# Assessing the usability of biomass-derived sheep wool fibers in sustainable construction: A comprehensive review

Y.K. Kong [a], Dariusz Alterman [b], Hideyuki Murakami [a,c], Chiharu Tokoro [a,*]

[a] *Faculty of Science and Engineering, Waseda University, Japan*
[b] *School of Science, Technology and Engineering, The University of the Sunshine Coast, 90 Sippy Downs Drive, Sippy Downs, QLD, 4556, Australia*
[c] *Research Center for Structural Materials, National Institute for Materials Science, 1-2-1, Sengen, Tsukuba-City, 305-0047, Japan*

A B S T R A C T

Amid the growing awareness of climate change, the use of renewable resources has become essential for promoting sustainable and eco-friendly construction practices. Sheep wool fibers, known for their superior thermal insulation and acoustic properties, have gradually attracted the attention of researchers in civil engineering. However, owing to the relatively recent exploration of sheep wool in concrete, a systematic understanding of sheep wool fiber-reinforced cementitious composites (SWFRCC) remains limited, particularly in terms of its microstructure, which hinders its commercial application. This study presents a comprehensive review of the usability of sheep wool fibers in concrete, with a focus on workability, compressive strength, flexural strength, thermal insulation, acoustic performance, and durability. In addition, this study provides potential applications, highlights the current challenges, and proposes future research directions for SWFRCC. This review aims to enhance the understanding of sheep wool fibers and SWFRCC, offering valuable insights for advancing sustainable construction practices.

## 1. Introduction

Rapid urbanization over the past century has significantly increased the demand for concrete, leading to extensive production and consumption of ordinary Portland cement (OPC) (Neville, 1981). Modern concrete has become the most widely used man-made material on Earth since the 20th century (Chu et al., 2023). According to Statista (https://www.statista.com/), the total volume of cement produced worldwide was approximately 4.1 billion tons in 2023. However, this high amount of cement and concrete production significantly contributes to the total carbon dioxide ($CO_2$) emissions (Kong et al., 2022a, 2022b, 2022c) (Zajac et al., 2022). In developing countries, the building sector accounts for over 50 % of investments that drive economic and social growth. However, this sector also consumes a substantial amount of resources (such as raw stone, gravel, and sand), generates approximately 30 % of the world's solid waste, and uses 40–50 % of the global energy (Fahmy et al., 2014; Hetimy et al., 2024). To meet various building requirements, different types of modern concrete are manufactured to ensure that concrete structures meet safety, comfort, and durability standards across various performance criteria, including fire safety,

acoustic comfort, thermal efficiency, and weather resistance (Neville, 1981; Eurocode 2, 2004; ACI, 1995). Therefore, pursuing the best balance between these properties is a major task for current concrete structures.

The concept of green building materials encompasses both natural materials and a significant amount of waste (Gradinaru et al., 2016; Imbabi et al., 2012). Although raw materials for concrete production are widely available, there are opportunities to utilize local waste with suitable properties for concrete manufacturing. Given the increasing use of natural resources and the ongoing demand for affordable, lightweight, easily processable, and durable materials in various applications, the focus has shifted towards natural insulation materials and natural fibers as viable alternatives to metals owing to their superior properties (Wanasekara et al., 2012; Ioan et al., 2010; Kulkarni et al., 2023). Natural insulation materials and fibers have proven beneficial to the environment, society, and economy (Corscadden et al., 2014; Bosia et al., 2015; Zach et al., 2012). As a result, developers and designers are inspired and encouraged to use these natural materials in modern buildings (Valenza et al., 2015). Sheep wool is often highlighted as a natural material that is relevant to green and sustainable building requirements.

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**Abbreviations**

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| AI | Artificial intelligence | LCA | Life cycle assessment |
| $CO_2$ | Carbon dioxide | LCC | Life cycle cost |
| CT | Computer tomography | NRC | Noise reduction coefficient |
| OPC | Ordinary Portland cement | SCMs | Supplementary cementitious materials |
| FRC | Fiber-reinforced composites | SEM | Scanning electron microscopy |
| GFRC | Glass fiber reinforced-concrete | SWFRCC | Sheep wool fiber-reinforced cement composites |
| GWP | Global warming potential | STC | Sound transmission class |
| GHP | Guarded hot plate method | SFRC | Steel fiber-reinforced concrete |
| HFM | Heat flow meter method | TRL | Technology readiness level |
| ICC | Infilled cementitious composites | TLC | Transmission loss coefficient |
| ITZ | Interfacial transition zones | UHPC | Ultra-high performance concrete |
| | | UHPFRC | Ultra-high performance fiber-reinforced concrete |
| | | W/CM ratio | Water-to-cementitious ratio |

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Average sheep produces approximately 2.3–3.6 kg of raw wool per year that are sheared due to health concerns for the animals (Corscadden et al., 2014). However, in many countries, these sheared wools are not properly disposed or recycled. Approximately 95 % of raw sheep wool is unsuitable for the textile market, making annual shearing a significant cost burden for farmers. Before disposal, the wool must be sterilized at 130 °C due to its classification as special waste (Corscadden et al., 2014) (Pulido et al., 2013). According to the European Environmental Regulations (EC Regulation 1069 and EU Regulation 142), raw sheep wool must be sent to specialized sites for incineration or landfills. It can only be buried or burned without a permit if it has been washed or disinfected beforehand (Parlato et al., 2022a). Hence, instead of simply being disposed of, an increasing number of researchers are focusing on the natural insulating properties of sheep wool and exploring its potential in civil engineering (Helepciuc, 2017; Alyousef et al., 2019, 2022; Parlato and Porto, 2020; Ghermezgoli et al., 2021).

Sheep wool is emerging as a competitive material in the insulation industry due to its unique properties, including excellent thermal performance, moisture regulation, and inherent flame resistance, positioning it as an ideal natural option for diverse insulation applications (Hetimy et al., 2024) (Al-Homoud, 2005). Additionally, the reinforcement properties of sheep wool have been investigated for nearly two decades. Owing to its natural crack-bridging capacity, the flexural and tensile strengths of concrete can be significantly enhanced by the addition of sheep wool fibers (Alyousef et al., 2019, 2020). Therefore, it is of utmost importance to assess the applicability of sheep wool fiber reinforced cementitious composites (SWFRCC) by reviewing the existing literature.

While some literature reviews on SWFRCC exist, this material remains relatively new and underdeveloped compared to other fiber-reinforced concretes, such as steel fiber-reinforced concrete (SFRC) and ultra-high-performance fiber-reinforced concrete (UHPFRC) (Chu et al., 2023; Kong et al., 2022d). Current review papers on SWFRCC have certain limitations. First, most studies focus on a specific property of SWFRCC (e.g., insulation performance), without systematically reviewing other commonly considered mechanical properties, such as workability (Hetimy et al., 2024). Additionally, although several articles have reviewed the mechanical properties of SWFRCC, their durability has not been comprehensively evaluated or comparatively assessed (Kulkarni et al., 2023; Tiza et al., 2021; Patrucco et al., 2024). This lack of information on durability raises questions regarding the lifespan of SWFRCC structures and the underlying reaction mechanisms.

To address this gap, the present review systematically summarizes the applications of sheep wool fibers in modern concrete and building technology. Specifically, the influence of sheep wool fibers on various concrete properties is comprehensively evaluated, including the workability, compressive strength, flexural strength, thermal insulation, acoustic performance, and durability. Meantime, a life cycle assessment analysis for SWFRCC is summarized. Furthermore, current possible

applications and several future research directions are highlighted to aid researchers in exploring the potential use of sheep wool fibers in building materials. This review is anticipated to provide new insights into SWFRCC.

## 2. Roadmap of the literature review for SWFRCC

A schematic of this review is shown in Fig. 1 to clearly demonstrate the roadmap. The figures used in this roadmap were cited from (Alyousef et al., 2020; Cardinale et al., 2017). The present review consists of three major parts: the origin, process, and properties of sheep wool fibers; production of SWFRCC; and properties of SWFRCC. Specifically, the origin and processing sections provide detailed explanations of the manufacturing procedure of sheep wool fibers and SWFRCC. The manufacturing process of SWFRCC generally follows traditional fiber-reinforced concrete production. This section summarizes the common mix designs for SWFRCC. Finally, the properties of SWFRCC are focused on mechanical properties (i.e., workability, compressive strength, and flexural strength), insulation performance (i.e., thermal insulation and acoustic performance), and durability. This roadmap follows the traditional production process of SWFRCC, guiding interested readers to consider future optimizations of SWFRCC from its origin to its final product.

## 3. Origin, process and properties of sheep wool fibers

### 3.1. Origin of wool fibers

Sheep are the world's primary source of wool fibers, producing the highest global yield. Owing to the diversity of sheep breeds, over 200 distinct types of wool have been identified. Among these, Merino, Romney, and Blue-faced Leicester are the most popular wool-manufacturing breeds. Goats are another primary source of natural fibers, with Cashmere and Angora goats producing mohairs and cashmeres, respectively. Angora rabbits produce fine, soft wool fibers that are used in knitting because of their softness and warmth. Llamas and alpacas, which belong to the camel family, produce wool fibers that are softer than sheep wool and are commonly used in textiles. Finally, musk oxen wool, known as qiviut, is one of the softest and warmest fibers on Earth. However, because of their rarity and high cost, musk oxen fibers are unsuitable for use in construction (Kulkarni et al., 2023). Given the popularity and wide availability of sheep wool fibers, this review focuses exclusively on these fibers and their applications in concrete products.

Given the biological origin of sheep wool fibers, it is important to consider their hygienic safety, biostability, and environmental impact during and after incorporation into concrete. Collie et al. (2025) compared the biodegradation behavior of wool and other textile fibers in aerobic composting conditions. They found that untreated wool biodegraded more slowly, but still to a far greater extent than all the
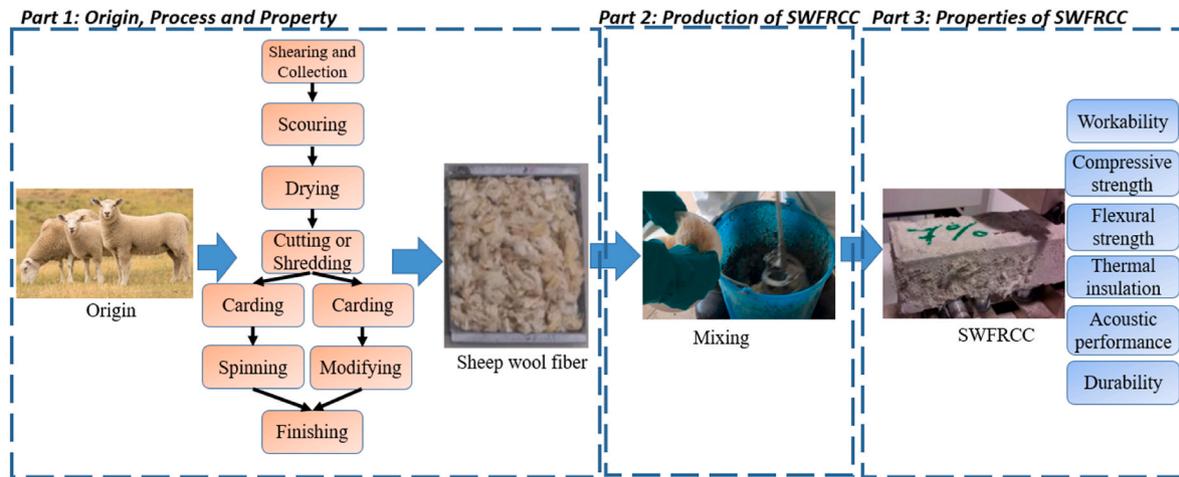
**Fig. 1.** Roadmap of the present review (Cardinale et al., 2017 (Cardinale et al., 2017); and Alyousef et al., 2020 (Alyousef et al., 2020)).

synthetic fibers. It means that sheep wool fibers indeed are faced with the biodegradation problem. However, note that unprotected wool fibers embedded in low-alkaline or carbonated zones could undergo slow biodegradation, especially under moist conditions, which indicates that the wool fibers in cement matrix may not degrade as fast as the natural biodegradation. On the other hand, there is a theoretical risk that organic decomposition by-products, such as ammonia or sulfur compounds, could be released, potentially affecting indoor air quality (Ozek, 2024).

### 3.2. Process of sheep wool fibers

Several steps are involved in the manufacturing of sheep wool fibers. Depending on the desired outcome and fiber properties, the processing of sheep wool fibers for use in concrete can be approached through two separate paths. Path 1 involves Shearing → Cleaning (Scouring) → Cutting/Shredding → Carding → Spinning → Ready for concrete. Path 2 involves Shearing → Cleaning (Scouring) → Cutting/Shredding → Tensile Treatment → Surface Modification → Ready for concrete. Fig. 2 illustrates the processing procedures for the sheep wool fibers. The sources of these figures are listed in Table 1. The major difference between these two paths lies in the processing after cutting and shredding. The steps are explained as follows (Kulkarni et al., 2023; Erdogan et al., 2020; Del Rey et al., 2017):

Shearing is the first step in sheep wool fiber production. Sheared and collected wool often contains impurities such as dirt, grease, and lanolin. Therefore, cleaning (scouring) is necessary. The raw wool fibers are washed to remove grease, dirt, and other contaminants. This step is crucial because impurities can affect the bonding and performance of the wool in concrete. The scouring process typically involves the use of warm water and detergents or mild alkalis to thoroughly clean fibers. Cutting or shredding reduces the wool fibers to shorter lengths (typically ranging–10-50 mm) suitable for use in concrete mixtures.

