Jurnal
Teknologi

Full Paper

STRUCTURAL BEHAVIOUR OF COIR FIBRE-REINFORCED FOAMED CONCRETE WALL PANEL SYSTEM

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Article history
Received
7 July 2015
Received in revised form
3 November 2015
Accepted
3 March 2016

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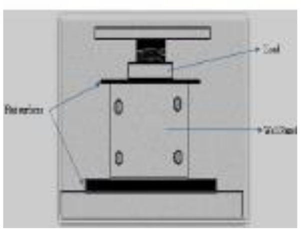
Graphical abstract



Abstract

Lightweight foamed concrete (LFC) can be modified to have a reliable amount of compression protection, making it possibly to be used in low-rise building as load-bearing walls. LFC with coir fibre has experienced massive improvement in its strength compared to the normal LFC. Therefore, this particular investigation explores the contribution of coir fibre in the lightweight walling construction in terms of structural behaviour under axial compression. Fundamental steps need to be carried out to investigate thoroughly its behaviour before this innovative product can be used in practice. Coir fibre has potential to be used as replacement for the coarse aggregate in concrete to produce structural concrete. The experimental results shown that when 1400kg/m^3 and 700kg/m^3 density samples were associated to become one single solid concrete, the total density will be reduced and the thermal performance of the concrete will be enhanced. In this case, the panel recorded higher strength under compression than the control specimen. Due to the integrity of the reinforcing agent, the panel yielded better enhancements in the structural behaviour because natural fibres have strong resistance upon compression.

Keywords: Foamed concrete, structural behaviour, low rise construction

Abstrak

Konkrit ringan berbusa boleh dimodifikasi untuk mempunyai kekuatan mampatan yang baik di mana perkara ini membolehkan ianya diaplikasi untuk pembinaan dinding tanggung beban untuk bangunan rendah. Konkrit Ringan berbusa dengan gentian sabut kelapa memberikan keputusan yang baik dari aspek kekuatan mampatan jika dibandingkan dengan Konkrit Ringan berbusa tanpa sebarang bahan tambah. Oleh itu, kajian ini khususnya meneroka sumbangan gentian sabut kelapa dalam pembinaan dinding ringan dari segi tingkah laku struktur bawah mampatan paksi. Langkah asas perlu dijalankan untuk menyiasat dengan teliti tingkah laku sebelum produk inovatif ini boleh digunakan dalam praktis sebenar pembinaan. Serat sabut kelapa mempunyai potensi untuk digunakan sebagai pengganti agregat kasar dalam konkrit untuk menghasilkan konkrit struktur. Keputusan eksperimen menunjukkan bahawa apabila sampel berketumpatan 1400kg/m^3 and 700kg/m^3 dikaitkan untuk menjadi salah konkrit pepejal tunggal, jumlah ketumpatan akan dikurangkan dan prestasi haba konkrit akan dipertingkatkan. Dalam kes ini, panel itu mencatatkan kekuatan yang lebih tinggi di bawah mampatan daripada spesimen kawalan. Oleh kerana integriti ejen pengukuhan, panel menghasilkan keputusan yang lebih baik dalam tingkah laku struktur kerana gentian asli mempunyai rintangan yang kuat terhadap mampatan.

Kata kunci: Konkrit ringan berbusa, tingkah laku struktur, pembinaan bangunan rendah

1.0 INTRODUCTION

Lightweight foamed concrete (LFC) is also known as porous concrete and it is noticeable because of its favorable characteristics. It is highly flow ability, low self-weight, controlled low strength and excellent thermal properties. Though LFC has very low strength when compared to conventional concrete, but it shows better response in thermal and acoustic properties. One of the interesting characteristics is the density of LFC can be changeable depends on the applications. Previous studies shows that the dry density of LFC is varied from 400kg/m3 to 1600kg/m3 and range of compressive strengths is from 0.5 – 10N/mm^2 [1]. Its 87% to 23% lighter than conventional concrete. According to (Liew,2005) there are several ways to reduce the density of concrete by using lightweight aggregates, foam, high air concrete and no-fine aggregate. Density of LFC depends on the amount of foam added into the mix by foam generator. It lessened the dead load and lighter when compared to conventional concrete [2].

