcements contained both peaks and troughs: this helped in developing the idea of obtaining pitches. However, they used woven metallic reinforcement not twisted steel bars. Utz (2007) presented the idea of rods crossing one another creating spaces between them; furthermore, he focused on the measurement of angles corresponding to the longitudinal axis from between 20 to 70 degrees, which is expected to grant both a higher resistance to load and shear as well as a higher bond interlocking with concrete. Then, Wright et al (2014) focused on using a spiral strip on top of a rod with flanges and twisting one bar right after the other, and mainly was concerned with the angles of the pitches created. On the other hand, Boguslavschi et al. (2016) focused on twisting one bar on itself as a single element claiming that it increases both bond with concrete as well as its increase in load resistance; however, the effect on ductility was not discussed within that patent which was also the case with Schmidt (1940). As both patents claimed that twisting reinforced steel bars enhanced its mechanical properties granting a higher resistance to load and bond interlocking with concrete due to the deformed shape that resulted from the process of twisting the bars. Meanwhile, these patents did not examine the effect of the process of twisting reinforcing bars on the overall ductility and the modulus of toughness of the twisted steel bars; the need to research these effects and their possible applications have emerged.

2 RESEARCH SIGNIFICANCE

On the other hand, enhancing ductility of steel has been subject to recent studies. One of the recent innovations was by Yamasaki (2017) who produced high-strength steel rods with high ductility through altering the chemical components of the steel alloy itself. A very similar approach was performed by Tian et al (2014) where in addition to changing the chemical composition of the steel, a re-crystalized ultra-fine grain structure was developed. Although this line of research is very common in literature, it is extremely expensive in practice as changing the chemical composition of steel at new temperatures needs innovations in the steel production industry itself, which is for sure not as economic as the regular readily available steels; hence, the efforts of these researchers cannot directly affect the construction industry at least on the short-run. On the other hand, the ductility enhancement of reinforced concrete members has been increasingly researched by members of the academic community in the field of structural engineering. Numerous researchers like (El Maghraby et al, 2010), (Meng and Elkhayat, 2016) and (Nguyen et al, 2013) have worked on using fiber reinforced polymers (FRP) within the reinforced concrete to enhance ductility. However, this approach significantly increases the cost as FRP is more expensive than steel. Hence, the ductility enhancement alternative that could be more feasible when compared to changing the steel microstructure and using FRP is spinning the steel; however, this expected effect of ductility enhancement has not been directly studied by researchers who worked on the spinned steel so far. That gap in research triggered the idea discussed in this paper of twisting two 10 mm reinforced steel bars on one another using the power lathe; through analyzing their characteristics, we could know their future potential use as a different method of reinforcement inside of concrete sections focusing on its effect on ductility and toughness. Twisting the two reinforced steel bars on one another creates pitches because of twisting. Three important concepts encouraged examining the concept of ductility of twisted reinforcement. The first concept is mainly concerned with a higher strain value. Since an additional length is required to spine the bar, the strain becomes larger since change in length of the bar increases; so, dividing the change in length by the original length of the twisted bar will result in obtaining a higher strain value. The second concept is concerned with the tendency of the twisted bar itself, when subjected to high tension, to deform to its original straight form, which will cause an additional strain inducing a pre-strain condition. Hence, the strain does not start from zero rather from a value before which increases the max strain value as well. Finally, the third and most important concept of ductility is mainly focused on the twisted bar being pre-stressed; the yielding point is expected to be achieved a bit earlier while the point at fracture is expected to occur at higher strains; so dividing the value of deformation at the point of fracture by the deformation value at yielding point, the ductility value will be higher. Accordingly, this paper focuses on studying the characteristics of spinned steel bars through performing several tests. First, microscopic tests to examine the microstructure of the spinned steel before loading were performed. Second, destructive tests were performed on the spinned steel bars themselves to study their mechanical properties and compare them to those of straight steel bars. Finally, bond test was performed to examine the interaction between the spinned steel and its surrounding concrete.

