Evaluation of Pumice Lightweight Concrete as Material for Thin-Shell Structures

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ABSTRACT

The properties of concrete depend on cement content, water-cement ratio, and the types and mechanical properties of aggregates used. The strength of pumice lightweight concrete is governed by the strength of mortar and pumice aggregates in the mixture. The properties of fresh and hardened pumice lightweight concrete, such as workability, density, compressive and flexural strengths, are among the parameters required in the design of thin shell structures. These parameters, which involved two batches, were dealt with in this research, and the results are in line with American Concrete Institute 318 requirements. Absolute volume methods as stipulated by American Concrete Institute Committee 211.2-98 were used for selecting and adjusting proportions for lightweight concrete. The two hand mixed batches were used to evaluate the concrete. As a result, the excessive pumice lightweight aggregates content of batch No.1 proved to have poor strength. The reduced pumice lightweight aggregates content of batch No. 2 established satisfactory strength results. The average specific gravity and water absorption of pumice lightweight aggregates were 1.1 and 98.3%, respectively. Pumice lightweight concrete achieved a compressive strength of 23.6 N/mm^2 measured at 28 days as compared with American Concrete Institute 318, which requires at least 17 N/mm^2. Pumice lightweight concrete satisfies the requirements of the code for the design of thin shell structures. Therefore, pumice lightweight aggregates can be used as a partial replacement of normal weight aggregates for the design and construction of thin shell structures up to 18.75%.

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1. Introduction

Building and construction activities are as old as human existence, as mankind has always required shelter for residence and activities so as to guarantee survival, safety, comfort, and endurance (Ede, 2011). Some structures are made of reinforced Portland cement concrete and are commonly used worldwide because of the availability, strength, economy, and sustainability of their constituent materials. Gagg (2014) argued that concrete is the most consumed material, with three tons per year used for every person in the world. ACI 225R-19 states that concrete is a composite material that consists of a mixture of hydraulic cement, aggregates, and water, with or without admixtures, fibers, or other cementitious materials. It is one of the basic materials used in construction because of its availability and affordability. The qualities of both fresh and hardened concrete continue to be modified and improved by improvements in concrete technology, according to Ferraris and Gaidis (1992), enhancing the strength, stability, and durability of concrete structures. One of the main goals of a good and effective structural design is to decrease the self-weight of the structure while increasing the mechanical properties and decreasing structural member sizes. Therefore, the use of conventional aggregates in concrete for thin-shell structures is substituted by pumice aggregates. Since pumice aggregates are lighter, they offer a reduced self-weight of the structure. These factors enable structures to be erected in areas with soils of low bearing capacity, which results in low construction costs. The study, therefore, intended to investigate the properties of pumice lightweight concrete for the design and construction of thin shell structures.

1.1 *Pumice lightweight concrete*

Pumice Lightweight Concrete (PLC) is a type of concrete having a lower density than normal concrete, produced from aggregates such as gravel or crushed stones. The ingredients of PLC include Portland cement, pumice stones, pumice sand, pumice powder, pozzolan and water. Lightweight concrete is also defined as concrete with dry densities in the range of 800 kg/m^3 to 2000 kg/m3.

Schlaich and Zareef (2008) and Zongjin Li (2011) defined structural lightweight concrete as having a compressive strength in excess of 17 N/mm^2 with a bulk density of less than 1950 kg/m^3. Clark (2005) states that the density of normal weight concrete ranges from 2200 kg/m3 to 2600 kg/m3.

1.2 *Pumice lightweight aggregates*

There are varieties of lightweight aggregates that can be used in the production of lightweight concrete, such as pumice, scoria, and cinder materials. The final properties of lightweight concrete depend on cement content, water-cement ratio, type, and the mechanical properties of lightweight aggregates. According to the American Concrete Institute, pumice lightweight aggregates can be used for structural applications. ACI 213R-14 specified that structural lightweight concrete with a minimum of 28-days has a compressive strength and density of 17 N/mm^2 and 1840 kg/m^3 respectively. However, pumice lightweight concrete with a compressive strength of less than 17 N/mm^{2}is considered non-structural lightweight concrete. Other properties of pumice lightweight aggregates (PLA) deemed to be important are as stipulated in Table 1. Regardless of these, pumice lightweight concrete is endowed with improved thermal characteristics, such as better fire resistance and dead load reduction, which results in a low cost of labour, transportation, and form-works (Hedjazi, 2019).

1.3 *Thin-shell concrete structures*

A concrete shell, also called a "Thin Shell" concrete structure, is composed of a thin shell of concrete formed in such a way that it is self-supporting, often with no interior columns or exterior buttresses. The shells are most commonly flat plates and domes, which take the form of toroids, conoids, cylindrical shells, or ellipsoids of cylindrical sections (Jyothi, 2015). A reinforced concrete structure with a thin shell has a geometry that is specifically designed to produce membrane forces that support the structure against gravity (Boothby et al., 2005). Boothby et al. (2005) added that some type of edge stiffening utilizing a perimeter beam or diaphragm is necessary if the precisely sculpted curving form of a thin shell is interrupted. During construction, these changes proved to be adequate edge stiffening for the shell. Jyothi (2015) stated that the stability of thin-shell lightweight concrete structures depends on the three-dimensional load-carrying behaviour, which is determined by the geometry of their forms, the nature of the applied load, and thicknesses, which are small compared to other dimensions. Before the invention of lightweight aggregates concrete, normal weight aggregates were used to produce concrete for thin-shelled concrete structures successfully, but with a lot of reinforcement, which was quite heavy compared to lightweight aggregates concrete. Pumice lightweight concrete was successfully designed and constructed in dome roofs, membrane structures, and legendary architectural structures using lightweight aggregates of concrete. Such elegance, economy, and efficiency in buildings have reduced the self-weight of the structure and are more cost-effective than normal-weight concrete.