Higher air content within the LFC will result in lower density, higher porosity and decrease of strength. The bubbles are sized typically 0.3-0.4mm diameter enclosed by cement. The stability of foam is actually created by these bubbles in foamed mortar. Meanwhile, the bubbles produced from the foam machine will replace the coarse aggregates and lead to reducing of density and compressive strength as well. The air voids in low density are typically bigger than in high density because of the dosage of foam added. The high amount of foam will generate more continuous pores within the concrete meanwhile less and rarely continuous pores in high density as shown in Figure 1.

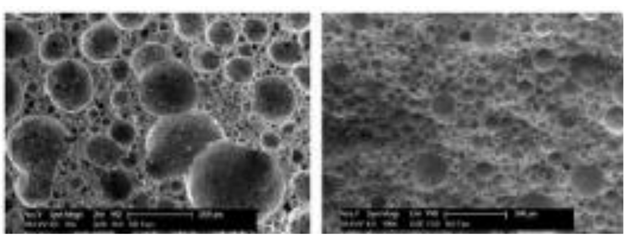


Figure 1 Air voids in 500kg/m^3 (left) and 1000kg/m^3 (right) [3]

LFC possess more advantages in terms of its properties compared to normal strength concrete. It has faster building rate in construction industry and also reduction of dead load. Since LFC is light in weight, it has low handling cost and lower haulage. Advantage of lower density LFC is excellent thermal conductivity which can gives better insulation properties in terms of fire and sound absorption due to the cellular microstructure [3]. Thermal conductivity of a LFC sample with density of 1000kg/m^3 is reported to be one-sixth of the value of common cement-sand mortar [4]. The values of thermal conductivity are 5-30% of those recorded on normal weight concrete and the range between 0.1 W/mK and 0.7 W/mK for dry densities of 600-1600kg/m^3. LFC classified to be less efficient than denser concrete in reducing the transmission of air-borne sound [5]. Normal weight concrete tends to deflect sound waves, meanwhile LFC absorbs it, thus LFC has higher sound absorption capacity. The cellular concrete does not contain significant acoustic insulation characteristics [6]. On the other hand, LFC also has its disadvantages as shown in table below. Table 1 shows the advantages and disadvantages of LFC.

Table 1 Advantages and disadvantages of LFC

Advantages	Disadvantages
Rapid and relatively simple construction	Very sensitive with water content in the mixture
Economical in terms of transportation as well as in reduction of manpower	Difficult to place and finish because of the porosity and angularity of the aggregate. In some mixes, the cement mortar may separate the aggregate and floats towards the surface
Significant reduction of overall weight results in saving structural frames, footing or piles	
Most of lightweight concrete have better nailing and sawing properties than stronger conventional concrete	Mixing time is longer than conventional concrete to assure proper mixing

LFC is a lightweight, cost effective, easy to fabricate with good workability excellent performance on thermal and acoustic insulation, fire resistance and shock absorption [7] but unable to perform well structural applications due to its low compressive strength. Several researchers previously have investigated the fine aggregates inclusion in the mortar matrix to enhance the mechanical properties of LFC (Jones and McCarthy, 2000). However, the studies on the utilization of fiber-reinforcement in LFC are very limited [8]. Due to the concerns on sustainability, LFC wall panels provides many benefits such as good thermal properties and resource efficiency. LFC became an ideal core material for composite sandwich structures because of its low density and low strength.

Flexural performance of composite panels produced by carbon fibre reinforced polymer (CFRP) face sheets and aerated autoclaved concrete (AAC). Structural system is depending on the approach of a sandwich fabrication with tough FRP composites layers bonded in inner AAC panel [9]. Combination of FRP and AAC, which is lightweight in nature, has promising to be used for faster fabrication of panelized application, alleviation of disaster, to reduce manpower in construction. Previously, CFRP has been used with normal concrete and was observed to provide ability of phenomenal reinforcement. Compressive strength of polypropylene fibre reinforced concrete has increased about 52% when compared to control LFC.

Arisoy and Wu [10] investigated on the polyvinyl alcohol (PVA) fibre as reinforcing agent in aerated concrete with density of 800-1600kg/m^3. As a result, they have found that fibre-reinforced aerated concrete experienced an increment in flexural strength, flexural ductility The application of Alkali-activated Ground Granulated blast-furnace Slag (AA GGBS) can be widen for sustainable varieties of precast masonry materials and cast in place structural fill [11]. Oil palm shell foamed geopolymer concrete (OPSFGC) with densities of 1300kg/m^3 and 1500kg/m^3 could be mentioned as insulating and structural, Class II. However, OPSFGC, Class I structural grade concrete with density of 1700kg/m^3 possess compressive and thermal conductivity as 30MPa and 0.58W/mK respectively [12].

