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CHARACTERIZATION OF LIGHTWEIGHT CELLULAR CONCRETE

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Abstract: Lightweight cellular concrete (LCC) is an alternative construction material with growing applications over the past three decades. It is mainly composed of hydraulic cement, water, and pre-formed foam. Its lightweight, ease of placement, and insulating property make it a suitable material for structural backfill, utility insulation, and road construction. Being an innovative material with diverse potential applications in the construction industry, it is worth knowing typical engineering characteristics of this material. So far, various laboratory tests were conducted on LCCs at different Canadian laboratories. These include tests for resilient modulus, elasticity modulus, shear strength, tensile strength, hydraulic conductivity, thermal conductivity, and freeze-thaw resistance. The laboratory tests were conducted on LCCs with densities ranging from 400kg/m^3 to 600kg/m^3. These are typical densities of the LCCs that have been so far used in Canada for different applications. According to the test results, the resilient modulus and modulus of elasticity of the LCC vary over the ranges of 0.12 – 0.35 MPa and 850 MPa – 1,100 Mpa respectively, while the Poisson's ratio range is 0.19 – 0.26. The freeze-thaw test results, on the other hand, indicates the relative dynamic modulus of the LCCs exceeds 80% after 350 freeze-thaw cycles. These show that LCC has excellent resistance to freeze-thaw even though their stiffness is low compared to chemically stabilized pavement materials. In this paper, the mechanical and thermal properties of the lightweight cellular concrete that have been determined in various Canadian laboratories using standard and non-standard test methods will be compiled and presented. Besides, comparison of the test results with the results of similar tests that have been performed outside Canada will be incorporated. Furthermore, results of some mechanical testing based on different densities will also be shown and analyzed.

1 INTRODUCTION

Lightweight Cellular Concrete (LCC) or Foamed Concrete is a cementitious material with a typical plastic density ranging from 375 to 1600 kg/m^3 (Ozlutas 2015) that contains a homogeneous air bubble structure in the mix. It was first patented in 1923 (Valore 1954) and been using as a void filler material in the 1970s. The application of LCC in construction provides several benefits such as reducing earth pressure, resistance to freezing and thawing, mitigate settlement, good thermal insulation (Tiwari 2017, Maruyama and Camarini 2015). LCC is often used in construction projects which required light material and excellent workability. For instance, construction project such as bulk filling, trench reinstatements, floor screeds, thermally insulating foundations, and stabilizing soils (Mydin 2010, Ozlutas 2015).

LCC has been a useful backfilling material in the world. However, researchers have found that LCC could be a viable option as structural materials (Jones and McCarthy 2005). Studies have proven that LCC could be a feasible choice for structural applications such as stabilization of weak soil (Drusa et al. 2011, Lee et al. 2009), replacement of weak soil in sandwich solution for foundation slabs (Hulimka et al. 2013), industrial concrete floor (Kadela and Kozlowski 2016).

LCC starts to gain its attention in transportation infrastructure as it provided numerous benefits (Hajek et al. 2016, Ramamurthy et al. 2009):

1. Straightforward and quick pouring – the contractor is capable of producing and pouring 400 to 600 m^3 per day to reduce the construction time and cost.
2. Self-compacting
3. Excellent Freeze-Thaw resistance
4. Environmental friendly

Several road constructions have been done with the LCC due to these benefits mentioned above. For instance, LCC has been used in an industrial zone in the UK as subbase material to replace the original layer which consists of peat (Drusa 2016). Illinois also apply LCC in their road construction to provide a solution to the soft organic underlying soil, and it benefits the contractor by lowering unit cost, reduced construction time, and higher quality of material (Drusa 2013). Application of LCC are also found in Canada, Alberta used the LCC as subbase material in bus-lane construction. Ontario also applied LCC in rural road and highway (Maher and Hagan 2016).

Though there are several LCC applications and studies, there are still lacking a complete and thorough guide of LCC. Mechanical properties of LCC at a specific low density (400 to 600 kg/m^3) needs to be adequately examined.

