Article

Suitability of Foamed Concrete for the Composite Floor System in Mid-to-High-Rise Modular Buildings: Design, Structural, and Sustainability Perspectives

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Abstract: This study investigates the application of lightweight foamed concrete (FC) in modular building floor systems to address challenges in lifting and transportation within modular construction. Initially, a literature review identifies FC's characteristics and optimum mix design, considering its sustainability and strength. The comprehensive review highlights that FC can be a lightweight alternative to replace traditional concrete in floor structures. Further, this study conducted the life cycle assessment and indicates that FC with coarse fly ash substitution is the optimum mix, which releases less greenhouse gas emission (i.e., 740.89 kg CO_2-eq/1 m^3) than other mixes. Subsequently, the study conducted design verification and parametric study of composite floor systems (i.e., cold-formed steel-FC, timber-FC, and steel deck-FC). The results show similar flexural and shear performance compared to normal-weight concrete despite its lower density (1600 kg/m^3) compared to normal-weight concrete (2400 kg/m^3). Further, the reduction of modulus of elasticity (43% of normal-weight concrete's value) in FC increases deflection by 22–46% and 11–15% for steel-FC and timber-FC floor systems, respectively. Overall, the outcome shows that FC can be an efficient alternative for mid-to-high-rise modular building floor construction. Its lightweight nature can reduce the module's weight, making modular construction more cost-effective.

Keywords: foamed concrete; life cycle assessment; steel-concrete composite floor; sustainable construction material; timber-concrete composite floor

1. Introduction

Modular construction, which utilises off-site manufacturing and on-site assembly, has been the preferred method to reduce construction time and cost in urban development [1]. This is because it offers several advantages over conventional on-site construction, including speed of installation on-site, the economy of scale in manufacturing, and improved manufacturing quality and accuracy [1,2]. The method also enhances the overall safety of construction by eliminating labour-intensive formwork installation, striking, and materials handling [3]. However, due to off-site manufacturing, the restrictions on the weight of the elements for lifting and transportation become a limitation for the material selection for the structural elements [4]. In volumetric construction modules, floor slabs account for a significant proportion of the total weight [5]. Therefore, the overall module dimensions are dependent on the construction materials. The precast concrete system is widely used for building constructions, such as frame, floor slab, and modular construction [3]. This material offers rapid construction and cost savings, particularly for suspended floors [6]. Precast concrete provides inherent advantages in terms of fire resistance, acoustic insulation, and thermal capacity compared to other construction materials [3]. However, the primary drawback of the concrete module is its relatively high weight (25 to 30% heavier than the steel alternative), leading to increased expenses for the tower crane. Thus, concrete has

constraints on its application in 3D volumetric modular construction. Alternatively, it is commonly used in panelised prefabricated construction [7].

Research has been conducted to enhance the efficient utilisation of concrete in mid-to-high-rise modular building constructions [4,7–9]. A preliminary study indicated that utilising lightweight concrete (LWC) for floors in volumetric modules can decrease the weight of modules during hoisting by up to 40% [4]. LWC with various densities can be achieved by substituting coarse aggregate with lightweight alternatives (e.g., expanded clay, pumice, shale, and fly ash aggregate). Industrial wastes and by-products have been used to substitute coarse aggregate to produce lightweight concrete [10–15]. However, using these alternative concrete aggregates within the industry is limited to the availability in each region [10]. Thus, foamed concrete (FC), which adds air voids into the concrete mixture [16,17], has been introduced as the more commercially attainable alternative. FC is a lightweight cellular concrete with a 400–1850 kg/m^3 density, with random air voids created by the mixture of foam agents in a mortar [18]. The primary FC mix comprises cement, water, fine aggregate, foam agents, and no coarse aggregate. Moreover, in recent years, FC applications in construction as a lightweight non-and semi-structural material have increased due to high flowability, low aggregate usage, and excellent thermal insulation compared to lightweight-aggregate concrete and normal-weight concrete (NWC) [16,19]. However, compared to lightweight-aggregate concrete and NWC, FC has comparatively weak structural properties, especially flexural and tensile strength, which restricts the growth of its application as a structural element [19]. Research has been focused on increasing the FC's flexural and tensile strength properties by adding fibres to the mix design [20,21]. It was found that adding fibres (i.e., PP fibres) to FC can increase the overall flexural and tensile strength [5,22].

Further, more research has been conducted to enhance the lightweight advantage of FC and achieve satisfactory structural performance through composite pairing with other materials [4,5]. Cold-formed steel and timber are commonly used with FC due to their lightweight and high elasticity [23,24]. The development of FC as floor composites enables the utilisation of both the rigidity of concrete and the elastic behaviour of steel or timber, such as cold-formed steel-FC composite (CFSFCC), timber-FC composite (TFCC), and steel deck-FC composite (SDFCC). The components of a composite floor system consist of floor slab and joists, which are joined by connectors (e.g., bolts and shear studs) that have various functions in the load transmission mechanism. A composite floor system can achieve more efficient material use by utilising the strength of each material. The composite system combines the compressive strength of concrete on the slab section with the tensile strength of more ductile materials (e.g., cold-formed steel, steel deck, and timber) as the joists. Furthermore, concrete composite modules have several advantages over all-steel modules, including durability, fire resistance, waterproofing, and acoustic impedance. These advantages are due to the inheritance of the merits of concrete material [7]. However, concrete production contributes significantly to greenhouse gas emissions to the environment [25]. Modular construction industries actively seek sustainable alternatives to reduce high carbon-intensive construction materials and reduce thermal energy consumption in the building. Upon initial observation, FC shows promise as a sustainable material due to its lightweight and high thermal insulation rating [16].

The design of FC composite floors is currently based on the traditional standard, which hinders the application of FC in modular construction. The current design standards for composite steel and concrete, EN 1994-1-1:2004 [26] and AS/NZS 2327:2017 [27], and for timber structures, EN 1995-1-1:2004 [28] and AS 1720.1-2010 [29] have limitations regarding the use of LWC. Further, they do not specifically address its use in FC. Thus, designers design the FC composite floor systems based on lightweight aggregate concrete design specifications. However, FC's mechanical properties (i.e., density and modulus of elasticity) significantly differ from lightweight-aggregate concrete. This is primarily due to the physical composition of FC, which includes air voids and the absence of coarse aggregates [5,16]. A higher distribution of air voids leads to a decrease in the density of FC.

Therefore, the lower density FC results in a reduced modulus of elasticity and strength [5]. The properties of the FC in composite floors lead to variations in its structural behaviour under different loading conditions. This is particularly evident in the more brittle nature of FC compared to lightweight aggregate concrete, which makes it more susceptible to the formation of microcracks [16]. Thus, it creates an uncertainty in the structural design of FC composite using lightweight-aggregate concrete's mechanical properties.

Therefore, this study aims to comprehensively assess FC's structural and sustainability performance in modular building floor constructions, focusing on optimising mix designs and evaluating composite floor systems. Initially, a comprehensive review of FC mix design and physical, fresh, and mechanical properties is conducted to identify suitable mix designs for floor construction. Then, the optimum mix design is derived via conducting a life cycle assessment on FC mixes with a minimum required compressive strength of 25 MPa (EN 1994-1-1:2004 [26] and ACI 318-14 [30]). The optimum mix design is used to produce FC composite floor systems (CFSFCC, TFCC, and SDFCC). Design verification of these composite floor systems is assessed via analytical method based on standards (EN 1994-1-1:2004 [26], AS/NZS 2327:2017 [27], EN 1995-1-1:2004 [28], and AS 1720.1-2010 [29]). Finally, a parametric study is conducted to determine the factors that affect the composite floor systems' flexural and shear strengths and deflections.

2. Methods

This study comprises three methods: data collection (Section 2.1), sustainability assessment (Section 2.2), and design verification (Section 2.3). Data collection was initially conducted to examine the current research in FC and its application in floor construction. Then, the sustainability of the FC mix design was evaluated using a life cycle assessment. The design verifications for the modular building composite floor systems were also performed to ensure structural performance. The overview of the research methods is presented in Figure 1.

2.1. Data Collection

This study examined recent research articles, such as academic journals, conference proceedings, theses, and technical papers, to determine the properties of FC composite as a floor structure. The abstract and citation databases Scopus, Web of Science, and Google Scholar are used to identify the articles indexed from 1 January 2010 to 31 May 2023 and focused on the subject area of Engineering and Material Science. The data collection procedure is depicted in Figure A1 in Appendix A. Data collection aims to investigate different mix designs and the structural performance of FC as a composite material in floor structures. Thus, the research articles in the search results are manually screened to determine their relevance to the FC composite study topic. Firstly, the selection process involves choosing articles based on the title, abstract, and keyword information. Then, the articles are further screened based on the relevance of information in the abstract and main body. A similar data collection approach has been used in previous studies [5,10,16,17,31] to derive cementitious materials' optimum mix design strength performance. An overview of the collected data from the articles is presented in Section 3.

2.2. Sustainability Assessment

The sustainability assessment aims to identify the most suitable FC mix to be used as structural elements with comparatively low negative environmental impacts. This can be achieved via conducting a life cycle assessment (LCA), which gives quantitative environmental emissions of producing 1 m^3 of several FC mix designs based on several indicators [32,33]. This study adheres to the LCA system boundary specified in the AS ISO 14040:2019 [34] and EN 15978 standards [35] (Figure 2). This LCA utilised a "cradle to gate" boundary with the Recipe Midpoint (H)/World Recipe H method [32]. The scope of the "cradle to gate" boundary is considered in three stages: (1) material extraction, including raw material extraction and transportation (cradle); (2) manufacturing stage,

specifically the production of mortar mix; and (3) supply stage of the product (gate), excluding treatment and disposal activities [32]. The environmental impacts in this LCA model are derived from the European Reference Life Cycle (ELCD) [36] and Australian National Life Cycle Inventory (AusLCI) [37] databases with scientific theory following the ReCiPe format 2016 [32], using LCA software SimaPro 8.2.0.0 [33]. Previous studies have used this approach to determine the sustainability of materials [38–40].
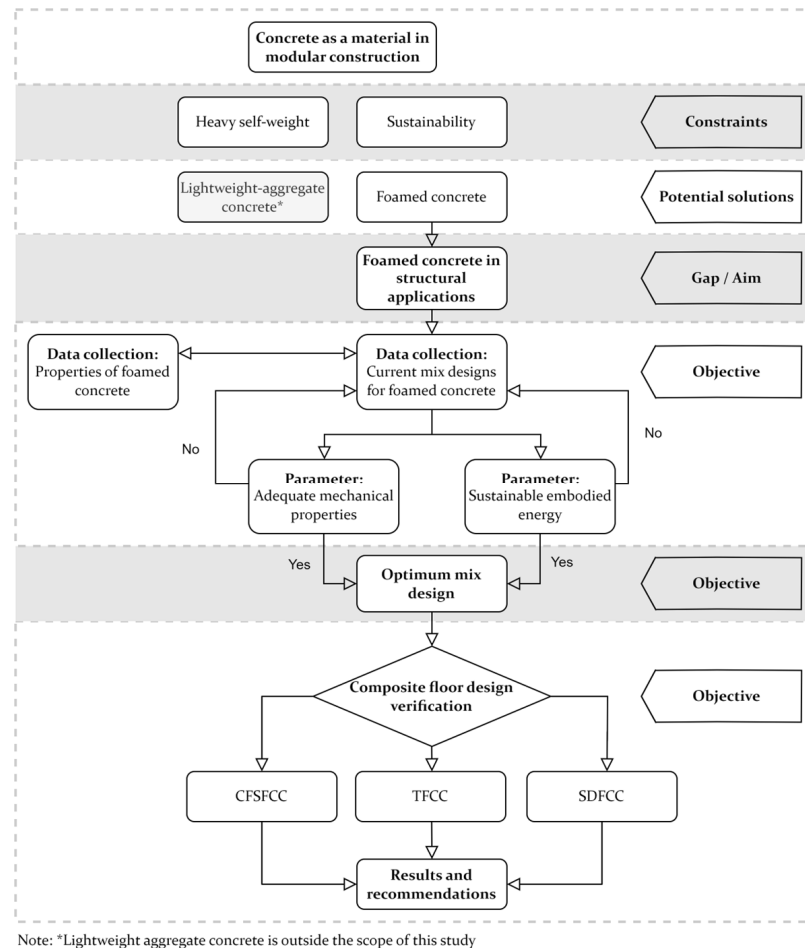

