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Prediction of Density and Thermal Conductivity of Foamed Concrete Using Non-destructive Testing Techniques

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ملخص البحث

تحظى الخرسانة الرغوية الخفيفة بقدر كبير من الاهتمام فى مجال الانشاءات نتيجة لتوافر بعض الخواص الجيدة بها مثل الوزن المنخفض والعزل الحرارى الجيد والمقاومة العالية للحريق. وبالرغم من الاهتمام بهذا النوع من الخرسانات الا انه يوجد نقص فى المعرفة والقدرة على توقع ومعرفة الخواص الميكانيكية والفيزيائية لها. وتحظى طرق الاختبارات الغير متلفة بأهمية كبيرة لدى المهندسين لتحديد خواص الخرسانة. ويتضمن هذا البحث 18 خلطة من الخرسانة الرغوية تحتوى على الرمل والجير كمواد مالئة لدراسة العلاقة بين الخواص المختلفة للخرسانة الرغوية واختبار سرعة النبضات فوق الصوتية باستخدام عدة طرق إحصائية مختلفة. وتبين من البحث انه يمكن استخدام اختبار سرعة النبضات فوق الصوتية لتقدير ومعرفة خواص الخرسانة الرغوية الخفيفة.

ABSTRACT

Due to the superior characteristics of foamed concrete such as low density, high thermal insulation and high fire resistance, it is gaining popularity in the construction field. Despite its growing usage, there remains a lack of information content regarding its physical and mechanical properties. It is of parallel interest to engineers/contractors to predict such properties using methods of non-destructive testing, when necessary. In this respect, a total of 18 mix proportions/experiments with two types of fillers (i.e. sand and lime powder) are conducted to investigate the relationship between thermal conductivity and density – on one part - and Ultrasonic Pulse Velocity (UPV) for foamed concrete, on the other. Using statistical and non-linear optimization methods, it is concluded that there is a strong correlation between them; enabling the estimation of thermal conductivity coefficient and density by using UPV testing.

Keywords: Foamed concrete, Non-destructive tests, Taguchi orthogonal array, Ultrasonic pulse velocity, Compressive strength, Thermal conductivity

1. Introduction

Normal weight concrete (NWC) is widely used in the construction field due to its advantages (i.e. adequate strength, durability and well-knowledge about its manufacturing). Although the mentioned advantages, it still suffers from some deficiencies such as its low strength to weight ratio and high thermal conductivity. These deficiencies can be avoided without great influence on the other advantages by using the foamed concrete that can be considered a solution for many problems facing the use of (NWC). Foamed concrete is obtained by introducing (0.1-1.0 mm) air bubbles into a conventional mortar to form the porous structure consists of cement paste with internal voids (0.1-1.0 mm) [1-7]. In comparison to (NWC), it implements superior characteristics such as low density with adequate strength, high fire resistance and excellent thermal and acoustic properties [8]. Although the grow of foamed concrete application, it still suffers from lag of knowledge about it.

Ultrasonic pulse velocity (UPV) is a non-destructive that can be used for concrete investigation and quality determination by measuring the velocity of waves inside concrete. This velocity is very sensitive to internal voids quantity and pattern. It is the most popular non-destructive test due to its simplicity [9]. UPV is gaining more popularity in the recent years in concrete investigations due to its simplicity and capability of quality determination with lower cost, structural damage and time consumption [10]. Although these great advantages, UPV results still suffer some non-reliability – especially with compressive strength prediction – due to the interference with other factors affecting concrete properties. Therefore, many researches were conducted to obtain more reliable models relating UPV and concrete properties. Regarding foamed concrete, many earlier mentioned that the density and pore system is the main factor influencing foamed concrete properties [3,11&12]. Thus, UPV has more efficiency to represent the density dependent properties.

The objectives of this study are to investigate the influence of foamed concrete composition on UPV test results and to obtain empirical models that can be used for predicting physical and mechanical properties of foamed concrete.