3 EXPERIMENTATION

3.1 Procedure of Twisting

The procedure is carried out by aligning two steel bars and welding their tips together from both ends to avoid their separation. Following on that, they are fixed from one end and the other end is inserted in the rotating shaft of the power lathe while the twisting process takes place as shown in Figure 1. The number of spines or pitches is controlled by the number of rotations performed by the power lathe and by stopwatch time to maintain the intended number of pitches per meter. The following number of pitches discussed in this study is 11 pitches per meter. To avoid the occurrence of cracks during the twisting process, a speed of approximately 120 rpm was obtained during the twisting process.

Figure 1: Twisting the bars using the power lathe

It is worth to note that to obtain 1 m of spinned steel, an additional length of 30 mm of each bar was acquired as the twisting process decreased some of the original length of the two bars taking a total of 60 mm additional length from the two bars twisted on one another. Knowing the exact length, volume of spinned steel samples was calculated by multiplying it to the unit weight of steel to obtain weights of steel. Then, equating the weight of spinned steel to the weight of the straight steel that is desired to obtain the cross sectional area, and solving for the diameter, which is 14 mm. That means that two 10 mm spinned steel bars are equivalent to one 14 mm straight bar in terms of weight.

3.2 Testing Program

Since the idea of using the spinned steel inside concrete section is still non- orthodox, so it was necessary to conduct some conceptual experimental work to ensure that the idea under study would be promising. Hence, two tests were conducted. The first test is the Scanning Electron Microscopy Test (SEM) and the second one is the direct tension test. The first test was conducted to make sure that during spinning the two steel bars together, there were no sizeable cracks developed and the steel was not damaged. Secondly, the tension test was conducted to examine the characteristics of the spinned steel and to determine how the new characteristics could be beneficial. Following on that bending test was performed to assure the ductility of the spinned steel and no visual cracks developed from bending. Finally, Spinned steel bond testing was performed to examine its behavior within the reinforced concrete section itself.

3.2.1 Scanning Electron Microscopy (SEM) Test

The SEM test enables viewing the internal stratification within a material at different microscopic scales. This test was performed according to ASTM E2142 – 08 (2015) to assure that no damageable cracks occurred during spinning process are of a size that constitute any danger to the reinforcement. Figure 2, Figure 3 and Figure 4 represent the surface within the spinned steel at different microscopic altitudes. Figure 2 shows the spinned steel at a microscopic altitude of 200 micrometers with no obvious cracks at all at that scale. Also, Figure 3 shows the microscopic altitude at 20 micrometers with no obvious cracks at all at that scale. On the other hand, Figure 4 shows the microscopic altitude at 10 micrometers in which two cracks have appeared that are circled in Figure 4. That means that one of these two circled cracks has a size of approximately 20 micrometers while the other one has a size of approximately 15 micrometers. Hence, it is safe to say that because these cracks are very small, their damage is minor and so are considered non-damageable and of a negligible size. Consequently, the spinning process could be considered as a non-crack-inducing process that does not induce any cracks in the steel.

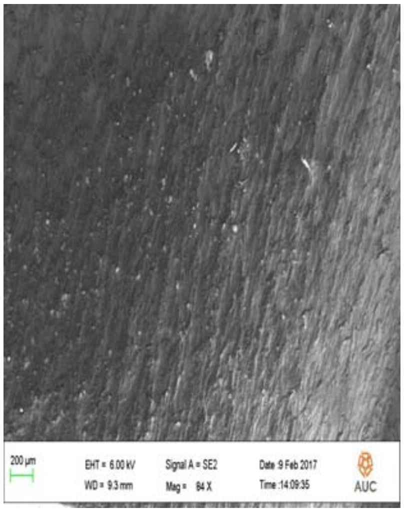

Figure 2: The spinned steel at a microscopic altitude of 200 micrometers.

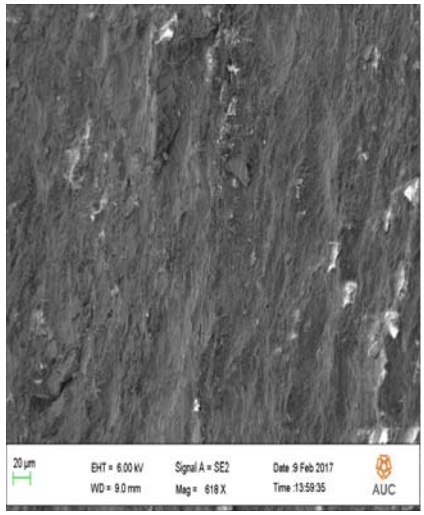

Figure 3: The spinned steel at a microscopic altitude of 20 micrometers.

