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Strength and Toughness of Lightweight Foamed Concrete with Different Sand Grading

By Siong Kang Lim*, Cher Siang Tan, Xiao Zhao***, and Tung Chai Ling******

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Abstract

Lightweight Foamed Concrete (LFC) is one of the recent advancement of concrete technology in civil engineering. Different gradation of sand in lightweight foamed concrete will change the physical properties of the concrete. This paper aims to study the fresh and hardened properties of lightweight foamed concrete with density of 1300 ± 50 kg/ m^3 that produced by using different gradations of sand. Four categories of sand gradations, ranging from 2.36 mm to 0.60 mm were used. Cube and prism specimens were cast and cured in water curing as well as 7-day initial water curing followed by air curing conditions. The measured spread values indicated that the finer sand used in the foamed concrete has lowered its workability and increases its water to cement ratio for desired consistency and stability. It was noted that the specimens prepared with 0.60 mm sand have obtained the highest compressive and flexural strengths as well as flexural toughness compared with the specimens prepared with coarser sand gradations.

Keywords: *Lightweight Foamed Concrete (LFC), sand grading, consistency, strengths, toughness*

1. Introduction

The increment of urban development and declines of natural resources has pushed civil engineers to look for innovative and sustainable construction materials. Even though the usage of concrete or mortar has been practised in the early civilization, the development of concrete technology is still continued in enormous speed in the 21st Century (Aïtcin, 2000; Cyr and Shah, 2002; Idorn, 2005). Researches have been made in many remarkable area, e.g., self-healing concrete (Jonkers *et al*., 2010; Wu *et al*., 2012), self-consolidating or self-compacting concrete (Peng and Hwang, 2010; Aslani and Nejadi, 2012; Naik *et al*., 2012), high strength concrete (Naik *et al*., 2012; Xu *et al*., 2013), concrete admixtures (Kapelko, 2006; Sanchez and Sobolev, 2010; Liu *et al*., 2011) and lightweight concrete (Jones and McCarthy, 2005; Nambiar and Ramamurthy, 2008; Ramamurthy *et al*., 2009; Liu and Song, 2010) in order to produce stronger, safer, economical and eco-friendly concrete.

Lightweight concrete is developed to minimize the self-weight of a building structure whilst reduce the dependence on vast volume of natural resources. The lightweight concrete technology can be categorized into three main area i.e., autoclaved aerated concrete, lightweight aggregate concrete and lightweight foamed concrete. Lightweight Foamed Concrete (LFC) is lighter than normal weight concrete due to the existence of artificial air bubbles trapped in cement mortar when suitable foaming agent is applied (Ramamurthy *et al*., 2009). With the advancement of technology, LFC is widely used in construction sector for both structural and non-structural purpose. It offers advantages such as low densities ranging from 600 to 1900 kg/m^3, high flowability, self-compacting, minimum consumption of aggregate, and excellent thermal and sound insulations as compared to normal concrete. In practice, the fresh and hardened properties of LFC shall be investigated before it can be adopted for the construction applications. The consistency and stability of fresh mixed foamed concrete is compulsory to prevent a separation of artificial air bubbles and cement mortar as well as broken of the bubbles, which would affect the hardened properties of concrete. This measurement was also related to the fresh mix rheological property (Jones and McCarthy, 2005a; Nambiar and Ramamurthy, 2007a; 2008). Previous study reported that replacement of sand with coarse fly ash as filler exhibited 2.5 times higher spread value compared to conventional cement-sand mix. The enhanced consistency and workability were attributed by different particle shape and size of fine aggregate (Ramamurthy *et al*., 2009). Finer fly ash increased the water to solid ratio of foamed