Note: *Lightweight aggregate concrete is outside the scope of this study

Figure 1. Research methods.
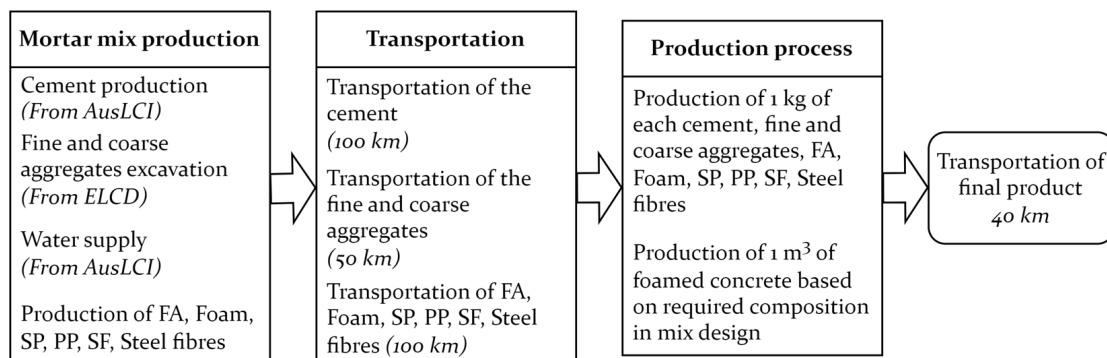

Figure 2. System boundary of LCA.

The "cradle to gate" boundary approach is chosen to assess the mix design of sustainable concrete's potential during the material production phase. This approach is sufficient for selecting the optimal mix design, specifically in the material selection [41]. Without it, other boundary approaches would need to consider durability parameters such as the

building design, lifespan, and demolition or reuse plan [41]. The LCA considers midpoint and endpoint characterisations to identify various environmental impacts with different uncertainties through multiple indicators [32]. Eighteen midpoint impact indicators from the LCA of producing 1 m^3 of FC are classified into three endpoint categories: human health, ecosystem quality, and resources. More details of the LCA are provided in Section 3.4.

2.3. Design of Composite Floor Systems

Design verification of FC composite floor systems is studied using analytical methods, including CFSFCC, TFCC, and SDFCC (Figure 3). The design verification aims to assess the appropriateness of using FC as a composite material for floor slabs in modular buildings according to the existing design standards (i.e., EN 1994-1-1:2004 [26], EN 1995-1-1:2004 [28], AS/NZS 2327:2017 [27], and AS 1720.1-2010 [29]). Similar analytical method approaches have been used in previous studies [42,43]. The steel-concrete composite floor system (CFSFCC, SDFCC) design must be carried out to satisfy both ultimate limit states (ULS) and serviceability limit states (SLS) in the composite stage of the components [26,27]. In addition, the timber-concrete composite floor system (TFCC) necessitates a separate design check for long-term durability and short-term requirements [28,29]. Different parameters are applied in the analytical model to observe the impact of these parameters on the flexural, shear, and serviceability deflection behaviour of the composite floor sections. The variable parameters in the FC composite floor systems are considered, including concrete density, concrete flange thickness, joist type, joist specification, joist section, and joist spacings, as shown in Table 1. Details of the design verification are provided in Section 4.
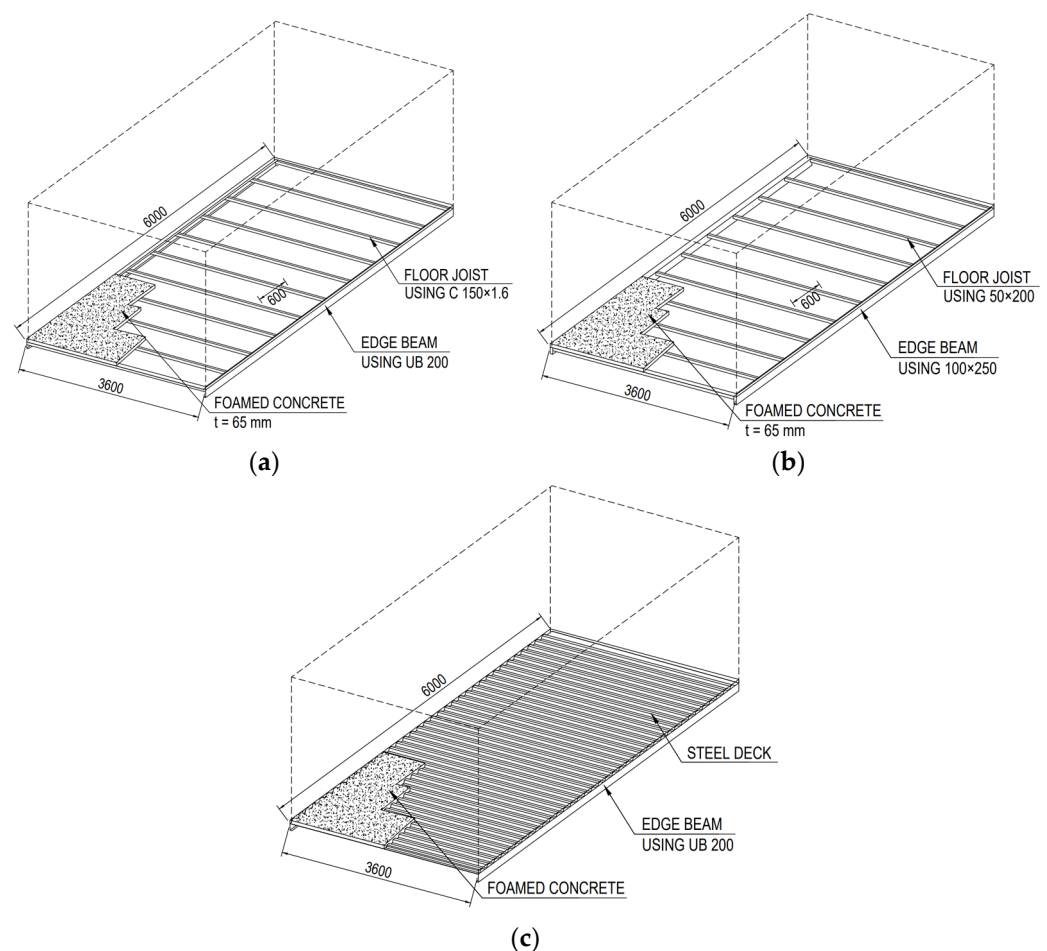

Figure 3. Types of FC composite floor systems: (**a**) CFSFCC, (**b**) TFCC, and (**c**) SDFCC.

Table 1. Design parameters of FC composite floor systems.

Parameters	CFSFCC	TFCC	SDFCC
Design standard	EN 1994-1-1:2004 and AS/NZS 2327:2017	EN 1995-1-1:2004 and AS 1720.1-2010	EN 1994-1-1:2004, AS/NZS 2327:2017, and SDI C-2017
Concrete compressive strength at 28 days	f_c = 25 MPa	f_c = 25 MPa	f_c = 25 MPa
Concrete flange thickness (mm)	65, 75, 90	65, 75, 90	50, 70, 90, 115
Type	Joist using cold-formed steel C-section	Rectangular joist using LVL Truform [43,44]	Profiled steel deck sheeting type SMD TR60$^+$ (type A) [45] and BONDEK$^{®}$ (type B) [46]
Material specification	S350, F_y = 350 MPa	E_2 = 10,700 MPa $f_{t,d}$ = 18.4 MPa $f_{b,d}$ = 32.8 MPa $f_{s,d}$ = 3.82 MPa $f_{c,d}$ = 8.64 MPa	A: F_y = 350 and 450 MPa B: F_y = 550 MPa
Section dimension (mm)	CFS-C150 t = 1.5, 1.9 CFS-C200 t = 1.5 mm	50 × 200, 50 × 250, 50 × 300	A: t = 0.9, 1.0, 1.2 B: t = 0.75, 0.9, 1.0
Joist spacing, centre-to-centre (mm)	400, 500, 600	400, 500, 600	-
Bolt shear connector	d = 12 mm, F_y = 800 MPa (grade 8.8)	d = 12 mm, F_y = 800 MPa (grade 8.8)	d = 12 mm, F_y = 800 MPa (grade 8.8)

Where f_c denotes the cube compressive strength of concrete (MPa), F_y denotes the yield strength of the material (MPa), E_2 denotes the modulus of elasticity of timber material (MPa), $f_{t,d}$ denotes the tensile stress capacity of timber material (MPa), $f_{b,d}$ denotes the bending stress capacity of timber material (MPa), $f_{s,d}$ denotes the shear stress capacity of timber material (MPa), $f_{c,d}$ denotes the compressive stress capacity of timber material (MPa), t denotes the component thickness (mm), and d denotes the component diameter (mm).

3. Material Characteristics and Optimum Mix Design of FC

This section reviews FC's material, strength and sustainable performance and identifies the suitable FC mix design for composite floor systems.

3.1. Material Properties

Research has been focused on improving the properties of FC to enhance its suitability for structural applications, including mechanical properties (i.e., compressive and flexural strengths), physical properties (i.e., drying shrinkage and air void distribution), and fresh properties (i.e., consistency, stability, and workability) [5,16,17]. The components of FC include both primary (i.e., cement, water, fine aggregates, and foaming agents) and supplementary (i.e., filler, plasticisers, and fibres) elements [47]. Supplementary materials are often used in the mix design to improve mix design consistency and long-term strength and to reduce cost [17,48]. An overview of FC material properties is covered within this section, including physical properties, mechanical properties, durability properties, and alternative supplementary materials.

3.1.1. Physical Properties

The strength and durability of FC are determined by the durability of the foam component and air void properties [16,49]. Several factors can influence the air void distribution of hardened FC. These factors include mix design compositions, foam agents, and the type of curing [17]. Further, the high water-to-cement (w/c) ratio notably impacts FC, increasing porosity [50]. The studies by Mehta [51] and Hughes [52] indicated that the permeability and pore size distribution of Portland cement pastes increased when the w/c ratio was increased from 0.3 to 0.9. This increase in the w/c ratio resulted in larger pores with larger diameters [51,52]. Thus, the optimum w/c ratio is highly considerable, as it affects the fresh properties of FC, including preventing segregation and leakage [53,54] and maintaining stability in the free-flow state [16,55].

Supplementary materials can be added to increase the strength and durability of the FC mix. Fly ash is the most common supplementary material, which can replace up to 67% of cement to achieve higher strength than cement alone [56] and reduces the drying shrinkage strains up to 2.6 times [5,57]. However, the strength development time is longer in the concrete with fly ash binder [56]. Minimising drying shrinkage can be crucial as the low paste and aggregate content in low-density FC significantly impacts the shrinkage

behaviour [57]. Further, fly ash in coarse size can also be utilised for fine aggregate replacement to replace sand [5]. As fly ash prolongs the strength development of FC, silica fume is commonly used to strengthen the mix quickly due to its filler characteristics and pozzolanic behaviour [17].