From this point on, the two paths diverge. In Path 1, carding is performed to disentangle, clean, and align the wool fibers in a parallel arrangement. This step is essential for creating a uniform fiber structure. The spinning process then twists the wool fibers to create a yarn or thread. In Path 2, however, tensile treatment is applied using mechanical or chemical methods to enhance the tensile strength and bonding properties of the fibers. This is followed by surface modification, typically through coating, to improve the adhesion between sheep wool fibers and the cement matrix. Once these processes are completed, the fibers are ready for use in concrete.

Path 1 (Carding and Spinning) primarily involves mechanical processes, focusing on fiber alignment and distribution, whereas Path 2 (Tensile Treatment and Surface Modification) focuses on modifying the fiber properties to enhance the mechanical strength and bonding with concrete. In some cases, these two paths can be combined, and the carded fibers may still undergo tensile treatment or surface modification for improved performance.

### 3.3. Structures and properties of sheep wool fibers

Different breeds and processing methods lead to variations in the structures and properties of sheep wool fibers, including fiber diameter, fiber length, aspect ratio, tensile strength, ultimate tensile strain, water absorption capacity, and thermal conductivity. These parameters are crucial for evaluating the suitability of sheep wool fibers as construction materials.

Fig. 3a–c summarize the SEM images of sheep wool fibers obtained from the existing literature (Ghermezgoli et al., 2021; Del Rey et al., 2017; Dénes et al., 2022). Sheep wool fibers are covered by an outer layer consisting of scale-like cells. This layer favors adherence between the fibers and cement matrix (Dénes et al., 2022). Cook (1984) provided an illustrative cross-sectional image of sheep wool fibers. From the inside to the outside, sheep wool fibers included the medulla, cortex, scale-cell layer, and epicuticle (Fig. 3d). These four components contribute to wool's desirable characteristics including insulation, water resistance, and mechanical properties. Specifically, in addition to outer scale-cell layer, the medulla is the central part of the fiber and consists of a hollow core. This structure can influence the fiber's thermal and acoustic properties, making it a valuable addition to construction materials (Lakshmanan, 2022). The cortex, located in the middle layer, comprises the bulk of the fiber and is responsible for its flexibility, elasticity and resilience (Lakshmanan, 2022). Lastly, epicuticle is the outermost layer, providing additional protection and contributing to the fiber's moisture management capability (Lakshmanan, 2022). However, the slight differences in the surface morphology, as shown in Fig. 3, could affect the interaction between the fiber and concrete, which should be further investigated.

To demonstrate the varying properties of sheep wool fibers, Table 2 lists the various sheep wool fibers used in the existing literature in chronological order, suggesting a variety of combinations between the fiber and concrete. From the table, it can be observed that the selected fibers used in concrete generally exhibit a stable fiber size range, with diameters between 10 and 130 μm and length from 10 to 120 mm. While the length of sheep wool fiber is comparable to that of steel fibers, their diameter is significantly smaller. This fineness contributes to an enhancement in the overall tensile strength of the concrete (Alshahrani and Kulasegaram, 2023). Furthermore, as reported by Parlato et al. (2022b), sheep wool fibers conditioned under wet, oven-dried, and ambient environments showed very similar performance, suggesting

Fig. 2. Processing of sheep wool fibers.

that thermal and hygrometric conditions have minimal impact on their properties. The tensile strengths of sheep wool fibers ranges from 105 MPa to 390 MPa, with ultimate tensile strains reaching up to 50 %, indicating highly ductile behavior. Their substantial water absorption capacity (approximately 35–50 %), highlights their hydrophilic nature. Additionally, the low thermal conductivity values (0.038–0.054 W/mK) confirm their suitability as an insulating material.

## 4. Production of SWFRCC

This section summarizes state-of-the-art SWFRCC reported in the literature. Considering the relatively novel use of sheep wool fiber, it is important to clarify production process of SWFRCC. Fig. 4 illustrates the SWFRCC products at various stages: mixing (Cardinale et al., 2017), fresh (Štirmer et al., 2014), curing (Cardinale et al., 2017), and hardening stages (Štirmer et al., 2014) (Alyousef et al., 2020). In its hardened state, the appearance of SWFRCC closely resembles that of commercial concrete. The manufacturing of SWFRCC largely follows conventional

**Table 1**
Reference for the cited figures in Fig. 2.

| Number | Category | Reference |
|---|---|---|
| 1 | Shearing | Redd Summit, Preparing for sheep shearing |
| 2 | Cleaning (Scouring) | Cleancroft, Part 2-Clapdale Wool |
| 3 | Cutting/Shredding | Youtube |
| 4 | Carding | Wikipedia: Carding |
| 5 | Spinning | Textile School |
| 6 | Tensile treatment & Surface modification | Pawlak et al. (2020) |
| 7 | Sheep wool fiber | Alyousef et al. (2020) |
| 8 | Clothing | Ebay |
| 9 | SWFRCC | Štirmer et al. (2014) |
| 10 | Sheep wool insulation | Homebuilding Renovating, Sheep wool insulation |

fiber-reinforced concrete (FRC) production, incorporating cement, supplementary cementitious materials (SCMs), water, fine aggregates, coarse aggregates, chemical admixtures (e.g., superplasticizers (SP)), and fiber. However, due to the high water demand of sheep wool fibers, the average water-to-cementitious material (W/CM) ratio for SWFRCC mixes is slightly higher (approximately 0.59) than the typical range for standard concrete (0.4–0.5) (Levy, 2012). To maintain adequate workability, the wool fiber content is usually limited to below 10 wt%.

Table 3 presents the mix proportions of SWFRCC formulations, including pastes, mortals and concretes in chronological order (Gradinaru et al., 2016; Alyousef et al., 2019, 2020; Cardinale et al., 2017; Alyousef, 2022; Fantilli et al., 2017; Gelana et al., 2019; Maia Pederneiras et al., 2019; Al-Kafri et al., 2020). All mixing proportion data have been converted to a mass-based percentage, calculated as the mass of each component relative to the total mass of the SWFRCC mixtures. For each mix, information regarding the treatment, length, and content for the added sheep wool fibers is provided. The table highlights common SWFRCC mix designs and illustrates how wool fibers are incorporated with other concrete components. Mixture design parameters and processing variables, such as fiber aspect ratio, dispersion methods, and surface modification treatments, play a critical role in influencing fiber-matrix interactions and overall composite performance. Gradinaru et al. (2016) reported that a higher fiber aspect resulted in a 7.30 % increase in flexural tensile strength while maintaining at the same split tensile strength. This improvement is attributed to the enhanced crack-bridging capacity and post-cracking toughness

(Chu and Kwan, 2019a). With respect to dispersion methods, achieving a uniform fiber distribution is essential for consistent mechanical performance. In SWFRCC, fiber dispersion is largely influenced by the fiber content. Several studies (Alyousef et al., 2019) (Alyousef et al., 2020) (Cardinale et al., 2017) (Alyousef, 2022) have indicated that an optimal fiber content is approximately 2.0 wt%, beyond which non-uniform reinforcement can be caused, leading to reduction of mechanical performance. The effect of surface modification treatments is also significant. For example, Maia Pederneiras et al. (Maia Pederneiras et al., 2019) washed the wool fibers with neutral detergent and dried at 40 °C, effectively removing surface impurities and enhancing fiber–matrix bonding. Alyousef et al. (2020) employed saltwater treatment, and found that saltwater-treated fibers demonstrated higher compressive strength than untreated fibers at all curing ages. This modification likely alters the ionic exchange capacity of the fiber surface, improving resistance to alkali attack (Ryvolova et al., 2021).

For revealing the mechanism of how sheep wool fibers bond in the cement matrix, a microstructural analysis is needed. Fig. 5 compares the microstructure of plain concrete and SWFRCC (Del Rey et al., 2017). From the figure, Alyousef reported that the presence and homogenous distribution of wool fibers in the matrix could act as a bridging agent between concrete components, inhibiting fracture propagation and enhancing sound absorption in concrete composites (Del Rey et al., 2017). Nevertheless, studies investigating the microstructure-property relationship for SWFRCC are scarce, and many problems remain unsolved, which will be discussed later.

## 5. Properties of SWFRCC

After reviewing the production of sheep wool fibers and SWFRCC, this section focuses on comparing and evaluating the various properties of SWFRCC. Considering the primary functions of SWFRCC as both a building support and insulation, the properties reviewed include workability, compressive strength, flexural strength, thermal insulation, acoustic performance, and durability.

### 5.1. Effect of sheep wool fibers on workability

Workability is critical property for construction materials, as it directly influences the mechanical performance and long-term durability of cement-based composites (Kong and Kurumisawa, 2023a) (Powers, 1968) (ASTM C143, 2020). Several physical properties of
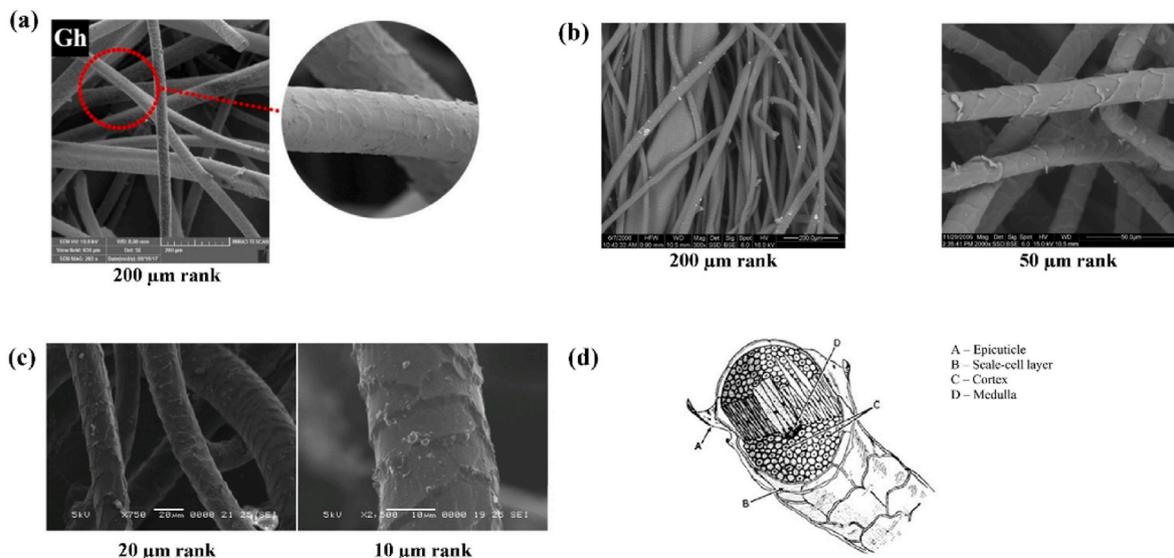


**Fig. 3.** Microstructure of (a) SEM image of Ghezel (Ghermezgoli et al., 2021); (b) SEM image of Merina (Del Rey et al., 2017); (c) SEM image of Tigaie (Dénes et al., 2022); and (d) illustrative structure of sheep wool fiber (Cook, 1984).

**Table 2**
Properties of sheep wool fibers.

| Reference | Fiber properties | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Breed | Fiber diameter/ μm | Fiber length/ mm | Aspect ratio | Tensile strength/MPa | Ultimate tensile strain | Water absorption capacity/% | Thermal conductivity/ W/mK |
| Valenza et al. (Valenza et al., 2015) | Sicilian | – | 1, 6, 20 | – | – | – | – | – |
| Grădinaru et al. (Gradinaru et al., 2016) | Țurcana | – | 20~50 | – | – | – | – | – |
| Rey et al. (Del Rey et al., 2017) | Merina | – | 60~80 | – | – | – | – | – |
| | Entrefino | – | 70~80 | – | – | – | – | – |
| | Churro | – | 80~120 | – | – | – | – | – |
| Alyousef et al. (Alyousef et al., 2019) | – | 95~130 | ~70 | 550~650 | ~390 | 50.20 % | – | – |
| Dénes et al. (Dénes et al., 2019) | – | – | – | – | – | – | 35 | 0.038-0.054 |
| Ghermezgoli et al. (Ghermezgoli et al., 2021) | Ghezel | 34.5 | – | – | – | – | – | – |
| | Arkharmerino | 22.7 | – | – | – | – | – | – |
| | Ghezel crossbred with Arkharmerino | 30.1, 26.6 | – | – | – | – | – | – |
| Alyousef (Alyousef, 2022) | – | 95~130 | 60~70 | 550~650 | ~390 | 50.20 % | – | – |
| Dénes et al. (Dénes et al., 2022) | Tigaie | $100 \times 10^6$, $63.5 \times 10^6$ | – | – | – | – | – | – |
| Parlato et al. (Parlato et al., 2022b) | Merino | ~95 | 160~220 | – | 134.57 (saturated specimens), 144.02 (normal conditioning), 133.65 (dry specimens), 137.31 (entire population) | 42 (saturated specimens), 43 (normal conditioning), 43 (dry specimens), 42 (entire population) | – | – |
| Starkova et al. (Starkova et al., 2022) | Latvian dark-headed breed | 17~73 | 10 | – | 178 | 34.4 | – | – |
| | | 17~73 | 30 | – | 142.8 | 25.9 | – | – |
| | | 17~73 | 50 | – | 105.8 | | – | – |



**Fig. 4.** SWFRCC products at the mixing (Cardinale et al., 2017), fresh (Štirmer et al., 2014), curing (Cardinale et al., 2017), and hardening stages (Štirmer et al., 2014) (Alyousef et al., 2020).

sheep fibers can affect the workability of cement-based mixtures, such as type/configuration, quantity, fiber length, and proportions of the plain mix. It is widely recognized that longer fibers reduce the workability to a greater extent than shorter fibers (Valenza et al., 2015).

