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Bio-based ultra-lightweight concrete applying miscanthus fibers: Acoustic absorption and thermal insulation

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ABSTRACT

Acoustic and thermal comfort play an important role in the building environment. This study investigates ultra-lightweight concrete incorporating Miscanthus fibers as lightweight aggregates to improve sound absorption and thermal insulation properties. Miscanthus fibers (MF) is a kind of sound absorption biomass that can dissipate sound noise thanks to its porous and flexible inner structures and fibrous shape. However, its acoustic absorption performance in cement-based materials is rarely investigated. Therefore, the acoustic absorption and thermal insulation of ultra-lightweight Miscanthus concrete (ULMC) is investigated using two different kinds of Miscanthus fibers. Meanwhile other mechanical properties were characterized, including bulk density and flexural strength. Results showed ULMC with 30% 2–4 mm MF obtained an ultra-low density (554 kg/m^3), thermal conductivity (0.09 W/(m·K)) and high acoustic absorption coefficient (0.9) at low frequencies. It is found that the acoustic performance of ULMC can be improved by optimizing the dosage and shape of Miscanthus fibers. The developed green and sustainable bio-based ULMC possesses an excellent acoustic absorption and thermal insulation and is very suitable to use as indoor ceiling boards and in non-structural walls to make indoor living environment comfortable and energy-saving.

1. Introduction

As governments and industries are striving to save energy and reduce environmental burden for years, concrete with low carbon footprint and unique functions are attractive and promising for a sustainable society [1–5]. Lightweight concrete (LWC) is a type of cementitious materials with density from 800 kg/m^3 to 2000 kg/m^3 and has the potential to obtain good thermal insulation and acoustic absorption properties [6,7]. Due to the large variations in aggregates, admixtures and preparation process, LWCs can possess different properties in terms of density, thermal and acoustic properties, mechanical property and sustainability. Therefore, proper selection of lightweight aggregates and production procedures are the keys to prepare LWC with low environmental impact and improved functionalities.

One type of ultra-lightweight concrete (ULWC) invented in the previous researches [8–10] showed excellent thermal insulation and ultra-low density. The applied lightweight aggregate (LWA) was produced from waste glass with a special procedure. Reuse of this unrecyclable waste glass to tackle the problems of over landfilling and contamination of environment is a promising recycling method [11,12]. According to the previous studies, this expanded waste glass can be applied in cementitious mixtures to produce ULWC, with drying density lower than water (~800 kg/m^3) and thermal conductivity around 0.12 W/(m·K) [9]. However, the acoustic absorption property of ULWC is rarely investigated, which is an important aspect that is associated with the quality of indoor living environment. Recent researches have shown bio-based lightweight aggregates like hemp and Miscanthus fibers can function as sound absorption materials in cement and concrete [13]. Gle et al. [14,15] investigate the acoustic absorption of hemp fiber reinforced concrete by experimental and modelling methods. The results show the hemp fibers itself can greatly absorb sounds and also can increase the acoustic performance of bio-concrete. Therefore, it is promising to hybridize expanded waste glass and plant fibers as lightweight aggregates in LWC to increase the acoustic absorption performance and thus improve the quietness in indoor environment.

In this study, Miscanthus fibers are adopted to improve the unique functions of ULWC. Miscanthus fiber has received much attention due to its environmentally friendliness and wide spread availability, especially

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in Europe [16]. Miscanthus can also act as a kind of lightweight aggregate in cementitious materials to prepare lightweight concrete [17–19]. Miscanthus has low particle density and its porous structure has a positive effect on acoustic absorption like hemp [13,15]. The inter-particle pores and intra-particle pores all contribute to the dissipation of sound waves. Moreover, the high porosity of Miscanthus fibers can further contribute to a lower thermal conductivity of Miscanthus lightweight concrete [20–24]. It is noteworthy that the structure of Miscanthus fibers is a complex core-shell structure, as shown in Fig. 1. One single Miscanthus particle consists of the outer shell called epidermis structure, while the middle and inner structures are sclerenchyma and parenchyma, respectively. Thus, the contribution of different parts of Miscanthus fibers to acoustic performance is hypothesized to be different, which should be investigated. Therefore, the hybridization uses of different parts of Miscanthus fibers and expanded waste glass to prepare ULWC with low density, high thermal insulation and excellent acoustic absorption is interesting and needs detailed investigation.

From the above perspectives, the objective of this paper is to investigate the acoustic absorption and thermal insulation properties of ultra-lightweight concrete by incorporating Miscanthus fibers and expanded waste glass. Two kinds of Miscanthus fibers are used, which are 0–2 mm and 2–4 mm fibers. A performance evaluation of the developed ULMC is carried out, including the mechanical properties, acoustic absorption coefficient and thermal conductivity. The mechanism of the improvement in insulation properties of ULMC are explored by scanning electron microscopy.

2. Methodology

2.1. Starting materials

2.1.1. Raw miscanthus fibers

Miscanthus fibers (MF) adopted in this study was provided and further treated by Vibers (the Netherlands). The raw granules of MF were different in size and shape, hence sieving was carried out to produce a uniform granules of the fibers. Sieves with 2 and 4 mm diameter were applied to classify MF with the use of a sieving machine. The length of the two kinds of MF was approximately 2–20 mm. Fig. 2 exhibits the morphology of 0–2 mm and 2–4 mm MF, respectively. Fig. 3 presents the scanning electron microscopy (SEM) images of the utilized 0–2 mm and 2–4 mm MF, whose surface were sputtered with gold and were observed by JOEL JSM-5600 with an accelerating voltage of 10 kV. The used 2–4 mm MF possesses porous structures. Large amounts of mesopores and stem walls are existed in the fibers. The pore size is in the range of 20–50 μm. However, for 0–2 mm MF, it shows a more compacted porous structure, where the pore size is much smaller and tighter than those of 2–4 mm MF. The water absorptivity of the two MFs are shown in Table 1. The 0–2 mm MF has a higher water adsorption capability (396% at 48 h) compared to 2–4 mm MF (290%), The finer fibers can absorb water more quickly at early age and reach equilibrium much sooner than larger fibers. The types of sugar leached from miscanthus are mainly arabinose, galactose, glucose, xylose and mannose, with a concentration of 0.06 mg/ml, 0.09 mg/ml, 0.19 mg/ml, 0.16 mg/ml and 0.05 mg/ml, respectively [13].

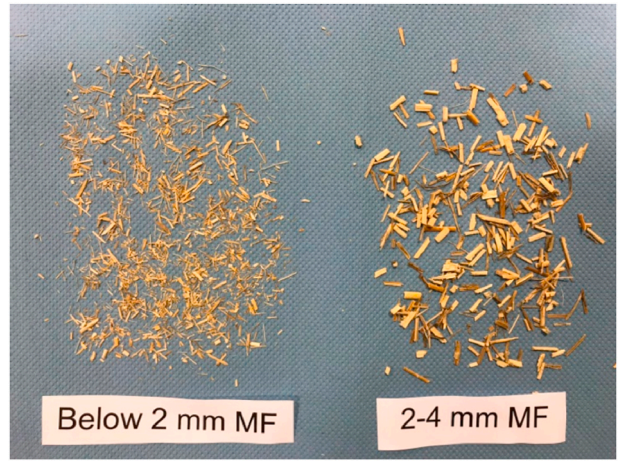

Fig. 2. Morphology of the 0–2 mm MF and 2–4 mm MF.

2.1.2. Expanded waste glass

The expanded waste glass (EWG) was produced from recycled glass through a special procedure, which was adopted as lightweight aggregate to produce ULMC in this study [9]. Five different sizes of EWG were adopted in this research, with a particle size distribution of EWG from 0.25 to 8.0 mm, which are detailed exhibited in Fig. 4 (a). The SEM of the adopted EWG is presented in Fig. 4 (b), which was observed using the same instrument as that of MF. The physical properties and oxides composition of EWG are shown in Table 2 and Table 3. The water absorption is quite low compared to other kinds of commercial LWAs [9], especially in the first hour of soaking, reaching around 1.0% by mass. This is attributed to the closed external surface observed from Fig. 4 (b). Therefore, the adopted EWG had little influence on the workability of ULMC, and in turn slightly reduced the w/c ratio at the beginning of cement hydration, preventing micro-bleeding at the interface of LWA. Hence the Liaver EWG can be blended in the cementitious mixtures directly without pre-soaking.