3.1.2. Mechanical Properties

In the structural design of the floor, the material's mechanical properties, such as compressive and flexural strengths, govern the suitability of their application. FC has relatively low compressive and flexural strengths, which decrease exponentially as density decreases [58]. Various factors have been found to impact the strength of FC, including particle size and distribution, pore formation, direction of loading, age, water content, characteristics of ingredients used, and method of curing [59–61]. However, including fibres in FC has been found to alter the material properties, shifting it from a brittle state to a ductile, elastic-plastic state [21]. Fibre-reinforced foamed concrete can incorporate various types of fibres, including Polypropylene (PP) fibre [62], polyvinyl alcohol fibre [63], sisal fibre [64], and steel fibre [65]. PP fibres can improve FC's tensile and flexural strengths [5,66]. Adding PP fibres also increases energy absorption and crack control [20]. Bing et al. [22] studied the effect of PP fibres and silica fume on the splitting tensile strength of FC. Their study found that adding PP fibre reinforcement increases the splitting tensile strength at 28 days between 31 and 50%. Further, the addition of silica fume increases the rate of strength development at 28 days to 85–90% of the corresponding 90-day strength, compared to the percentage of 80–85% for FC without silica fume [22], as shown in Figure 4.
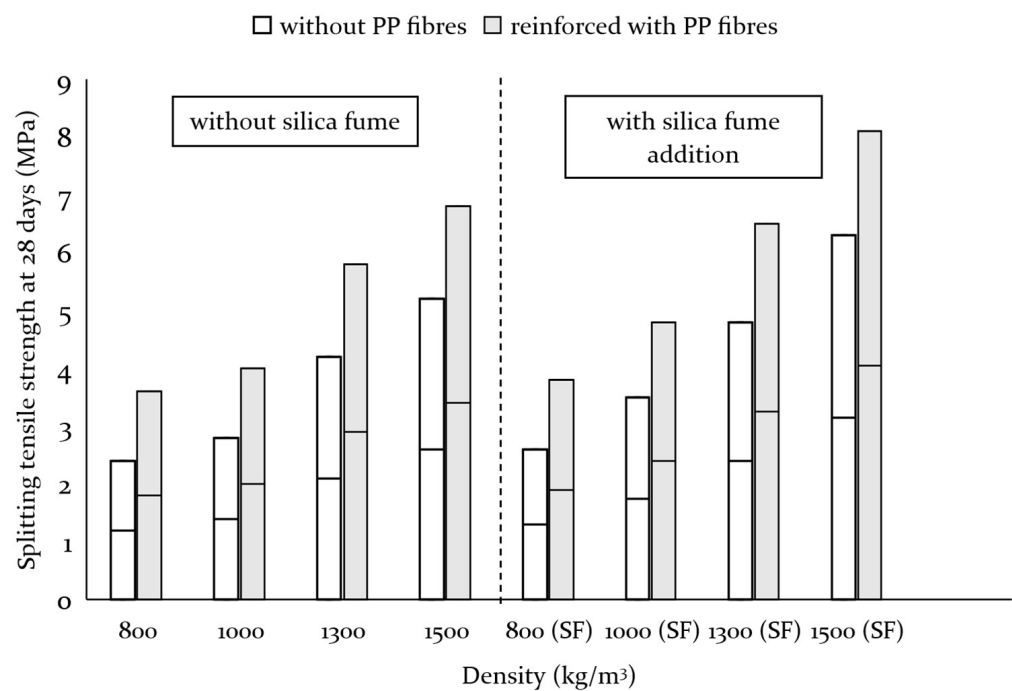

Figure 4. Effect of PP fibre and silica fume on the splitting tensile strength of FC at 28 days [22].

Attributing supplementary materials in increasing the FC strength-to-weight ratio is important for modular-based floor construction. It allows the production of floor structures with the same design strength but lower in density [19,22]. The lower-density floor structure has lower self-weight and accommodates the crane lifting capacity limitation. In addition, the lower-weight element also benefits the overall structure, including less stress developed in the structures and foundations [5].

3.1.3. Durability Properties

The presence of air voids in FC's finished state slightly reduces its overall durability compared to NWC [16]. Nevertheless, the inclusion of air voids offers durability benefits in terms of permeability and resistance to aggressive environments [17]. When the density decreases, FC absorbs less water. This is due to a decrease in the paste volume phase and, as a result, a reduction in capillary pore volume [16,17]. In addition, the FC with increased pore content and lower density shows significant resistance to aggressive chemical assault and freeze-thaw [16,17].

The material's low density and high open porosity also expedite the carbonation process [67,68]. Thus, a higher w/c ratio leads to reduced carbonation resistance as it promotes the formation of more capillaries [68]. Carbonation-induced shrinkage can potentially lead to cracking and reduced durability [67,68]. The carbonation resistance of FC can be enhanced by partially replacing cement with fly ash, as the volcanic reaction of fly ash improves the pore structure. However, it should be noted that when the water-binder ratio is relatively high, foamed concrete with fly ash partially replacing cement may exhibit lower carbonation resistance [69].

Furthermore, the addition of fibre (i.e., PP fibre) composition in the FC mix design provides a positive impact regarding durability [70,71]. The inclusion of fibre decreases the drying shrinkage of FC [72]. Therefore, an increase in abrasion resistance, sulfate exposure resistance, and freeze-thaw resistance can be observed [70,71].

3.1.4. Alternative Supplementary Materials

Moreover, with the growing significance of sustainable construction [73], particularly in modern methods like modular construction, research has explored the feasibility of replacing synthetic fibres with natural fibres [74,75]. Natural fibres may replace synthetic fibres to create materials with a reduced environmental impact. There is limited research on applying natural fibres as fibre-reinforced foamed concrete [76]. The study conducted by Castillo-Lara et al. [62] compared the inclusion of PP and natural henequin fibres in a fibre-reinforced foamed concrete panel subjected to a bending load. The results indicate that panels made with PP fibres outperformed those made with natural henequin fibres in bending capacity and displacement. However, it is essential to mention that natural henequin fibres are more sustainable than PP fibres despite their significant strength reduction. The inclusion of fibres will increase the flexural capacity of FC in structures.

3.2. Sustainability Characteristics of FC

The environmental impact of a building occurs throughout its entire life cycle. One aspect of this impact is the consumption of heat and electricity during the building's use phase, which is directly linked to greenhouse gas emissions [77]. Up to 68.8% of the energy consumed in the use phase of a building is due to space heating [77]. Using sustainable building materials with higher thermal insulation ratings, particularly for building envelopes, such as floors and walls, will reduce emissions by decreasing the building's heating energy demand [77,78]. FC is a potential alternative to conventional concrete for flooring applications. FC possesses exceptional thermal insulation properties due to its cellular microstructure [16]. Compared to regular concrete, the thermal conductivity values of lightweight concrete are 5–30% lower. These values range from 0.1 to 0.7 W/mK for dry densities of 600–1600 kg/m^3 and decrease as the densities decrease [66]. FC has been tested for ground-supported slabs in low-rise dwellings, demonstrating superior thermal insulation to normal concrete [79].

In modular construction, most components are manufactured off-site and transported to the site. This transportation process accumulates additional energy due to the transportation of the prefabricated floor slabs and contributes to 13% of the overall greenhouse gas emissions in the construction process [80]. The metric used for calculating volumetric transportation primarily relies on the weight of the prefabricated slabs/modules [80]. Therefore, the choice of materials significantly impacts the total weight of the transported

components. FC can achieve the same minimum strength requirement as normal concrete by using a density of 1300 kg/m^3, which is only 54% of the weight of normal concrete for the same volume. Therefore, utilising FC as the construction material for the floor can increase transportation efficiency by allowing for the transportation of a greater volume over the same distance. Thus, the FC is a potential alternative material to improve the sustainable performance of modular construction.

Zimele et al. [81] evaluated the life cycle performance of FC production, which had a density of 1150 kg/m^3 and compressive strength of 12.5 MPa. The study analysed the global warming potential, expressed as the emission of greenhouse gases measured in CO_2 equivalents. The total calculated CO_2 emissions from 1 kg of FC are 0.44 kg CO_2-eq, with 94% of the emissions being contributed by Portland cement. The FC mix design includes a 46% Portland cement component, which is crucial for enhancing the compressive strength. The study also proposed replacing Portland cement CEM I 42.5 N with cement containing 11–35% fly ash and cement containing 18–35% blast furnace slag. This substitution can reduce total CO_2 emissions in the global warming potential impact category by 18% and 39%, respectively. The production method of FC also affects CO_2 emissions. Introducing the gas production method can reduce total CO_2 emissions by up to 34.62 kg per 1 m^3 of FC produced with intensive mixing technology and up to 30.5 kg per 1 m^3 for traditionally mixed FC [82].

3.3. Optimum FC's Mix Design for Floor Construction

The American standard, ACI 318-14 [30], specifies that the compressive strength of concrete used for composite floors must be at least 21 MPa. Further, the British standard, BS 5950-3.1:1990 [83], specifies that the minimum lightweight concrete grade to be used is LC20/25, with a characteristic cylinder strength of 20 MPa and a corresponding cube strength of 25 MPa. EN 1994-1-1:2004 [26] also specifies the minimum concrete grade, LC20/22 [84].

Therefore, this study selects the mix designs for the composite floor from the literature [5,22,65] based on their minimum 28 days compressive strength of 25 MPa. Previous studies have also used coarse fly ash to replace sand in fine aggregate to improve the mechanical properties of FC [5,22,56]. Additionally, the addition of PP fibres [5,22], silica fume [22], and steel fibres [65] has been explored to create a suitable mix with the minimum required compressive strength. A control mixture of NWC, with a 2400 kg/m^3 density and compressive strength of 25 MPa, is selected to compare FC's strength and sustainable performance. The FC mix designs were chosen within the 1300–1800 kg/m^3 range densities. Details of selected mix designs are presented in Table 2.

Table 2. Mix designs for 1 m^3 of FC and NWC as control.

Mixes		FC1	FC2	FC3	FC4	FC5	FC6	FC7	NWC
Density (kg/m^3)		1800	1600	1400	1400	1300	1300	1800	2400
Material (kg)	Cement	500	500	500	500	431	431	698	300
	Water	150	330	289	289	304	304	217	150
	Sand	1150						776	700
	FA$_{coarse}$		770	611	611	507	507		
	Foam (L)	200	200	300	300	300	300	223	
	SP	10	10	10	10	10.1	10.4	6.2	
	PP			3.5	7.0		7.2		
	SF					76	76	78	
	Steel fibres							31	
	Gravel								1000

Where FA denotes fly ash, SP denotes superplasticiser, PP denotes polypropylene fibre, and SF de notes silica fume.