Cardinale et al. (2017) investigated the thermal and mechanical characterization of sheep wool fiber-reinforced cement mortar panels.

During sample preparation, a higher quantity of water was added to ensure workability owing to the increasing percentage of wool fibers. Alyousef et al. (2019) conducted a series of measurements on the fresh and hardened properties of SWFRCC, increasing the sheep wool fiber content from 0 %, 0.5 %, 1 %, 1.5 %, 2 %, 3 %, 4 %, 5 %, and 6 % by weight of mix. The measured slump values for these samples are plotted

**Table 3**

SWFRCCs with various mixed proportions ((Gradinaru et al., 2016) (Cardinale et al., 2017) (Fantilli et al., 2017) (Alyousef et al., 2019) (Gelana et al., 2019) (Maia Pederneiras et al., 2019) (Al-Kafri et al., 2020) (Alyousef et al., 2020) (Alyousef, 2022)).

| Ref. | Mix ID | Wool source | Treatment | Fiber length (mm) | Fiber content (wt. %) | Cement/ wt.% | SCMs*/ wt.% | Water/ wt.% | W/ CM* | Sand/ wt.% | Gravel/ wt.% | SP*/ wt.% |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Gradinaru et al., 2016 (Gradinaru et al., 2016) | SSC 0.35 % | Țurcana breed | – | 20~30 | 0.35 | 15.37 | 0.00 | 8.45 | 0.55 | 34.29 | 40.26 | 1.3 |
| | LSC 0.35 % | | – | 50~60 | 0.35 | 15.37 | 0.00 | 8.45 | 0.55 | 34.29 | 40.26 | 1.3 |
| | SSC 0.80 % | | – | 20~30 | 0.80 | 15.07 | 0.00 | 9.79 | 0.65 | 33.62 | 39.46 | 1.3 |
| | LSC 0.80 % | | – | 50~60 | 0.80 | 15.07 | 0.00 | 9.79 | 0.65 | 33.62 | 39.46 | 1.3 |
| | SSCFA 0.80 % | | – | 20~30 | 0.80 | 13.70 | 1.52 | 8.90 | 0.65 | 33.96 | 39.86 | 1.3 |
| | LSCFA 0.80 % | | – | 50~60 | 0.80 | 13.70 | 1.52 | 8.90 | 0.65 | 33.96 | 39.86 | 1.3 |
| Cardinale et al., 2017 (Cardinale et al., 2017) | SW2 | Raw wool unspun | – | 10 | 2.00 | 23.18 | 3.97 | 14.23 | 0.52 | 56.65 | 0.00 | 0 |
| | SW5 | | – | 10 | 5.00 | 21.41 | 3.69 | 17.81 | 0.71 | 52.33 | 0.00 | 0 |
| | SW7 | | – | 10 | 7.00 | 20.03 | 3.47 | 21.00 | 0.89 | 48.96 | 0.00 | 0 |
| Fantilli et al., 2017 (Fantilli et al., 2017) | L | – | – | 16 | 0.50 | 22.11 | 0.00 | 11.06 | 0.50 | 66.33 | 0.00 | 0 |
| | LT | – | Plasma-treated wool fiber | 16 | 0.50 | 22.11 | 0.00 | 11.06 | 0.50 | 66.33 | 0.00 | 0 |
| Alyousef et al., 2019 (Alyousef et al., 2019) | F1 | – | – | ~70 | 0.50 | 13.36 | 0.00 | 6.68 | 0.50 | 28.05 | 51.42 | 0 |
| | F2 | – | – | ~70 | 1.00 | 13.29 | 0.00 | 6.64 | 0.50 | 27.91 | 51.17 | 0 |
| | F3 | – | – | ~70 | 1.50 | 13.22 | 0.00 | 6.61 | 0.50 | 27.77 | 50.91 | 0 |
| | F4 | – | – | ~70 | 2.00 | 13.16 | 0.00 | 6.58 | 0.50 | 27.64 | 50.66 | 0 |
| | F5 | – | – | ~70 | 3.00 | 13.03 | 0.00 | 6.52 | 0.50 | 27.37 | 50.17 | 0 |
| | F6 | – | – | ~70 | 4.00 | 12.91 | 0.00 | 6.45 | 0.50 | 27.10 | 49.69 | 0 |
| | F7 | – | – | ~70 | 6.00 | 12.66 | 0.00 | 6.33 | 0.50 | 26.59 | 48.75 | 0 |
| Gelana et al., 2019 (Gelana et al., 2019) | 0.5 % (sheep wool) control | Menz | – | – | 0.50 | 15.91 | 0.00 | 7.26 | 0.46 | 28.41 | 47.92 | 0 |
| | 1 %(sheep wool) control | | – | – | 1.00 | 15.83 | 0.00 | 7.22 | 0.46 | 28.27 | 47.68 | 0 |
| | 1.5 % (sheep wool) control | | – | – | 1.50 | 15.75 | 0.00 | 7.19 | 0.46 | 28.13 | 47.45 | 0 |
| | 2 %(sheep wool) control | | – | – | 2.00 | 15.68 | 0.00 | 7.15 | 0.46 | 28.00 | 47.22 | 0 |
| Maia Pederneiras et al., 2019 (Maia Pederneiras et al., 2019) | W 1.5_10 %c | – | Washed with neutral detergent and dried at 40 °C | 15 | 0.04 | 14.35 | 0.00 | 13.23 | 0.92 | 72.38 | 0.00 | 0 |
| | W 3.0_10 %c | | | 30 | 0.02 | 14.21 | 0.00 | 14.08 | 0.99 | 71.69 | 0.00 | 0 |
| | W 1.5_20 %c | | | 15 | 0.08 | 14.39 | 0.00 | 12.91 | 0.90 | 72.63 | 0.00 | 0 |
| | W 3.0_20 %c | | | 30 | 0.05 | 14.39 | 0.00 | 12.91 | 0.90 | 72.65 | 0.00 | 0 |
| | W 1.5_10 %cl | | | 15 | 0.04 | 9.31 | 5.40 | 14.76 | 1.00 | 70.49 | 0.00 | 0 |
| | W 3.0_10 %cl | | | 30 | 0.02 | 9.36 | 5.43 | 14.33 | 0.97 | 70.86 | 0.00 | 0 |
| | W 1.5_20 %cl | | | 15 | 0.08 | 9.37 | 5.43 | 14.21 | 0.96 | 70.91 | 0.00 | 0 |
| | W 3.0_20 %cl | | | 30 | 0.05 | 9.37 | 5.43 | 14.22 | 0.96 | 70.93 | 0.00 | 0 |
| Al-Kafri et al., 2020 (Al-Kafri et al., 2020) | SW0.09 % | Local | – | – | 0.04 | 15.08 | 0.00 | 9.47 | 0.63 | 30.16 | 45.24 | 0 |
| | SW0.12 % | | – | – | 0.05 | 15.08 | 0.00 | 9.47 | 0.63 | 30.16 | 45.24 | 0 |
| | SW0.14 % | | – | – | 0.06 | 15.08 | 0.00 | 9.47 | 0.63 | 30.16 | 45.23 | 0 |
| Alyousef et al., 2020 (Alyousef et al., 2020) | F | - | – | ~70 | 0.50 | 15.31 | 0.00 | 7.65 | 0.50 | 30.62 | 45.92 | 0 |
| | F1 | - | – | ~70 | 1.00 | 15.23 | 0.00 | 7.62 | 0.50 | 30.46 | 45.70 | 0 |
| | F2 | - | – | ~70 | 1.50 | 15.16 | 0.00 | 7.58 | 0.50 | 30.31 | 45.47 | 0 |
| | F3 | - | – | ~70 | 2.00 | 15.08 | 0.00 | 7.54 | 0.50 | 30.17 | 45.25 | 0 |
| | F4 | - | – | ~70 | 3.00 | 14.94 | 0.00 | 7.47 | 0.50 | 29.87 | 44.81 | 0 |
| | F5 | - | – | ~70 | 4.00 | 14.79 | 0.00 | 7.40 | 0.50 | 29.59 | 44.38 | 0 |
| | F6 | - | – | ~70 | 6.00 | 14.51 | 0.00 | 7.26 | 0.50 | 29.03 | 43.54 | 0 |
| | MF1 | - | Modified by salty water for 24 h in room temperature | ~70 | 0.50 | 15.31 | 0.00 | 7.65 | 0.50 | 30.62 | 45.92 | 0 |
| | MF2 | - | | ~70 | 1.00 | 15.23 | 0.00 | 7.62 | 0.50 | 30.46 | 45.70 | 0 |
| | MF3 | – | | ~70 | 1.50 | 15.16 | 0.00 | 7.58 | 0.50 | 30.31 | 45.47 | 0 |
| Alyousef, 2022 (Alyousef, 2022) | WF1 | – | – | 70 | 0.50 | 18.64 | 0.00 | 9.01 | 0.48 | 35.82 | 36.03 | 0 |
| | WF2 | – | – | 70 | 1.00 | 18.55 | 0.00 | 8.96 | 0.48 | 35.64 | 35.85 | 0 |
| | WF3 | – | – | 70 | 1.50 | 18.46 | 0.00 | 8.92 | 0.48 | 35.47 | 35.68 | 0 |
| | WF4 | – | – | 70 | 2.00 | 18.37 | 0.00 | 8.88 | 0.48 | 35.29 | 35.50 | 0 |
| | WF5 | – | – | 70 | 2.50 | 18.28 | 0.00 | 8.83 | 0.48 | 35.12 | 35.33 | 0 |
| | | – | | | | | | | | | | |

*(continued on next page)*

**Table 3** (*continued*)

| Ref. | Mix ID | Wool source | Treatment | Fiber length (mm) | Fiber content (wt. %) | Cement/ wt.% | SCMs*/ wt.% | Water/ wt.% | W/ CM* | Sand/ wt.% | Gravel/ wt.% | SP*/ wt.% |
|------|--------|-------------|-----------|-------------------|------------------------|--------------|-------------|-------------|--------|------------|--------------|-----------|
| | MWF1 | | Modified by salty water for 24 h in room temperature | 70 | 0.50 | 18.64 | 0.00 | 9.01 | 0.48 | 35.82 | 36.03 | 0 |
| | MWF2 | | | 70 | 1.00 | 18.55 | 0.00 | 8.96 | 0.48 | 35.64 | 35.85 | 0 |
| | MWF3 | | | 70 | 1.50 | 18.46 | 0.00 | 8.92 | 0.48 | 35.47 | 35.68 | 0 |
| | MWF4 | | | 70 | 2.00 | 18.37 | 0.00 | 8.88 | 0.48 | 35.29 | 35.50 | 0 |
| | MWF5 | | | 70 | 2.50 | 18.28 | 0.00 | 8.83 | 0.48 | 35.12 | 35.33 | 0 |

Note*: SCMs = Supplementary cementitious materials; W/CM=Water-to-cementitious material (cement + SCMs) ratio; SP=Superplasticizer.
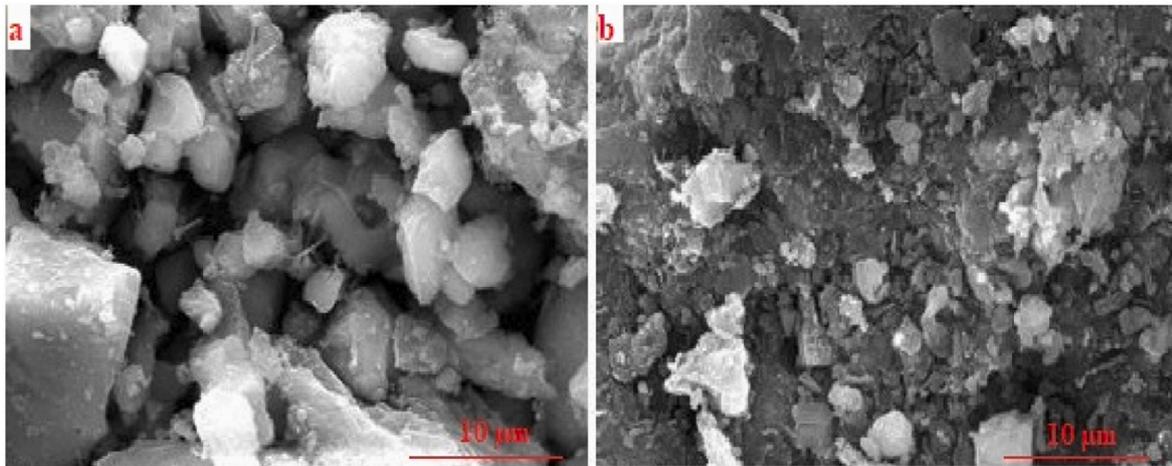


**Fig. 5.** SEM images of (a) plain concrete and (b) SWFRCC (Alyousef, 2022).

in Fig. 6a (Alyousef et al., 2019). A pronounced decreasing trend in the workability of SWFRCC was observed when the fiber content was increased. Similarly, Gelana et al. (2019) measured the slump of SWFRCC, revealing a negative effect of the fiber content on the workability of concrete mixtures (Fig. 6b). This phenomenon generally occurs because the high specific surface area and fineness of sheep wool fibers absorb more water, reducing the amount available for normal concrete flow. As a result, the workability of the cement-based mixtures decreased. Therefore, adjusting the water-to-cementitious (W/CM) ratio and fiber content is crucial for preparing SWFRCC. If not well controlled, poor workability can lead to casting failures and damage to mixing equipment.

