STRENGTH ENHANCEMENT AND COST ANALYSIS FOR LIGHTWEIGHT FOAMED CONCRETE IN RESIDENTIAL BUILDINGS

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ABSTRACT

This study presents a primary batch of results for an ongoing extensive experimental program related to protein based foamed concrete. Compressive strength is herein investigated as a function of dry density, water content, curing conditions, cement type and, most importantly, foaming agents (employed in the cement paste). Structural Foamed Concrete (SFC) was investigated using a fixed water/cement ratio, CEM I-52.5 N cement, wet-burlap (23 ± 3°C) curing conditions, variable polypropylene fiber content (calculated as a percentage of cement content). Initially, three different foaming protein-based agents were utilized/tested, prior to selecting the agent yielding the highest concrete compressive strength; the latter agent continued as a fixed parameter in the current investigation. This experimental study comprises ninety six (96) foamed concrete specimens with a dry density ranging from 1500 to 1600 kg/m^3. The different polypropylene fiber percentages were investigated to enhance the compressive and tensile strength/properties. Results showed that the optimal polypropylene fiber – cement content based (by weight) - dose of 0.3% yields a 32% increase and 27% increase for compressive and tensile strength, respectively. Furthermore, on utilizing the outcomes of the material testing program – for a hypothetical cost analysis study related to a seven-storey building of 400 m^2 footprint – a 3 % construction cost reduction is obtained; noting that significant energy savings are anticipated on using foamcrete for slab elements.

Keywords: Foamed concrete, polypropylene fibers, mechanical properties, compressive strength, tensile strength, stress-strain, construction cost reduction.

1. INTRODUCTION

Lightweight foamed concrete (LWFC) is a cellular cementitious material obtained by introducing preformed foam into the cementitious matrix. This combination gives rise to the development of air voids within the underlying microstructure of the material. In turn, this yields a series of advantageous properties including: 1) low self-weight, especially for low densities [1], [2], which is important for refurbishment operations; also lessening the overall loads in buildings; 2) thermal insulating characteristics and acoustic absorption [3], [4], which are useful for realizing partition walls and infills to meet the increasingly demanding requests from the perspective of energy performance of buildings; 3) fire resistance [5], which is also a desirable feature in infills walls; 4) workability [6]. Additionally, enhanced variants of LWFC may also include other constituents that replace a portion of traditional aggregates; contributing towards higher strength and durability of the material; such as fly ash and silica fume [7]; or recycled components like electric arc furnace slag [8], [9], recycled glass; or foundry slag [10], which comes in-line with the sustainable re-use of by-products from other manufacturing processes.

Despite all advantageous traits mentioned above, achieving a compressive strength that is comparable to conventional concrete has always been paramount for researchers in the foamcrete field. The low compressive strength of foamcrete has always been a challenge that impaired its application in several venues. Thus, the experimental program herein, presents one means of strength enhancement of foamed concrete (using polypropylene fibers). The outcome (mechanical properties/parameters) is consequently utilized to model the slab elements within an eight-story residential building, now comprising both foamcrete and conventional concrete elements. Cost analysis is undergone on material savings; noting that energy savings also exist for such a replacement of foamed concrete to conventional concrete, in slab elements.

2. EXPERIMENTAL PROGRAM

In addition to the three samples of the preliminary – foaming agent selection phase - this program comprises a total of 96-foamed concrete samples: 84 cubes for compression; 12 for splitting (tensile). For the compression tests, three cube sizes are considered. (50 x 50 mm, 100 mm x 100 mm and 150 mm x 150 mm), per test, to infer upon the mold/size yielding best results; whilst noting that the dimensions for all samples are presented in subsequent sections; abiding by ASTM C513/C513M for compression test samples; ASTM C192/C192M and ASTM C496/C496M for the splitting tests.

