Mechanical Properties and Forensic Failure Analysis of Eco-Concrete with Twisted Aluminium Can Waste Fibers

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Abstract. The growing accumulation of aluminium can waste presents an environmental challenge, while the construction industry seeks eco-friendly materials to reduce its footprint. Recycling aluminium waste into fibers offers a sustainable strategy for concrete production; however, its effects on mechanical properties and durability remain insufficiently explored. This study investigates the incorporation of twisted aluminium fibers derived from beverage can waste into concrete. Fibers were added at 0.00–3.00% by cement weight, and specimens were tested for compressive strength, water absorption, and crack patterns under compressive loading in accordance with SNI 1974:2011. Results show that increasing fiber dosage reduced compressive strength by up to 27.78% and increased water absorption by 182.24% compared with control specimens. Forensic failure analysis revealed a shift in failure modes, from brittle cone fracture in control concrete to cone–shear and shear-dominated mechanisms at higher fiber contents. Despite strength reduction, the fibers improved crack distribution and post-peak ductility, demonstrating their role in enhancing structural resilience. These findings highlight the potential of aluminium waste valorization for sustainable concrete, particularly in non-structural and crack-sensitive applications. They emphasize the importance of identifying an optimum fiber content (0.5–1.0%) and adopting improved mixing or hybrid approaches with supplementary cementitious materials to balance strength, ductility, and durability. **Keywords:** eco-concrete, twisted aluminium fiber, compressive strength, water absorption, forensic failure analysis.

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1 Introduction

Growing volumes of industrial and household waste raise global concerns for sustainability and public health. According to data from the National Waste Management Information System (NWMIS) of the Ministry of Environment and Forestry (MoEF), accessed on February 20, 2025, total waste generation across 277 regencies or Fmunicipalities reached 28.98 million tons in 2024, with metal waste—including aluminium cans—ranked among the ten most prevalent waste types. Of this total, about 61.92% (17.95 million tons) was adequately managed, while 38.08% (11.04 million tons) remained unmanaged [1]. Continuous population growth further exacerbates this problem by increasing waste volumes and placing additional pressure on the limited capacity of existing waste management facilities.

One of the recognized strategies to address this challenge is the application of the 4R principle: reduce, reuse, recycle, and replace. Recycling is essential in solid waste management, as it converts discarded materials into new or reusable resources. A wide range of inorganic waste can be recycled, including aluminium. Aluminium cans represent a significant fraction of inorganic waste due to their long decomposition period. Aluminium is widely used in packaging, with cans as the main contributor to waste. The rising demand for aluminium-based packaging directly increases the volume of waste generated, and without effective management systems, this trend will further aggravate environmental pollution [2].

In parallel with these environmental concerns, the rapid growth of the construction industry has accelerated innovation in building materials, particularly concrete. Concrete is a composite material made from portland cement or other hydraulic binders, combined with fine and coarse aggregates and water, and may also contain supplementary ingredients to produce a hardened mass. It is the most widely used construction material worldwide due to its high compressive strength, ease of casting, and relatively low production cost. However, concrete is brittle, making it prone to sudden cracking with limited deformation capacity. To enhance ductility and post-cracking performance, fiber reinforcement has been extensively investigated as an effective solution [3]. Fibers act as crack-bridging elements, controlling crack propagation and maintaining structural integrity after cracking occurs [3]. Different types of fibers—including steel, polypropylene, and natural fibers—have been applied, yet the mechanical performance of fiber-reinforced concrete depends strongly on fiber type, geometry, dosage, and distribution within the concrete matrix [4].

Among potential alternatives, aluminium can waste offers significant potential for valorization as a fiber reinforcement material. Aluminium is lightweight, corrosion resistant, and easily formable, which makes it suitable for processing into fibers. In the present study, aluminium can waste was mechanically processed into twisted fibers. The twisted shape is expected to enhance mechanical anchorage within the concrete matrix, increase pull-out resistance, and improve stress transfer across cracks. Furthermore, the twisted geometry may reduce the risk of sudden fiber slippage during failure, compared with straight fibers, which generally exhibit weaker mechanical interlocking [5]. With these properties, twisted aluminium fibers are expected to improve crack behavior and post-peak ductility of concrete.

