Experimental Investigation on Interfacial Behavior of Spiral Waste Iron Lathe Fibers Using Pull Out Test

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Abstract. *Fiber-reinforced cementitious composites exhibit enhanced ductility, crack resistance, and energy dissipation due to fiber–mortar interaction within the interfacial transition zone (ITZ). However, the interfacial behavior of irregular waste-derived fibers, particularly spiral-shaped iron lathe waste, remains insufficiently understood. This study experimentally investigates the bond performance and failure mechanisms of spiral waste iron lathe fibers embedded in a mortar matrix using single-fiber pull-out testing. Mortar specimens with a cement-to-sand ratio of 1:2 was prepared, and single fibers with a diameter of 1 mm were symmetrically embedded within double-cube specimens. Pull-out tests were conducted under displacement-controlled loading to obtain load–slip responses. Bond stress and energy dissipation were calculated from the experimental data, while mean, standard deviation, and coefficient of variation (CV) were used to assess data homogeneity. The results indicate that fiber–mortar interaction is governed by adhesion, friction, and mechanical interlocking mechanisms. Three failure modes were observed, namely pull-out, fiber rupture, and mixed failure, demonstrating strong sensitivity of interfacial behavior to local bonding conditions. Pull-out failure exhibits gradual post-peak softening and higher energy dissipation, whereas fiber rupture shows a sudden load drop and lower energy absorption capacity. All measured parameters are statistically homogeneous with CV values below 20%, confirming data reliability. This study demonstrates that irregular waste lathe fibers can effectively contribute to crack-bridging and energy dissipation, highlighting their potential as sustainable reinforcement in cement-based composites.*

Keywords: Energy dissipation; Fiber reinforced mortar; Interfacial bond behavior; Pull-out test; Spiral iron lathe waste fibers

1. Introduction

Fiber reinforced concrete offer significant advantages in improving the mechanical performance of cement-based materials, particularly in terms of ductility, crack resistance, and energy dissipation capacity. These improvements are primarily attributed to the crack-bridging mechanism, which refers to the ability of fibers to restrain microcrack propagation within the cementitious matrix, there by enhaning post-cracking behavior. In such systems, the overall performance of fiber-reinforced composites is strongly governed by the micro-level interaction between fibers and the matrix within the interfacial transition zone (ITZ).

Micromechanically, shear bonding behavior occurs due to the interaction between the tensile load and the relative displacement between the fiber and matrix during the tensioning process. (Al-Naimi and Abbas, 2025) stated that both direct tension and tension behavior of fiber-reinforced cementitious materials play a crucial role in increasing ductility through the fiber's contribution to the concrete's constitutive response. The load-displacement (P–Δs) curve is used to understand this nonlinear behavior.

(Wu *et al.*, 2023) showed that the bonding behavior of steel fibers in ultra-high-performance concrete (UHPC) is governed by ITZ. The failure response starts with debonding, shear friction, and failure such us rupture or pull out. It can be identified from the P–Δs curve. This curve is used to evaluate the interfacial shear strength (IFSS). (Deng *et al.*, 2023) said that this curve can divided into four stages: elastic, partial debonding, full debonding and pull out sliping. The area under this curve can be used to evaluate energy dissipation. Furthermore, (Yoo, Chun and Kim, 2020) state that increasing roughness improve frictional resistance and bond stress. It increased due to increased frictional resistance and enhanced mechanical locking. Similarly, (Faris *et al.*, 2021) confirmed that fiber geometry (twisted and straight fibers) has a strong influence on mechanical performance. Twisted fibers provide higher bonding capacity compared to straight fibers. The role of geometric configurations, such as bent end variations and bow-shaped deformations on the mechanical response of drawing, indicates the sensitivity of ITZ to fiber morphology (Li *et al.*, 2024).

In sustainable materials, research on the use of industrial waste as an alternative reinforcement is gaining increasing attention. (Liu *et al.*, 2022) stated that wood chips from lathes improving overall mechanical performance of composite due to mechanical interlocking. Therefore, material that promote mechanical interlocking have potential for structural aplication. Although there are limitations in their irregular shape

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and size distribution, this makes them interesting for micromechanical investigation. (Zhao *et al.*, 2025) stated that waste steel fibers increase the tensile strength and ductility of concrete. This demonstrates the strong potential of industrial waste metals as an alternative reinforcing material. Furthermore, (Wu *et al.*, 2023)showed that non-conventional fibers such as wire fibers can increase the bond capacity in high-strength mortars. This statement further strengthens the use of industrial waste fibers in structural applications. Furthermore, (Lin *et al.*, 2023) highlighted that energy dissipation in waste fiber-reinforced composites is strongly influenced by the ITZ characteristics, where the area under the P–Δs curve reflects the material's ability to absorb energy before failure. (Lin *et al.*, 2023)explains that pull-out testing under displacement-controlled conditions allows for a more accurate evaluation of bond-slip degradation in cementitious composites.