2. Materials and Methodology

2.1 Materials

Materials used for the production of lightweight concrete are Portland limestone cement class 42.5R, river sand from Mbalizi, pumice lightweight aggregates and water. At Mbeya University of Science and Technology, pumice lightweight aggregates were obtained at a depth of 0.5 m to 1.2 m (Figure 1). The pumice lightweight aggregates used were selected, sieved, and the quantity retained on a 19 mm sieve size was used.

Figure 1
Pumice Aggregates Section. Taking the Measurements to Reveal the Depth of Occurrence of Pumice Aggregates

2.2 Methodology

2.2.1 Gradation

A sieve analysis test was done to determine the particle size distribution of aggregates according to BS 812-103.1: 1985.

2.2.2 Specific gravity and water absorption

The experiments were conducted according to BS 812:2:1995 and ASTM C 567-05. The values for the specific gravity and water absorption of aggregates were measured as essential parameters of the strength or quality of materials.

Table 1
Properties of Pumice Lightweight Aggregates (Shiganza, 2021)

Parameters	Value	Standard value	Reference
Specific gravity(SSD)	1.1	< 2.4 (lightweight)	BS 812: Part 2: 1995
Water absorption [%]	98.3	-	BS 812: Part 2: 1995
Fineness modulus Index	6.8	6.0 – 6.9	BS 812-103.1: 1985
Flakiness Index [%]	25.3	25 % for general work, 30 for road works	BS 812-105.1:1989
Elongation Index [%]	23.0		
Organic Impurities	Orange	Standard materials	Kisunge (2012)

2.2.3 Shape tests

The particle shape tests of aggregates were conducted to determine the percentages of flaky and elongated particles enclosed in the pumice lightweight aggregates in accordance to BS 812-105.1:1989.The values for Flakiness Index and Elongation Index are given by Equation 1 and Equation, 2 respectively.

$$\text{Flakiness index (FI)} = \frac{X_i}{w_i} x100\% \qquad 1$$

$$\text{Elongation index (EI)} = \frac{Y_i}{w_i} x100\% \qquad 2$$

where X_i and Y_i are the weight of the flaky/elongated material passing though the specified gauge from each fraction, W_i is the minimum of pieces from each fraction

2.2.4 Mix design

The proportions of fine to coarse aggregates, cement and water requirements are estimated based on previous experiences with pumice lightweight aggregates (PLC). Step by step mixing design procedures followed the American Concrete Institute Method of Mix Design (ACI Committee 211.1–91) as described by Shetty (2009). The quantities per one cubic meter of Pumice Lightweight Concrete (PLC), estimated mix ratio, and the improved mix ratio are as shown in Table 2 were achieved.

Table 2
Estimated Concrete Ingredients for 1m^3 of PLC

Weight [kg]	Cement	F.A	PLWA	w/c
	529	864	307	185
Estimated Mix ratio	1.0	1.63	0.58	0.35
Improved mix ratio	1.0	1.6	0.6	0.35

2.2.5 Elasticity Modulus

Agreeing to ACI 318-14, the modulus of elasticity of concrete, E_c, shall be permitted to be calculated as the values of density or unit weight (w_c) are between 1440 kg/m^3 and 2480 kg/m^3, the value to be obtained should correlate with values in Table 3. Stiffness of modulus of rigidity is defined as the product of modulus of elasticity and moment of inertia, EI. For lightweight concrete the reduced modulus of rigidity can be of unbeneficial at times, than that in normal weight concrete. Elastic modulus (E_c) was determined using equations (3) or (4), the measured unit weight (w_c) of fresh pumice lightweight concrete was 1938 kg/m^3 (Table 8). From equation (3), the value of E_c, was found to be 13,677,307 N/mm^2 and from equation (4) was found to be 17,822 N/mm^2. These values recite in comparison to the values of E_c found in Table 9. Basically, the lower value of E_c for lightweight concrete means that it is more flexible, it means that these materials can be deformed easily, but the greater the value of E_c, indicate the materials are rigid, then lower value was adopted.

$$E_c = w_c^{1.5} C \sqrt{f'_c} \qquad 3$$

$$E_c = w_c^{1.5} 0.043 \sqrt{f'_c} \qquad 4$$

Where C is a coefficient depending upon the strength of the lightweight concrete required, the value equals 33 and the other values remain as stipulated in Table 9. According to ACI 318, C = 33 when = 23.6 N/mm^2 was used. The modular ratio (m) is the ratio of the modulus of elasticity of steel to the modulus of elasticity of pumice lightweight concrete. The modulus of elasticity of steel is 210,000 N/mm^2 and the modulus of elasticity of pumice lightweight concrete is 17,822 N/mm^2, then "m" is estimated to be 12.