1.1 Definition

The term “cellular concrete.” or “foamed concrete” can be referred to a type of lightweight concrete which contains stable air bubble or gas cell distributed homogeneously in the cement mix (ACI 523). Unlike the traditional Portland cement concrete, LCC does not contain any coarse aggregate in the mix (Maruyama and Camarini 2015). ASTM C796 gives a more detailed definition of the LCC as:

“A lightweight product consisting of Portland cement, cement-silica, cement-pozzolan, lime-pozzolan, or lime-silica pastes, or pastes containing blends of these ingredients and having a homogeneous void or cell structure, attained with gas-forming chemicals or foaming agents (for cellular concretes containing binder ingredients other than, or in addition to Portland cement, autoclave curing is usually employed)”

Another definition that has been widely cited noted that the foamed concrete is:

“A cementitious material having a minimum of 20 percent by volume of mechanically entrained foam in the plastic mortar or grout.”

This definition further narrows down the type of foamed concrete since air entrained concrete has lower entrained air (3-8%) and aerated concrete is formed chemically. (Barnes 2008).

The two definition both mentioned that the cellular concrete or foamed concrete is a cementitious material that contains air bubble or foam in the mix. Since this research is mainly using the material from Canada, it would be better to follow the definition from ASTM and ACI.

Currently, there are no test standards for cellular concrete in Canada. American Concrete Institute (ACI) published two guides for the cellular concrete with unit weight above 800 kg/m3 (ACI 523.3R) and less than 800 kg/m3 (ACI 523.1R). The two guides provide a general concept of the cellular concrete such as concrete properties, mixing procedures, and applications. It is noted that the application mentioned in ACI

523.1R is for roof deck application. American Society for Testing and Materials (ASTM) issued two standards for the foaming agent (ASTM C796 and ASTM C869).

1.2 Constituent Materials

The typical composition of lightweight cellular concrete contains Portland cement, Pozzolan materials, fine aggregate, water, and foam.

1.2.1 Portland cement

Typically Type I Portland cement, blast furnace slag cement and Portland pozzolan cement can be used as the base mix of cellular concrete. Type III and IIIA cement are also used if the mixture requires high early strength (ACI 523). The total cement contents are usually around 300 to 400 kg/m^3. The density of the cement can be adjusted depending on the strength requirements or the design density of the mix (Brady et al. 2001).

1.2.2 Pozzolan materials

The Pozzolan material is a finely divided material which is rich in silica or alumina. Pozzolanic by-product such as fly ash and blast furnace slag could benefit the contractor by reducing the cost, maintain consistency and increase strength in long-term performance (Kearsley and Wainwright 2001). Jones et al. (2017) stated that replacing Portland cement with fly ash up to 40% could significantly reduce the embodied carbon dioxide by 65% compared to the 100% Portland cement mix while has a similar 28 d strengths (0.25 MPa compared to 0.31MPa). However, the drawbacks of using fly ash are the slow rate of strength gain, and it might cause foam instability as the water demand might increase (Ozlutas 2015).

1.2.3 Fine aggregate

Fine sand is the typical fine aggregate to be used in producing cellular concrete. It is found that sand with a maximum size of 2 mm yields higher strength than 5 mm sand. BCA (1994) suggested replacing fine sand with course fly ash in mixes with a plastic density below 600 kg/m3.

1.2.4 Water

Water-cement ratio plays a vital role in cellular concrete. The w/c ratio needs to be determined based on the constituents materials to provide and maintain suitable workability of the mix. The typical range of w/c ratio is from 0.40 to 1.25 (Ramamurthy 2009). Insufficient water in the mix may lead to the collapse of the mix as the mix is too stiff which breaks the bubble while excess water could increase drying shrinkage (Nambiar and Ramurthy et al., 2006).

1.2.5 Foam

Pre-formed foam is essential in cellular concrete as it can control the plastic density of the mix (Wee et al. 2006). It is consists of a foaming agent and compressed air to help produce foam (BCA 1994). The foam should have homogeneous bubble structure to provide concrete with reasonable strength (Brady et al. 2001). The structure should be capable of resisting the pressure of the base mix until the initial setting time is reached as the air bubbles will be surrounded by the strong skeleton of concrete (Ramamurthy et al. 2009).