The concrete strength data are obtained from experimental studies [5,22,65]. The specimens used for testing the compressive strength at 28 days were 100 mm cubes. Figure 5a displays the compressive strength of the various FC mix designs after 28 days. This figure demonstrates that replacing 100% of the fine aggregates with coarse fly ash (mix FC2) reduces the density requirements of FC while maintaining the same compressive strength as the base mix (mix FC1). The result indicates that the coarse fly ash replacement mix exhibits a higher strength-to-weight ratio than the base mix. Moreover, incorporating PP fibres and silica fume can enhance the compressive strength of the FC mix designs (mix FC3–FC6). The steel fibres can also improve FC's compressive strength (mix FC7). However, it should be noted that the higher density of steel fibres can impact the overall density of the FC mixture.
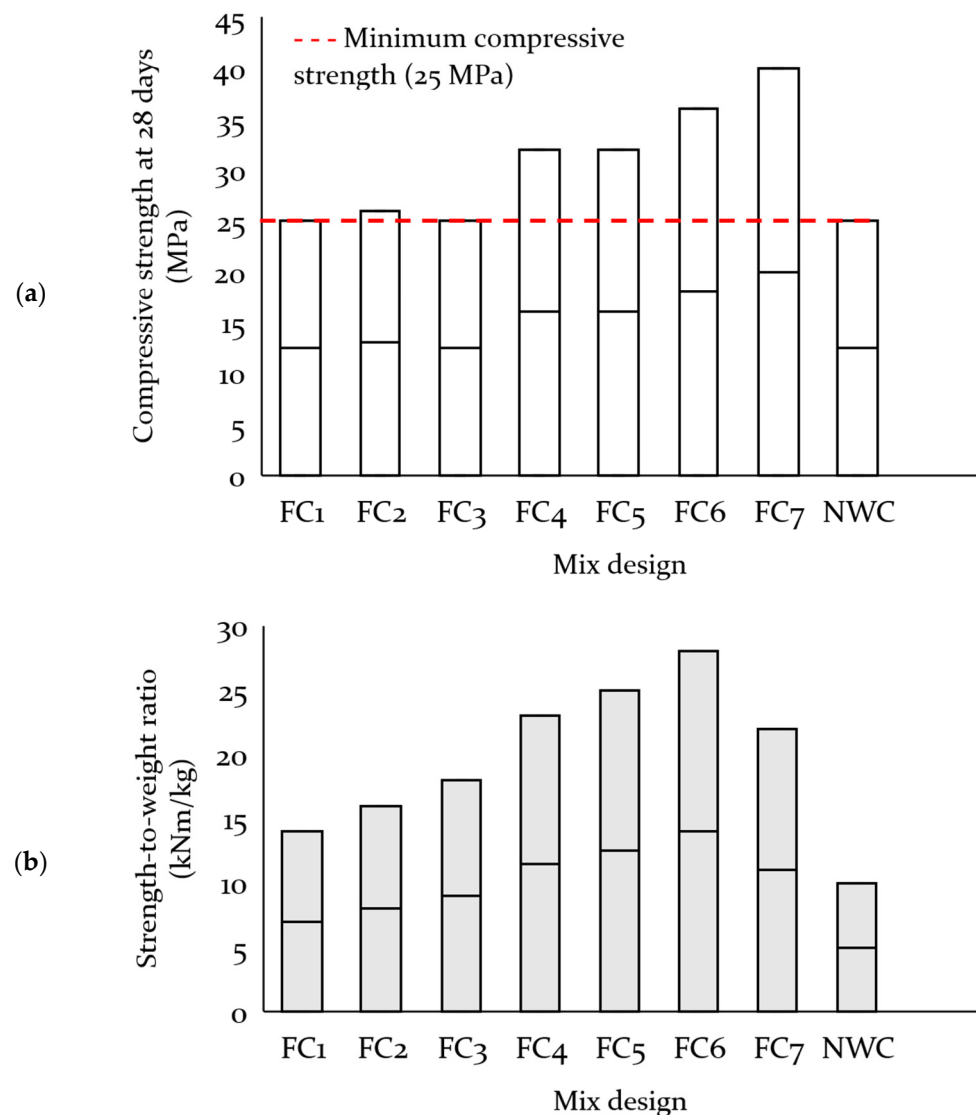

(a)

(b)

Figure 5. Results of FC mix design comparison in (**a**) compressive strength at 28 days and (**b**) strength-to-weight ratio.

In a mix design, it is recognised that FC generally exhibits a brittle behaviour [62], which restricts the attainable density needed to meet the minimum strength requirements for structural applications. Adding fibres in FC can change its mechanical behaviour from brittle to elastoplastic, resulting in increased compressive, tensile, and flexural strengths [62,74]. Moreover, the enhancement of compressive, tensile, and flexural strengths enables the utilisation of lower-density FC, resulting in a higher strength-to-weight ratio. A

comparison is made for several mix designs with different compositions in terms of the strength-to-weight ratio of FC at 28 days compressive strength, as depicted in Figure 5b. The initial mixture design of FC with a density of 1800 kg/m^3 achieves a strength-to-weight ratio of 13.89 kNm/kg. However, adding fibres can increase this ratio to a range of 17.86–22.86 kNm/kg, reducing the density by 1400 kg/m^3. This section aims to classify the FC mixes to comply with the minimum compressive strength for structural elements (25 MPa). Therefore, the FC mixes' strength-to-weight ratio is not considered a parameter in selecting the optimum mix design.

NWC has a lower strength-to-weight ratio than FC due to including gravel as the coarse aggregate in its mix composition. FCs, in contrast, lack coarse aggregate, resulting in reduced density and increased lightness. The use of fly ash as a substitute for sand fine-aggregate, along with the inclusion of silica fume and PP fibres, has reduced the required minimum density of the FC mix design to achieve a minimum compressive strength of 25 MPa. The FC mix design with the addition of silica fume and PP fibres, with a density of 1300 kg/m^3, achieves a strength-to-weight ratio of 27.69 kNm/kg, which is a 166% increase compared to the ratio of NWC with a density of 2400 kg/m^3 (10.42 kNm/kg).

Besides density, FC structural performance also significantly varies in the modulus of elasticity property (*E*). The BS EN 1992-1-1:2004 [85] standard defines the material properties of LWC. This standard applies explicitly to lightweight aggregate concrete with a density ranging from 800 kg/m^3 to 2200 kg/m^3. However, the BS EN 1992-1-1:2004 [85] standard does not provide specific material properties for FC. Figure 6a compares the strength variation with *E* values for NWC and LWC obtained from the standards AS 3600-2018 [86], BS 8110-1:1997 [87], and AISC 360-16 [88]. The most conservative value for LWC with a density of 1300 kg/m^3 is obtained from BS 8110-1:1997 [87]. In a study by Jones [5], the *E* of FC was considerably lower than the calculated equivalent compressive strength of NWC and LWC incorporating lightweight aggregate. The *E* increased in a nearly linear behaviour with density and strength. Table 3 shows the equations that can be used to calculate the *E* for FC containing sand and fly ash fine aggregates. FC with fly ash fine aggregate exhibits the lowest *E*, as depicted in Figure 6b. The inclusion of PP fibres in FC with fly ash fine aggregate increases the *E*, resulting in a more conservative value for the LWC equation specified in BS 8110-1:1997 [87], as shown in Table 3. Therefore, the *E* of the FC mix design is determined using the BS 8110-1:1997 [87] equation for each specific concrete density in the design verification.

Table 3. Equations to derive *E* for FC, NWC, and LWC.

Material	Reference	Equation
FC (sand fine aggregate)	Jones and McCarthy [5]	$E = 0.42 f_c^{1.18}$
FC (fly ash fine aggregate)	Jones and McCarthy [5]	$E = 0.99 f_c^{0.67}$
NWC	BS 8110-1:1997 [87]	$E = 9.1 f_c^{0.33}$
LWC	BS 8110-1:1997 [87]	$E = 1.7 \times 10^{-6} \rho^2 f_c^{0.33}$

Where *E* denotes the modulus of elasticity (MPa), f_c denotes the cube compressive strength (MPa), and ρ denotes the concrete density (kg/m^3).

3.4. Life Cycle Assessment

This study examines FC's life cycle assessment (LCA) using the ReCiPe 2016 method [32]. The LCA considers midpoint and endpoint characterisations to identify various environmental impacts with different uncertainties through multiple indicators [32]. Several FC mix designs with a minimum compressive strength of 25 MPa (FC1-FC7 and NWC) are analysed for their environmental impact through midpoint and endpoint categories. This section aims to compare the environmental impact of different compositions in the FC mix designs, between FC and the control mix of NWC, and to find the optimum FC mix design. The midpoint impact values for each FC mix are presented in Table 4.
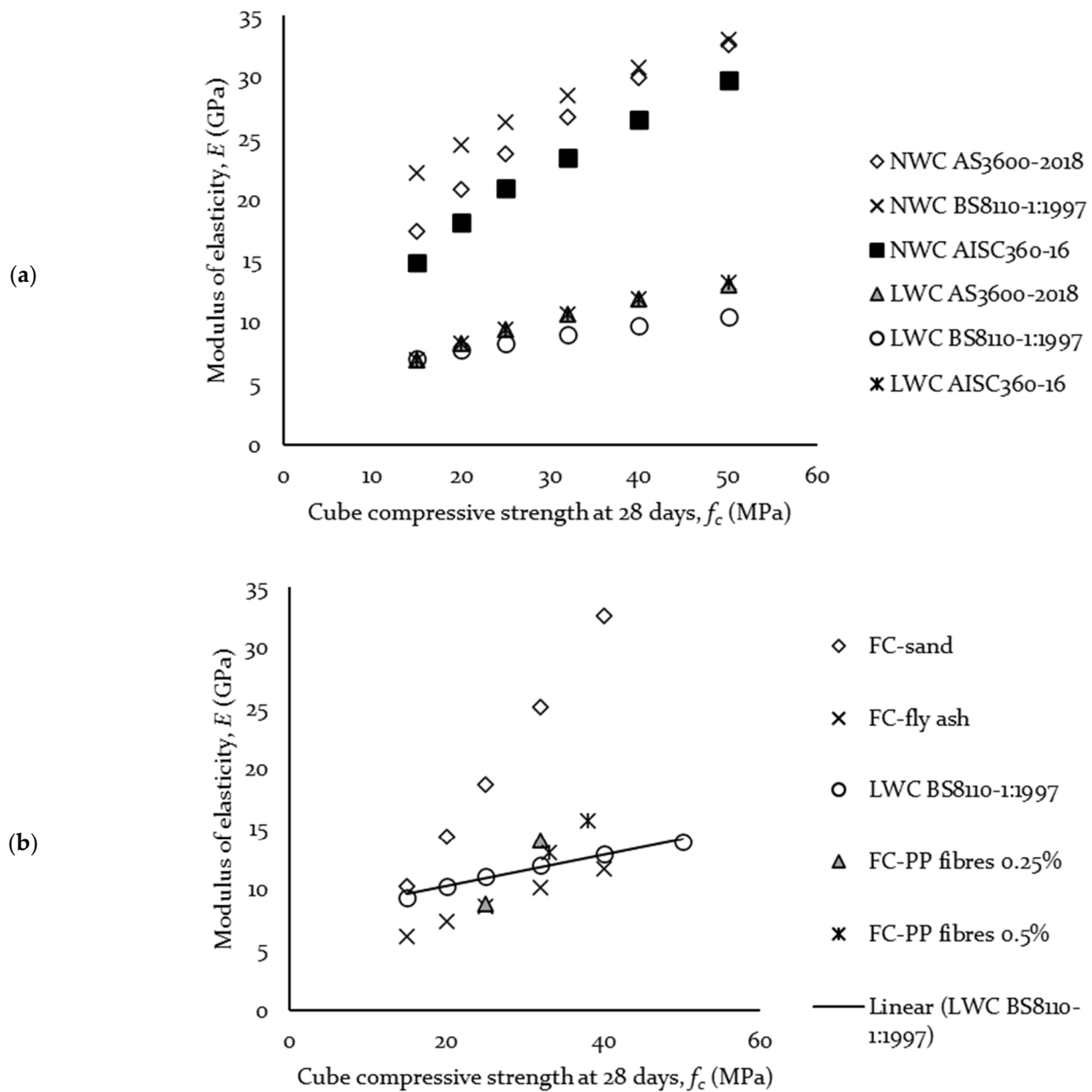
Figure 6. Different *E* based on (**a**) various concrete fc and standards and (**b**) various FC mix designs [5,86–88].

Table 4. Environmental impacts induced by the production of 1 m^3 of FC.