The high water absorption of sheep wool fibers is a key factor contributing to the reduced workability of SWFRCC. To address this issue, several strategies are recommended: (1) pre-treatment of fiber, (2) optimization of fiber content, (3) strict control of fiber type and quality, and (4) usage of superplasticizer. Specifically, pre-treatment of wool fiber such as through saltwater treatment can enhance their adhesion to the cement paste and potentially reduce water absorption. Maintaining and optimizing fiber dosage is crucial for ensuring uniform fiber dispersion, as excessive fiber content can lead to increased water demand and compromised workability. Moreover, controlling fiber characteristics, including length and aspect ratio, is essential for consistent performance. Finally, the addition of superplasticizer, is widely supported in the literature (Gradinaru et al., 2016) as an effective method to achieve adequate workability without increasing the W/CM ratio.

### 5.2. Effect of sheep wool fibers on compressive strength

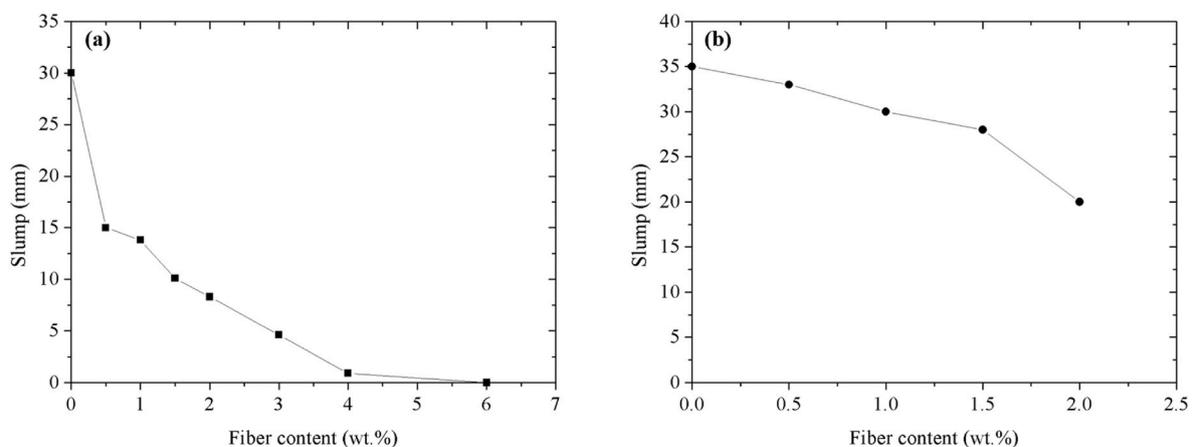The compressive strength is considered as one of the most important



**Fig. 6.** Workability change of SWFRCC modified from (a) (Alyousef et al., 2019) and (b) (Al-Kafri et al., 2020), detailed mixing parameters of which are listed in Table 3.

properties of concrete (Chu and Kong, 2021). The addition of fibers to cement-based mixtures is a traditional approach to enhance strength and ductility (Chu et al., 2023; Chu and Kwan, 2019b). Among these concrete products, UHPFRC is the most well-known owing to its extremely high strength and durability (Arora et al., 2019). With the pioneering work by Chu et al. (Kong et al., 2022d; Chu, 2021), self-leveling ultra-high-performance concrete (UHPC) technology and fiber-aggregate skeletons were developed for manufacturing infilled cementitious composites (ICC). Generally, steel fibers are the first choice for modern concrete products because of their superior hardness. However, steel fiber production is associated with an environmental burden (Stengel and Schießl, 2014). In contrast, the adoption of natural sheep wool fibers can significantly reduce pollution and energy consumption compared with traditional steel fibers.

However, most researchers reported a detrimental effect of sheep wool fibers on the concrete strength. Valenza et al. (2015) compared the influence of different sheep wool fiber lengths and contents on the 28-day compressive strength of cement paste, as shown in Fig. 7. A clear decreasing trend in the compressive strength was observed as the fiber content increased. Regarding the effect of the fiber length (Fig. 7a), at 13 wt % of cement, 6 mm sheep wool fiber reinforced samples showed the best properties, 1 mm the lowest, and 20 mm intermediate. The 20 mm fibers saturated the matrix, causing residual tension, while their tangled structure promoted cracking. The 1 mm fibers acted as fillers with no mechanical benefits, whereas the 6 mm fibers effectively reinforced the cement matrix. However, the addition of up to 23 wt % and 46 wt % of cement, the mechanical behavior was really worse. The fibers demonstrated no reinforcement function but promoted cracking in the samples. Another finding by Valenza et al. (2015), displayed in Fig. 7b, is that impurities inside the sheep wool fiber decreased the strength of the mixtures. These impurities can induce the formation of air bubbles, promoting the propagation of cracks.

Gradinaru et al. (2016) also studied the effect of the fiber length on the mechanical properties of fly ash-added SWFRCC. They found that the addition of 0.35 wt % short fiber (20–30 mm) resulted in a 28.14 % reduction in compressive strength compared to the reference group (0 % fiber content), while 0.35 wt% long fiber (50–60 mm) had little impact. The experimental results of Wani and Kumar (Ahmad Wani and ul Rehman Kumar, 2021) demonstrated a significant drop in compressive strength with the addition of sheep wool fibers. Alyousef et al. (2020) measured the compressive strength of SWFRCC until 180 days, as shown in Fig. 8, and observed a reduction in compressive strength. For concrete with 0.5–6 % sheep wool fiber content, the 7-day compressive strength decreased by 5.5–79.7 % compared to that of normal concrete. Similar reductions of 12.5–75.2 %, 9.8–64.3 %, 7.7–46.9 %, and 5.1–61.5 % were observed at curing periods of 14, 28, 90, and 180 days, respectively. This reduction in the compressive strength gradually decreased
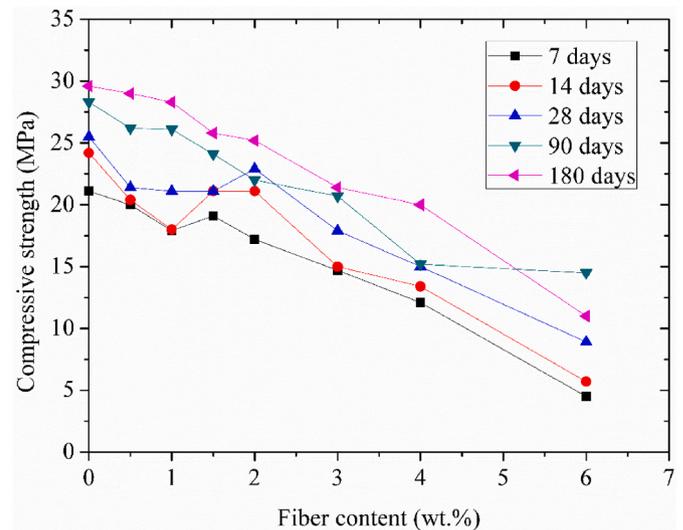


**Fig. 8.** 7~180-day compressive strength of SWFRCC (modified from (Alyousef et al., 2020)).

with longer curing times.

The reduction in compressive strength observed in SWFRCC can be attributed to three primary factors: (1) the low stiffness and strength of sheep wool fibers, (2) the increased porosity resulting from fiber geometry and water absorption, and (3) the comparatively lower density of the composite compared to plain concrete (Valenza et al., 2015) (Alyousef et al., 2020) (Ahmad Wani and ul Rehman Kumar, 2021). First, due to the low modulus of elasticity and limited compressive resistance, sheep wool fibers behave as soft inclusions within the cementitious matrix and contribute minimally to load-bearing capacity under compressive stress. Secondly, their crimped and porous morphology, along with high water absorption capacity, causes uneven moisture distribution during mixing. This often requires additional mixing water to maintain workability, thereby increasing the water-to-cementitious material (W/CM) ratio and internal porosity. Lastly, because of the significantly lower density of wool fibers compared to cement matrix, incorporating more than 1 % by weight leads to a softer and less dense composite, ultimately resulting in reduced compressive strength (Gradinaru et al., 2016; Alyousef et al., 2020; Ahmad Wani and ul Rehman Kumar, 2021). This significant decrease in compressive strength has substantially hindered the commercial application of sheep wool fibers in construction materials. To overcome this issue, a more detailed discussion will be given in Section. 7.
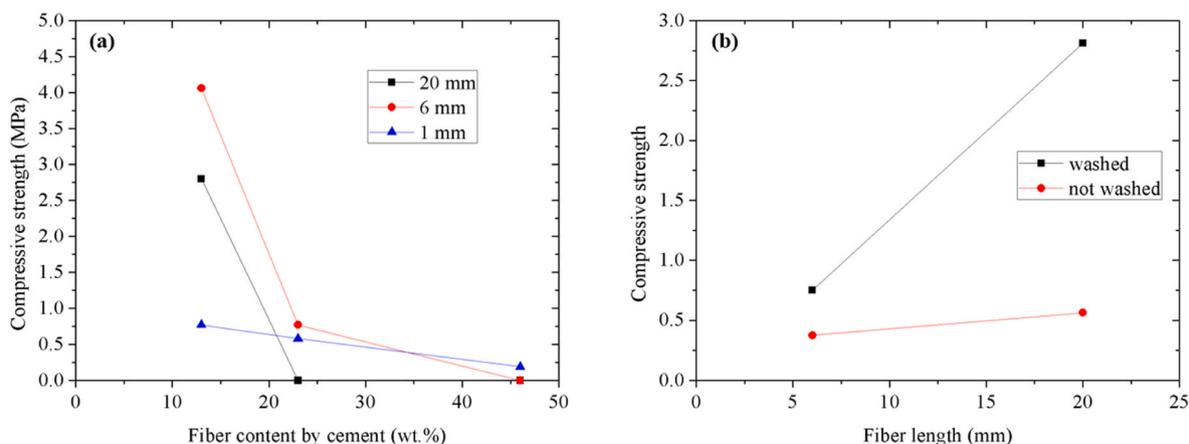


**Fig. 7.** Compressive strength versus the effect of (a) fiber length and content and (b) washed and non-washed fibers (modified from (Valenza et al., 2015)).

## 5.3. Effect of sheep wool fibers on flexural strength

The flexural strength is the ability of a concrete material to resist bending or flexure. This reflects the performance of concrete under load-bearing conditions, such as in pavements and beams (Huang et al., 2021; ASTM C78, 2021). Fibers can reinforce the flexural strength by virtue of their crack-bridging effect, which spans across cracks to transfer the concrete stress into a long path, preventing or delaying crack propagation (Mohammadhosseini and Yatim, 2017; Wu et al., 2018). This crack-bridging effect is also evident in SWFRCC, as reflected by the enhanced flexural strength.

Alyousef et al. (2019) evaluated the 7-day, 14-day and 28-day flexural strength of SWFRCC at prism beam specimens of 150 mm × 150 mm × 700 mm, in accordance with ASTM C78. The test results are shown in Fig. 9a. Generally, the flexural strength increased with the addition of sheep wool fibers, showing an improvement of up to 20.8 % in SWFRCC with a fiber content of up to 2 %. This trend was most notable during the early stages of curing. Interestingly, a decrease in flexural strength was observed when the sheep wool fiber content exceeded 2 %, which is explained later. Similar results were reported by Gelana et al. (2019), who cast C25 concrete with sheep wool fibers and conducted three-point loading tests, as shown in Fig. 9b. An increase in the flexural strength was identified up to 1.5 % fiber content, beyond which the flexural strength decreased.

Fantilli et al. (2017) conducted three point bending tests for wool fiber-reinforced cementitious mortars, observing a significant increase in flexural strength. The enhancement of the flexural strength of sheep wool fibers was associated with the crack-bridging effect, which improved the ductility. This enhancement can be explained by the SEM images of the interfacial transition zones (ITZ) between the sheep wool fibers and the cement matrix, as shown in Fig. 10 (Alyousef et al., 2022). This image shows a strong and uniform bond between the concrete matrix and sheep wool fibers. Good fiber coverage of cement hydration products was also discovered, further proving the good fiber-matrix adhesion. Such a dense matrix in ITZ leads to a more robust bond, enhancing the flexural strength and ductility (Alyousef et al., 2022). Meanwhile, higher fiber contents can help carry more tensile force along the soffit of flexural test specimens (Alyousef et al., 2019).

