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Subject

Compression-Flexure Relationship in Fibre Concrete Based on Wasted Aluminium

Presented and publicly defended on the ../../...., before the jury composed of:

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Abstract

The majority of the aluminium market involves the consumption of aluminium sheets, primarily shaped into drink cans. These cans become a significant source of virgin aluminium waste. While materials such as steel and polythene are used as replacements for concrete in various applications, they present certain issues: steel can corrode, and polythene can suffer from shrinkage and thermal conduction problems. Consequently, using recycled aluminium as a solution to these problems is a promising approach. This study aims to emphasize the importance of using self-compacting concrete reinforced with recycled aluminium fibres, focusing on its resistance to bending and compression. Additionally, it seeks to determine the relationship between these two resistances. Understanding these relationships would simplify the characterization of the mechanical behavior of concrete fiber, enabling it to be based on a relatively limited number of standard tests. The primary objective is to investigate the relationships between the compressive and flexural responses of concrete fiber and to quantify the effect of introducing various volume fractions of recycled aluminium fiber from cans in self-compacting concrete under compression and bending forces. Fiber fractions ranging from 1% to 5% were used, along with control concrete without fibres. The results demonstrated that both compression and bending strengths increased with the fiber fraction up to 3%. However, at fiber fractions of 4% and above, the properties were negatively affected up to the point of crack formation (or maximum resistance in compression). Consequently, the post-crack bending strength decreased significantly.

Keywords: self-compacting concrete, aluminium waste fibres, compression, flexure, post-crack bending strength

Résumé

La majorité du marché d'aluminium concerne la consommation des feuilles d'aluminium, principalement transformées en canettes de boisson. Ces canettes deviennent une source importante de déchets d'aluminium vierge. Bien que des matériaux tels que l'acier et le polyéthylène soient utilisés comme substituts du béton dans diverses applications, ils présentent certains problèmes : l'acier peut corroder et le polyéthylène peut souffrir de retrait et de problèmes de conduction thermique. Par conséquent, l'utilisation de l'aluminium recyclé comme solution à ces problèmes est une approche prometteuse. Cette étude vise à souligner l'importance d'utiliser du béton autoplaçant renforcé de fibres d'aluminium recyclé, en mettant l'accent sur sa résistance à la flexion et à la compression. De plus, elle cherche à déterminer la relation entre ces deux résistances. Comprendre ces relations simplifierait la caractérisation du comportement mécanique du béton fibré, permettant de le baser sur un nombre relativement limité de tests standardisés. L'objectif principal est d'étudier les relations entre les réponses en compression et en flexion du béton fibré et de quantifier l'effet de l'introduction de diverses fractions volumiques de fibres d'aluminium recyclé provenant de canettes dans du béton autoplaçant sous des forces de compression et de flexion. Des fractions de fibres allant de 1 % à 5 % ont été utilisées, ainsi que du béton témoin sans fibres. Les résultats ont montré que les résistances en compression et en flexion augmentaient avec augmentation de la fraction des fibres jusqu'à 3 %. Cependant, pour des fractions de fibres de 4 % et plus, les propriétés étaient négativement affectées jusqu'à l'apparition de fissures (ou la résistance maximale en compression). En conséquence, la résistance à la flexion après fissuration a diminué de manière significative.

Mots-clés : béton autoplaçant, fibres de déchets d'aluminium, compression, flexion, résistance à la flexion après fissuration

ملخص

يتضمن الجزء الأكبر من سوق الألومنيوم استهلاك صفائح الألومنيوم، والتي يتم تشكيلها أساسًا في علب المشروبات. تصبح هذه العلب مصدرًا كبيرًا لنفايات الألومنيوم البكر. بينما تُستخدم مواد مثل الفولاذ والبولي إيثيلين كبدائل للخرسانة في تطبيقات مختلفة، فإنها تقدم بعض المشاكل: الفولاذ يمكن أن يتآكل والبولي إيثيلين يمكن أن يعاني من الانكماش ومشاكل العزل الحراري. وبالتالي، فإن استخدام الألومنيوم المعاد تدويره كحل لهذه المشاكل يُعتبر نهجًا واعدًا. تهدف هذه الدراسة إلى التأكيد على أهمية استخدام الخرسانة ذاتية الدمك المدعمة بألياف الألومنيوم المعاد تدويرها، مع التركيز على مقاومتها للانحناء والضغط. بالإضافة إلى ذلك، تسعى إلى تحديد العلاقة بين هاتين المقاومتين. مما سيسهل فهم هذه العلاقات تصنيف السلوك الميكانيكي للخرسانة المسلحة بالألياف، مما يتيح الاعتماد على عدد محدود نسبيًا من الاختبارات القياسية. الهدف الرئيسي هو دراسة العلاقات بين استجابات الضغط والانحناء للخرسانة المسلحة بالألياف وتحديد تأثير إدخال نسب حجمية مختلفة من ألياف الألومنيوم المعاد تدويرها من العلب في الخرسانة ذاتية الدمك تحت قوى الضغط والانحناء. تم استخدام نسب الألياف التي تتراوح من 1% إلى 5%، بالإضافة إلى خرسانة بدون ألياف كشاهد. أظهرت النتائج أن مقاومتَي الضغط والانحناء زادت مع نسبة الألياف حتى 3%. ومع ذلك، عند نسب الألياف التي تبلغ 4% وأكثر، تأثرت الخصائص سلبًا حتى نقطة تكوين الشقوق (أو المقاومة القصوى في حالة الضغط). وبالتالي، انخفضت مقاومة الانحناء بعد التشقق بشكل كبير.

الكلمات المفتاحية: الخرسانة ذاتية الدمك، ألياف نفايات الألومنيوم، الضغط، الانحناء، مقاومة الانحناء بعد التشقق

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General Introduction

The construction industry constantly seeks innovative ways to improve concrete performance while addressing sustainability and cost concerns. One promising avenue is incorporating waste materials into concrete mixes. Aluminium is widely used across various industries, and its production and consumption generate substantial waste. The International Aluminium Institute reported that approximately 92 million tons of aluminium were produced globally in 2021, with a significant portion resulting in waste. Recycling aluminium scrap not only conserves natural resources but also reduces the environmental footprint. Using waste aluminium fibres in concrete offers an eco-friendly solution that enhances material properties and aligns with sustainable construction practices. Waste aluminium fibres have emerged as a valuable addition to concrete mixes, providing numerous benefits. By utilising waste aluminium, the construction industry can significantly reduce the environmental impact of aluminium waste disposal. The incorporation of these fibres in concrete can improve mechanical properties such as compressive and flexural strength, ductility, and crack resistance. Furthermore, using waste materials in concrete promotes resource efficiency and contributes to the circular economy, increasingly important as industries strive to reduce their carbon footprints. Estimates suggest that over 1.5 million tonnes of aluminium scrap are generated annually in the United States alone, highlighting the vast potential for recycling and repurposing this material in construction. The primary objective of this study is to investigate the optimal mix of waste aluminium fibres to enhance the performance of self-compacting concrete (SCC). Specifically, the research aims to determine the ideal fibre content that maximises compressive and flexural strength, thereby improving the overall durability and structural integrity of the concrete. By systematically varying the proportion of aluminium fibres in the concrete mix and evaluating the resulting mechanical properties, this study seeks to provide valuable insights into the benefits of incorporating waste aluminium fibres into SCC. This thesis is organised into four main chapters, each addressing a different aspect of the research:

- **Chapter 1** provides a comprehensive review of existing research on the use of fibres in concrete, focusing on aluminium fibres, covering the historical development of fibre-reinforced concrete, the properties and benefits of different types of fibres, and the specific advantages of using aluminium fibres.
- **Chapter 2** details the experimental procedures and materials used in this study, including the selection criteria for aggregates, the preparation of concrete mixes with

varying aluminium fibre contents, and the methods used for casting and curing the test specimens.

- **Chapter 3** presents the results of the laboratory tests conducted on the concrete specimens, with detailed analyses of the compressive and flexural strength data, highlighting the effects of different aluminium fibre contents on the mechanical properties of the concrete.
- **Chapter 4** explores the relationship between compressive and flexural strength in fibre-reinforced concrete, analysing the correlation between these two key properties and discussing the implications of the findings for practical applications.

In summary, this thesis aims to contribute to the sustainable development of the construction industry by demonstrating the feasibility and benefits of using waste aluminium fibres in self-compacting concrete. By identifying the optimal fibre content and elucidating the compression-flexure relationship, this research provides a solid foundation for the broader adoption of fibre-reinforced concrete in various structural applications.

CHAPTER 01: LITERATURE REVIEW

1.1. Introduction:

Fibre reinforced concrete is another type of concrete that uses fibrous material to enhance its structural integrity. Commonly used fibres include steel and synthetic fibres, providing tensile strength and reduced crack propagation. There has been limited use of wasted aluminium in concrete production for many years. the waste is expected to be fully utilized in the fibre concrete. The production of aluminium metal is increasing and it has been estimated that the production will reach 120 million tonnes by 2020. As a result, the amount of wasted aluminium is expected to grow significantly over the years. In this regard, the usage of aluminium waste as fibre reinforcement in concrete will provide an alternative solution for the environmental issues and a more sustainable material for the construction industries. The objective of this study is to investigate the potential of using aluminium waste as fibre reinforcement in concrete. The properties of fibre concrete with various mix designs and different volume fractions of aluminium waste are studied and compared with the conventional concrete as well as the conventional fibre concrete. The mechanical properties, such as compressive strength and flexural strength are investigated. Besides, the workability studies, such as slump test and compaction factor test are also carried out to study the effect of wasted aluminium on the fresh concrete. Last but not least, analysis shall be conducted on the cost comparison between the conventional fibre concrete and the wasted aluminium fibre concrete, as well as the benefit to the environment. It is expected that the results of this project will provide insights for the material improvement and findings will benefit the construction industries.

1.2. Properties of Fibre Concrete:

1.2.1. Strength:

Fibre concrete presents a formidable array of advantages, boasting exceptional flexural-tensile strength, resistance to spitting, impact resilience, and superior permeability and frost resistance. The core objective behind integrating fibres into the cement matrix is to fortify toughness, augment tensile strength, and counter plastic shrinkage cracking in mortar. This integrated approach not only enhances the resistance of conventionally reinforced structural members to cracking, deflection, and other serviceability conditions but also offers a comprehensive solution. Whether fibres are interwoven within the concrete body or applied as a protective skin of fibre concrete, the ultimate aim remains steadfast: optimizing the strength properties of fibre concrete. [1]

1.2.2. Durability:

Incorporating fibres into concrete presents a multifaceted impact on durability:

- ***Density and Sonic Velocity*****:** An inverse correlation is observed between fibre volume content and both apparent density and ultrasonic pulse velocity, indicating a potential enhancement in durability metrics.
- ***Shrinkage and Crack Prevention*****:** The addition of fibres reduces shrinkage by preventing cracks and leveraging the higher elastic modulus of fibres.
- ***Surface Resistivity*****:** Initially, surface resistivity improves with fibre content up to 0.3%. However, beyond this threshold, a decline is observed due to compromised flowability.
- ***Chloride Ion Penetrability*****:** The rapid penetration of chloride ions increases with fibre addition, attributed to a weak fibre-matrix interfacial transition zone. Nonetheless, the incorporation of mineral admixtures partially mitigates this effect through pozzolanic reactions and micro-cavity fill-up.
- ***Freezing and Thawing Resistance*****:** Fibre addition initially enhances freezing and thawing resistance, peaking at 0.02% content. However, further increments diminish this resistance, again due to flowability issues.
- ***Corrosion Resistance*****:** Fibres demonstrate comparable resistance to water, salt, and alkaline corrosion but exhibit weaker resilience to acid corrosion compared to Glass Fibres (GFs) and Carbon Fibres (CFs). However, conflicting conclusions regarding fibre's superior corrosion resistance require further clarification and analysis. [2]

1.2.3. Workability:

The inclusion of fibres in concrete can lead to decreased fluidity, potentially impacting its workability negatively. Fibres can pose challenges during mixing, handling, placing, and consolidation of fresh concrete, such as the formation of fibre balls, which can lead to inconsistencies and reduced performance in fibre reinforced concrete (FRC). During application, casting elements with fibres may require more labour time due to decreased fluidity, and achieving a smooth finish can be problematic when fibres concentrate on the surface. Interestingly, the fibre properties that most enhance the mechanical performance of the composite, such as content and aspect ratio (fibre length compared to its cross-section), also contribute to workability challenges. This often leads to a trade-off between improving hardened concrete properties and maintaining adequate fluidity. Fibres affect the movement of coarse aggregate particles due to dimensional compatibility, with higher fibre volume and length impeding aggregate movement and mixture flow. Recommendations suggest using fibres with lengths exceeding twice the maximum coarse aggregate size to enhance post-crack strength, but this can limit fibre use based on coarse aggregate volume. One strategy to mitigate these issues is increasing the matrix mortar content to effectively incorporate fibres. Numerous studies in international literature over the past decades have evaluated the impact of fibre addition on workability through traditional test methods.

1.3. Fibre Types for Concrete:

Use of different types of fibres has been shown to have multiple advantages, including reduced crack widths, improved concrete toughness, prevention of concrete spalling during fires, and reduced plastic shrinkage cracking [3].