Three statistical approaches are used in this study: (i) Taguchi orthogonal array method and analysis of variance (ANOVA) approach to investigate the influence of foamed concrete composition on UPV test results, (ii) linear regression to develop empirical models that can be used for mix design.

2. Experimental Program

2.1. Materials

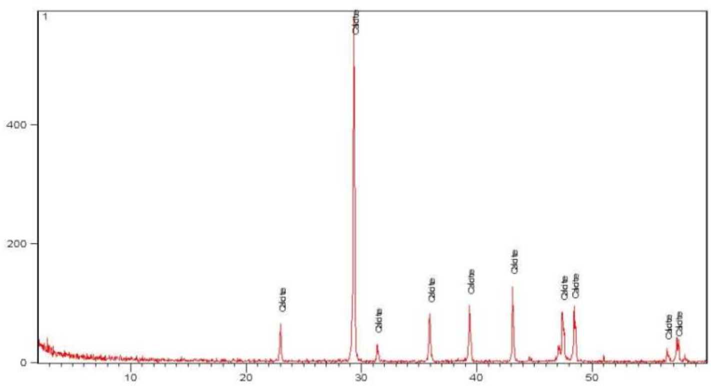
In this study, ordinary Portland cement (CEM I 42.5R) is used as a binder, with a chemical composition displayed in Table 1 and mechanical and physical properties displayed in Table 2. Natural sand of specific gravity (S.G = 2.59); sieved to avoid particles larger than 1.18 mm, is used as filler. Lime powder (calcium carbonate, CaCO3) of (S.G = 2.59) serves as a partial and full replacement for natural sand, (see chemical composition in Table 3). X-Ray Diffraction analysis (XRD), conducted for the latter, shows that it is predominantly formed of calcite (see Fig. 1).

Table (1): Chemical composition of ordinary Portland cement

Oxide	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O	Cl
%	19.29	4.52	3.59	62.08	1.80	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



Position (2θ)

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/m^3) was used. The foam is produced by blending foam agent, water and compressed air in a foam generator, as shown in Fig. 2.

a. Foam agent tank b. Generator set c. Produced foam

Fig. 2: Foam generator

2.2. Mix proportions

Eighteen mix proportions were designed and conducted to investigate the influence of ingredients on the foamed concrete properties; divided into two groups to investigate the foamed concrete in two density ranges, (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 (CaCO3/F) and foam volume per unit volume of concrete (Vf).

Table (3): Factors and levels

Levels	Group	Factors		
		(C/F) (A)	(CaCO3/F) (B)	(Vf) % (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 manufacturer to use mortars with present 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. Fig. 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 100 x 100 x 100 mm were saw-cut from each concrete panel to be tested - (according to ASTM C513-89 R95 [15]) - to determine the 28 days compressive strength.

2.5.2. Density (ρ)

Five cubes with dimensions 100 x 100 x 100 mm - (according to ASTM C513-89 R95 [15]) - were 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 [16]; from which the bulk density is calculated in Equation (1).

$$\rho = \frac{A}{B - C} \cdot \rho_w \qquad (1)$$

where ρw is the density of water.

2.5.3. 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 and maximum temperature capacity of 120oC) in single sided mode (according to ASTM C1044-12 [17]).

$$\lambda = (Q/A) \times (L/\Delta T) \qquad (2)$$

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

Fig. 4: Thermal conductivity test apparatus

2.5.4. Ultrasonic pulse velocity (UPV)

Ultrasonic pulse velocity (UPV) is a non-destructive test, which is applied on concrete to measure the velocity of waves through concrete. Velocity of waves is very sensitive to voids pattern. Test was conducted on specimens according to according to ASTM C597-02 [18].

$$V=L/T \quad (3)$$

Where V is pulse velocity (m/s), L is distance between centers of transducer faces in (m) and T is transit time in (s).