From the above results, the enhancement of flexural strength of SWFRCC is widely acknowledged though, the strength improvement plateau or even reverse beyond certain fiber contents. Generally, this limited enhancement can be explained by two major reasons that are low stiffness and strength of fibers, and increased porosity and void formation. Specially, at low to moderate fiber contents, sheep wool fibers are relatively well dispersed, effectively bridging cracks and improving load transfer across the matrix. However, as the fiber content increases beyond an optimal threshold (typically around 1.5–2 wt.%),

the fibers tend to tangle, clump, or form agglomerates due to their flexible, crimped nature. These clumps act as defects in the composite, creating weak points rather than contributing to reinforcement, which diminishes the flexural performance (Valenza et al., 2015). Meantime, the weakening effect observed by (Alyousef et al., 2019; Gelana et al., 2019) starting from the 2 % fiber content was explained by the poor non-uniform distribution of fibers within the concrete. Such an uneven distribution of fibers directly weakened the concrete specimens along specific planes, thereby reducing their capacity.

## 5.4. Effect of sheep wool fibers on thermal insulation

Thermal insulation is a crucial property of modern concrete structures because it resists heat transfer (Al-Homoud, 2005; Al-Jabri et al., 2005). Good thermal insulation helps to maintain comfortable indoor temperatures and enhances energy efficiency in buildings (Valenza et al., 2015; Štirmer et al., 2014). In a review article by GhaffarianHoseini et al. (2013), building energy efficiency, thermal performance, and material efficiency were considered as the three primary measures of sustainable buildings. Thermal insulation reduces the rate of heat flow via conduction, convection, and radiation. Thus, four major factors are considered when evaluating thermal insulation: thermal conductivity, thermal resistance, thermal conductance, and thermal transmittance (American society of heating, 2001). Table 4 lists the definitions and measured units of the four properties (Al-Homoud, 2005). Among these four categories, thermal conductivity has been the most studied for evaluating thermal insulation.

Two commonly used methods for measuring thermal insulation in concrete are the Guarded hot plate method (GHP) and heat flow meter method (HFM) (Corscadden et al., 2014; Dénes et al., 2022; Al-Jabri et al., 2005). In GHP, a sample is placed between a hot plate and a cold plate, maintaining a temperature difference across the plates. The heat flow through the sample is measured and the thermal resistance (R-value) is calculated (ASTM C177, 2019). GHP can be tracked using existing standards, such as ASTM C177 and EN 12664 (ASTM C177, 2019; BS EN 12664, 2001). An extension of this method, the guarded hot box (GHB), is specified in ASTM C1363 and uses a calibrated hotbox instead of plates (ASTM C1363-19 2019). The HFM measures the heat flow through a sample using heat flow sensors and offers a simpler and quicker alternative to GHP for steady-state measurements, as described in ASTM C518 (ASTM C518-21, 2021) (BS EN 12664, 2001). While other methods, such as the transient plane source method and laser flash analysis, exist, GHP and HFM are the most standard for concrete testing in practical applications. It should be noted that some of these methods (for example, thermal transmittance measurement) can be directly used to evaluate the thermal insulation of a structural scale coupled with the heat flux sensor.
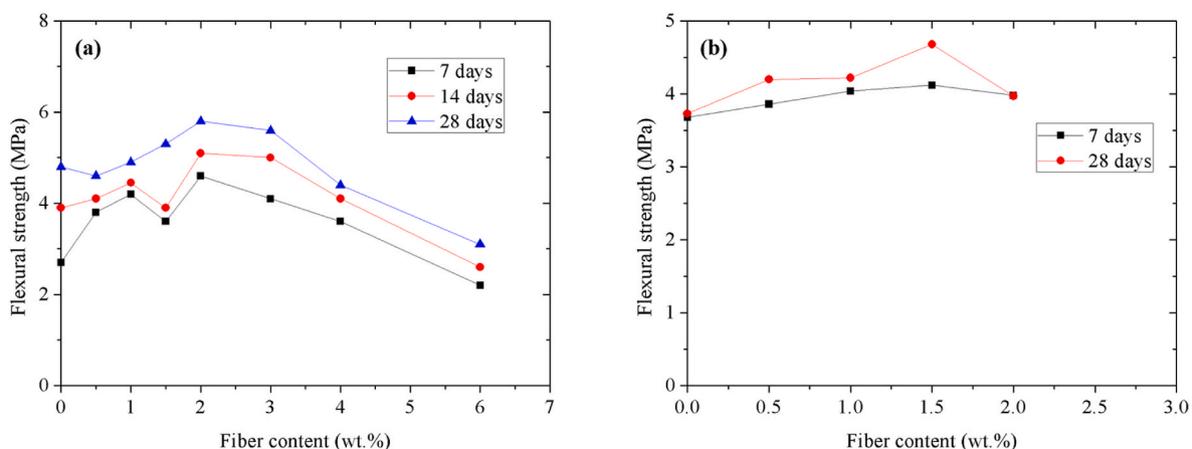


**Fig. 9.** Flexural strength results of SWFRCC with different fiber contents modified from (a) (Alyousef et al., 2019) and (b) (Gelana et al., 2019).
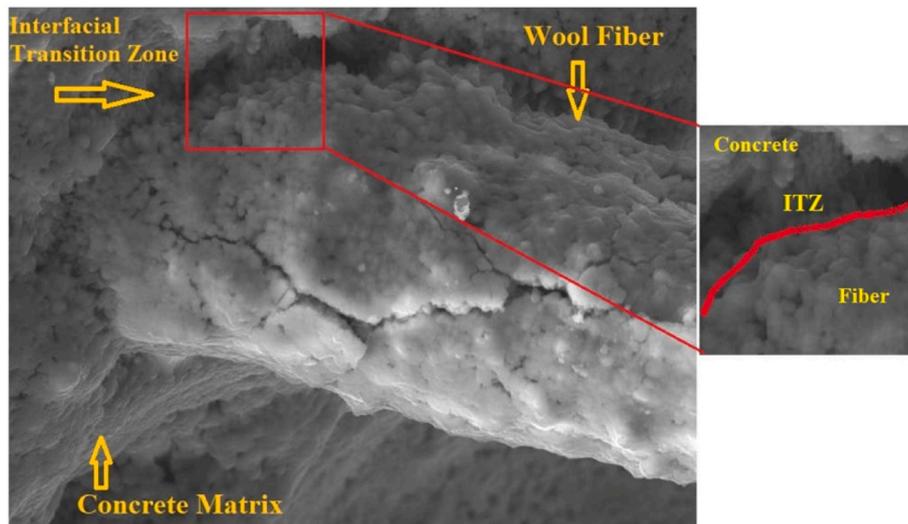
**Fig. 10.** SEM images of ITZ (Alyousef et al., 2022).

**Table 4**
Summary of thermal insulation properties.

| Categories | Definition | Unit | Abbreviations |
|---|---|---|---|
| Thermal conductivity | The rate of steady-state heat flow (W) through a unit area of a 1 m thick homogeneous material in a direction perpendicular to the isothermal planes. | W/mK (Btu/h-ft-F or Btu-in/hrft$^2$-F) | K-value |
| Thermal resistance | A measure of resistance to heat flow by limiting conduction, convection, and radiation. | m$^2$K/W (h-ft$^2$-F/Btu) | R-value |
| Thermal conductance | The rate of heat flow (W) through a unit surface area of a component with a temperature difference of 1 K between its two sides. | W/m$^2$K (Btu/h-ft$^2$-F) | C-value |
| Thermal transmittance | Thermal transmittance is the rate of heat flow through a unit surface area of a component with a 1 K temperature difference between its two surfaces. | W/m$^2$K (Btu/h-ft$^2$-F) | U-value |

One of the biggest advantages of SWFRCC is its excellent thermal-insulation properties. Fig. 11 shows the reported thermal conductivity against sheep wool fiber content in the existing literature, indicating a pronounced decrease in thermal conductivity with increasing fiber content. This trend suggests significant thermal insulation improvements with the addition of wool fibers to the cement composites. Other properties of sheep wool fibers also affect the thermal conductivity. Valenza et al. (2015) studied the effect of fiber length and whether the fibers were washed or unwashed on the thermal insulation of cement mortar. They found that shorter fibers (e.g., 6 mm compared to 20 mm, or 1 mm compared to 6 mm) promoted the formation of a compact insulating layer with the cement, whereas unwashed wool fibers induced air bubble formation in the matrix, contributing to reduced thermal conductivity (Valenza et al., 2015). Likewise, Fiore et al. (2020) revealed that shorter fibers contributed more to thermal insulation improvements but also led to greater mechanical weakening. Dénes et al. (2022) analyzed influence of synthetic resin and natural rubber latex on the thermal conductivity of sheep wool-based composites, finding that synthetic resin leads to higher thermal conductivity values compared to natural rubber latex.

The enhancement of the thermal insulation in concrete by sheep wool fibers can be summarized in three key aspects. First, sheep wool has naturally low thermal conductivity, which reduces heat transfer through the material and improves insulation (Zach et al., 2012). Second, the fibrous structure of sheep wool traps air pockets, which further inhibits the heat flow. Air is a poor conductor of heat; thus, air entrapment enhances the insulation (Ghermezgoli et al., 2021). Third, sheep wool can absorb and release moisture without compromising its insulation properties. Due to its ability in regulating moisture (kind of like "human-breath"), the risk of microbial growth or fiber decay is prevented (Tuzcu, 2007). This hygroscopic nature helps to maintain a stable internal temperature, contributing to thermal comfort (Valenza et al., 2015). Another important thing should be emphasized is the fire resistance of SWFRCC. Although sheep wool is flammable because of its organic component, it has a relatively higher ignition temperature (around 570–600 °C) compared to many other organic materials (Galaska et al., 2019). Meantime, thanks to the three abovementioned key factors, sheep wool fibers could provide a natural flame retardancy, which makes it a promising material in fire resistance (Alyousef et al., 2022).
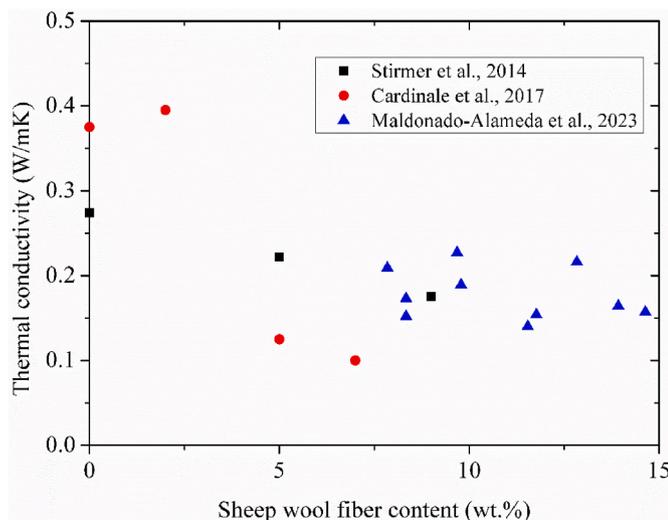


**Fig. 11.** Thermal conductivity vs. sheep wool fiber content (Štirmer et al., 2014) (Cardinale et al., 2017) (Maldonado-Alameda et al., 2023).

*5.5. Effect of sheep wool fibers on acoustic performance*

Apart from thermal conductivity, acoustic performance is another key insulation property of modern concrete buildings. Acoustic performance is crucial, particularly in urban environments where noise pollution can significantly impact the quality of life (Wijesinghe et al., 2024). Effective acoustic design minimizes sound transmission between spaces, enhances privacy, and contributes to the overall occupant comfort (Algaifi et al., 2024; Gao et al., 2024). One of the most effective solutions to absorb and dampen noise is the use of porous media. The primary sound-absorbing mechanism in porous media is the conversion of sound wave energy into thermal energy through internal friction, as sound travels through continuous voids (Kim and Lee, 2010; Kim et al., 2018). However, modern building structures are generally constructed with concrete and steel, which act as sound-reflecting materials, worsening the noise issues in both urban and rural areas (Kim et al., 2018). Various efforts have been made to develop sound absorbable cement-based materials, such as porous concrete (Park et al., 2005), cenosphere-reinforced cement (Tiwari et al., 2004), crumb-rubber-reinforced composites (Sukontasukkul, 2009), foam concrete (Zhang et al., 2015), polymer-modified drainage concrete (Gerharz, 1999), and porous ceramic materials (Cuiyun et al., 2012). Despite these advancements, sustainability remains a challenge, prompting greater attention toward recyclable and renewable sound-absorbing fibrous materials.

To evaluate acoustic performance, both laboratory methods (e.g., ASTM C423) and in situ standards (e.g., ISO 11654) are commonly used to assess sound absorption, transmission, and impact insulation. Sound absorption and acoustic material properties are typically measured for potential sound absorbent cement-based composites. Table 5 lists the relevant standards and methods used for their evaluation. It can be seen that the normal sound absorption is measured by the sound absorption coefficient, noise reduction coefficient (NRC), normal incident sound absorption, and acoustic impedance. Several studies have investigated the acoustic properties of sheep wool. Zach et al. (2012) used the prepared sheep wool samples to investigate the insulation properties for building materials under frequently occurring and strict climatic conditions. Their experimental results revealed an inverse correlation between the bulk density of wool and air flow in the pore structure and further proved the acoustic insulating ability of sheep wool. These findings align with those of Symons et al. and Ye et al. (Symons et al., 1995; Ye et al., 2006). Hence, it is worth trying to adopt sustainable sheep wool in cement-based materials to improve acoustic performance.