2.1 Material Properties

Herein, a variety of materials are used for casting the aforementioned samples (See Table 1): Foaming agent(s), Water, Cement, Filler 1 (Calcium Carbonate), Filler 2 (Sand), Additive 1 (compressive strength enhancer & shrinkage reducer) and Additive 2 (Polypropylene fibers). The tailored inorganic hydrocarbon chain material (MICROCORE® T500) is selected to undergo the current experimental campaign, based on the preliminary batch tests (See Table 3). Herein, three patented foaming agents are considered: (i) MICROCORE® T500; an adapted hydrocarbon chain groupwith the advantage of producing a stable foam of density 40 to 80 gm/liter, (ii) Lithofoam SL-200; an alkali resistant foam forming agent based on highly active proteins (i.e. polymers existing in a natural state composed of 20 different amino acid monomers); also producing stable foam, and (iii) Mastercell 10; a protein-based concentrated liquid foaming agent that produces rheoplastic lightweight foam. Ordinary Portland cement CEM I 52.5 N conforming to Egyptian Standard norm 4756-1/2013 and technically complying with BS EN 197-1/2011 is used for all samples. Calcium carbonate ($CaCO_3$) serves as the primary filler agent, along with sieved sand (filler 2), both used for all samples. The latter is less than 800 μ in diameter, passing through sieve no. 25 with a bulk density 1.55 t/m^3, according to EN 1097-3. The incorporated additives comprise: (i) compressive strength enhancer & shrinkage reducer and (ii) polypropylene fibers of 12 mm length, 34 μ in diameter and a Young’s modulus of 3750 MPa (See Figure 1). Whereas the foaming agent is, in fact, an adapted hydrocarbon chain group beholding the advantage of generating stable foam of density 40 to 80 gm/liter.

Figure 1: Incorporated polypropylene fibers (12 mm in length and 34 μ in diameter)

Table 1: Foamed concrete components & target mix design leading to the selected foaming agent (see shaded area)

Component	**Unit**	**Mix**		
		Mix # 1	**Mix # 2**	**Mix # 3**
Cement	Type	OPC 52.5 (N) - Bani Suif		
	Quantity (kg)	700		
Water	Quantity (kg)	262.5	270	272.5
Filler (1)	Type	$CaCO^3$ < 150µ		
	Quantity (kg)	300		
Filler (2)	Type	Sand < 800 µ		
	Quantity (kg)	300		
Additive (1)	Type	MICROCORE®□ C4T	LithoPore NWFs	N.A
	Quantity (kg)	7	3	0
Additive (2)	Type	Polypropylene Fiber 12mm		
	Quantity (kg)	2		
Foam	Type	MICROCORE®□ T500	LithoFoam SL-200	Protein Foam
	Density (gm/L)	80	80	80
	Volume (L)	245	310	300
	Weight (kg)	19.6	24.8	24
Fresh Density (Kg/m^3)		1591.1	1599.8	1598.5
Actual Fresh Density (Kg/m^3)		1581	1597	1610
Actual Dry Density (Kg/m^3)		1438	1445	1476
Average Compressive Strength (MPa)		25.45	13.86	5.5

2.2 Foamed concrete Mixing

The process comprises blending of Portland CEM I 52.5 N, calcium carbonate and sand (altogether) with tap water until a homogeneous paste is reached. This is followed by the addition of the protein-based foaming agent, according to the pre-set mix design in Mix # 1 of Table 1; ultimately, generating a stable foam that results consequently in a consistent foamed concrete paste.

2.3 Specimens, Instrumentation and Test Procedures

For all tests displayed herein, a universal testing machine (UTM) ELE of 2000 kN loading capacity and an automatic TDS-530 data logger were deployed for specimen-loading and accurate strain-measurement, respectively. (i) According to ASTM C109, compressive tests were conducted onto a total of 84 cube samples, comprising variant fiber percentages; cast in 50 mm, 100 mm and 150 mm molds; tested at 7, 28 and 90 days (See Table 2). A loading rate of 1.4 kN/sec was applied, with a set point of 0.1 kN, until peak load at failure is reached and recorded; (ii) For splitting (tensile) tests: As per ASTM C192/C192M and ASTM C496/C496M, twelve cylindrical samples of dimensions 3" x 6" (76.2 mm x 152.4 mm) were experimented with axis normal to loading direction, using the aforementioned ELE 2000 kN at a loading rate of 1.1 kN/sec until failure.

