ISSN 2229-5518

Factors Influencing the Physical and Mechanical Properties of Foamed Concrete – Modelling and Optimization

Mahmoud Galal [a1], Tarik Youssef [b], Ahmed F. Abdel-Aziz [a2]

Abstract — Due to its superior characteristics, such as low density, high thermal insulation and high fire resistance, foamed concrete is gaining popularity in the construction field. Nonetheless, lack of knowledge remains regarding the prediction of the mechanical and physical properties of foamed concrete; necessitating further experimentation and modelling. This effort comprises eighteen mix proportions (experiments) with two different types of fillers (sand and lime powder); divided into two groups (density ranges); Group I: 563-to-1016 kg/m^3 and Group II: 935-to-1374 kg/m^3. The purpose of this study is to investigate the influence of input-proportions/ratios such as: foam volume, lime-to-filler ratio and cement-to-filler ratio on the physical and mechanical properties of foamed concrete. These properties include density, compressive strength, flexural strength and thermal conductivity. Three statistical approaches are used for this investigation: (i) Taguchi orthogonal array method to get the optimal conditions to obtain a target value; (ii) the analysis of variance (ANOVA) approach to know the influence of different factors on the various properties and (iii) the multiple linear regression approach to develop empirical relationships that can be used for mix design. It is concluded that the foam volume fashions a paramount effect on density and compressive strength; amounting to 92.5 and 91.5% contribution – on average – for the aforementioned density ranges, respectively. The two parameters of lime-to-overall-filler ratio and cement-to-filler ratio yield a significantly lower effect. Foam-concrete density has proven most influence in determining both compressive strength magnitude and thermal conductivity. Two models, based on minimizing the square-error approach, are proposed to calculate the latter output parameters as a function of foam concrete density.

Index Terms— Foamed concrete, Compressive strength, Material properties, Optimization, Taguchi orthogonal array, Thermal insulation, ANOVA

1 Introduction

Foamed concrete is a multi-functional material which can be considered a key solution to many problems facing the construction field. Significant developments have taken place in foamed concrete manufacturing to fulfill its growing needs. It is considered one of the lightweight concrete classifications; consisting of Portland cement paste (mortar) with internal well-distributed pores; created by introducing air bubbles (0.1-1.0 mm) into the paste to produce a porous structure [1-7]. In comparison to conventional concrete, it implements superior characteristics such as low density, high fire resistance and excellent thermal and acoustic properties [8].

Foamed concrete can be classified according to production process to two types: i) autoclaved aerated concrete, in which aluminum powder, most commonly used, is added to the mortar and autoclave cured to generate gas bubbles by chemical reactions with calcium hydroxide, ii) preformed foamed concrete, in which preformed foam, stable air bubbles, is added to the mortar [6, 7, 9 and 10].

Concerning the preformed foamed concrete - the scope of this study - it can be produced in wide range densities; varying from 400 to 1600 kg/m^3 to fulfill the various requirements in the construction field [3]. However, it remains to suffer from low compressive strength due to its low density. This limits its application to an extent (i.e. it is commonly used as wall material for high thermal insulation, light partitioning and roof insulation) [7]. In addition, there is hindrance in the field of mix design of foamed concrete. Therefore, practice plays a greater role than that of scientific means in the manufacturing field.

Many researchers have conducted investigations on foamed concrete to improve its mechanical properties and reported that the dry density and the pore structure have the most significant influence on the mechanical properties of foamed concrete [11, 12]. However, further research is yet necessary to: (i) increase the currently available knowledge, (ii) develop a mix-design approach to produce foamed concrete for different purposes.

In this study, the main objectives are to investigate the influence of different mix proportions and using different filler types - of preformed foamed concrete - on its physical and mechanical properties (particularly compressive strength and thermal properties). The obtained empirical models – from this study - can be used for predicting density, compressive strength and other properties for foamed concrete. Three statistical approaches are used for this investigation: (i) Taguchi orthogonal array method; (ii) the analysis of variance (ANOVA) approach to know the influence of different factors on the various properties and to get the optimal conditions to obtain a target value and (iii) the multiple linear regression approach to develop empirical relationships that can be used for mix design.

- *a¹ Structural Engineering Department, Faculty of Engineering, Ain Shams University, Egypt. E-mail: Mahmoud.galal@eng.asu.edu.eg*
- *b Structural Engineering Department, Faculty of Engineering, The French University of Egypt. E-mail: Tarik.youssef@ufe.edu.eg*
- *a² Structural Engineering Department, Faculty of Engineering, Ain Shams University, Egypt. E-mail: masterlab22@yahoo.com*

2 EXPERIMENTAL STUDY

2.1 Materials

In this program, ordinary Portland cement (CEM I 42.5R) is used as a binder, where the chemical composition is displayed in Table 1 and mechanical-and-physical properties are displayed in Table 2. Natural sand of specific gravity (S.G = 2.59) - sieved to avoid particles larger than 1.18 mm - is used as filler. Lime powder (calcium carbonate, $CaCO_3$) of (S.G = 2.59) serves as a partial and full replacement for natural sand. X-Ray Diffraction analysis (XRD), conducted for the latter, shows that it is predominantly formed of calcite (See Figure. 1).