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*Assistant Professor, Faculty of Engineering & Science, Universiti Tunku Abdul Rahman, 53300 Kuala Lumpur, Malaysia (E-mail: sklim@utar.edu.my)
**Senior Lecturer, Faculty of Civil Engineering, Universiti Teknologi Malaysia, 81310 Johor Bahru, Malaysia (Corresponding Author; E-mail: tcsiang@utm.my)
***Associate Professor, College of Environment and Civil Engineering, Chengdu University of Technology, Chengdu, Sichuan 610059, China (E-mail: zhaoxiao@cdut.cn)
****Project Leader, Construction and Building Materials Sector, Nano and Advanced Materials Institute Limited, Hong Kong (E-mail: tcling@nami.org.hk)

concrete, which satisfied the consistency requirement (Jones and McCarthy, 2005a). Nambiar and Ramamurthy reported that the foamed mix with fine river sand will result in greater compressive strength than that of coarse river sand at various densities (Nambiar and Ramamurthy, 2006). Few detailed studies have been reported on the influence of different gradations of sand used in the production of foamed concrete. This paper aims to investigate the effects of using different gradations of sand, namely P2.36 mm, P1.18 mm, P0.90 mm and P0.60 mm to the fresh and hardened properties of 1300 ± 50 kg/m^3 lightweight foamed concrete in terms of consistency, stability, strengths as well as toughness.

2. Experimental Program

2.1 Materials

Production of Lightweight Foamed Concrete (LFC) with 1300± 50 kg/m^3 of density in this study was carried out by using raw materials namely Ordinary Portland Cement (OPC), oven dried river sand with different gradations, water and synthetic foaming agent. The OPC used as binder was locally manufactured by YTL Cement, complying to the Type I Portland cement as stated in ASTM C150 (ASTM, 2007a). Four categories of sand size were used, namely 100 percent passing through 2.36 mm sieve (P2.36 mm), 1.18 mm sieve (P1.18 mm), 0.90 mm sieve (P0.90 mm) and 0.60 mm sieve (P0.60 mm), respectively. All categories of sand used were classified as zone 4 fine sand with fineness modulus ranging from 1 to 2 (dominant sizes from 150 to 300 μm, specific gravity = 2.60) based on sieve analysis results in accordance with BS 882: 1992 (BSI, 1992). Normal tap water was chosen for preparing the foamed concrete. A locally available synthetic foaming agent with specific gravity of 1.03 was used as the foaming agent for lightweight foamed concrete.

2.2 Mix Proportions

Initial laboratory trials (series 1) for the four categories of Lightweight Foamed Concrete (LFC) produced with their respective sand gradation (P2.36 mm to P0.60 mm) were carried out. The trial mix aimed to obtain an optimum w/c ratio of the respective mix, corresponding to the optimum strength, without compromising the stability and consistency of fresh LFC. Stable foam with density of 45 ± 5 kg/m^3 was produced by dry preformed foam method (Aldrige, 2005; Ramamurthy *et al.*, 2009). The foaming agent was diluted with water in a ratio of 1:30 based on volume and the cement to sand ratio (c/s) was kept constant at one. The trial w/c ratio for the respective LFC mix ranged from 0.46 to 0.60, and was increased by an interval of 0.02. Summary of the experimental works for trial mixes (series 1) are tabulated in Table 1.

2.3 Specimens Preparation

Cube mould with a size of 100 × 100 × 100 mm and prism mould with a size of 40 × 40 × 160 mm were used to produce the cube and prism Lightweight Foamed Concrete (LFC) specimens. The specimens were demoulded after 24 hours of casting and then subjected to two different curing regimes as listed below:

Water curing condition (marked as “28Water” and “56Water”): specimens were totally submerged in water with temperature range from 26°C to 29°C until the testing age at 28 days and 56 days.

Water and air curing condition (marked as “7Water + 21Air”

Table 1. Summary of Experimental Works for Trial Mixes (Series 1)