Table 2: Experimental program comprising the number of samples per test-set and related parameters

Parameter	**Sample**	**Size**	**Testing Age**			**P. Fibers**
		(mm)	**7 days**	**28 days**	**90 days**	**%**
Phase 1: Compressive Strength (Cubes)	Cu 1 - 9	50 x 50	3	3	3	zero
	Cu 10 - 18	100 x 100	3	3	3	zero
	Cu 19 - 21	150 x 150	-	3	-	zero
	Cu 22 - 30	50 x 50	3	3	3	0.1
	Cu 31 - 39	100 x 100	3	3	3	0.1
	Cu 40 - 42	150 x 150	-	3	-	0.1
	Cu 43 - 51	50 x 50	3	3	3	0.3
	Cu 52 - 60	100 x 100	3	3	3	0.3
	Cu 61 - 63	150 x 150	-	3	-	0.3
	Cu 64 - 72	50 x 50	3	3	3	0.5
	Cu 73 - 81	100 x 100	3	3	3	0.5
	Cu 82 - 84	150 x 150	-	3	-	0.5
Phase 2: Tensile Strength (Cylinders)	Cl 1 – 3	76.2 x 152.4	-	3	-	zero
	Cl 4 – 6	76.2 x 152.4	-	3	-	0.1
	Cl 7 – 9	76.2 x 152.4	-	3	-	0.3
	Cl 10 - 12	76.2 x 152.4	-	3	-	0.5

3. RESULTS AND DISCUSSION

3.1. Compressive Test Results and Discussion

As per Table 2, the number of replicates/samples per test is indicated. Each test-set is defined by three parameters: (i) sample size, (ii) percentage of P. fibers and (iii) age at testing (e.g. three replicates are assigned to 100 x 100 mm foamcrete cubes; comprising 0.3% P. fibers; at 28 days, respectively). In turn, a total of 84 samples were cast in Phase 1 of this research effort (See Figure 2), wherein the effect of the aforementioned parameters is observed. Figure 3 displays the compressive strength values for 50 mm^3 samples (i.e. 50 x 50 x 50 mm) and 100 mm^3 samples at age(s) of 7 days, 28 days and 90 days; each comprising the aforementioned P. fiber percentages (zero, 0.1%, 0.3% and 0.5%). It is evident that the 100 mm^3 samples yield compressive strength (f_{cu}) values, higher than their 50 mm^3 counterparts, particularly at 28 and 90 days, by values ranging from 2 to 3 MPa. Furthermore, on comparing the results of the three different mold sizes (50 mm^3, 100 mm^3 and 150 mm^3) at 28 days: 100 mm^3 cubes yield a moderately higher f_{cu} (> 7%) than their lesser 50 mm^3 and bigger 150 mm^3 counterparts; more pronounced in mixes comprising 0.3 and 0.5 % polypropylene fibers. This comes in agreement to the experimental results of Mydin et al.[11], wherein the 100 mm^3 cube yields f_{cu} values greater than that of 50 mm^3 and 150 mm^3 cubes by 16.25% and 12.25%, respectively. Hypothetically, compressive strength decreases with the increase of concrete specimen dimension – as per M. Dehestani et al. [12] – which justifies the f_{cu} decrease or the 150 mm^3 cube. As for the 50 mm^3 cube, this unanticipated decrease could be attributed to the high stress concentration onto the limited (non-representative) cross-section; which could be rectified should a mortar-cube compression test device replace the (UTM) of 2000 kN capacity. In turn, the 100 mm^3 cube can be considered as the most-representative sample size, given the size of comprised fine aggregate (< 20 mm; See BIS: 516) as well as the optimal yielded compressive strength value(s).

Cube Samples (Variant Sizes) **Brazilian Test Set-up**

Figure 2: Compressive strength samples (left) and tensile testing sample (right)

On the other hand – and on comparing the effect of variant PP-fiber percentages onto the 100 x 100 x 100 mm foamcrete cube-samples (See Figure 3) – it is witnessed that the f_{cu} values of 0.3 % PP-fiber are either greater than that of 0.5% PP-fiber or equal, for 50 x 50 x 50 mm cube-samples and 100 x 100 x 100 mm cube-samples, respectively. This implies that 0.3% PP-fiber serves as an optimal dose for the P. fiber additive at hand.

