STRENGTH PROPERTIES OF LIGHTWEIGHT FOAMED CONCRETE WITH STEEL FIBRE

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Abstract

The advancement in lightweight cementitious composite strength enhancement has promoting the usage of lightweight material across modern construction industry. Likewise, lightweight foamed concrete (LFC) was introduced as an alternative material in the construction industry due to its properties including good thermal and sound insulation, lighter in weight and cost-effectiveness. In corresponded to LFC strength issue which often found to be diminished due to its lower density and porous structures. Studies have shown that the incorporation of steel fibre into concrete can recover the diminished strength of lightweight foamed concrete. Hence, this research focusses on the strength properties of LFC incorporate with 30 kg/m^3 of steel fibre. Three types of LFC were prepared in this study including a trial mix of LFC (LFC-TM), a control mix of LFC (LFC-CTR), and LFC with 30 kg/m^3 steel fibre (LFC-30SF). The LFC-CTR and LFC-30SF were cast based on the obtained optimum water-to-cement ratio from the plotted performance index graph, which was 0.56 for both mixes. The fresh properties of LFC-CTR and LFC-30SF were determined based on the result obtained from fresh density, flow table and inverted slump tests. Besides, the strength properties studied for LFC-CTR and LFC-30SF were compressive strength, splitting tensile strength and flexural strength at 7, 28 and 56 days after curing. From the test results obtained, the compressive, splitting tensile and flexural strength of LFC was found to be improved by adding the steel fibre into the mix. As for the fresh properties of LFC, the stability was found to decrease after the steel fibre was added into the mix, while the flowability and consistency was observed with an improvement subject to fibre addition. In short, incorporating steel fibre can improve the strength properties of LFC, which driving their usability and encouraging wider adoption across modern industries.

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1.0 INTRODUCTION

As one of the major components in construction sector, concrete behaviours are highly dependent on the mixing proportions of raw materials and the type of raw materials used. Other than that, concrete can be categorised base on density into ordinary normal weight concrete, heavyweight concrete, and lightweight concrete. Likewise, lightweight concrete refers to low density concrete produce through artificial modification on its matrix, which normally has a density value ranges from 300 to 2000 kg/m^3 (Hedjazi, 2019). The lightweight concrete can be produced using lightweight aggregate, artificial entrained air, or a foaming agent, and is commonly used in construction because it is thermally and acoustically insulating, lighter, and more cost-effective.

Lightweight foamed concrete (LFC) is a cellular concrete made by entraining the foam into cement mortar using a suitable foaming agent (Brady, Watts, and Jones, 2001). The foam can be formed by mixing the foaming agent gently in the plastic cement mortar, or it can be formed by aerating the foaming agent before being added to the mixture (Alonge and Ramli, 2013). Around 20% volume of foamed concrete contains entrapped air pores caused by the entrained foam in mortar slurry. However, coalescence can result in much larger voids, especially at the top of pours, thus making the LFC high-strength development more challenging. The application of LFC is commonly found in the construction industry nowadays. Therefore, LFC is useful in the construction industry as it brings many benefits. There are several advantages of LFC, i.e. LFC is lighter than ordinary concrete. Artificially incorporating foam into plastic mortar reduces concrete density. The density has decreases because the amount of concrete has increases (Swati, 2020). The LFC is a highly porous microstructure (Elrahman *et al.,* 2021). This microstructure has caused the LFC to be light in weight, so the adjacent sub-structure is not subjected to much vertical stress. LFC has lower heat conductivity than ordinary concrete. This is due to microscopic air voids inside having low thermal conductivity. Hence, LFC can reduce the heat conducted through it and lower the temperature of a building. The LFC also has better fire resistance and good sound insulation compared to normal cement. Sound waves cannot pass through a void medium. Consequently, sound wave energy may become trapped within voids or empty areas (Lim *et. al,.* 2021). LFC has water retention properties. The LFC contains multiple air bubbles, which cause a high percentage of porosity. LFC also has a low permeability coefficient. Next, LFC has high resistance to freezing and thawing. The microscopic air bubbles have caused void structures in hardened concrete. The concrete's internal stress is reduced during the freezing and thawing. As a result, the cracking of concrete will not occur easily. LFC is more economical than the normal concrete. The cost of manufacturing LFC is lower because the foam entrained into plastic mortar will increase the volume of concrete. Besides, the construction cost will decrease as the material used is decreased. On top of that, the LFC is easier to transport and handle than normal concrete. Hence, the transportation fees will be economical.