Table 1. Chemical composition of ordinary Portland cement.

Oxide	SiO_2	$Al2O_3$	Fe_2O_3	CaO	MgO
%	19.29	4.52	3.59	62.08	1.80
Oxide	SO_3	K_2O	Na_2O	Cl	
%	3.61	0.29	0.45	0.09	

Table 2. Mechanical and physical properties of ordinary Portland cement.

Compressive strength- 2 days	(MPa)	19.50
Compressive strength- 28 days	(MPa)	51.25
Setting time	(minutes)	123
Fineness (Blaine)	(cm²/gm)	3732

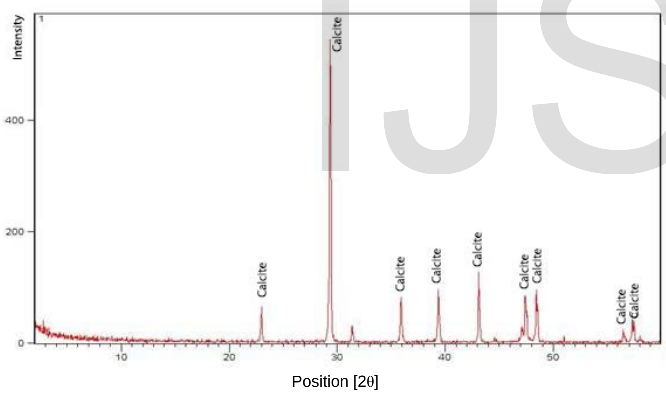


Fig. 1. XRD test results of lime powder.

Foaming agent, **LithoFoam SL 200-L**, based on highly-active foam forming proteins, pre-foamed foam (at 80 kg/m³) was used. The foam is produced by blending foam agent, water and compressed air in a foam generator, as shown in Figure. 2.

a. Foam agent tank.

b. Generator set.

c. Produced foam.

Fig. 2. Foam generator.

2.5 Mix Proportions

Eighteen mix proportions were designed and conducted to investigate the influence of each ingredient on the foamed concrete physical/mechanical properties. The experimental program is divided into two groups; each of a particular density range, (Group I: 563 to 1016 kg/m³ and Group II: 935 to 1374 kg/m³). Factors under study were determined and displayed in three levels (See Table 3). These factors are cement-to-filler ratio (C/F), lime powder-to-the overall filler ratio ($CaCO_3$/F) and foam volume per unit volume of concrete (V_f).

Table 3. Factors and levels.

Levels	Group	Factors		
		(C/F) (A)	($CaCO_3$/F) (B)	(V_f) % (C)
1	I	1	0	60
2		1.4	0.4	68
3		2	1	75
1	II	1	0	37
2		1.4	0.4	50
3		2	1	60

2.3 Water-Solids Ratio

Preformed foamed concrete is manufactured by adding preformed foam to cement mortar with a specific consistency (defined in terms of water-solid ratio). Optimal consistency is crucial; since using mortars at higher or lower consistency than the optimal, leads to foamed concrete with density ratio (defined as ratio of measured fresh density to design density) above unity. It is recommended - by the foam manufacturers - to use mortars with percent flow (measured by standard flow table [13]) in the range of 40 % to 50 % to obtain optimal consistency. Stiff mixes with low water-solids ratio causes bubbles to break. On the other hand, loose mixes with high water-solids ratio causes bubbles to merge and segregate [14]. Contrary to conventional concrete, water-cement ratio is not an influential factor on the compressive strength of foamed concrete [3], thus not considered in this study.

2.4 Specimen Preparation

The process of foamed concrete manufacturing is described as follows: Portland cement and filler (sand and/or lime powder) were initially mixed in a horizontal mixer; water was added to the mixer; foam - at its final form was then added - to the homogeneous paste. Finally, full homogeneous foamed concrete was cast in 600 x 600 x 100 mm steel panels. The concrete panels were cured using wet burlap sheets for 28 days.

Figure. 3 shows the process of foamed concrete manufacturing.

a. Empty mixer.

b. Solid materials.

c. Adding water.

d. Mixing paste.

e. Adding foam.

f. Final product.

Fig. 3. Foamed concrete manufacturing process.

2.5 Experimental Procedures

2.5.1 Compressive Strength

Four cubes of dimensions 100x100x100 mm were saw-cut from each concrete panel to be tested - (according to ASTM C513-89 R95 [15]) - to determine the 28-day compressive strength.

2.5.2 Flexural Strength

Three prisms of dimensions 100x100x350 mm were saw-cut from each concrete panel to be tested using simple beam with center-point loading (according to ASTM C293-02 [16]) to calculate the modulus of rupture (R) as shown in Eqn 1:

$$R = 3PL/((2bd^2)) \quad (1)$$

where R is the modulus of rupture in (MPa), P is the maximum load at failure in (Newtons), L is span-length in (mm), b is the specimen width in (mm) and d is the specimen depth in (mm).