Mix details	Sand Gradation	c/s	Preformed stable foam	w/c	Curing condition	Investigated properties
ILT-P2.36 -0.46	100 % passing through 2.36 mm sieve; 56% of sand in range of 0.60 to 0.15 mm sizes	Cement to sand ratio was kept constant at 1 for comparison purpose	2.0 ± 0.2% (Percentage of stable foam used was based on total weight of solids)	0.46	Totally immersed in water at constant temperature of 26°C	1. Fresh properties (flow table spread value and inverted slump cone spread value) 2. 14-day compressive strength to density ratio of 100×100×100 mm cube specimen (Average value of three specimens for each mix proportion)
ILT-P2.36 -0.48				0.48		
ILT-P2.36 -0.50				0.50		
ILT-P2.36 -0.52				0.52		
ILT-P2.36 -0.54				0.54		
ILT-P1.18 -0.48	100 % passing through 1.18 mm sieve; 59.7% of sand in range of 0.60 to 0.15 mm sizes			0.48		
ILT-P1.18 -0.50				0.50		
ILT-P1.18 -0.52				0.52		
ILT-P1.18 -0.54				0.54		
ILT-P1.18 -0.56				0.56		
ILT-P0.90 -0.50	100 % passing through 0.90 mm sieve; 60.8% of sand in range of 0.60 to 0.15 mm sizes			0.50		
ILT-P0.90 -0.52				0.52		
ILT-P0.90 -0.54				0.54		
ILT-P0.90 -0.56				0.56		
ILT-P0.90 -0.58				0.58		
ILT-P0.60 -0.52	100 % passing through 0.60 mm sieve; 62.8% of sand in range of 0.60 to 0.15 mm sizes			0.52		
ILT-P0.60 -0.54				0.54		
ILT-P0.60 -0.56				0.56		
ILT-P0.60 -0.58				0.58		
ILT-P0.60 -0.60				0.60		

and "7Water + 49Air"): specimens were subjected to 7 days of initial water curing at temperature range of 26°C to 29°C, and then exposed to air curing in laboratory for 21 days and 49 days respectively with the temperature of 29°C to 32 °C and average relative humidity of 55% to 65% until testing ages at 28 days and 56 days.

2.4 Testing Methods

2.4.1 Fresh Properties

The flow table test was used to determine the consistency of the fresh mixed mortar (slurry) as described in ASTM C 1437 (ASTM, 2007b). A higher flow table spread value of the mixture indicates a higher fluidity of the mortar mix. After the stable foam was blended into the mortar mix thoroughly, the produced foamed concrete was filled into the inverted slump flow cone without any compaction and vibration in accordance with ASTM C 1611 (ASTM, 2005). The inverted flow cone spread value was measured for the respective trial mixes in series 1 (refer to trial mixes results in Table 2) to determine its optimal w/c ratio corresponding to the optimum compressive strength and consistency. Besides, the designed density of foamed concrete in this study has been fixed at 1300 kg/m^3. The acceptable variable between the designed and measured density has been fixed as ± 50 kg/m^3 in accordance with typical industrial practice in manufacturing of foamed concrete (Jones and McCarthy, 2005b).

2.4.2 Compressive Strength

Compressive strength of foamed concrete was determined by using universal compression test machine with a constant loading rate of 0.1 kN/s in accordance with BS 4551 (BSI, 1980). Cube specimens with a size of 100 × 100 × 100 mm were used for this test.

2.4.3 Flexural Strength

The prism specimens with a size of 40 × 40 × 160 mm were subjected to the center-point loading flexural test in accordance with ASTM C 293 (ASTM, 2008). The test was conducted at a constant rate of 0.1 mm/minute by using Instron universal testing machine.

2.4.4 Flexural toughness

The flexural strain of each specimen was calculated by using the extension in horizontal plane divided by span length, 150 mm. Since the results given by the Instron testing machine were composed of the applied load and extension in y-direction (vertical), therefore conversions of the y-direction extension to horizontal plane extension by using Pythagoras theorem were done as shown in Fig. 1.

The 28-day stress-strain diagrams were plotted. The areas under the flexural stress-strain diagrams that represented the total energy to fracture of each specimen, also termed as toughness of the material were computed by using integration method as