While numerous studies have been conducted on fiber-reinforced cementitious composites, previous investigations have largely focused on engineered fibers with controlled geometries or standard recycled steel fibers. In contrast, research on lathe-scrap iron fibers, characterized by irregular spiral morphology and random geometry, is limited. This is particularly relevant to the interfacial bonding behavior and pull-out mechanisms. The irregular surface configuration of lathe-scrap iron fibers can significantly affect frictional resistance, mechanical locking, and energy dissipation during fiber pullout.

Although previous studies have investigated fiber-mortar interactions and pullout behavior, they have focused on controlled fiber geometries or well-defined recycled steel fibers. In contrast, research on lathe-spun steel fibers with spiral and random geometries is still very scarce. Consequently, the interfacial shear strength (IFSS) formulation for these non-uniform and randomly shaped waste materials is currently underdeveloped (Faris *et al.*, 2021) while energy dissipation analysis has not been integrated into pullout systems. Therefore, this study investigates the interfacial bonding behavior of scrap steel fibers embedded in a mortar matrix using pullout testing. The investigation begins with the load-shear (P–Δs), interfacial shear strength (IFSS), tensile energy dissipation, and failure mechanisms associated with fiber debonding and shear friction. The results are expected to provide further insights into the micro-mechanical interactions between irregular scrap steel fibers and cementitious matrices for sustainable construction material applications.

2. Method

2.1 Research Methode

This study using experimental methode. It involved the fabrication and testing of mortar specimens using single-fiber pull-out tests. This test was used to evaluate the bond–slip behavior of waste iron lathe fibers embedded in a cementitious matrix. The specimens were prepared in the form of double-cube mortar blocks. The dimensions are 5 × 5 × 5 cm for each cube section. The illustration can be seen at Figure 1.

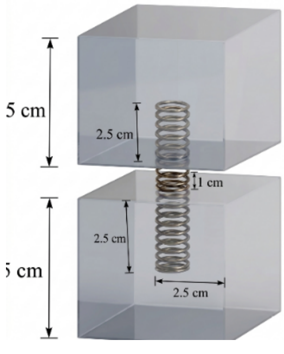


Figure 1. Configuration and Geometri of Specimen

The mortar mixture consisted of Portland Composite Cement (PCC) and fine sand. The ratio of cement-and sand is 1:2. The fine aggregate used was sand. It had to passing a No. 50 sieve. Water was added gradually to obtain a homogeneous mortar mixture with sufficient workability for casting. The fibers diameter is 1 mm and a total length is 60 mm. During specimen preparation, the fibers were positioned through a perforated Styrofoam. The separator plate placed between two cube molds. The separator plate served to divide the mold symmetrically and maintain fiber alignment during casting. An embedded length (Le) of 25 mm was provided on each side of the mortar specimen. A central clearance of 10 mm was left between the two mortar blocks. Since the fibers were symmetrically embedded in the two mortar blocks, the total effective embedded length used in the IFSS calculation was taken as 50 mm. This was derived from the combined embedded length of both sides of the specimen. During specimen preparation, the mortar was poured gradually onto both sides of the mold. It was then carefully compacted to minimize trapped air voids and ensure uniform distribution. After 24 hours, the specimens were removed from the molds and cured in water for 7 days before testing.

2.2. Testing Setup and Formulation

Pull-out testing was conducted using a Universal Testing Machine (UTM). Tensile loading was applied under controlled conditions. Displacement was recorded at the loading rate until failure. During testing, the specimen was positioned so that the fiber axes coincided with the vertical loading direction. Both mortar blocks were held in place using rigid anchoring fixtures to prevent undesired movement during loading. The applied tensile force (P) and the corresponding slip displacement (Δs) at the fiber ends were continuously recorded using an automated data system. Testing was terminated when complete fiber pullout or fiber breakage occurred. All sample preparation, curing, and testing procedures were performed consistently for the three specimens to ensure the reliability and repeatability of the experimental results. After testing, tensile force (P) and shear displacement (Δs) data were obtained. From the available data, bond stress was calculated. Bond stress is the interfacial tension between the fiber or reinforcement and the mortar matrix. This stress is used to evaluate the fiber-mortar bond performance, the effectiveness of fiber bridges, the tensile mechanism, and the fiber's contribution to ductility and energy dissipation. The equation one used to calculate the bond stress is as follows:

