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Investigation of Bond between Fibre Reinforced Polymer (FRP) Composites Rebar and Aramid Fibre-Reinforced Concrete

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Abstract This paper reports on a study of the bond between Aramid fibre-reinforced concrete (AF) and glass fibre reinforced polymer (GFRP) rebars. Three types of GFRP rebars were used, namely, ribbed, helically deformed, and sand-coated bars. Traditional concrete was used as the reference cementitious material. Comparative analysis showed that the compressive strength of the Aramid fibre concrete was lower than that of the traditional concrete and this was attributed to the flocculation of the fibres in the concrete. Conversely, the impact strength of the AF was superior to that of reference concrete. A comparison of the bond strength in the GFRP-reinforced control and the GFRP-reinforced AF concrete samples showed that the introduction of the GFRP rebars in the latter produced mixed results. That is, the bond strength between the concrete and the ribbed bars was increased when Aramid fibres were used. However, the addition of Aramid fibres to the concrete did not increase the bond strength at the inteface of the helical rebar and, in the case of sand-coated GFRP rebar, the use of the Aramid fibres resulted in the reduction of bond between the concrete and this type of rebar.

Keywords Aramid fibres, Concrete, Adhesion, Mechanical testing

1. Introduction

Reinforced concrete is a composite material and it can perform its designated functions only if there exists adequate bond between the reinforcement and concrete [1-4]. Generally, steel reinforcing bar is used as reinforcement in concrete structures. However, corrosion of the reinforcing steel bars in concrete can lead to serious problems [5] such as structural and durability deficiencies in the structures. It has been found that fibre reinforced polymer (FRP) rebars have a great potential to counteract such problems [6]. FRP reinforcing bars have several advantages over conventional reinforcing steel, namely FRP has higher tensile strength and fatigue resistance, and lower creep deformation and unit weight. Besides, FRP is naturally corrosion-resistant and it does not contribute to electro-magnetism [7]. In spite of the advantages of FRP reinforcement over conventional steel reinforcement, a direct substitution between FRP and steel rebar is not possible due to various differences in the mechanical and physical properties of the two types of bars. The main challenges that prevent the wide-scale use of FRP rebars as reinforcing materials for concrete structures are:

- When subjected to tensile force in the direction of fibres, FRP exhibits linear elastic behavior up to failure. Therefore, it does not have any yield point which means it exhibits no ductility [8].
- The modulus of elasticity for some types of FRP, namely aramid fibre-reinforced polymer (AFRP) and glass fibre reinforced polymer (GFRP) is much lower than steel, hence deflection and crack widths may control the design of reinforced concrete structures [9].
- The bond behaviour of FRP rebars with concrete is different from that of steel rebars due to the non-isotropic material properties and the different surface texture of the FRP rebars [10].
- Higher cost of FRP compared to steel, lack of familiarity with the new technology and limited availability of literature contributed to the slow adaptation of FRP as concrete reinforcement [11].

Despite these challenges, FRP reinforcing bars have been introduced as reinforcement in concrete structures subjected to aggressive environments such as chemical and wastewater treatment plants, sea walls, floating docks, and under water structures [12-14] not only because of their perceived capacity to endure in corrosive environments but also because of the other stated favorable attributes.

Numerous studies have been carried out to investigate the bond development of FRP rebars in traditional concrete.

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Researchers [15, 16] have studied the bond strength that is attained between different types of FRP bars in normal concrete and observed that the strength is dependent on the embedded length of the bar. More specifically, it is stated that the bond strength of the FRP rebar is reduced as the length of embedment increased. It was also reported that the strength of the concrete has bearing on whether the bond failure takes place at the rebar/concrete interface or within the concrete [15]. Further, as would be expected, the geometrical features of the deformation on the FRP have influence on the bond stress developed in traditional concrete and it is reported [17] that a certain minimum depth of projection should be made available to ensure acceptable bond performance.

In this study, the performance of FRP rebars in aramid fibre-reinforced was investigated. Fibre reinforced concrete (FRC) may be defined as a composite materials made with Portland cement, aggregate, and incorporating discrete discontinuous fibres. The role of the randomly-distributed discontinuous fibres is to bridge across cracks that develop in the concrete, and hence, help to provide same post-cracking 'ductility'. The fibres tend to increase the strain at peak load, and provide a great deal of energy absorption in the post-peak portion of the load/deflection curve [18]. The focus of this study is on the bond strength of fibre-reinforced concrete mixtures made with different types of FRP rebars.