The usage of fibre as an additive to concrete is increasing nowadays. Fibre reinforcement concrete (FRC) is utilised extensively in construction due to its characteristics and application. The inclusion of fibre in concrete has brought advantages to its properties. Fibre-reinforced concrete has more crack and shrinkage resistance than conventional concrete. As a matter of fact, the fibres in concrete are distributed throughout the concrete at relatively small spacing, which provide uniform resistance in all directions (Rao and Rao, 2014). On top of that, fibre-reinforced concrete will have higher ductility due to the uniform distribution of fibre in concrete (Yao, Li, and Wu, 2003). Besides, some fibres also increased the mechanical strength of concrete. Fibre act as a reinforcement component when incorporated into concrete to improve its performance. Fibres are commercially accessible and made from steel, plastic, glass, and other natural materials (Behbahani, Nematollahi and Farasatpour, 2013). Steel fibre is one type of the fibre that widely used in the production of fibre reinforced concrete. In the manufacturing of fibre-reinforced concrete, steel fibre is a common type of fibre. There are a few types of steel fibre, such as corrugated steel fibre, twisted steel fibre, hooked-end steel fibre and straight fibre (Larsen and Thorstensen, 2020). Steel fibres are available in various shapes and sizes, with lengths ranging from 0.25 in. to 2.5 in. (0.6 cm to 6.4 cm) and diameters ranging from 0.02 in. to 0.04 in (0.05 cm to 1.0 cm). In producing steel fibre-reinforced concrete (SFRC), the amount of fibre used is often expressed as a percentage or volume fraction. The different volume fractions of steel fibre will produce different behaviour in SFRC.

In this research, the steel fibres used are discrete, short, with an aspect ratio range of 20 to 100. The added steel fibre in fresh concrete can improve the shear resistance, toughness and assist in crack control (Chanh, 2015). Hence, the introduction of steel fibre into LFC was expected to recover the diminished strength in LFC.

The optimum water to cement ratio of LFC-CTR and LFC-30SF were obtained by selecting the peak performance index from the compressive strength tests on LFC-TM. Besides, the engineering strength properties of LFC-30SF, regarding compressive strength, splitting tensile strength and flexural strength, were investigated through standardize testing method. While the influence of steel fibre on the fresh properties of lightweight foamed concrete, including its flowability and stability were examined as well.

2.0 MATERIALS AND METHODOLOGY

2.1 Materials

The materials used in this research including Orang Kuat Ordinary Portland Cement, fine aggregates passing (600 μm), water, SikaAER-50/50 foaming agent, STAHLCON hooked-end type steel fibre and silica fume.

2.2 Ordinary Portland Cement (OPC)

In this study, the Orang Kuat Ordinary Portland Cement - CEM I 52 N manufactured by YTL Cement Sdn. Bhd. was used as the OPC cement. It was certified by MS ISO 9001, MS ISO 14001, OHSAS 18001 and MS EN 197-1:2014. The Orang Kuat Ordinary Portland Cement was being sieved through a 300 μm sieve to avoid hydrated cement clinker during the production of LFC. After sieving, the sieved OPC was stored in an air-tight container to avoid dampness.

2.3 Fine Aggregates

This research utilises sand as fine particles for filler material in producing LFC. To eliminate the moisture content within sand which will affecting the W/C ratio, it was subjected to oven drying at a temperature of 100°C for a duration of 24 hours. The particles size of sand was controlled within 600 μm by passing through a 600 μm sieve. Eventually, a sieve analysis was conducted to determine the grading of sand which obtaining the fineness modulus at 2.89.