Table 1. 1 General Properties of Fibres [4]

Fibres	Diameter (μm)	Specific Gravity	Modulus of Elasticity (GPa)	Tensile Strength (GPa)	Elongation to Failure (%)
Chrysotile Asbestos	0.02-20	2.55	164	3.1	2-3
Crocidolite Asbestos	0.1-20	2.55	196	3.5	2-3
E-Glass	9-15	2.56	77	2-3.5	2-3.5
AR-Glass	9-15	2.71	80	2-2.8	2-3
Fibrillated Polypropylene	20-200	0.91	5	0.5	20
Steel	5-500	7.84	200	1-3	3-4
Stainless Steel	5-500	7.84	160	2.1	3
Carbon Type I	3	1.90	380	1.8	0.5
Carbon Type II	9	1.90	230	2.6	1.0
Aramid (Kevlar)	10	1.45	65-133	3.6	2.1-4.0
Cellulose	-	1.2	10	0.4	-
Wood	-	1.5	71	09	-
Nylon (Type 242)	>4	1.14	4	0.9	15

1.3.1. Plastic fibres:

Plastic fibres predominantly comprise polypropylene (PP), a semi-crystalline thermoplastic that has been industrially produced on a large scale since 1954. PP boasts properties such as odorlessness and hypo allergenicity, making it suitable for various applications in the food and pharmaceutical industries. Furthermore, PP fibres are recyclable, contributing to sustainability efforts. Plastic fibres are typically divided into two groups:

- **Microfibres*:***

Straight fibres, typically ranging from 5 to 20 mm in length and 0.02 to 0.20 mm in diameter, find primary application in various construction contexts. They are commonly utilized in hall floors, both on and under concretes, in screeds, and within walls. These fibres are predominantly incorporated into fresh concrete to modify setting properties. Specifically, they can adjust consistency (the flow properties of fresh concrete) and/or shrinkage properties during setting. Additionally, they contribute to enhancing concrete waterproofness. Furthermore, they play a crucial role in improving concrete properties, including augmenting fire resistance, enhancing impact and shock resistance, and reducing abrasion.

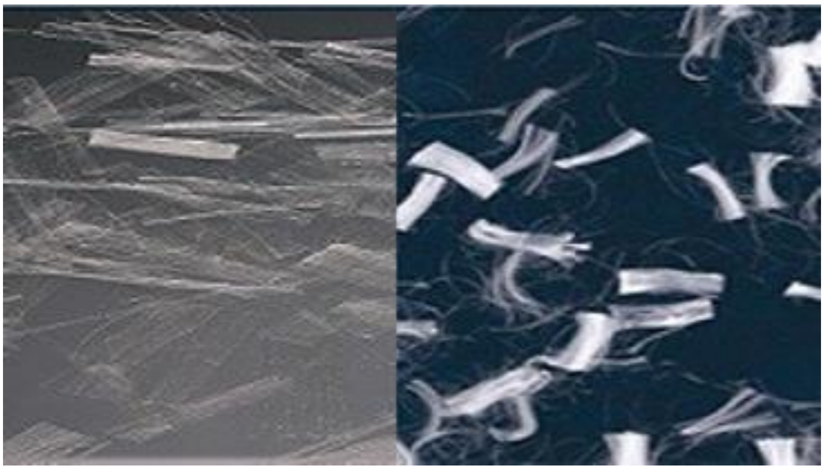

Figure 1. 1 Different forms of microfibres

- **Macrofibres:**

Manufactured typically with a length ranging from 30 to 65 mm and a diameter usually between 0.4 and 1.2 mm, these fibres aim to enhance the mechanical properties of concrete. They are available in straight, corrugated, and specially shaped variations, with surface contours designed to optimize force transmission between concrete and fibres, allowing for the use of shorter fibres while maintaining efficacy.

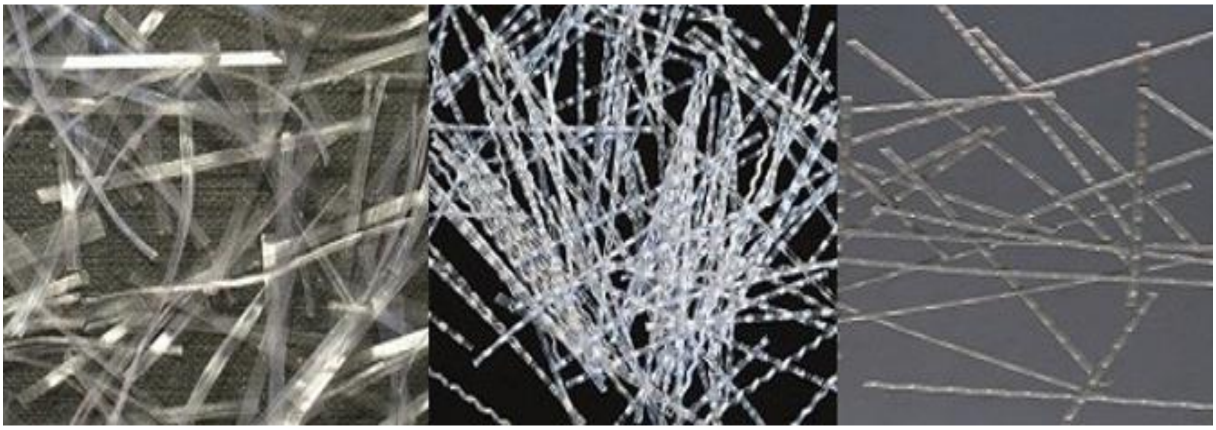

Figure 1. 2 Different forms of macrofibres

1.3.2. Glass fibres:

In 1931, the introduction of glass fibres (GF) marked a significant milestone in the reinforcement of mortar and concrete. These fibres are crafted by pulling molten glass through specialized holes, forming around 200–240 individual strands, which are later cut into smaller segments. Notably, glass fibre originates as a by-product of the glass manufacturing process, often discarded in substantial amounts by industries. Utilizing these fibres not only enhances the mechanical strength of concrete but also offers a sustainable solution for managing industrial waste disposal. [5]

Figure 1. 3   Glass fibres

Offering designers and builders a versatile material renowned for its strength and composition. Its inherent properties empower the realization of ambitious designs, whether replicating traditional, historic elements or pioneering futuristic aesthetics. With its ability to be cast and finished in a myriad of styles and shapes, GRC transcends limitations, enabling the creation of bespoke architectural features. Adaptability is a hallmark of GRC, making it suitable for diverse projects. Commonly employed in commercial settings, GRC finds application in exterior building façade panels, where it manifests as architectural concrete. These panels, characterized by their thinness and lightweight nature, afford unparalleled creative latitude compared to conventional concrete, opening avenues for innovative design expression. [6]

Table 1. 2 Chemical composition of different types of glass fibres [7]

	Types of glass fibres								
	AR	**E**	**C**	**A**	**R**	**S**	**D**	**Rezal**	**Cemfil**
SiO_2	61	53-54	60-65	70	60	62-65	73-74	60	62
Al_2O_3	-	14-15.5	2-6	2.5	25	20-25	0.5	5	0.8
CaO	5	-	14	9	6	-	-	10	5.6
MgO	-	20-24	1-3	0.9	9	10-15	0.5-0.6	-	-
B_2O_3	-	6.5-9	2-7	0.5	-	0-1.2	22-23	-	-
Na_2O	17	-	8-10	12.5	-	0-11	1.3	5	14.8
ZrO_2	10	-	-	-	-	-	-	5	16.7
FeO_3	0.3	-	0.5	-	-	-	-	-	-
TiO_2	-	-	-	-	-	-	-	-	0.1

1.3.3. Steel fibres:

In the 1960s, the initial theoretical explorations of Fibre Reinforced Concrete (FRC) primarily focused on Steel Fibre Reinforced Concrete (SFRC). Over time, SFRC has emerged as the predominant type of fibre concrete, although its dominance is gradually being challenged by synthetic fibre reinforced concrete. Steel fibres play a crucial role in enhancing the toughness of cement and concrete formulations. Initially employed primarily for crack control, they substituted the secondary reinforcement typically utilized for this purpose in flat slabs, pavements, tunnel linings, and various repair applications. Presently, while steel fibres continue to find extensive use for these purposes, their application is expanding into structural roles. They are increasingly employed to either supplant conventional steel reinforcement or complement it in structural applications.

Figure 1. 4 Steel Fibre Reinforced Concrete (SFRC)

Enhanced toughness can mitigate cracking resulting from fluctuations in temperature or humidity and bolster resistance against dynamic loads, such as fatigue, impact, blasts, or seismic activity. It's worth noting that while fibre additions result in only marginal strength enhancements, except at high fibre volumes, their primary impact lies in augmenting the concrete's post-peak load-bearing capability.

The original straight and smooth fibres are now rarely utilized due to their insufficient bonding with the matrix. Modern fibres, on the other hand, feature rough surfaces, hooked or enlarged ends, or are crimped or deformed along their lengths, all designed to enhance bonding. Round fibres are typically produced by cutting or chopping wires, with diameters typically ranging from 0.25 to 1.0 mm. Flat fibres may be produced by shearing sheets or flattening wire, with cross-sectional dimensions typically falling within the range of 0.15 to 0.40 mm thick and 0.25 to 0.90 mm wide. Crimped and deformed fibres of a number of different geometries have also been produced; the deformations may extend along the full length of the fibre, or be restricted to the end portions. Some examples of deformed fibres are shown in Figure 1.5.

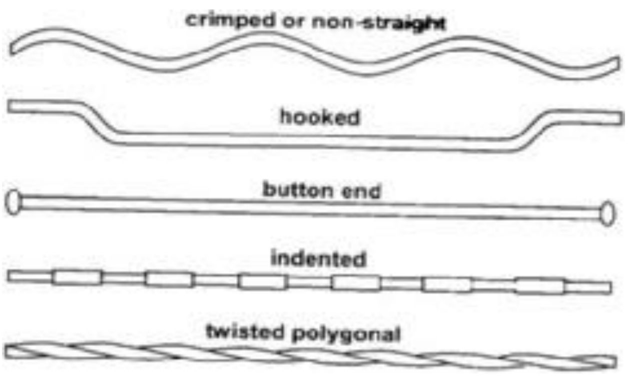

Figure 1. 5 Commonly available deformed steel fibres

1.3.4. Natural fibres:

The use of natural fibres in concrete production is encouraged due to the abundance of locally available options. This approach leverages various types of natural fibres, which are abundant in many regions. The concept of reinforcing brittle materials with such fibres is not novel; historically, materials like straw and horsehair have been employed to strengthen bricks and plaster. In developing countries, readily accessible natural fibres suitable for concrete reinforcement can be broadly categorized, as illustrated in Figure 1.6 [8]

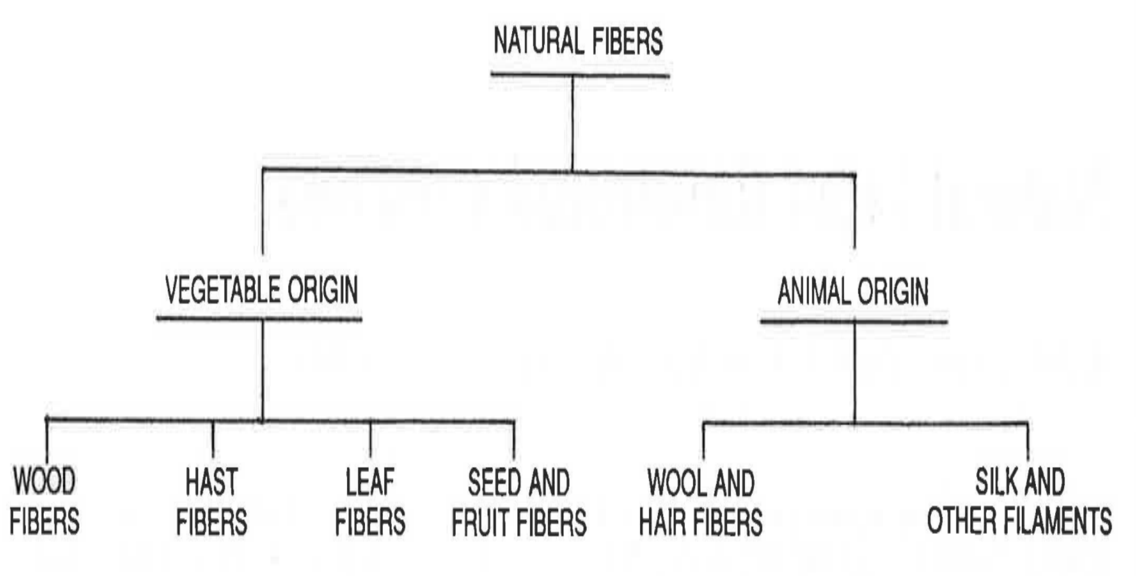

Figure 1. 6 Classification of natural fibres

- **Plant fibres:**

Among the numerous vegetable fibres employed in the construction sector for blending into concrete, mortar, and plaster, only the "hard fibres" are deemed appropriate. These primarily include leaf fibres like flax and sisal, as well as coconut fibre. Plant fibres exhibit mechanical properties that are non-uniform and challenging to categorize technically in terms of strength characteristics. As a result, their technical application is no longer prevalent today, but rather of historical significance. This is particularly relevant for the restoration of older structures.

Figure 1. 7 Sisal fibre

Figure 1. 8 Coconut fibres

- **Animal fibres :**

These fibres were historically utilized in concrete, more commonly in mortar, due to their affordability and easy accessibility. Primarily, coarse animal hair was employed, often sourced locally. Examples include:

- Horse hair, extensively used in mortar and wall plaster until around 1950.

- Cattle hair, particularly that of yaks in Asian regions.