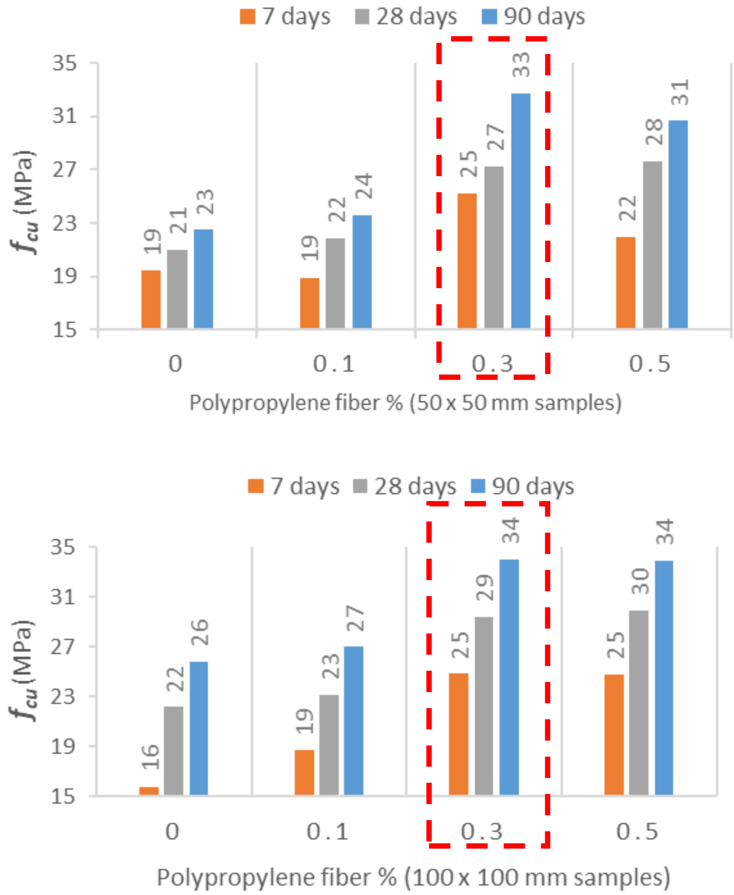


Figure 3: Compressive test results for (a) 50 x 50 mm samples (top); and (b) 100 x 100 mm samples (bottom)

3.2. Tensile (Splitting) Test Results and Discussion

In this test series, twelve cylindrical foamcrete samples were cast and cured for 28 days prior to testing according to ASTM C496. The samples are of a 3-inch diameter and 6-inch height (3" x 6"), equivalent to (76.2 mm x 152.4 mm). Samples were placed with its axis normal to the loading direction (See Figure 2); wherein the machine compression line-load is applied uniformly along the cylinder length; causing the cylinder to split along the vertical plane due to indirect tensile stress generated by Poisson's effect.

Table 3 displays the experimental values obtained, wherein the splitting tensile strength f_t is calculated using the mean load-at-failure (F_{max}) for three replicates:

$$f_t = 2F_{max} / (\pi DL) \tag{1}$$

where D and L are cylinder diameter and length, respectively. Results show that the tensile strength increases with the increase of fiber content. The tensile strength values f_t presented (1.64, 1.49, 2.09 and 2.12 MPa) for (0, 0.1, 0.3 and 0.5 % P. fibers), respectively, each reflect the mean of three replicates. The increase of f_t from 0.3% to 0.5% is an insignificant value of 1.4%; implying that 0.3% is an optimal value for the P. additive (See Figure 4); equally matching that for concrete compressive strength f_{cu} (Figure 3); wherein the f_t / f_{cu} ratio lies in the range of 6.5 to 7.2%.

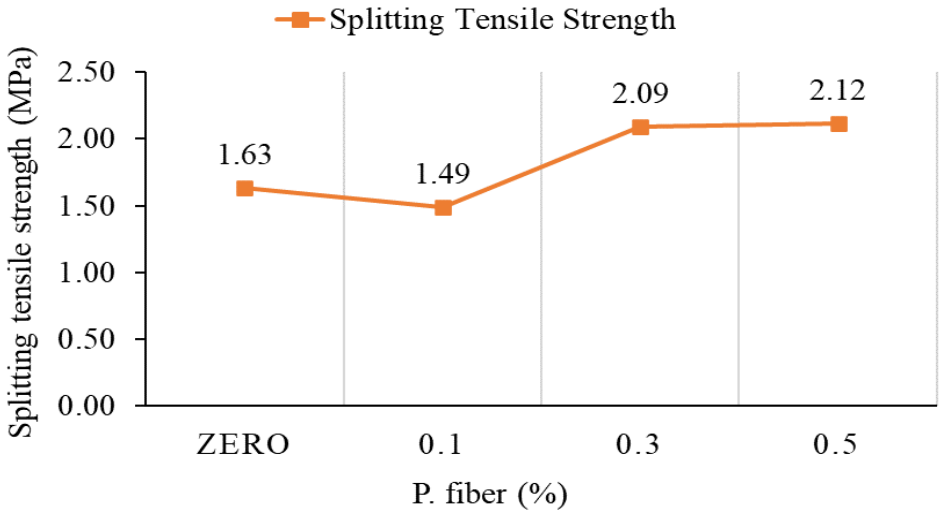


Figure 4: Tensile test results for 3” x 6” cylinders (at 28 days)