2. Materials

2.1. Aramid Fibre

Aramid fibres, with many favorable properties, are amongst the high performance modern fibres that are potentially of interest to civil and structural engineers [19]. The term aramid is used to refer to aromatic polyamides containing chains of aromatic (benzene) rings linked together with –CO- and –NH- end groups. Many forms can be produced, but those based on para links on the aromatic ring generally give the strongest fibres [20]. Some of the technical data on this type of fibre is provided in Table 1.

Table 1. Technical data of Aramid fibres

Type of fibre	Fibre Length (cm)	Fibre diameter (μm)	Density (gr/cm^3)	Break Elongation (%)	Tensile Strength (MPa)
Aramid	3~4	14	1.44	3.6	3600

Aramid Fibre offers a unique combination of characteristics that sets it apart from other synthetic fibres:

- High strength (excellent strength-to-weight properties)
- High modulus of elasticity
- High dimensional stability
- Excellent heat, cut and chemical resistance
- No melting point (degradation only starts at 500°C)
- Low flammability
- High electrical resistance
- High corrosion resistance

2.2. Fibre Reinforced Polymer Rebars

As a composite material, the mechanical properties of FRP rebars vary significantly from one sample to another depending on the nature and volume of fibres, the mechanical properties of the resin and the fibre orientation. It is therefore not possible to establish universal values for the mechanical properties and only indicative values can be given. A comparison of FRP and steel rebars mechanical properties is shown in Table 2 [21].

The choice of a manufacturing process of the FRP bars depends on the type of matrix and fibres, the temperature required to form the part and to cure the matrix, and the cost effectiveness of the process. There are various manufacturing options available, including hand lay-up, filament winding and braiding among others, but pultrusion is the most common one. Aspects of the manufacturing process are cover in literature [21] and some types of GFRP bars are shown in Figure 1.

Table 2. Typical GFRP and steel reinforcement mechanical properties

Property	GFRP	Steel
Tensile Strength	900 MPa	370 MPa
Break Elongation	1-3%	20-23%
Density	1.9 gr/cm^3	7.85 gr/cm^3

Figure 1. Glass fibre reinforced polymer (GFRP) rebars a) helically deformed b) ribbed c) sand coated

3. Methods

All concrete mixtures were prepared using a mechanical mixer with a nominal capacity of 50 l. The process of mixing the concrete was done in the following order: the dry ingredients (cement, sand and coarse aggregates) were initially blended. Next, the water was gradually added and mixed together for 3 minutes. The fibres were then carefully sprinkled by hand in small amounts on the surface of the mixture followed by short period of mixing. This step was taken to avoid fibres balling and to achieve the highest uniformity in fibre distribution. The amount of Aramid fibre used was 0.5% based on volumetric measurement of the concrete. The mix proportions are provided in Table 3. For comparative analysis, a reference concrete mixture was produced in the same proportions shown in Table 3, with the exclusion of the fibres. After the mixing, the concrete with the fibre was used for the casting of the Aramid-type concrete samples and that without fibre for the control samples.

Three 150 mm cubes of concrete samples were prepared for the respective compressive and bond strength tests. Three prisms measuring 40 × 40 × 160 mm were also made for the impact flexural test. The concrete cubes that were used for the bond strength test had 12 mm diameter rebars centrally placed in the cast surfaced. Three different types of rebars, each having surface characteristics as displayed in Figure 1 were incorporated in the control and Aramid fibre-reinforced concrete samples. To promote development of strength, the concrete samples were cured in a water bath at 20 ± 2°C until the time of testing. Compressive strength tests were conducted at 7 and 28 days and the impact strength test was carried out at 28 days. The concrete samples that housed the 12 mm diameter bars were used to measure adhesion between concrete and reinforcement at 28 days.