$$\tau = \frac{P}{\pi d L_e} \qquad (1)$$

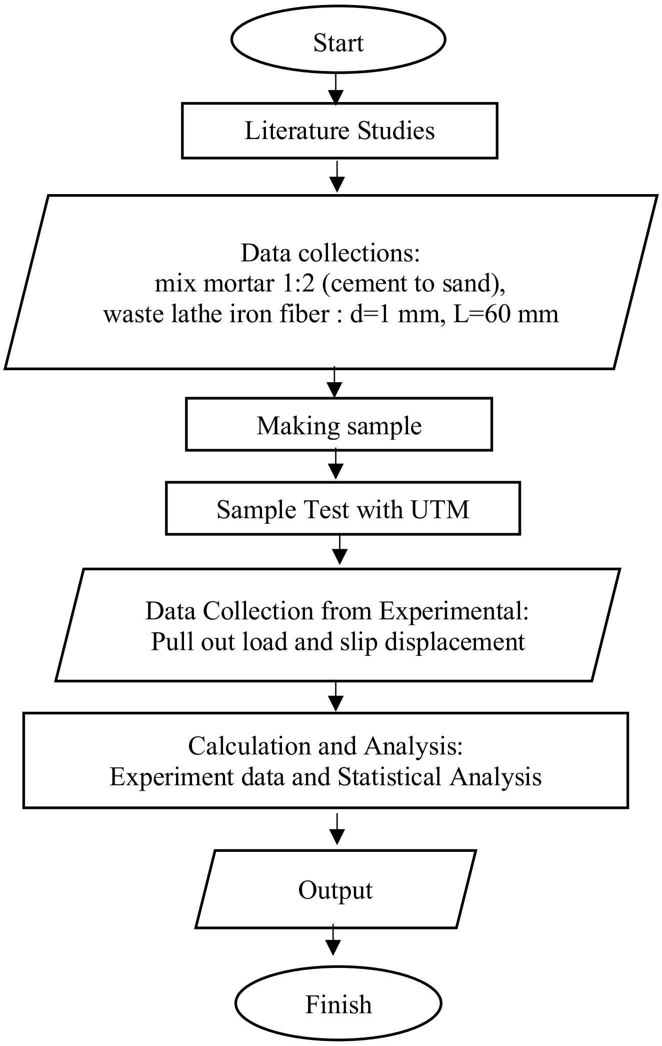
Where τ = bond stress (N/mm2), P = maximum pull-out load (N), d = diameter fiber (mm) dan L_e = embedment length (mm). In this experiment, a double embedment length was used because both sides of the specimen were embedded in the mortar matrix.

The next step is to determine energy dissipation. Energy dissipation is the amount of energy absorbed by the system during the fiber pulling process until failure occurs. This value indicates the fiber's ability to absorb energy before failure. It also reflects the material's toughness and ductility. Generally, energy dissipation is calculated as the area under the load-shear curve. However, because experimental data are usually obtained in discrete data points, calculations are generally performed using the trapezoidal method as follows equation two:

$$W_d = \sum \left(\frac{P_i - P_{i-1}}{2} \right) (\Delta s_i - \Delta s_{i-1}) \qquad (2)$$

Where W_d = energy dissipation (N.mm), P_i = pull-out load at the i-th data point (N), $P_{(i-1)}$ = maximum pull at the (i-1) th data poin (N), Δs_i = slip displacement at the i-th data point (mm) dan Δs_{i-1}= slip displacement at the (i-1)-th data poin.

Furthermore, the calculation results are presented in Table 1 and Figure 3. These results are used for further analysis and discussion also have been corrected with statistical analysis. Statistical analysis that is used is average, standart of deviation and coeffisient of variabel. The results and discussion are then interpreted to formulate conclusions as the final research outcome. An overview of the research procedure can be made as a flowchart. It shown in Figure 2.