3. Results, Analysis And Discussion

3.1. Statistical approaches

Taguchi orthogonal array (TOA) is a statistical method developed as an efficient and systematic approach (optimization technique) to obtain the optimum conditions of the parameters affecting properties of the final product to get the target value [10-19]. The Taguchi orthogonal array method can be used to study a large number of variables with a lesser number of experiments [19]; 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 Fig. 5).

ANOVA is a statistical procedure to be applied on the experimental results to determine the significance and contribution-percentage of each parameter on the performance and differentiate the variance due to parameters and errors [21]. The F test is conducted according to 95% confidence to obtain the F ratio; which has to be greater than the tabulated value if the parameter has a significant influence on the performance. The P value is calculated for each parameter to assure its significance if its value is less than 0.05. ANOVA was applied in this investigation by using the “Minitab” software to verify the results obtained from the Taguchi method.

linear regression approach was applied to obtain relationships between two dependent 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.

Table (3): L9 (3^3) Orthogonal Array (Experimental Results)

Mix No	Group	Factors[1]			Density (kg/m3)	Compressive strength (MPa)	Thermal conductivity (W/m.k)	UPV (m/s)
		A	B	C				
1	I	A1	B1	C1	1016	4.14	0.35	2054
2		A1	B2	C2	747	1.61	0.20	1844
3		A1	B3	C3	565	1.03	0.16	1654
4		A2	B1	C2	834	2.20	0.22	1927
5		A2	B2	C3	593	1.26	0.17	1496
6		A2	B3	C1	857	3.69	0.24	1897
7		A3	B1	C3	563	0.85	0.15	1573
8		A3	B2	C1	938	5.15	0.32	2229
9		A3	B3	C2	726	2.57	0.20	1774
10	II	A1	B1	C1	1339	11.81	0.43	2611
11		A1	B2	C2	1098	5.81	0.38	2328
12		A1	B3	C3	935	3.71	0.31	2116
13		A2	B1	C2	1118	6.95	0.39	2569
14		A2	B2	C3	935	4.12	0.30	2239
15		A2	B3	C1	1325	10.79	0.44	2634
16		A3	B1	C3	1015	5.25	0.34	2257
17		A3	B2	C1	1374	14.46	0.45	2879
18		A3	B3	C2	992	6.40	0.33	2216

[1] Factors A, B and C represent (C/F), (CaCO3/F) and (Vf).

Table (5): Mean response of each factor in correspondence with levels – UPV

Levels	Group	Factors UPV (m/s)			Levels	Group	Factors UPV (m/s)		
		A	B	C			A	B	C
1	I	1851	1851	2060	1	II	2352	2479	2708
2		1773	1856	1848	2		2481	2482	2371
3		1859	1775	1574	3		2451	2322	2204
Difference in mean value		86	84	489	Difference in mean value		129	160	504

3.2.1. Ultrasonic pulse velocity (UPV)

Fig. 5 illustrates that the main effective parameter on UPV is foam volume (Vf) then the lime/filler (CaCo3/F) and cement/filler (C/F) parameters. The differences in mean responses of C/F, CaCO3/F and Vf for Group I are 86, 84 and 489, respectively. As for Group II, the corresponding values are 129, 160 and 504, respectively.

Table (6): Analysis of variance (ANOVA) results for UPV

Group	Source	DF	Adj SS	Adj MS	F-ratioa	F-ratiob	P-Value	(%) Contribution
I	C/F	2	13326	6663	0.09	5.14	0.911	3.06
	CaCO3/F	2	12467	6233	0.09	5.14	0.916	2.87
	Vf	2	355751	177875	13.44	5.14	0.006	81.76
	Error	2	53590	26795				12.31
	Total	8	435134					100
II	C/F	2	27342	13671	0.17	5.14	0.849	5.30
	CaCO3/F	2	50258	25129	0.32	5.14	0.736	9.73
	Vf	2	395474	395474	9.81	5.14	0.013	76.57
	Error	2	43382	21691				8.40
	Total	8	516456					100

Source: source of variation, DF: degree of freedom, Adj SS: adjusted sum of square, Adj MS: adjusted mean square (variance), a Calculated F- ratio and b Tabulated F – ratio

Analysis of variance (ANOVA) is shown in Table 6 wherein the level of importance of various factors shows agreement with the results obtained from analysis of means. Percentage of contribution-values for C/F, CaCO3/F and Vf for Group I are 3.06%, 2.87% and 81.76% respectively. The corresponding values for Group II are 5.30%, 9.73% and 76.57%, respectively.