1.3 Cellular concrete concerning sustainable construction

Cellular concrete is a lightweight construction material that can fill up to 80 to 90 percent of air void at low densities. The high air void content significantly reduced the number of ingredients used and wasted produced (Ozlutas 2015). Jones and McCarthy (2005) noted that the self-flowing ability of cellular concrete excludes the need for compaction, which saves the energy from placement. Furthermore, it is easy to excavate and remove from the site due to its low strength.

Cellular concrete reduces the use of non-renewable primary sources such as coarse aggregate and fine aggregate at densities below 600 kg/m^3 (BCA 1994). Alternatively, Jones et al. (2012) stated that recycled (demolition fines) and industry by-product (fly ash) can be used in cellular concrete as filler. Moreover, fine fly ash could provide several benefits such as reducing embodied carbon dioxide (eCO_2) and drying shrinkage strains, Ozlutas (2015) demonstrated the influence of replacing Portland cement with fly ash up to 40% in Figure 1.

In pavement construction, cellular concrete provides a sustainable solution to soft soil base. This is due to its good constructability such as short install time, reducing excavation time, self-compacting, and can be placed in winter (Maher 2016).

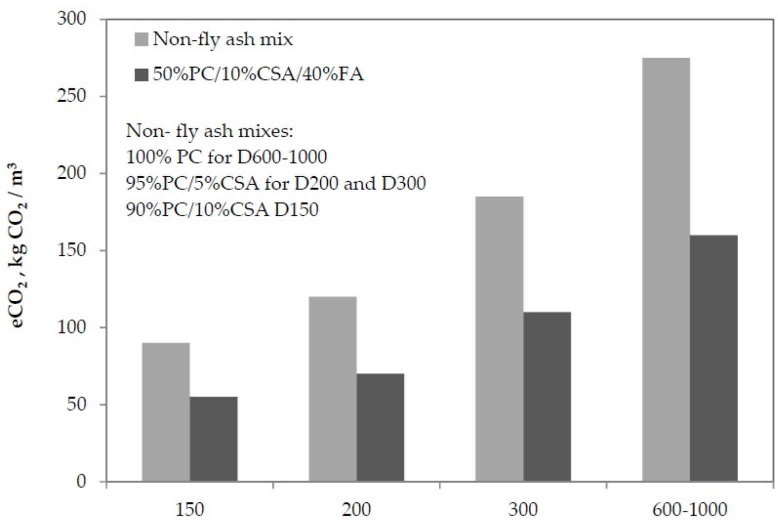

Figure 1 Influence of plastic density and fly ash on the eCO2 of foamed concrete (Ozlutas 2015)

1.4 Application of Lightweight Cellular Concrete

Lightweight cellular concrete has been widely used in civil and structural engineering areas due to its distinctive properties such as reduced density, low thermal conductivity, excellent flowability, self-compaction ability, and its relative cost-effectiveness (Amran et al. 2015). Sari and Sani (2017) summarized the applications of cellular concrete with different density, as shown in Table 1. The typical density of cellular concrete in the application is between 1,000 kg/m^3 to 1,500 kg/m^3, which mainly used for cast-in-place wall, prefabrication, and housing applications. Densities between 300 kg/m^3 to 600 kg/m^3 is related to pavement construction as it provides soil stabilization and road construction functions.

Table 1 Summary of foamed concrete applications based on density (Sari and Sani 2017)

Density (kg/m^3)	Application
300-600	Replacement of existing soil, soil stabilization, raft foundation.
500-600	Currently being used to stabilize a redundant, geotechnical rehabilitation and soil settlement. Road construction.
600-800	Widely used in void filling, as an alternative to granular fill. Some such applications include filling of old sewerage pipes, wells, basement, and subways.
800-900	Primarily used in production of blocks and other non-load bearing building element such as balcony railing, partitions, parapets, etc.
1,100-1,400	Used in prefabrication and cast-in-place wall, either load bearing or non-load bearing and floor screeds.
1,100-1,500	Housing applications.