- Goat hair, employed for plaster, including fine plaster applications

However, owing to the considerable variation in the mechanical properties of animal hair, their technical application is no longer prevalent today. Instead, their significance lies mainly in historical contexts, particularly in the restoration of older structures. [9]

1.3.5. Aluminium fibres:

Aluminium constitutes a 100% recycled material. In terms of mechanical, chemical, and physical attributes, it shares similarities with steel, allowing for comparable methods of forming, casting, melting, and machining. Often, steel equipment and techniques are utilized interchangeably with aluminium [10] which is a highly recyclable, lightweight, durable, malleable, corrosion-resistant, and robust material. [11]

Table 1. 3 Properties and characteristics of Aluminium

Property	Metric	Units	English	Units
General Density	2.5e3 - 2.9e3	kg/m^3	156 - 181	lb/ft^3
Mechanical Yield Strength	3e7 - 5e8	Pa	4.35 - 72.5	ksi
Tensile Strength	5.8e7 - 5e8	Pa	8.41 - 79.8	ksi
Elongation	0.01 - 0.44	% strain	-	% strain
Hardness (Vickers)	1.18e8 - 1.48e9	Pa	-	HV
Impact Strength (un-notched)	1.9e5 - 2e5	J/m^2	-	ft.lbf/in^2
Fracture Toughness	2.2e7 - 3.5e7	Pa/m^0.5	20 - 31.9	ksi/in^0.5
Young's Modulus	6.8e10 - 8.2e10	Pa	9.86 - 11.9	10^6 psi

Experimental findings unequivocally demonstrate the efficacy of incorporating aluminium fibres in enhancing split tensile strength in concrete. Notably, the inclusion of looped-end aluminium fibres has shown a marked increase in tensile strength, enabling concrete to bear loads even in the presence of initial crack formations. Furthermore, the augmentation of splitting tensile strength is observed to improve with higher fibre volume fractions, emphasizing the scalability and adaptability of this approach.

The integration of scrap aluminium fibres which comes in various forms confers significant technical advantages to concrete, augmenting its mechanical properties and structural resilience. These benefits, elucidated through empirical evidence and theoretical frameworks, underscore the potential of this innovative technique in advancing the performance standards of concrete structures. [12].

Figure 1. 9 Looped aluminium fibres

Figure 1. 10 Shredded aluminium fibres

Figure 1. 11 Aluminium chips

1.4. Recycling Aluminium Waste:

Aluminium recycling is a crucial process involving collection, sorting, and transforming discarded materials into new items, contributing to sustainable resource management. This integral practice helps divert aluminium waste from landfills, conserving natural resources. With its recyclability and durability [13].

The process in generally as follows:

- **Collection of Scrap:**

The initial step involves gathering discarded aluminium from streets and waste dumping areas, which is then transported to recycling facilities.

- **Sorting of Aluminium:**

In this critical process, aluminium, steel, and other metal products are meticulously sorted and thoroughly cleaned.

- **Shredding:**

Cleaned aluminium is placed on a conveyor belt and shredded into tiny bits with specific dimensions.

- **Passing beneath Magnets:**

Shredded aluminium pieces undergo a process where they pass beneath magnets to remove any traces of other metals, ensuring the purity of the aluminium.

- **De-coating:**

Specialized de-coater machines are employed to remove decorations, paints, stickers, and other coatings from the aluminium.

- **Surface texturing:**

The surface of cleaned and shredded aluminium fibres is scratched to enhance friction with surrounding materials

- **Transportation:**

The final stage involves transporting the ingots to packing areas, where they are packaged and transported to factories for labelling and filling before returning to shops for sale to consumers.

1.5. Benefits of Using Wasted Aluminium in Fibre Concrete:

1.5.1. Environmental**:**

Utilizing recycled materials in construction offers significant environmental advantages. By repurposing materials that would otherwise be discarded into construction waste bins, we mitigate the environmental impact of waste disposal. Additionally, recycling helps conserve natural resources by reducing the need for virgin materials, thereby preserving habitats and minimizing soil degradation caused by mining or deforestation.

Recycled building products also contribute to energy efficiency. The recycling process typically consumes less energy compared to extracting and processing new materials. For example, recycling aluminium requires approximately 95% less energy than producing it from raw bauxite. This reduction in energy consumption further decreases the carbon footprint of construction projects, promoting sustainability in the built environment. [14]

1.5.2. Economical:

A thorough cost-benefit analysis reveals that utilizing recycled materials can yield significant economic advantages. While the initial investment in recycled materials may occasionally be higher, the long-term savings are evident through reduced disposal expenses, decreased energy costs during production, and potential financial incentives from government grants supporting sustainable construction practices. In the larger context, the cost-effectiveness of recycled materials serves as a compelling incentive for developers and contractors seeking to harmonize financial prudence with environmental responsibility.

- ***Decreased Waste Disposal Expenses:*** Recycling construction materials minimizes waste generation, leading to cleaner construction sites and reduced fees associated with waste disposal.
- ***Lowered Production Costs:*** The energy efficiencies gained from using recycled materials translate into reduced production expenses, thereby enabling cost savings that can be passed on to consumers.
- ***Incentives for Sustainable Construction:*** Both governmental and private entities often provide financial incentives for incorporating sustainable materials into construction projects, further enhancing the economic benefits associated with the use of recycled materials. [14]

1.5.3. Technical:

Incorporating scrap aluminium fibres into concrete presents a promising avenue for enhancing its mechanical properties, particularly in terms of strength and durability. As demonstrated in various studies, the strategic integration of aluminium fibres not only bolsters the post-cracking behaviour of concrete but also reinforces its structure, mitigating brittleness by effectively bridging micro and macro cracks [15], [16]. This approach enhances the material's ability to withstand tensile strains and serves to stitch cracks, thereby fortifying its structural integrity.

Moreover, the versatility of aluminium fibres, available in various shapes and sizes such as looped-end, chips, etc., further enhances their applicability in concrete reinforcement. The abundance of aluminium scrap, estimated at a staggering 17 million tonnes worldwide with projections reaching 21 million by 2020, presents a readily available resource for this purpose. Additionally, with approximately 95% of aluminium from industries like automobile and construction being recycled in Europe, the feasibility of sourcing this material for concrete reinforcement is further underscored.

1.6. Manufacturing Process of Fibre Concrete with Wasted Aluminium:

The process of making aluminium fibres involves several straightforward steps aimed at turning raw aluminium into uniform fibres suitable for laboratory uses. This process ensures that the final product meets quality standards consistently.

- First, aluminium soft drink cans are collected from places like junkyards, restaurants, and coffee shops. These cans are chosen because they're easy to find and cost-effective.
- Next, the cans are cleaned thoroughly to remove any dirt or contaminants. This cleaning involves disinfecting and washing to ensure the aluminium is clean and free from impurities.
- After cleaning, the tops and bottoms of the cans are cut off, leaving only the cylindrical body. Machines are used to cut this body into strips of equal width, usually around 25 millimetres. This step ensures all the strips are the same size.
- Then, the strips are further cut into smaller pieces to make fibres. These pieces are typically 25 millimetres long and 5 millimetres wide. Precision cutting is essential to ensure the fibres are uniform.
- Once cut, the aluminium fibres are collected and stored carefully to keep them clean and dry. Proper storage prevents contamination and maintains the quality of the fibres.

1.7. Applications of Fibre Concrete based on Wasted Aluminium:

The uniform dispersion of fibres throughout the concrete mix provides isotropic properties not common to conventionally reinforced concrete. The applications of fibres in concrete industries depend on the designer and builder in taking advantage of the static and dynamic characteristics of this new material.

1.7.1 Infrastructure Advancements:

Fibre-reinforced concrete (FRC) has brought about significant advancements in various infrastructure projects, notably in runways, aircraft parking, and pavements [17]. By incorporating fibres into the concrete mix, these structures exhibit enhanced durability and load-bearing capacity compared to conventional concrete. For instance, in the construction of runways and aircraft parking areas, FRC slabs with reduced thickness demonstrate equivalent performance to thicker conventional slabs, thereby optimizing material usage and reducing construction costs.

Figure 1. 12 Fibre reinforced pavement

1.7.2 Enhancing Structural Stability:

One of the critical applications of FRC lies in tunnel lining and slope stabilization [18]. The use of FRC in these contexts has revolutionized construction practices by eliminating the need for traditional reinforcement methods like mesh reinforcement and scaffolding. This not only accelerates construction timelines but also enhances structural stability and safety in underground and slope environments. Moreover, FRC's resistance to blast and shock waves makes it invaluable in the construction of blast-resistant structures, mitigating potential damages in high-risk areas.

Figure 1. 13 Fibre reinforced concrete tunnel segments

1.7.3 Innovative Construction Techniques:

Fibre-reinforced concrete is ideal for thin-section shapes, where traditional reinforcement placement would pose challenges. Additionally, spraying FRC enables the creation of irregularly shaped products. FRC serves as a viable alternative to plain concrete, offering significant weight savings with thinner sections while maintaining equivalent strength to thicker plain concrete sections. Subsequent sections will delve into the various applications [19]

FRC enables the adoption of innovative construction techniques, facilitating the fabrication of thin-shell structures, walls, pipes, and manholes [20]. By leveraging the structural properties of fibres, designers and builders can create intricate and resilient structures with reduced material thickness. This not only enhances structural efficiency but also minimizes material consumption and construction time. Additionally, FRC reinforces concrete pipes and manholes, enhancing their strength and longevity while reducing the risk of handling damages during installation and transportation.

Figure 1. 14 Thin shell FRC structure in Valencia, Spain

In conclusion, the diverse applications of fibre concrete underscore its transformative impact on modern construction practices. From infrastructure enhancements to structural stability and innovative construction techniques, FRC offers a versatile and efficient solution for addressing the evolving needs of the construction industry.

1.8. Challenges and Limitations:

The integration of aluminium fibres into concrete presents a promising avenue for enhancing the mechanical properties and performance of concrete structures. However, despite its potential benefits, aluminium fibre reinforced concrete (AFRC) encounters several challenges and limitations that hinder its widespread adoption and implementation in construction practices.

1.8.1 Cost Considerations:

Cost remains a significant barrier to the widespread use of AFRC. The cost of fibre-reinforced polymers (FRPs), including aluminium fibres, can be prohibitively high, particularly when considering factors such as procurement, transportation, and installation costs. Additionally, the cost of delivering a unit of force can vary significantly depending on location, order quantity, and the form in which the material is supplied. These cost considerations can render AFRC economically unfeasible for many construction projects, limiting its application in the industry.

Brittleness and Failure Mode:

Brittleness is a fundamental characteristic of aluminium fibres, as with other FRPs. While these fibres possess high strain capacities, their brittle nature introduces challenges in the structural behavior of AFRC. Unlike steel reinforcements, which exhibit ductile behavior and allow for redistribution of loads upon failure, the failure of brittle aluminium fibres can result in sudden and catastrophic failure of the entire structure. This inherent brittleness compromises the anticipated strength and reliability of AFRC, raising significant safety concerns in structural applications.

1.8.2 Microstructural Challenges:

The microstructural characteristics of AFRC also pose challenges to its performance. Aluminium fibres introduce complexities such as stress rupture, a phenomenon where fibres experience creep deformation leading to failure over time. Unlike traditional concrete, which exhibits relatively stable behavior under load, AFRC's susceptibility to stress rupture undermines its predictability and reliability in structural analysis and design. Understanding and mitigating these microstructural challenges are essential for ensuring the long-term durability and performance of AFRC structures.

The compatibility of composite fibres with the concrete matrix is another drawback. To ensure effective fibre adhesion to the matrix, the characteristics of the fibres and the concrete mix must be precisely matched. Composite reinforcements may be less effective and less durable due to incompatibility [21]

- ***Lack of Comprehensive Analysis Methods:***

A notable limitation of AFRC is the absence of comprehensive and standardized analysis methods. Despite advancements in material science and structural engineering, there is a lack of universally accepted methodologies for evaluating the behaviour of AFRC structures. Existing analysis methods often fail to accurately capture the unique characteristics and performance aspects of AFRC, leading to uncertainties in design and performance prediction. Developing robust analysis methods tailored to the specific properties of AFRC is crucial for ensuring its safe and effective use in construction projects. [22]

Looking ahead, future research should focus on addressing these challenges, further refining optimization techniques, and exploring novel types of fibres for FRC. Additionally, the integration of FRC into construction codes and standards should be encouraged to promote its wider adoption in practice. [23]

1.9. Conclusion :

The exploration of aluminium waste as fibre reinforcement in concrete presents a promising avenue for enhancing the mechanical properties and sustainability of concrete structures. This chapter delved into various aspects of fibre-reinforced concrete (FRC), highlighting its benefits, manufacturing processes, applications, and associated challenges.

The integration of aluminium fibres offers significant environmental advantages by repurposing discarded materials and reducing reliance on virgin resources. Economically, the use of recycled materials in construction can yield long-term cost savings through reduced disposal expenses, energy efficiency, and potential incentives for sustainable practices. Additionally, aluminium fibres enhance the technical properties of concrete, particularly in terms of strength, durability, and structural stability. The Applications of fibre concrete span across infrastructure advancements, structural stability enhancements, and innovative construction techniques, offering versatile solutions to modern construction needs. However, challenges such as cost considerations, brittleness, microstructural complexities, and the lack of comprehensive analysis methods hinder the widespread adoption of aluminium fibre reinforced concrete.

CHAPTER 02: EXPERIMENTAL PROGRAM

2.1. Introduction:

The test program aimed primarily to evaluate the performance of waste aluminium fibre reinforced concrete (FRC) mixtures when subjected to compression and flexure, investigating specific characteristics such as peak compression and bending results. Five types of waste aluminium fibres were utilized at varying volume fractions from 1% to 5%. Each mixture design targeted a strength of 20 MPa without fibres to ensure proper workability. Thirty-six concrete batches (18000 cm^3 for each batch) were prepared, with each batch yielding three 10×10×10 cm cubic moulds for compression tests and three 40×10×10 cm beams for flexural tests. Various tests, were conducted to characterize the properties of the materials employed. Additionally, slump flow and density tests were performed for each batch to assess their fresh-state properties. This chapter offers comprehensive insights into the materials used, mixture designs, specimen preparation, and testing methodologies employed in the study.