Table 2. Screening of Trial Mixes (Series 1) Results

Mix details	Stability[1]	Flow table spread value[2] (mm)	Inverted slump cone spread value[2] (mm)	Average hardened bulk density (kg/m^3)	14-day Compressive strength (MPa)	14- day compressive strength to density ratio[3] (MPa per 1000 kg/m^3)
ILT-P2.36 -0.46	1	180	413	1295	2.98	2.30
ILT-P2.36 -0.48	1.03	217	499	1345	3.83	2.85
ILT-P2.36 -0.50	1.04	249	535	1350	4.06	3.01
ILT-P2.36 -0.52	0.97	272	559	1259	3.31	2.63
ILT-P2.36 -0.54	0.99	326	623	1297	3.05	2.35
ILT-P1.18 -0.48	1.02	174	398	1330	3.67	2.76
ILT-P1.18 -0.50	1.03	199	433	1342	3.94	2.94
ILT-P1.18 -0.52	1.04	224	481	1349	3.98	2.95
ILT-P1.18 -0.54	0.97	238	524	1259	3.31	2.63
ILT-P1.18 -0.56	0.99	267	587	1287	2.97	2.31
ILT-P0.90 -0.50	0.99	208	445	1295	3.77	2.91
ILT-P0.90 -0.52	1.02	214	469	1330	3.89	2.92
ILT-P0.90 -0.54	1.01	225	475	1305	4.39	3.36
ILT-P0.90 -0.56	1.03	232	491	1345	3.65	2.71
ILT-P0.90 -0.58	0.99	270	503	1290	3.19	2.47
ILT-P0.60 -0.52	1.03	194	333	1339	4.27	3.19
ILT-P0.60 -0.54	1.04	203	380	1352	4.42	3.27
ILT-P0.60 -0.56	1.02	210	443	1318	4.52	3.43
ILT-P0.60 -0.58	1.03	224	481	1348	4.51	3.35
ILT-P0.60 -0.60	1.03	245	496	1308	4.38	3.35

Note: ILT = initial laboratory trial.
[1]Stability = proportion of measured fresh density to designed hardened density.
[2]Flow table and inverted slump cone spread values were obtained based on average diameter of four different angles.
[3]4-day compressive strength was obtained based on average crush value of three cube specimens.
The highlighted mixes have been chosen due to its highest strength to density ratio among the trial mixes in same category of sand grading.

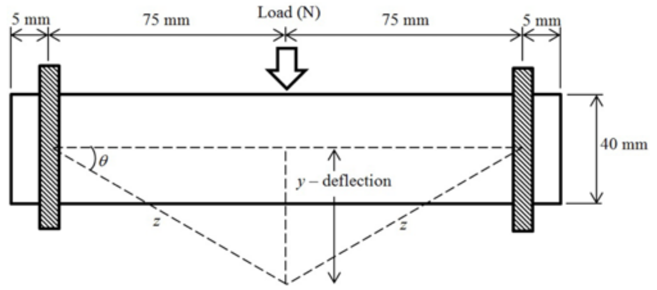

Fig. 1. Conversion of the y-Direction Extension to x-Direction Extension by using Pythagoras Theorem (simply supported prism)

shown in Eq. (1):

$$u_t = \int_0^{\varepsilon_f} \sigma d\varepsilon \qquad (1)$$

where, u_t = Toughness (J/m^3)
ε = Strain (10^{-6} mm/mm)
ε_f = Strain upon failure (10^{-6} mm/mm)
σ = Flexural strength (MPa)

3. Results and Discussion

The results of trial mixes (series 1) of Lightweight Foamed Concrete (LFC) are given in Table 2. After screening the trial mixes results, the optimal mix of each category of foamed concrete prepared with specific sand grading was selected for further investigation on the strengths and toughness properties of LFC (series 2). Table 3 shows the mix details and investigated properties of the selected optimal mixes (series 2). The results of the series 2 experimental work are depicted in Figs. 2 to 4 and Table 4.

3.1 Initials Laboratory Trials (ILT) in Series 1 Experimental Works

The optimal trial mixes (series 1 - ILT) selected for further investigation (series 2 - CLFC) possess an optimum strength to density ratio (performance factor) (Kurama *et al*., 2009), consistent and yet without compromising its stability based on the results from Table 2. The stability of the fresh mixed foamed concrete was kept constant to nearly one, without conceding the segregation and bleeding. Furthermore, the measured hardened density of produced foamed concrete was kept in range of ±50 kg/m^3 difference corresponding to the designed density at 1300 kg/m^3.