Yasar *et al.* [13] established a structural lightweight concrete produced by fly ash as mineral additives and basaltic pumice as aggregates. They have discovered lightweight concrete with dry density of 1850kg/m^3 and 25MPa compressive strength, in which contained 20% of fly ash as cement replacement by weight basis. Current sandwich panels made up by two stiff facings with separation and bonded strongly with the centre core lighter weight and weaker material. According to Tang *et al*., [14], the structural behaviour of a concrete can be identified by the mode of failure, bond-slip relationship and bond strength. In addition, Finite Element Analysis (FEA) of reinforced structural materials and sandwich panels were studied by Pokharel and Mahendran [15] and Khalfallah and Ouchenane [16]. The effective bond performance between steel sheets or reinforcing bars and concrete elements must take into consideration when producing its reliable analysis. Kayali, 2004 reported the bonding between concrete steel elements is one of the crucial properties that leading to the better functioning of a composite panel. Chemical bonding and friction forms between steel sheeting and concrete as a result of surface effects will mainly contribute to the strength of bonding.

Furthermore, the use of LFC in composite action with steel sheeting in lightweight composite walling construction was investigated by Mydin and Wang, [17]. Two series of tests were conducted on composite wall panels consisting of two outer skins of profiled thin-walled steel sheeting with LFC core under axial compression, thickness of 0.4mm and 0.8mm respectively [18, 19]. The pressure on the steel sheeting much more lower than normal strength concrete during construction due to lower density of LFC, so that it allows thin steel sheet to be used [20].

2.0 EXPERIMENTAL SETUP

LFC was found to have consistently good compressive strength, giving it potential as a load bearing wall material. This section presents the procedures of the investigation on the LFC wall panel with an infill core under axial compression. Figure 2 shows the prototype of the LFC sub-panel and joined wall panel. Two sets of prototypes of each mix were cast in order to investigate the structural performance when load is imposed on them. Prototypes of 0.675m x 1.5m LFC wall panel were cast in the size of 0.3m x 0.3m as shown in Figure 3. The thickness remains constant, while the height and width were reduced to accommodate the sample in the compression machine (Universal Testing Machine).

The strength of this prototype will determine the properties of the big scale LFC wall panel. As the first step, an experimental approach to the behaviour of the normal LFC wall panel was assessed as a control specimen, followed by the fibre-reinforced LFC wall panel. The detailed data comprising of the preliminary results, observations and behaviour were analysed to determine the strength of the prototypes. The wall panels were tested 28 days after casting. The top and bottom of the samples were placed flat prior to the test to ensure equal load distribution as shown in Figure 4. Observations were made on the general behaviour and also on the cracks on the concrete. Also, the buckling on the concrete and the pattern of the failure mode based on the graph were recorded for further analysis.

Figure 2 The prototype of LFC sub-panel and joined wall panel

Figure 3 Prototypes of LFC wall panel after curing process

Figure 4 Compression test of prototype of LFC wall panel

Figure 5 shows a prototype of the LFC wall panel which was mechanically joined for structural test. The infill between the wall panels should be taken into consideration. When the 1400kg/m^3 and 700kg/m^3 samples were associated to become one single solid concrete, its density was reduced and the thermal performance of the concrete enhanced. Figure 6 shows the arrangement of the wall panel for the compressive test.

Figure 5 Overview of the prototype of the LFC wall panel

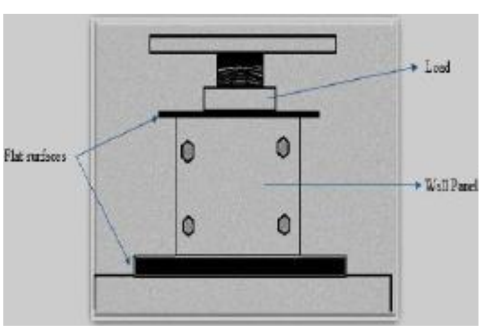


Figure 6 Front elevation of wall panel test up for structural performance

3.0 RESULTS AND DISCUSSION

3.1 Compressive Strength

The structural behaviour of FRLFC consisting of two panels with infill core material was explained in detailed under axial compression in this study. A control LFC wall panel was investigated as well to carry out a clear analysis of the comparable data for the performance of the wall panel. The following are the discussions on the detailed behaviour and effects of coir fibre as an additive on the LFC walling system. Also, the failure mode and failure load were obtained and recorded from the investigation. Table 2 shows the results of the compressive tests conducted on both wall panels.