2.2. Characterization of Materials Used:

2.2.1 Materials:

- ***Sand:***

Sand from dunes, classified as 0/5, sourced from the Sand Quarry at El Houche, OUM ALI, TEBESSA.

- ***Cement:***

Cement CPJ-CEM 1 42.5 (P-L) originating from the EL MALABIOD TEBESSA cement plant conforms to the Algerian standard NA 442.

Table 2. 1 Characteristics of cement

Standard designation (Mpa)	32,5	42,5	52,5
True class σ 'c (Mpa)	45	55	> 60

- ***Water:***

The mixing water used in the production of concrete mixes comes from the laboratory faucet (regular water).

- ***Gravel:***

There are various sizes of gravel for concrete, and selecting the gravel dimension is crucial as it determines the properties of the concrete in both its fresh and hardened states. We used an aggregate of granular class measuring between 8 and 15 mm, originating from the ELMALABIOD quarry in TEBESSA.

- ***Aluminium waste:***

Our choice of aluminium waste specifically encompasses beverage cans, which are collected and processed into fibres.

Table 2. 2 Characteristics of aluminium waste

Material	form	colour	density
Aluminium waste	Fibres	Silver	2.7

- ***Adjuvant:***

The high water-reducing superplasticizer POLYFLOW SR 5400 was supplied by Soluest products. It enables the production of high-quality concrete and mortar in terms of strength and flowability. In addition to its main function as a superplasticizer, it significantly reduces the water content of the concrete.

Table 2. 3 characteristics of POLYFLOW SR 5400

Characteristics	**Form**	**colour**	**Ph**	**Density**	**Recommended dosage**
Result	liquid	Brown	5 ± 1	1,07 ± 0,02	0.25% to 2.5%

2.2.2 Tests on aggregates:

- ***Particle size analysis:***

It consists of determining the size distribution of the grains constituting the sample using nested sieves, with openings decreasing from top to bottom. The sample under study is placed on the upper sieve, and the classification of the grains is obtained by vibrating the sieve column. [24]

Figure 2. 1 Sieve shaker

The results of the test for the aggregates used are represented by the particle size distribution curves (Sand 0/5; gravel 8/15 and gravel 15/25).

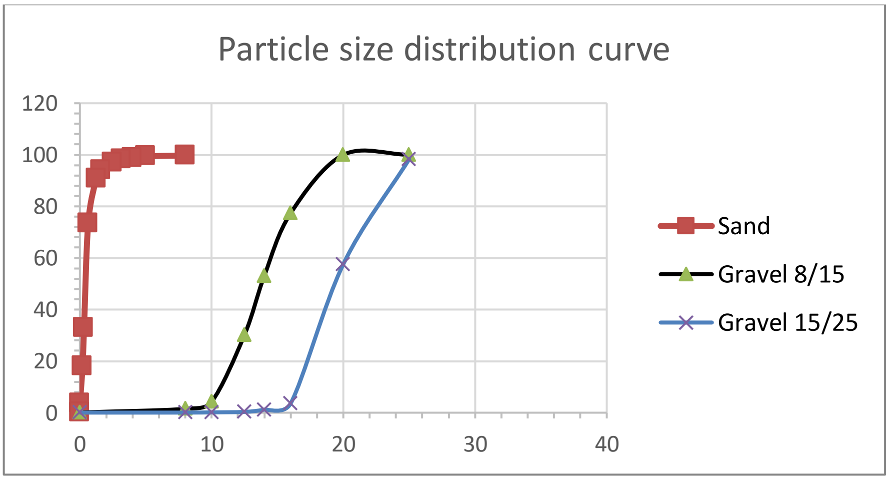

Figure 2. 2 Particle size distribution curve

- ***Apparent and absolute density:***

The density of a material refers to the mass contained within a unit volume of that material. Absolute volume disregards any voids present, whereas apparent volume incorporates both intra- and inter-granular voids.

The results are presented in the table:

Table 2. 4 Absolute and apparent density of aggregates [25]

Material	Absolute density (g/cm3)	Apparent density (g/cm3)
Gravel 8/15	2.56	1.56

Gravel 15/25	2.58	1.62
Sand	2.56	1.58

2.3. Composition of mixtures:

2.3.1 Ordinary concrete: supimer

For the formulation of ordinary (vibrated) concrete, a practical and simplified method known as the "DREUX GORISSE" method was employed. This method offers a straightforward and rapid approach to defining a composition formula tailored to the concrete being investigated. The operational procedure is outlined as follows:

- ***Strength criterion:***

The concrete should be designed such that its average compressive strength at 28 days reaches the characteristic value σ'28j. This value should, as a safety measure, exceed the minimum compressive strength σ28j required for the stability of the structure by at least 15%.

σ'28j = 1.5 σ28j….1

The desired strength for the control concrete at 28 days is:

σ28j=20Mpa….2

Hence, the targeted average strength for the control concrete at 28 days is :

σ'28j =1.5*20=30Mpa….3

- ***Cement and water mix:***

The C/E ratio is determined using the Bolomey formula:

R'28 = G σ'c($\frac{C}{E}$ -0.5)

Hence :

$\frac{C}{E}$ = (R'28 /G σ'c)+0.5

R'28 : Targeted resistance at 28 days.

σ'c : True class of cement.

G : Granular coefficient.

C : Cement mix (Kg of cement /m3 of concrete).

E :Water mix (Kg of water / m3 of concrete or litre of water /m3 of concrete).

Table 2. 5 Quality of aggregates

Quality of aggregates	Dimension Dmax of aggregates		
	Small Dmax< 12,5 mm	Medium 20 <Dmax< 31,5	Large Dmax> 50 mm
Excellent	0,55	0,60	0,65

Good	0,45	0,50	0,55
Fair	0,35	0,40	0,45

Hence: G=0.50 mm.

The selected cement is a CPJ-CEM 1 42.5 (P-L) so :

$$(C/E)=(20/0.5*42.5)+0.5= 1.441$$

Dosage of 1m³ concrete:

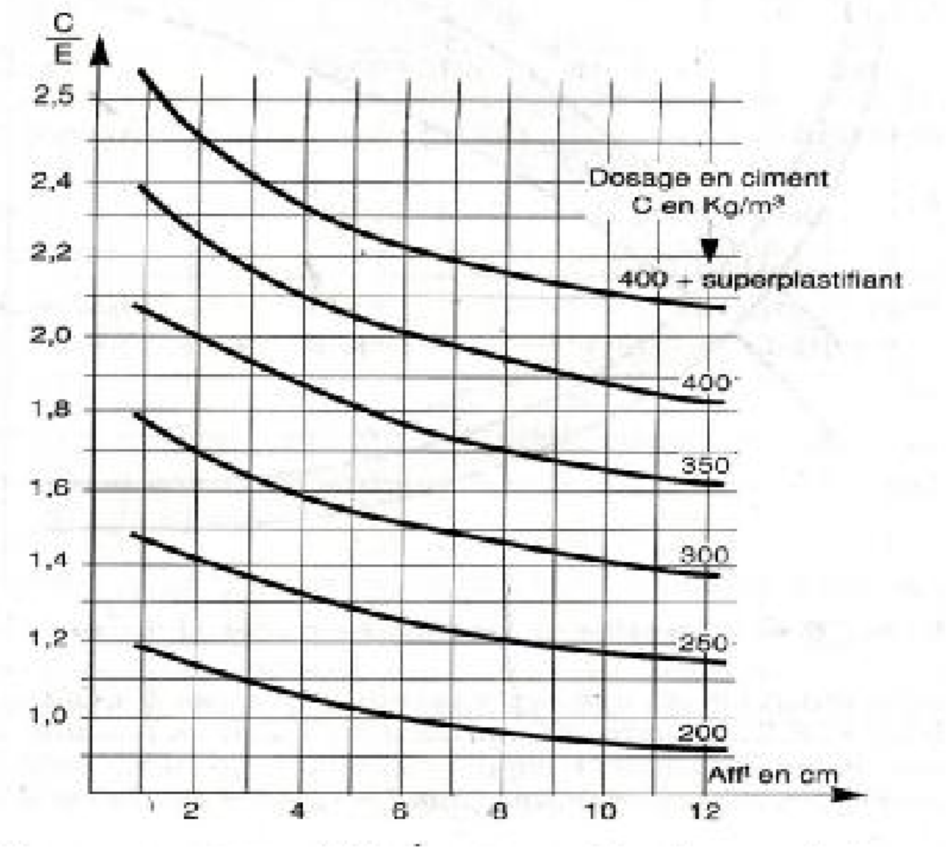

Figure 2. 3 Chart allowing the determination of cement dosage.

C/E=1.441 , A=8cm

So : C=250 kg

E=173.49 kg

- *Reference granular curve:*

This curve corresponds to the combination of sand and gravel aggregates.

On the same granulometric analysis graph (percentage of sieve openings versus sieve module or diameter) previously obtained, we draw a reference granular curve OAB with:

- Point O is located at coordinates: [0.080, 0].
- Point B is located at coordinates: [D, 100], (D: the diameter of the largest aggregate).
- The break point A corresponds to the following coordinates:

➢ *On the x-axis:*

  - If D ≤ 20 mm, the abscissa is at D/2.
  - If D > 20 mm, the abscissa is located midway between the module 38 (5mm) and the module corresponding to D.
  - The largest aggregate has a diameter D = 25 mm, so the break point has an abscissa of:

D/2 = 12.5 mm.

➢ *For the vertical axis:*

It is determined by the following formula: $y = 50 - D + K + Ks + Kp$

Where K is a correction factor dependent on the cement dosage, aggregate shape (rounded or crushed), and compaction efficiency.

The values of the coefficient (K) are listed in the table:

Table 2. 6 Coefficient (K) values

Vibration	Low		Normal		High	
Sand type	Rounded	Crushed	Rounded	Crushed	Rounded	Crushed
400+adj	**-2**	**0**	**-4**	**-2**	**-6**	**-4**
400	**0**	**-2**	**-2**	**0**	**-4**	**-2**
350	**+2**	**+4**	**0**	**+2**	**-2**	**0**
300	**+4**	**+6**	**+2**	**+4**	**0**	**+2**
250	**+6**	**+8**	**+4**	**+6**	**+2**	**+4**
200	**+8**	**+10**	**+6**	**+8**	**+4**	**+6**

➢ Note:

If the fineness modulus is high (indicating coarse sand), an additional adjustment will be made to elevate point A, resulting in an increase in the sand dosage, and vice versa.

The value of Ks is calculated as follows:

Ks = 6Mf – 15 / (Mf is generally either 2 or 3)

K = 0 for C = 350 kg/m³

K = -2 for C = 400 kg/m³

Kp = 0 for non-pumped concrete

For Ks, if the sand fineness modulus is high, an adjustment will be made to raise point A. Mf can range from 2 to 3, with an optimal value around 2.5.

K = 0 when C = 350 kg/m³

K = -2 when C = 400 kg/m³

Kp = 0 for non-pumped concrete

For Ks, if the sand fineness modulus is high, an adjustment will be made to elevate point A. Mf can vary from 2 to 3, with an optimal value around 2,5.

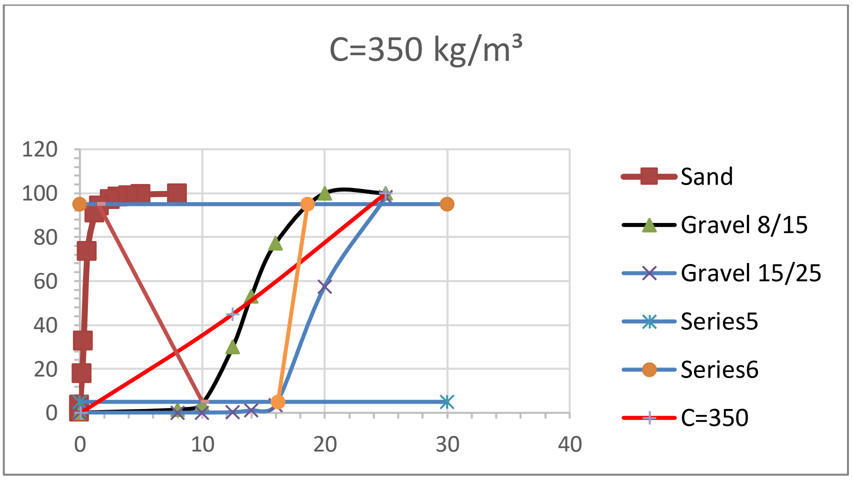

Figure 2. 4 Granulometric curve of cement (C=350 kg/m³)

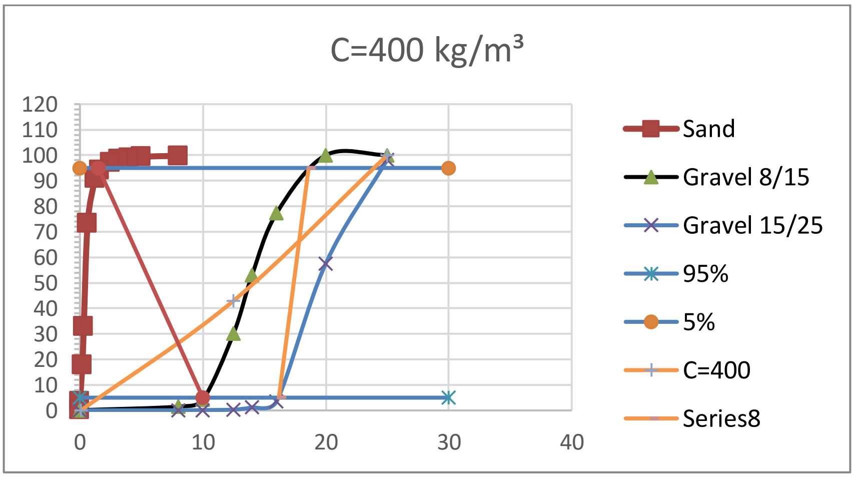

Figure 2. 5 granulometric curve of cement (C=400 kg/m³)

Table 2. 7 Ordinary concrete aggregate percentages

Cement	c=350	c=400
Sand %	27.5	26.4
Gravel 8/15 %	40.5	40.6

Gravel 15/25 %	32	33

- **Compactness coefficient:**

Calculation of the compactness coefficient “Y”:

The compactness coefficient “Y” is the ratio of the volumes of solid materials (cement and aggregates) to the total volume, i.e., 1 m3 of fresh concrete.