2.4 Water

In accordance with ASTM C1602 (ASTM, 2006), tap water was selected as the mixing water for all lightweight foamed concretes in this research. Likewise, all lightweight foamed concretes were cast using tap water presented with a specific gravity of 1.0. Identically, the same water was employed during the curing process of LFC, while it was stored in the enclosed curing tank to prevent excessive moisture loss during the hydration process. The water temperature in the curing tank was kept at a room temperature of 25 ºC.

2.5 Foaming Agent

By utilising a foam generator, the foaming agent were combined with water and compressed air to generate foam bubbles. The compressed air was pressurised and maintained at 5 kg/m^3. The foaming agent used in this study was SikaAER-50/50 in compliance with ASTM C796 (ASTM, 2009). The foaming agent produced stable foam, which has a density of 45 kg/m^3 with a tolerance limit of ± 5 kg/m^3.

2.6 Steel Fibre

This study employed hooked-end steel fibre branded by STAHLCON as the reinforcement fibre. It consists of a diameter of 0.55 mm and a length of 35 mm and made by cold-drawn wire in compliance with BS EN 14889 Part 1 (British Standards Institution, 2006).

2.7 Silica Fume

The micro silica supplied by Scancem Materials Sdn. Bhd. was added during the production of LFC as a pozzolana to enhance its strength properties.

2.8 Mix Proportions

In this study, the absolute volume method was applied in designing the mix proportions of both LFC-CTR and LFC-30SF as shown in Table 1. Noted that cement to sand ratio was 1:1 and the silica fume dosage refer to 10 % by mass of cement.

Besides, the foam percentage is based on the weight of dry mix, i.e. cement and sand weight.

2.9 Specimens Preparation and Testing Methods

In this study, a total of 150 specimens were prepared while 60 of them were trial mixes. All the trial mixes were undergone a compressive strength test to determine the optimum water to cement ratio. The rest of 90 specimens were the control mix (LFC-CTR) and steel fibre mix (LFC-30SF). For each type of mix, 15 cube specimens, 15 cylindrical specimens and 15 prism specimens were prepared for the compressive, splitting tensile and flexural strength tests, respectively. Besides, the fresh properties tests, namely the flow table test, inverted slump test and fresh density test, were carried out before casting.

2.10 Fresh Density Test

The fresh density test was performed in compliance with ASTM C138 (ASTM, 2009). Fresh density test calculates the weight of bulk or compacted aggregates per cubic meter. The apparatus required consist of a container with one liter capacity and a weighing machine. First, the well mixed fresh concrete was filled into the container, and the excess foamed concrete was struck off. Afterward, the filled container was weighted on the weighing machine to assess its fresh density. The process can be repeated by adding foam into the well mixed concrete mixture until the desired concrete density was reached.

2.11 Flow Table Test

In line with ASTM C230 (ASTM, 2009), the consistency of LFC-TM, LFC-CTR, and LFC-30SF was tested using a flow table test. The apparatus involved in the flow table test was a flow table and mould. The freshly mixed foamed concrete was poured into the mould positioned at the centre until it is fully filled. The mould was lifted and removed slowly, leftover concrete was raised and dropped on the flow table for a maximum of 25 times. The amount of drop in the flow table was recorded, and the slump spread diameter was measured.

2.12 Inverted Slump Test

The inverted slump test was performed to study the workability of concrete in compliance with ASTM C1611 (ASTM, 2009). The result of the inverted slump test was obtained by measuring the spread diameters of the fresh concrete. A slump cone and a base plate were used to perform the test. Firstly, the slump cone was placed inversely on the centre of the base plate. Then, hold the slump cone tightly on the base plate to avoid leaking concrete mix from the bottom. Next, the freshly mixed LFC was poured into the inverted slump cone until it was fully filled. The excess concrete was removed to provide a flat top surface. Lastly, the slump cone was raised vertically and slowly at about 1 ft. The slump spread diameter was measured and recorded.