2.5.3 Density

Five cubes with dimensions 100 x 100 x 100 mm - (according to ASTM C513-89 R95 [15]) - were saw-cut from each concrete panel to be tested. Oven-dry mass (A), saturated surface-dry mass in air (B) as well as the immersed mass of saturated specimen in water (C) were recorded according to ASTM C642-97 [17]; from which the bulk density is calculated in Eqn 2:

$$\rho = (A/(B-C))\rho_w \quad (2)$$

where ρ is the density of foamed concrete and ρ_w is the density of water.

2.5.4 Thermal Conductivity

For thermal conductivity, one specimen of dimensions 300 x 300 x 100 mm was saw-cut from each panel and oven dried to be tested using an in-lab fabricated guarded hot plate apparatus (of inner dimensions 300 x 300 x 150 mm) in single sided mode (according to ASTM C1044-12 [18]).

$$\lambda = ((Q/A)(L/\Delta T)) \quad (3)$$

where λ is thermal conductivity in (W/mk), Q is heat flow rate in watts (W), A is the specimen area in square meters (m^2), L is the specimen thickness in meters (m) and ΔT is the temperature difference across the specimen in degree Kelvin (k) .

Fig. 4. Thermal conductivity test apparatus.

3 Results, Analysis and Discussion

3.1 Applied Statistical Approaches

Taguchi orthogonal array (TOA) is a statistical method developed as an efficient and systematic approach (optimization technique) to obtain the optimum values of the parameters affecting properties of the final product to get the target output value (e.g. density or compressive strength) [20-22]. The Taguchi orthogonal array method can be used to study a large number of variables with a lesser number of experiments [20]; for which it is applied to the current study. TOA is applied in the following sequence: (i) factors under study are selected, ii) levels for each factor are chosen (See Table 3), (iii) orthogonal array L9 (3^3) is constructed (See Table 4), (iv) mean responses in correspondence with levels are computed (See Table 5), (v) plots of mean responses with levels are plotted (See Figures 5 and 6).

ANOVA is a statistical procedure applied onto experimental results to determine the significance and contribution-percentage of each parameter on the performance output, as well as differentiate the variance due to parameters and errors [22]. Associated to ANOVA is the F test: conducted according to 95% confidence to obtain the F ratio. The latter has to exceed the tabulated value to prove that the parameter has significant influence on the performance output. The P value is calculated for each parameter to assure its significance if its value is less than 0.05.

ISSN 2229-5518

As shown in the following section, ANOVA is applied using the "Minitab" software to verify the results obtained from the Taguchi method. Furthermore, a multiple linear regression approach is applied to obtain relationships between a dependent/output variable and two or more independent (input) variables.

3.2 Results and Discussion

Experimental and corresponding predicted results are illustrated in Table 4 in the L9 (3^3) Taguchi orthogonal array; wherein the observed-versus-predicted results are displayed.

The mean responses of density and compressive strength for each factor are illustrated in Table 5 in correspondence of levels.

Table 4. L9 (3^3) Orthogonal Array (Experimental versus Predicted Results)

Mix No	Group	Factors[1]			Density (ρ) (kg/m^3)		Compressive Strength (f_c) (MPa)		Flexural Strength (f_t) (MPa)		Thermal Conductivity (λ) (W/mk)	
		A	B	C	Obs*	Pred*[2]	Obs*	Pred*[2]	Obs*	Pred*[3]	Obs*	Pred*[4]
1		A1	B1	C1	1016	1001	4.14	3.90	1.21	1.08	0.35	0.34
2		A1	B2	C2	747	773	1.61	2.14	0.44	0.45	0.20	0.23
3		A1	B3	C3	565	552	1.03	0.60	0.37	0.30	0.16	0.16
4		A2	B1	C2	834	795	2.20	2.39	0.66	0.60	0.22	0.27
5	I	A2	B2	C3	593	591	1.26	0.85	0.33	0.36	0.17	0.17
6		A2	B3	C1	857	901	3.69	4.15	1.09	0.97	0.24	0.28
7		A3	B1	C3	563	606	0.85	1.21	0.21	0.26	0.15	0.16
8		A3	B2	C1	938	933	5.15	4.51	1.31	1.34	0.32	0.31
9		A3	B3	C2	726	688	2.57	2.75	0.58	0.69	0.20	0.22
10		A1	B1	C1	1339	1362	11.81	11.68	3.11	3.01	0.43	0.47
11		A1	B2	C2	1098	1112	5.81	6.65	1.46	1.50	0.38	0.37
12		A1	B3	C3	935	898	3.71	2.45	0.81	0.98	0.31	0.31
13		A2	B1	C2	1118	1143	6.95	7.75	1.95	1.79	0.39	0.38
14	II	A2	B2	C3	935	944	4.12	3.78	0.92	1.08	0.30	0.31
15		A2	B3	C1	1325	1289	10.79	11.23	2.65	2.75	0.44	0.46
16		A3	B1	C3	1015	976	5.25	5.22	1.73	1.36	0.34	0.34
17		A3	B2	C1	1374	1335	14.46	12.89	3.63	3.67	0.45	0.48
18		A3	B3	C2	992	1071	6.40	7.64	1.39	1.65	0.33	0.33

where:

[1] Factors A, B and C represent (C/F), ($CaCO_3$/F) and (V_f); Obs* indicates observed values; Pred* indicates predicted values (with superscripts 2,3 & 4); [2] Predicted values are obtained from equations 5 to 8; [3] Predicted values are obtained from section 3.2.5; [4] Predicted values are obtained from section 3.2.6 (represented later).