Although the enhanced acoustic properties of sheep wool for façades and roofs have been widely investigated, systematic research on SWFRCC began relatively late. Alyousef (2022) pioneered the study of sheep wool fiber effects on the acoustic properties of concrete composites in 2022. They measured and calculated the sound absorption coefficient, NRC, sound transmission loss coefficient (TLC), and sound transmission class (STC) of SWFRCC based on ASTM E1050 and ASTM

**Table 5**
Standards and methods for evaluating sound absorption and acoustic material properties.

| Standard | Measured item | Unit | Description | Reference |
|---|---|---|---|---|
| ASTM C423 – Standard Test Method for Sound Absorption and Sound Absorption Coefficients by the Reverberation Room Method | Sound absorption coefficient ($\alpha$[1]), noise reduction coefficient (NRC[2]). | Dimensionless. | Measuring the sound absorption of materials using a reverberation room, where the decrease in sound levels is recorded after sound excitation stops. | ASTM C423 (2008) |
| ISO 354 – Acoustics: Measurement of Sound Absorption in a Reverberation Room | Sound absorption coefficient, practical absorption area. | Dimensionless (sound absorption coefficient), $m^2$ (absorption area). | Measuring sound absorption in a reverberation room. | ISO 354 – acoustics (2003) |
| ASTM E1050 – Standard Test Method for Impedance and Absorption of Acoustical Materials Using a Tube, Two Microphones, and a Digital Frequency Analysis System | Normal incidence sound absorption coefficient. | Dimensionless (0–1). | Utilizing an impedance tube, two microphones, and digital analysis to measure sound absorption at normal incidence, ideal for small samples. | ASTM e1050 (2012) |
| ISO 10534-2 – Acoustics: Determination of Sound Absorption Coefficient and Impedance in Impedance Tubes, Part 2: Transfer-Function Method | Normal incidence sound absorption coefficient and acoustic impedance. | Dimensionless for absorption coefficient, impedance in rayls. | Measuring sound absorption through an impedance tube | ISO 10534-2 – acoustics (1998) |
| ASTM E2611 – Standard Test Method for Normal Incidence Determination of Porous Material Acoustical Properties Based on the Transfer Matrix Method | Normal incidence sound absorption coefficient, reflection coefficient, impedance, and transmission loss. | Dimensionless (for coefficients), rayls (for impedance). | Measuring acoustic properties of porous materials by using the transfer matrix method. It determines both absorption and transmission characteristics. | ASTM e2611 (2019) |
| ISO 11654 – Acoustics: Sound Absorbers for Use in Buildings: Rating of Sound Absorption | Weighted sound absorption coefficient ($\alpha w$). | Dimensionless. | Classifying the sound absorption properties of materials based on measured data across different frequency bands, assigning a single rating ($\alpha w$). | ISO 11654 (1997) |
| EN 1793-1 – Road Traffic Noise Reducing Devices: Test Method for Determining the Acoustic Performance, Part 1: Intrinsic Characteristics of Sound Absorption | Sound absorption coefficient. | Dimensionless. | Assessing the sound absorption performance of noise barriers typically used along highways. | EN 1793 (2017) |
| ISO 9053 – Acoustics: Determination of Airflow Resistance | Airflow resistance. | Pascal-seconds per meter (Pa·s/m). | Measuring the airflow resistance of porous materials, which is closely related to their sound absorption properties. | ISO 9053 (2020) |
| JIS A 1405-1 – Method of Test for Sound Absorption of Acoustical Materials by Reverberation Room Method | Sound absorption coefficient. | Dimensionless. | Measuring the sound absorption properties of acoustical materials in a reverberation room | JIS A 1405 (2007) |
| ASTM C384 - Standard Test Method for Impedance and Absorption of Acoustical Materials by the Impedance Tube Method | Acoustic impedance, sound absorption coefficient (at normal incidence) | Dimensionless for the sound absorption coefficient (0–1), rayls (Pa·s/$m^2$) for acoustic impedance | Using an impedance tube to measure the acoustic impedance and absorption coefficient of acoustical materials at normal incidence. | ASTM C384 (2004) |

Note: [1] $\alpha = 1 - \dfrac{p_2^2}{p_1^2}$, where $\alpha$ is the sound absorption coefficient, $p_2$ represents the reflected wave sound pressure, and $p_1$ is the direct wave sound pressure.

[2] NRC $= \dfrac{\alpha_{250} + \alpha_{500} + \alpha_{1000} + \alpha_{2000}}{4}$, where $\alpha_{250}$, $\alpha_{500}$, $\alpha_{1000}$, and $\alpha_{2000}$ represent the sound absorption coefficients at 250, 500, 1000 and 2000 Hz respectively.

E413-16. The test results, shown in Fig. 12, indicated that sheep wool fibers significantly increased the sound absorption coefficient and enhanced the acoustic performance of the concrete. Concrete with 1 wt % wool fiber and modified wool fiber demonstrated sound absorption coefficients of 0.66 and 0.75, respectively, at 2000 Hz, compared to 0.25 for the control mix. Additionally, the NRC increased notably with the fiber content for both the wool fibers and modified wool fibers. However, regarding the sound TLC and STC, these values in wool fiber concrete mixtures were lower than those in ordinary concrete. Specifically, the sound TLC range for concrete mixtures with wool fibers and modified wool fibers is 20–38 dB at 2000 Hz, which is lower than that of standard concrete mixtures.

Similar results were reported by Oancea et al. (2018), who found that concrete samples containing sheep wool balls displayed a higher sound absorption coefficient than conventional samples. The ability of materials to absorb sound energy is influenced by factors such as the density, thickness, porosity, fiber diameter, airflow resistivity, tortuosity, surface impedance, compression, air gap, and multilayers (Alyousef et al., 2020; Kim et al., 2018). The primary mechanism behind the improved sound absorption can be attributed to the highly porous and naturally crimped structure of the sheep wool fibers. This structure creates air pockets within concrete, increasing its overall porosity and acting as sound traps that prevent noise from passing through the material (Alyousef et al., 2020; Alyousef, 2022; Kim et al., 2018).

### 5.6. Effect of sheep wool fibers on durability

Durability issues in concrete structures, such as carbonation, reinforcement corrosion, alkali-silica reaction, sulfate attack, and freeze-thaw cycles, often lead to cracking owing to mechanical, thermal, and chemical stresses (Martı-Pérez et al., 2000). Among these, carbonation, chloride penetration, and sulfate attack are critical factors that affect durability, particularly in aggressive environments (Hossain et al., 2015; Bernal and Provis, 2014). Over the past several decades, numerous studies have been conducted to understand the mechanisms behind durability problems and to find sustainable solutions to improve concrete performance (Yang et al., 2015; Arbi et al., 2016; Pasupathy et al., 2016; Kalla et al., 2015; Ramezanianpour and Moeini, 2018; Feo et al.,

2020; Robalo et al., 2020). For fiber-reinforced composites (FRC), the bond between the fibers and cementitious matrix is a decisive element for durability performance. It has been reported that the composite integrity of glass-fiber-reinforced cement-based composites may be degraded owing to the chemical interaction between these two constituents (Brandt, 2005). A similar phenomenon has been observed in SWFRCC, where the highly alkaline environment of the cement matrix leads to the degradation of the natural wool fibers. This degradation mechanism has been investigated by Wei and Meyer, who used meta-kaolin to reduce the alkalinity of the pore solution, significantly mitigating the deterioration of natural fibers (Wei and Meyer, 2015). Fantilli and Jóźwiak-Niedźwiedzka (2020) also examined the influence of OPC alkalinity on natural wool-reinforced mortar and confirmed that lowering the alkalinity of the cement paste improved the resistance of sheep wool fibers within the matrix.

Alyousef et al. (2022) tested the water absorption and chloride diffusion in SWFRCC to assess durability performance, with results shown in Fig. 13. The addition of wool fibers up to 1 % and modified wool fibers up to 2 % reduced the water absorption of the mixtures compared with plain concrete without wool fibers, which slightly increased the sorptivity. Similar results were observed in the chloride diffusion tests. Concrete mixtures with 0.5 %, 1 %, and 1.5 % fibers had decreased chloride penetration, with the lowest penetration depth of 10.5 mm observed for 1 % modified wool fibers at 90 d, which was 44 % lower than that 18.9 mm of plain concrete. However, a higher fiber content increased the permeability and penetration depth. These results suggest that the controlled addition of sheep wool fibers can slightly improve the durability of concrete, whereas higher additions can be detrimental to the durability development.

Maia Pederneiras et al. (Maia Pederneiras et al., 2019) studied the open porosity of sheep wool fiber-added cement mortar and found that higher porosity led to reduced durability. Their results showed that for the cement-based mortars, the open porosity increased from 20.18 % to 20.91 % when fiber contents increased 10 %. While, for the cement-lime modified mortars, the porosity exhibited a greater increase from 23.93 % to 25.49 %. This could be explained by two factors. First, the degradation of sheep wool fibers compromises the durability of SWFRCC, making pretreatment of the fibers necessary to increase their chemical
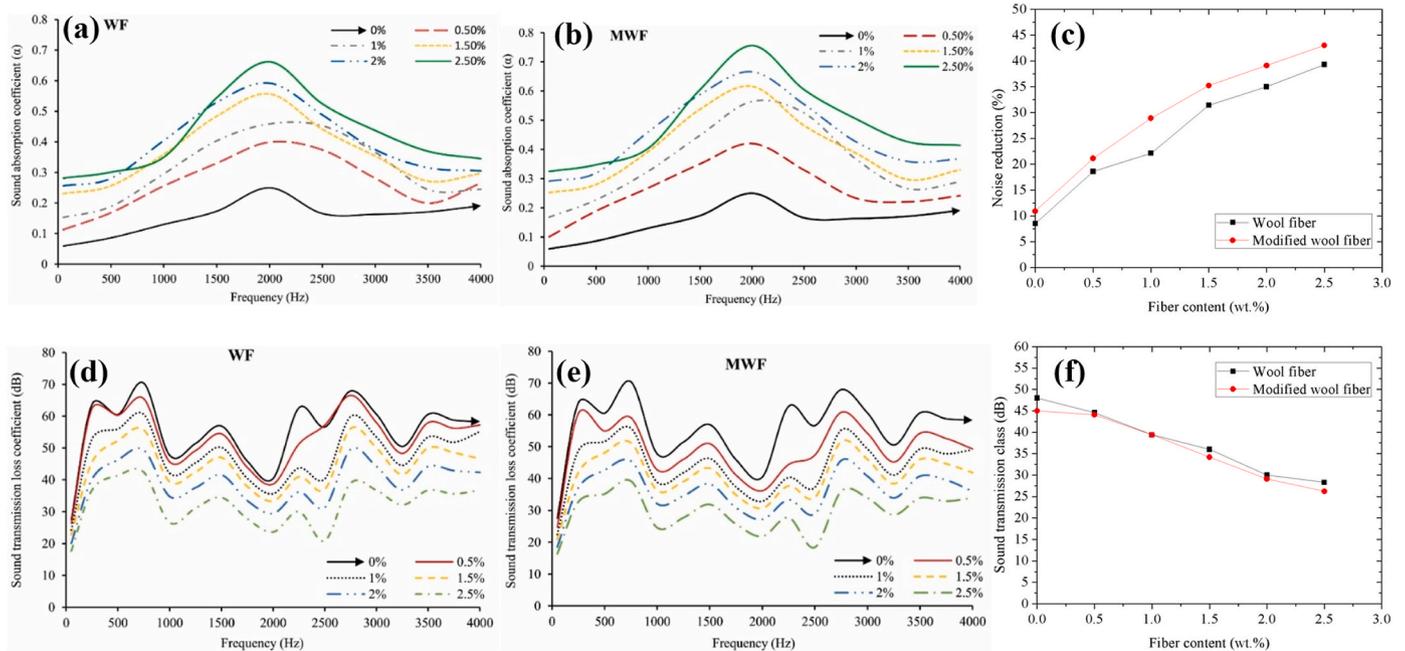