Prior studies have demonstrated that deformed metallic fibers can significantly enhance ductility and crack resistance of concrete due to improved bonding mechanisms [6]. Nonetheless, several studies have reported that under certain conditions—such as poor fiber distribution—metallic fibers can reduce compressive strength, even at relatively low dosages [7]. The reduction in strength is typically attributed to: (1) increased porosity resulting from micro-voids around fibers; (2) disruption of the interfacial transition zone (ITZ) between cement paste and aggregates due to fiber–matrix incompatibility; and (3) non-uniform fiber distribution that causes fiber balling and the formation of weak zones within the concrete.

To obtain a more comprehensive understanding of these phenomena, it is essential to complement mechanical tests such as compressive strength and water absorption with an investigation of failure mechanisms. For this purpose, forensic failure analysis offers an effective approach. This technique enables the identification of crack patterns, propagation directions, and the correlation between fiber distribution and structural failure modes [8]. Forensic analysis of fiber-reinforced concrete can thus offer valuable insights into the root causes of strength reduction—whether stemming from increased porosity, poor fiber–matrix bonding, or non-uniform fiber dispersion. By examining these failure patterns, researchers can determine safe limits for fiber dosage in waste-based concrete, particularly when incorporating twisted aluminium fibers.

Based on this background and literature review, the present study aims to investigate the effects of varying dosages of twisted aluminium fibers on the compressive strength and water absorption of concrete. In addition, the study seeks to identify crack patterns and failure characteristics of fiber-reinforced concrete through a forensic failure analysis approach.

2 Materials and Methods

2.1 Materials

The materials used in this study consisted of:

1. Ordinary Portland Cement (Type I), used as the primary binder.
2. Fine aggregate: natural sand from a local source, meeting the requirements of SNI 03-2834-2000.
3. Coarse aggregate: crushed gravel with a maximum size of 40 mm, sourced locally and complying with SNI 03-2834-2000.
4. Clean water, free from impurities, oil, and harmful chemicals.
5. Twisted aluminium fibers: produced by cutting aluminium can waste into strips (average length ~50 mm, width 2 mm). The strips were manually twisted to form a helical geometry, with ~360° rotation every 10–15 mm along the fiber length.

Fig. 1. Shape of twisted aluminium fibers

2.2 Concrete Mix Design

The concrete mix design used in this study was prepared in accordance with the provisions of SNI 03-2834-2000. The designed concrete had a target compressive strength of f'c = 25 MPa, a slump of 60–180 mm, and a water–cement ratio (w/c) of 0.57. Seven fiber contents were used: 0.00% (control), 0.50%, 1.00%, 1.50%, 2.00%, 2.50%, and 3.00% by cement weight. Mixing was carried out manually. The detailed mix proportions for each variation of twisted aluminium fiber addition are presented in Table 1.

Table 1. Concrete mix design

Concrete Production Plan per Variation (3 Specimens + 10% Allowance)					
Variation of Twisted Aluminium Fiber Content	**Twisted Aluminium Fiber (kg)**	**Cement (kg)**	**Sand (kg)**	**Coarse Aggregate (kg)**	**Water (L)**
0.00%	0.000	5.678	12.224	20.814	3.237
0.50%	0.028	5.678	12.224	20.814	3.237
1.00%	0.057	5.678	12.224	20.814	3.237
1.50%	0.085	5.678	12.224	20.814	3.237
2.00%	0.114	5.678	12.224	20.814	3.237
2.50%	0.142	5.678	12.224	20.814	3.237
3.00%	0.170	5.678	12.224	20.814	3.237

2.3 Methods

The experimental program was designed to provide a comprehensive understanding of the effects of twisted aluminium fiber incorporation on the mechanical properties and failure behavior of concrete. Three main tests were conducted: (1) compressive strength, (2) water absorption, and (3) forensic failure analysis through post-compression crack pattern observation.