2.1.3. Cement matrix of ULMC

The cementitious material used for ULMC was CEM III 52.5 N cement, which was provided by ENCI, Heidelberg Cement (the Netherlands). The oxides composition of the cement was analysed by X-ray fluorescence (XRF), as shown in Table 3. Superplasticizer (SP) was used to optimize the flowability of the fresh ULMC paste. Air entraining agent (AE) was used to introduce extra air voids to further decrease the density of ULMC.

2.2. Experimental design

2.2.1. Mix design of ULMC

The mix design methodology of the ULMC applied a modified A&A model, as reported in previous studies [25,26]. The Miscanthus fibers were used to replace EGW with each particle size by 10%, 20% and 30% by volume, which were marked as M10, M20 and M30, respectively. The

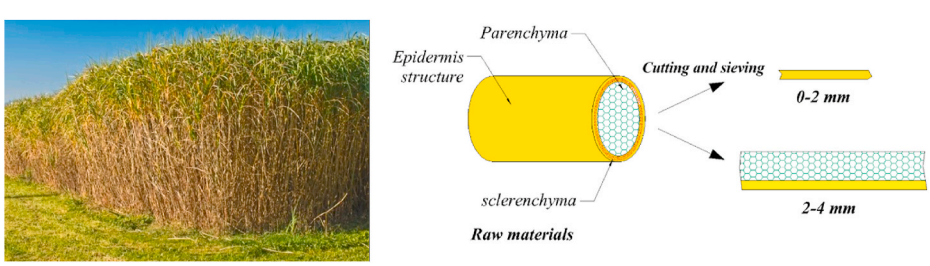

Fig. 1. Schematic diagram of the microstructure of two different kinds of Miscanthus fibers: 0–2 mm and 2–4 mm.

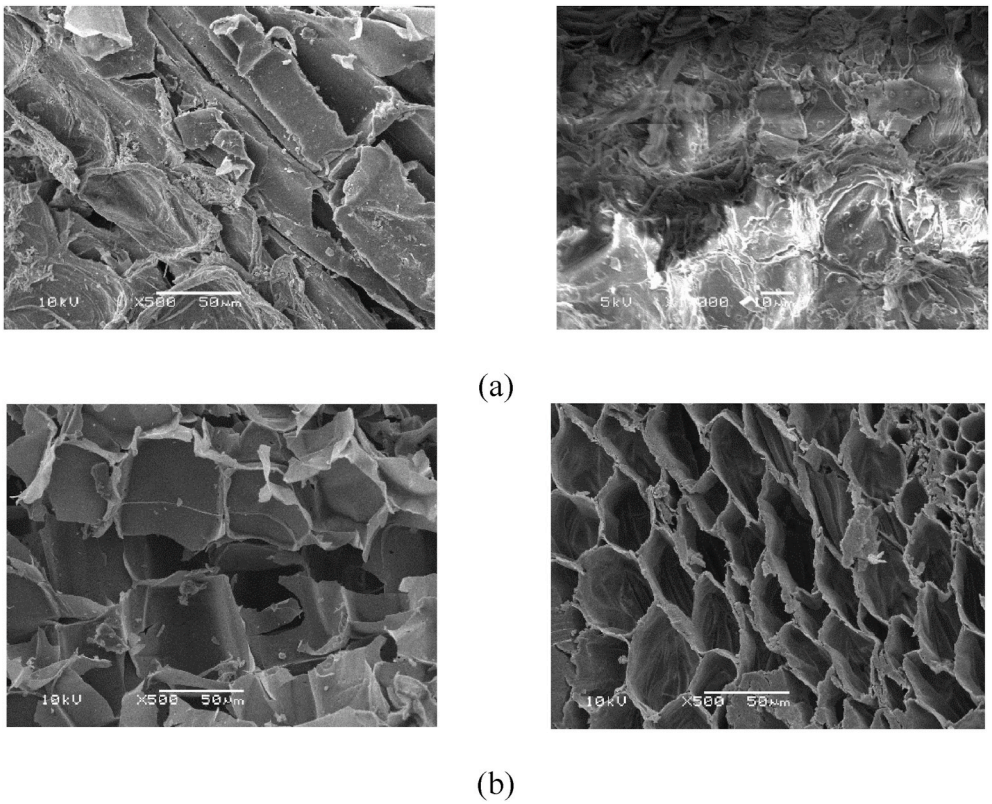

Fig. 3. SEM of the utilized Miscanthus fibers (a) 0–2 mm and (b) 2–4 mm (Magnification: ×500).

Table 1
Water absorptivity of miscanthus fibers with different sizes.

Water absorptivity (%)	10 min	30 min	1 h	6 h	12 h	24 h	48 h
0–2 mm MF	330	361	372	384	391	394	396
2–4 mm MF	180	210	224	271	281	289	290

water to cement ratio was fixed as 0.45. SP was used to increase the workability of the fresh concrete paste, which was determined to be 1 wt % as the optimum. The designed recipes of ULMC mixtures are presented in Table 4.

2.2.2. *Mixing procedures*

Miscanthus fibers should be pre-soaked in water before mixing with cementitious materials to keep water to binder ratio constant during the mixing. In brief, 50 g of MF was weighed and placed in a 500 ml beaker filled with distilled water. Then MF was filtrated through an 80 μm sieve to remove water. Afterwards, the surface water remaining on MF was dried by carefully clapping the MF with paper. Then water-saturated MF was ready for use.

In terms of preparation of ULMC, the cement and EWG were firstly mixed for 1 min without water. Afterwards, 70% of distilled water was added and mixed with the cement and EWG for 2 min. Then, the superplasticizer and 30% of distilled water were added and mixed for another 2 min. Finally, Miscanthus fibers was added and mixed for 3 min with the above mixture. The temperature during production of ULMC

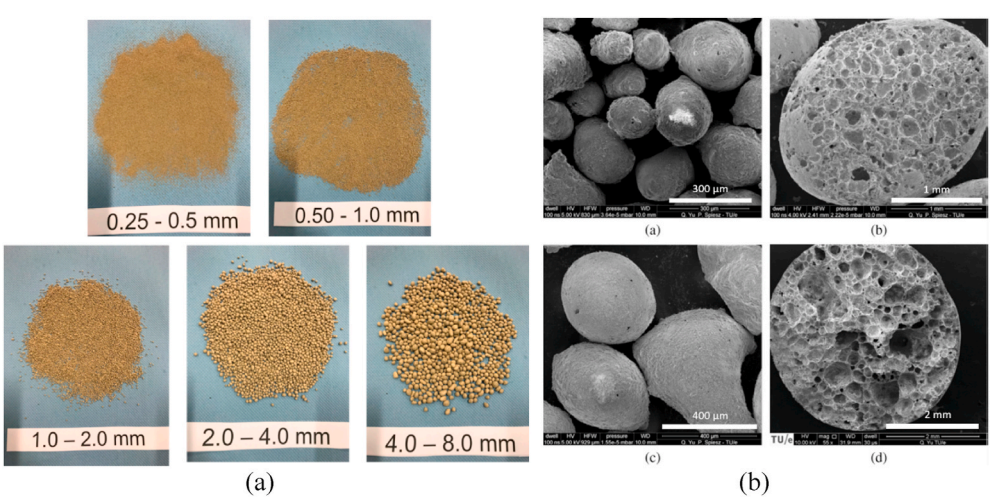

Fig. 4. (a) Morphology of expanded waste glass with different sizes and (b) SEM image.

Table 2
Densities, water absorption and mechanical properties of the used EWG.