Generally, UPV is very sensitive to the quantity of the internal voids in any type of concrete, so foam volume has the main contribution in the change of results. The trend of change of results due to the increase of lime powder content can be explained by that the finer fillers lead to more better distribution for pores, therefore less density and less UPV. For cement content, the results are cannot be used for a clear conclusion.

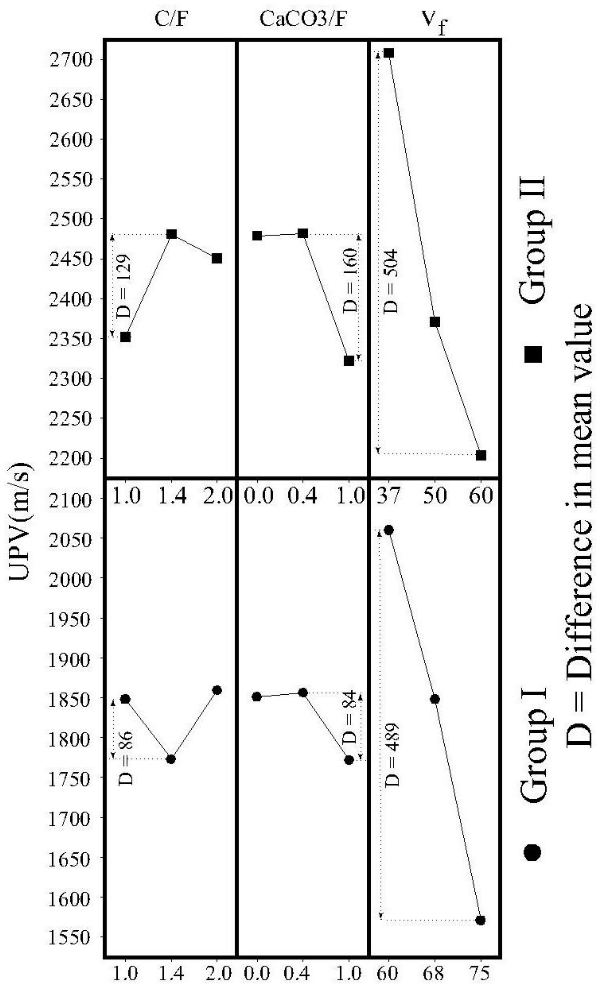


Fig. 5: Mean responses for main effects on UPV

3.2.2. UPV versus density

As shown in Fig. 6, variation in density has significant influence on UPV. An empirical relationship was developed.

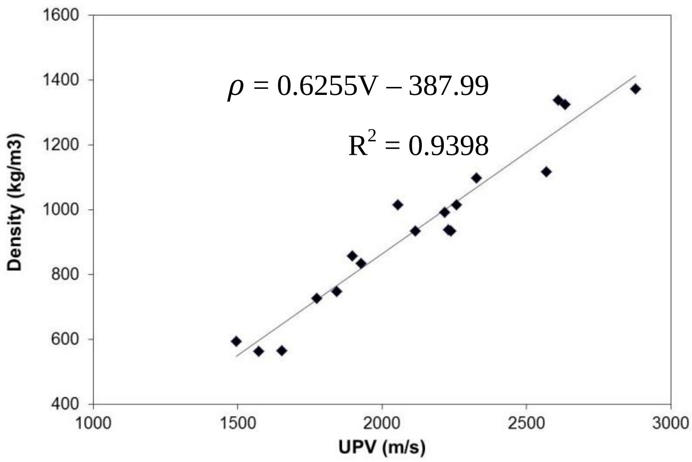


Fig. 6: Relationship between UPV and density

3.2.3. UPV versus compressive strength

As shown in Fig. 7, relation between compressive strength and UPV is strong. It can be explained by that the density is the main influential factor on compressive strength as mentioned by many authors [8&22]. In addition, UPV test results are very sensitive for voids content which expressed by density.