The effect of water to cement ratios on flow table and inverted slump cone spread values, as well as 14-day compressive strength to density ratio is tabulated in Table 2. The flow table spread value and inverted slump cone spread value in Table 2 indicate that the fluidity and consistency of the fresh cement-sand mortar and foamed concrete are depended on the quantity of water in the mixes. Both spread values were increased when the w/c ratio increased by an intervals of 0.02 for each LFC category. The results in Table 2 show that the w/c ratios of the selected trial mixes (highlighted with bold font) were increased by an interval of 0.02 from 0.50 to 0.56 when the gradation of sand getting finer in order to obtain optimum strength to density ratio in each category of trial mixes. This was due to larger total surface area of finer sand required more water to moistening the surface area, subsequently provided the consistency of the fresh mixes. The consistency of the mixes helped in more even distribution of stable foam in the fresh cement mortar, thus enhanced the strength performance of foamed concrete. Results in Table 2 show that inappropriate w/c ratio triggered lower strength performance of LFC. Stiffer or too slurry condition of the mixes (indicated by both the split table and inverted cone spread values) cause the

Table 3. Summary of Experimental Works for Selected Optimal Mixes (Series 2)

Mix details	Sand grading	c/s	w/c	Preformed stable foam[1]	Curing condition[2]	Investigated properties
CLFC-P2.36-W (ILT-P2.36-0.50)	P2.36 mm	1.0	0.50	1.8 to 2.2 %	28Water	28 and 56 days compressive strengths. 28 and 56 days flexural strengths. 28-day flexural toughness
CLFC-P2.36-A (ILT-P2.36-0.50)					7Water + 21Air	
CLFC-P1.18-W (ILT-P1.18-0.52)	P1.18 mm		0.52		28Water	
CLFC-P1.18-A (ILT-P1.18-0.52)					7Water + 21Air	
CLFC-P0.90-W (ILT-P0.90-0.54)	P0.90 mm		0.54		56Water	
CLFC-P0.90-A (ILT-P0.90-0.54)					7Water + 49Air	
CLFC-P0.60-W (ILT-P0.60-0.56)	P0.60 mm		0.56		56Water	
CLFC-P0.60-A (ILT-P0.60-0.56)					7Water + 49Air	

Note: c/s = cement to sand ratio, w/c = water to cement ratio, ILT = initial laboratory trial, CLFC = Cement based lightweight foamed concrete.
[1] Percentage of stable foam used was based on total weight of solid (cement plus sand).
[2] 28Water: 28-day water curing; 7Water+21Air: 7-day water and 21-day air curing; 56Water: 56-day water curing; 7Water+49Air: 7-day water and 49-day air curing.

adverse effects on the consistency and uniformity of fresh mixes, thus lower its strength performance (Ramamurthy *et al*., 2009; Nambiar and Ramamurthy, 2006).

3.2 Results of Series 2 Experimental Works

Based on the screening process of trial mixes results, the four optimal w/c ratios range from 0.50 to 0.56 were used in preparing the cement based lightweight foamed concrete mixes, namely CLFC-P2.36-0.50, CLFC-P1.18-0.52, CLFC-P0.90-0.54 and CLFC-P0.60-0.56 respectively (refer to the details in Table 3). Further experimental investigations (series 2) were focused on the hardened properties of the respective Cement based Lightweight Foamed Concrete (CLFC) specimens, i.e., compressive strength, flexural strengths and flexural toughness. Two curing conditions were adopted as described in section 2.3 and all the test results are discussed in the following sections.

3.2.1 Compressive Strength

Figure 2 shows that the 28 and 56 days compressive strength of CLFC increased when the gradation of sand used getting finer. The larger total surface area of the finer sand particles required higher percentage of hydrated cement paste to bond them together, thus made the microstructure more solid. In addition, the micro-fine sand fillers were efficiently filled up the macro-pores in the CLFC. According to Nambiar & Ramamurthy (2007b), finer filler material helps in producing more uniform and narrower artificial air-voids distribution, thus increases the compressive strength.

Referring to the results shown in Fig. 2, the air-cured specimens gained higher 28-day compressive strength compared to the water-cured specimens, under the same sand gradation category. The air-cured specimen prepared with P0.60 mm sand filler obtained the highest 28-day compressive strength i.e., 7.15 MPa. This circumstance is due to specimens cured under 7Water + 21Air condition developed initial strength more rapidly than the equivalent specimens that cured in water (28Water). The comparative higher ambient temperature in Malaysia's tropical environment accelerated the hydration of C_3S and C_2S compounds in OPC by providing sufficient heat at the early stage (Fattuhi, 1988; Neville, 2011). However, the strength development of the air-cured specimens was decelerated at the 56 days of age due to water evaporation faced by the specimens, thus resulted in insufficient water for complete hydration of cement grains. The 56-day water-cured specimens that subjected to the constant temperature and 100% humidity obtained comparatively higher strength (6.83 to 9.77 MPa) than that of the air-cured specimens at the same 56-day age (6.66 to 9.13 MPa).