No	Impact Category	Unit	FC1	FC2	FC3	FC4	FC5	FC6	FC7	NWC
1	Climate change	kg CO$_2$ eq	741.911	740.889	881.907	881.907	810.565	827.763	**1026.579 ***	290.028
2	Ozone depletion	kg CFC-11 eq	1.21×10^{-5}	1.21×10^{-5}	1.62×10^{-5}	$\mathbf{1.67 \times 10^{-5}}$ *	1.52×10^{-5}	1.65×10^{-5}	1.56×10^{-5}	2.14×10^{-6}
3	Terrestrial acidification	kg SO$_2$ eq	2.750	2.744	3.369	3.397	3.140	3.201	**3.768 ***	0.958
4	Freshwater eutrophication	kg P eq	0.013	0.013	**0.018 ***	**0.018 ***	**0.018 ***	**0.018 ***	0.016	0.001
5	Marine eutrophication	kg N eq	0.732	0.731	1.071	**1.072 ***	1.063	1.065	0.845	0.034
6	Human toxicity	kg 1,4-DB eq	31.097	30.659	40.124	40.266	38.588	38.912	**43.416 ***	7.267

Table 4. *Cont.*

No	Impact Category	Unit	FC1	FC2	FC3	FC4	FC5	FC6	FC7	NWC
7	Photochemical oxidant formation	kg NMVOC	2.118	2.106	2.442	2.464	2.228	2.274	**2.926** *	0.910
8	Particulate matter formation	kg PM10 eq	0.940	0.938	1.129	1.138	1.048	1.066	**1.308** *	0.348
9	Terrestrial ecotoxicity	kg 1,4-DB eq	0.031	0.031	**0.044** *	**0.044** *	0.043	0.043	0.040	0.003
10	Freshwater ecotoxicity	kg 1,4-DB eq	0.127	0.124	0.149	0.151	0.140	0.144	**0.167** *	0.041
11	Marine ecotoxicity	kg 1,4-DB eq	0.413	0.410	0.567	**0.571** *	0.553	0.562	0.545	0.059
12	Ionising radiation	kBq U235 eq	0.714	0.714	1.488	2.192	0.804	**2.269** *	0.648	0.011
13	Agricultural land occupation	m^2a	21.475	21.518	**30.950** *	**30.950** *	30.672	30.685	27.949	1.694
14	Urban land occupation	m^2a	11.452	11.461	15.088	15.088	14.545	14.548	**16.863** *	3.317
15	Natural land transformation	m^2	0.044	0.044	0.059	0.059	0.057	0.057	**0.062** *	0.022
16	Water depletion	m^3	19.726	19.170	22.656	22.664	21.194	21.221	**24.184** *	8.494
17	Metal depletion	kg Fe eq	32.157	32.163	44.797	44.805	43.946	43.982	**61.052** *	5.005
18	Fossil depletion	kg oil eq	169.858	169.463	216.806	222.990	199.791	212.722	**228.846** *	51.555

* The number in bold shows the highest value out of the mixes.

The eighteen midpoint impact indicators from the LCA of producing 1 m^3 of FC (Table 4) are classified into three endpoint categories: human health (impact categories no. 1, 2, 6–8, 12), ecosystem quality (impact categories no. 3–5, 9–11, 13–15), and resources (impact categories no. 16–18).

3.4.1. Impacts on Human Health

The effects of different types of pollution on human health are classified as climate change, ozone depletion, human toxicity, photochemical oxidant formation potential, particulate matter, and ionising radiation. Several FC mix designs are assessed: base mix with sand as fine aggregate (FC1), mix with the substitution of sand with coarse fly ash (FC2), mix with the addition of 0.25% and 0.50% PP fibre (by mix volume) (FC3, FC4), mix with the addition silica fume (FC5), mix with the addition of PP fibre and silica fume (FC6), mix with the addition of steel fibres (FC7), and also NWC mix as control. The manufacturing and usage of 1 m^3 FC results in an increase in the human health category, especially in greenhouse gas emission (kg CO_2 equivalent) of between 156% and 254% when compared to the value of NWC (Table 4), according to climate change, which is used as a general indication for CO_2 generation in the material's life cycle.

The mix of FC2 with 1600 kg/m^3 density contributes to 156% and 464% more negative impact on climate change and ozone depletion, respectively, compared to NWC (Table 4). It shows that the highest percentage of CO_2 generation is reduced by substituting sand as fine aggregate with coarse fly ash. Further reduction can be achieved by partially substituting the cement with fine fly ash, which is not considered in this research. The mix FC6 with 1300 kg/m^3 density contributes to 185% and 668% (Table 4) more negative impact on climate change and ozone depletion, respectively, compared to NWC. The rise in greenhouse gas emissions associated with using FC is governed by increased manufacturing of cement and synthetic materials made in controlled facilities. Furthermore, the increase in cement and the addition of synthetic materials prove the impact on health in other categories, including photochemical oxidant formation, particulate matter, human toxicity, and ionising radiation.

3.4.2. Impacts on Ecosystem Quality

The contamination that harms the ecosystem and affects the number of species is called ecosystem quality. It includes terrestrial acidification, freshwater eutrophication, marine eutrophication, terrestrial ecotoxicity, marine ecotoxicity, agricultural land occupation, urban land occupation, and natural land transformation. Compared with other FC mixes, the highest ecosystem quality impacts in almost all impact categories are the FC mixes containing PP fibre (FC3, FC4) and steel fibre (FC7). The FC base mixes (FC1) and coarse fly ash (FC2) show the lowest ecosystem quality impacts in all categories compared with other FC mixes (Table 4). However, for an FC density of 1800 kg/m^3 (FC1), compared to NWC, the use of FC throughout its entire life cycle has significant impacts on ecosystem quality, namely the increased terrestrial, freshwater, and marine ecotoxicity by values of 933%, 202%, and 595%, respectively.

3.4.3. Impacts on Ecosystem Quality

The impacts of natural resource depletion include the depletion of metals, water, and fossil fuels. Lower values of water, metal, and fossil fuels are consumed when producing FC without the addition of synthetic materials. The base mix consists of sand fine aggregate (FC1) and coarse fly ash fine aggregate (FC2), contributing to lower values than other FC mixes (Table 4). Compared to NWC, using FC, with a density of 1800 kg/m^3 (FC1), increased value by 132%, 542%, and 229%, respectively. In contrast, most of the NWC's composition is natural gravel. In comparison, FC utilises more water, cement, and a foaming agent than regular concrete, which explains the increased resource impact.

Overall, regarding endpoint characterisation, the FC base mix (FC1) and the FC mix with coarse fly ash substitution as fine aggregate (FC2) have the least detrimental effects on sustainability amongst FC mixes. This is because FC2 only contains coarse fly ash as the fine aggregate replacement, which is a naturally sustainable material. On the other hand, synthetic materials, such as silica fume, PP fibre, and steel fibre that comprise FC3–FC7, account for the more significant increase in negative sustainability impacts. According to this study's life cycle assessment (LCA), PP fibre is widely used in the industry. However, it is essential to note that PP fibres have a significant negative environmental impact on greenhouse gas emissions (GHGE). However, the inclusion of fibre content is proven to increase the strength-to-weight ratio of the FC significantly. Therefore, more sustainable fibre alternatives need to be studied to be able to produce a more optimum FC mix design for structural purposes.

Additionally, compared to the FC1–FC2, the FC3–FC7 have a lower density, which indicates that the mix designs will require more foaming agents to attain the lower density. The synthetic foaming agent, which is factory-produced, is commonly used in the industry and has a relatively high impact on the environment due to the chemical compositions and energy usage for production.

Further, the increase of cement content compared to NWC also contributes to the higher value of negative impacts. However, the additional cement content is necessary to ensure the FC achieves the required mechanical performance and self-flowing workability to be used as a structural material. This comparison study aims to determine the suitable FC mix design that complies with the minimum compressive strength at 28 days of 25 MPa and has a lower environmental impact. Therefore, to achieve a lower weight than NWC while maintaining a lower environmental impact, the preferred mix design is FC2 with a 1600 kg/m^3 density.

Overall, the LCA study indicates that the FC mix negatively impacts human health, ecosystems, and natural resources more than NWC. The primary reason is the higher cement content and the use of synthetic materials (i.e., chemical-based foaming agents and PP fibres), as opposed to NWC. Consequently, commonly used FC mix designs with commercially available compositions are not appropriate for sustainable practices compared to NWC. Hence, future research should incorporate a more sustainable composition (i.e., natural-based foaming agents and natural fibres).

4. Design Verification of Composite Floor

4.1. Overview of Composite Floor Systems

The increasing use of composite floor systems, primarily steel–concrete and timber–concrete composites, can be attributed to their flexibility, adaptability, and potential for disassembly and reuse. Controlled manufacturing techniques enhance these systems' positive environmental and economic effects [23]. Steel–concrete composite encompass various types, including steel-deck slabs [26,27,89], sandwich panels [18,62,63,90], and steel joists–concrete flange [42,91]. On the other hand, timber–concrete composite is commonly used as a joists-slab floor system. Extensive research has been conducted on using sandwich panels as a composite material for integrating lightweight concrete, particularly FC [18,62,63]. The numerous advantages of these materials include their high strength-to-weight ratio, damage tolerance, impact resistance, and thermal and noise insulation properties [62]. In addition, FC is pursued as a composite material to enhance the fire resistance on the floor structure due to its inherent inflammability and low thermal conductivity [5]. A study reported that in a 100 mm thick FC slab test, a 2.5 and 3.75 hours fire resistance was observed at oven-dry densities of $1250 \, \text{kg/m}^3$ and $930 \, \text{kg/m}^3$, respectively, with also proportionally less strength loss than NWC, especially at lower densities [5].

Another advantage of incorporating FC as a composite material in floor systems is serviceability performance (vibration response and energy dissipation behaviour). FC is used as topping material in composite floor applications such as steel-concrete decks. Vibration responses and energy dissipation are governed by the FC topping thickness on the composite slab [92]. The composite slab of FC has a damping ratio of approximately 3–5% [92,93], whereas the damping ratio for floor systems is typically 1–3% [94]. The lowest fundamental natural frequency of the FC composite slab satisfies the minimum requirement of the standard code of practice for the design of floors [95]. This study's design verification focuses on sustainability performance based on the life cycle assessment of FC mix designs and structural performance (flexural, shear and deflection) based analytical method. Several FC mix designs with a minimum compressive strength of 25 MPa are studied in this section to assess their suitability for structural material use.

4.2. Analytical Method Design Outlines

The general design provision for LWC with lightweight aggregate has been established and included in the design standards. However, no established design standards specifically addressed FC material in composite floor system design. The similarity in LWC material properties, specifically low density, between FC and LWC allows for the use of design provisions outlined for LWC to verify FC flexural and shear strength in composite floor system design. Due to the lack of experimental data on the flexural and shear strength of FC in composite floor systems, this study relies on an analytical method for design verification based on standards (composite steel and concrete, EN 1994-1-1:2004 [26] and AS/NZS 2327:2017 [27], and for timber structures, EN 1995-1-1:2004 [28], AS 1720.1-2010 [29]). The design verification consists of CFSFCC, TFCC, and SDFCC floor systems. Then, a parametric study is conducted to analyse different factors affecting the flexural and shear performance of the composite floors.

4.2.1. Design Outline of CFSFCC

The CFSFCC floor system design must be carried out to satisfy both ultimate limit states (ULS) and serviceability limit states (SLS) in the composite stage of the components. In the ULS, refer to EN 1994-1-1:2004 [26], the longitudinal force that can be withstood and transferred by the shear connection of a composite beam is limited by either the shear strength of the fastener or by the bearing resistance of the concrete flange in contact with the fastener. In the case of a fully composite system, the force carried by the shear connection, which is equal to the force developed in the concrete flange, is limited either by the compressive strength of the concrete flange or by the tensile strength of the steel beam.

According to EN 1994-1-1:2004 [26], for steel beams with Class 1 or 2 cross-sections, the moment capacity of the composite system with partial shear connection varies between the plastic moment capacity of the bare steel beam and the plastic moment capacity of the fully composite beam. It can be calculated using either conservative linear interpolation or equilibrium methods. In the SLS, the flexural stiffness of the composite system can be determined by considering the shear bond coefficient. Then, the effective flexural stiffness of a composite system can be determined by considering the system as fully composite. Kyvelou [96] developed detailed guidelines for implementing cold-formed steel paired with a concrete flange as a composite floor system. Lukačević et al. [42] also developed guidelines for using FC as a floor section.