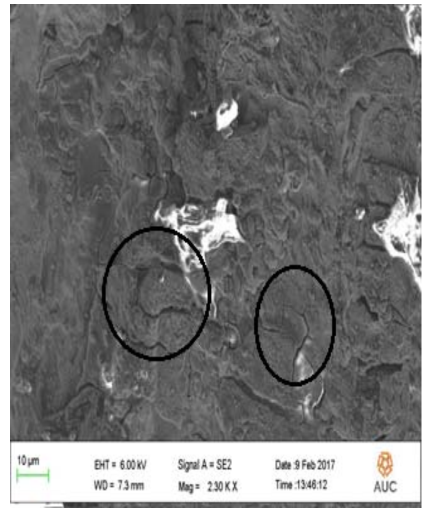

Figure 4: The spinned steel at a microscopic altitude of 10 micrometers.

3.2.2 Tension Test

Direct tension test was performed according to ASTM A370-17 on a control set of three specimens of straight bars of a 10 mm diameter and on another two sets of three spinned steel specimens of different spins per meter (11,17) within each of them two 10 mm bars were spinned together. As eleven spins per meter was to be better number of spins in terms of (load, ductility and energy absorption). The tension test results are presented in Figure 5 and Figure 6 and Figure 7

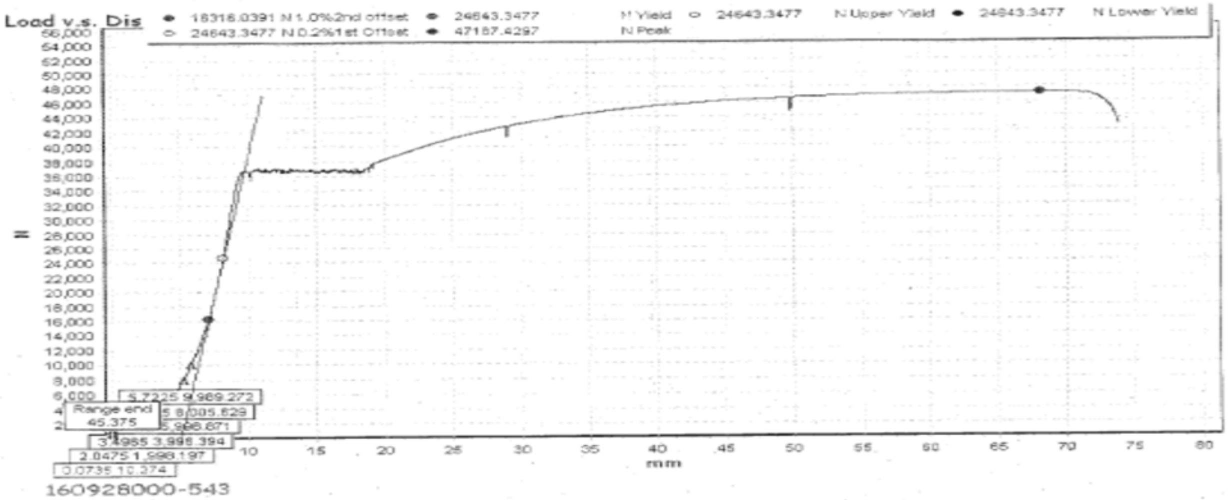

Figure 5 :Load – deflection curve for a straight bar specimen 10 mm

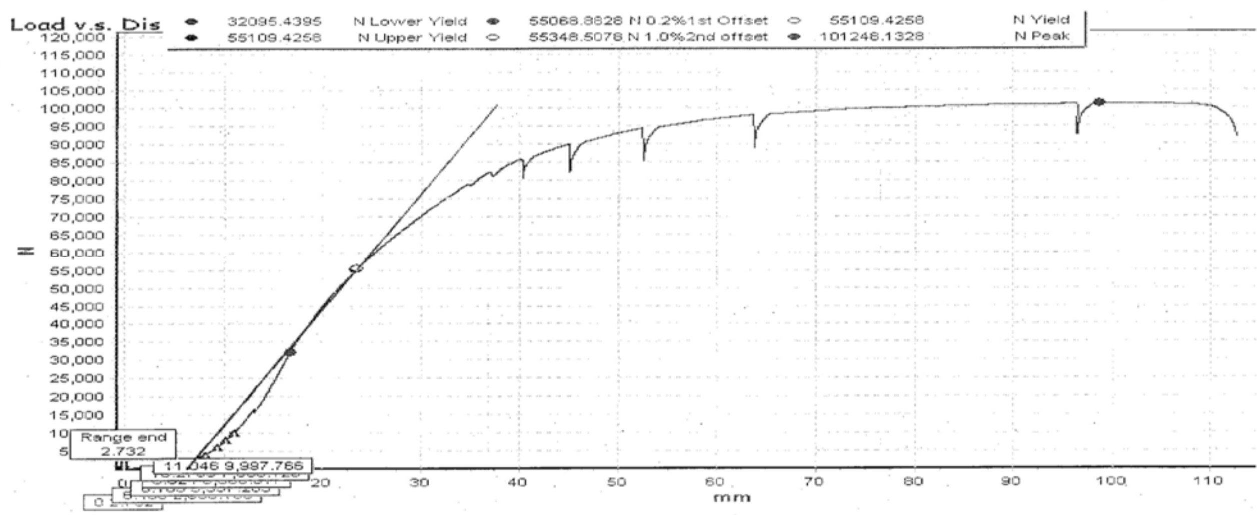

Figure 6: Load – deflection curve for a spinned specimen 11 spins per meter

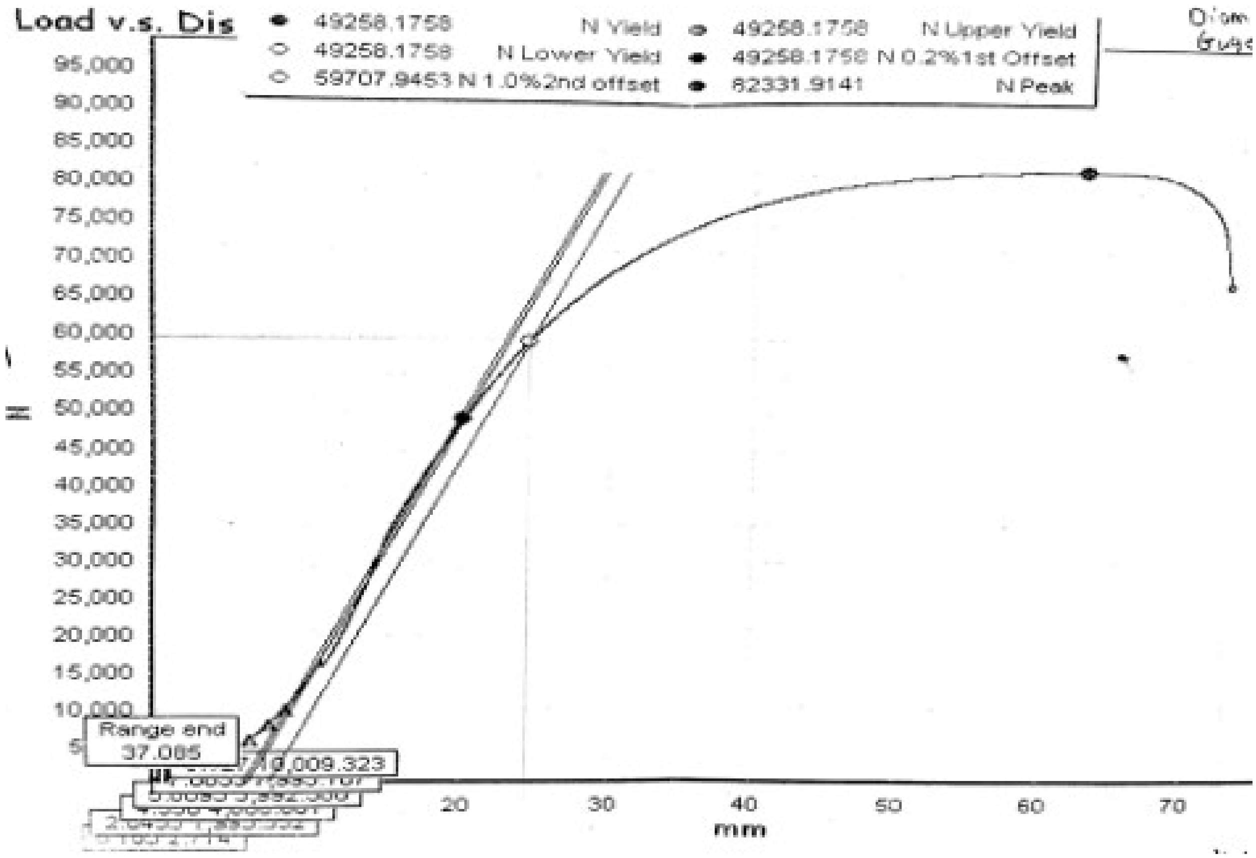

Figure 7: Load – deflection curve for a spinned specimen 17 spins per meter

The ultimate load that the straight bar specimen withstood was 47167 N while that of the a spinned bar specimen with 11 spins per meter was 101246 N. Hence, the ultimate load of the two spinned bars is higher than that of a straight bar, and the 11 spins per meter was higher than that of the 17 spins per meter; however, the real obvious change is in the elongation as the elongation if two straight conventional bars will still remain the same as that of one straight bar which was 74 mm while the elongation of the two spinned bars reached 112 mm which is significantly larger than what two straight bars would achieve together. That means that spinning the bars have significantly enhanced their ductility and the energy absorbed by the bars till failure (represented by the area beneath the curve) has been significantly increased, which can be explained more in Stress – Strain Curves of Figure 8 and Figure 9.