3.2.2 Flexural Strength

Figure 3 shows the 28 and 56 days flexural strength of CLFC were increasing when the gradation of sand getting finer from P2.36 mm to P0.60 mm under both curing conditions. The trends were same as the compressive strength development of the CLFC. These results further proved that the larger total surface area of finer sand enhanced the bonding between hydrated cement pastes and fillers. The stronger bonding of the finer sand particles and cement matrices increased the shear resistant and

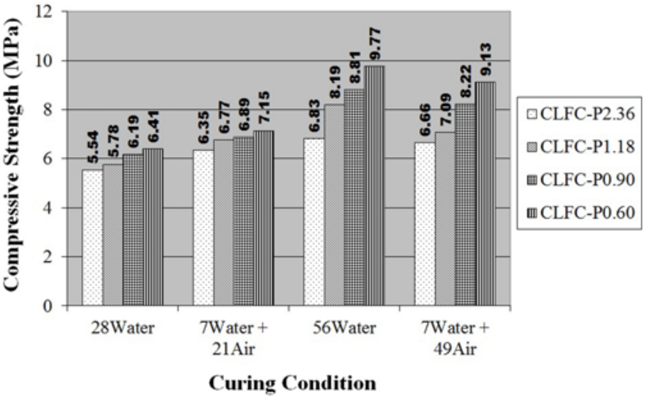

Fig. 3. Effect of Different Sand Gradations on 28 and 56 Days Flexural Strength of CLFC Prism Specimens under Two Different Curing Conditions

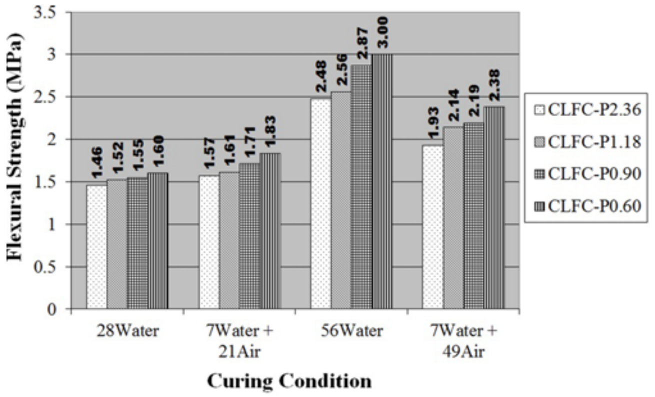

Fig. 2. Effect of Different Sand Gradations on 28 and 56 Days Compressive Strength of CLFC Cube Specimens under Two Different Curing Conditions

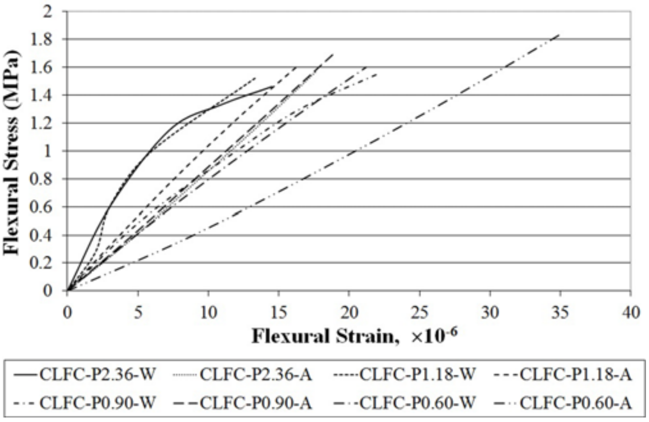

Fig. 4. Flexural Stress-Strain Relationship of 28-Day CLFC Prism Specimens under 28 Water and 7 Water + 21 Air Curing Conditions

Table 4. Flexural Toughness of CLFC Prisms Prepared with Different Sand Gradations