4.2.2. Design Outline of TFCC

The design of the TFCC floor system must meet both the SLS and ULS in the short and long terms (end of service life). The ULS is assessed by comparing the maximum shear force in the connection, the maximum stress in concrete, and the combination of axial force and bending moment in timber with their respective design values. The primary serviceability verification is controlling maximum deflection, which also indirectly verifies the floor's susceptibility to vibration, as recommended by AS/NZS 1170.0:2002 [97]. The "Gamma Method" is used for short-term verifications. At the same time, the "Effective Modulus Method" was recommended by Ceccotti [98] to be used for long-term verifications to consider the creep effect of different materials. In EN 1995-1-1:2004 [26], design guidelines have been put forward. The design procedure has also been considered for implementation; refer to the AS/NZ standard [43]. Yeoh provided detailed guidelines on applying timber–concrete composite floor systems; refer to EN 1995-1-1:2004 [28] and AS 1720.1-2010 [29].

4.2.3. Design Outline of SDFCC

In the design of the SDFCC floor system, the failure mechanism is often controlled by slip at the interface between the materials in the shear span [99]. Under flexural load, microcracks formed at the base of the concrete structure near the areas of high load, leading to subsequent detachment at the interface between the steel deck and the concrete. As the load increased, additional cracks formed and propagated upwards to the surface of the concrete. However, composite slabs had a significant post-cracking bending moment capacity, and the plastic flexural capacity of the composite slabs was not reached [100]. Conforming to EN 1994-1-1:2004 [26] and AS/NZS 2327:2017 [27], determining the bending resistance of composite slabs should be based on the plastic theory of both steel and concrete, considering full or partial shear connection. In this verification, the shear connection is assumed to be fully connected because it has been observed that the plastic neutral axis of the composite section is located above the steel sheeting. The bending resistance calculation in this standard does not consider the influence of the modulus of elasticity of concrete. As a result, it primarily relies on the steel deck's axial force capacity and the concrete's compressive strength. The compressive strengths of NWC and FC are assumed to be equal, resulting in the same bending moment capacity.

For the SDFCC floor system, the bending resistance is also determined according to the SDI C-2017 [89] guideline for comparison study. The guide uses the Load and Resistance Factor Design (LRFD) approach and the shear bond method to classify the composite slab as under-reinforced or over-reinforced based on the failure condition. In this verification, the positive bending moment resistance is classified as under-reinforced. The moment resistance for the composite deck slab can be determined by considering the yield moment for a cracked cross-section. The *E* of concrete affects the calculations of the cracked section's moment inertia and the distance from the top slab to the neutral axis of the cracked section (modular ratio). For vertical shear strength, according to EN 1994-1-1:2004 [26], determining the bending resistance of composite slabs involves initially assessing the requirement for shear reinforcement in the profile member. Verification is necessary to ensure that the shear force resulting from loads acting on the cross-section does not exceed the shear resistance

of the member in the absence of shear reinforcement. The shear resistance is determined by the combined contribution of the concrete cross-section area and the steel deck acting as tensile reinforcement. In SDI C-2017 [89], the one-way shear strength is a crucial limit state requirement for composite deck slabs and flexural strength.

4.3. CFSFCC Floor System Results and Discussion

4.3.1. Effect of Concrete Density

In the ULS, concrete densities affect the flexural moment and shear behaviour of the CFSFCC floor by impacting the design load and bearing resistance capacity of the concrete flange. Compared to the joist's weight, the weight of the concrete flange has a significant percentage of the permanent load (self-weight load). The decrease in the weight of FC compared to NWC offers a lower design load value. However, in the calculation of longitudinal force in the shear connection, the capacity is governed by the bearing resistance of the concrete flange in contact with the fastener, not by the shear strength of the fastener. The concrete's compressive strength and E affect the bearing resistance of the concrete flange in contact with the fastener.

With the same concrete compressive strength of 25 MPa, using FC significantly decreases the E, resulting in a lower flexural moment and shear capacity value. The lower value of self-weight is paired with a lower value of the flexural moment and shear capacity, which results in a relatively stable capacity/load ratio for flexural and shear, as shown in Figure 7a,b (with joist spacings of 600 mm, 500 mm, and 400 mm). Additionally, the reduced weight of the FC is accompanied by a significantly lower E compared to NWC. This leads to a decrease in the effective flexural stiffness of the composite system, resulting in a more significant deflection under permanent and imposed loads. The deflection increases by approximately 1–2 mm, representing a 22–46% increase, as shown in Figure 7c (with joist spacings of 600 mm, 500 mm, and 400 mm).

4.3.2. Effect of Concrete Flange Thickness

In the ULS, concrete flange thickness affects the flexural moment behaviour of the CFSFCC floor by impacting the design load and plastic composite moment behaviour. The increase of concrete flange thickness results in the increase of weight of self-weight as permanent load. However, increasing concrete flange thickness increases the steel section tensile lever arm distance in composite moment load distribution, resulting in a higher moment capacity of CFSFCC. Increasing concrete flange thickness from 65 mm to 90 mm increases the flexural moment capacity/load ratio from 2.08 to 2.30 for an FC density of 1600 kg/m^3. However, the increase in concrete flange thickness reduces the shear capacity/load ratio from 2.47 to 2.33.

4.3.3. Effect of CFS Joist Section

In this parametric study, three CFS joist sections are compared, including C150 mm with thicknesses of 1.5 mm and 1.9 mm and C200 mm with thicknesses of 1.5 mm. In C150 mm, using 1.9 mm thickness results in higher tensile strength of the section, as it has a higher value in section area than 1.5 mm thickness. In the fully composite condition, the composite section's flexural moment and shear capacity are governed by the tensile strength of the steel, which means the C150 mm with a thickness of 1.9 mm offers a higher capacity than 1.5 mm thickness. In the SLS, the C200 mm with a thickness of 1.5 mm has a higher value of second moment of area compared to the C150 mm sections, resulting in higher effective flexural stiffness of the composite system. Hence, the section with C200 mm offers lower deflection than the C150 mm sections.
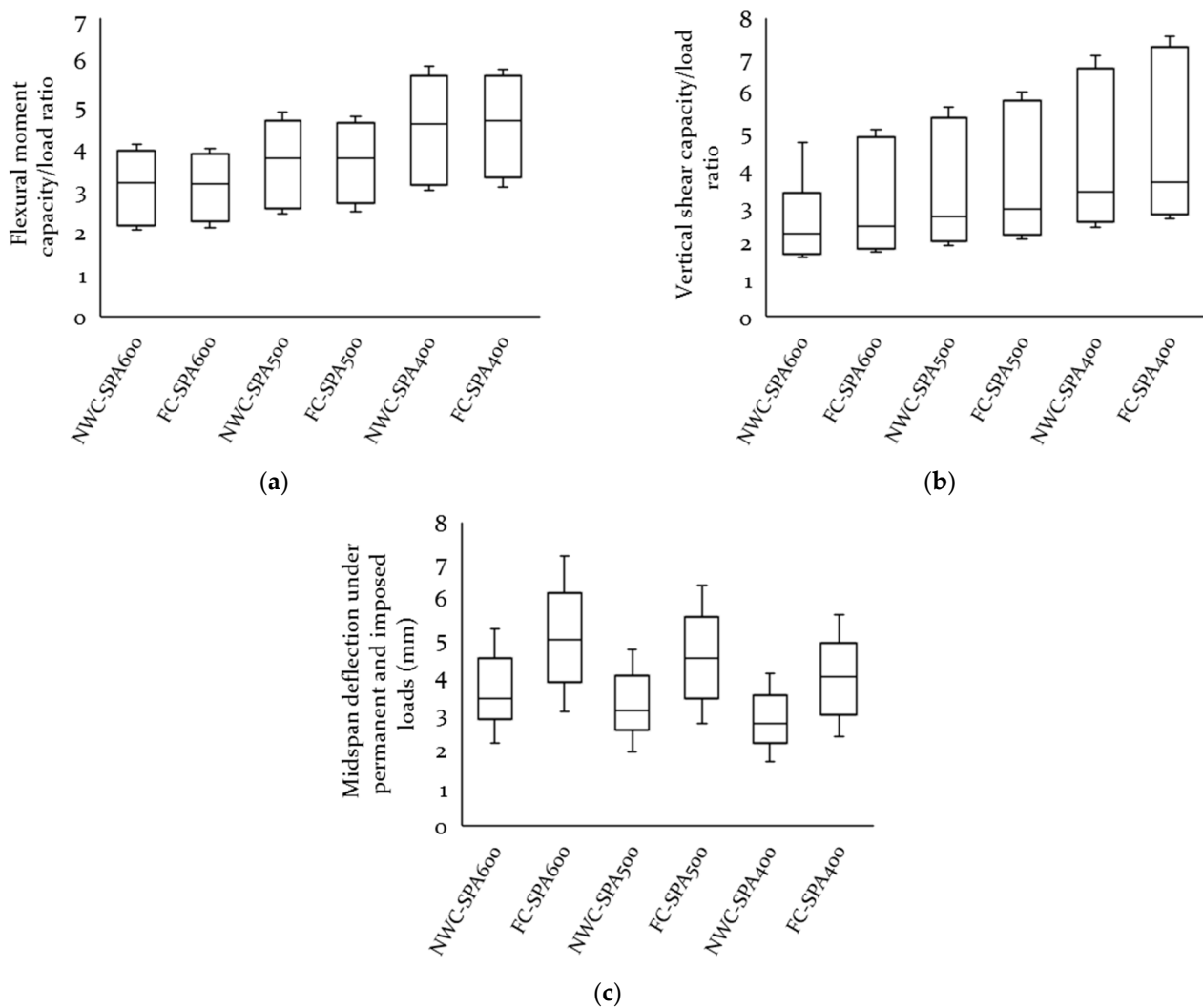
(a)

(b)

(c)

Figure 7. CFSFCC design results in (**a**) flexural moment capacity/load ratio, (**b**) vertical shear capacity/load ratio, and (**c**) midspan deflection under permanent and imposed load [26,27].

4.3.4. Effect of Joist Spacing

In this parametric study, three joist spacings are considered in the design, including 400 mm, 500 mm, and 600 mm. The spacing affects the effective width of the distributed loads, resulting in higher design loads attributed to the sections with larger joist spacing. In the full shear connection condition, the transfer area of compression load in the longitudinal force by the shear connection is affected by the width of the concrete flange cross-section.