EWG *D* (mm)	Bulk density (kg/m^3)	Specific density (kg/m^3)	Crushing resistance (N/mm^2)	1 h water absorption (wt.%)	24 h water absorption (wt.%)
EWG 0.25-0.5	300	540	> 2.9	0.88	3.90
EWG 0.5–1.0	250	450	> 2.6	1.59	8.50
EWG 1.0–2.0	220	350	> 2.4	1.71	7.63
EWG 2.0–4.0	190	310	> 2.2	0.55	7.80
EWG 4.0–8.0	170	300	> 2.0	1.30	9.11

was approximately 20 °C.

After mixing, the fresh ULMC paste was cast into moulds and vibrated on a jolting table. Workability of ULMC was measured by the mini spread-flow test [27]. Fresh ULMC paste was placed into a normal conical ring and followed by 15 times jolting. The diameter of cement paste was measured perpendicularly 4 times after jolting and the average value was noted as the slump flow. After 1 day from casting, samples were stripped from the moulds and placed in a climate chamber with a relative humidity of above 95% and temperature of around 20 °C. After 7- and 28-days curing, respectively, the properties and performances of ULMC samples were measured.

2.3. Performance evaluation of ULMC

2.3.1. Densities

The fresh density of the reference sample, M10, M20 and M30 was determined following EN 12350-6 (2009) [28]. After mixing, the fresh ULMC paste was first placed in a 1 L graduate cup to determine the fresh density. Afterwards, the ULMC samples were cast in the moulds of two sizes, i.e. 100 mm × 100 mm × 100 mm and 150 mm × 150 mm × 150 mm. After 1 day curing in a climate chamber, the specimens were stripped from the moulds and continued curing for 7 and 28 days at 20 °C, following EN 12390-2 (2009) [29]. Cubic samples with the size of 100 mm × 100 mm × 100 mm were used to determine the dry density of ULMC (Standard EN 12390-7 (2009) [28]). The average density of three test specimens was calculated as the final density of the concrete.

2.3.2. Compressive and flexural strength

The reference sample, M10, M20 and M30 cubes with the size of 150 mm × 150 mm × 150 mm were used to determine the compressive strength at 7 and 28 days (Standard EN12390-3) [30]. The ULMC concrete bars with the size of 40 mm × 40 mm ×160 mm were used to test the flexural strength at 7 and 28 days (Standard EN 196-1) [31]. The average strength of three test specimens was calculated as the final strength of the concrete.

2.3.3. Acoustic absorption

Acoustic absorption efficiency of ULMC was determined with the impedance tube method as shown in Fig. 5. Specifically, the fresh ULMC paste was cast in the cylindrical mould with the size of 40 mm in diameter and 80 mm in height. After 28 days curing, the reference sample, M10, M20 and M30 for sound absorption test were ready for use. The mechanism of sound absorption test is briefly described as follows. The sound generator emits a plane wave and spread through the tube before reflecting by the ULMC. The ULMC reflects, absorbs and transmits the wave and by detecting the generated sound wave, the sound absorption coefficient of ULMC can be calculated. Every sample was tested twice to ensure the reliability of the results.

2.3.4. Thermal conductivity of ULMC

The ULMC cubes with the size of 100 mm × 100 mm × 100 mm were first dried at 105 °C overnight to a constant mass (Standard EN12390-7) [28]. The heat transfer analyser modelled ISOMET model 2104 was used to determine the thermal properties of the reference sample, M10, M20 and M30. Both the volumetric heat capacity (J/(m^3·K)) and the thermal conductivity (W/(m·K)) of materials can be tested. Fig. 6 shows the thermal conductivity test carried out by this analyser and the

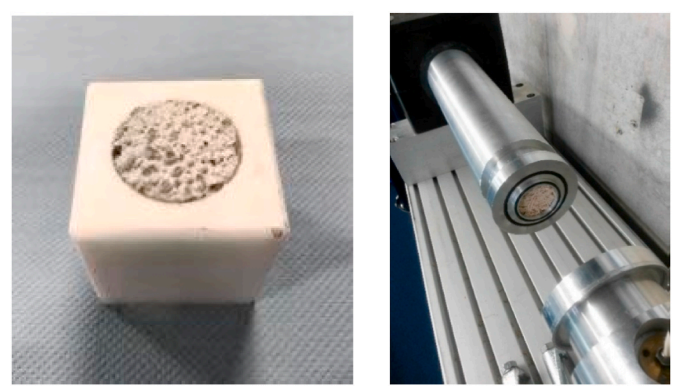

Fig. 5. Pictures of the mould for acoustic absorption and the used impedance tube.

Table 3
Oxides composition of the used cement and EWG.

Oxides composition	CaO	SiO_2	Al_2O_3	Fe_2O_3	K_2O	Na_2O	SO_3	MgO	LOI[a]
Cement	64.60	20.08	4.98	3.24	0.53	0.27	3.13	1.98	0.4
EWG	6.4	71	2	0.5	1	13	–	2	0.9

[a] Loss on ignition.

Table 4
Mix design of ULMC.

ULMC	CEM 52.5 N (kg/m^3)	EWG (kg/m^3)					Water (kg/m^3)	SP (%)	AE agent (kg/m^3)	0–2 MF (vol %)	2–4 MF (vol %)
		0.25–0.5 mm	0.5–1 mm	1–2 mm	2–4 mm	4–8 mm					
Reference	403	23.70	35.60	27.30	47.10	57.30	184	1.0	2.25	0	0
M1-10	403	21.33	32.00	24.57	42.39	51.60	184	1.0	2.25	10%	0
M1-20	403	18.96	28.48	21.84	37.68	45.84	184	1.0	2.25	20%	0
M1-30	403	16.59	24.92	19.11	32.97	40.11	184	1.0	2.25	30%	0
M2-10	403	21.33	32.00	24.57	42.39	51.60	184	1.0	2.25	0	10
M2-20	403	18.96	28.48	21.84	37.68	45.84	184	1.0	2.25	0	20
M2-30	403	16.59	24.92	19.11	32.97	40.11	184	1.0	2.25	0	30

Miscanthus lightweight concrete cube. The temperature during test is constant at 20 °C. The average thermal conductivity of three test specimens was calculated as the final thermal conductivity of the concrete.

2.3.5. Water permeable porosity

The porosity test for the reference sample, M10, M20 and M30 was carried out with the vacuum saturation approach, following ASTM C642-13 (2013) [32]. The porosity can be calculated with:

$$\phi v, water = \frac{ms - md}{ms - mw} \times 100 \quad (1)$$

where ϕ_v, water is the water-permeable porosity (%), m_s is the mass of saturated sample in surface dry condition (g), m_w is the hydrostatic mass of the water-saturated sample (g) and m_d is the mass of oven dried sample (g).

2.3.6. UPV test

Ultrasonic pulse velocity (UPV) test was used to test the strength and voids of the reference sample, M10, M20 and M30, following ASTM C597-09 [33]. It measures the velocity of an ultrasonic pulse passing through a concrete structure. Direct method was used during the whole test, which requires access to two surfaces of the concrete cubes. Each specimen was tested thrice, and the average value was determined as the final velocity of the concrete.

2.3.7. Scanning electron microscopy

The microstructure of ULMC was observed by scanning electron microscopy (SEM), which was conducted by JOELJSM-5600 instrument with an accelerating voltage of 10 kV. The surfaces of the tested ULMC samples were pre-treated with sputtered gold before the SEM test.