Table 3: Tensile test results for 3” x 6” foamcrete cylinders

Notation	Fiber %	P (kN) @ 28 days			Mean	St.dev	Splitting Tensile Strength (MPa)
Cl 01 -03	zero	24.7	32.4	32.4	29.83	3.63	1.64
Cl 07 - 09	0.1	28.1	28.5	24.8	27.13	1.66	1.49
Cl 13 - 16	0.3	35.8	40.5	38	38.10	1.92	2.09
Cl 19 - 21	0.5	38.8	36.7	40.3	38.60	1.48	2.12

4. COST SAVING ANALYSIS ON A TRADITIONAL BUILDING USING FINITE ELEMENT (ETABS V20)

The above obtained results – for strength enhanced foamed concrete - encourage the current cost analysis; comparing foamed concrete to conventional concrete. The case study included a multi-storey building comprising 7 floors as shown in Figure 5. Structural modeling is, herein, conducted twice; the first one used ordinary conventional concrete and the other using the achieved foam concrete; however for slab elements only. The effect of replacing ordinary concrete with foamed concrete on the overall behavior of the structure: the total loads, the response in earthquakes, and the most evident effect the overall construction cost. In each model the stresses were studied and the structural elements were designed using the internal design template of Etabs v20 Program to unify the comparison. The results are as follows:

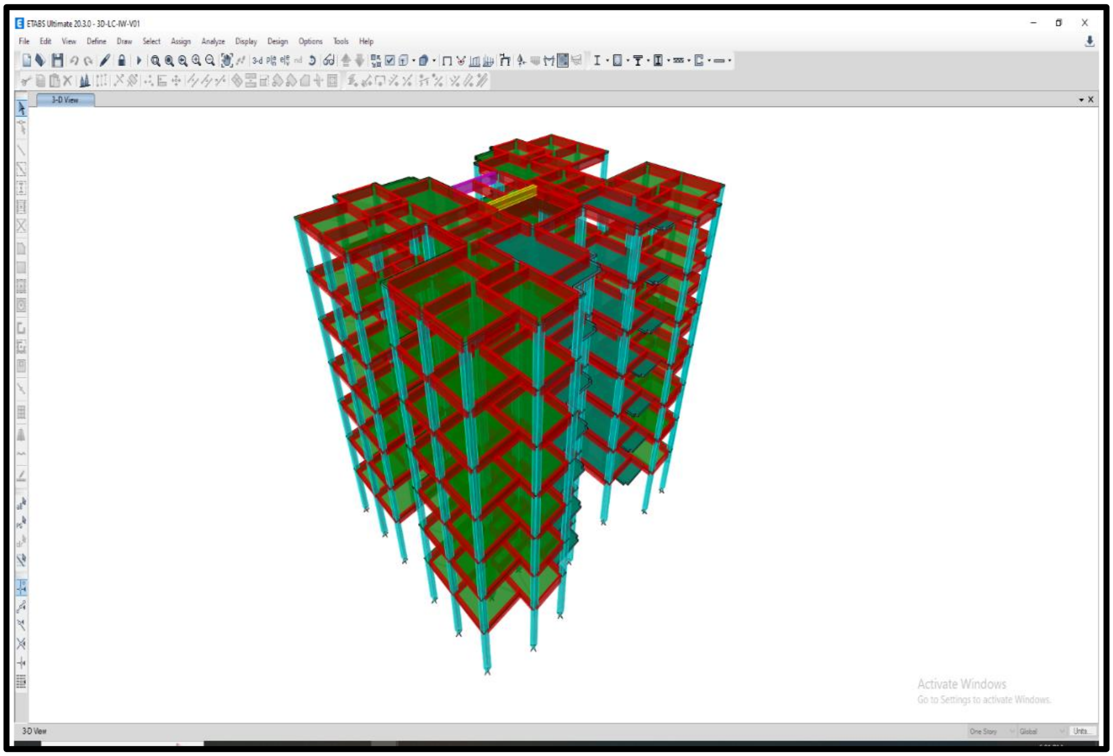
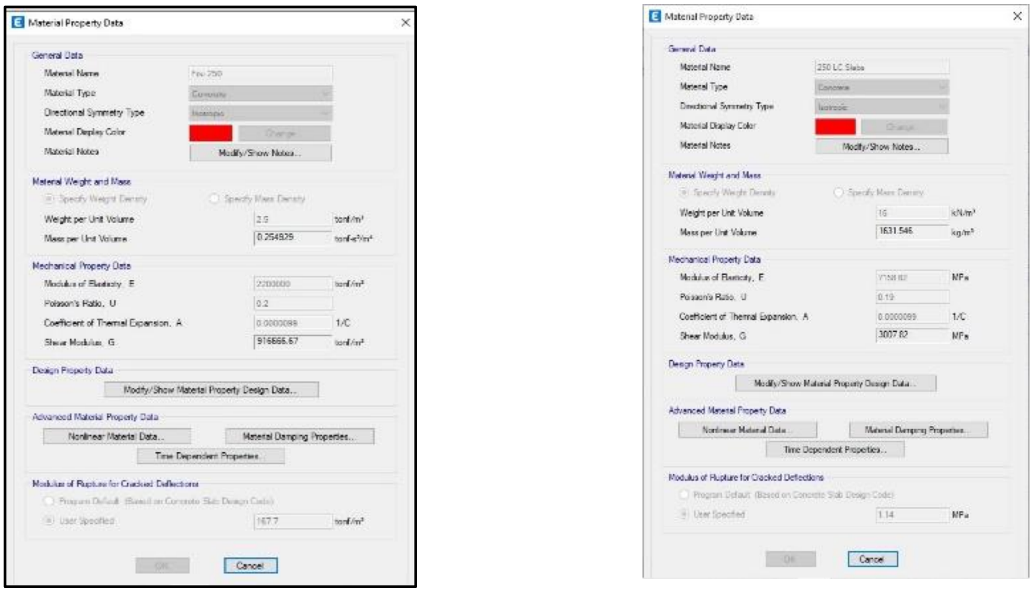