4.4. TFCC Floor System Results and Discussion

In general, in the verifications of ULS, several calculations have been carried out, including the effective flexural stiffness value of the composite section, timber strength demand and inequalities, concrete strength demand and inequalities, and connection strength demand and inequalities. In the verifications of SLS, calculations include effective flexural stiffness of the composite section for deflection check and deflection inequalities. The verifications of ULS and SLS are highly governed by the effective flexural stiffness value, which is affected by concrete flange properties. The use of FC as the concrete flange will affect the properties of the overall stiffness due to the lower *E* compared to NWC. Using FC with 1600 kg/m^3 density offers lower self-weight in permanent load compared to NWC with 2400 kg/m^3 density, as the concrete flange has the majority of the self-weight compared to other components, such as LVL joists—the decrease of concrete

density resulting in a significant decrease of design moment and shear. However, the reduction of FC's self-weight is paired with the decline in *E*, which affects the effective flexural stiffness, resulting in a stable timber combined bending and tension load/capacity ratio, as shown in Figure 8a (in the short-term and long-term).
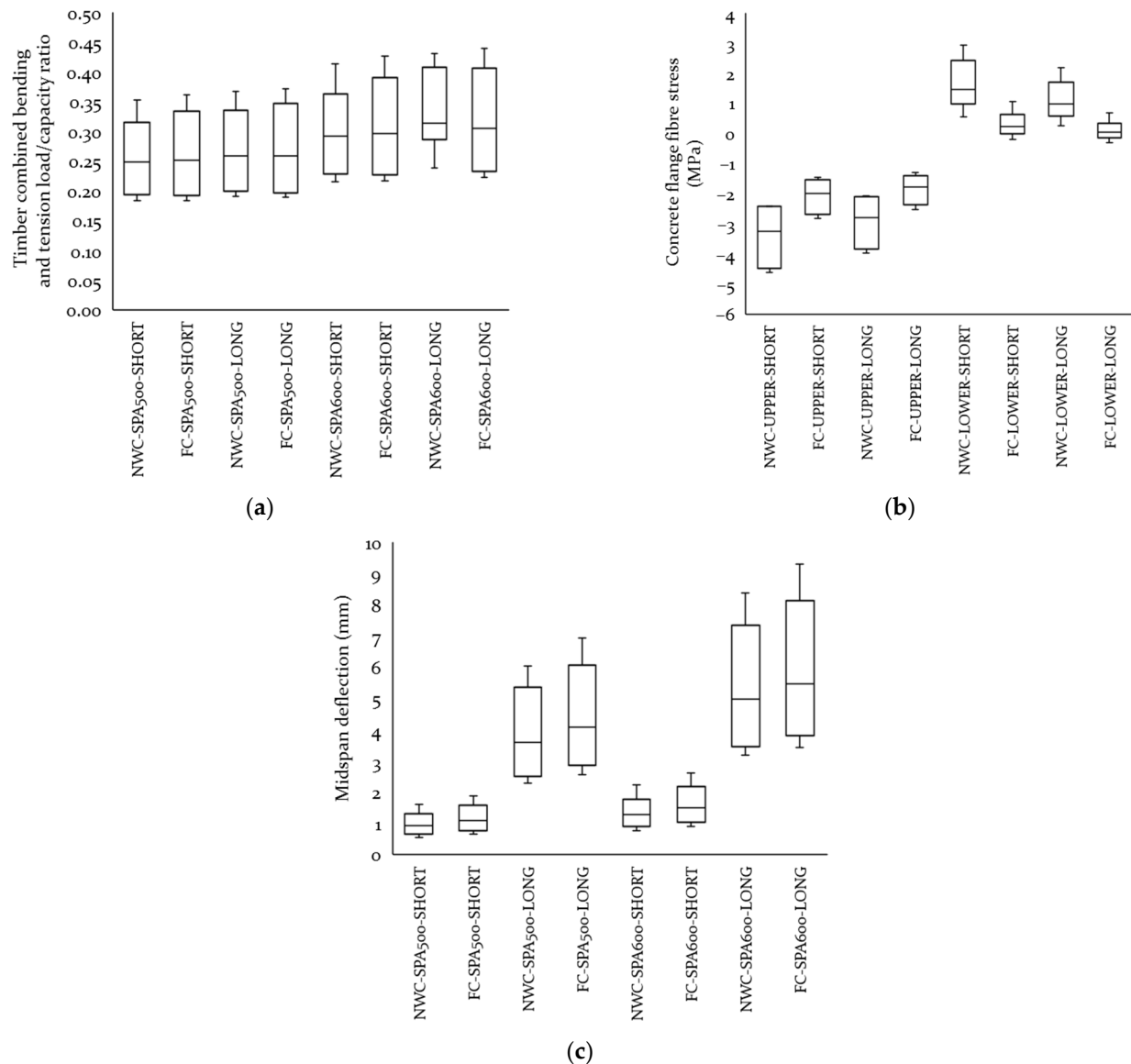

Figure 8. TFCC design results in (**a**) timber combined bending and tension load/capacity ratio, (**b**) concrete upper and lower fibre stress, and (**c**) midspan deflection in the short-term and long-term [28,29].

Each process's bending stiffness properties, including ULS and SLS short-term and long-term verifications, are determined. Effective flexural stiffness is calculated with the contribution of the *E* of timber and FC, which is lower than NWC. In the ULS short- and long-terms, the reduction of concrete densities in FC compared to NWC resulted in reduced upper and lower fibre stress, as shown in Figure 8b (with the joist spacing of 600 mm in the short-term and long-term). Reducing stress in the lower fibre is significant because it changes the concrete flange stress behaviour from tension to compression.

In the short-term and long-term SLS, the reduction of concrete densities in FC compared to NWC results in reduced effective composite flexural stiffness. The reduction of composite effective flexural stiffness increases deflection in the short-term and long-term,

as shown in Figure 8c (with the joist spacings of 500 mm and 600 mm). Furthermore, the increase of joist sections from 50 mm × 200 mm to 50 mm × 300 mm and the decrease of joist spacing from 600 mm to 400 mm positively impact the ULS and SLS short-term and long-term. The substitution of NWC with FC with a density of 1600 kg/m^3 is suitable for application in the TFCC floor system.

4.5. SDFCC Floor System Results and Discussion

4.5.1. Effect of Concrete Density and Steel Deck Thickness

The variation in the steel deck thickness gauge has a minor impact on the moment capacity of the composite slab. Reducing the thickness of the steel deck decreases its overall cross-sectional area, thereby reducing its yield capacity against flexural loads. The flexural moment strength is represented by the ratio of moment capacity to load. The EN 1994-1-1:2004 [26] and AS/NZS 2327:2017 [27] standards indicate that decreased concrete density leads to a higher flexural moment capacity/load ratio, as shown in Figure 9a. The reason is that a lower self-weight of the concrete slab with the same flexural capacity contributes to this increase. Additionally, changes in the modulus of elasticity do not affect the flexural capacity. The reduction in steel deck thickness from 1.2 mm to 0.9 mm leads to a decrease in flexural moment capacity from 56.86 kNm to 44.21 kNm, representing a 15–22% decrease.
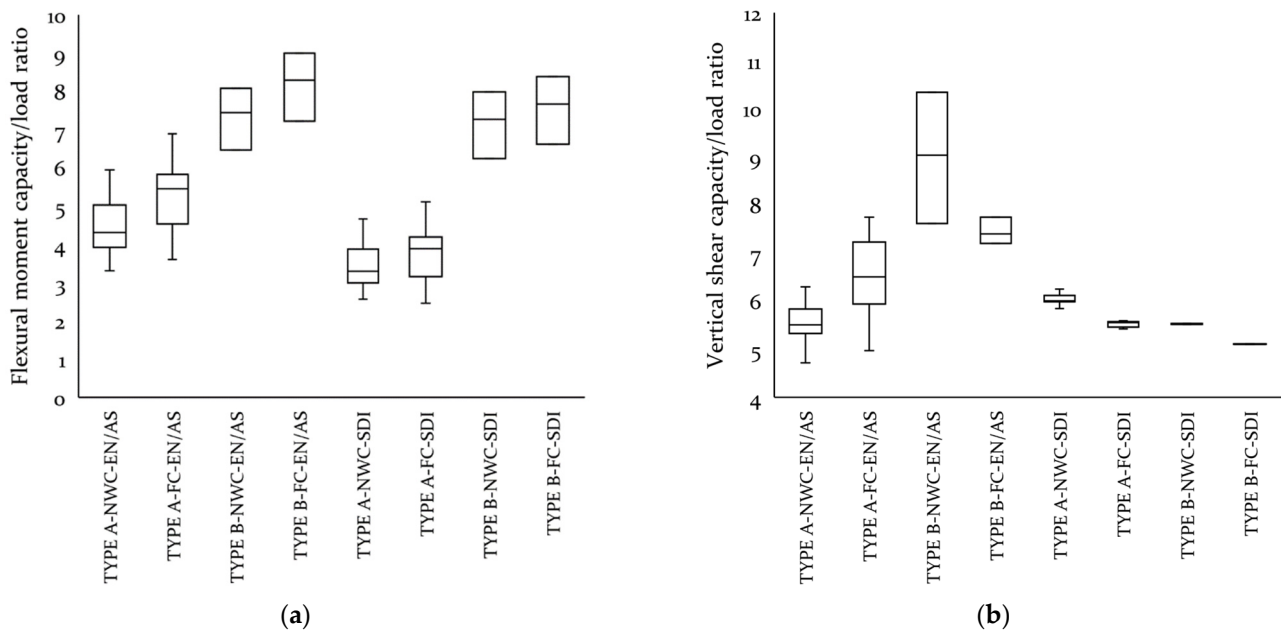

(a) (b)

Figure 9. SDFCC design results in (**a**) flexural moment capacity/load ratio and (**b**) vertical shear capacity/load ratio, refer to EN 1994-1-1:2014 [26] and AS/NZS 2327:2017 (EN/AS) [27] and SDI C-2017 (SDI) [89].

In contrast, the SDI C-2017 [89] standard indicates that reducing concrete density decreases the flexural moment capacity. Decreased concrete density leads to a lower *E*, reducing the flexural capacity. However, there is also a reduction in concrete self-weight, which decreases flexural load, resulting in a stable decrease in flexural moment capacity/load ratio as the concrete density decreases—implementing the SDI C-2017 [89], between the NWC (2350 kg/m^3 density) and FC (1600 kg/m^3 density), resulting in a reduction of flexural capacity from 37.20 kNm to 34.35 kNm, representing an 8% decrease. The flexural moment capacity of a composite slab with a deck thickness of 1.2 mm decreases by 5–14% when the concrete density decreases from 2350 kg/m^3 to 1600 kg/m^3, resulting in a reduction of flexural moment capacity from 43.85 kNm to 40.19 kNm. However, due to the decrease in self-weight in FC, resulting in a slight increase in the flexural moment capacity/load ratio compared to NWC, as shown in Figure 9a (with steel deck type A (SMD TR60$^+$) and type

B (BONDEK®)). Overall, the flexural moment capacity from SDI C-2017 [89] is much less than that of EN 1994-1-1:2014 [26] and AS/NZS 2327:2017 [27] standards because of the attribution of concrete *E*, particularly in lower-density concrete.

In terms of vertical shear strength, the impact of using various steel deck thickness gauges on the vertical shear capacity of the composite slab is negligible. Reducing the thickness of the steel deck decreases its overall cross-sectional area, thereby reducing its yield capacity against vertical shear loads. The concrete density of the composite slab influences the vertical shear capacity/load ratio. Following EN 1994-1-1:2014 [26] and AS/NZS 2327:2017 [27] standards, a decrease in concrete density results in a comparable shear capacity and reduces the load. Consequently, using lower-density concrete allows for a higher capacity/load ratio than higher-density concrete, as shown in Figure 9b. In SDI C-2017 [89], the distinction between NWC (density > 2100 kg/m^3) and lightweight concrete (density $\leq$ 2100 kg/m^3) results in a modification factor (λ) that accounts for the reduced mechanical properties of lightweight concrete compared to NWC with the same compressive strength. This modification factor significantly impacts the vertical shear capacity of the composite slab. The SDI C-2017 [89] standard provides more significant findings regarding the vertical shear capacity/load ratio, particularly in concrete with lower density.

4.5.2. Effect of Concrete Flange Thickness

The utilisation of various concrete thickness gauges significantly impacts the moment capacity of the composite slab. Reducing the thickness of the concrete slab primarily results in a decrease in the composite slab's self-weight and flexural capacity. According to EN 1994-1-1:2014 [26] and AS/NZS 2327:2017 [27] standards, the thickness reduction of concrete from 115 mm to 50 mm for a density of 1600 kg/m^3 significantly decreases flexural capacity. The decrease in capacity ranges from 71.15 kNm to 34.00 kNm, representing a reduction of 20–52% in value. SDI C-2017 [89] also demonstrates reduced flexural moment capacity with varying concrete thickness. The reduction in concrete thickness from 115 mm to 50 mm results in a relatively similar decrease in flexural capacity, ranging from 51.57 kNm to 24.05 kNm, representing a 22–53% decrease in value.