3. Results and discussion

3.1. Physical properties

The spread flow of ULMC is presented in Fig. 7 (a). Both 0-2 and 2–4 mm MF decrease the flowability of ULMC as the replacement of MF amount increases. Due to the pre-treatment of fibers, reduction in flowability is not attributed to the water absorption of miscanthus fibers, but closely related to the aspect ratio and volume fraction of MF in cement paste. The fresh density and dry density of ULMC are presented in Fig. 7 (b). The fresh densities of all ULMC mixtures are around 700 kg/m^3, suggesting the pre-soaked MF has only slight influence on the fresh densities of ULMC mixtures. The reason behind this phenomena is the high porosity and water absorption of MF [13]. The dry densities of all ULMC samples are less than 800 kg/m^3, which is lower than the minimum density of LWC defined by standard – EN 206-1 (2001) [34]. Hence the designed Miscanthus concrete is an ultra-lightweight concrete. It can be observed from Fig. 7 that the dry density of ULMC decreased with the increasing dosage of MF. This phenomenon should be attributed to two reasons. Firstly, the MF is a porous material with inter-particle porosity of 52.2% and intra-particle porosity of 38.3% and particle density around 250 kg/m^3 [13], which means the dried MF is more porous and lightweight than expanded waste glass. Secondly, the high percentage of MF can have an impact on the internal packing of ULMC. The long and stiff MF can push the surrounding expanded waste glass apart and change the packing of the granule structure. Hence, the ULMC becomes more porous due to the additional of MF and also more air is entrapped in the ULMC mixtures.

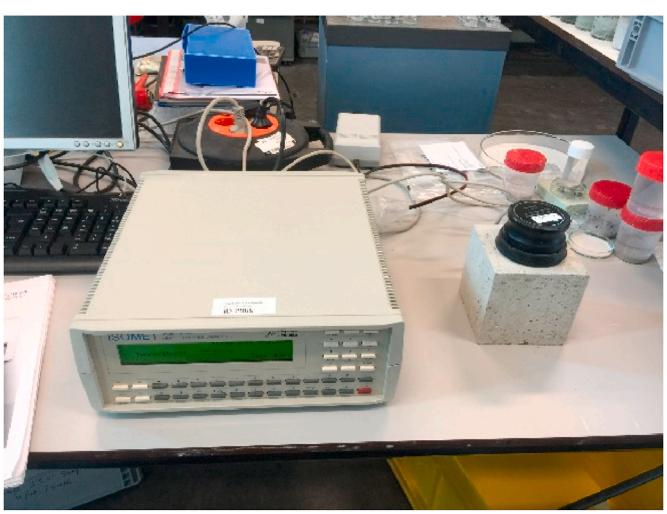

Fig. 6. Test picture of thermal conductivity of ULMC.

The compressive strength and flexural strength of ULMC at the age of 7 days and 28 days are presented in Fig. 8. All the groups of ULMC show decreased strengths with the increasing dosages of MF. The compressive strength of reference mixture at 28 days reduces from 8.42 MPa to 3.99 MPa with 30% 2–4 mm MF replacement of EWG. Meanwhile, ULMC with 0–2 mm MF show slightly lower compressive strength than those of 2–4 mm samples, reaching 3.8 MPa with 30% MF substitution. 0–2 mm MF possesses a lower mechanical strength and a lower particle density [13], and the surface is smoother than 2–4 mm MF, indicating a weak bonding between fibers and hardened cement paste. Therefore, miscanthus fibers have a negative effect on compressive strength of ULMC. This phenomenon is probably attributed to two reasons. Firstly, the crushing resistance of MF is much lower than that of expanded waste glass, which means the average strength of lightweight aggregates applied in ULMC decreased dramatically. In general, the compressive strength of lightweight concrete is much dependent on the strength of lightweight aggregates used in the cement matrix. This can also explain the relatively slow rate (20%) of strengths development of ULMC from 7 days to 28 days. Secondly, the organic materials leached from the MF retard the hydration process of cement, which is detailed investigated in a previous research [13]. The C–S–H formation is much slower because of the retarding effect of sugar in the MF. However, the late age strength of ULMC needs further investigation since the retardation effect may have positive effect on the later strength.

However, flexural strengths of ULMC only slightly decease with the addition of 2–4 mm MF, ranging from 1.09 MPa to 1.59 MPa. This phenomena is probably due to the bridging effect of MF demonstrated by many researchers [19,35,36]. With the increased load on ULMC, the 2–4 mm MF will become active and resist part of the load. However, the retarding effect of leached sugar on cement hydration as mentioned above can compromise the positive bridging effect. Therefore, the two opposite effects resulted in a slight decrease in the flexural strength of ULMC with the incorporation of 2–4 mm MF. However, the flexural strength dramatically decreases to 0.95 MPa at 28 days for ULMC with addition of 30% 0–2 mm MF. The smooth flat surface of the 0–2 mm MF leads to a poor bonding with the cement paste and a fiber pull-out failure without any stress transfer.

3.2. Acoustic absorption of ULMC

The acoustic absorption coefficient of ULMC with different dosages of 2–4 mm MF are presented in Fig. 9. It can be observed that the M10 sample reaches a moderate sound absorption coefficient of approximately 0.58 at the frequency of 712 Hz. However, the sound band width that exceeded absorption efficiency of 0.5 is relatively low, reaching only 142 Hz showing a poor absorption in low frequencies. However, when 20% 2–4 mm MF replaced EWG in the ULMC, the peak of sound absorption coefficient increased to 0.73 and the sound frequency also shifted to higher value of 784 Hz. The band width of frequencies above the efficiency of 0.5 also increased to 247 Hz, indicating the sound that can be effectively absorbed increased. Furthermore, the sample with

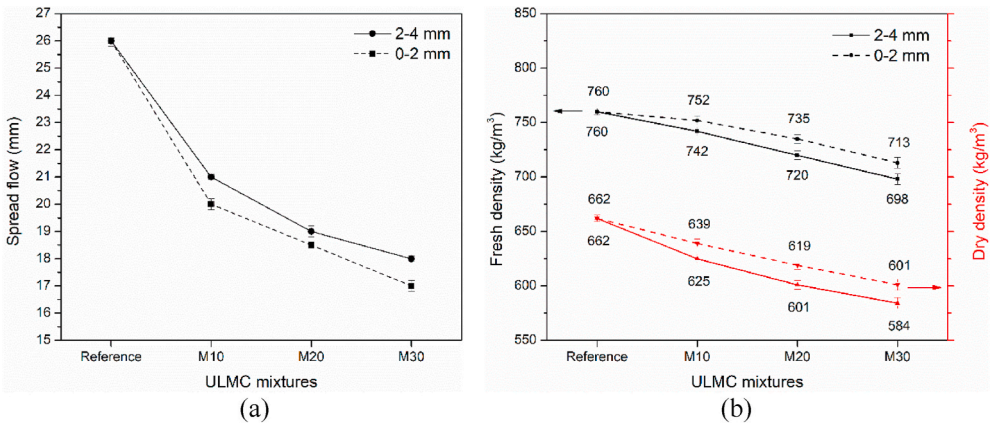

Fig. 7. Spread flow (a) and fresh/dry density (b) of the designed ULMC.

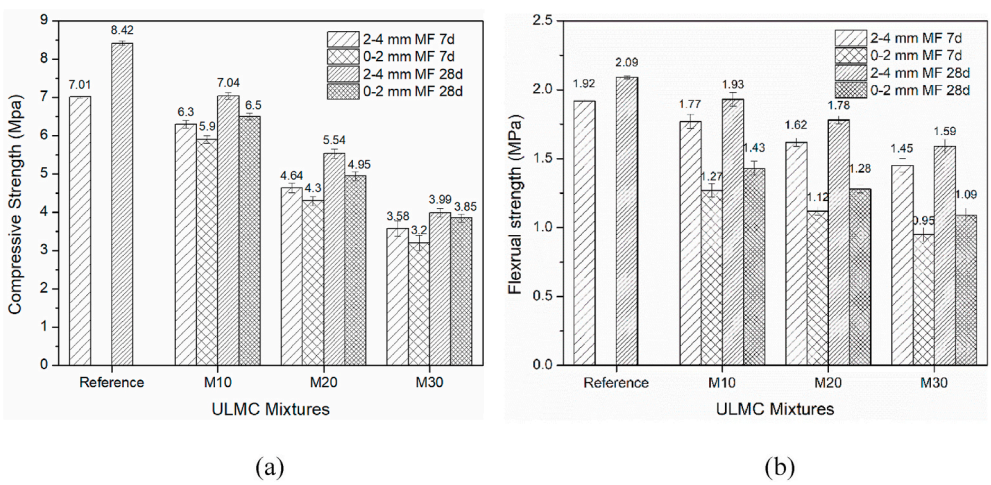

Fig. 8. Compressive (a) and flexural (b) strength of the designed ULMC at 7 and 28 days.