Table 5. Mean response of each factor in correspondence with levels – density and compressive strength.

Levels	Group	Factors					
		Density ρ (kg/m^3)			28 days - Compressive Strength (MPa)		
		A	B	C	A	B	C
1		776	804	937	2.26	2.40	4.33
2		761	759	769	2.38	2.67	2.13
3	I	742	716	574	2.86	2.43	1.05
Difference in mean value		34	88	363	0.60	0.27	3.28
1		1124	1157	1346	7.11	8.00	12.35
2		1126	1136	1069	7.29	8.13	6.39
3	II	1127	1084	962	8.70	6.97	4.36
Difference in mean value		3	73	384	1.59	1.16	7.99

3.2.1 Density

Density is considered the most important foamed concrete characteristic, due to its great influence on mechanical and physical traits, such as compressive strength and thermal insulation, respectively.

It is observed from Figure 5 that the main effective parameter on density is foam volume (V_f); followed by lime powder/filler ($CaCO_3$/F) and finally, cement/filler (C/F). The differences in mean responses of C/F, $CaCO_3$/F and V_f for Group I are 34, 88 and 363, respectively. As for Group II, the corresponding values are 3, 73 and 384, respectively. These results are in agreement with the outcomes of Xu et al. [8]; wherein foam volume has the most significant influence on density. For this study, the optimal parameters for minimum density are C/F = 2, $CaCO_3$/F = 1 and a V_f of 75% - by volume - for Group I. As for Group II, the corresponding values are: C/F = 1, $CaCO_3$/F = 1 and V_f = 60%.

Analysis of variance (ANOVA) is shown in Table 6 wherein the level of importance of various factors shows agreement with the results obtained from (TOA). Percentage of contribution-values for C/F, $CaCO_3$/F and V_f for

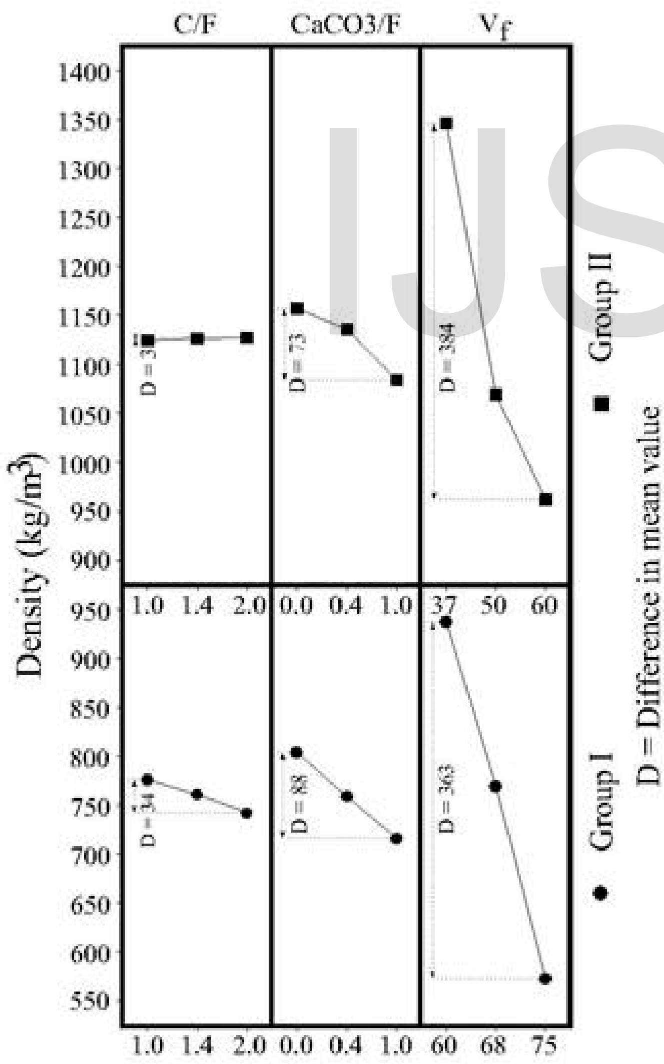


Fig. 5. Mean responses for main effects on density.

Group I are 0.78%, 5.37% and 90.94%, respectively. The corresponding values for Group II are 0.00%, 3.40% and 94.14%, respectively. Optimal conditions for minimum density are C/F = 1.0, $CaCO_3$/F = 1.0 and V_f = 60% for group (I) and C/F = 2, $CaCO_3$/F = 1.0 and V_f = 75% for group II.

As shown in Figure 5 and Table 6, foam volume V_f has the highest influence on density as it is considered the main source of pores within foamed concrete. However, the slight decrease in density due to increase of lime powder content can be attributed to the incorporation of finer filler. The latter case results in better pore-distribution, less bubble merging as well as less segregation tendency. This explanation meets the reports of the majority of earlier efforts [2, 3 and 14]. As regards the influence of C/F on density, it is obviously insignificant to the degree of neglection.

Table 6. Analysis of variance (ANOVA) results for density.