1,600-1,800	Recommended for slabs and other load-bearing building element where higher strength required.

The application of lightweight cellular concrete become popular in the world. For instance, it has been a solution for the southern US regions that are suffering from the housing shortage or the adverse weather such as hurricanes and earthquakes. In Canada, lightweight cellular concrete is used as a filler for tunnel annulus grouting, flowable fills and in geotechnical applications. The annual market size of lightweight cellular concrete in the UK is estimated to be 250,000 to 300,000 m^3 annually which includes an extensive mine stabilization project. This is the same market size in Korea while it is used as an essential component in a floor heating system. Lightweight cellular concrete was used as a subbase material in Holland due to the low traffic loading and considered cost-effectiveness at the times of repair and rehabilitation. The lightweight cellular concrete also provides resistance to freeze-thaw and frost heave in concrete paving (Amran et al. 2015).

2 CHARACTERIZATION TESTS AND STANDARDS

Over the past ten years, a number of materials characterization tests had been performed in different Canadian laboratories on lightweight cellular concretes with various unit weights. The tests were done to evaluate the stiffness under monotonic loading to determine the shear strength parameters, assess the freeze-thaw resistance, determine the insulation capacity, and measure the hydraulic conductivity of the materials.

Most of the laboratory tests were performed in accordance with standard procedures stated in ASTM or AASHTO standards. In the absence of standard testing protocols for LCC, test methods that had been devised for other materials, which are similar to LCC in various contexts, were adopted based on best practice or expert opinion. Resilient modulus test conducted according to ASTM D 7369 and direct shear test performed as per ASTM D 3080 are among these tests.

The complete list of laboratory tests conducted to characterize the material is shown in Table 2. The results of these tests are presented and discussed in the following section.

Table 2 List of laboratory tests

No.	Test Description	Test Method
1	Resilient Modulus	ASTM D 7369
2	Indirect tensile strength	ASTM D 6931
3	Modulus of elasticity and Poisson's ratio	ASTM C 469
4	Freeze-thaw resistance	ASTM C 666, procedure B
5	Hydraulic conductivity	ASTM D 5084
6	Thermal conductivity	ASTM C 518 and ASTM D 5334
7	Monotonic direct shear test	ASTM D 3080

3 TEST RESULTS AND DISCUSSION

Test results of indirect tensile strength testing and resilient modulus test were shown in Table 3. The indirect tensile test was applied on 15 specimens with three different densities, which are 400, 500 and 600 kg/m^3. ASTM D6931 was used to perform the test. It is clear that the indirect tensile strength of the lightweight cellular concrete increase as density increase, with an average of 0.12, 0.22 and 0.35 MPa for the three densities. Resilient modulus test was also done on 15 specimens with 400, 500 and 600 kg/m3 density. Results showed that the resilient modulus follows the same trend as the indirect tensile strength, with an average of 389, 550 and 725 MPa for three densities. It also exceeds the typical resilient modulus values ranges (34 to 290) for the Unified Soils Classification System (USCS) materials (Papagiannakis, 2008).

Table 3 Test results of Indirect Tensile Strength test and Resilient Modulus test

Parameter	400 (kg/m^3)					500 (kg/m^3)					600 (kg/m^3)				
IDT (Mpa)	0.09	0.13	0.13	0.12	0.14	0.23	0.27	0.24	0.19	0.19	0.4	0.34	0.37	0.33	0.28
Mr (Mpa)	343	384	458	374	388	477	515	557	580	623	696	801	739	752	641

Figure 2 and 3 demonstrates the box plot of the test results which give a clear view of the data trend.