Figures 2 Flowchart

3. Results and Discussion

Experimental specimen were tested using a Universal Testing Machine (UTM). The UTM provided load (P) and slip displacement (Δs) data. Based on these raw data, bond stress and energy dissipation were calculated using equations one and two. In equation one, the maximum bond stress was calculated based on the maximum load and slip displacement. For each specimen, the maximum value before failure was extracted and used as a representative parameter of the pullout behavior. In contrast to the bond stress, energy dissipation was calculated from the sum of the load and slip of each stage using equation two. The results of the experimental calculations and investigation of the pullout behavior of lathe waste steel fiber are presented in Table 1.

Table 1. Results of The Experimental and The Investigation of Lathe Waste Steel Fiber Pullout.

Specimen	P_{mak} (N)	Δs_{maks}(mm)	d (mm)	Le (mm)	τ (N/mm^2)	Wd (N.mm)	Failure
1	54	14.04	1	50	0.344	414.19	Pull Out
2	71.06	13.8	1	50	0.452	512.07	Pull Out
3	61.11	10.79	1	50	0.389	421.09	Fiber Rupture
Average	62.06	12.88			0.40	449.11	
Standart deviation	8.57	1.81			0.05	54.63	
Coefficient of variation (CV) (%)	13.81	14.06			13.81	12.16	

The results show that average of the maximum pull-out load recycled lathe waste steel fiber is 62.06 N and the average slip displacement is 12.88 mm. The average of interfacial bond stress between the fiber and mortar is 0.4 N/mm², while the average of three speciment of energy dissipation is 449.11 N·mm.

The interfacial bond tension (τ) depends on the combined contribution of chemical adhesion, frictional resistance, and mechanical interlocking between the fiber surface and the surrounding mortar matrix. This mechanism provides resistance to fiber pull-out. Lower interfacial resistance facilitates fiber extraction. Higher resistance increases the load required for pull-out, potentially leading to fiber rupture.

Specimens 1 and 2 demonstrate that the load transfer capacity at the fiber-mortar interface is insufficient to withstand fiber tension. This results in fiber pullout failure. In this case, failure is governed by adhesive bond release followed by shear along the embedded length. The interfacial resistance that occurs begins with weakened adhesion, with shear stress being less than tensile force, causing increased displacement slip. As a result of the increased slip displacement, cracks occur at the fiber-mortar interface, weakening the mechanical locking, and pullout failure occurs.

In contrast, Specimen 3 exhibits a difference in the form of broken fibers. This indicates that the interfacial load transfer is high enough that the fiber's tensile capacity fails before any bond release occurs. This behavior indicates that the load carried is transferred to axial tension within the fiber until it reaches its tensile limit. The interfacial load transfer capacity is large enough to cause the fiber's tensile capacity to fail first. From a mechanical perspective, the transition from tension to rupture reflects a critical balance between the interfacial load transfer capacity and the fiber's tensile capacity. Simply put, the maximum transferable interfacial force approaches or exceeds the fiber's tensile resistance.

Energy dissipation behavior also differs among specimens. Energy dissipation is strongly influenced by interfacial friction and the progressive unbonding process during fiber extraction from the mortar matrix. Specimens 1 and 2, which exhibit pull-out failure, exhibit a more stable post-peak response. This process indicates continued energy absorption through progressive shear and frictional resistance. In contrast, Specimen 3, which experienced fiber breakage, exhibits limited post-peak deformation capacity, resulting in a more limited contribution to energy dissipation. The contribution of post-peak deformation is reflected in the bond stress-slip curve. This is illustrated by a gradual reduction in bond stress accompanied by an increase in slip displacement. This process indicates dominant pull-out behavior and energy dissipation through interfacial friction. This behavior is illustrated in Figure 3. The bond stress–slip relationship can be simply expressed by the shape of the curve. If the curve falls gradually after the peak and slip continues to increase, it indicates dominant pull-out and high dissipation energy. If the curve falls sharply after the peak, it indicates rupture and low dissipation energy.