Table 3

Modulus of elasticity concrete and component

	Ordinary concrete [N/mm²]		**Lightweight concrete [N/mm²]**
Aggregates	70 000 – 140 000		14 000 – 35 000
Hardened cement aggregates		7 000 – 28 000	
Concrete	14 000 – 42 000		10 000 – 18 000

Source: Křížová (2015)

2.2.6 Tests on pumice lightweight concrete

2.2.6.1 Compressive strength

The 150 mm × 150 mm × 150 mm concrete cubes were prepared, cured for 3 days, 7 days, and 28 days, and crushed. The weight of the specimen was measured and the density of fresh concrete was calculated. According to the ACI 213R-14 guide for Structural Lightweight Concrete (SLC), there are three different lightweight concrete divisions in terms of strength range and density as shown in Table 4, and the concrete to be used as structural lightweight concrete should meet requirements as stipulated in Table 5, that a compressive strength of 17 N/mm2 and above is recommended.

Table 4

Lightweight Concrete Classification

Strength class	**Compressive strength [N/mm²]**	**Density of fresh concrete [kg/m³]**
Low strength	0.7 - 2.0	300 - 800
Moderate strength	7 - 14	800 - 1350
High strength	17 - 63	1350 - 1920

Source: ACI 213R (2013)

Table 5

Limit For Compressive Strength

Application	**Material**	**Minimum f_c' [N/mm²]**	**Maximum f_c' [N/mm²]**
General	Normal weight and lightweight	17	None
Special moment frames and special structural walls	Normal weight	20	None
	Lightweight	20	35[1]

(1) The limit is permitted to be exceeded where demonstrated by experimental evidence that members made with lightweight concrete provide strength and toughness equal to or exceeding those of comparable members made with normal weight concrete of the same strength.

2.2.6.2 Tensile strength

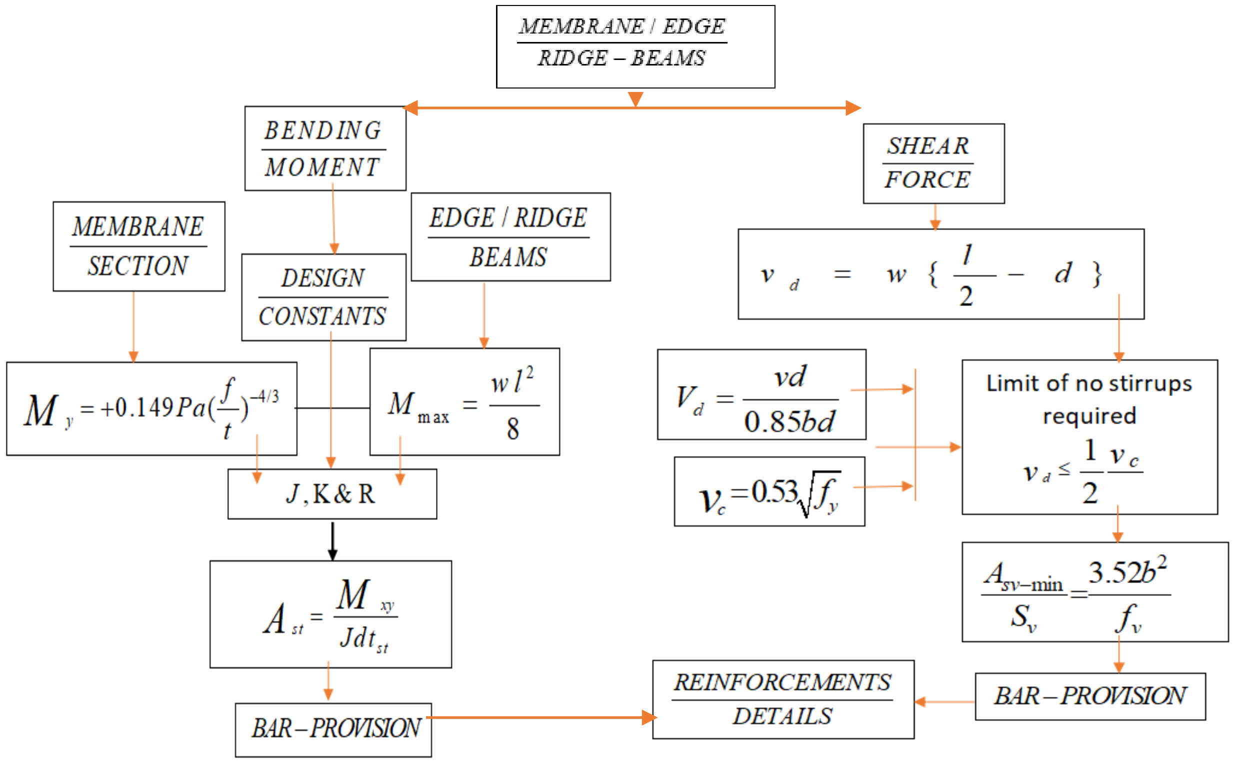
The determination of tensile strength of the test of unreinforced pumice lightweight concrete was done by a flexural strength test. The three-point flexural strength test was done on a beam of 100 × 100 × 500 mm, for the trial mixes 01 and 02 as stipulated in Table 8.The modulus of rupture (MoR) was calculated by the relation (N/mm^2), where the maximum load ***P*** was applied at the center of the test specimen at a rate of 6.75–6.90 kN/sec until failure. The failure load was recorded for estimating the resistance and durability of concrete by determining the modulus of rupture (Table 8). L is the length of the specimen; b and d are the beam's breadth and depth, respectively.