2.13 Compression Test

In this study, the compressive strength test accordance to BS EN 12390-3 (British Standards Institution, 2019) was conducted on LFC-TM, LFC-CTR, and LFC-30SF. Cubic specimens (100 mm x 100mm x 100mm) of LFC-TM, LFC-CTR and LFC-30SF were prepared for compressive strength test at 7 days, 28 days, and 56 days. The test was carried out using the concrete compression machine with a loading rate of 1 kN/s.

2.14 Splitting Tensile Test

The splitting tensile strength test carried out for LFC-CTR and LFC-30SF was in accordance with BS EN 12390-6 British Standards Institution, 2010). A concrete compression machine was used to conduct the splitting tensile strength test. Cylindrical specimens of LFC-CTR and LFC-30SF were prepared for splitting tensile strength test at 7, 28 and 56 days. Firstly, the surface of the cylindrical specimen and the platform of the concrete compression machine were cleaned to ensure no debris present. Next, the cylindrical specimen was then positioned in a steel mould. The bearing strips were placed at the upper and bottom of the concrete specimen to uniformly distribute the load along the longitudinal axis of cylindrical specimen. Then, the steel mould was adjusted to the centre of the loading machine and the specimen was loaded at the loading rate of 0.5 kN/s until it failed and cracked appear on its surface.

2.15 Flexural Test

The flexural strength test was carried out for LFC-CTR and LFC-30SF in accordance with BS EN 12390-5 (British Standards Institution, 2019). The prism specimens (40 mm x 40 mm x 160 mm) were prepared for the flexural strength test. A Shimadzu Universal Testing Machine was used to conduct the flexural strength test in accordance with BS EN 12390-5 standard. A three-point flexural test was used in conducting the flexural strength test of LFC-CTR and LFC-30SF. Two loading lines were marked at 20 mm from each edge of the prism specimen. The prism specimen was loaded at 0.2 mm/min until it failed and cracked appear on its surface.

Table 1: Mix proportions

Specimen	W/C Ratio	Material (kg/m^3)						Foam Percentage (%)
		Cement	Sand	Water	Foam	SF	Silica Fume	
LFC-CTR	0.56	562.50	625.00	350.00	8.45	0	62.50	0.68
LFC-30SF	0.56	549.00	610.00	341.60	9.21	30.00	61.00	0.74

Note: The mix proportions are based on 1m^3 concrete volume using absolute method.

3.0 RESULTS AND DISCUSSION

3.1 Compression Test (Trial Mix)

To evaluate the optimum W/C ratio, both LFC-CTR and LFC-30SF compressive strength was complied with various W/C ratio to obtain the performance index graph at different curing age. In this research, the W/C ratio of the trial mix proportions range from 0.52 to 0.68 with an incremental interval of 0.04, whereas for both LFC mix, the W/C ratio with highest performance index was indicated as the optimum W/C ratio. Likewise, all W/C ratio achieved acceptable average hardened densities, range within 1600 ± 50 kg/m³. For the performance index, it was governed by both compressive strength and density, which defined as MPa per 1000 kg/m³. From Figure 1 below, a W/C ratio of 0.56 was observed with the highest performance index at both 7 and 28 days. Thus, it can be concluded that the optimum W/C ratio for LFC-CTR was 0.56. Identically from Figure 2, 0.56 W/C ratio achieved the highest performance index at 7 and 28 days. Therefore, the optimum W/C ratio for LFC-30SF was 0.56 as well.

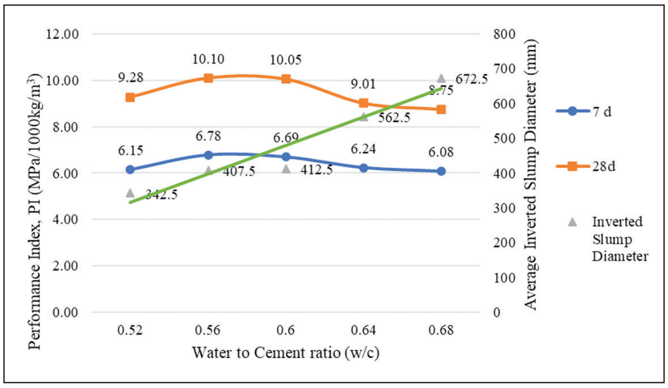

Figure 1: Performance index of trial mixes (LFC-CTR)