**Fig. 12.** The acoustic properties of concrete mixes reinforced with wool fiber (WF) and modified wool fiber (MWF) include sound absorption coefficients ((a) WF- and (b) MWF-reinforced); (c) noise reduction (modified); sound TLC ((d) WF- and (e) MWF-reinforced); and (f) STC (modified) (Alyousef, 2022).
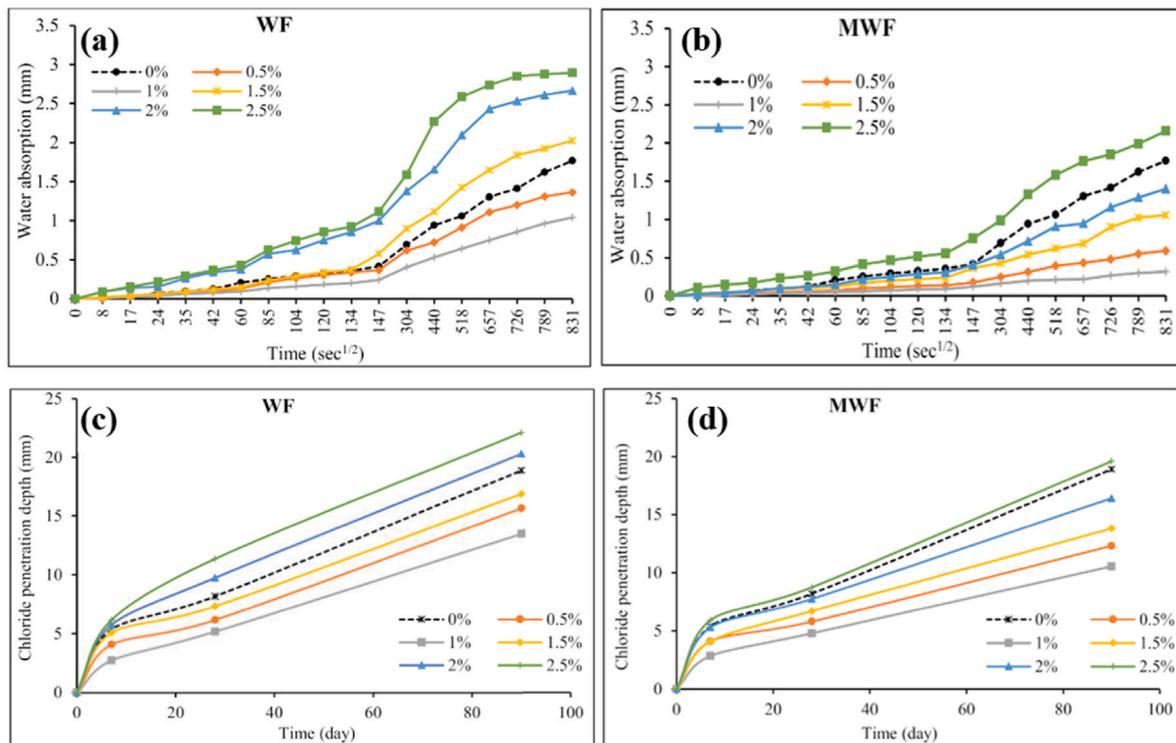
**Fig. 13.** Water absorption of (a) WF- and (b) MWF-reinforced concrete; and chloride penetration depth of (c) WF- and (d) MWF-reinforced concrete (Alyousef et al., 2022).

resistance. Second, a high content of sheep wool fibers results in an uneven distribution of fibers and increased pore volumes in the concrete matrix. Consequently, the density of the concrete decreases, providing more space to absorb water (Shawnim and Mohammad, 2019; Amer et al., 2021). Regarding shrinkage resistance of SWFRCC, it is still not reported yet though, imparting shrink resistance to wool fiber is needed to make them machine-washable (Hassan and Carr, 2019). For increasing the shrink resistance, several common treatments are used, including oxidative, enzymatic, radiation, polymeric coatings, sol-gel coatings, and plasma treatments (Hassan and Carr, 2019) (Kadam et al., 2021). The shrink-proofing of wool fibers restrains shrinkage-induced deformation and cracking in the surrounding matrix (Aghaee and Khayat, 2021). Considering the short history of SWFRCC, long-term freeze-thaw resistance, carbonation and durability under sulfate attack have not been systematically studied. Therefore, it is strongly suggested to conduct the durability-related experiments for SWFRCC both in mechanism exploration and appropriate dosage determination.

### 5.7. A statistic summary of the effect of sheep wool fibers on SWFRCC

According to the above, the mechanical properties of SWFRCC are systematically reviewed. To improve clarity and facilitate comparison in the analysis of fresh and hardened properties, quantitative indicators such as the slump/strength change ratio should be employed. Supplementary Table S1 summarizes the effects of sheep wool fiber on the aforementioned properties of concrete. Note that, even for the same property, various testing methods exist. For example, compressive strength can be measured at different curing ages, e.g., 7-day, 14-day, 28-day, etc. and acoustic performance can be expressed by noise reduction and sound transmission. Therefore, we only focus on the change ratio of the properties, calculated as the increased/decreased value divided by the reference property, to display the degree of improvement or reduction. The workability decreases remarkably with the addition of sheep wool fiber. From the data, 0.5 wt % addition of

sheep wool fiber content could cause around 30 % reduction in slump. When the amount is greater than 6 wt %, there is no any slump detected. For compressive strength, a reduction of approximately 25 % is observed owing to the ∼2 wt % addition of sheep wool fiber. It should be noted that Gelana et al. (2019) reported a rise in the 7-day compressive strength up to 13.7 % with the addition of 0.5, 1, 1.5, and 2 wt%. They carefully controlled the aggregate and fiber content during mixing, which may improve the packing density of the entire mixture. These results encourage the use of sheep wool fibers for concrete mixing (Chu et al., 2023). The flexural strength increases sharply up to 70.4 % with the addition of less than 4 wt %. Regarding insulation properties, both thermal and acoustic performances show a dramatic increase with the continuous addition of sheep wool fiber. Specifically, the thermal conductivity is reduced by approximately 27.1 % with the addition of ∼7 wt %; noise reduction can be increased averagely 203 %; and sound transmission can be reduced averagely 21.4 % with the fiber addition of ∼2.5 wt %. Finally, durability is represented by chloride penetration depth, where negative values indicate reduced penetration, proving higher durability. The statistical results showed that the durability can be continuously improved by up to 47 % when sheep wool fiber with less than 1 wt %.

Overall, apart from workability, there is significant potential for sheep wool fibers used in concrete production to improve the mechanical properties (even the compressive strength). Therefore, they provide an opportunity for the development of sustainable natural materials in the industry.

## 6. Life cycle assessment for SWFRCC

In addition to evaluating mechanical and thermal performance, the sustainability benefits of SWFRCC should also be assessed through life cycle assessment (LCA) and life cycle cost (LCC) analyses.

*6.1. Life cycle analysis*

Natural fibers such as sheep wool are renewable, biodegradable, and require significantly less energy for production compared to synthetic or mineral fibers. While the body of literature on environmental assessments of virgin wool products is not extensive, it is by no means scarce. Most existing LCA studies on wool focus primarily on the farming phase, with particular attention to allocation procedures during this stage. Henry reviewed the environmental impacts of wool and identified three common allocation approaches: (1) no allocation, (2) biophysical basis or (3) economic basis. Additionally, Barber and Pellow (Pellow and Barber, 2006) reported on the energy use and global warming potential (GWP) associated with the production of Merino wool top from New Zealand, as summarized in Table 6. Their findings show a total GWP of 2.229 kg $CO_2$-e/kg for Merino wool (Pellow and Barber, 2006) which is lower than that of the conventional micro steel fibers with the diameter of 0.15 mm (2.670 kg $CO_2$-e/kg) (Stengel and Schießl, 2014), and also lower than that of glass fiber (2.60 kg $CO_2$-e/kg) (Domenek et al., 2004; Moutik et al., 2024). According to the Inventory of Carbon and Energy (ICE) written by Hammond and Jones, the embodied energy of the recycled wool is 20.9 MJ/kg, substantially lower than general insulation materials (45 MJ/kg) (Hammond and Jones, 2008) and glass fiber (46 MJ/kg). These comparisons clearly suggest that sheep wool fiber imposes a lower environmental burden relative to conventional fiber materials, reinforcing its suitability as a sustainable building material.

*6.2. Life cycle cost*

Another frequently discussed concern in the construction sector is life cycle cost (LCC). LCC refers to the total cost of ownership of a product, material, or system throughout its entire lifespan. It encompasses not only the initial design and construction costs, but also the expenses associated with operation, maintenance, and eventual demolition or disposal (Dong, 2018). Corscadden et al. (2014) provided a detailed cost breakdown, estimating the cost per 0.4 kg of finished product at $5.67. In order to directly show the cost-effectiveness of SWFRCC, a comparison of LCC was conducted among SWFRCC, SFRC and glass fiber reinforced-concrete (GFRC), with compressive strengths controlled to be similar (35 ± 2.5 MPa). Prior to the LCC analysis, several assumptions were made: (1) Transportation and usage phase impacts were assumed identical across all concrete types; (2) Except for the fiber component, all other constituents in the concrete mixtures were sourced from the same suppliers to ensure consistency; (3) All monetary values were standardized to United States dollars (USD) based on the current exchange rate.

A literature review was conducted to estimate the LCC of steel fibers and glass fibers. According to (Yang et al., 2024) (Stengel and Schießl, 2014), the unit costs were reported as 2.09 $/kg (converted from 1.8 €/kg) for steel fibers and 0.36 $/kg (converted from 11.78 Yuan/m³ of concrete) for glass fibers. Therefore, the LCC of sheep wool fiber was identified as the highest among the three. The unit costs of other major components: cement, water, sand, and aggregates were referenced from (Stengel and Schießl, 2014) (Zheng et al., 2025). Table 7 presents the material components of SWFRCC, SFRC and GFRC, each designed to achieve comparable mechanical properties. The amount of each component was transferred into mass percentage (%). The quantities of individual components are expressed as mass percentages, and the LCC values, shown in the ninth column, represent the total cost per metric

**Table 6**
Energy use and GWP for 1 kg merino wool top from New Zealand (Pellow and Barber, 2006).

| Impact category | On farm | Processing | Transport | Total |
|---|---|---|---|---|
| Total energy (MJ/kg wool top) | 22.550 | 21.700 | 1.490 | 45.730 |
| GWP (kg $CO_2$-e/kg wool top) | 1.655 | 0.471 | 0.103 | 2.229 |

ton of concrete in USD. The results indicate that SFRC exhibited the highest LCC, followed by SWFRCC, while GFRC had the lowest. These findings can be attributed to several key factors. Firstly, due to lower density of sheep wool fibers compared to steel fibers, the mass of wool fiber required for the same volume fraction is significantly lower. This directly reduces the fiber usage in SWFRCC, contributing to a lower overall LCC than that of SFRC. However, the high unit cost of sheep wool fibers, primarily due to limited industrial production and lack of economies of scale, elevates the total cost. In contrast, steel and glass fibers are produced industrial scale with optimized supply chains, yielding a more favorable cost-performance ratio. Particularly when compared to glass fiber, the LCC cost of SWFRCC was found to be nearly double that of GFRP. Furthermore, the long-term durability of wool fibers in concrete is compromised by biodegradation and alkaline attack, especially in the absence of surface treatments. To ensure adequate fiber-matrix bonding and longevity, additional chemical treatments or coatings are often required, further increasing the cost of wool fibers. On the other hand, steel and glass fibers, especially those treated for alkali resistance, typically require less maintenance or protection, thus resulting in lower LCC over the product's life span.

From a circular economy perspective, the utilization of sheep wool, often considered as an agricultural by-product or waste, enhances resource efficiency and support waste valorization. Additionally, when sourced locally, sheep wool fibers can significantly reduce the transportation-related emissions associated with conventional construction materials. Although dedicated LCA studies on SWFRCC remain limited, existing evidence suggests that it holds promise in lowering the environmental footprint of concrete production. However, the relatively high LCC of SWFRCC remains a concern, largely attributable to its underdeveloped processing methods and susceptibility to degradation. Future research should focus on conducting comprehensive cradle-to-grave assessments to quantify the full environmental and economic benefits of SWFRCC and guide its optimization for practical application.

## 7. Challenges and future perspectives for SWFRCC

*7.1. Possible applications of SWFRCC*

From the above, we can see that the lower workability and compressive strength may hinder the wide application of SWFRCC in construction work. However, considering the controlled reduction degree and potentially improved flexural strength, insulation properties, and durability, SWFRCC remains a great candidate for construction and building materials. According to the 2024 Hokkaido Regional Development Bureau Road Design Guidelines (supported by JIS A1108, JIS A1113, and JIS A1106) (Hokkaido regional development bureau road, 2024) and statistical analysis in Section 5, the potential application of SWFRCC is presented here. The 28-day compressive strength of SWFRCC is achieved at the C30 level (32 MPa (Gradinaru et al., 2016)) with the addition of 0.35 wt%. SWFRCC can be adopted in reinforced concrete structures in marine and splash zones (RC-1S, design strength of 21 MPa), concrete barriers (RC-4S, design strength of 24 MPa), and underwater concrete for cast-in-place piles (RC-11, design strength of 30 MPa). RC-1S, RC-4S and RC-11 are all the structural elements, reflecting that SWFRCC meets or exceeds the strength requirements for some structural applications. It should be noted that underwater and marine environments require concrete with good durability, especially for resistance to chloride attack. Thus, SWFRCC with improved durability are a strong player in this area.

Meanwhile, SWFRCC can be used for components that require good sound and thermal insulation, but are not as critical for mechanical properties. First, acoustic insulation panels are always required in music studios, theaters, and residential buildings, in which sound absorption is essential. A 50-STC wall assembly can reduce the airborne sound transmission from one side by approximately 110–60 dB on the opposite side. This reduction can be attributed to the lowering of the volume of a

**Table 7**
Material components (mass percentage) and LCCs of SWFRCC, SFRC and GFRC.

| FRC type | Mix ID | Cement | Water | Sand | Aggregate | Fiber* | SP | Total cost/USD/ton | Ref. |
|----------|--------|--------|-------|------|-----------|--------|-----|--------------------|------|
| SWFRCC | WF1 | 18.64 | 9.01 | 35.82 | 36.03 | 0.50 | 0.00 | 89.69 | Alyousef (2022) |
| SFRC | SFRC1.5a_1.25 | 17.10 | 7.70 | 25.35 | 44.98 | 4.87 | 0.00 | 120.62 | Xue et al. (2019) |
| GFRC | GF-30-45 | 11.68 | 5.38 | 27.33 | 48.60 | 1.48 | 0.27 | 45.49 | Ajay and Kumar (2020) |

Note*: Fiber for SWFRCC, SFRC and GFRC refers to sheep wool fiber, steel fiber and glass fiber, respectively.

rock concert to the level of normal conversations (Ghermezgoli et al., 2021). Natural fibers serve as sound traps, absorbing sound energy and reducing noise transmission. Second, non-load-bearing walls or facades in buildings generally only require good thermal insulation properties; hence, SWFRCC can serve as a thermal insulation non-structural element in this situation. Meanwhile, using SWFRCC in these nonstructural elements can align well with sustainable construction practices. According to the American Concrete Institute (ACI), these non-loading structures can be classified into four categories: Class F0 (exposure class for mild conditions) of 2500 psi (approximately 17.2 MPa), Class F1 (exposure class for moderate conditions) of 3000 psi (approximately 20.7 MPa), and Classes F2 and F3 (exposure class for severe conditions) of 3500 psi (approximately 24.1 MPa) (ACI Committee, 2019). Therefore, the current SWFRCC product can be applied to all these classes. Third, certain types of cladding or protective barriers may favor the natural fire resistance of sheep wool.