Y = Vm/1000

Where:

Vm = Vg + Vs + Vc, expressed in liters.

Vm = Absolute volume of solid materials.

Vg = Volume of gravel.

Vs = Volume of sand.

Vc = Volume of cement.

The absolute volume of the entire cement and aggregates is given through the compactness coefficient. Table 2.8 provides the specific values of this coefficient.

Table 2. 8 Coefficient of compactness values [25].

Consistency	Tightening	Compactness coefficient						
		Dmax =5	Dmax =8	Dmax=12.5	Dmax=20	Dmax=31.5	Dmax=50	Dmax=80
soft	Stitching	0.750	0.780	0.795	0.805	0.810	0.815	0.820
	Low vibration	0.755	0.785	0.800	0.810	0.815	0.820	0.825
	Normal vibration	0.760	0.790	0.805	0.815	0.820	0.825	0.830
Plastic	stitching	0.760	0.790	0.805	0.815	0.820	0.825	0.830
	Low vibration	0.765	0.795	0.810	0.820	0.825	0.830	0.835

	Normal vibration	0.770	0.800	0.815	0.825	0.830	0.834	0.840
	powerful vibration	0.775	0.805	0.820	0.830	0.835	0.840	0.845
Firm	Low vibration	0.775	0.805	0.820	0.830	0.835	0.840	0.845
	Normal vibration	0.780	0.810	0.825	0.835	0.840	0.845	0.850
	powerful vibration	0.785	0.815	0.830	0.840	0.845	0.850	0.855

Vm=Vg+Vc+Vs

D=20mm, y=0.825

D=25mm, y=x

D= 31.4mm, y=0.827

31.5-20 = 11.5 => y=0.005

5 => x

y=0.827

- **supplementary correction:**

Ycos = Y-0.03= 0.797

c=C/3.1

c=350/3.1=112.9L

V=1000y-c

=1000*0.797-112.9=684,1L

c=400/3.1 =129.03L

V = 1000*0.797-129.03= 667,97L

- **Absolut volume :**
- **Sand :**

C=350 => 684.1*(27.5/100)= 188.128L

C=400 => 667.97*(26.4/100) = 176.344 L

- **Gravel 8/15 :**

C=350 => 684.1*(40.5/100) = 277.061L

C=400 => 667.97*(40.6/100) = 271.196L

- **Gravel 15/25 :**

C=350 => 684.1*(32/100) = 281.912 L

C=400 => 667.97*(33/100) = 225.753L

Table 2. 9 composition of ordinary concrete (c=350 kg/m^3)

Materials	Absolute density	Kg/m^3	Apparent density	L/m^3
Sand	2.56	297.242	1.58	188.128
Gravel 8/15	2.56	432.215	1.56	277.061
Gravel 15/25	2.56	453.878	1.62	281.912
Water	1	173.49	1	173.49
Cement	3.1	350	3.1	112.9

Table 2. 10 composition of ordinary concrete (c=400 kg/m^3)

Materials	Absolute density	Kg/m^3	Apparent density	L/m^3
Sand	2.56	258.624	1.58	176.344
Gravel 8/15	2.56	423.066	1.56	271.196
Gravel 15/25	2.56	365.72	1.62	225.753
Water	1	173.49	1	173.49
Cement	3.1	400	3.1	129.03
W/C	/	0.434	/	1.345

2.3.2. Self-compacting concrete formulation:

Currently, most formulations for Self-compacting concrete are empirical in nature. The Dreux-Gorisse method, lacking consideration for admixtures and additives, proves unsuitable. Hence, formulations rely on accumulated experience [24]. The formulation approach employed in this experimental study for designing SCC compositions is based on four key points:

- The volume of aggregates is limited by maintaining a G/S ratio (mass of gravels to mass of sand) close to 1.
- Cement dosage of 400 kg/m^3
- Entrapped air volume (A) is approximately 5%

- The dosage of superplasticizer is determined based on the recommended doses and fluidity (as indicated by the slump test). Our target is a slump flow of 600 to 750 mm.

- The dosage of superplasticizer is determined experimentally based on the formulation of ordinary concrete. maintaining identical cement quantities and granular proportions. The aim is to find ordinary concrete with high, fluidity, and a G/S ratio close to 1, then add the admixture until achieving SCC. It's important to note that only one parameter can be changed, hence the preservation of the same granular proportions and cement dosage
- To compare the performance of different concretes independently of the cement's influence, the cement dosage was set at 400 kg/m³.
- The G/S ratio is set at 1 to increase the amount of sand, which ensures better stability and provides a sufficient quantity of mortar, thereby reducing the amount of coarse aggregates to avoid the risk of blockage.

Gravel (G) + Sand (S) + Cement (C) + Water (W) + Air (A) + aluminium fibres (Af) =1000l

2.4. Mixing and Preservations:

The mixing process is relatively simple and straightforward. For each batch, dry aggregates and aluminium fibres are first placed inside the blender (Figure 2.6) and mixed.

Figure 2. 6 Laboratory blender

Afterwards, water and superplasticizer are added to the mix. The final mixture is then poured into pre-oiled moulds (3 cubes and 3 prisms), which are left to dry for approximately 24 hours before demoulding. Specimens are then marked and left curing in water for 28 days.

Figure 2. 7 Concrete samples curing in water

For each series, mix quantities are calculated for 18000 cm3

Figure 2. 8 Cubic mould (10*10*10 cm^3)

Figure 2. 9 Prismatic mould (10*10*40 cm^3)

- ***1st series:***

Af= 1% C = 4 kg/m3 = 4/2.7 = 1.482 l/m3

A= 5 l/m3

W/C= 0.434, C=400 kg/m3 = 400/3.1 = 129.03 l/m3

W=173.49 l/m3

G+S=1000-129.03-173.49-5-1.482= 690.1 l/m3

G/S=1 so G=S = 690.1/2 = 345.05 l/m3

Sp= 1.5 % C = 6 kg/m3 = 6/1.07 = 5,61 l/m3

Table 2. 11 composition of SCC (1st series)

Componants	l/m^3	absolute density	kg /m^3
Af	0.02223	2.7	0.060021
G	5.175	2.56	13.249
S	5.175	2.56	13.249
W	2.60	1	2.60
C	1.93545	3.1	5.999895
Sp	0.08415	1,07	0.090041

- ***2nd series:***

Af=2% C = 8kg/m3 = 8/2.7 = 2.96 l/m3

A= 5 l/m3

W/C= 0.494, C=400 kg/m3 = 400/3.1 = 129.03 l/m3

W=173.49 l/m3

G+S=1000-129.03-173.49-5-2.96= 689.52 l/m3

G/S=1 so G=S= 344.76 l/m3

Table 2. 12 Composition of SCC (2^{nd} series)

Componants	l/m³	absolute density	kg /m³
Af	0.017778	2.7	0.11988
G	5.1714	2.56	13.239
S	5.1714	2.56	13.239
W	2.60	1	2.60
C	0.77418	3.1	5.999895
Sp	0.08415	1,07	0.0900405

- ***3^{rd} series:***

Af=3% C =12kg/m3= 12/2.7= 4.444 l/m3

A= 5%

W/C= 0.494, C=400 kg/m3 = 400/3.1 = 129.03 l/m3

W=173.49 l/m3

G+S=1000-129.03-173.49-5-4.444= 688.036 l/m3

G/S=1 so G=S= 344.018 l/m3

Table 2. 13 composition of SCC (3^{rd} series)

Componants	l/m³	absolute density	kg /m³
Af	0.026664	2.7	0.179982
G	5.1612	2.56	13.213
S	5.1612	2.56	13.213
W	2.60	1	2.60
C	0.77418	3.1	5.999895
Sp	0.08415	1,07	0.0900405

- ***4^{th} series:***

Af= 4% C = 16 kg/m3 = 16/2.7 = 5.926 l/m3

A= 5%

W/C= 0.494 , C=400 kg/m3 = 400/3.1 = 129.03 l/m3

W=173.49 l/m3

G+S=1000-129.03-173.49-5-5.926 = 686.551 l/m3

G/S=1 so G=S= 343.276 l/m3

Table 2. 14 composition of SCC (4th series)

Componants	l/m³	absolute density	kg /m³
Af	0.035556	2.7	0.240003
G	5.14914	2.56	13.1818
S	5.14914	2.56	13.1818
W	2.60	1	2.60
c	0.77418	3.1	5.999895
Sp	0.08415	1,07	0.0900405

- ***5th series:***

Af= 5 % C = 20 kg/m3 = 20/2.7 = 7.407 l/m3

A= 5%

W/C= 0.494 , C=400 kg/m3 = 400/3.1 = 129.03 l/m3

W=173.49 l/m3

G+S=1000-129.03-173.49 -5-7.407 = 684.074 l/m3

G/S=1 so G=S= 342.037 l/m3

Table 2. 15 composition of SCC (5th series)

Componants	l/m³	absolute density	kg /m³
Af	0.044442	2.7	0.2999835
G	5.1306	2.56	13.1342
S	5.1306	2.56	13.1342
W	2.60	1	2.60
c	0.77418	3.1	5.999895
Sp	0.08415	1,07	0.0900405

- **6th series:**

Af = 0%

A= 5%

W/C= 0.494 , C=400 kg/m3 = 400/3.1 = 129.03 l/m3

W=173.49 l/m3

G+S=1000-129.03-173.49-5 = 692.48 l/m3

G/S=1 so G=S= 346.24 l/m3

Table 2. 16 composition of SCC (6^{th} series)

Componants	l/m^3	absolute density	kg $/m^3$
Af	0	2.7	0
G	5.1936	2.56	13.2956
S	5.1936	2.56	13.2956
W	2.60	1	2.60
C	1.93545	3.1	5.999895
Sp	0.08415	1,07	0.090041

2.5. Fresh state tests:

2.5.1 Slump Flow Test:

A fresh batch of concrete is poured into a mould designed in the shape of a frustum of a cone. Without any additional compaction, the concrete is allowed to settle naturally after the mould is removed. Once the spreading process stops, two perpendicular diameters of the concrete are measured, and the average of these diameters is recorded as the slump flow. This test is employed to assess the consistency and flow potential of freshly mixed self-consolidating concrete before it hardens [26]. It’s important to note that self-compacting concrete is characterized by forming a disc with a diameter between 60 and 75 centimetres.

Figure 2. 10 Abrams cone

2.5.2 Concrete Density:

Fresh concrete is poured into a 1-liter measuring pot, and its weight is recorded. Subsequently, the density (represented by the symbol γ) is determined using the equation

$\gamma = \frac{\text{weight}}{\text{volume}}$.

This equation allows for the calculation of density based on the weight and volume of the concrete sample.

Figure 2. 11 Concrete density test

2.6. Tests carried out in Hardened-State:

2.6.1 Uniaxial Compression Test:

The uniaxial strength, frequently denoted as the unconfined compressive strength, of a concrete specimen can be characterized as the utmost stress capacity showcased when subjected to a unidirectional force, commonly applied along the axial direction of a cylindrical sample. This pivotal strength attribute encapsulates the maximum load sustainability of a specimen throughout the experimental assessment, divided by the cross-sectional area of the specimen, serving as a fundamental indicator of its structural integrity and load-bearing capability under uniaxial stress conditions [27].

The maximum load reached, denoted as P (MN), and the loading surface area, denoted as S (m^2), allow us to calculate the maximum stress (compressive strength) as follows:

$$\sigma c \text{ (MPa)} = P / S$$

The test was carried out using “Controls” manual compression machine with a maximum force of 1500 KN (Figure 2.12).

Figure 2. 12 Uniaxial compression machine

2.6.2 Flexure Test:

The two-point loading test is a method used to determine the flexural strength of hardened concrete specimens. This method, described by the British Standards Institution, involves applying a load to the centre zone of the specimen using a two-point loading arrangement [28]. In this test, the concrete specimen is placed in the flexural testing machine with two supports (Figure 2.13), which are considered as simply supported conditions. The load is applied at the centre of the specimen and transmitted to two points until the specimen fails. The load is directly measured by the testing machine and displayed on the machine's screen.

This setup ensures that the moment is concentrated in the centre zone of the specimen, allowing for an accurate determination of the flexural strength. The schematic diagram in Figure 2.12 illustrates the arrangement of the specimen, supports, and loading points.

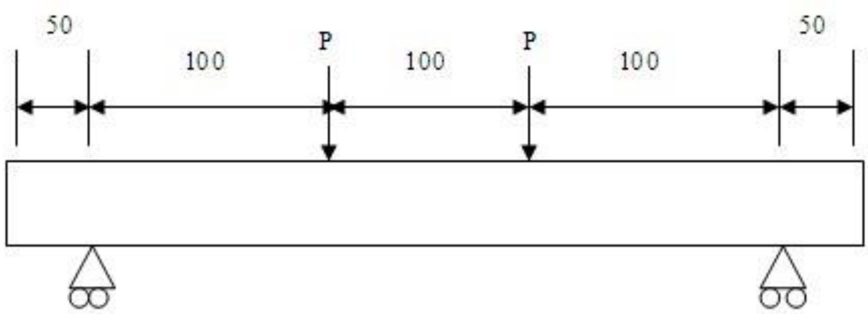

Figure 2. 13 Two-point loading test arrangement

Figure 2. 14 Flexure test machine

2.7. Conclusion:

This chapter provided a comprehensive account of the experimental program designed to evaluate the performance of waste aluminium fibre reinforced concrete (FRC) mixtures concerning their compressive and flexural properties. The study incorporated five distinct types of aluminium fibres, each introduced at varying volume fractions ranging from 1% to 5%, into concrete mixtures formulated to achieve a baseline strength of 20 MPa in the absence of fibres. Extensive testing protocols were applied to assess the materials, mixtures, and the specimens prepared from these mixtures. This included evaluations of fresh-state properties such as slump flow and density, ensuring a thorough understanding of the workability and homogeneity of the concrete mixtures. The experimental framework involved the preparation of 36 concrete batches. Each batch yielded three cubic and three prismatic specimens, which were systematically tested to gather reliable data on their performance under compression and flexure.