Group	Source	DF	Adj SS	Adj MS	F-Ratio	P-Value	Contribution (%)
I	C/F	2	1710	854.8	0.02	0.977	0.78
	$CaCO_3$/F	2	11706	5853	0.17	0.848	5.37
	V_f	2	198390	99195	30.12	0.001	90.94
	Error	2	6347	3173.5			2.91
	Total	8	218153				100
II	C/F	2	14	7	0.00	1.000	0.00
	$CaCO_3$/F	2	8517	4258	0.11	0.901	3.40
	V_f	2	235849	117924	48.10	0.000	94.14
	Error	2	6180	3090			2.46
	Total	8	250560				100

where: Source: source of variation; DF: degree of freedom; Adj SS: adjusted sum of square; Adj MS: adjusted mean square.

To estimate the density magnitude, multiple linear regression models were obtained and are expressed as follows:

$$\rho_{(Group-I)} = 1985.860 + 2.895(C/F) - 74.342(CaCO_3/F) - 1693.358(V_f) \quad (5)$$

(R^2 = 0.947) (For mixtures with density up to 1000 kg/m^3)

$$\rho_{(Group-II)} = 2483.540 - 33.509(C/F) - 87.061(CaCO_3/F) - 2414.596(V_f) \quad (6)$$

(R^2 = 0.964) (For mixtures with density over 1000 kg/m^3)

3.2.2 Compressive Strength

Compressive strength is the leading property that restricts the applications of foamed concrete, so determination or estimation of its value is paramount in the field of foamed concrete manufacturing. Accurate estimation of compressive strength is directly proportional to cost and time saving, in terms of producing concrete that is capable of fulfilling various requirements.

Figure. 6 shows that the effective parameters on compressive strength and density are the same. The differences in mean response of C/F, $CaCO_3$/F and V_f for group I are 0.6, 0.27 and 3.28 respectively, and for group II are 1.59, 1.16 and 7.99 respectively.

ISSN 2229-5518

Analysis of variance was conducted; Table 7 shows that the level of importance of various factors meet the results obtained from (TOA). Contribution-percentage values for C/F, $CaCO_3/F$ and V_f for group I are 3.23%, 0.74% and 90.94% respectively, and for group II are 4.06%, 2.17% and 91.93% respectively. Optimal conditions for maximum compressive strength are C/F = 2, $CaCO_3/F$ = 0.4 and V_f = 37% for group (I) and C/F = 2, $CaCO_3/F$ = 0.4 and V_f = 60% for group II.

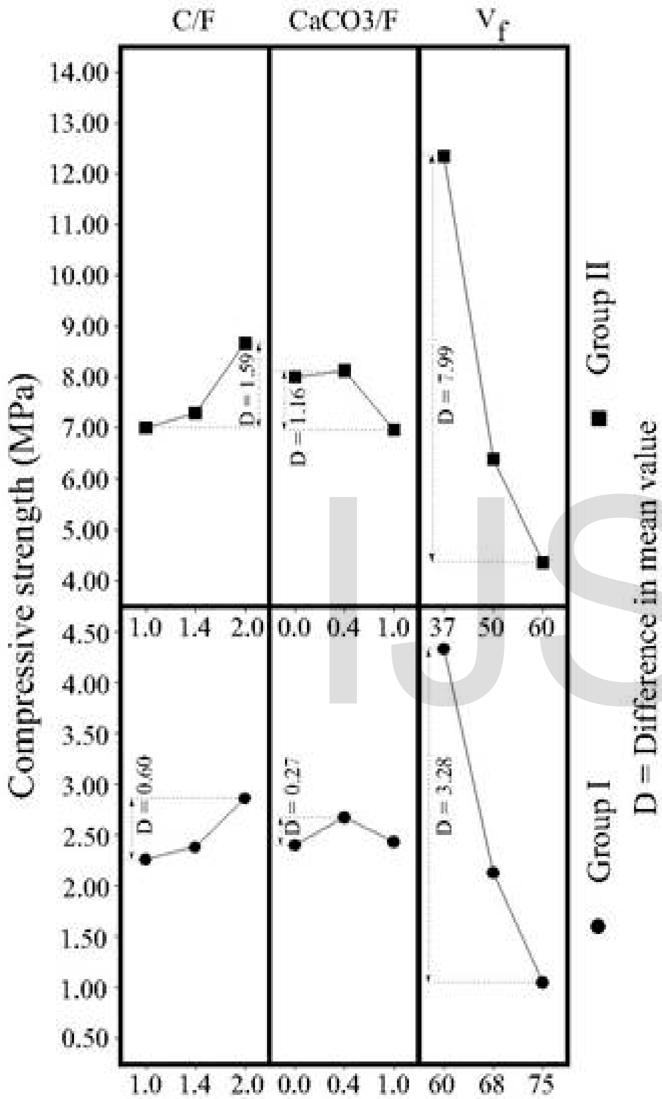


Fig. 6. Mean responses for main effects on compressive strength.