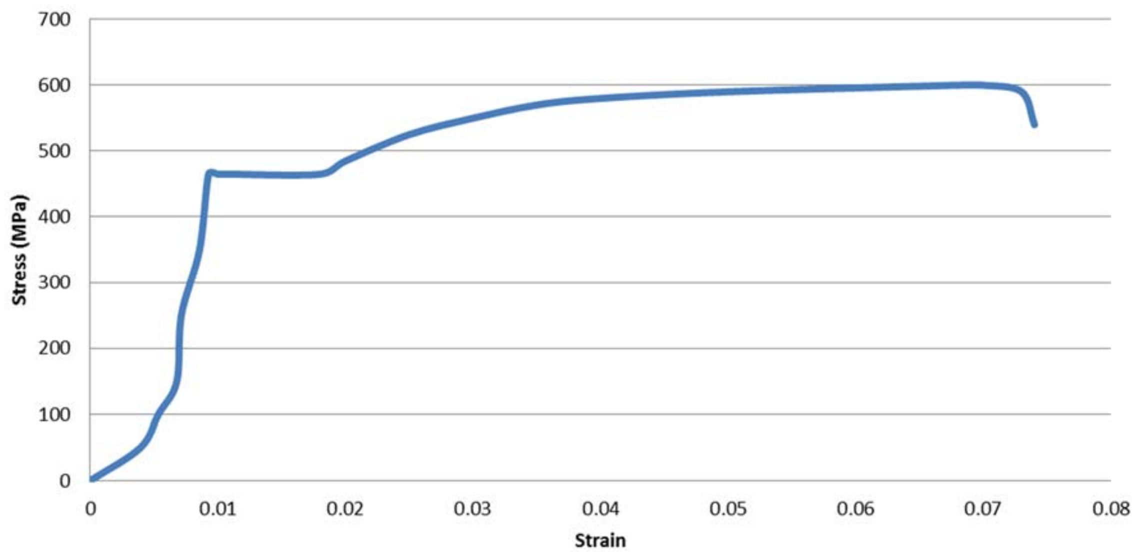

Figure 8: Stress – strain curve for a straight bar specimen

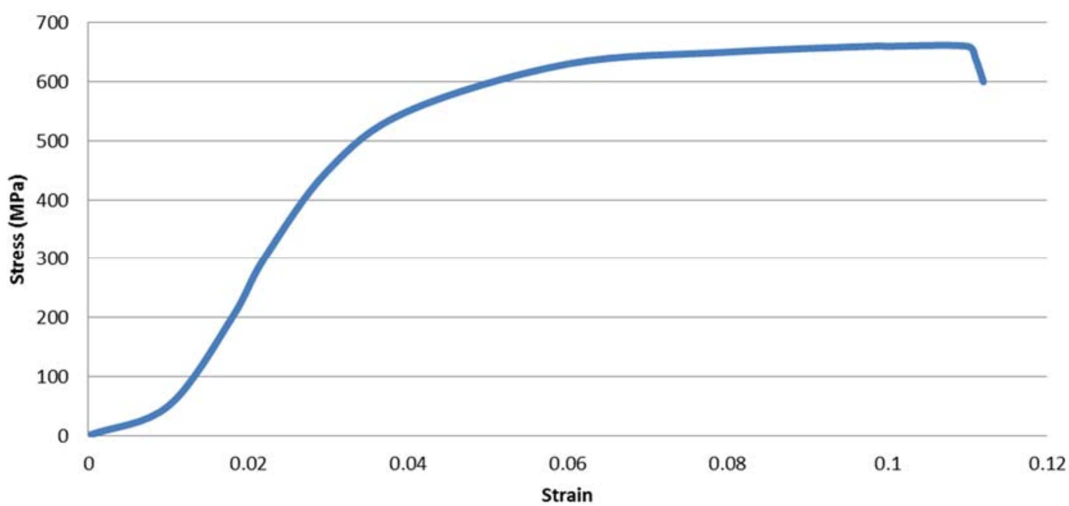

Figure 9: Stress – strain curve for a spinned specimen of 11 spins per meter

This enhancement in ductility can be also seen when comparing the stress – strain diagram of the spinned specimen shown in Figure 9 to that of the straight bar specimen shown in Figure 8. On the other hand, the ultimate strength has changed. This change in strength is attributed to the fact that the bars are not straight anymore which means that when calculating the stress, the load is not simply divided by the circular cross-sectional area of the bar as the area normal to the axial force in the case for the spinned steel became nearly oval. Hence, and although the ultimate load is still nearly the same as that carried by two straight bars, the change in the cross-sectional area due to the tilt in the bars is the main reason for the minor in ultimate strength. This tilted cross-sectional area could be obviously seen when examining the mode of failure shown in 10. However, this change in strength is still less than the increase in ductility which means that the area beneath the stress – strain curve of the spinned specimen shown in Figure 9 is significantly larger than that of the straight bar specimen shown in Figure 8. This area beneath the curve is the modulus of toughness which represents the energy absorbed per unit volume of the material till its failure. A