Figure 5: Extruded view of the multi-story building

4.1 Material selection

The first model used the ordinary conventical concrete having the properties: compressive strength of concrete (f_{cu}) 25 MPa, weight per unit volume 2500 kg/m^3, modulus of elasticity (E) 22000 MPa, Poisson ratio 0.2, Modulus of Rapture 3 MPa. All the structure members have the same material properties. Ordinary conventical concrete was applied to the whole model.

The second model used the mentioned foam concrete (for the slabs only) having the properties: compressive strength of concrete (f_{cu}) 25 MPa, weight per unit volume 1600 Kg/m^3, modulus of elasticity (E) 6220 MPa, Poisson ratio 0.215, Modulus of Rapture 1.14 MPa. All the other else structure members have the same material properties as the first model ordinary conventical concrete. The lightweight foam concrete blocks used as wall partitions having compressive strength (f_{cu}) 2 MPa, weight per unit volume 600 kg/m^3. This is shown in Figure 6.



Material Property Data

General Data
Material Name: Fcu 250
Material Type: Concrete
Directional Symmetry Type: Isotropic
Material Weight and Mass
● Specify Weight Density ○ Specify Mass Density
Weight per Unit Volume: 2.5 tonf/m³
Mass per Unit Volume: 0.254929 tonf-s²/m⁴
Mechanical Property Data
Modulus of Elasticity, E: 2200000 tonf/m²
Poisson's Ratio, U: 0.2
Coefficient of Thermal Expansion, A: 0.0000099 1/C
Shear Modulus, G: 916666.67 tonf/m²
Modulus of Rupture for Cracked Deflections
○ Program Default (Based on Concrete Slab Design Code)
● User Specified: 167.7 tonf/m²

Material Property Data

General Data
Material Name: 250 LC Slabs
Material Type: Concrete
Directional Symmetry Type: Isotropic
Material Weight and Mass
● Specify Weight Density ○ Specify Mass Density
Weight per Unit Volume: 16 kN/m³
Mass per Unit Volume: 1631.546 kg/m³
Mechanical Property Data
Modulus of Elasticity, E: 7158.62 MPa
Poisson's Ratio, U: 0.19
Coefficient of Thermal Expansion, A: 0.0000099 1/C
Shear Modulus, G: 3007.82 MPa
Modulus of Rupture for Cracked Deflections
○ Program Default (Based on Concrete Slab Design Code)
● User Specified: 1.14 MPa