Foam volume is the main influential factor on pore formation, as mentioned before, so it is considered the main factor affecting all foamed concrete properties. Concerning the lime powder, increasing it results in increasing in compressive strength until a certain limit because of its positive effect on pores distribution in addition to micro filling effect (See Figure 7), but the excess in its dosage leads to decrease in compressive strength. This result can be explained by that more dosage of lime powder results in excess water demand which leads to more capillary pores in the paste and therefore reduction in compressive strength. The effect of changing in cement content and lime powder content increases in higher densities due to the increasing in paste volume in the foamed concrete. Nambiar and Ramamurthy [14] used a similar explanation to explain the increase of water absorption at higher densities that water absorption is affected mainly by the paste phase.

Table 7. Analysis of variance (ANOVA) results for compressive strength.

Group	Source	DF	Adj SS	Adj MS	F-Ratio	P-Value	Contribution (%)
I	C/F	2	0.5953	0.2976	0.10	0.906	3.23
	$CaCO_3/F$	2	0.1369	0.06843	0.02	0.978	0.74
	V_f	2	16.7650	8.3824	30.09	0.001	90.94
	Error	2	0.9390	0.4695			5.09
	Total	8	18.4362				100
II	C/F	2	4.5770	2.288	0.13	0.883	4.06
	$CaCO_3/F$	2	2.4440	1.222	0.07	0.936	2.17
	V_f	2	103.602	51.801	34.16	0.001	91.93
	Error	2	2.0780	1.0410			1.84
	Total	8	112.701				100

where: Source: source of variation; DF: degree of freedom; Adj SS: adjusted sum of square; Adj MS: adjusted mean square.

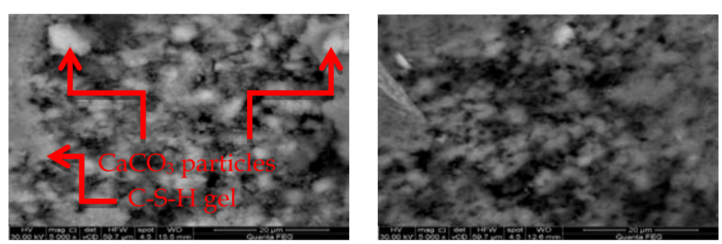
For estimation of compressive strength value, multiple linear regression models were obtained and they are expressed as follows:

$$F_{C(Group-I)} = 16.490 + 0.612(C/F) - 0.001(CaCO_3/F) - 22.000(V_f) \quad (7)$$

(R^2 = 0.918) (For mixtures with density up to 1000 kg/m^3)

$$F_{C(Group-II)} = 23.087 + 1.654(C/F) - 1.108(CaCO_3/F) - 35.298(V_f) \quad (8)$$

(R^2 = 0.936) (For mixtures with density over 1000 kg/m^3)



(a) SEM image for sample with $CaCO_3/F$ = 0.40 (b) SEM image for sample with $CaCO_3/F$ = 0.00

Fig. 7. SEM images

3.2.3 Density Versus Compressive Strength

As shown in Figure. 8, variation in density has significant influence on compressive strength. An empirical relationship was developed – through the approach of minimizing the sum of square of error (SSE) - where density served as the base for a power constant. In turn, the magnitude of the latter satisfies the least SSE criteria. Babu et al [23] mentioned in their report that the relationship between density

ISSN 2229-5518

and compressive strength for light weight concrete is represented as: (f_c = 10.3× $\rho^{1.918}$×10^{-6}); Xu et al. [8] developed a model of similar structure (f_c = 2.43× $\rho^{2.997}$×10^{-9}), while the model developed by Kan and Demirboga [24] was in logarithmic form (Fc = 13.8 Ln (ρ) - 85).

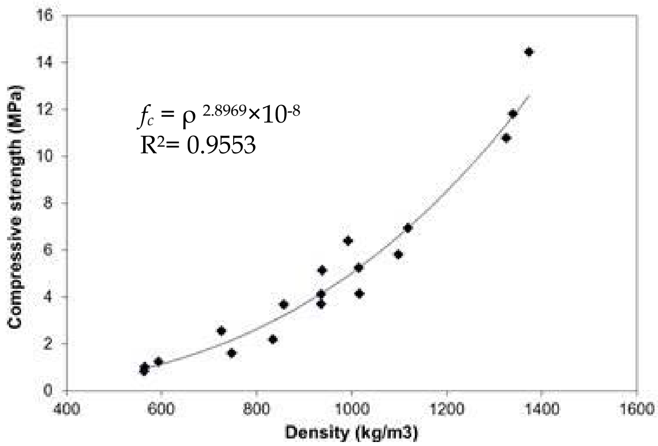


Fig. 8. Relationship between density and compressive strength.

3.2.5 Compressive Strength Versus Flexural Strength

It is obvious, in Figure 9, that the flexural and compressive strength abide by a linear directly proportional relationship. This comes in agreement with the common consensus and earlier efforts.