The potential market for sheep wool fibers in concrete is driven by the increasing demand for sustainable, energy-efficient, and eco-friendly building materials. With growing awareness of environmental impacts, both industry and government stakeholders are promoting low-carbon construction practices, thereby creating opportunities for integration of bio-based materials such as sheep wool fibers. Several market segments are especially well-position to adopt SWFRCC, including green building and sustainable architecture, infrastructure in marine and coastal environments, and agricultural or rural construction projects where natural materials and thermal efficiency are particularly valued.

### 7.2. Challenges and limitations of SWFRCC

As discussed above, SWFRCC can be ready for industrialization. However, compared to the natural development of sheep wool fibers in clothing, buildings, etc., SWFRCC is still limited to laboratory tests, with most studies focusing on evaluating its mechanical and durability properties. To date, there have been no documented pilot plants or large-scale industrial applications of SWFRCC. Most studies involve small-scale tests on concrete specimens with varying amounts of sheep wool fibers, suggesting that more development and scaling, including pilot testing and field trials, are needed for industrial implementation. Several challenges and limitations remain in the current research and future applications of SWFRCC. One of the most important issues for SWFRCC is reduced workability and compressive strength. The main reason for this problem is the limited understanding of the interaction between sheep wool fiber and concrete, which could result in the increased porosity of SWFRCC. The reliability of SWFRCC has not been fully assessed. From this aspect, some challenges for SWFRCC can be listed as follows: (1) ambiguous properties of different sheep wool fibers, (2) limited understanding of the compatibility between fibers and binders, (3) insufficient investigation of durability, (4) lack of full-scale element tests and its life cycle assessment analysis, (5) concerns in commercialization and scale-up production; (6) potential of biodegradation and fire resistance reduction; (7) absence of prediction and optimization methods for SWFRCC mix design.

(1) Owing to their different breeds and dimensions, sheep wool fibers display various properties. Compared with sheep wool fibers, conventional fibers, such as steel fibers, have a mature production process and quality control. However, the absence of standardized methods for processing or modifying sheep wool fibers presents a significant challenge in ensuring consistent material properties. This variability makes it difficult to predict or control the performance of wool fibers across different regions, ultimately hindering quality assurance and reliability in construction applications.

(2) Since there is no standard for producing sheep wool fibers, these non-unified fibers directly lead to different water demands and binding abilities, resulting in difficult control of the W/CM ratio and compatibility between fibers and binder. Without certain modifications, the workability is easily spoiled, and a high porosity occurs in the matrix. These voids also lead to lower compatibility and reduced compressive strength, and the flexural strength can be decreased with a high content. The limitation in compressive strength hinders the application of SWFRCC in important structural elements (e.g., columns and beams).

(3) More attention should be paid to the durability and microstructure of SWFRCC. While an appropriate fiber content may slightly improve durability through an enhanced ITZ and a denser matrix, excessive fiber content can lead to higher porosity and fiber degradation, thereby reducing the lifespan of the concrete structure. Furthermore, other common durability concerns, such as carbonation, sulfate attack, and freeze-thaw cycles, are not thoroughly investigated. SWFRCC is considered to various durability challenges, particularly as fiber content increases. Higher contents of sheep wool fibers can result in increased porosity, which adversely impact durability by facilitating the ingress of water, ions, and gases. This, in turn, increases the risk of freeze-–thaw damage, promotes sulfate attack, and allows deepens carbonation front to develop, potentially compromising the protection of embedded reinforcement. Without sufficient durability tests, the lifespan of SWFRCC products remains unknown, leading to difficulties in LCA.

(4) State-of-the-art tests for SWFRCC are all on the laboratory scale, but there is no study focusing on the specific performance of structural or nonstructural elements at a 1:1 scale. A thorough study on the sustainability of wool fiber composites is necessary, as a comprehensive LCA of SWFRCC remains limited. Even though the sustainability of natural fiber has been proved by numerous researchers (Hetimy et al., 2024; Patrucco et al., 2024), the manufacturing process, especially the chemical pre-treatment process, still leaves the unneglectable environmental impacts. It is also essential to consider the cost-effectiveness and scalability of the process to ensure its practical implementation.

(5) Commercializing and scaling up SWFRCC remains a significant challenge due to limited full-scale studies. The complexity and cost associated with efficient fiber processing, coupled with difficulties in achieving uniform fiber dispersion in large-scale concrete mixing, can lead to inconsistent material performance. Additionally, the natural variability of sheep wool fibers complicates quality control efforts, and the absence of established industry standards further impedes widespread construction adoption. Although sheep wool is often considered an agricultural by-product, its cost-effectiveness at scale remains uncertain. To support the practical application of SWFRCC, it is essential to establish standardized processing protocols, develop scalable

mixing techniques, and implement performance-based specifications.

(6) In addition to mechanical limitations, the long-term performance of SWFRCC may be affected by factors such as biological degradation concerns. As an organic material, sheep wool is susceptible to microbial attack (e.g., mold, bacteria, fungi) in moist or poorly ventilated environments, particularly before or during the early stages of cement hydration.

(7) Considering the short development history of SWFRCC, there is extremely limited data on the mix design and mechanical properties of SWFRCC. The limited dataset presents challenges in drawing comprehensive conclusions or performing mix design optimization tailored to specific performance requirements. The absence of a prediction model and optimization method makes it difficult to design mix proportions with the required properties, directly leading to repeated trial experiments and high costs both in labor and materials.

### 7.3. Future perspectives for SWFRCC

Based on the above discussion, several suggestions and future perspectives are outlined here. These suggestions are raised to develop mature SWFRCC from compositions to the final product.

First, the properties of sheep wool fibers should be controlled and further improved. The considerable variation in the chemical and mechanical properties of sheep wool fibers is largely attributed to individual animal differences and is therefore inherently unavoidable. However, deviations can be minimized through precise control of processing parameters. Note that it is important to systematically study how the use of wool fibers with varying properties can lead to variations in the properties of SWFRCC, which would indicate its applicability.

The chemical stability and compatibility of sheep wool fibers with cement binders should be investigated further. Improved chemical resistance would help maintain the crack-bridging effect within the cement matrix, whereas improved compatibility could enhance the mechanical properties of SWFRCC. Several possible pretreatment methods for sheep wool fibers have been proposed, including saltwater soaking, NaOH treatment, heat treatment, plasma modification, and polymer coatings (Hetimy et al., 2024; Kulkarni et al., 2023). Among the various pre-treatment methods for sheep wool fibers prior to incorporation into concrete, two major approaches stand out. The first is salt water treatment, in which wool fibers are soaked in a NaCl solution to remove surface impurities and partially denature the outer keratin layer. This enhances fiber–matrix bonding and reduces early-stage degradation (Alyousef, 2022). The similar approach involves alkali soaking using NaOH/Ca(OH)$_2$ solutions, which modifies fiber's surface roughness, thereby improving mechanical interlocking and adherence to the cementitious matrix (Patrucco et al., 2024). The second main method is plasma modification, which alerts surface chemistry of wool fibers without substantially affecting their internal structure, offering a non-chemical alternative (Patrucco et al., 2024). Among these methods, saltwater treatment is most commonly recommended, due to its relative maturity, effectiveness and cost-efficiency. Hence, the surface modification of sheep wool fibers should be an upcoming stage for improving the performance of SWFRCC.

The effectiveness of SWFRCC depends on the compatibility between the wool fibers and the concrete matrix. To ensure compatibility, it is essential to understand the chemical, mechanical, and thermal interactions between wool and concrete components. Because such properties can be represented by its microstructure, observation of as-processed and after-tested samples should be further investigated. Observation of microstructural changes over time or mechanical tests can provide useful information for understanding the strengthening or degradation mechanisms of SWFRCC. In this sense, computed tomography (CT) should be applied (Kong et al., 2023). CT can identify key factors, such as porosity and tortuosity, which affect the mechanical and insulation properties. Furthermore, CT technology can display fiber orientation within the matrix, helping to identify how different amounts of sheep wool fibers might lead to an uneven distribution. With the aid of it, a dynamic investigation of the chemical reaction between the fiber and binder during this time period can be performed to provide a clearer explanation of the degradation mechanism of natural fibers.

In this manner, the relationship among material, process, structure, and property should be systematically investigated. Finally, after conducting the aforementioned studies, there will be a much larger database consisting of sheep wool fiber properties, mechanical properties of SWFRCC and its structure, and LCA results than the existing database. Such a database can be utilized for the optimization of mix design, considering higher performance and sustainability (Kong and Kurumisawa, 2023b; Cakiroglu et al., 2023). This database has two functions: index and machine learning training. With the growing number of SWFRCC mix designs, the compiled database can serve as a valuable reference for designers seeking mixtures with specific performance requirements. By stabilizing the quality of sheep wool fibers, the consistency of both structural and non-structural SWFRCC elements can be improved. This comprehensive dataset also lays the foundation for establishing standardized practices for incorporating sheep wool fibers into concrete. In the context of the Big Data era, such datasets present an opportunity to develop predictive models through machine learning. Future research should actively integrate advanced artificial intelligence (AI) techniques. Machine learning applied to one-dimensional data—such as mixture composition, fiber dosage, and curing conditions—can predict key mechanical properties like compressive and flexural strength, reducing the need for extensive physical testing. Deep learning also holds promise for automating fiber classification, defect detection, and quality control using image data from optical or electron microscopy, ensuring consistency in fiber geometry and distribution. AI-driven optimization and processing will be essential for scaling up SWFRCC production while maintaining performance and reliability (Huang et al., 2020; Yao et al., 2024; Liu et al., 2024).

The motivation behind this research is to address the existing gaps in the understanding of the overall mechanical properties of SWFRCC and to explore their potential applications. This study not only fills a critical void in the literature by providing comprehensive data on properties of SWFRCC's but also identifies key knowledge gaps, particularly the limited research on durability. By highlighting these areas, this work supports the advancement and potential commercialization of SWFRCC. The findings provide valuable insights for the scientific community and offer a clear direction for future research in sustainable and bio-based construction materials.

## 8. Conclusions

This review provides a comprehensive summary of the origin of sheep wool fibers, manufacture of SWFRCC, and mechanical properties of SWFRCC. It includes a systematic discussion on the mechanical and insulation properties of SWFRCC, focusing on workability, compressive strength, flexural strength, thermal insulation, acoustic performance, and durability. Meantime, a life cycle assessment for SWFRCC is also provided to evaluate its sustainability. Finally, potential applications, challenges, and future perspectives for research in the realm of SWFRCC are highlighted. Based on an in-depth discussion, the following conclusions are drawn.

(1) Microstructural analysis revealed that sheep wool fibers have a scale-like cell structure on their surface, which enhances bonding with the cement matrix. This strong fiber coverage results in a denser ITZ between the cement matrix and fibers, thereby improving the overall strength and ductility.

(2) The addition of sheep wool fibers reduces the workability and compressive strength of concrete mixtures owing to their high water demand and porous structure. Although the flexural

strength increases owing to the crack-bridging effect, this improvement diminishes when the fiber content exceeds a certain threshold (typically 2% by weight) owing to uneven fiber distribution.

(3) The addition of sheep wool fibers significantly enhances the thermal insulation and acoustic performance, which can be attributed to their highly porous and naturally crimped structure. The air pockets within the cement matrix trap heat and sound, thereby reducing the thermal conductivity and increasing sound absorption.

(4) Compared with conventional concrete, the durability performance of SWFRCC remains unclear. The existing results suggest that sheep wool fibers may slightly improve the durability of concrete by reducing the water absorption and enhancing the ITZ with the cement binder. However, the alkalinity of cement degrades the durability of sheep wool fibers, necessitating pretreatment to increase chemical resistance.

Although sheep wool fibers can enhance the insulation properties of concrete, several challenges hinder the widespread application of SWFRCC, primarily because of the reduced fresh and hardened properties and unclear durability performance. Future research should focus on further modification of sheep wool fibers, understanding the material-process-microstructure-property relationship, and durability of SWFRCC. Through these studies, the optimization of process parameters with the help of machine learning, followed by full-scale tests and LCA evaluation, should be recommended. Sheep wool insulation offers promising potential as a sustainable option for green building projects; however, overcoming the challenges ahead will require effective collaboration between researchers, industry, and policymakers.

## CRediT authorship contribution statement

**Y.K. Kong:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Dariusz Alterman:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization. **Hideyuki Murakami:** Writing – review & editing. **Chiharu Tokoro:** Writing – review & editing, Supervision.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.dibe.2025.100730.

## Data availability

No data was used for the research described in the article.

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