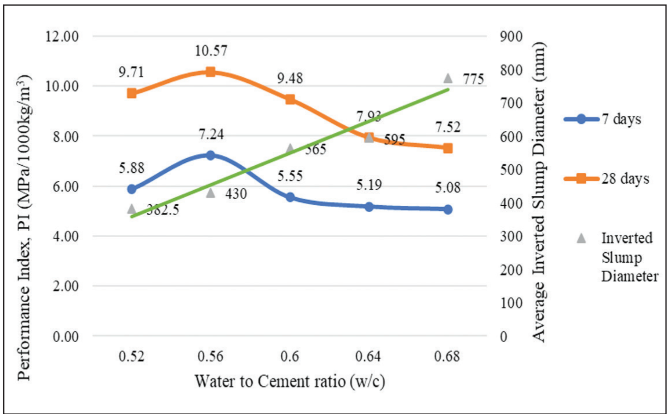

Figure 2: Performance index of trial mixes (LFC-30SF)

3.2 Fresh Properties

In this research, fresh properties tests including fresh density test, flow table test and inverted slump test were carried out to examine the flowability, consistency and stability of LFC. The fresh density test is carried out to ensure LFC density maintained at 1600 ± 50 kg/m³. Besides, the LFC-CTR and LFC-30SF specimens were cast at lower range of acceptable density, as to avoid the unstable air bubbles from bursting during the hardening process, which tends to increase the LFC hardened density. The consistency was defined as the fresh to target density ratio, a consistency close to unity indicates a well-balanced mixture as per designed proportion which is convenient for proper handling and placement. Besides, the stability was defined as fresh to hardened density ratio, a stability close to unity refer to a stable mixture where air and water content of LFC remain largely unchanged during the hydration process, thus a minimal shrinkage and settling effect correspond to a consistent and predictable product. From Table 2, the fresh density of LFC-CTR and LFC-30SF were maintained within the acceptable range. Based on the result obtained from the flow table test, the flowability of the mortar mix for LFC-30SF was higher than that of LFC-CTR. Besides, the spread diameter of the LFC-30SF was larger than that of control mix, this might be due to the high specific gravity of the steel fibre increased the gravitational force of the LFC-30SF, thus obtained smaller flow table drop number and larger spread diameter than that of the control mix. On the other hand, the stability of LFC-30SF was found to be slightly lower than LFC-CTR but the effect was no significant. Any instability phenomenon which are very common in lightweight foamed concrete was associated with the bubble rising towards the top of the specimen due to buoyancy force, which may slightly change the LFC matrix properties (Jones, Ozlutas and Zheng, 2016). Therefore, the stability test was carried out to show that the absence of this instability phenomenon, and the unity check of 0.96 indicate the LFC matrix become denser after hydration process.

3.3 Compression Test

Figure 3 shows the comparison of compressive strength for LFC-CTR and LFC-30SF at different curing age. Overall, both LFC shows an increasing trend of compressive strength from 7 to 56 days of curing. The compressive strength of LFC-CTR was 10.18 MPa, 12.86 MPa and 13.71 MPa at testing age of 7, 28 and 56 days, respectively. Likewise, LFC-30SF was observed with compressive strength of 10.40 MPa, 15.30 MPa and 15.56 MPa at testing age of 7, 28 and 56 days. From the results, LFC-30SF achieve overall higher compressive strength than LFC-CTR at all testing age. While concrete compressive

Table 2: Fresh properties of LFC-CTR and LFC-30SF

Sample	Fresh Density (kg/m³)	Flow Table Spread, (number of drop)	Average Inverted Slump Diameter (mm)	Consistency	Stability
LFC-CTR	1556.000	27	405.000	0.973	0.972
LFC-30SF	1566.070	23	436.750	0.979	0.968

strength progressively increases with longer period of hydration process, LFC-30SF can achieve compressive strength of 13.49 % higher than LFC-CTR after 56 days of curing. Overall, the results proved that the inclusion of steel fibre will enhance the compressive strength of LFC. Steel fibre embedded within the LFC provide reinforcement for the cellular matrix which able to holds the structure together (Awang and Ahmad, 2012). Besides, the steel fibre within LFC-30SF act as stress distributor to reallocate developed internal stress by bridging across cracks when subject to external loadings.