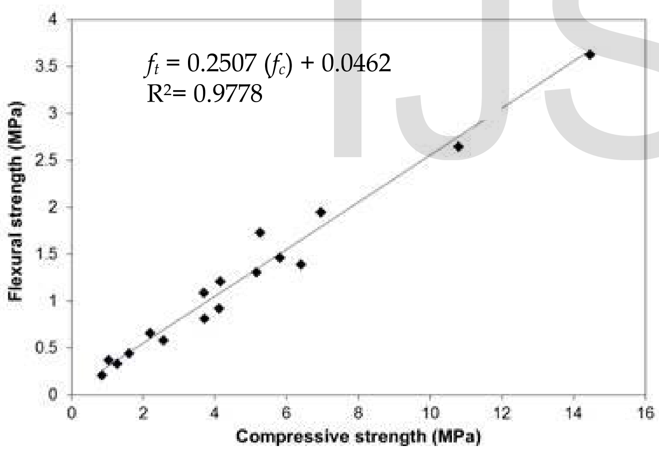


Fig. 9. Relationship between flexural and compressive strength.

3.2.6 Density Versus Thermal Conductivity

Thermal conductivity is the most important parameter of foamed concrete, particularly for non-structural foamed concrete. In turn, developing a model relating thermal conductivity to density is of great importance (Figure. 10). The derived linear model – based on SSE optimization - shows that the change of density by a value of 100 kg/m^3 corresponds to a change in thermal conductivity by 0.04 W/mk. This agrees with the outcome of many authors [3&25]. The high agreement between the linear model and the experimental data – given the single input variable (density ρ) for the former – confim density as the most influential factor for thermal conductivity.

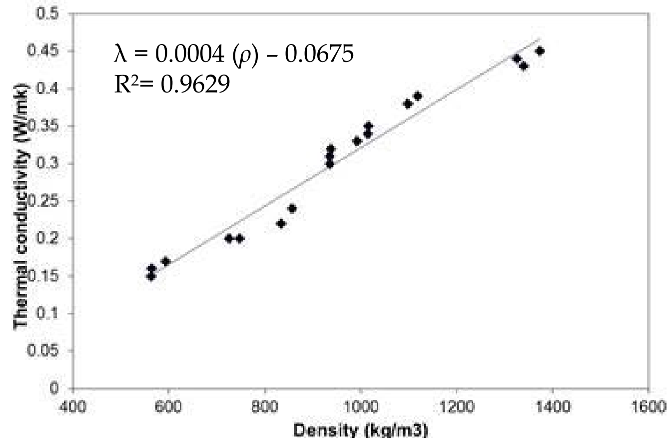


Fig. 10. Relationship between density and thermal conductivity.

4 CONCLUSION

This study was conducted to add to the already existing information content regarding preformed foamed concrete. The experimental work – comprising 18 samples – was analyzed/modeled by the means of various statistical approaches. The drawn conclusions can be summarized as follows:

- The Taguchi orthogonal array (TOA) is an appropriate method to investigate and determine the influence of foamed concrete composition on its physical and mechanical properties The results obtained from (TOA) yield high agreement with the Analysis of Variance (ANOVA) approach.
- Regarding density: (i) foam volume has proven to be the main influential factor, with a contribution percentage for low density concrete (Group I) and high density foamed concrete (Group II) – as per ANOVA - equating 90.94% and 94.14%, respectively; (ii) lime-to-overall-filler ratio yielded a contribution percentage for low density and high density foamed concrete equating 5.37% and 3.40%, respectively; (iii) finally, cement-to-filler ratio yielded the least/insignificant effect on density with a contribution percentage of 0.78% and 0.00%, respectively.
- Regarding compressive strength: (i) foam volume yielded the highest contribution percentage for both low density (Group I) and high density foamed concrete (Group II); equating 90.94% and 91.93%, respectively; (ii) cement-to-filler ratio presented a contribution percentage of 3.23% and 4.06%, respectively; (iii) finally, lime-to-overall filler presented the least effect on density with a contribution percentage of 0.74% and 2.17%, respectively.
- The cement-to-filler ratio and lime-to-overall-filler ratio, both have marginal influence on the compressive strength of foamed concrete. However, this influence is greater for the high density range than for the low density range. This is due to the higher cement paste volume in higher densities.
- The lime-to-filler ratio has minor influence on density; it does not contribute – along with foam - to the formation of pores, yet it improves overall pore-distribution as well as

minimizes the potential pore-loss.

- Although foam volume is - by far - the most influential parameter on foamed concrete properties in this study, considering many other factors and/or additives is anticipated to yield sizeable influence.
- The proposed power based model in this study, for density versus compressive strength, conforms with earlier efforts. These models are predominantly in the form of factored power-based density.
- Density is confirmed to be the main influential factor on thermal conductivity; which manifests in the directly proportional proposed linear relationship within the current study.

ACKNOWLEDGMENT

The authors feel indebted to the selflessness and genuine help of all engineers and employees at the DEMIX Ready Mix Concrete plant. Particular gratitude goes to Dr. Hany Elshafie (Ain Shams University); currently at the capacity of Quality Control Manager for DEMIX Inc.

REFERENCES

[1] A. A. Hilal, N. H. Thom and A. R. Dawson, "On Entrained Pore Size Distribution of Foamed Concrete," ELSEVIER. Cement Concrete Research, vol. 75, pp. 227-233, 2015.

[2] E. K. K Nambiar and K. Ramamurthy, "Air-Void Characterisation of Foam Concrete," ELSEVIER. Cement Concrete Research, vol. 37, pp. 221-230, 2007.