2.3.1 Compressive Strength Test of Concrete

Compressive strength was tested on 28-day cylindrical specimens using a compression testing machine in accordance with SNI 1974:2011. Strength was calculated from maximum load divided by specimen area using Equation (1) below.

$$f'c = \frac{P_{max}}{A} \qquad (1)$$

Where f'c is the compressive strength of the cylindrical concrete specimen (N/mm² or MPa); P_{max} is the maximum compressive load (N); and A is the cross-sectional area of the cylindrical specimen (mm²).

2.3.2 Absorption Test of Concrete

The water absorption test indirectly measures concrete porosity, as concrete with larger or more numerous pores absorbs more water. This testing method refers to SNI 03-3495-1994. The dry specimen was weighed (W_{dry}), then immersed in water for 24 hours until fully saturated. After immersion, the specimen is removed, the surface is dried, and it is weighed again to obtain the wet weight (W_{wet}). The percentage of water absorption (WA) is calculated using Equation (2)

$$WA(\%) = \frac{W_{wet} - W_{dry}}{W_{dry}} \times 100\% \qquad (2)$$

A high water absorption value indicates increased porosity or voids, which often correlate with reduced compressive strength.

2.3.3 Forensic Failure Analysis

Forensic failure analysis provides deeper insight into concrete behavior under loading by qualitatively observing fracture mechanisms and crack propagation, complementing

quantitative tests such as compressive strength and water absorption. In this study, visual analysis of failed cylindrical specimens from compressive tests was conducted and documented using a high-resolution camera. Crack patterns—including cone, shear, and vertical fractures—were then classified following Bazant & Planas [8] for fracture mechanics and SNI 1974:2011 for failure mode identification. This approach clarifies the relationship between fiber distribution, porosity, and the observed changes in strength and crack resistance. Reference failure modes according to SNI 1974:2011 are presented in Figure 2.

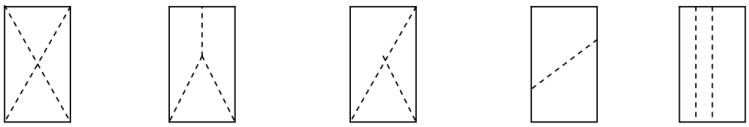


Fig. 2. Forms of failure patterns during the compressive strength test according to SNI 1974:2011

Caption for Figure 2:

a) Cone failure mode
b) Cone and splitting failure mode
c) Cone and shear failure mode
d) Shear failure mode
e) Columnar (parallel-to-axis) failure mode

3 Results and Discussions

3.1 Compressive Strength Test of Concrete

The average compressive strength of concrete at 28 days is shown in Table 2.

Table 2. Average compressive strength test results of concrete at 28 days

Variation of Twisted Aluminium Fiber Content (%)	Average Compressive Strength Value (Mpa)	Percentage of Compressive Strength Reduction (%)
0.00	25.113	0.000
0.50	20.408	18.735
1.00	20.400	18.767
1.50	20.154	19.747
2.00	19.374	22.853
2.50	18.410	26.691
3.00	18.136	27.782

Visually, the graph illustrating the relationship between the average compressive strength of concrete and the percentage of added twisted aluminium fibers is shown in Figure 3.

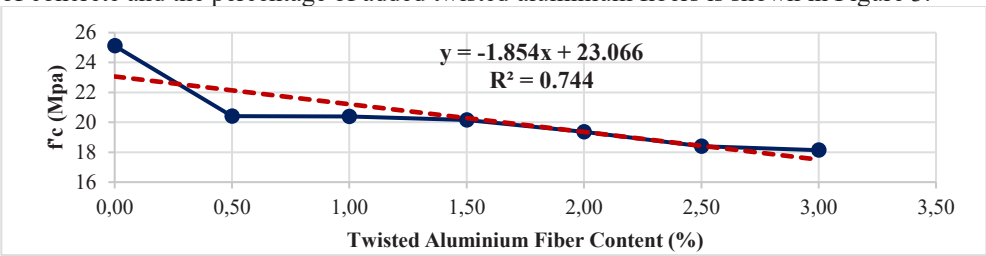


Fig. 3. Average compressive strength test results of concrete at 28 days

The results indicate that adding twisted aluminium fibers does not increase the compressive strength of concrete. In fact, strength decreased starting from the lowest dosage (0.50%), with a reduction of 18.735% compared to the control concrete. This decline continued up to the maximum dosage of 3.00%, resulting in a total reduction of 27.782%. A simple linear regression of fiber dosage versus compressive strength produced the following equation:

$$y = -1.854x + 23.066 \quad \text{with } R^2 = 0.744 \qquad (3)$$

Where x represents the dosage of twisted aluminium fibers (%). The negative slope indicates that for every 1% increase in the dosage of twisted aluminium fibers, the compressive strength ($\Delta_{f'c}$) decreases by approximately 1.854 Mpa.