2.2.7 Typical design of thin-shell structures

The design of sophisticated shell structures requires a combined knowledge of architectural and structural. A structural shell design normally involves a series of activities as specified by Farshad (1992) as follows:

i. The choice of a shell geometry which meets the overall architectural requirements;
ii. Selection of the shell's and its supporting members' dimensions;
iii. Preliminary analysis and design of the edge and ridge boundaries of the shell;
iv. Comprehensive analysis and detailed design of the shell; and
v. The structural system

In shell structures, the shell body is only an element of the whole structural system. The membrane shell is usually accompanied by strengthening members such as edge and/or ridge beams. The structural unity of these elements is of major importance. To ensure the integrity of the structure as a whole, the analysis and design of structural systems is based on the working stress (WS) method as stipulated by Durka *et al*. (1996). The WS method is the traditional method of design used for reinforced concrete, steel and timber construction. The conceptual basis of the WS method assumes that the structural material obeys Hooke's law and that appropriate safety can be ensured by suitably limiting the stresses to the material strength and the working loads (service loads). Step by step, highlighted procedures are explained in a flow diagram with typical formulae.



2.2.8 Design parameters of thin shell

Pumice lightweight concrete meets the requirements of ACI 213R-03 for durability and thin shell strength. The load analysis and design parameters desirable for thin shell structures are compressive strength, tensile strength, modulus of elasticity, and modular ratios. For the present study, the membrane and its membrane boundary elements were designed by following the Working Stress Method (WSM) as explained in section 2.2.7. Preliminary member sizing and load analysis were calculated by following procedures as stipulated by Mosley *et al.* (1999).

2.2.9 Mix design

The strength of concrete is controlled by the mixing proportioning characteristics of the concrete ingredients (Table 6). All the procedures for mix design were according to Shetty (2009).

Compressive strength (fc′) levels commonly required by the construction industry for design strengths of cast-in-place, precast, or pre-stressed concrete are economically obtained with lightweight concrete (Shideler 1957; Hanson 1964; Holm 1980a) as cited by ACI 213R-03. ACI 318-14:

Building Code Requirements for Structural Concrete specifies the value of fc′, which must be in accordance with (a) through (c):

a) Elastic modulus and compressive strength limits are specified in Tables 3 and 5, respectively.
b) The durability requirements outlined in section 2.2.8.2; and
c) The structural strength requirements outlined in Section 2.2.8.3.

Table 6
Concrete Ingredients

Ingredients	Trial Mix 01	Trial Mix 02
Pumice aggregates[kg/m^3]	308	307
Fine aggregates[kg/m^3]	1039	864
Cement content[kg/m^3]	411	529
Water content[kg/m^3]	185	185
Air entrapped (%)	2	5
Water/cement ratio	0.45	0.35
Mixing ratio	1:2.53:0.75	1:1.63:0.58

2.2.9.1 Concrete durability requirements

The resistance of the concrete to fluid penetration affects the durability of concrete. This is primarily affected by the w/c ratio and the composition of cementitious materials used in concrete. The code emphasized the w/c ratio for achieving low permeability to meet durability requirements. Because determining the w/c of concrete is difficult, the value of fc′ chosen should be consistent with the maximum w/c ratio required for durability. Maximum w/c ratio limits are not specified for lightweight concrete because the amount of mixing water that is absorbed by the lightweight aggregates makes the calculation of w/c indeterminate. As a result, the minimum fc′ requirement is used to ensure high-quality cement paste, exposure categories, and concrete cover for thin shells as defined by ACI 318-14. For the design purposes of concrete and reinforcement, the concrete strength was set at 23.6 N/mm^2 at 28 days and a 460 N/mm^2 characteristic strength was adopted.

2.2.9.2 Structural strength requirements

The use of pumice lightweight concrete in the design of thin-shell combines strength, stability, and consideration of the effects of the expected eccentricity of the geometry of the shell surface; the inconsistency in curvature; inflexible properties of materials; cracking of hardened concrete; and possible deformation of supporting elements. To improve the resistance to buckling, the provision of two mats of reinforcement is required; one near each outer surface of the shell and the other at the middle of the membrane, increasing the rise of the shell so as to reduce the bending moment so as to increase the load carrying capacity of the compression member.