(a) Material of first model having conventical concrete for all members

(b) Material of Second model having foam concrete for Slabs only

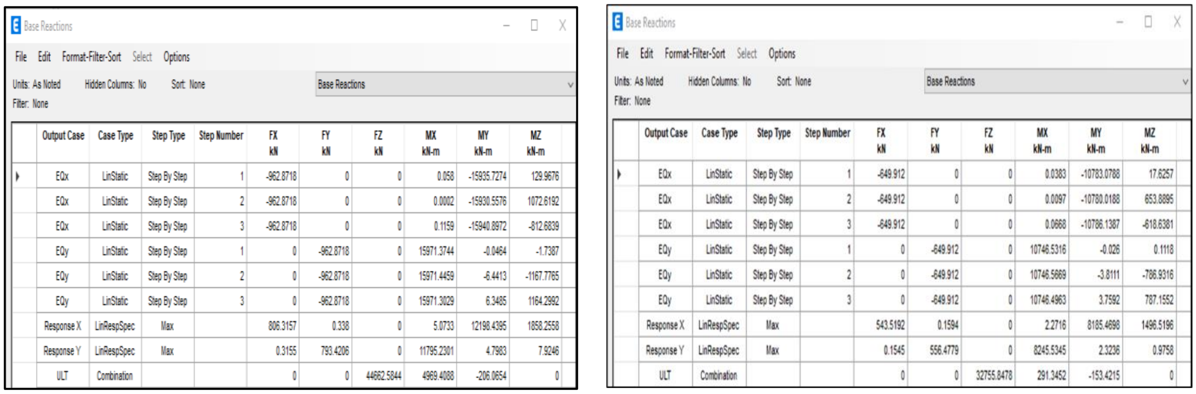
Figure 6: Materials selection for two models

4.2 Total Loads and the Building Response in Earthquakes

The total loads had a decrease about 27.62% than that of first model using ordinary conventical concrete as well as base shear of buildings have been investigated showing second model having a decrease in base shear about 33.03% than that of first model using ordinary conventical concrete in both X-direction and Y-direction for static earthquake loads. For the Response Spectrum it showed a decrease about 33.09% in X-direction and 33.39% in Y-direction for second model that of first model. The draft of second model showed a decrease about 15.83% in X-direction and 27.31% in Y-direction than the draft values of first model using ordinary conventical concrete. This is shown in Table 4 and Figure 7.

Table 4: Total loads & base reactions for the two Etabs V20 models

Model	1st Model RC for all members	2nd Model LC for slabs & wall partitions only	Reduction Percentage
Total Loads (kN)	44662.58	32755.85	26.66 %
Base Shear X-direction (kN)	962.87	649.91	32.50 %
Base Shear Y-direction (kN)	962.87	649.91	32.50 %
Response Spectrum X (kN)	806.32	543.52	32.59 %
Response Spectrum Y (kN)	793.42	556.48	29.86 %
Draft X-direction (mm)	0.004674	0.003934	15.83%
Draft Y-direction (mm)	0.005159	0.00375	27.31 %



Units: As Noted Hidden Columns: No Sort: None Base Reactions
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Output Case	Case Type	Step Type	Step Number	FX kN	FY kN	FZ kN	MX kN-m	MY kN-m	MZ kN-m
EQx	LinStatic	Step By Step	1	-962.8718	0	0	0.058	-15935.7274	129.9676
EQx	LinStatic	Step By Step	2	-962.8718	0	0	0.0002	-15930.5576	1072.6192
EQx	LinStatic	Step By Step	3	-962.8718	0	0	0.1159	-15940.8972	-812.6839
EQy	LinStatic	Step By Step	1	0	-962.8718	0	15971.3744	-0.0464	-1.7387
EQy	LinStatic	Step By Step	2	0	-962.8718	0	15971.4459	-6.4413	-1167.7765
EQy	LinStatic	Step By Step	3	0	-962.8718	0	15971.3029	6.3485	1164.2992
Response X	LinRespSpec	Max		806.3157	0.338	0	5.0733	12198.4395	1858.2558
Response Y	LinRespSpec	Max		0.3155	793.4206	0	11795.2301	4.7983	7.9246
ULT	Combination			0	0	44662.5844	4969.4088	-206.0654	0