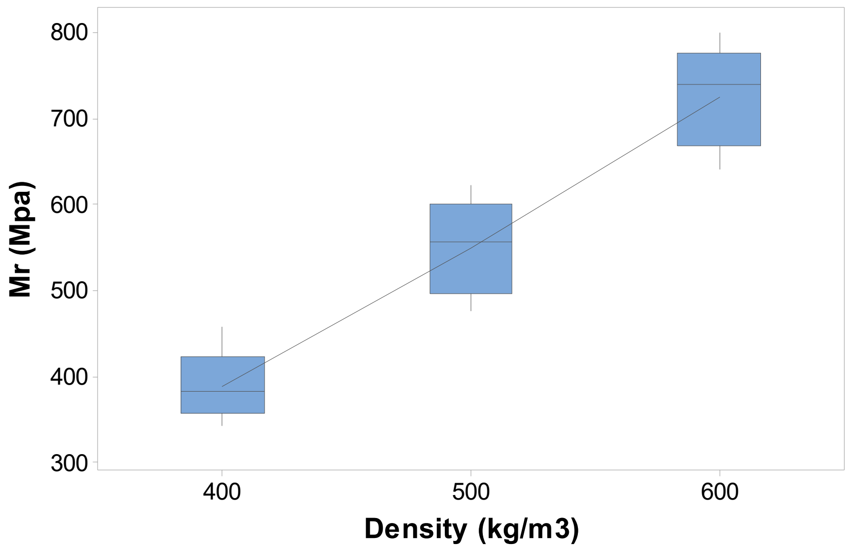

Figure 2 Box plot of the Resilient Modulus test results

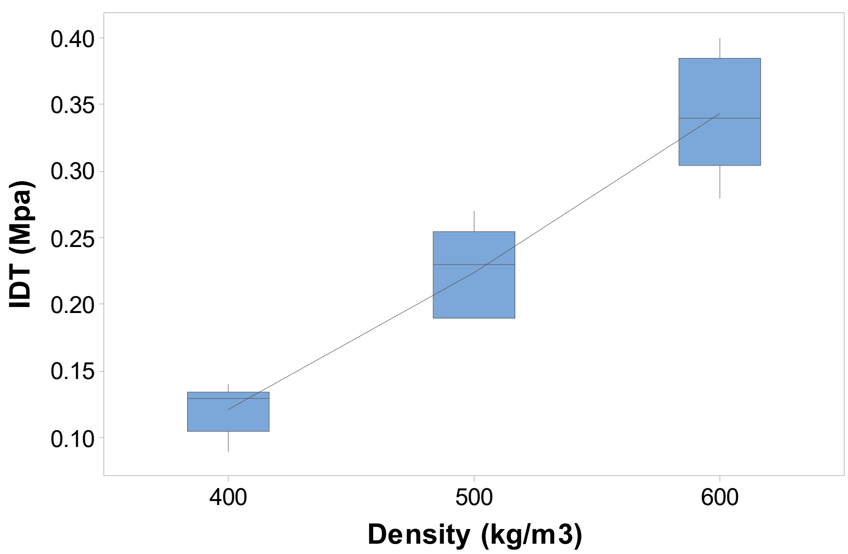

Figure 3 Box plot of the Indirect Tensile Strength test results

Table 4 shows the results of compressive strength test base on ASTM C495. Six 75 mm diameter by 150 mm high cylindrical samples with different density were tested at 65 and 71 days. Results demonstrated that the compressive strength increased as the density increase. Modulus of Elasticity (E) and Poisson's Ratio are tested for 400, 475, and 600 kg/m^3 following the ASTM C469. The E value for 400 and 475 density is similar or even higher. However, the Poisson's ratio range from 0.19 to 0.28 except for the 400 kg/m^3 sample which has a value of 0.47.

Table 4 Test results of Unconfined Compressive Strength, Modulus of Elasticity and Poisson's Ratio

Density (kg/m^3)	UCS (MPa)	E (GPa)	Poisson's Ratio	Age
400	0.72	0.85	0.28	71
400	0.73	1.09	0.47	65
475	1.43	0.89	0.2	71
475	1.28	0.85	0.19	65
600	2.76	1.33	0.24	71
600	2.44	1.27	0.2	65

The freeze-thaw test has been done on 475 and 575 kg/m^3 density specimens at 28-days based on ASTM C666 Procedure B. Figure 3 and 4 demonstrate the results of the freeze-thaw test. According to the specification, the test should continue until 300 cycles or the relative modulus of elasticity drops to 60% of its initial modulus. It is clear that for both density samples, the relative dynamic modulus of elasticity still exceed 80% after 350 cycles, which notes that the samples have good freeze-thaw resistance.