3. Results and Discussion

3.1 Pumice lightweight aggregates.

A sieve analysis test of pumice lightweight aggregates was done. The particle size distribution and fineness modulus (FM) measured were 6.81 as shown in Table 8. Most of the aggregates range between 5 mm and 10 mm. It is where the graph is slightly flat (Figure 2), thus the average gradation line, and the results demonstrate the aggregates are coarse. Pumice absorbs excessive water (98.3%), which should be considered during concrete mix design, production, and construction. In addition, since the water absorption of pumice aggregates is quite high, in order to maintain the concrete strength, the aggregates should be kept cool; rapid hardening of concrete should be avoided as it may lead to cracking and loss of strength.

3.2 Flakiness and Flakiness Indexes

Basing on test results, the flakiness index of 25.3 % and the elongated index of 23.0 % were found and are both less than 30%, which is good according to BS 812-105.1:1989. The high percentage of flaky and elongated particles in the mix reduces the strength and workability of concrete.

Table 7

Particle Size Distribution

Sieve size (mm)	Mass retained (g)	Mass Retained %	Cum. Mass Retained %	Mass Passing %	Specification Limits	
75.0				100.0	100	100
37.5	17.0	1.5	1.5	98.5	95	100
19.0	419.1	37.2	38.8	61.2	40	85
9.5	360.1	32.0	70.8	29.2	20	55
4.75	111.9	9.9	80.7	19.3	10	30
2.36	140.8	12.5	93.2	6.8	-	-
1.18	49.7	4.4	97.6	2.4	-	-
0.6	18	1.6	99.2	0.8	-	-
0.3	4.4	0.4	99.6	0.4	-	-
0.15	*4.3*	0.4	100.0	0.0	-	-
Mass Passing Through 75µm m4 (g).	0	0.0	100.0	0.0	-	-
Total passing 75µm m3+m4 (g).	1125.3	100.0	6.81	0.0	-	-
Fineness Modulus (FM)			6.81			

Figure 2

Gradation Curve

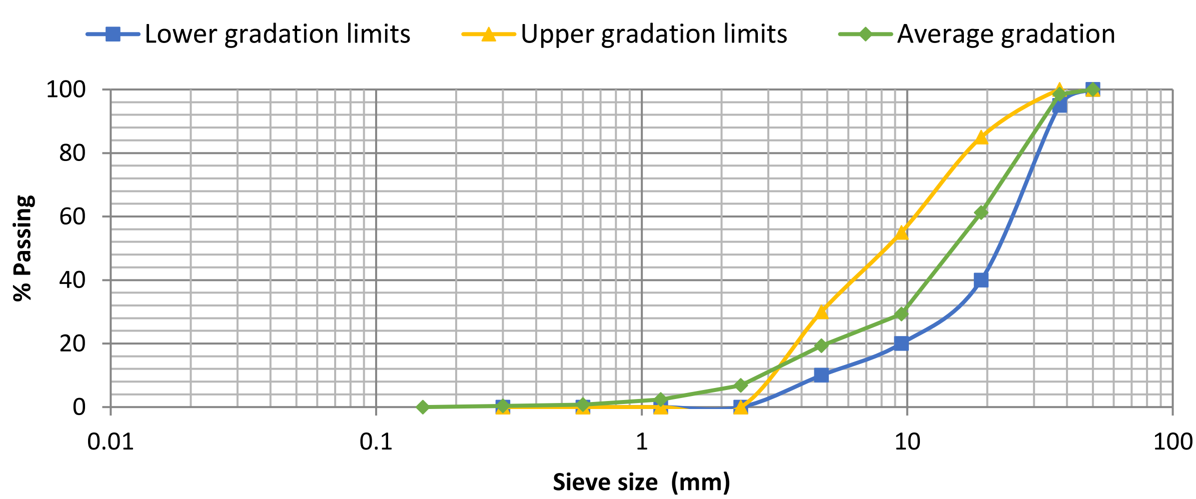


Table 8
Properties of Pumice Lightweight Aggregates and Pumice Lightweight Concrete

Property	**Trial mixes result**		**Standard**
	Mix 1	**Mix 2**	
Flakiness index of aggregates [%]	-	25.34	BS 812-105.1:1989
Elongation index of aggregates [%]	-	23.00	BS 812-105.1:1989
Density of fresh concrete [k/mm^3]	1,753	1,938	ACI 213R (2013)
Density of hardened concrete [k/mm^3]	1864	1947	BS 812: Part 2: 1975
Specific gravity of concrete	-	1.13	BS 812: Part 2: 1975
Absorption of aggregates [%]	-	98.35	BS 812: Part 2: 1975
Compressive strength of concrete [N/mm^2]	16.88	23.60	ACI 213R (2013)
Tensile strength of concrete [N/mm^2]	14.49	16.57	ACI 213R (2013)
Fineness modulus of aggregates	-	6.81	ASTM C33

3.3 Strengths of pumice lightweight concrete

Two batches of pumice lightweight concrete were made (Table 6). The mixes were used to evaluate the properties of fresh and hardened concrete, which were then analyzed based on the specification limits specified in section 2.2.6; the strength of pumice lightweight concrete for compression and tensile in comparison to mechanical properties as shown in Table 8. The strength of concrete increases rapidly in parallel with an increase in the volume of cement and a reduced volume of fine aggregates. The reduced volume of pumice lightweight aggregates and the increased volume of Portland cement in the mixing ratio, the compressive strength increased from 16.88 N/mm^2 to 23.60 N/mm2, the tensile strength increased from 14.49 N/mm^2 to 16.57 N/mm2, and the measured density of fresh concrete increased from 1753 kg/m^3 to 1938 kg/m^3 while the density of hardened concrete ranged from 1864 kg/m^3 to 1947 kg/m^3 (Table 8). As the results, the mix with the highest compressive and tensile strengths is in the range of the required values for structural lightweight concrete, Trial mix 02.