The reduction in compressive strength with twisted aluminium fibers can be explained by several mechanisms:

1) *Increased porosity due to weak transition zones*
   The addition of twisted aluminium fibers may generate micro-voids around the fibers, particularly at the fiber–cement paste interface (interfacial transition zone / ITZ). This ITZ generally exhibits weaker bonding compared to the cement paste–aggregate interface, thus becoming the initiation point of cracks under loading [9].
2) *Disruption of concrete matrix density*
   Non-homogeneous fiber distribution can cause fiber balling, especially with twisted fibers that have a complex geometry. These fiber clusters interfere with the filling of cement paste around aggregates, increase the number of connected pores, and reduce the overall density of the concrete.
3) *Effect of twisted fiber geometry*
   Although the twisted shape is expected to improve pull-out resistance through mechanical interlocking, under compressive loading it may create stress concentrations around the fiber spirals. Such localized stress accumulation accelerates the formation of initial cracks.

3.2 Absorption Test of Concrete

The average water absorption of concrete at 28 days is shown in Table 3.

Table 3. Average water absorption test results of concrete at 28 days

Variation of Twisted Aluminium Fiber Content (%)	Average Water Absorption Value (%)	Percentage Increase in Water Absorption (%)
0.00	0.478	0.000
0.50	0.593	24.125
1.00	0.673	40.820
1.50	0.872	82.501
2.00	1.085	126.996
2.50	1.217	154.626
3.00	1.349	182.240

Visually, the graph illustrating the relationship between the average water absorption value of concrete and the percentage of aluminium spiral fiber addition is shown in Figure 4.

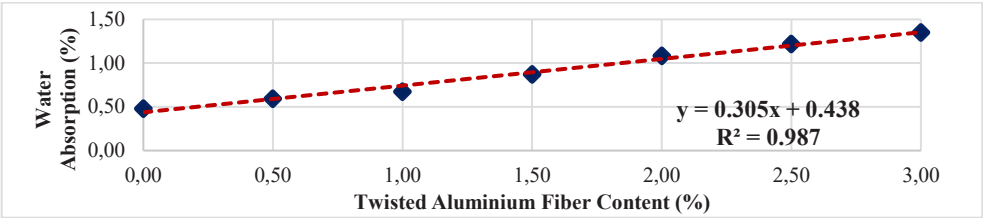


Fig. 4. Average water absorption test results of concrete at 28 days

The data in Table 3 and Figure 3 indicate that the water absorption value of concrete consistently increases with the addition of twisted aluminium fibers control concrete (0.00% fibers) had the lowest water absorption (0.478%), while concrete with 3.00% fibers had the highest (1.349%), nearly three times greater than the control. The water absorption test results yield the following linear regression equation:

$$y = 0.305x + 0.438 \quad \text{with } R^2 = 0.987 \qquad (4)$$

With x representing the aluminium spiral fiber content (%). The positive slope indicates that each 1% increase in aluminium spiral fiber content raises the water absorption (Δ_{WA}) by approximately 0.305 percentage points.

This increase indicates higher concrete porosity due to the addition of twisted fibers. Several factors may explain this phenomenon:

1) *Formation of microvoids around the fibers*
   The mixing process of spiral fibers may trap air or generate microvoids at the fiber–cement paste interface (interfacial transition zone), thereby creating more pathways for water absorption.
2) *Non-uniform fiber distribution*
   At higher fiber contents, the tendency for fiber balling increases. This condition can create pocket voids or less dense zones, which enhance the water absorption capacity of the concrete.
3) *Differences in surface properties between aluminium and cement paste*
   Aluminium is relatively hydrophobic compared to cement paste, leading to weaker interfacial bonding and the potential formation of micro-channels that allow water ingress.