Specimen series no.	Curves' trend line Equation	R^2	Maximum flexural stress, σ(MPa)	Corresponding flexural strain, $\varepsilon \times 10^{-6}$	Total flexural toughness (J/m^3)
CLFC-P2.36-W	$\sigma = -0.0078\varepsilon^2 + 0.2126\varepsilon$	0.9964	1.46	14.5	14.4
CLFC-P2.36-A	$\sigma = 0.0004\varepsilon^2 + 0.0825\varepsilon - 0.01$	0.9997	1.57	17.6	13.3
CLFC-P1.18-W	$\sigma = -0.0067\varepsilon^2 + 0.2040\varepsilon$	0.9910	1.52	13.3	12.8
CLFC-P1.18-A	$\sigma = 0.0007\varepsilon^2 + 0.1099\varepsilon + 0.0036$	0.9998	1.61	16.3	13.7
CLFC-P0.90-W	$\sigma = -0.0014\varepsilon^2 + 0.1015\varepsilon$	0.9997	1.55	21.9	19.4
CLFC-P0.90-A	$\sigma = 0.00005\varepsilon^2 + 0.0895\varepsilon - 0.0124$	0.9996	1.71	19.05	16.1
CLFC-P0.60-W	$\sigma = -0.0003\varepsilon^2 + 0.0813\varepsilon + 0.0087$	0.9996	1.60	21.3	17.7
CLFC-P0.60-A	$\sigma = 0.0002\varepsilon^2 + 0.0464\varepsilon - 0.0326$	0.9978	1.83	34.9	29.9

Note: CLFC=Cement based lightweight foamed concrete; W=28-day water curing condition; A=7-day water and 21-day air curing condition.

flexural behavior of the prism specimens, thus increased its flexural strength.

On the aspect of curing condition, 56 days of water curing regime provided the better environment for cement hydration process up to the testing age compared to the 7 days initial water curing plus further air curing regime. Possible reasons of this phenomenon were interpreted in the previous discussion on compressive strength in section 3.2.1.

3.2.3 Flexural Toughness

Figure 4 shows the flexural stress-strain relationship of each specimen under both curing conditions. All CLFC specimens show nonlinear behavior based on the plots in Fig. 4. In general, the specimens such as CLFC-P0.90 and CLFC-P0.60 that prepared with finer sand gradations observed more ductile behavior than that of the specimens prepared with the coarser sand gradations. The better distribution of the air voids in the CLFC-P0.90 and CLFC-P0.60 mixes might help in the enhancement of its ductility.

Table 4 shows the 28-day flexural toughness value of each CLFC prism specimen which is computed by integrating the curve's trend line equation. The toughness values of water-cured and air-cured specimens were ranging from 12.8 to 19.4 J/m^3 and 13.3 to 29.9 J/m^3 respectively. The toughness values of the water-cured specimens didn't show increment of toughness when the grade of sand used was getting finer, since the highest value was obtained by the CLFC-P0.90-W instead of CLFC-P0.60-W. However, the difference of the both toughness values is small. On the other hand, the air-cured specimen prepared with finer sand gradation obtained a higher toughness value than that of the specimen with coarser sand gradation. The highest toughness value in this study was achieved by the CLFC-P0.60-A as shown in Table 4. Air-cured specimens have more consistent toughness values than that of the water-cured specimens. This might due to the free moisture content retained in the water-cured specimens affected its extension during the flexural test, thus varied the flexural strain and eventually made the results not constant. In general, it can still be concluded that the 28-day flexural toughness of the studied CLFC specimens has increased when the sand gradation used was getting finer.

4. Conclusions

This study shows that the used of sieve size P0.60 mm sand (finest grading in the study) has provide the better quality in production of Cement based Lightweight Foamed Concrete (CLFC) than that of the coarser gradations of sand (P2.36 to 0.90 mm). Several conclusions can be drawn from the experimental investigations:

1. The water to cement ratio of CLFC has increased when the CLFC was made with finer gradation of sand ranging from P2.36 mm to P0.60 mm in order to achieve appropriate consistency and stability in preventing separation of artificial air bubbles and cement mortar, or broken of the air bubbles.
2. Compressive and flexural strengths of CLFC have increased when the tested specimens were prepared with finer sand grading.
3. In general, ductility and flexural toughness of the CLFC specimens increases when the sand used getting finer from P2.36 mm to P0.60 mm.
4. Full water curing condition provides a better environment for compressive and flexural strengths development up to 56 days than that of the air curing condition.

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