Regarding vertical shear strength, the choice of concrete thickness gauge significantly impacts the vertical shear capacity of the composite slab, as outlined in EN 1994-1-1:2014 [26] and AS/NZS 2327:2017 [27] standards. The reduction in concrete thickness from 115 mm to 50 mm decreases vertical shear capacity. Specifically, the capacity decreases from 99.94 kN to 64.49 kN, representing a 12–35% decrease in value. This decrease is attributed to the concrete's 1600 kg/m^3 density. In contrast, SDI C-2017 [89] provides a more consistent outcome in reducing vertical shear capacity associated with a decrease in concrete thickness. The reduction in concrete thickness from 115 mm to 50 mm decreases vertical shear capacity from 77.02 kN to 71.32 kN, representing a decrease of 3–7% in value.

4.5.3. Effect of Steel Deck Section and Grade

Using a concrete density of 1600 kg/m^3, based on the SDI C-2017 [89] standard, a parametric analysis is conducted to compare the Type A (SMD TR60$^+$) steel deck, which has F_y of 350 MPa and 450 MPa to the F_y of 550 MPa of Type B (BONDEK®) steel deck. Significant disparity is observed in the flexural moment capacity/load ratio between the two types of steel decks. Specifically, the Type B exhibits a notably higher capacity in this regard. The calculation demonstrates that the steel grade and the distance between the steel deck centroid and the top of the concrete slab primarily influence the ratio. The Type B steel deck has a greater value of the cracked moment of inertia than the Type A kind due to the high depth of the steel deck centroid to the top of the concrete slab. This results in a higher flexural moment capacity.

In terms of vertical shear strength, based on the SDI C-2017 [89] standard, the steel deck shape and grade parameters have a negligible effect on the vertical shear strength of the composite slab, as the shear behaviour is not affected by the steel deck properties but

by the connection between the steel deck and the structural elements. According to EN 1994-1-1:2014 [26] and AS/NZS 2327:2017 [27], the properties of the steel deck have a minor impact on the vertical shear capacity. This is because the steel deck primarily functions as the tensile component in the composite slab.

4.6. Discussion on Design Verification Results

Although the self-weight of the composite floor systems was decreased by using FC as a flange section, the strength capacity was also decreased. The low *E* value of FC is the main cause of the loss in the strength capability of the composite floor system. The analytical methods used for flexural strength in timber-concrete (TFCC) and steel-concrete (CFSFCC, SDFCC) composite floor systems differ. Based on the composite plastic moment theory, the steel-concrete floor systems calculation considers a plastic neutral axis determined by the capacities of each material (the steel joist section's tensile strength and the concrete flange section's compressive strength). Given that the compressive strengths of FC and NWC concretes are equal, the method does not substantially take this into account. Conversely, the TFCC's "Effective Modulus Method" for calculating flexural strength bases the flexural capacity on a composite calculation between the *E* of each material (timber and concrete). As a result, the difference in *E* between FC and NWC has a more significant impact on the flexural capacity.

Furthermore, the difference in *E* value between the two concretes has little bearing on the shear strength of composite floor systems, which are typically determined by the shear capacity of the floor joists (CFS steel, LVL timber, and steel deck sections). Furthermore, a noticeable difference can be seen in deflection when using FC compared to NWC. This is because composite floor systems consider the effective flexural stiffness of composite sections. However, the deflection results remain within the requirement limit.

5. Summary, Conclusions, and Recommendations

The lifting and transportation challenges have limited the concrete application in mid-to-high-rise modular building constructions. In this case, FC can be considered an alternative material due to its lightweight nature and beneficial properties. Currently, there are still limitations on the research of FC for structural element purposes and the composite behaviour of FC, especially for prefabricated floor systems. Therefore, this study assessed FC's structural and sustainability performance in modular building floor constructions, focusing on optimising mix designs and evaluating composite floor systems.

In general, FC exhibits low-strength properties in its basic compositions. The inclusion of supplementary materials (e.g., fly ash, PP fibre, silica fume) has been investigated to increase the overall mechanical and physical properties of FC. The role of supplementary materials in increasing the FC strength-to-weight ratio is important for modular-based floor construction. It allows the production of floor structures with the same design strength but lower density. The lower-density floor structure has lower self-weight, accommodating the crane lifting capacity limitation. This will reduce the transportation and lifting costs. Consequently, it reduces the construction cost of modular buildings.

This study identified the optimum FC mix designs with different supplementary materials based on the minimum required compressive strength at 28 days of 25 MPa and the sustainability aspect. This study used LCA to assess the environmental performance of FC mixes (human health, ecosystem quality, and resources), with the boundaries within the extraction, processing of raw materials, and transportation of finished materials. FC mix design consists of coarse fly ash as fine aggregate with 1600 kg/m^3 density (FC2), achieved the minimum compressive strength and has the least negative environmental impact compared to other FC mixes. However, compared to NWC (with a density of 2400 kg/m^3), the LCA result shows that FC has a significant adverse environmental impact due to higher cement content and high synthetic materials (e.g., foaming agent, PP fibres, silica fume). These synthetic materials are essential in achieving high-strength and low-density FC mix design.

To assess the suitability of employing FC as a structural element of mid-to-high-rise modular buildings, design verification of composite floor systems, including CFSFCC, TFCC, and SDFCC, is carried out. Design verification analyses and compares the flexural, shear, and deflection performances of basic modular floor elements (size 6 m × 3.6 m) using the properties of FC and NWC as the floor flange section. The design verification is assessed using analytical methods and design standards (i.e., EN 1994-1-1:2004 [26], EN 1995-1-1:2004 [28], AS/NZS 2327:2017 [27], and AS 1720.1-2010 [29]). A parametric study is conducted to determine other factors affecting the structural performance of the composite floor systems, including concrete flange thickness, floor joist section, and floor joist spacing.

With a 1600 kg/m^3 density (FC2), FC offers lesser weight (67%) and a much lower E (43%) than NWC. The lower weight reduces the design load on the floor systems, affecting the flexural strength, shear strength, and serviceability deflection. Various standards provide distinct equations for calculating the E in LWC. The equation for LWC in BS 8110-1:1997 [87] gives the most conservative value of E to be used in the design calculation of FC. The design verification result indicates that using FC as a floor flange in composite floor systems increases flexural and shear performances compared to NWC. However, the reduced self-weight of the FC flange is accompanied by a lower strength capacity, leading to a comparatively stable capacity/load ratio. The reduction of the composite floor system's strength capacity is primarily attributed to the low E value of FC. Compared to NWC, FC tends to be more brittle in behaviour, which affects the overall stiffness of the composite structure and strength capacity. Further, the primary impact of utilising FC is the increase in the composite floor's deflection. However, it remains within the specified requirements. In general, the changes in design parameters (concrete flange thickness, floor joist section, and floor joist spacing) resulted in inconsequential changes in the floor system's capacity/load ratio and deflection. In addition, the adequate compressive strength of FC in the floor system also performs the horizontal force transfer by supporting the diaphragm action.

In conclusion, the outcome indicates that FC is suitable for use in composite floor systems of mid-to-high-rise modular building constructions. The lower self-weight of FC (1600 kg/m^3 density) compared to lightweight-aggregate concrete (1800 kg/m^3) and NWC (2400 kg/m^3 density) can overcome the current lifting and transportation limitations. With the highly repetitive fabrication in modular construction, the slightest weight reduction can significantly affect the overall project, resulting in more efficient workability and cost savings. Regarding strengths and deflection, using FC provides performance similar to NWC. It proves that the material is capable to withstand design loads. However, the negative environmental impacts in the production of FC become the drawbacks in considering the material as a sustainable alternative.

6. Future Research and Recommendations

According to the LCA results, the common FC mix designs have a detrimental environmental impact because of the synthetic composition (i.e., chemical-based foaming agent and PP fibre). Nevertheless, the synthetic composition can be minimised with natural alternatives (i.e., natural-based foaming agents and natural fibres [101]). Hence, future research must consider incorporating natural fibres in FC to enhance the sustainability of composite floor systems. In addition, this study focuses on the sustainability aspect by limiting the LCA to the FC material production phase, specifically the "cradle to gate" approach. Thus, the future analysis should focus on the environmental impacts of utilising FC in all structural elements throughout the building's lifespan, including demolition and reconstruction. Therefore, the energy-saving benefits of FC in thermal conditioning can also be evaluated.

In addition, this study focuses on specific composite floor systems that are suitable for modular building construction. Alternative composite floor systems can be suggested to meet FC's structural requirements. Furthermore, the current study is focused on utilising an analytical method to evaluate the structural capacity of composite floor systems. Thus,

future studies can utilise an experimental approach to assess the structural behaviour of composite floor systems in the short and long terms (structural durability).
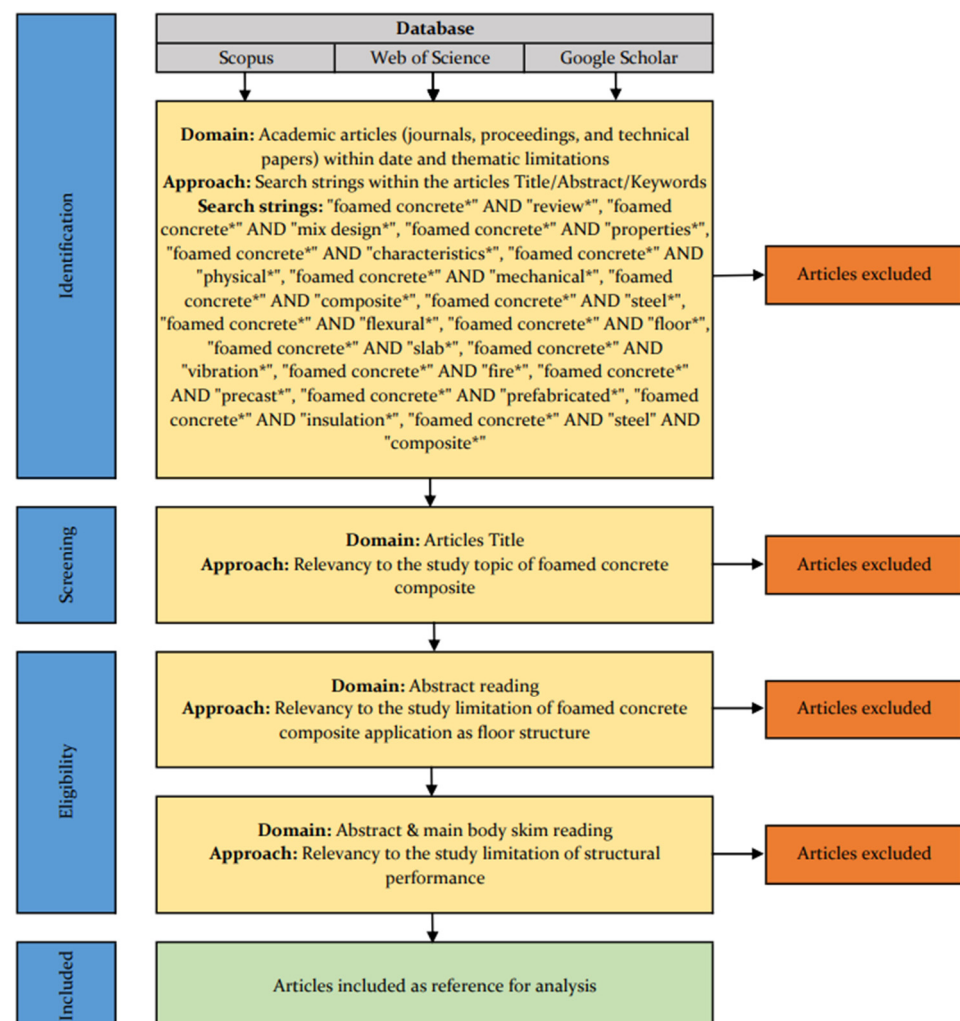
Appendix A

Figure A1. Data collection procedure.

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