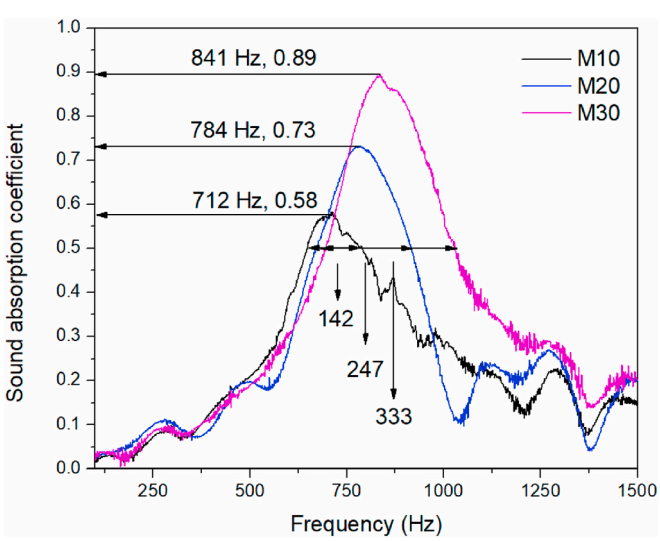

Fig. 9. Acoustic absorption coefficient of ULMC with different dosages of 2–4 mm MF.

30% MF shows the highest sound absorption efficiency. The sound absorption efficiency reached 0.89 at the frequency of 841 Hz. The band width of the sound absorption efficiency higher than 0.5 is 333 Hz ranging from 712 to 1050 Hz. Therefore, it can be concluded more 2–4 mm MF incorporated in lightweight concrete can result in higher sound absorption and cover more range of sound frequencies, meaning more sound can be effectively absorbed by ULMC.

The phenomena may be attributed to two reasons. Firstly, porous and lightweight materials possess a higher acoustic absorption compared to dense materials. 2–4 mm MF is a kind of lightweight biomaterial with large amounts of open interconnected pores which is rather different from expanded waste glass (closed shell structure that prevent pores connected to outer space). Researches [14] show that compacted long hemp fibers can have a sound absorption coefficient of 0.9 at frequencies from 400 to 1000 Hz, which obtains the similar physical properties to Miscanthus fibers. Secondly, porosity of ULMC could increase with the incorporation of 2–4 mm MF, which can be further evidenced by the porosity test. Therefore, both factors contribute to the improved acoustic absorption of ULMC.

The sound absorption of ULMC incorporating 0–2 mm MF is presented in Fig. 10. Generally, the acoustic absorption of pure cement paste is pretty low, with the sound absorption coefficient ranging from nearly 0 to 0.2 depending on different processing conditions [37]. The reference sample only reaches a sound absorption coefficient of 0.25 at the frequency of 800 Hz. With the increasing content of 0–2 mm MF, the sound insulation of ULMC increased slightly, reaching only 0.39 at the same frequency. As MF content increased to 20% and 30%, the sound absorption of ULMC remains relatively stable, indicating a limited rise in sound insulation performance. This phenomenon can be explained by the different microstructure of different shapes of Miscanthus fibers. 0–2 mm MF has a morphology of smooth outer shell of the straw,

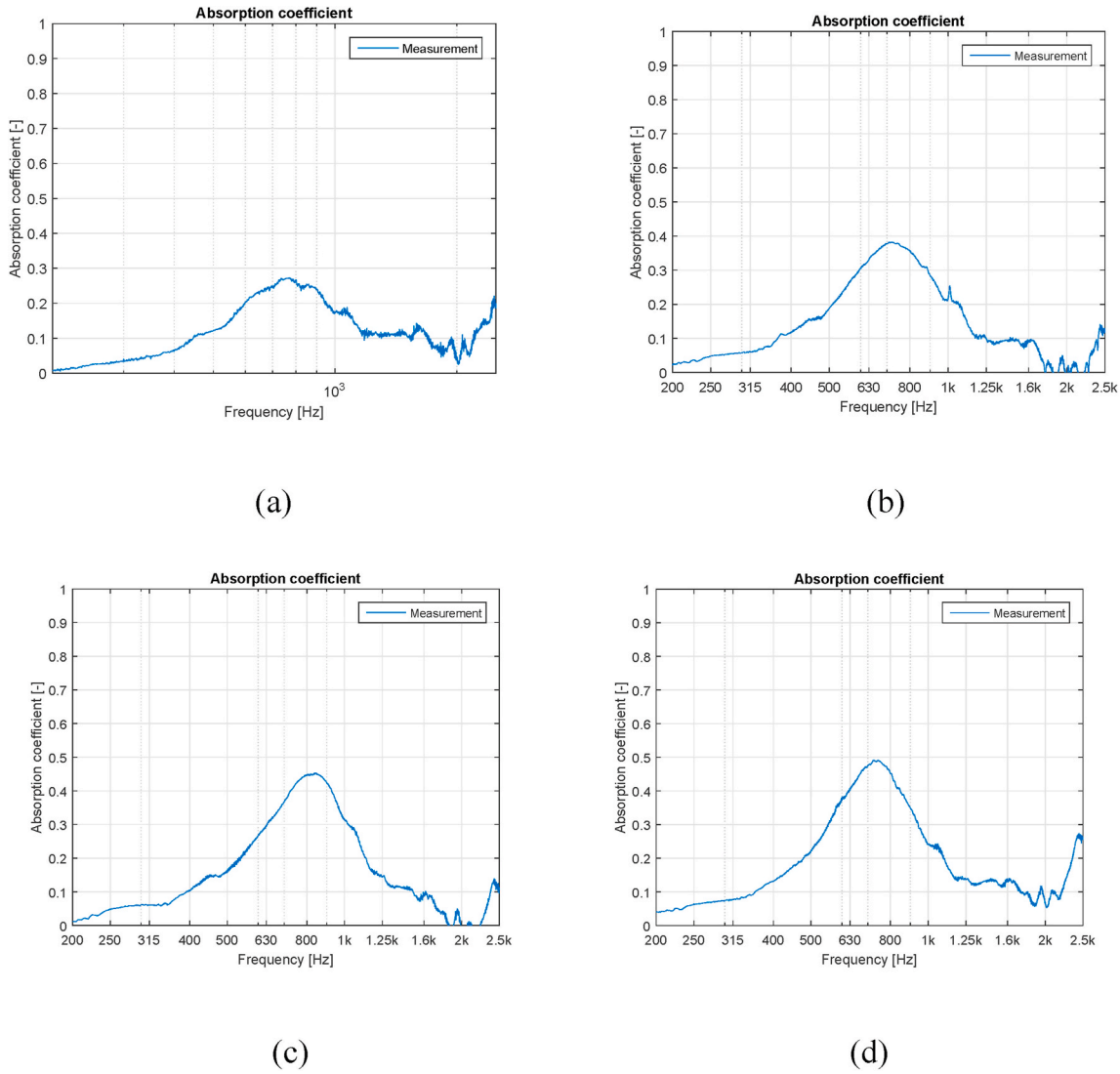

Fig. 10. Sound absorption coefficient of ULMC with 0–2 mm MF (a) Ref (b) 10% MF (c) 20% MF (d) 30% MF.

resulting in a less porous microstructure as shown in Fig. 3. Therefore, in this study 2–4 mm MF is the optimal biomaterial for the enhancement of sound insulation property.