3.3 Relationship Between Compressive Strength and Water Absorption

By comparing the regression equations for compressive strength and water absorption (Equations 3 and 4), the relationship between the change in compressive strength and water absorption can be obtained by comparing the reduction in compressive strength (df'c) with the increase in water absorption (dWA) for each percentage of twisted aluminium fiber. The relationship between compressive strength and water absorption can be seen in the following calculation

$$\frac{\Delta_{f'c}}{\Delta_{WA}} = \frac{-1.854}{0.305} \approx -6.079 \text{ MPa per 1\% water absorption}$$

Visually, the relationship between compressive strength and water absorption is shown in Figure 5.

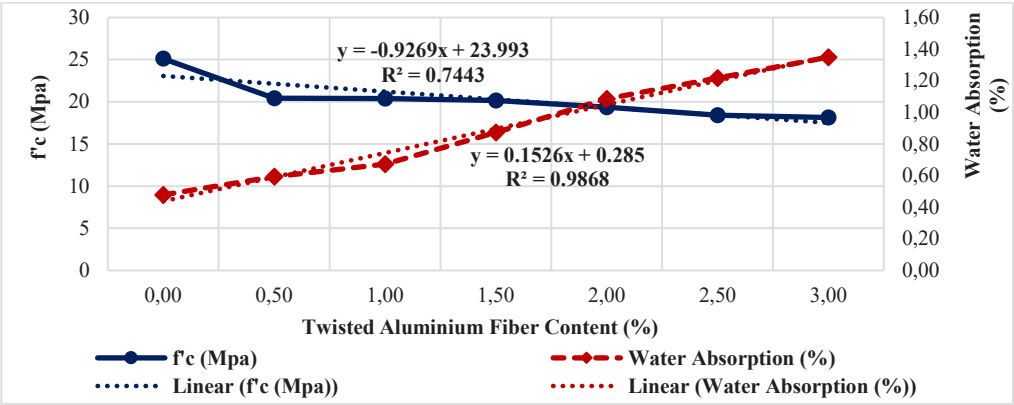


Fig. 5. The relationship between concrete compressive strength and concrete water absorption

The calculations, together with Figure 4, indicate an inverse relationship between compressive strength and water absorption. Each 1-percentage-point increase in water absorption corresponds to an approximate decrease in compressive strength of ±6.079 MPa.

This supports the hypothesis that increased porosity from aluminium fibers is the main cause of strength reduction. The rise in porosity may occur because of the formation of an interfacial transition zone (ITZ) around the fibers, fiber balling at high fiber content due to non-homogeneous mixing—resulting in voids and uneven aggregate distribution—and the relatively smooth surface of aluminium and its natural oxide layer, which interacts poorly with the cement paste.

These results are consistent with various studies on metal fiber-reinforced concrete, which indicate that increased porosity in the interfacial transition zone (ITZ) directly leads to higher water absorption and reduced compressive strength [9][10]. Moreover, the use of metal fibers with poor dispersion tends to lower compressive strength due to the formation of air voids around fiber clusters (balling effect) [11]. Therefore, the correlation between compressive strength and water absorption observed in this study aligns with the theory that porosity is the primary controlling variable in the relationship between water absorption and compressive strength. However, the final effect of aluminium fiber addition strongly depends on fiber shape, size, content, mixing method, and bonding conditions in the interfacial transition zone (ITZ).

3.4 Forensic Failure Analysis

Concrete failure patterns were analyzed qualitatively by visual inspection of cylinders after compressive strength testing, referring to the classification in SNI 1974:2011. All specimens were photographed using a high-resolution digital camera at consistent distances and angles. The photographs were then analyzed to identify the main crack paths, propagation directions, and fracture surface shapes. Crack patterns were grouped into five failure mode categories according to SNI: (1) cone failure, (2) cone and splitting, (3) cone and shear, (4) shear failure, and (5) columnar failure. The results of the crack pattern analysis on cylinder samples after compressive testing for each variation of twisted aluminium fiber content, along with the interpretation of the dominant failure patterns based on SNI 1974:2011, are presented in Tables 4 and 5.