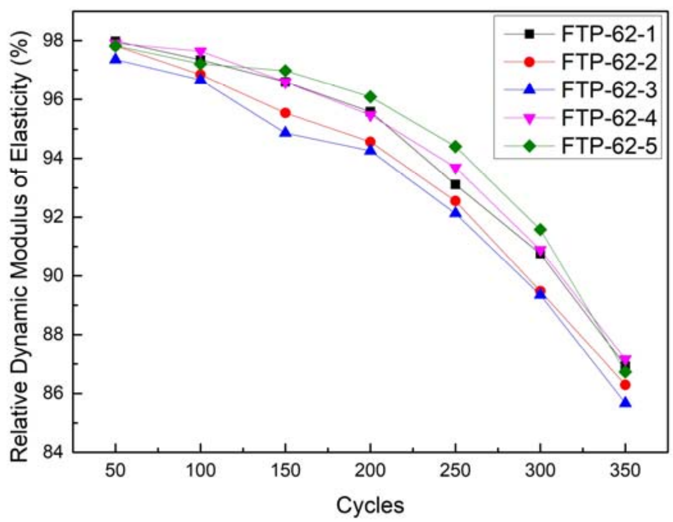

Figure 3 Results of Freeze-thaw test (475 kg/m^3)

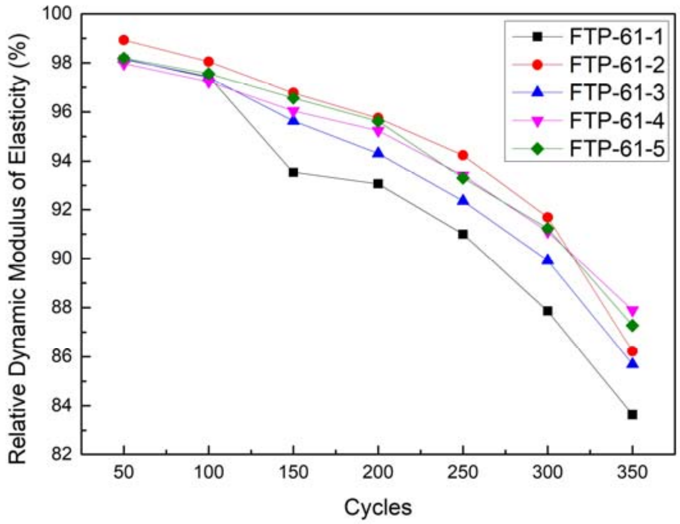

Figure 4 Results of Freeze-thaw test (575 kg/m^3)

The hydraulic conductivity test has been conducted on five specimens with different densities following ASTM D 5084. The results are noted in Table 5. The size of the specimens is 70 mm diameter by 150 mm high cylinder. The test results show there is no direct relationship to density.

Table 5 Test results of Hydraulic Conductivity testings

Density (kg/m^3)	Final Hydraulic Conductivity
400	6.02E-06 cm/s @ 72 mins
405	3.16E-06 cm/s @ 94 mins
475	4.37E-06 cm/s @ 62 mins
475	1.4E-06 cm/s @ 76 mins
600	5.7E-07 cm/s @ 122 mins

Thermal Conductivity tests were done on 400, 475, and 600 kg/m3 specimens. The dimension is 300X300X75 mm for all plate specimens. Two ASTM test standard was applied in this tests, which are ASTM C5334 and C518. Table 6 noted the test results. It is clear that the thermal conductivity of the three density range from 0.05 to 0.09 for ASTM C5334, while test results of ASTM C518 range from 0.076 to 0.101. Both of the results shown the increasing trend as density increase.