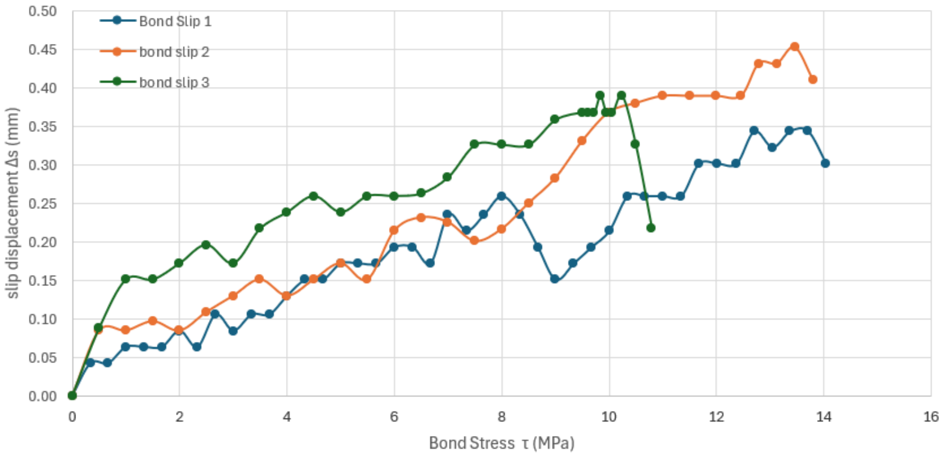


Figure 3. Bond Stress and Slip Displacement Relationship

In the case of fiber pullout, the bond stress–slip curve shows a gradual decrease after reaching a peak value, accompanied by a relatively large slip displacement. This behavior results in a larger area under the curve. This is evidence of a high energy absorption capacity. This response reflects ductile behavior. Ductile is the behavior of a material that dissipates a large amount of energy before complete failure.

Conversely, fiber breakage is characterized by a sharp decrease in the curve immediately after reaching the peak. Another characteristic is that the slip displacement is small. Consequently, the area under the curve is much smaller. This is evidence of a low energy absorption capacity. This behavior represents brittle failure. Brittle failure occurs when a material rapidly loses its load-bearing capacity and is unable to dissipate significant energy. For mixed-mode conditions, energy absorption falls somewhere in between. A mixed-mode response can occur in systems where the failure transition between pullout and breakage depends on local interface conditions. This results in a semi-ductile response with moderate energy dissipation capacity.

The experimental data were then analyzed using statistical parameters. This analysis was conducted to evaluate the homogeneity of the data set and to determine whether the results represented the tensile load, bond stress, and energy dissipation of recycled lathe waste steel fibers. The statistical tests included the mean, standard deviation, and coefficient of variation (CV). ((Pélabon *et al.*, 2020)state that the coefficient of variation (CV) is a standard measure for comparing variability across quantitative properties, making it highly relevant for materials testing. CV is recognized internationally as an indicator for assessing data homogeneity. The interpretation criteria for CV are defined as follows: values <10% indicate very high homogeneity, 10–20% indicate homogeneous data, 20–30% indicate moderate variability, and values >30% indicate high variability.

The experimental results showed that all evaluated parameters exhibited CV values below 20%. This confirms the statistical homogeneity of the dataset. Therefore, the average values can be considered representative of the mechanical characteristics of the recycled lathe waste steel fiber system. The slightly higher CV values observed for slip displacement (Δsmax) compared to bond stress are due to the inherent variability of post-cracking slip behavior. This behavior is strongly influenced by the local interfacial conditions between the irregular spiral-shaped fibers and the mortar matrix. Nevertheless, all CV values remain within acceptable limits, confirming that the experimental data are reliable and suitable for further analysis.

4. Conclusion

The new insight has been provided into the interfacial behavior of spiral-lathe waste iron fibers embedded in a cement mortar matrix through experimental pull-out testing. The findings emphasize that the interfacial transition zone (ITZ) plays a critical role in regulating load transfer efficiency, damage evolution, and energy dissipation mechanisms in lathe fiber and cement.

Fibers derived from irregularly shaped waste activate several interfacial resistance mechanisms. The active mechanisms are adhesion, friction, and mechanical locking. These three mechanisms collectively control the transition between pull out and rupture failure modes. This indicates that the mechanical response of non-standardized fibers is highly sensitive to local interface conditions. These conditions lead to a disturbed balance and resulting in ductility and brittleness.

The spiral lathe waste iron fibers, despite their non-uniform geometry, are capable of providing effective crack bridging and energy dissipation. Crack bridging is a mechanism where fibers crossing a crack remain connected to both sides of the crack, preventing the crack from opening or widening abruptly. Crack bridging usually occurs in conjunction with debonding, slippage, fiber pull-out, or fiber rupture. If the fibers undergo gradual pull-out, crack bridging can persist for longer, resulting in greater energy absorption. The crack bridging and energy dissipation performance confirms the potential of iron lathe waste fibers as a sustainable alternative reinforcement material for cement-based composites.

Overall, this study broadens the understanding of fiber-mortar interactions in irregular recycled metal fibers and provides a micromechanical basis for future applications in sustainable construction materials

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