Table 3. Mix proportions of the mixes

Cement (kg/m^3)	Water (kg/m^3)	Aggregate (Fine/Coarse) (kg/m^3)	Aramid Fibre (kg/m^3)
425	195	1820	14.4

4. Results and Discussion

4.1. Compressive Strength Results

After 7 and 28 days of curing, the 150 mm cubes were tested to determine the compressive strength (Figure 2) of each type of concrete. The testing machine which has a maximum capacity of 2000 kN, applied a loading of 0.50 kN /s (ASTM C39) to the samples. Compressive strength test results of the Reference (Ref) and Aramid fibre-reinforced (AF) concrete samples were are given in Table 4. As seen in Table 4, the compressive strength of Aramid-fibre reinforced concrete specimens at 7 and 28 days were 9.45% and 8.2% respectively less than the reference concrete at the same age. The reduction in strength that occurred after the fibres were incorporated in the concrete can be explained by the fact that, although clumping of fibres was minimized, it was not abated. This reduction in compressive strength is therefore attributed to the clumping of the fibres which resulted in the degradation of the uniformity of the concrete.

Table 4. Compressive strength of Aramid fibre and reference concrete

Sample	7-day strength (MPa)	28-day strength (MPa)
Reference concrete	37.5	47.25
Aramid concrete	33.96	43.38

Figure 2. Testing of compressive strength test specimen

4.2. Charpy Impact Test Results

Impact resistance (dynamic energy absorption as well as strength) is one of the important attributes of fibre reinforced concrete. The prismatic specimens having the dimensions of 40 × 40 × 160 mm were used to conduct the impact flexural test with Charpy equipment shown in Figure 3. The samples, before and after testing, are displayed in Figure 4.

Figure 3. Testing of Impact Charpy strength test specimen

Figure 4. Reference and Aramid fibre-reinforced samples before (a) and after (b) test

Charpy impact strength test results of Reference (Ref) and Aramid fibre-reinforced (AF) concrete samples were 91.7 and 104.0 $N.mm/mm^2$ respectively. The Charpy impact strength was calculated using Equation 1.

$$\text{Impact Resistance } (Nmm/mm^2) = M/A \qquad (1)$$

Where
M = The value read from quadrant kgf.m (convert to N.mm)
A = Cross-sectional area (mm^2)

The average impact stress of three specimens was used for each strength result. It is seen that after the addition of Aramid fibres, the impact strength of the concrete was raised by about 7.62% at 28 days. The action of the randomly-oriented Aramid fibres assisted in controlling the propagation of micro-cracks present in the matrix, firstly by micro-reinforcing the mortar and increasing the resistance to tensile forces. This improves the overall cracking resistance of matrix itself. Later in the fracture formation, the fibres bridge small cracks that are developed during the application of the load on the member, thereby reducing the inclination of the cracks to widen and propagate.

These mechanisms enhanced the post-fracture stress transfer capability in concrete, promoted higher dynamic fracture toughness, decreased dynamic crack velocities in the micro-environment and increased the absorption of energy under impact loads [22-23]. An improvement in the flexural impact strength is therefore seen when the fibres were introduced in the concrete.

Another important observation in this series of test was that the damage on the opposite side of the loaded sample is appreciably less than that obtained in the reference concrete. This improvement is ascribed to the increased in the capacity of the concrete to absorb the energy generated once the fibres were added.

4.3. Pull-out Test Results

The setup of the concrete samples for the bond strength is illustrated in Figure 5 and the actual test to determine the level of adhesion between the Aramid fibre-concrete and each GFRP bar was determined on machine shown in Figure 6. The reference (Ref) and Aramid fibre-reinforcement (AF) concrete samples before and after the test are shown in Figure 7 and the bond strength test results of the specimens are provided graphically in Figure 8. Calculation of bond strength was done using Equation 2.

Calculation of bond stress,

$$\tau = P/\pi.\ \phi.\ l \tag{2}$$

Where;
τ= Bond Stress (N/mm^2)
ϕ = The average diameter of the test bar (mm) was used to include the effect of deformation
l= Anchorage length (mm)

A comparative analysis of the three sets of load/deflection graphs in Figure 8 shows that, the defection related to the peak load of each fibre-reinforced sample is larger than that obtained in the corresponding Ref sample. This larger deflection is the effect of the Aramid fibres which reduced the brittleness of the traditional concrete. An examination of Figure 8 showed the bond strength of the fibre-reinforced concrete got higher as the GFRP rebar in the concrete changed from sand-coated to helical to ribbed. The same observance is seen in the associate Ref samples. The characteristics of the surface texture and geometry make the difference. As the projection of the rebar got longer (as in the case of the ribbed bar), the effective embedded surface area increased and this elevated the level of adhesion and frictional force.