The schematic diagram of the sound insulation of ULMC is shown in Fig. 11. As the sound is generated from the loudspeaker, three kinds of sound can be generated: 1) the reflected sound, 2) the absorbed sound and 3) the transmittance sound. More 2–4 mm MF in ULMC can improve the amount of the inter-particle and intra-particle pores and contact

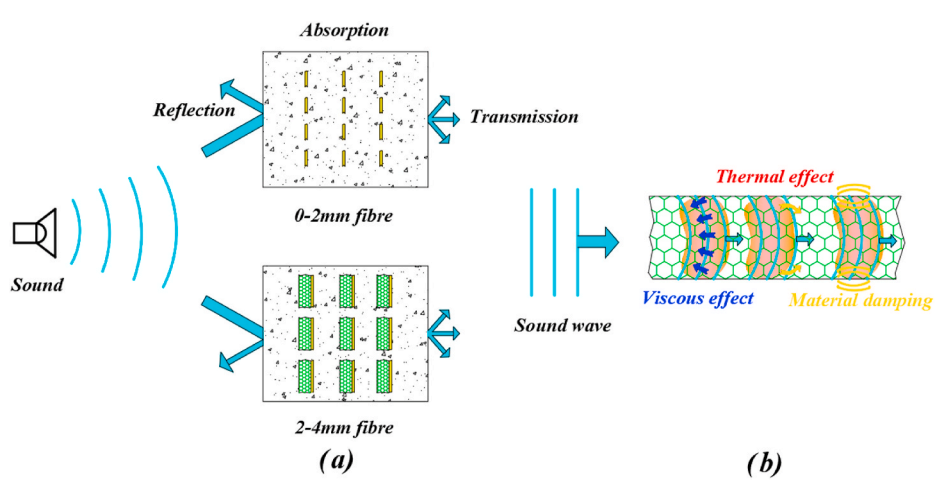

Fig. 11. Schematic diagram of mechanism of (a) sound absorption by ULMC (b) sound absorption by a single 2–4 mm MF.

areas with air molecules, thus considerably having a beneficial effect to dissipate sound energy. Moreover, acoustic waves can propagate through the 2–4 mm MF better than 0–2 mm MF because of the increasing amount of intra-particle porosity. Hence the sound absorption performance of ULMC with 2–4 mm MF is improved in low frequency. It is noteworthy that the intra-particle pores in 2–4 mm Miscanthus fibers further improve the connectivity between the inter-particle pores, thus increasing the consumption of acoustic energy by converting into thermal energy. However, for 0–2 mm MF, the shape is mainly outer shell with rigid surface, showing negligible function as an insulation material.

The scanning electron microscopy of ULMC fracture surface is shown in Fig. 12. It can be observed from Fig. 12 (a) that the inter-particle pores and intra-particle pores both exist in the ULMC matrix containing 2–4 mm MF, which is beneficial for the sound absorption of ULMC. The pores in the straw of Miscanthus are concentrated and also positively influence the acoustical absorption property of ULMC. However, for 0–2 mm MF shown in Fig. 12 (b), the smooth surface of the fibers has negative effect on the sound insulation properties of ULMC. The dense surface structure of 0–2 mm MF plays a significant role on reflecting the sound wave by the rigid surface.

The porosity of ULMC tested by vacuum saturation approach is presented in Table 5. It is obvious that the porosity increases with the incorporation of more 2–4 mm MF. The reference samples obtained the lowest porosity as 21.8% while the M30 reached the highest porosity of 28.0%. The increase in porosity is mainly attributed to the random distribution of Miscanthus fibers in cement matrix. The pores created in the mixing of the cement paste and fibers can increase thanks to the long and stiff Miscanthus fibers, and thus form voids between them. The pores are mainly in the size of millimetre and in combination with the intra-particle pores (micrometre sized), improving the sound absorption efficiency of ULMC.

Table 5
Porosity and 24 h water absorption of ULMC.

ULMC	Reference	M10	M20	M30
24 h water absorption (%)	13.2 ± 0.1	16.2 ± 0.2	19.4 ± 0.1	20.7 ± 0.3
Porosity (%)	21.8 ± 0.2	24.6 ± 0.3	26.1 ± 0.2	28.0 ± 0.3

Other lightweight concretes incorporated with plant fibers were also investigated by other researchers, for instance, hemp concrete, which is similar as Miscanthus concrete. Table 6 shows the sound properties of different kinds of bio-based sound insulation materials to make a comparison with the ULMC in this study. Hemp concrete made with starch binder can obtain sound absorption of 0.7 at 1250 Hz [38]. However, the strength of this material is very low (0.55 MPa). Lightweight concrete with sunflower stalk and corn stalks were also investigated but reaching a relatively low sound absorption coefficient compared to ULMC (see Table 6). The reason may be due to the different production approaches and properties of plant fibers. Gle's research indicated that sound absorption is affected by the pores of bio-based LWC, which is mainly a combination of micro pores in cement paste and intra-particle pores in plant fibers, and larger inter-particle pores between the fibers. Hence, the acoustic absorption of ULMC located among the high sound absorption of pure Miscanthus fibers, and the variation of the reference hardened concrete.

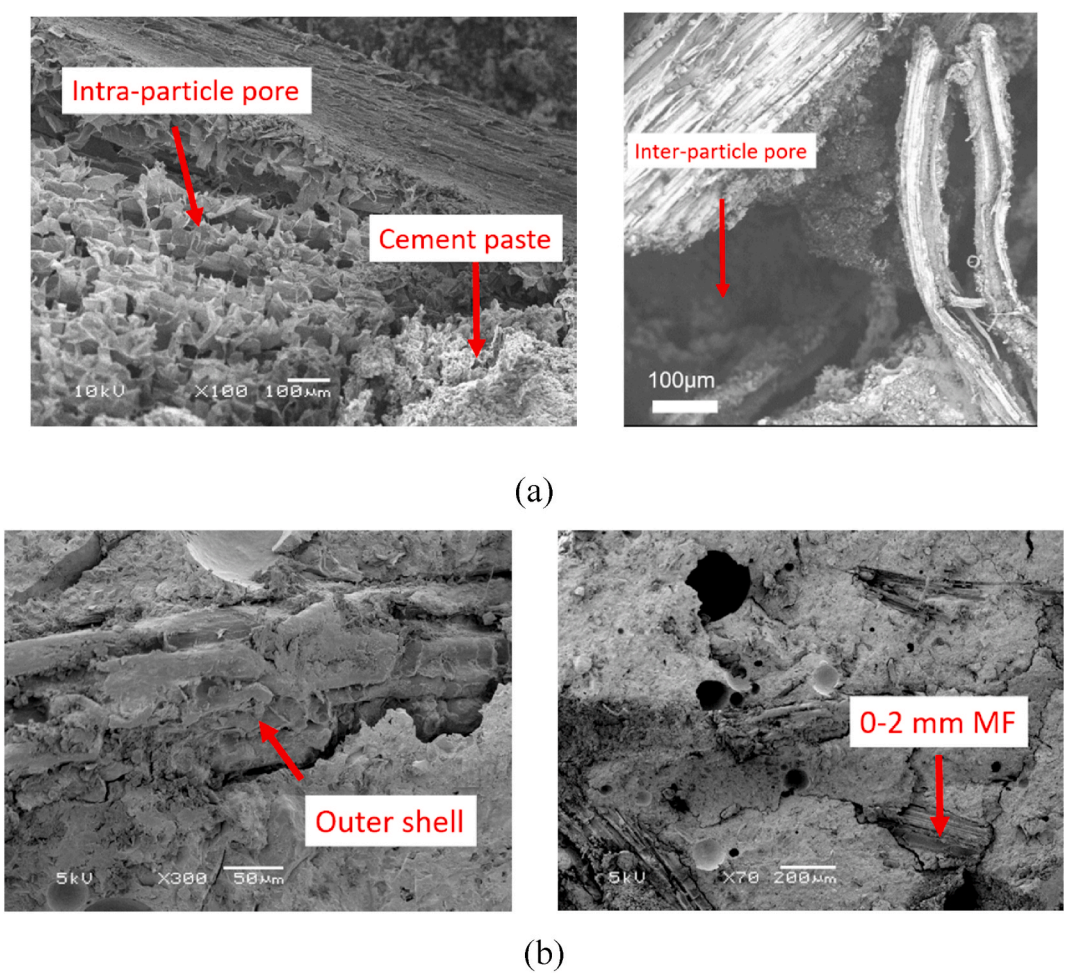

Fig. 12. SEM of fracture surface of ULMC (a) 2–4 mm MF (b) 0–2 mm MF.