comparison between the moduli of elasticity, resilience and toughness of the spinned and straight bars could be seen in Table 1. Although the modulus of elasticity has decreased due to spinning the bars, the moduli of resilience and toughness have significantly increased due to the significant increase in the strains that the spinned specimen experienced when compared to those experienced by the straight specimen. This could point out that the reduction in the modulus of elasticity is mainly due to the change in cross-sectional area coupled with the significant increase in elastic strain (which is inversely related to the modulus of elasticity)

Table 1: Comparison between the moduli of elasticity, toughness and resilience of the spinned and straight bars.

	Spinned Bars 11 Spins	Straight Bar
Modulus of Elasticity (MPa)	21,985	212,004
Modulus of Toughness (MPa)	57.16	36.36
Modulus of Resilience (MPa)	5.25	1.17

Figure 10: The mode of failure of the spinned steel specimen.

3.2.3 Bending Test

The cold-bending test was performed according to ASTM A370 - 17 (American Society for Testing Materials, 2017) to guarantee ductile behavior of the spinned bars when subject to bending. The test was performed on three spinned specimens. The three specimens exhibited the same deformed shape under the same load. As shown in Figure 11. The bent specimen behaved in a ductile manner with no brittle fracture experienced by the specimen during bending and no signs of brittleness in the bent spinned bars.