Table 2 Compressive strength of the samples

Sample	Reference	Total density (kg/m^3)	Breaking load (N)	Compressive strength (N/mm^2)
Coir fibre-reinforced LFC wall panel	FRLFC	1320	288319.3	6.507
Normal LFC wall panel	NLFC	1320	214647.0	4.769

Based on the investigation, it can be seen that FRLFC recorded higher strength under axial compression than the control specimen. Due to the integrity of the reinforcing agent, FRLFC yielded better enhancement in structural behaviour because natural fibres have strong resistance upon compression. The strength and bonding between the particles of the LFC wall panel were improved with age. These sandwich panels were kept for 28 days in room condition for the curing process to develop the bonding and allow the concrete to strengthen up. Panels also were left in an ambient surrounding for some days to dry out. Coir fibre as reinforcement in the LFC wall panel had high failure strain which is able to provide a better compatibility between the fibres and the matrix. In both cases, the sample was able to sustain its maximum load which was applied during compression. However, FRLFC yielded 27% better improvement in strength before it reached failure than the normal LFC wall panel due to the addition of the reinforcing agent. The FRLFC sample attained ductile mode before it reached failure mode; meanwhile, the control sample without any reinforcement attained fragile mode at the plateau regime [21].

As mentioned earlier, the strong bonding between the coir fibre and the matrix enhanced the shear strength of the concrete. Mechanical connectors such as screws and nuts held the panels strongly even after they reached failure, thus enabling them to withstand the applied force. The control sample exhibited more brittle failure than the

FRLFC after reaching peak strength because it weakened the solid skeleton by shrinkage due to the absence of reinforcing agents and the increase in porosity. In addition, the crack progression conditions, such as location, direction and shape of the LFC wall panels were similar in both cases but different in the impact by the force applied during the experiment. In this case, fibres which were spread randomly could control the widening of cracks when being compressed and control the shrinkage of the concrete. It indicates a good cohesion between the fibres and the matrix and the wall panel was strengthened by reinforcement. Figure 7 and Figure 8 show the difference in the cracks which were formed after the samples reached failure.

Figure 7 The transformation of the cracks during failure mode on the control specimen

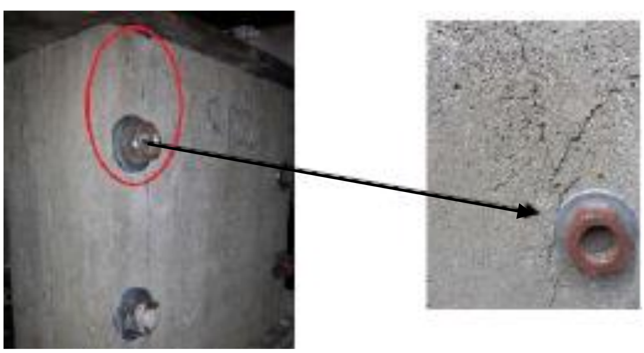


Figure 8 Small cracks on the surface of the FRLFC

It did not cause the sample to break apart because it reacted as an anti-micro crack agent. The fibre can be stretched beyond its elastic limit without rupture due to the helical arrangement of the micro fibrils [21]. Based on the data obtained, it can be concluded that FRLFC possess lower strength than normal weight concrete but its strength can still be considered relevant. The highest mechanical strength was produced with the reinforcement coir fibre as it had a large diameter and high concentration of lignin. Since it was extracted from matured coconuts, it had more lignin and less cellulose, making it stronger and durable when compared to other the fibres [22]. Even though unable to be used as the main structural elements in buildings, but it is still promising for other applications such as non-load bearing wall and floors. Nevertheless, it is necessary to gain information on its structural behaviour before it is considered as a load bearing element in building construction by conducting further investigations to quantify its strength and fire resistance. LFC would be less demanding due its lower natural strength than normal weight concrete. Additives and modifications used in the walling system will be established for future application in building constructions.

3.2 Mode of Failure

Observations were made on the general behaviour of the panel including concrete cracks and failure mode. Figures 9 and 10 present the load versus displacement graphs for the control specimen and FRLFC.