Table 6
Sound absorption, compressive strength and density of several bio-based materials.

Bio-based materials	Sound absorption coefficient at a frequency (Hz)	Compressive Strength (MPa)	Density (kg/m^3)	Literature
M30-ULMC	0.9 at 800	2.99	554	This study
Hemp-Starch	0.7 at 1250	0.55	168	[38]
Sunflower-Chitosan	0.1–0.2 at 1000-2000	2.0	150–200	[39]
Hemp-GGBS	0.5 at 400-2000	NM	522	[40]
Hemp-lime[1]	0.5 at 600	NM	573	[41]
Hemp-lime[2]	0.9 at 1000	NM	180–300	[42]
Hemp-lime[3]	0.9 at 800	1.2	415	[43]
Hemp particles	1 at 800	0	120	[15]

GGBS: Ground granulated blast-furnace slag; NM: Not mentioned.

3.3. Thermal conductivity of ULMC

Thermal insulation property is a critical parameter in designing and applying lightweight concrete. The thermal properties of all the designed ULMC with different additions of MF are presented in Fig. 13. The thermal conductivity is decreased considerably with the increasing dosage of both kinds of MF. However, 2–4 mm MF shows more reduction on thermal conductivity of ULMC than 0–2 mm MF. The M2-30 ULMC reaches a thermal conductivity of 0.09 W/(m·K), decreasing 24.5% compared with the reference ULMC. However, for the sample M1-30, the reduction percentage is only 15.0%.

The reasons for the reduction in thermal conductivity are attributed to the porous structure and fibrous shape of Miscanthus fibers and also their influence on the packing of cement paste. When 30% MF substituted EWG in cement, it means the large amount of fibers will influence the internal packing of the ULMC. Generally, a less dense granular packing leads to better thermal insulation due to more air voids entrapped in the cement matrix. Therefore, more MF in mixtures indicates more air voids and less density of ULMC and consequently reduced thermal conductivity. Previous researches on thermal properties of lightweight concrete indicated that thermal conductivity is closely related to density and porosity of the concrete [8–10,44,45]. Secondly, the porous structure of 2–4 mm MF can introduce more voids in cement paste and act as a heat insulator, making the thermal conductivity of ULMC even lower.

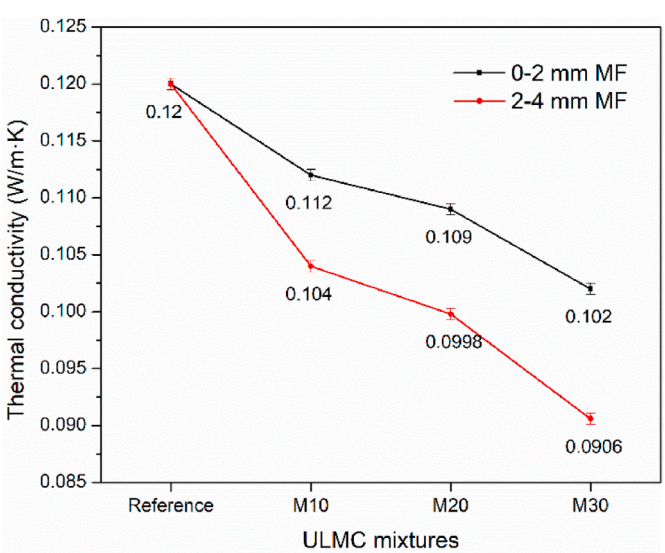

Fig. 13. Thermal conductivities of ULMC with the incorporation of MF.

The UPV test can show the inner voids and inhomogeneity of concrete without destroying the sample. The results of UPV test of ULMC are shown in Table 7. The UPV decreases significantly with the incorporation of 10% MF (2857–2490 m/s). This phenomenon is in accordance with the results from the porosity test. It is obvious that the more MF incorporated in concrete, the more air voids and inhomogeneity of concrete exist. Generally, UPV is the essential method to detect large pores in the aggregate and mortar interface. The 30% MF dosage ULMC obtained the largest number of pores as the UPV reaches the lowest value to 2142 m/s. Therefore, M30 obtains the best thermal insulation performance (0.09 W/m·K).

The schematic diagram of heat transfer in ULMC is illustrated in Fig. 14. Heat transfer analyser produces heat that is transferred by ULMC through three media: (1) cement matrix (2) expanded waste glass and (3) Miscanthus fibers. The thermal conductivities of a single particle of MF and expanded waste glass are 0.10 W/(m·K) and 0.07 W/(m·K), respectively [46]. However, the thermal conductivity of hardened cement paste is around 1.70 W/(m·K). Therefore, the reference sample already obtained a relatively low thermal conductivity than normal concrete since all the lightweight aggregates were EWG (0.12 W/(m·K)). However, Miscanthus fibers can further lower the thermal conductivity of ULMC even with a slightly higher intrinsic thermal conductivity. If it is assumed that the MF is a spherical shape similar to EWG, the thermal conductivity of ULMC should be slightly higher than the reference sample according to Ref. [47]:

$$K = \frac{k0v0 + k1v1\frac{3k0}{(2k0+k1)} + k2v2\frac{3k0}{(2k0+k2)}}{v0 + v1\frac{3k0}{(2k0+k1)} + v2\frac{3k0}{(2k0+k2)}} \quad (2)$$

This equation describes the heat transfer through composite materials including one continuous phase and two dispersed phases. K is the effective thermal conductivity of ULMC, k_0 is the conductivity of cement matrix, k_1 is the conductivity of EWG, k_2 is the conductivity of MF and v is the volume fraction of each phase respectively. However, there is a difference between the theoretical conductivity and experiment result. This is attributed to the fibrous shape of MF, leading to an interfacial thermal resistance (ITR) that can increase the thermal resistance of MF, thus reduce the thermal conductivity of ULMC [48]. As can be seen from the SEM shown in Fig. 12, the interface between cement matrix and Miscanthus fibers is not perfectly attached. Also, the aspect ratio of MF is much higher than EWG, indicating a larger contact area than EWG. Thus, the fibrous shape of MF can increase the interface thermal resistance (ITR) and function as a thermal barrier in cement paste, making the diffusion of heat more difficult. However, the contribution to thermal insulation from MF is quite small compared to its contribution to acoustical absorption of ULMC. The reason is the EWG obtains an internal core-shell structure that contributes to better thermal insulation for ULMC. Meanwhile, MF introduces the air voids and further increases the thermal resistance in ULMC, resulting in slight increase in thermal insulation.

Equation (3) defines the relationship between thermal conductivity and density is used:

$$\lambda = a0 \times e^{b0\times\rho} \quad (3)$$

Where λ is the thermal conductivity (W/(m·K)), ρ is the density (kg/m^3), and a_0 and b_0 are constant parameters. For instance, ACI committee suggest 0.072 W/(m·K) and 0.00125 m^3/kg for a_0 and b_0 [8]. In this study, the a_0 and b_0 are 0.022 W/(m·K) and 0.00258 m^3/kg respectively according to the thermal conductivities and dry densities of ULMC calculated from Table 5 and Fig. 7. The results are plotted in Fig. 15.

Table 7
UPV test of ULMC with 2–4 mm MF.