Table 4. Results of the crack pattern analysis of concrete cylinder samples after compressive strength testing (1)

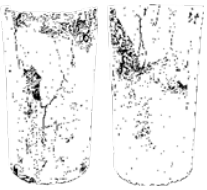
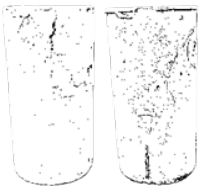
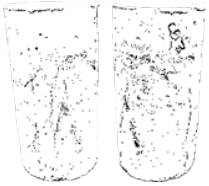
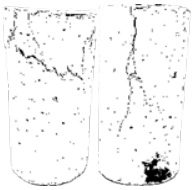
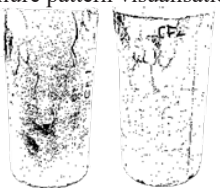
Normal concrete (0%)	**Concrete with 0.50% twisted aluminium fiber content**	**Concrete with 1.00% twisted aluminium fiber content**	**Concrete with 1.50% twisted aluminium fiber content**
Sample image  (a) (b)	Sample image  (a) (b)	Sample image  (a) (b)	Sample image  (a) (b)
Failure pattern visualisation  (a) (b)	Failure pattern visualisation  (a) (b)	Failure pattern visualisation  (a) (b)	Failure pattern visualisation  (a) (b)
Failure mode: Cone failure (mode 1)	Failure mode: Cone and shear failure (mode 3)	Failure mode: Cone and shear failure (mode 3)	Failure mode: Cone and shear failure (mode 3) + shear failure (mode 4)

Table 5. Results of the crack pattern analysis of concrete cylinder samples after compressive strength testing (2)

Concrete with 2.00% twisted aluminium fiber content	**Concrete with 2.50% twisted aluminium fiber content**	**Concrete with 3.00% twisted aluminium fiber content**
Sample image  (a) (b)	Sample image  (a) (b)	Sample image  (a) (b)
Failure pattern visualisation  (a) (b)	Failure pattern visualisation  (a) (b)	Failure pattern visualisation  (a) (b)
Failure mode: Cone and shear failure (mode 3) + shear failure (mode 4)	Failure mode: Cone and shear failure (mode 3) + shear failure (mode 4)	Failure mode: Cone and shear failure (mode 3) + shear failure (mode 4)

Tables 4 and 5 show that failure modes shifted from brittle cone failure (Mode 1) in fiber-free concrete to cone–shear (Mode 3), and predominantly shear (Modes 3+4) at higher fiber

contents. This shift corresponds with reduced compressive strength (up to 27.78% at 3.00% fiber) and increased water absorption (up to 182.24%), indicating greater porosity and altered failure paths due to fibers. Twisted aluminium fibers promoted more uniform crack distribution and reduced crack width, but also reduced compressive strength and increased water absorption. These findings indicate that, even with a qualitative approach, the observations are consistent with the mechanical data and provide a clear depiction of the transition in failure behavior in aluminium waste fiber-reinforced concrete.

Further forensic failure analysis classified the crack patterns into three categories based on fiber content, with the analysis details as follows:

1) *Group 1 – 0.00% (Control, Cone Failure – Mode 1)*
   Cracks initiate from microcracks in the load-contact zone due to high stress concentration and then propagate into a single cone-shaped fracture plane typical of brittle concrete. The failure mechanism is sudden brittle failure, without any internal crack-propagation restraint. This finding aligns with Neville (2012), who stated that plain concrete without fibers predominantly fails in a cone mode with minimal post-peak deformation [7].
2) *Group 2 – 0.50–1.00% (Cone & Shear – Mode 3)*
   The addition of twisted aluminium fibers begins to hinder vertical crack propagation, redirecting part of the fracture energy to inclined shear planes. The cone pattern remains visible at the core of the load, but shear planes start developing along the specimen sides. Crack distribution becomes more uniform, crack widths decrease, and post-peak behavior shows a slight increase in ductility. This result is consistent with the crack-bridging concept by Li et al. (1993), where fibers restrain the main cracks and transfer part of the fracture energy to shear mechanisms, resulting in more uniform crack distribution and increased ductility [12]. Pham (2025) emphasizes that fiber stiffness and geometry influence post-peak behavior, crack-width control, and failure mode transition, supporting the observation that twisted aluminium fibers can optimize energy dissipation and structural resilience [13].
3) *Group 3 – 1.50–3.00% (Combination of Cone & Shear with Predominant Shear – Mode 3+4)*
   At higher fiber contents, the cone at the load core becomes smaller, and shear planes dominate the failure mechanism. Voids and fiber clustering due to manual mixing act as initiation points for shear cracks, while fiber bridging still helps control large cracks. Crack distribution is uniform, but compressive strength decreases significantly due to increased porosity and weaknesses in the interfacial transition zone (ITZ). This finding aligns with Yuan et al. (2020), who reported that increased porosity and non-uniform mixing weaken the ITZ, although fibers improve shear capacity and ductility [14]. Additionally, Wang et al. (2025) note that fiber type and content are critical; high fiber content can cause fiber agglomeration, increasing porosity and reducing compressive strength, even though fiber bridging continues to enhance ductility and post-peak performance [15]. Therefore, optimizing fiber mixing and distribution is crucial to maximize the benefits of fibers in concrete.

Based on the forensic failure analysis from Group 1 to Group 3 above, it can be generally concluded that the addition of twisted aluminium fibers shifts the concrete failure mechanism from brittle cone failure toward a combination of cone–shear, and at higher fiber contents, toward predominantly shear failure. This change indicates that fibers are effective in improving crack distribution and control; however, excessive addition increases porosity and reduces peak strength. These findings suggest the existence of an optimum fiber content that balances increased ductility with strength retention, which warrants further investigation through mix design optimization and more homogeneous mixing methods.

3.5 Discussions

Although the incorporation of twisted aluminium fibers led to a reduction in compressive strength, the forensic failure analysis provides evidence of a significant improvement in crack behavior and post-peak ductility. The shift in failure modes—from brittle cone failure in plain concrete to cone–shear and shear-dominated mechanisms in fiber-reinforced specimens—indicates that the twisted aluminium fibers were effective in redistributing stresses and delaying catastrophic brittle collapse. This observation is consistent with the crack-bridging mechanism described by Li et al. [12] and the findings of Banthia and Trottier [6], who reported that deformed metallic fibers enhance ductility and control crack propagation.

From a sustainability perspective, the results highlight that the addition of waste aluminium fibers contributes to the circular economy by valorizing one of the most abundant types of municipal waste. Even though the compressive strength decreased, the use of recycled fibers transforms a non-biodegradable waste stream into a functional component of concrete. Similar to the conclusions drawn by Suchorab et al. [10] regarding the incorporation of electronic waste fibers, this study demonstrates that strength reduction can be offset by improvements in ductility and crack control, making such composites suitable for non-structural and crack-sensitive applications (e.g., pavements, thin panels, lightweight blocks).

Furthermore, the clear linear relationship identified between water absorption and compressive strength provides an empirical basis for understanding the porosity–strength trade-off in metallic waste fiber concrete. This finding aligns with previous reports by Yuan et al. [14] and Wang et al. [15], which emphasized that porosity and fiber clustering at higher dosages govern the reduction in strength despite improvements in ductility. Therefore, while compressive strength alone decreased, the study contributes both to sustainable material development and to the forensic understanding of failure mechanisms in eco-concrete. Future studies are recommended to integrate aluminium waste fibers with supplementary cementitious materials (e.g., fly ash, silica fume) and advanced mixing methods to minimize porosity, thereby achieving a better balance between strength, ductility, and sustainability.

4 Conclusions

Based on the test results and forensic failure analysis of eco-concrete reinforced with twisted aluminium fibers from waste cans, it can be concluded that twisted aluminium fibers improved crack distribution and ductility but reduced compressive strength due to increased porosity. Water absorption strongly correlated with strength reduction, confirming the porosity–strength trade-off. Valorizing aluminium waste supports sustainable concrete development, with an optimum fiber content of 0.5–1.0%. Future studies are recommended to integrate supplementary cementitious materials (SCMs) and employ advanced mixing techniques to optimize performance.

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