Table 6 Test results of Thermal Conductivity test (ASTM C5334 and ASTM C518)

Density (kg /m^3)	Age	C5334	C518
400	38	0.05	0.076
400	38	0.05	0.078
475	38	0.07	0.084
475	38	0.07	0.087
600	38	0.08	0.098
600	38	0.09	0.101

Monotonic direct shear testing had been done on 475 kg/m^3 samples following ASTM D3080. Three 75 mm diameter by 150 mm high cylinder were tested. The monotonic direct shear test had been done on intact, saw cut and cold joint samples with confining stress of 10, 30 and 60 kPa. Table 7 shown the comparison of cohesion and friction angle between LCC and other typical geotechnical materials. It is found that LCC has better cohesion and friction angle than sand, silt, and clay, which could be an alternative material when used in geotechnical applications.

Table 7 Comparison of cohesion and friction angle between LCC and other materials (Ortiz et al. 1986)

Material	Cohesion (kPa)	Friction angle
Sand	0	30-34
Silt	2-3	25-32
Clay	6-10	6-24
LCC (saw cut)	3	43
LCC (cold joint)	33	38
LCC (intact)	7	47
Rock	30,000	49

ANOVA (Analysis of Variances) test has been performed on the above data to examine the influence of density versus other parameters. A significance level of 5% was used in the test, and the results are shown in Table 7. It is clear that the p-value of unconfined compressive strength, Modulus of Elasticity, Resilient Modulus, Indirect Tensile Strength, and Both of the Thermal Conductivity tests have not exceeded 0.05, which indicated that the results are significant and prove that the density of lightweight cellular concrete has an impact on these parameters. This is considered reasonable as these parameter increase as densities increase. However, the p-value of Poisson's ratio is 0.191, this shown that the densities may not influence Poisson's ratio.

Table 7 Results of ANOVA test

UCS vs Density

Source	DF	Adj SS	Adj MS	F-value	P-value
Density	2	3.6417	1.8209	87.4	0.002
Error	3	0.0625	0.0208		
Total	5	3.7042			

E vs Density

Source	DF	Adj SS	Adj MS	F-value	P-value
Density	2	0.2025	0.1013	9.68	0.049
Error	3	0.0314	0.0105		
Total	5	0.2339			

Poisson's ratio vs Density

Source	DF	Adj SS	Adj MS	F-value	P-value
Density	2	0.038	0.0190	3.02	0.191
Error	3	0.019	0.0063		
Total	5	0.057			

Mr vs Density

Source	DF	Adj SS	Adj MS	F-value	P-value
Density	2	283085	141543	49.16	0.000
Error	12	34553	2879		
Total	14	317638			

IDT vs Density

Source	DF	Adj SS	Adj MS	F-value	P-value
Density	2	0.1235	0.0617	51.74	0.000
Error	12	0.0143	0.0012		
Total	14	0.1378			

Thermal Conductivity (C5334) vs Density

Source	DF	Adj SS	Adj MS	F-value	P-value
Density	2	0.0012	0.00062	37	0.008
Error	3	0.0001	0.00002		
Total	5	0.0013			

Thermal Conductivity (C518) vs Density

Source	DF	Adj SS	Adj MS	F-value	P-value
Density	2	0.00052	0.00026	70.41	0.003
Error	3	0.00001	0.000004		
Total	5	0.00053			

4 CONCLUSION

Lightweight Cellular Concrete is an alternative construction material that raised its attention in recent decades. Due to its densities, it could have various application in construction. It has several benefits in construction such as good constructability, self-compacting, environmentally friendly. In this study, tests were performed on low density lightweight cellular concrete (400 to 600 kg/m^3) to evaluate its properties. Findings were listed as below:

- The resilient modulus and indirect tensile strength show good consistency. The test results of resilient modulus shown that the lightweight cellular concrete has a higher value than the typical range for subbase and subgrade materials.
- The result of the freeze-thaw test shown that lightweight cellular concrete still has a value of at least 80% of the relative dynamic of elasticity after 350 cycles. This demonstrates that the lightweight cellular concrete has good freeze-thaw resistance.
- ANOVA test has been performed on the test data, and it is shown that the density of cellular concrete has an influence on Unconfined Compressive Strength, Modulus of Elasticity, Resilient Modulus, Indirect Tensile Strength and Thermal Conductivity, while Poisson's ratio seems does not have a connection with density.

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