ULMC	Reference	M2-10	M2-20	M2-30
UPV (m/s)	2857 ± 8	2490 ± 15	2320 ± 6	2142 ± 32

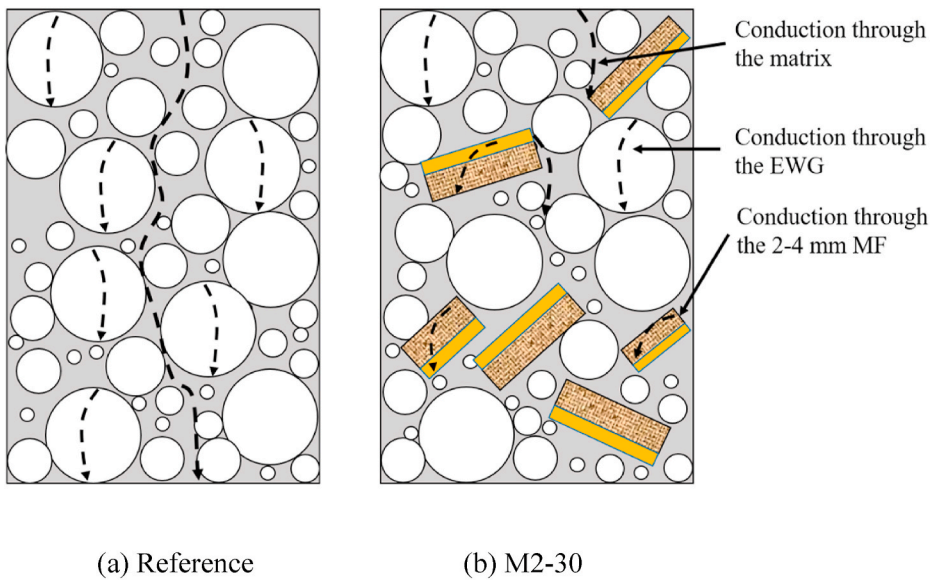

Fig. 14. Schematic illustration of mechanism of heat transfer by conduction in ULMC.

The relationship between thermal conductivity and compressive strength of different types of lightweight concrete is shown in Fig. 16. Almost all the LWC presented here, a positive relationship between thermal conductivity and compressive strength is observed. The ULMC presented in red obtain higher compressive strength than other kinds of lightweight concrete having the similar thermal conductivity, for instance, foam concrete and porous concrete [49]. Other lightweight concrete with the use of pumice, tuff and diatomite, since the production method is quite different, thus the density is beyond the upper limit of ULWC (800 kg/m^3) [50]. It is important to choose the suitable lightweight aggregate and mix design to produce ultra-lightweight concrete. Therefore, it can be concluded the developed ULMC has a better performance in thermal insulation, while possesses moderate compressive strength at the same time.

3.4. Comparison with other lightweight insulation panels

There exist different kinds of insulation panels on the market, in which the most popular materials are gypsum, glass wool and foam for drop-ceiling boards or non-structural walls. In some scenarios, these materials are used to produce layered structures, for example, a sandwich structure consisting of glass wool and gypsum board. These materials possess low thermal conductivity and high acoustical sound absorption, however, with a high CO_2 footprint during production and sometimes harmful to health. For instance, high temperature involved during glass wool preparation. Specifically, natural sand and recycled glass are mixed and heated to 1450 °C to produce glass. Moreover, complex production method like connection of each fibers by using resin and further heated at 200 °C and calendared to provide strength are needed. For the harmful aspect, glass wool used for insulating appliances appears to produce human disease that is similar to asbestosis, which can cause respiratory problem or irritation to the eyes [51].

The bio-based ULMC possesses comparable or better thermal insulation and acoustical absorption capability to the traditional insulation boards. Moreover, it has better ecological advantages by using waste Miscanthus fibers as lightweight aggregate. Since Miscanthus fiber itself is a widely available natural resource in Europe, so the cost and energy consumption are much lower than commercial lightweight materials.

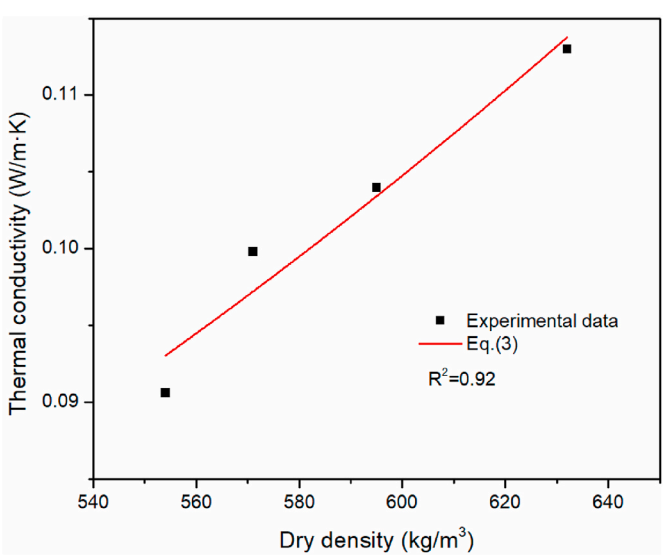

Fig. 15. The thermal conductivity versus dry density of ULMC.

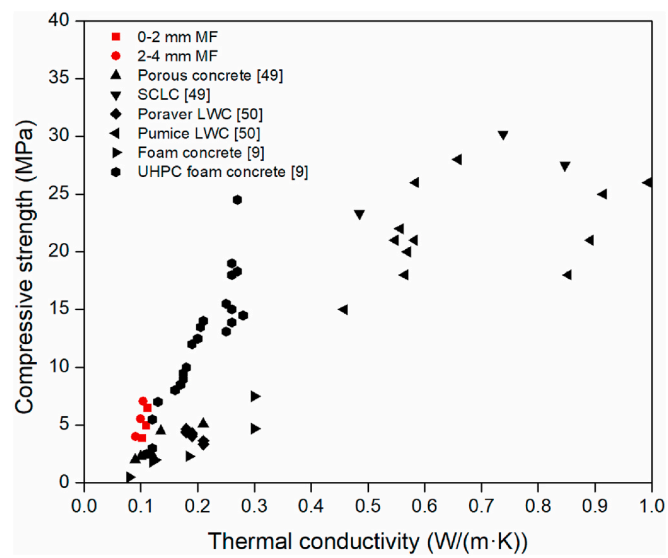

Fig. 16. Thermal conductivity versus compressive strength of different kinds of LWC.

Moreover, thanks to the CO_2 sequestration during Miscanthus growth, this results in a carbon dioxide equivalent mitigation potential of 117% [52]. Furthermore, the porous structure in the stem can function as insulating cells in the ULMC. Therefore, applying MF in ULMC shows much better ecological potential than traditional insulation boards.

4. Conclusions

This paper presents the research of developing ultra-lightweight Miscanthus concrete (ULMC) incorporating Miscanthus fibers (MF) and expanded waste glass (EWG), with the extra efforts on the effects of different format of MF on acoustic absorption. Acoustic absorption coefficient of ULMC is greatly improved to 0.9 at low frequencies by the incorporation of 2–4 mm Miscanthus fibers. Moreover, the thermal conductivity of ULMC decreases to 0.09 W/(m.K) by the contribution of both EWG and MF. Overall, the developed ultra-lightweight Miscanthus concrete (ULMC) can help to reduce environmental impact and to function as indoor insulation and as lightweight material for heat and noise insulation. According to the current results, the following conclusions can be drawn:

- The addition of Miscanthus fibers in cement matrix decreases the density and compressive strength of ULMC, while the flexural strength remains stable. 2–4 mm MF has a better performance than 0–2 mm MF in terms of enhancement of the flexural strength.
- An increasing percentage of 2–4 mm MF leads to a higher acoustic absorption coefficient of ULMC with a wider frequency band. To obtain a high sound absorption above 0.5 at frequencies of 600–1200 Hz, the incorporated MF percentage in the ULMC mixture should be more than 20% 2–4 mm MF. However, 0–2 mm MF has negligible effect on acoustic absorption of ULMC due to the dense surface structure.
- The thermal insulation performance of ULMC slightly improves because more air voids and interfacial thermal gaps are introduced by the fibrous Miscanthus particles. UPV test shows the large pores exist in the interface of fibers and cement matrix. The lowest thermal conductivity of ULMC reaches 0.09 W/(m·K).
- The main LWAs adopted to prepare ULMC are the expanded Miscanthus fibers and expanded waste glass, indicating a novel approach to efficiently recycle the waste biomass and waste glass, contributing to the sustainable development of cement and concrete industry.

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.

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