3.4 Splitting Tensile Test

Figure 4 shows the splitting tensile strength of LFC-CTR and LFC-30SF at 7-, 28- and 56-days testing age. Both LFC were cast in cylindrical specimens of 100 mm diameter and 200 mm height to carry out the splitting tensile strength test. Prior to testing, the specimens at 7-days testing age were over dried for 4 hours before testing, while specimen at 28- and 56-days testing age will go through 24-hours oven dry process. Likewise, the splitting tensile strength of both LFC-CTR and LFC-30SF increased from 7 to 56 days of curing. The splitting tensile strength of LFC-CTR was 5.67 MPa, 7.90 MPa and 18.14 MPa at 7-, 28- and 56-days testing age, respectively. While the splitting tensile strength of LFC-30SF was 6.48 MPa, 9.91 MPa and 10.38 MPa, respectively at 7-, 28- and 56-days testing age. For comparison, the LFC-30SF achieve overall higher splitting tensile strength than LFC-CTR at all testing age. Additionally, LFC-30SF achieve splitting tensile strength of 27.52 % higher than LFC-CTR after 56 days of curing. In general, the steel fibre bridging effect able to distribute loads and stresses evenly across the concrete. As a result, stress concentration at stress critical point diminished which tends to inhibit cracks formation and propagations. Moreover, the discrete and short steel fibre tends to have a uniform dispersion across the LFC matrix, thus result in a homogenous LFC mixture reinforced by steel fibre in all parts of concrete specimen. Overall, the addition of steel fibre can enhance the LFC splitting tensile strength and cracks resistance.