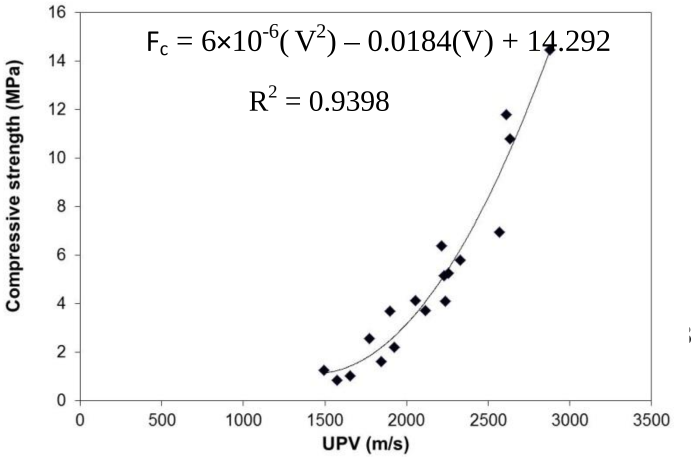


Fig. 7: Relationship between UPV and compressive strength

3.2.4. UPV versus thermal conductivity

Thermal conductivity is the most important parameters of foamed concrete, especially the non-structural foamed concrete, thus a model relating thermal conductivity and UPV is very important (see Fig. 8). The fitted curve (line) describes Due to the linear relationship it can be considered that the volume of voids in foamed concrete is the main influential factor on thermal conductivity.

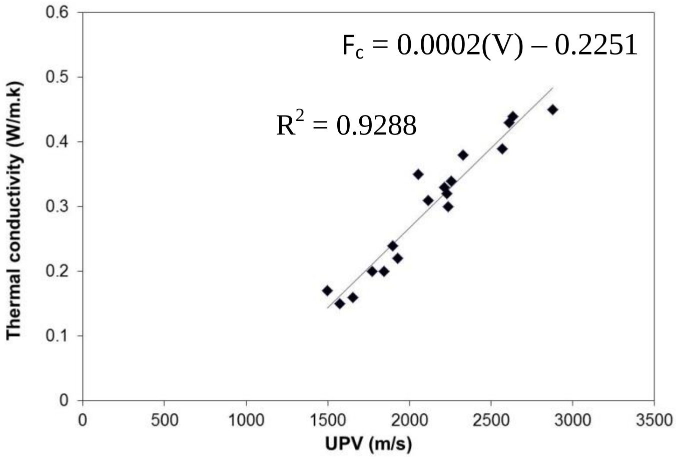


Fig. 8: Relationship between UPV and thermal conductivity

4. Conclusions

This study was conducted to add to the already existing information content regarding preformed foamed concrete. The experimental work – comprising 18 samples – was analysed/modelled 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 UPV through foamed concrete. The results obtained from (TOA) yield high agreement with the Analysis of Variance (ANOVA) approach.

- Foam volume has proven to be the main influential factor, with a contribution percentage for low density concrete and high density foamed concrete – as per ANOVA - equating 81.76% and 76.57%, respectively; (ii) lime-to-overall-filler ratio yielded a contribution percentage for low density and high density foamed concrete equating 2.87% and 9.73%, respectively; (iii) finally, cement-to-filler ratio yielded the least/insignificant effect on density with a contribution percentage of 3.06% and 5.30%, respectively.

- The previous point indicates that UPV – sensitive to pore system – can be used for foamed concrete investigation with more reliability than conventional concrete.

- UPV yields strong relationships with density, compressive strength and thermal conductivity.

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