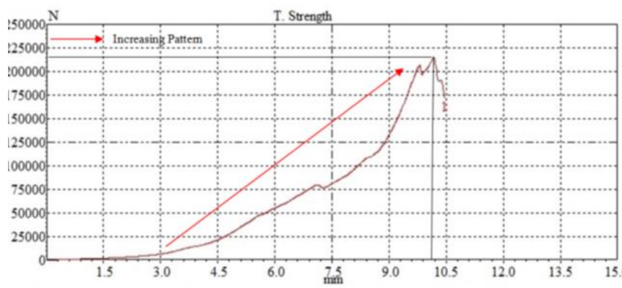


Figure 9 The load (N) versus displacement (mm) graph for control LFC wall panel

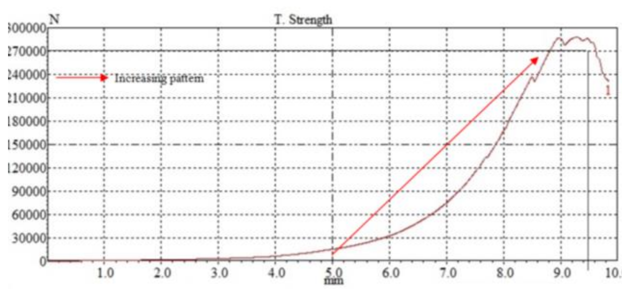


Figure 10 The load (N) versus displacement (mm) graph for FRLFC

The top and bottom of the prototype were placed flat in the machine prior to testing to ensure the distribution of equal load throughout the sample. Fracture patterns highlight the differences between the failure modes of the specimens. The figures above show the maximum strength (ultimate load) yielded by the prototypes of the control LFC wall panel and FRLFC. In both cases, the test samples were able to sustain the maximum load applied for considerable axial deformation. The displacement recorded for both samples to reach failure mode is almost similar but different amount of forces were obtained. The control specimen reached early failure under lower force and was unable to withstand with pressure exerted when compared to FRLFC. However, both specimens showed an initially linear reading, and after certain displacement the graph experienced an increasing pattern where the load increased gradually by means of a compression machine until it reached its peak strength.

The linear line at the beginning corresponds to the un-cracked stage of the walls, and the following pattern describes the performance of the wall panels until yielding its optimum strength. Based on the graphs above, a drastic increment in load was recorded after 3.0mm in the control specimen, meanwhile in FRLFC, that occurred at 5.0mm. The control specimen without any reinforcement experienced a sudden fall in strength with excessive compression at failure. The load applied on it was continuously increased after the first minor drop at 7.2mm, to attain its optimum strength at plateau regime. There is a small variation in the displacement between the first minor drop and the peak strength of the control LFC wall panel before a sudden decrease in load. The graph shows excessive load was applied after a certain displacement and minor cracks started to emerge on the surface of the panel during that period. At this stage, it was recorded that the load was higher than the initial minor drop in the load based on the graph. It was observed that the initial cracks occurred at the side of the panels near to the joiners and held vertical direction as well. Further cracks started to appear following the first one at the middle front surface. It developed into larger cracks as the load was increased and finally stopped at the peak strength. Figure 11 and Figure 12 show the failure pattern on the surface of the control specimen and FRLFC.

Figure 11 (a) Cracks on the side and (b) middle surface of the control specimen

Premature failure was observed, which was related to pore distribution and larger air voids during casting as confirmed during post-experiment observations. The development of cracks was more vigorous on the side of the face of the panels than in the middle portion. As expected, the maximum strength of the FRLFC wall panel was attributed to the reinforcement of fibres. In both cases, the failure was initiated with the formation of minor cracks and followed by the crushing of the panels. It was found that failure of FRLFC was localized around tiny cracks on the surface of the panel without any significant damage on the rest of the section before failure and was due to fibre reinforcement.

Figure 12 (a) Cracks on the side and (b) middle surface of FRLFC after failure

The panel attained more ultimate strength than the control LFC wall panel and experienced quite smooth drop of load between 9.0 and 10.0mm displacement. At almost a similar displacement, the maximum force exerted on FRLFC before failure was larger than the control sample due to the reinforcing agent. The cracks initiated at the connectors at the right side and it developed vertically and reached the bottom of the panel in correspondence to the loading point as shown in Figure 13.