3.4 Typical design calculation results

3.4.1 Design results

As a result, from calculated moments of force, the area of reinforcements provided is Y10-125 (1,256 mm^2) to frustrate a sagging moment of 948,000 N-mm on the membrane shell at both the top and bottom of the membrane layers. The moments stressed the edge beams and ridge beams are 19.328 kN-m, and 28.125 kN-m, consequently, the area of reinforcements of 3Y20 (943 mm2) and 4Y20 (1,260 mm2) at the bottom of beams were provided to counteract the beam's sagging moments, the area of reinforcements 3Y16 (603 mm2) and 2Y20 (628 mm2) provided at the top of beams to exaggerate the hogging moments respectively, were adopted. Since the limit of no required stirrups was reached, the minimum shear reinforcements were required—stirrup diameter of 10 mm and spacing of 90 mm (Y10–90) were also adopted for the purpose of preventing diagonal tension cracks.

3.4.2 Pumice lightweight concrete in design of thin shell

The application of thin shell is then fulfilled by the specific objectives of this thesis. Both pumice lightweight aggregates and pumice lightweight concrete, the parameters of which are subjected to laboratory experiments, are within the required specification limits as required by *Building Codes Requirements for Structural Concrete (ACI 318-11), an ACI Standard and Commentary.* The parameters needed for designing a thin shell, such as modulus of elasticity, modular ratios, and strengths attained, the analysis of the structural loading and concrete structural design was carried out using working stress methods and BS 8110. The study concluded by applying the intended parameters in the design of thin-shell concrete structures.

4. Conclusions and recommendations

4.1 Conclusions

The findings show that pumice lightweight concrete has the desired strength and can be used as an alternative material for the construction of thin-shell structures. The modified pumice lightweight concrete mix ratio of 1:1.6:0.6, that is, cement, sand and pumice aggregate parts, demonstrated satisfactory results. It is suitable for use in the design of thin shell structures. Under good design and construction, pumice lightweight concrete can suitably be used to enhance structural integrity and constructional value.

4.2 Recommendations

It is therefore recommended to Structural Engineers, Architects, Quantity Surveyors, Contractors, and Consultants and other Construction industry stakeholders to realize the exclusive returns and emphasize on the technology of using pumice lightweight concrete as structural materials. More research is required to pave the way for the utilization of pumice lightweight concrete in high-strength, high-performance, and ultra-high strength-performance concrete.

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Appendix

Typical example of thin-shell concrete structure design

Farshad (1987) argued that the choice of thickness of thin-shell concrete is based on stability and construction requirements. The application of established parameters is fulfilled by the ACI 318-14 requirements as described in section 2.2.8. The stresses in a reinforced concrete shell under normal loading are usually smaller compared to the criteria to be satisfied. The general guideline requires a thickness to chord width ratio of considered sound choice for concrete shell thickness and puts the actual shell well in the range of being "thin shell" structures.

Hyperbolic paraboloid shell roof

The research addresses the design of a hyperbolic paraboloid (HP) shell roof of multipurpose usage, which covers a space of 44 m2 (Figure 3).

HP shell roofs are lightweight shell structures whose structural members (tie beam, edge beam, and ridge beam) develop their stability from the form and not the weight. HP is among the anticlastic shell types which are used for large column free areas with very small slab thicknesses. An anticlastic shell type is selected for the purpose of reducing the self-weight of the concrete roof by using reinforced Pumice Lightweight Concrete (PLC) properties (Table 8). The form of the roof offers high load-carrying capacity with more space than any other similar types of roofs. Consider the parameters given in Table 8 and the hyperbolic shell roof shown in Figure 3. The whole shell structure rests at its four corners on vertical column supports. The applied loading is uniformly distributed with intensity P on the straight line generator of the shell.

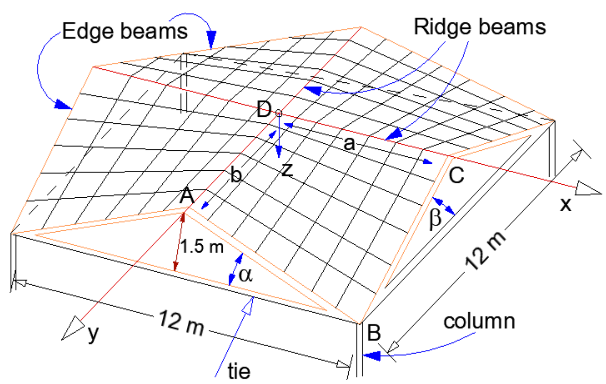
Table 9

Design Parameter

	f_{st} [N/mm²]	f'_c [N/mm²]	λ < 1	MoR [N/mm²]	E_c [N/mm²]	Fineness Modulus [FM]	Modular ratio [M]
Average Values	16.57	23.60	0.509	18.545	17,822	6.81	12

Figure 3

A Combined Hyperbolic Shell Roof Composed of Four Hyper Units



Preliminary load analysis

The analysis of the load-carrying capacity of a structure in any method should be the same as for normal weight concrete. The determination of design constants should be based on the lightweight concrete obtained from laboratory experiments. As far as the elastic modular materials are concerned, the estimated modular ratio m≈ 12, thus: modulus of elasticity ofsteel reinforcement is 210,000 N/mm² and the short-term static modulus of elasticity of pumicelightweight concrete is 17,822 N/mm² (section2.2.5). The permissible tensile stress in the steel is 140 N/mm² and the permissible compressive stress for the concrete is 7 N/mm².