Figure 11: Side view of the cold-bent specimen

3.2.4 Bond Test

To assure that the bond between the spinned steel and the surrounding concrete is strong the bond test was performed according to ASTM C900-15. The specimen is a cylinder of a 150 mm diameter and a 300 mm height, embedded in it is the reinforcement to be tested. To compare the bond strength of the spinned steel to different sizes of reinforcing bars, three control groups were tested corresponding to one spinned group. Each group consisted of 2 specimens for consistency in results. In control group 1, a steel bar of a diameter of 12 mm is embedded in each cylinder specimen. In control group 2, two straight steel bars of diameter 10 mm are embedded in each cylinder specimen. In control group 3, a steel bar of diameter 16 mm is embedded in each cylinder. Finally, for the spinned group, two steel bars of diameter 10 mm of 11 spins per meter are spinned together and are embedded in each cylinder specimen. Hence, 3 cubes of dimension 150 mm × 150 mm × 150 mm were casted to ensure that the desired compressive strength of 55 MPa was reached.

Table 2: Results of Bond tests

Specimen	Type of Failure	Failure Force (N)
Ø12 Specimen 1	Steel slipped 20 mm out of cylinder	72000
Ø12 Specimen 2	Steel slipped 15 mm out of cylinder	73000
	Average	72500
2Ø10 straight Specimen 1	Concrete broke in 2 halves	92500
2Ø10 straight Specimen 2	Concrete broke in 3 parts	96500
	Average	94500
Ø16 Specimen 1	Slipping failure	115500
Ø16 Specimen 2	Slipping failure	129000
	Average	122250
2Ø10 11 spins Specimen 1	Steel broke without slipping or concrete fracture	91000
2Ø10 11 spins Specimen 2	Steel broke without slipping or concrete fracture	93000
	Average	92000

The results of the bond tests are shown in *Table 2*. These results when examined in correlation with the mode of failure of the spinned steel shown in Figure 12**Error! Reference source not found.** prove that the bond between the spinned steel and the concrete is strong to the extent that the failure did not occur in the concrete and the steel did not slip off from the concrete; however, failure occurred in the steel itself which means that the bond between the concrete and the spinned steel was even stronger than the steel itself. On the other hand, when comparing the bond between the spinned steel to that of the other straight steel samples one could see that all the other samples using straight steel either failed due to slippage of the steel out of the concrete block or due to failure in the concrete block itself. This is mainly attributed to the fact that the contact surface area between the concrete and the spinned steel is significantly larger than that between the concrete and straight bars. This bond of two 10 mm spinned steel bars is even stronger than the bond of two straight 10 mm bars as the failure for these two straight bars occurred in the concrete block itself suggesting that the interlocking between the spinned steel and the concrete strengthens the bond between them. However, it is worth to note that bond strength is also a function of concrete strength; hence, these results may change in cases of different concrete strengths. The results obtained by Spinned steel in bond testing inside of concrete can be of paramount cost saving of additional lengths in development and splice length of reinforced concrete sections.

Figure 7: The Failure mode of spinned steel specimen

4 CONCLUSIONS AND RECOMMENDATIONS

Based on the scope of this work, the materials and technique incorporated, the following conclusions can be drawn:

- The spinning process of the steel did not induce significant cracks within the spinned steel bars.
- The spinning process of the steel bars significantly increased their ductility.
- The spinned steel bars have significantly higher moduli of toughness and resilience when compared to those of straight bars which could be attributed to the increase in ductility.
- The spinned steel bars behave in a ductile mode when subjected to cold bending.
- When examining the mode of failure that occurred in the spinned steel bars, it could be concluded that the bond between the concrete and the spinned steel bars is significantly higher than that of straight bars ; straight bars slip off the concrete block when subjected to the bond test, meanwhile spinned steel stays in place attached to the failed concrete section.

Based on these conclusions, an ongoing research is being performed to assess the use of spinned steel bars in reinforced concrete beams subject to static and impact loading. To validate the real-life application of the spinned steel, a pilot study needs to be performed on a larger scale involving spectrum of reinforcement and spinned bars at various pitches.

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