[3] K. Ramamurthy, E. K. K Nambiar and G. I. S. Ranjani, "A Classification of Studies on Properties of Foam Concrete," ELSEVIER. Cement Concrete Composites, vol. 31, pp. 388-396, 2009.

[4] M. A. Othuman and Y. C. Wang, "Elevated-Temperature Thermal Properties of Lightweight Foamed Concrete," ELSEVIER. Construction and Building Materials, vol. 25, pp. 705-716, 2011.

[5] K. Jitchaiyaphum, T. Sinsiri and P. Chindaprasirt, "Cellular Lightweight Concrete Containing Pozzolan Materials," ELSEVIER. Procedia Eng, vol. 14, pp. 1157-1164, 2011.

[6] A.M. Neville and J. J. Brooks, Concrete Technology. Pearson Education Limited, Harlow, United Kingdom, pp. 357-358, 1987. (Book style)

[7] C. Ma and B. Chen, "Experimental Study on The Preparation and Properties of A Novel Foamed Concrete Based on Magnesium Phosphate Cement," ELSEVIER. Construction and Building Materials, vol. 137, pp. 160-168, 2011.

[8] Y. Xu, L. Jiang, J. Xu and Y. Li, "Mechanical Properties of Expanded Polystyrene Lightweight Aggregate Concrete and Brick," ELSEVIER. Cement Concrete Research, vol. 27, pp. 32-38, 2012.

[9] A. J. Hamad, "Materials, Production, Properties and Application of Aerated Lightweight Concrete," International Journal of Materials Science and Engineering, vol. 2, pp. 152-157, 2014.

[10] A. A. Aliabdo, A. M. Abd-Elmoaty and H. H. Hassan, "Utilization of Crushed Clay Brick in Cellular Concrete Production," ELSEVIER. Alexandria Engineering Journal, vol. 52, pp. 119-130, 2014

[11] [H. Esmaily and H. Nuranian, "Non-Autoclaved High Strength Cellular Concrete From Alkali Activated Slag," ELSEVIER. Construction and Building Materials, vol. 25, pp. 200-206, 2012.

[12] D. K. Panesar, "Cellular Concrete Properties and The Effect of Ssynthetic and Protein Foaming Agents," ELSEVIER. Construction and Building Materials, vol. 44, pp. 575-584, 2013.

[13] ASTM C230-03, "Standard Specification for Flow Table for Use in Tests of Hydraulic Cement," Annual Book of ASTM standards: V. 4.01. International; 2005.

[14] E. K. K Nambiar and K. Ramamurthy, "Influence of Filler Type on The Properties of Foam," ELSEVIER. Cement Concrete Composites, vol. 28, pp. 475-480, 2006.

[15] ASTM C513-89 R95, "Standard Test Method for Obtaining and Testing Specimens of Hardened Lightweight Insulating Concrete for Compressive Strength," Annual Book of ASTM standards: V. 4.02. International; 2005.

[16] ASTM 293-02. Flexural Strength of Concrete (Using Simple Beam With-Center-Point Loading). Annual Book of ASTM standards: V. 4.02. International; 2005.

[17] ASTM C642-97," Density, Absorption, and Voids in Hardened Concrete," Annual Book of ASTM standards: V. 4.02. International; 2005.

[18] ASTM C1044-98," Standard Test Method for Using a Guarded-Hot-Plate Apparatus or Thin-Heater Apparatus in the Single-Sided Mode," Annual Book of ASTM standards: V. 4.06. International; 2005.

[19] ASTM C597-02," Standard Test Method Pulse Velocity Through Concrete," Annual Book of ASTM standards: V. 4.06. International; 2005.

[20] E. Ozbay, A. Oztas, A. Baykasoglu and H. Ozbebek, "Investigating Mix Proportions of High Strength Self Compacting Concrete by Using Taguchi Method," ELSEVIER. Construction and Building Materials, vol. 23, pp. 694-702, 2009.

[21] H. Tanyıldızı, "Post-Fire Behavior of Structural Lightweight Concrete Designed by Taguchi Method," ELSEVIER. Construction and Building Materials, vol. 68, pp. 565-671, 2014.

[22] O. K. temur, E. Arıcı, S. Yıldız and B Gökçer, "Performance Evaluation of Cement Mortars Containing Marble Dust and Glass Fiber Exposed to High Temperature by Using Taguchi Method," ELSEVIER. Construction and Building Materials, vol. 60, pp. 17-24, 2014.

[23] D. S. Babu, K. G. Babu KG, and T. H. Wee, "Effect of Polystyrene Aggregate Size on Strength and Moisture Migration Characteristics of Lightweight Concrete," ELSEVIER. Cement Concrete Composites, vol. 28, pp. 520-527, 2006.

[24] A. Kan and R. Demirbog ˘a, "A Novel Material for Lightweight Concrete Production," ELSEVIER. Cement Concrete Composites, vol. 31, pp. 489-495, 2009.

[25] Weigler H and Karl S, "Structural lightweight aggregate concrete with reduced density – lightweight aggregate foamed concrete," Int J Lightweight Concrete, pp. 101-104, 1980.