By using the constants established in the working stress method,

Let $\mathcal{K}$ and $\mathcal{J}$ indicate the characteristic parameters identifying the location of the neutral axis and the lever arm of the moment due to internal forces. Then, from the highlighted expressions:

$$K = \frac{1}{1+\dfrac{t_{st}}{mP_{cb}}} = \frac{1}{1+\dfrac{140}{12\times 7}} = 0.375$$

$$J = 1 - \frac{K}{3} = 1 - \frac{0.375}{3} = 0.875$$

$$R = 0.5P_{cb}JK = 0.5\times 7\times 0.875\times 0.375 = 1.148$$

For the selected L = 12 m, the h/12 = 0.17, value of h = 2.04 m. Consider the minimum

f = 1.5 m and a =b = 6.0 m.

Estimated value of shell thickness t = 90 mm, Using BS 8110, imposed loads of shell roof (12 m × 12 m) equals to 1.5 kN/m². Expected dead load from finishes is1.5 kN/m².

The estimated dead load from membrane is given by:

$$= 0.09\times 24 = 2.16 kN / m^2$$

Total dead load = 1.5 + 2.16 = 3.66 kN/m²

The ultimate design load

$$P = 1.4\times 3.66 + 1.6\times 1.5 = 7.524 kN / m^2$$

Shear force $N_{xy}$from:

$$\tau = -\frac{ab}{2f}P = -\frac{6\times 6}{2\times 1.5}\times 7.524 = -90.288 kN / m$$

The principal stresses related with this internal force can be obtained from the relationship:

$$\tau\sigma = N_{xy} = -90.288 kN / m$$

From which applied shear force is found as:

$$\sigma = \frac{N_{xy}}{t} = \frac{-90.288}{0.09} = \pm 1,000.32 kN$$

Design of membrane section

Design moment

The shell membrane is hinged at the edge; as a result, the maximum moment will occur at y_1 distance from the edge:

$$y_1 = 0.55a\left(\frac{f}{t}\right)^{-1/3} = 0.55\times 6\left(\frac{1.5}{0.09}\right)^{-1/3} = 1.292m$$

Then, the maximum moment stressed by the membrane shell

$$M_y = 0.149\times 7.524\times 6^2\left(\frac{1.5}{0.09}\right)^{-4/3} = 0.948\text{kN-m}$$

Since, the bending moments are reduced by increasing the shell rise, as the results the moments attained are too small to course large effects on the entire structural system.

Area of reinforcements

The reinforcing steel ratio required along the straight-line generators, can be calculated as:

$$A_{st} = \frac{M_{xy}}{Jdt_{st}} = \frac{0.948\times 10^6}{0.875\times 140\times 7} = 1{,}106mm^2$$

By comparing the required area of steel ratio with the minimum required area of steel ratio:
Percentage,

$$\rho_{st} = \frac{1{,}106}{150\times 70} = 0.10533 > 0.00365(\rho_{\min})$$

Then, provide Y10 @ 125 (1,256 mm^2) in two (2) layers top and bottom of reinforcement.

Design of edge beams

Establishing of edge beam

Maximum moment ($M_{\max}$) will occur at the mid span of edge beam.

$$M_{\max} = \frac{wl^2}{8} = 7.524\frac{(\sqrt{1.5^2+6^2})}{8} = 5.817\text{kNm}$$

Equating the Moment of resistance with the maximum moment obtained:
$M_r = Rbd^2 = 5.817\text{kN-m}$, the depth (d) of the beam approximately will be 184 mm in order to be sure of the size of beam's depth. Assume the concrete cover of 20 mm, the main bar of 25 mm diameter and 8 mm diameter of stirrup bars, beam height of 250, then the effective depth of the beam (**d**) is given from the following relationship:

$$d = h - \text{cover} - \frac{1}{2}dia._{main} - dia._{links}$$

Then; the obtained beam depth (d) is 210 mm and the beam's size is 150 mm × 250 mm was provided.