The results and observations from these tests provided valuable insights into the characteristics and behaviours of waste aluminium fibre reinforced concrete. This comprehensive experimental study not only highlighted the potential of using waste aluminium fibres in concrete but also established a solid foundation for the detailed analysis of their mechanical properties, which will be further explored in the subsequent chapters. Through meticulous experimentation and analysis, this chapter sets the stage for a deeper understanding of the potential benefits and applications of waste aluminium fibre reinforced concrete in construction and engineering.

CHAPTER 03: EXPERIMENTAL RESULTS AND DISCUSSIONS

Introduction:

This chapter provides an overview of the experimental findings, with detailed data presented. Initially, key properties of freshly mixed self-compacting concrete based on waste aluminium fibres, such as density and slump flow, are outlined. Subsequently, the results from uniaxial compression, flexural, and direct tension tests are summarized. Additionally, the chapter delves into a discussion of these results, starting with an analysis of self-compacting fibre reinforced concrete (SCFRC) properties in their fresh state. It then proceeds to discuss findings from the uniaxial compression and flexure.

Fresh state tests:

Slump flow test:

Figure 3. 1 Slump flow test on SCC

Table 3. 1 Slump flow test values

Series	1	2	3	4	5	6
Slump flow (mm)	650	660	655	643	640	667
Density (Kg/m³)	2207	2213.5	2219.7	2225	2230	2200

Concrete density:

Table 3. 2 Density values of each series

Series	1	2	3	4	5	6
Density (Kg/m³)	2207	2213.5	2219.7	2225	2230	2200

Hardened state tests:

3.3.1 Uniaxial Compression Test

Compression tests are conducted on cubic specimens (10x10x10) cm^3 using a hydraulic press with a maximum capacity of 15000 KN (see Figure). Compression strength was assessed according to the NF P 18-406 standard.

Tests were performed at a loading rate of 0.5 MPa/s.

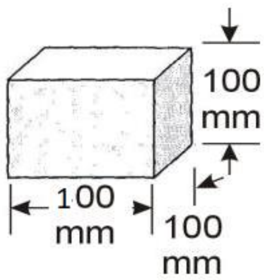

Figure 3. 2 Section details of cubic mold

- ***Test results:***

Test results are as follows:

Table 3. 3 Uniaxial Compression test results of AFC specimen

Series		Fc28(MPa)			Average
	Af %	1	2	3	
1	0	24.6	18.5	22.5	21.87
2	1	24.7	24.4	25.4	24.83
3	2	25.6	25.5	26.5	25.87
4	3	25.9	25.6	26.2	25.9
5	4	15.7	25.3	18.7	19.9
6	5	21.4	17.5	17.8	18.9

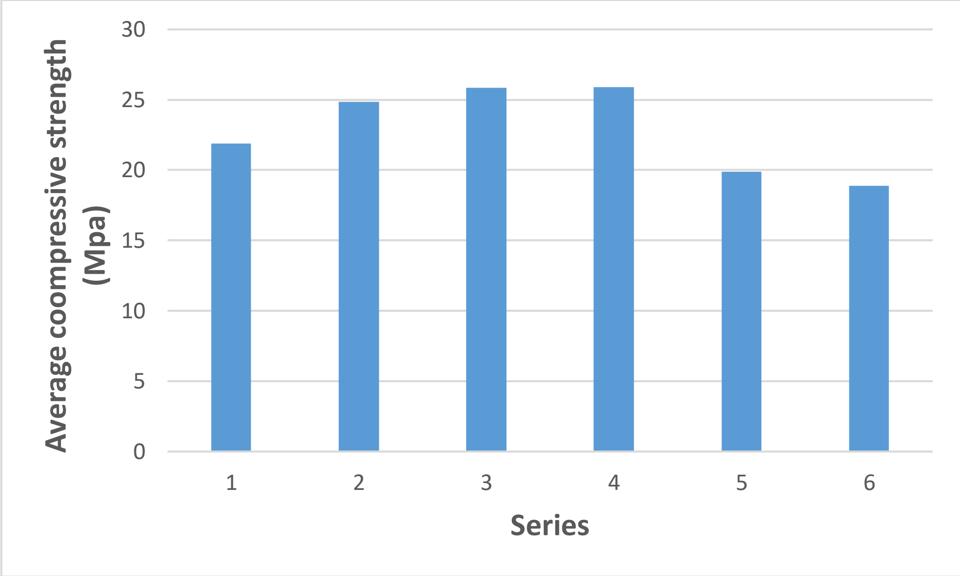

Figure 3. 3 Comparison of average compressive strength of test specimen

- ***Failure Description:***

  - ***Control Series (0% Aluminium Fibres):***

The specimens in Series 0, which did not contain any aluminium fibres, exhibited typical brittle failure. Cracks initiated across the specimens and propagated rapidly, resulting in a sudden and explosive failure. The average compressive strength for this series was 21.87 MPa.

Figure 3. 4 Typical brittle failure of test specimen

- ***Series with 1-4% Aluminium Fibres:***

For Series 2 (1% fibres), Series 3 (2% fibres), Series 4 (3% fibres), and Series 5 (4% fibres) the presence of aluminium fibres appeared to enhance the structural integrity of the concrete under compressive loads. The failure mode in these series was less explosive compared to the control series. The cracks propagated more slowly, and the fibres seemed to bridge the cracks, delaying complete failure. The average compressive strengths for these series were 24.83 MPa, 25.87 MPa, 25.90 MPa and 19.9 MPa respectively, indicating a positive effect of aluminium fibres on specimen integrity and failure behavior. However, the average strength of the specimen seems to take a downward slope indicating decreasing resistance to loading forces.

Figure 3. 5 enhanced structural integrity of concrete compared to previous specimens

- ***Series with 5% Aluminium Fibres:***

In Series 6 (5% fibres), the specimens exhibited a combination of brittle and ductile failure modes. Similar to Series 5, the results were inconsistent. Some specimens showed improved post-cracking behavior due to fiber bridging, while others failed more abruptly. The average compressive strength for this series was 18.9 MPa. This suggests that an optimal fiber content might exist below 5%, as higher fiber content did not consistently enhance performance and may have introduced flaws.

3.3.2 Flexural Test:

Eighteen beam specimens measuring 400×100×100 mm were cast and subjected to testing under normal conditions, with and without the inclusion of fibres. These specimens were divided into six series: 1, 2, 3, 4, 5, and 6.

6th series comprised three control specimens labelled 6A, 6B, and 6C, which did not contain any fibres. 1st series included three specimens labelled 1A, 1B, and 1C, where 1% soft drink/aluminium can fibres were added to the concrete mix.

Similarly, series 2, 3, 4, and 5 consisted of specimens labelled 2A, 2B, 2C, 3A, 3B, 3C, 4A, 4B, 4C, 5A, 5B and 5C, where 2%, 3%, 4%, and 5% of soft drink tin fibres, respectively, were incorporated into the concrete mix.

Experimental testing involved placing the prisms on a loading frame and utilizing a two-point loading system, as depicted in Figure.

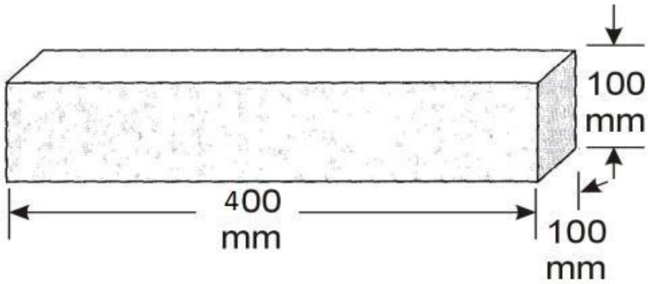

Figure 3. 6 Section details of prism mold

- ***Test results:***

Test results are as follows:

Table 3. 4 Flexural test results of AFC specimen

Series	Af %	1		2		3		Average Peak load (KN)	Average flexural strength (MPa)
		Peak (KN)	Ft28 (MPa)	Peak (KN)	Ft28 (MPa)	Peak (KN)	Ft28 (MPa)		
1	0	18.96	2.13	12.49	1.4	12.15	1.36	14.54	1.63
2	1	19.29	2.17	15.81	1.77	13.28	1.49	16.13	1.81
3	2	17.23	1.93	18.57	2.08	16.19	1.82	17.33	1.94
4	3	18.59	2.09	20.56	2.31	15.87	1.78	18.34	2.06
5	4	15.27	1.71	18.68	2.10	16.39	1.84	16.78	1.88
6	5	16.04	1.8	13.76	1.54	15.27	1.71	15.03	1.68

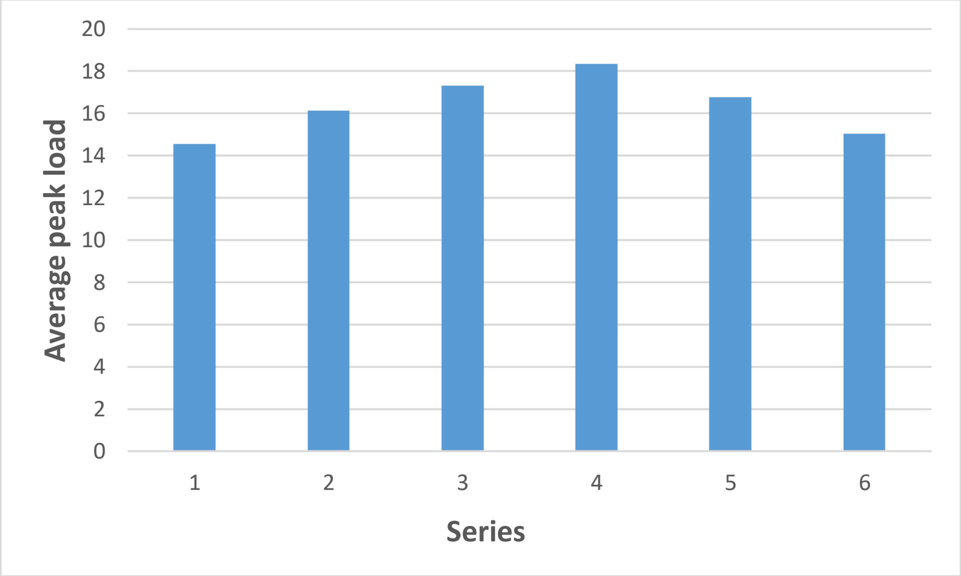

Figure 3. 7 Comparison of average peak load of test specimen

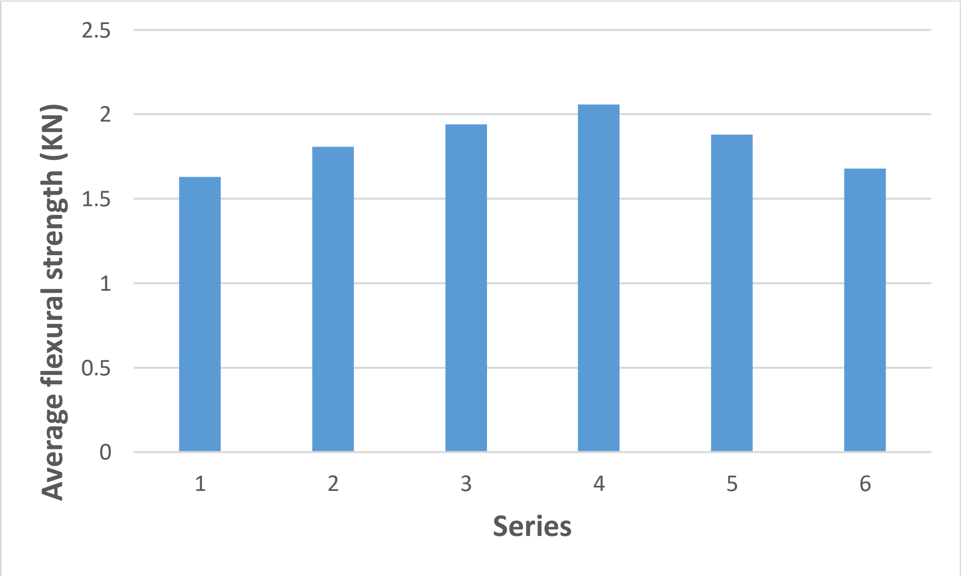

Figure 3. 8 Comparison of average flexural strength of test specimen

Load-Primary Crack Behaviour:

The primary crack load behavior in the flexural test results for self-compacting concrete with varying percentages of aluminium fibres reveals significant insights into the material's performance under stress.

- ***Series 1 (0% Aluminium Fibres):***

- The primary cracks began to appear at loads of 14.06 kN, 9.99 kN, and 9.12 kN, which correspond to 74%, 80%, and 75% of the peak loads, respectively. This indicates a relatively early onset of cracking, reflecting the absence of reinforcing fibres.