Figure 13 (a) Small cracks on the surface of FRLFC (b) Wide cracks on the control specimen

After a series of cracks was formed, it was observed that FRLFC sustained the maximum load for a very short displacement before failure. Fibre reinforcement changed the brittle failure behaviour of the sample into ductile elastic behaviour. The variation was caused by the increased capacity in the strength of the coir fibre, which can lead to the change of the failure mode. It can be concluded that due to the integrity of fibres, the wall panel achieved a higher peak strength compared to the control specimen, reducing the cracks formed on the face of the wall panel, and that the development of the densification of fibres is related to the maintenance of that specimen after failure. During the formation and widening of shear cracks, the coir fibres that bridged these cracks provided resistance to this cracking action due to the fibre reinforced mechanisms. Contribution to the shear resistance offered by the internal fibre will strengthen the wall panels. This investigation has provided general information on the properties and failure of these samples. Both FRLFC and the control sample have showed different patterns of failure on its surface when being tested under axial compression. Figures 14 and 15 show the condition of the infill materials of both the control and coir fibre wall panels post experiment.

Figure 14 The condition of the infill material of the control LFC wall panel

Figure 15 The condition of the infill material of FRLFC

The most attractive feature is that the use of infill materials on both panels considerably provides many useful benefits. It is important to study the influence of the infill materials for the bonding between the wall panels. The main aim of adding an infill mix is to enhance the thermal performance in the LFC wall panel. However, it also plays a vital role in providing better compatibility and acts as a binder for the two sub-panels. Figure 16 shows that the sample is able to stand without any mechanical connectors as the infill acts as an interconnector between the two sub-panels and provides them a better bonding.

Figure 16 The sample without any mechanical connectors

It was observed post experiment that the infill material was able to hold the panels together to enable them to resist the applied load. The bond between these panels should be considered. With low density, it provides good compatibility and increases the interaction between the panels, thus enhancing the properties due to the fibre inclusion compared to the control specimen. Figures 17 and 18 show the conditions of infill mix in both samples.

Figure 17 The bonding between fibres and particles in the infill

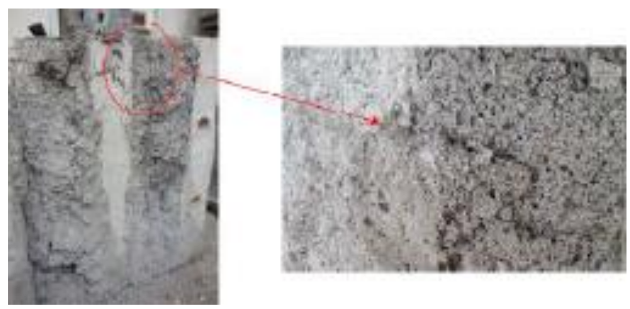


Figure 18 The bonding of infill material without any reinforcements

Both infill materials carry the least compressive strength in the system to be able to hold back the force due to its low density. Moreover, no single crack was observed in the infill material from a plan view. Even the cracks formed on the wall panel do not affect the stability of the infill material. In FRLFC, the infill mix offered better resistance to the occurrence of micro spalling when compared to the control specimen. The coir fibre acted as aggregates in the mix and therefore contributed in protecting the crack openings. Meanwhile, in the control specimen, the infill was observed to be crushed when dismantled due to the loose bonding between the particles. Figures 19 and 20 below show the condition on the internal surface of both FRLFC and the control specimen after being dismantled.

Figure 19 The condition of the control sub-panel after dismantling

Figure 20 The condition of the FRLFC sub-panel after dismantling

4.0 CONCLUSION

Based on the investigations, the following conclusions were made with the experiments and analysis on the structural and fire resistance performance of lightweight foamed concrete (LFC) wall panels with coir fibre. Coir fibres are abundantly available, low in density, biodegradable, recyclable and relatively cheap compared to various natural fibres, so that it can be used in the LFC products to enhance its behaviour in terms of strength. When 1400kg/m^3 and 700kg/m^3 samples were associated to become one single solid concrete, the total density will be reduced and the thermal performance of the concrete will be enhanced. In this case, FRLFC recorded higher strength under compression than the control specimen. Due to the integrity of the reinforcing agent, FRLFC yielded better enhancements in the structural behaviour because natural fibres have strong resistance upon compression.

Acknowledgement

The authors would like to thank the funding bodies of this research: Universiti Sains Malaysia under USM Short Term Grant. No. 304/PPBGN/6312147.

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