(a) Base Reactions of first model having conventical concrete for all members

Units: As Noted Hidden Columns: No Sort: None Base Reactions
Filter: None

Output Case	Case Type	Step Type	Step Number	FX kN	FY kN	FZ kN	MX kN-m	MY kN-m	MZ kN-m
EQx	LinStatic	Step By Step	1	-649.912	0	0	0.0383	-10783.0788	17.6257
EQx	LinStatic	Step By Step	2	-649.912	0	0	0.0097	-10780.0188	653.8895
EQx	LinStatic	Step By Step	3	-649.912	0	0	0.0668	-10786.1387	-618.6381
EQy	LinStatic	Step By Step	1	0	-649.912	0	10746.5316	-0.026	0.1118
EQy	LinStatic	Step By Step	2	0	-649.912	0	10746.5669	-3.8111	-786.9316
EQy	LinStatic	Step By Step	3	0	-649.912	0	10746.4963	3.7592	787.1552
Response X	LinRespSpec	Max		543.5192	0.1594	0	2.2716	8185.4698	1496.5196
Response Y	LinRespSpec	Max		0.1545	556.4779	0	8245.5345	2.3236	0.9758
ULT	Combination			0	0	32755.8478	291.3452	-153.4215	0

(b) Base Reactions of second model having foam concrete for Slabs only + low wall density

Figure 7: Base reactions for two models

4.3 Quantity of Concrete and Cost analysis

Columns and foundations were designed and optimized in the second model and it was obvious that the decrease in the total weight of the building reduced the stress ratio of columns and also decreased the base reaction which will accordingly enhance the behavior of the building against earthquakes due to total decrease in mass source. The total volume for each structural element of the two models was calculated verses its unit price per meter cube and a comparison for each item in the structural skeleton was held without taking into consideration the architectural finishes.

The volume of plain concrete as well as reinforced concrete for foundation was decreased magnificently by 21.78% and 37.15% respectively. The volume of the smells as well as the beams is almost the same. The volume of columns decreased by 10.59%. The main evident change was then clear in the unit price for reinforced foam concrete slabs which increase by about 30 dollars than normal reinforced concrete which have an impact increase of the cost of about 13.89%. Despite these changes, the overall cost for the second building made of foam concrete slabs and lightweight foam concrete blocks as wall partitions was shown to give a marginal decrease of 3.07%; however, significant benefits are anticipated where foamed concrete well known for heat insolation, sound barrier, mobile signal connectivity and being ecofriendly material. Nonetheless, this study lacked emphasizing on serviceability and reinforcement aspects that will be re-addressed in the future.

Table 5: Cost comparison for two Etabs v20 models and reduction percentage

Item	1st Model RC			2nd Model LC + RC			Reduction Percentage
	Volume (m^3)	Unit Price ($)	Cost ($)	Volume (m^3)	Unit Price ($)	Cost ($)	
Foundation P.C	102.4	40	4,096	80.1	40	3204	-21.78 %
Foundation R.C	132.7	168	22,293.6	83.4	168	14011.2	-37.15 %
Smells	23.64	168	3,971.52	23.66	168	3974.88	+0.08 %
Columns	124.42	260	32,349.2	111.24	260	28922.4	-10.59 %
Slabs	344.3	180	61,974	344.3	210	70581.5	+13.89 %
Beams	22	250	5,500	22	250	5500	0.00 %
Total Cost			130,184.32			126,193.98	-3.07 %

4.4 Results and Discussions:

- Foamed concrete can reach a reasonable density 1600 kg/m3 with promising compressive strength more than 30 MPa which can be used as structural reinforced concrete.
- The best results obtained for the foamed concrete produced in this paper is at 0.3 % polypropylene fiber.
- The replacement of foamed concrete with conventical concrete in some structural elements results in reduction in the building total mass and the reduction in base shear and thus allover costs

5. CONCLUSIONS

From experimental test results of mechanical properties of structural foam concrete and the coast saving analysis on an existing building, the following was concluded:

1. Foam concrete is suitable for use as structural material.
2. Adding polypropylene fiber with recommended dose of 0.3% enhances the mechanical properties of foam concrete especially compressive strength and tensile splitting strength.
3. Structural foam concrete can play a significant role in energy saving as well as overall cost saving in construction field.

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