- ***Series 2 (1% Aluminium Fibres):***

- Primary cracks appeared at 14.66 kN, 13.30 kN, and 10.23 kN, representing approximately 76%, 84%, and 77% of the peak loads. The addition of 1% aluminium fibres delayed the appearance of primary cracks slightly compared to Series 1, enhancing the material's initial crack resistance.

- ***Series 3 (2% Aluminium Fibres):***

- The primary cracks were observed at loads of 14.13 kN, 15.51 kN, and 11.66 kN, corresponding to 82%, 84%, and 72% of the peak loads. With 2% aluminium fibres, the onset of primary cracks was further delayed, showing improved performance and higher crack resistance.

- ***Series 4 (3% Aluminium Fibres):***

- Primary cracks appeared at 14.11 kN, 17.69 kN, and 12.14 kN, which are about 76%, 86%, and 76% of the peak loads. The 3% fibre content demonstrated the highest delay in primary crack formation, highlighting the optimal reinforcing effect of aluminium fibres.

- Series 5 (4% Aluminium Fibres):

- The primary cracks were observed at 12.36 kN, 14.08 kN, and 12.96 kN, corresponding to 81%, 75%, and 79% of the peak loads. Increasing the fibre content to 4% still provided good crack resistance, though not significantly better than 3%.

- ***Series 6 (5% Aluminium Fibres):***

- Primary cracks began at 12.83 kN, 10.32 kN, and 12.37 kN, representing approximately 80%, 75%, and 81% of the peak loads. At 5% fibre content, the material's performance in delaying crack initiation was comparable to that of 4%, indicating potential issues with fibre distribution and workability at higher percentages.

Peak Strength:

The flexural test results revealed a notable increase in peak strength with the addition of aluminium fibres to the self-compacting concrete specimens. The control series without fibres achieved a peak flexural strength of 2.13 MPa. With the introduction of 1% aluminium fibres, the peak strength increased slightly to 2.17 MPa, indicating a modest improvement. As the fibre content increased to 2%, the peak strength rose further to 2.08 MPa, showing a continued positive trend. The most significant enhancement was observed in the series with 3% aluminium fibres, which achieved the highest peak flexural strength of 2.31 MPa. This suggests that 3% fibre content provides optimal reinforcement, maximising the flexural performance.

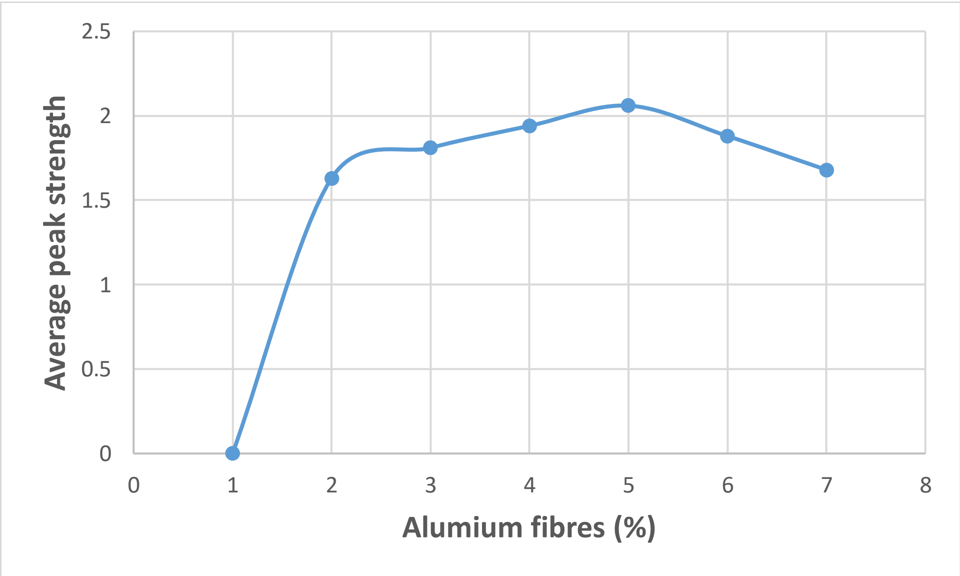

Figure 3. 9 Average Peak Flexural Strength of Concrete Specimens with Varying Aluminum Fiber Content

However, further increasing the fibre content to 4% and 5% led to a slight decline in peak strength to 2.10 MPa and 1.80 MPa, respectively, indicating that excessive fibres may hinder performance due to potential issues with fibre distribution. Overall, the addition of aluminium fibres up to 3% significantly improved the peak flexural strength of the concrete specimens.

Failure Description:

- ***Control Series (0% Aluminium Fibres):***

In Series 1, which did not contain any aluminium fibres, the specimens primarily exhibited brittle failure. Cracks initiated at the bottom surface of the specimen (tension side) and propagated quickly to the top surface, resulting in sudden and complete fracture. The average peak load for this series was 14.54 KN, and the average flexural strength was 1.63 MPa.

Figure 3. 10 Brittle failure of test specimen

- ***Series with 1% Aluminium Fibres:***

Series 2 (1% fibres) demonstrated a more ductile failure compared to the control series. The presence of aluminium fibres helped in crack bridging, which slowed down the crack propagation. The specimens exhibited multiple cracking before final failure, indicating improved post-cracking behaviour. The average peak load was 16.13 kN, and the average flexural strength was 1.81 MPa.

- ***Series with 2% Aluminium Fibres:***

In Series 3 (2% fibres), the specimens showed further improvement in ductility. The aluminium fibres effectively delayed the complete separation of the cracked sections. The cracks were finer and more distributed, which helped in maintaining the structural integrity of the specimens under load. The average peak load for this series was 17.33 KN, and the average flexural strength was 1.94 MPa.

- ***Series with 3% Aluminium Fibres:***

Series 4 (3% fibres) exhibited the most enhanced ductile failure behavior. The specimens showed significant resistance to crack propagation due to the higher content of aluminium fibres. Multiple cracks were observed, and the fibres effectively held the cracks together, delaying the final failure. This series had the highest average peak load of 18.34 kN and an average flexural strength of 2.06 MPa, indicating the optimal performance of the concrete mix with 3% aluminium fibres.

- ***Series with 4% Aluminium Fibres:***

In Series 5 (4% fibres), the specimens displayed inconsistent failure patterns. Some specimens showed good ductility, while others failed in a more brittle manner. This variability suggests potential issues with fiber distribution or fiber clumping, which could have affected the overall performance. The average peak load was 16.78 kN, and the average flexural strength was 1.88 MPa.

- ***Series with 5% Aluminium Fibres:***

Series 6 (5% fibres) also exhibited inconsistent failure modes, similar to Series 5. While the aluminium fibres contributed to some improvement in ductility, the overall performance was not as reliable. The higher fibre content may have led to difficulties in achieving uniform dispersion within the concrete matrix. The average peak load for this series was 15.03 kN, and the average flexural strength was 1.68 MPa.

Figure 3. 11 Test specimen showing post failure integrity with increased fiber content

Conclusion:

The incorporation of waste aluminium fibres into self-compacting concrete significantly enhances its mechanical properties, particularly in terms of compressive and flexural strength, as well as ductility. The optimal performance was achieved with a 3% fibre content, which provided the best balance between improved strength and ductility. Higher fibre contents (above 3%) did not consistently enhance performance and could introduce issues with fibre dispersion and workability.

These findings suggest that recycling waste aluminium fibres in concrete not only offers a sustainable use for such waste materials but also improves the structural properties of SCC, making it a viable option for construction applications where enhanced durability and performance are required. Further studies could explore the long-term durability and practical applications of this composite material in real-world conditions.

CHAPITER 04:
LINEAR REGRESSION ANALYSIS OF COMPRESSIVE AND FLEXURE STRENGTH

4.1. Introduction:

One of the primary objectives of this study is to establish correlations between the post-peak compressive response and the post-cracking flexural properties of Self-Compacting Fibre Reinforced Concretes (SCFRC). Understanding these relationships is crucial for engineers as it enables them to characterize the mechanical behaviour of SCFRC more effectively, facilitating modelling and design processes based on a limited set of standard tests.

This chapter begins with an analysis of the compressive and flexural test results, exploring how these properties are interrelated. Following this, the discussion extends to the outcomes of compression and tension tests, providing a comprehensive view of the mechanical behaviour of the materials under study.

4.2. Statistical Data Analysis

Statistical analysis serves as a fundamental aspect of data interpretation across various fields, spanning scientific research, business, and social sciences. It encompasses the utilization of mathematical and statistical methods to extract meaningful insights, unveil patterns, and draw inferences from datasets. In the realm of data analysis, researchers employ an array of statistical techniques and tests to compare variables, compute p-values, and ascertain statistical significance. These methodologies furnish a robust framework for deriving dependable conclusions and facilitating well-informed decision-making grounded in empirical evidence [29].

In scientific research, statistical analysis assumes paramount importance for several reasons, elucidating its indispensable role:

- **Data Interpretation**: Statistical analysis enables researchers to unravel complex and extensive datasets systematically. By organizing, summarizing, and scrutinizing data, it facilitates the identification of patterns, trends, and relationships embedded within the dataset.
- **Hypothesis Testing**: Central to scientific inquiry, statistical analysis empowers researchers to subject hypotheses to rigorous testing, thereby facilitating objective decision-making predicated on empirical evidence. Through hypothesis testing, researchers evaluate competing claims or theories, with statistical significance serving as a yardstick to accept or refute hypotheses.
- **Control of Confounding Factors:** Oftentimes, scientific investigations necessitate the control of confounding factors or variables capable of influencing the relationship between

variables of interest. Statistical methodologies like regression analysis and analysis of covariance (ANCOVA) furnish mechanisms to manage confounding variables, thereby enabling researchers to delineate and scrutinize the specific effects of the variables under scrutiny.

- **Error Detection and Quality Control**: Statistical analysis equips researchers with tools for detecting errors, ensuring quality control, and validating data integrity. By pinpointing outliers, inconsistencies, and data discrepancies, statistical techniques facilitate the rectification of errors, thereby upholding the integrity and precision of research findings.

4.3. Correlation Analysis

Correlation is a statistical measure indicating the degree to which two or more variables vary together.

4.3.1 Types of correlation:

There are several ways to describe or classify correlation, but three of the most significant include:

- ***Positive and Negative correlation:***

A positive correlation signifies that the variables increase or decrease in tandem, while a negative correlation indicates that as one variable increases, the other decreases. It is a statistical method revealing the strength and direction of relationships between pairs of variables [30].

- ***Simple, Partial and Multiple Correlation:***

Simple Correlation: This occurs when the study involves only two variables.

Partial Correlation: In partial correlation, the study involves three or more variables, but the focus is on two variables influencing each other while holding the effects of other influencing variables constant.

Multiple Correlation: This type of correlation involves the study of three or more variables simultaneously. [31]

- ***Linear and Non-linear Correlation:***

The correlation can be categorized as either Linear or Non-linear, depending on whether the ratio of change between the variables remains constant or not. [32]

- ***Positive Linear Correlation:***

There is a *positive linear correlation* when the variable on the x-axis increases as the variable on the y-axis increases. This is shown by an upwards sloping straight regression line.

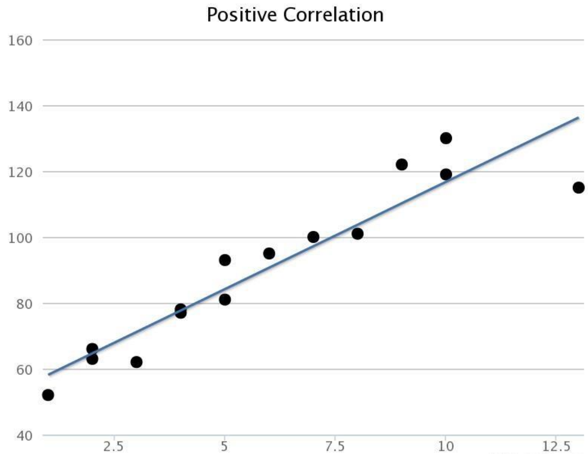

Figure 4. 1 Positive correlation

- ***Negative linear correlation:***

Occurs when one variable increase while the other variable decreases. This relationship is represented by a downward sloping straight regression line.

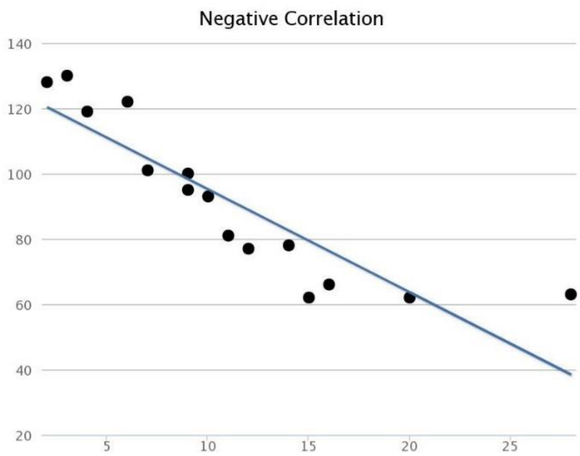

Figure 4. 2 Negative correlation

- ***Non-linear correlation*:**

Also known as curvilinear correlation, refers to a situation where there is a relationship between variables, but this relationship is not linear or straight.