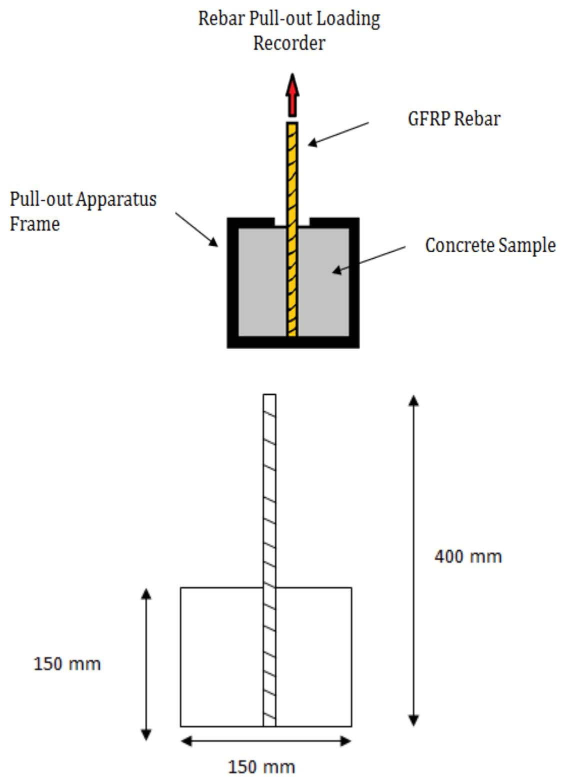
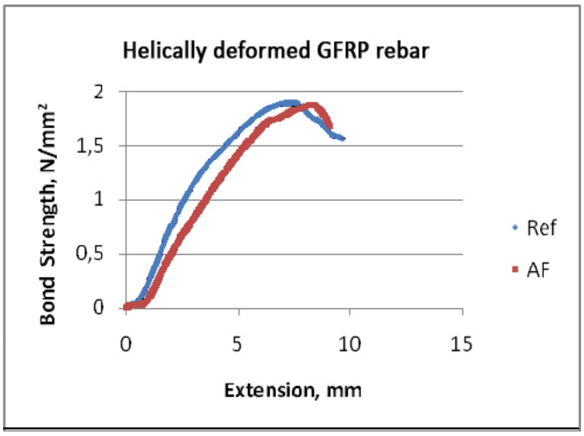
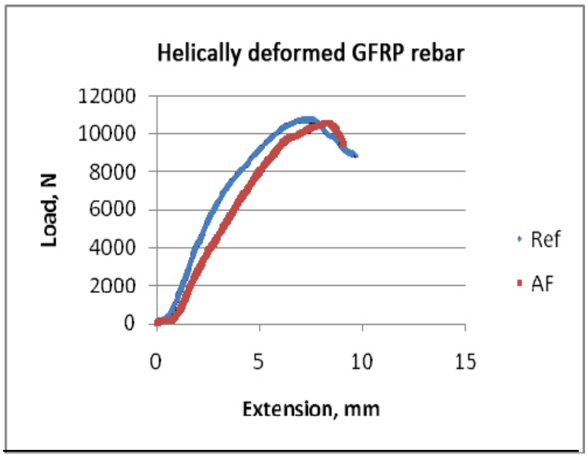


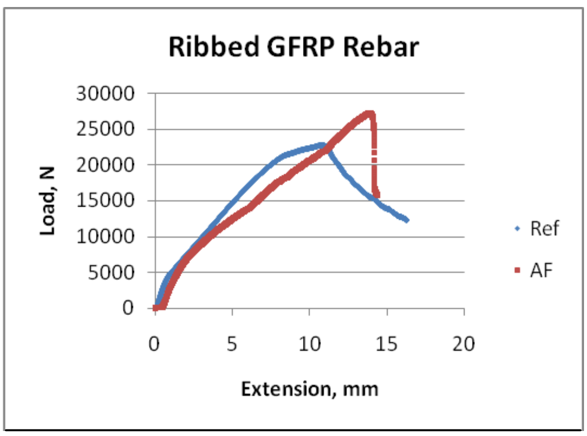
Figure 5. Setup of sample for bond stress test