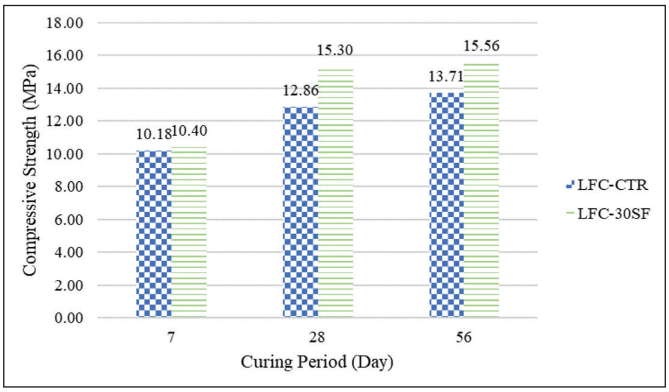

Figure 3: Compressive strength of LFC-CTR and LFC-30SF

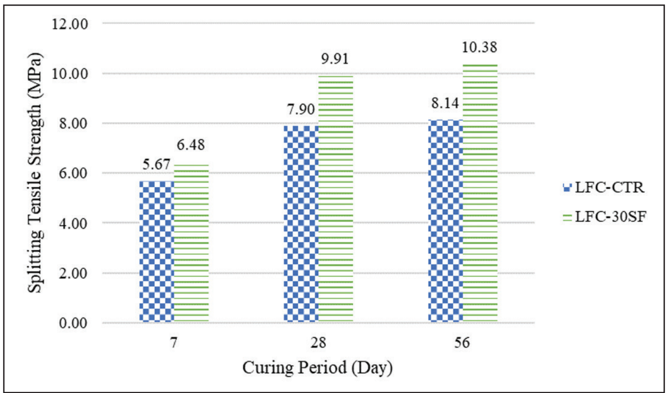

Figure 4: Splitting tensile strength of LFC-CTR and LFC-30SF

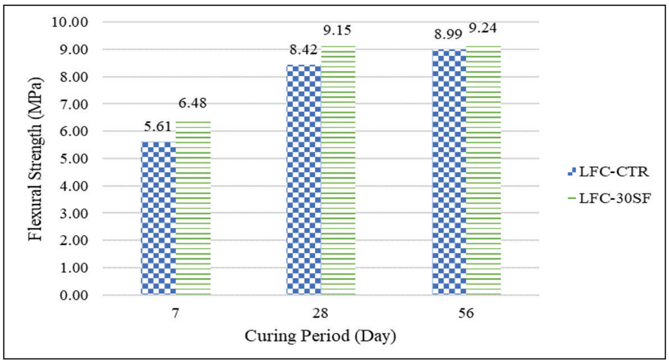

Figure 5: Flexural strength of LFC-CTR and LFC-30SF

3.5 Flexural Test

Figure 5 shows the flexural strength of LFC-CTR and LFC-30SF at 7-, 28- and 56-days testing age. LFC were cast in prism specimen of dimension 40 mm (width) x 40 mm (height) x 160 mm (length) for the flexural strength test. The flexural strength of LFC-CTR was 5.61 MPa, 8.42 MPa and 8.99 MPa at 7-, 28- and 56-days testing age, respectively. While LFC-30SF achieved flexural strength of 6.48 MPa, 9.15 MPa and 9.24 MPa, respectively at 7-, 28- and 56-days testing age. Identically, flexural strength of both LFC have the same trend of strength improvement along increasing curing age. According to the result, the overall flexural strength of LFC was slightly improved with the addition of steel fibres. The flexural strength of LFC-30SF was higher than LFC-CTR by 2.78 % after 56 days of curing. Overall, the testing result data reveal that the steel fibre has lower degree of influence on flexural strength enhancement when incorporating into LFC. The bridging effect by the steel fibre can be observed from the failure mode as shown in Figure 6.

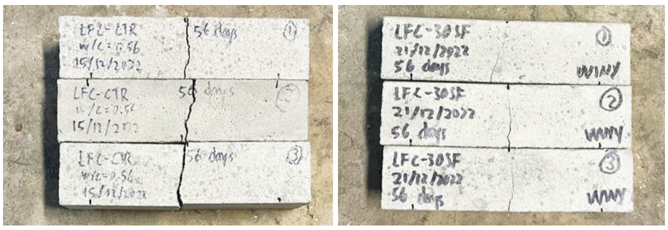

Figure 6: Failure mode of LFC-CTR and LFC-30SF

By comparing the failure mode between LFC-CTR and LFC-30SF. The LFC-CTR specimen failed by formation of deep crack at the specimen central critical point and catastrophically breaks into two parts. While the LFC-30SF specimen observed with gentler failure mode, whereby concrete first yield at the central of prism, followed by gradually cracks propagation along force action line and manage to hold tightly together by steel fibre after failure. As discussed, the role of the steel fibre is to provide the bridging effect to hold the LFC from separate apart under loading.

4.0 CONCLUSION

Based on the result data obtained from fresh and hardened concrete test, the aim and objectives of this research was accomplished. Lightweight foamed concrete (LFC-CTR) and lightweight foamed concrete incorporated with 30 kg/m^3 steel fibre (LFC-30SF) were produced at 1600 ± 50 kg/m^3 of fresh and hardened density with an optimal W/C ratio of 0.56. Within the scope of work of research, the following conclusion were made:

(1) The fresh properties tests, namely flow table test, inverted slump test and fresh density test, were carried out. The flowability and consistency of LFC was enhanced after adding the steel fibre. However, the stability of LFC was reduced after adding the steel fibre.

(2) The incorporation of steel fibre improved the engineering strength properties of LFC. The compressive strength of LFC-30SF was higher than LFC-CTR. Besides, the splitting tensile strength of LFC was significantly improved after adding the steel fibre into the mix. Although the incorporation of steel fibre in LFC do not possess significant improvement in terms of flexural strength, the effect of steel fibre was proven through the examination of the LFC specimen failure mode after the flexural test.

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PROFILES

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