Design loads of edge beams

Design load expected is from slab and beams self-weight. Established edge beams size is 150 mm × 250 mm, unit weight of concrete equals to 24 kN/m^3, the beam self - weight equals to:-

$$0.15\times 0.25\times 1.4\times 24(\sqrt{1.5^2}+6^2) = 7.793\text{kN/m}$$

Loads from membrane slab equals to

$$7.524\times 1.5\times 1.5 = 16.929\text{kN}$$

Total dead weight equals t:

$$7.793 + 16.929 \approx 25\text{kN}$$

Maximum moment

Maximum moment ($M_{\max}$) will occur at the mid span of edge beam, the span of beam is at an angle to straight line generator, then;

$$M_{\max} = \frac{wl^2}{8} = 7.524\frac{(\sqrt{1.5^2+6^2})}{8} = 19.328\text{kN-m}$$

Check for Lateral Stability

The lateral restraints have been provided at the center 6m from the supports

$L_{ef} = 6m < 60b = 60\times 0.15 = 9\text{m}$ and

$L_{ef} \le \frac{250b^2}{d} : 6m = \frac{250\times 0.15^2}{210} = 26.79\text{m}$,

It meets both criterions.

Area of reinforcements

Area of reinforcements for the edge beams:

$$A_{st} = \frac{M_{\max}}{Jdt_{st}} = \frac{19.328\times 10^6}{0.875\times 140\times 210} = 751mm^2$$

Comparing the required area of steel ratio with the minimum required area of steel ratio;
Percentage,

$$\rho_{st} = \frac{751}{150\times 210} = 0.02381 > 0.00365(\rho_{\min})$$

As a result,
Provide 3Y20 (943 mm^2) at the bottom and 3Y16 (603 mm^2) at the top of the edge beam.

Design of ridge beams

Design Load of ridge beams

Design load expected is from slab, beams self-weight and point load from cross beam. Established ridge beams size is 150 mm × 250 mm, unit weight of concrete equals to 24 kN/m^3, the beam self - weight equals to

$$0.15\times0.25\times6\times1.4\times24=7.56\text{kN}$$

Loads from membrane slab equals to

$$7.524\times1.5\times1.5=16.929\text{kN}$$

Total dead weight from beam self-weight and membrane is approximately equals to 25 kN

Add half of point loads from the same (ridge beam), as the results: the total dead weight to be carried by ridge beam equals to 37.5 kN

Maximum moment

Maximum moment (M_{max}) will occur at the mid span of ridge beams, the span of ridge beam is in line with straight line generator which is 6 m. Maximum moment (M_{max}) is

$$\frac{wl^2}{8}=\frac{37.5\times6^2}{8}=28.125\text{kN-m}$$

Area of reinforcements

Area of reinforcement will be given by the following relation:

$$A_{st}=\frac{M_{\max}}{Jdt_{st}}=\frac{28.125\times10^6}{0.875\times140\times210}=1,093mm^2$$

As the results; Provide 4Y20 (1,260 mm^2) at the bottom and 2Y20 (628 mm^2) at the top of the ridge beams.

Shear bar of edge and ridge beams

According to ACI code of practice of reinforced concrete, the design elements are shown in Figure 4.

Maximum shear force

Maximum shear force at the face of column is

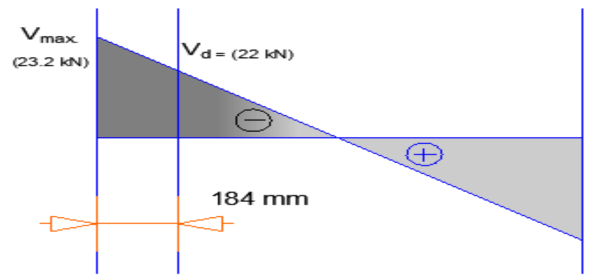
$$v_{\max}=\frac{wl}{2}=\frac{7.524\times6.185}{2}=23.2\text{kN}$$

But the design shear is to be assumed from a distance equal to the effective depth **d** from the face of support. Design shear force,

$$v_d=w\left(\frac{l}{2}-d\right)=7.524\left(\frac{6.185}{2}-0.21\right)=22\text{kN}$$

Figure 4

Shear Force Diagram



Design shear stress

$$v_d=\frac{v_d}{0.85bd}=\frac{22\times10^3}{0.85\times150\times210}=0.82\text{N/mm}^2$$

The calculated shear stress, as compared to shear stress carried by the concrete

$$v_c=0.53\sqrt{f_y}=0.53\sqrt{460}=11.37\text{N/mm}^2$$

The limit of no required stirrups.

$$v_d\le\frac{1}{2}v_c$$

$$0.82\text{N/mm}^2\le\frac{1}{2}\times11.37=5.68\text{N/mm}^2$$ Then;

$$0.82<5.68(kN/\text{mm}^2)-Ok$$

The minimum shear reinforcements required;

$$\frac{A_{v-\min}}{S}=\frac{3.52b^2}{f_y}$$

Spacing of shear stirrups by the relation,

$$S = \frac{d}{2} \, or \, \frac{d}{4} \, if \, (v_d - v_c) > 1.06\sqrt{f_y}$$

Since $(v_d - v_c) > 1.06\sqrt{f_y}$ $S = \frac{d}{2} = 105mm$

then;

$$A_{v-\min} = \frac{3.52b^2}{f_y} = \frac{3.52 \times 150^2}{460} = 172.17\text{mm}^2$$

$$= \frac{A_{v-req.}}{S_v} = \frac{172.17}{105} = 1.640$$

From Table A.4 BS8110,

$$\frac{A_{v-prov.}}{S_v} = 1.740$$

Provide Y10 – 9