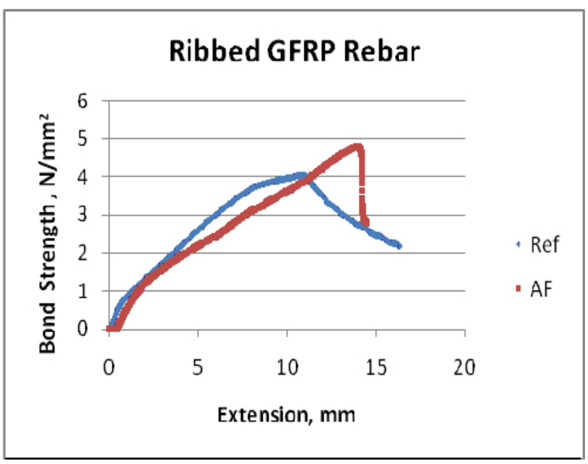
Figure 6. Pull-out test specimen positioned on testing equipment

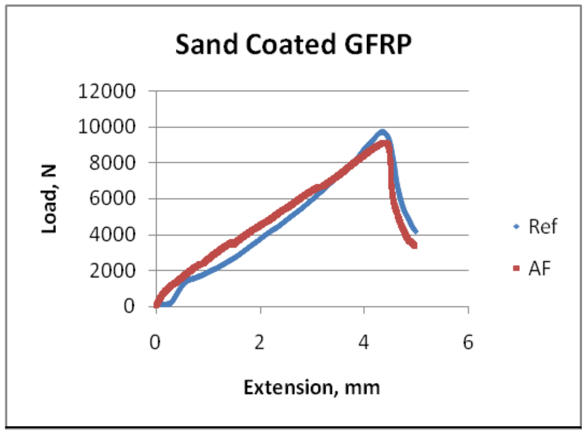
Figure 7. Pull-out test specimens before and after experiment











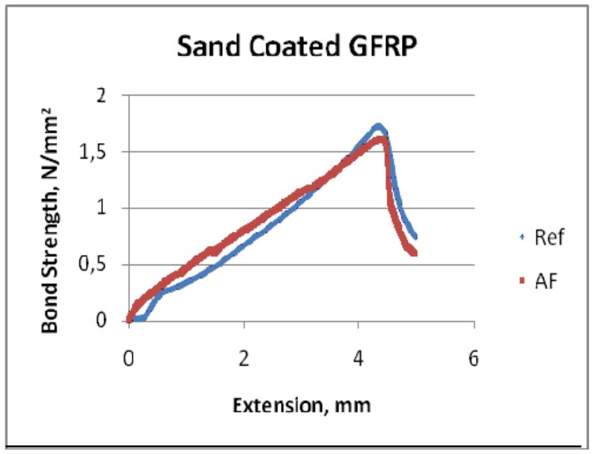


Figure 8. Graphs of the load (N) - extension (mm) and bond strength (N/mm^2)-extension (mm) data

An examination of Figure 8 showed the bond strength of the fibre-reinforced concrete got higher as the GFRP rebar in the concrete changed from sand-coated to helical to ribbed. The same observance is seen in the associate Ref samples. The characteristics of the surface texture and geometry make the difference. As the projection of the rebar got longer (as in the case of the ribbed bar), the effective embedded surface area increased and this elevated the level of adhesion and frictional force.

As the projection increases, the resistance received from the anchorage resulted in a high resistance to slippage that would have been evoked once the adhesion mechanism was destroyed under loading. The level of anchorage of the sand-coated GFRP in the concrete was low and hence, the bond strength was mainly through adhesion and frictional mechanism from the surface contact. The textured surface increased the contact surface and frictional resistance but, the resultant effect of these mechanisms was not comparable to that seen in ribbed and helical concrete specimens.

The influence of the Aramid fibre on the bond strength is also shown in Figure 8. It is seen that, the use of different types of GFRP rebars in the fibre-reinforced concrete (AF) did produce mixed results in bond strengths when comparison is made with the strength of respective reference sample (Ref). In the case of the ribbed GFRP bar, it is shown that the bond strength in the Aramid–fibre concrete was higher than that in the reference concrete. With regards to the sample with the helical deformed rebar, it was shown that the bond strength in the fibre-reinforced concrete was less than that which was obtained in the respective Ref sample. However, for structural purposes, this difference is considered inconsequential.