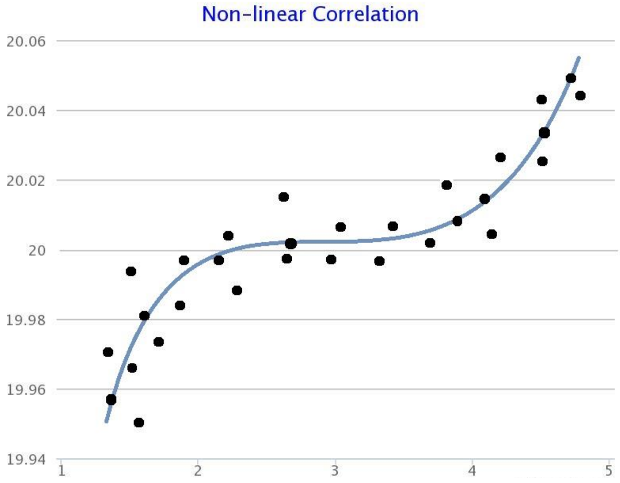

Figure 4. 3 Non-linear correlation

4.3.2 Measurement of correlation:

Quantifying the relationship between variables is crucial to harness the benefits of correlation studies. To achieve this, various methods of measuring correlation are available, as outlined below:

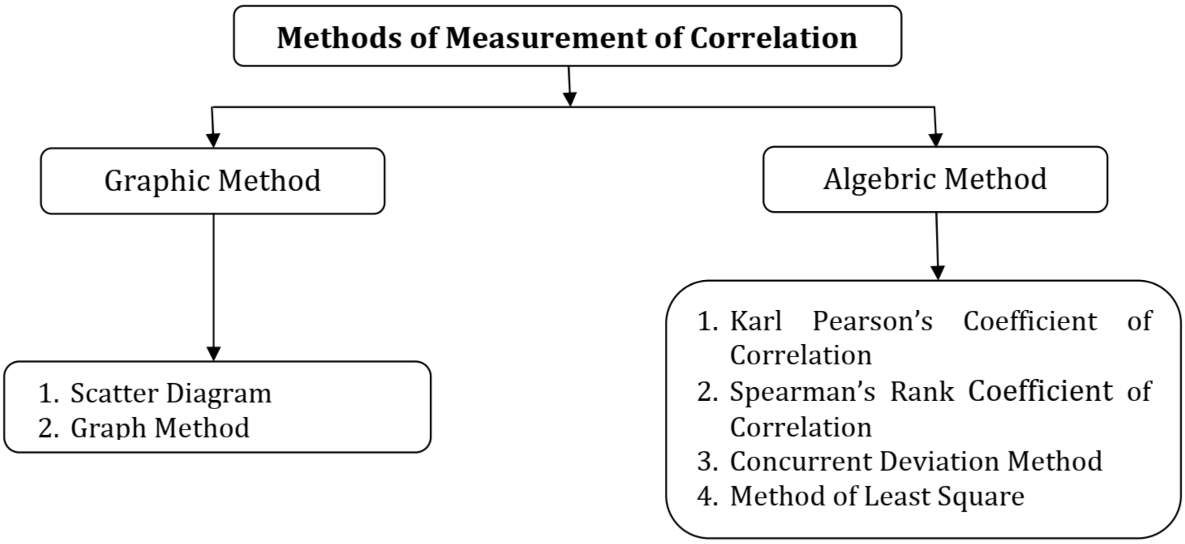

Figure 4. 4 Methods of measurement of correlation [31]

4.4. Regression Analysis

Regression analysis stands as one of the most frequently utilized statistical methods across social and behavioural sciences, as well as physical sciences. It entails the identification and assessment of the relationship between a dependent variable and one or more independent variables [30]. Linear regression, in particular, explores relationships that can be succinctly portrayed by straight lines or expanded to encompass multiple dimensions. This analytical approach proves invaluable in addressing a wide array of problems, with the potential for further enhancement through the transformation of original variables to establish linear relationships among them [33]. Simple linear regression analysis, a subset of regression analysis, involves predicting a continuous dependent variable using a single predictor. This method serves as a descriptive tool, with the primary objective of elucidating the relationship between two variables within a dataset.

4.4.1 Intercept:

The intercept is the point where the regression line intersects the y-axis. It provides a measure of the mean of the dependent variable when the slopes are zero. If the slopes are not zero, the intercept represents the mean of the dependent variable minus the product of the slope and the mean of the independent variable.

4.4.2 Slope:

The slope represents the change in the dependent variable as the independent variable changes. A zero slope indicates that the independent variable has no influence on the dependent variable. In a linear model, the slope is not the same as elasticity, because elasticity measures the percentage change in the dependent variable resulting from a one percent change in the independent variable.

4.4.3 Application:

- ***Mathematical model:***

To mathematically model the relationship between flexural and compressive strength, we employ a linear regression approach [34]. It has been established that the relationship between flexural and compressive strength is linear.

Let's denote compressive strength as "x" and flexural strength as "y." The equation for the linear regression model is represented as follows:

$y = mx + b$

Here, "m" signifies the slope, which represents the change in y for each unit change in x, and "b" indicates the y-intercept, representing the value of y when x is zero.

To determine the values of m and b, we'll calculate them using the given data points, employing the method of least squares to minimize the sum of the squared differences between the predicted values and the actual values.

First, we calculate the mean values for compressive strength ($\bar{x}$) and flexural strength ($\bar{y}$) :

$\bar{x}$ = (25.9+21.87+24.83+18.9+19.9+25.87) / 6 = 22.88 MPa

$\bar{y}$ = (2.06+1.94+1.81+1.88+1.68+1.63) / 6 = 1.84 MPa

Next, we calculate the deviations from the mean for both x and y:

$\Delta x = x - \bar{x}$, $\Delta y = y - \bar{y}$

then, we calculate the sum of the products of the deviations: $\Sigma(\Delta x * \Delta y)$:

$\Sigma(\Delta x*\Delta y)=(25.9-22.88)*(2.06-1.83)+(21.87-22.88)*(1.94-1.83)+(24.83-22.88)*(1.811.83)+$

$(18.9-22.88)*(1.88-1.83)+(19.9-22.88)*(1.68-1.83)+(25.87-22.88)*(1.63-1.83)$

$\Sigma(\Delta x* \Delta y) = 0.1945$

Now, we calculate the sum of the squared deviations for:

$\Sigma(\Delta x^2) = (25.9-22.88)^2 +(21.87-22.88)^2 +(24.83-22.88)^2 +(18.9-22.88)^2 +(19.9-22.88)^2 +$

$(25.87-22.88)^2$

$\Sigma(\Delta x^2) = 47.604$

the slope (m):

$m = \Sigma(\Delta x * \Delta y) / \Sigma(\Delta x\text{^}2)$

$m = 0.1945/47.604 = 0.004086$

y-intercept (b):

$b = \bar{y} - m * \bar{x}$

$b = 1.383-0.004086*22.88$

$b \approx 1.7365$

Therefore, the equation for the linear regression model is: $y \approx 0.004086x + 1.7365$

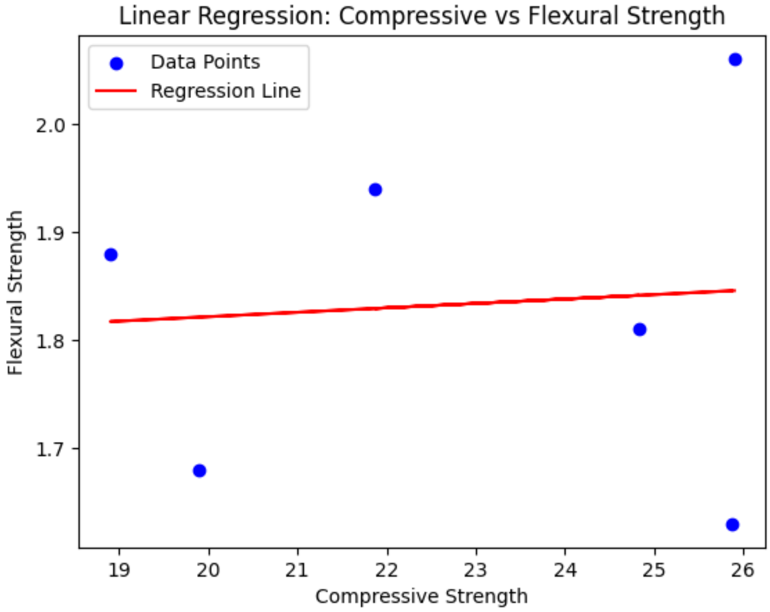

Figure 4. 5 Linear regression graph

- ***Python model:***

To facilitate the mathematical work a Python programme have been used to conduct the linear regression analysis and calculate predicted values for flexural strength using compressive strength test results :

```
import numpy as np
import matplotlib.pyplot as plt
from sklearn.linear_model import LinearRegression

# Function to collect data from the user
def collect_data():
    compressive_strength = []
    flexural_strength = []

    print("Enter the data points (compressive strength and flexural strength):")
    while True:
        comp_input = input("Enter compressive strength (or type 'stop' to finish): ")
        if comp_input.lower() == 'stop':
            break
```

```
        try:
            comp = float(comp_input)
            flex = float(input("Enter flexural strength: "))
            compressive_strength.append(comp)
            flexural_strength.append(flex)
        except ValueError:
            print("Invalid input. Please enter numerical values.")

    return np.array(compressive_strength).reshape(-1, 1), np.array(flexural_strength)

# Function to perform linear regression and plot the data
def perform_regression_and_plot(compressive_strength, flexural_strength):
    # Create and fit the model
    model = LinearRegression()
    model.fit(compressive_strength, flexural_strength)

    # Get the slope (coefficient) and intercept of the line
    slope = model.coef_[0]
    intercept = model.intercept_
    # Print the slope and intercept
    print(f"Slope (coefficient): {slope:.2f}")
    print(f"Intercept: {intercept:.2f}")

    # Print the equation of the line
    print(f"The equation of the line is: Flexural Strength = {slope:.2f} * Compressive Strength + {intercept:.2f}")

    # Predict flexural strength
    flexural_strength_pred = model.predict(compressive_strength)

    # Plot the data points
    plt.scatter(compressive_strength, flexural_strength, color='blue', label='Data Points')
    # Plot the regression line
```

```
    plt.plot(compressive_strength, flexural_strength_pred, color='red', label='Regression Line')

    # Label the plot
    plt.xlabel('Compressive Strength')
    plt.ylabel('Flexural Strength')
    plt.title('Linear Regression: Compressive vs Flexural Strength')
    plt.legend()

    # Show the plot
    plt.show()

def main():
    compressive_strength, flexural_strength = collect_data()
    if len(compressive_strength) > 0 and len(flexural_strength) > 0:
        perform_regression_and_plot(compressive_strength, flexural_strength)
    else:
        print("No data provided. Exiting.")

if __name__ == "__main__":
    main()
```

$$\text{Accuracy} = (\text{Actual Flexure Strength}/\text{Predicted Flexure Strength}) \times 100\%$$

Table 4. 1 Prediction accuracy of flexure strength

Series	Af%	Average compressive strength (MPa)	Average Flexure strength (MPa)	Prediction of flexure strength (MPa)	Accuracy (%)
0	0%	21.87	1.63	1.8275	112.08
1	1%	24.83	1.81	1.8999	104.95
2	2%	25.87	1.94	1.9182	98.94

3	3%	25.9	2.06	1.9189	93.27
4	4%	19.9	1.88	1.8101	96.17
5	5%	18.9	1.68	1.7756	105.63

4.5. Interpretation of Results

The analysis of the predictive accuracy across different series reveals notable insights into the model's performance. In Series 0, the predicted flexure strength exhibits an accuracy of 112.08%, indicating a slight overestimation of approximately 12.08% compared to the actual value. Similarly, Series 1 shows a prediction accuracy of 104.95%, suggesting a slight overestimation of around 4.95%. Conversely, Series 2 demonstrates a prediction accuracy of 98.94%, with the predicted value marginally lower, approximately 1.06%, than the actual value. Series 3 and 4 further underline the model's capability, with prediction accuracies of 93.27% and 96.17%, respectively. Despite minor deviations, the model maintains reasonable accuracy, with predictions falling within 6.73% and 3.83% of the actual values, respectively. Finally, in Series 5, the prediction accuracy reaches 105.63%, indicating a slight overestimation of approximately 5.63%. These results collectively suggest that the model exhibits robust predictive capability across varying air content percentages, with predictions consistently aligning closely with observed data.

4.6. Comparison with Previous Studies

Mechanical Behaviour of Concrete Reinforced with Waste Aluminium Strips [35]

Flexural Strength (y)= 0.0122 + 1.0546 × Tensile Strength(x)

Table 4. 2 Comparison of model's equation prediction accuracy

Series	Af%	Average Split Tensile Strength (MPa)	Average Flexure strength (MPa)	Prediction of flexure strength (MPa)	Accuracy (%)
0	0%	3.49	4.1	4.514	110.1
1	1%	3.75	4.433	4.659	105.1
2	2%	3.86	4.57	4.732	103.54
3	3%	3.89	4.847	4.757	98.14
4	4%	4.03	4.887	4.847	99.18

5	5%	3.92	4.387	4.785	109.07

4.7. Conclusion

In this chapter, the relationship between the compressive and flexural strengths of Self-Compacting Fibre Reinforced Concretes (SCFRC) was rigorously examined through linear regression analysis. The primary objective was to correlate the post-peak compressive response with the post-cracking flexural properties, providing a foundational understanding for engineers to model and design SCFRC structures based on a minimal set of standard tests.

The analysis encompassed a comprehensive statistical evaluation, highlighting:

- the importance of data interpretation, hypothesis testing, control of confounding factors, and error detection in scientific research.
- The study employed linear regression to model the relationship between compressive and flexural strengths, deriving a mathematical equation that effectively captures this relationship.
- The results of the regression analysis demonstrated a significant linear correlation between compressive and flexural strengths
- the linear model showing reasonable accuracy in predicting flexural strength based on compressive strength data.
- The predictive accuracy varied across different series, with minor deviations indicating a robust model performance. The accuracy percentages ranged from slight overestimations to marginal underestimations, consistently aligning closely with observed data.

Comparing these results with previous studies on similar materials reinforced with waste aluminium strips revealed that the current model holds a competitive predictive accuracy.

The comparison underscored the model's efficacy in different contexts, reaffirming the linear relationship between flexural and compressive strengths.

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