Conversely, the difference in bond strength between the two types of concrete is more noticeable when the sand-coated GFRP bar is used. Two observations will be used to explain the reduced bond strength at the interface between the sand-coated GFRP rebar and the AF sample. Firstly it is observed that the depth of the projection of the particle on the sand-coated bars was not significant (Figure 9). It was also observed that the spaces between the sand particles are narrow. From these observations it can be concluded that the space that is available between the particles could not accommodate any significant amount of fibre-reinforced mortar to resist slippage. Besides, it can also be plausibly presumed that in the sand-coated AF sample, at the interface between the fibre-reinforced concrete and the sand particles, the fibre would have reduced the contact between the concrete and the rebar as illustrated in Figure 9.

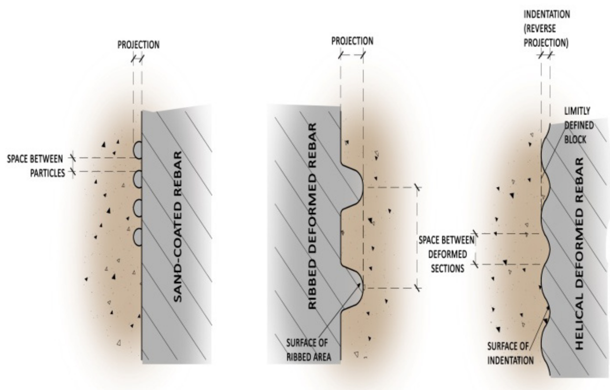


Figure 9. Sketch showing the interface between Aramid fibre-reinforced concrete and a) sand-coated, b) ribbed and c) helically deformed rebars

This reduction in contact would contribute to a reduction in friction at the concrete and rebar interface. Hence, although the fibres bridged the cracks formed in the concrete and contributed to improvement in resistance to bond failure, the highlighted factors collectively mitigated the effectiveness of the AF concrete at the surface of the sand-coated bar and obliterated any positive effect and thereby resulted in a decrease in bond strength.

Compared to the sand-coated AF sample, the interaction of the deformed surfaces of the ribbed-bar and the AF concrete (Figure 9) is optimized through i) higher projection, ii) adequate space between the deformed sections and iii) higher ratio of ribbed surface area to the fibre surface area. From i) and ii) a rectangular block is formed between the ribs that is adequate to accommodate the fibre-reinforced mortar. A higher ratio between the area of the ribbed surface and the area of the fibre surface reduced the negative effect of fibre coverage on the deformed surface. The resultant effect is that the fibre-reinforced 'mortar block' provides a significant resistance to slippage and crack arrestor, and thus the bond strength in the ribbed reinforced AF concrete was higher than the corresponding Ref sample.

It should be pointed out that, although the compressive strength of the AF concrete was less than the control, bond strength of the helical-ribbed AF samples was almost equal to that of the control Ref showing that there was a little ameloriation in bond strength that was gained from the reinforced mortar in the indentation. However, the mortar block formed with the helical deformed rebar in the AF concrete is less defined, in that it is more shallow and narrow and hence the attributes derived from the reinforced mortar in the indentation was not sufficient to produce higher bond strength than that of the corresponding Ref sample.

5. Conclusions

From this study, the following represent the findings.

- The compressive strength of concrete was reduced by the addition of Aramid fibres. The reduction in strength is attributed to the flocculation of the Aramid fibres.
- The impact resistance of fibre-reinforced concrete specimen was higher than that of control specimen. The micro-reinforced mortar reduced the development and rate of propagation of cracks.
- The damage on the opposite side of the loaded surface of the fibre-reinforced concrete was more severe than that of the control concrete. This attribute is ascribed to the fibres in the concrete that enhanced the dynamic fracture toughness and increased the absorption of energy under impact loads.
- The addition of Aramid fibres resulted in an increase in the bond strength of concrete when the ribbed GFRP rebar was used. The fibre in the mortar between the ribs of the rebar improved the tensile strength and increased the resistance to slippage at the interface at the concrete and rebar. The fibres also functioned as crack arrestors, by transferring stress across any occurring crack. This phenomenon consequently led to a stronger clasp of concrete on steel and an increase in bond strength.
- However, the bond strength between the concrete and the respective helical-deformed and sand-coated rebars was not improved with the addition of the Aramid fibre.

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