AIN SHAMS UNIVERSITY

FACULTY OF ENGINEERING

Structural Engineering

Characterization and Modeling the Behavior of Foamed Concrete

A Thesis submitted in partial fulfillment of the requirements of the degree of

Doctor of Philosophy in Civil Engineering

(Structural Engineering)

by

Mahmoud Galal Mohamed Hassan

Master of Science in Civil Engineering

(Structural Engineering)

Faculty of Engineering, Ain Shams University, 2018

Supervised By

Dr. Ahmed Fathy Abdelaziz

Dr. Tarik Abdelfattah Youssef

Cairo - (2018)

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Date:14 May 2018

Statement

This thesis is submitted as a partial fulfillment of the “Doctor of Philosophy” degree in Civil Engineering Engineering, Faculty of Engineering, Ain shams University.

The author carried out the work included in this thesis, and no part of it has been submitted for a degree or a qualification at any other scientific entity.

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Thesis Summary

Due to its superior characteristics, such as low density, high thermal insulation and high fire resistance, foamed concrete is gaining popularity in the engineering construction field. Foamed concrete one of light weight concrete classification (LWC); typically consists of cement, filler (sand and/or lime powder), water and foaming agent; in which air or gas bubbles are introduced into conventional mortar to give it the aforementioned properties.

Despite the abundance of research in the past decade, lack of knowledge remains regarding the prediction of the mechanical and physical properties of foamed concrete with/without adding mineral additives such as microsilica and fly ash; necessitating further experimentation and modelling. The common practice of casting foamed concrete in Egypt – for insulation purpose – is predominantly a function of experience rather than design.

In this regards, the purpose of this study is to investigate the influence of input-proportions/ratios such as: foam volume,sand-to-filler ratio and filler-to-cement ratio - in addition to adding fly ash and microsilica to mixtures - on the physical, mechanical and functional properties of foamed concrete. These properties include density, absorption, compressive strength, flexural strength and thermal conductivity.

This effort comprises experimental work followed by statistical analysis and modelling. The latter includes a multi-linear regression approach as well as a "Machine Learning" method based on "Artificial Neural Networks" (ANN), for the purpose of deducing an adequate model for foam concrete mix design.

The experimental work comprises of two phases, (i) Phase I includes 216 mix proportions (experiments) with two different types of filler (sand and lime powder); divided into three groups; Group I: the used filler is lime powder, Group II: filler is fully replaced by sand and Group III: the filler is partially replaced by sand, (ii) Phase II includes 16 mix proportions, designed by the

Taguchi orthogonal array (TOA) method and conducted through partial replacement of filler by fly ash and/or micro silica.

Three statistical approaches used for this investigation are: (i) Analysis of means (ANOM) 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 multi-linear regression approach to develop empirical relationships that can be used for mix design. In addition, artificial neural network (ANN) was used as a machine learning method to deduce a model to be used for mix design.

This thesis has brought forth an abundance of outcomes, the main which are:

- **Ingredient Contribution Using Statistical Analysis**: Foam volume is of paramount effect on density; amounting to 91.58%, 94.16 and 85.01% contribution for the aforementioned groups, respectively. Foam volume equally influences compressive strength; amounting to 90.69%, 90.43 and 76.79% contribution for the aforementioned groups (Group I, Group II and Group III), respectively. The two parameters of lime-to-overall-filler ratio and cement-to-filler ratio yielded a significantly lower effect than foam volume.
- **Compressive Strength and Density:** For a mix proportion of: filler/cement (0.50), sand/filler (0.20) and foam volume (V_F = 45% of overall concrete volume), the highest compressive strength achieved was 21 MPa; corresponding a density of 1487 kg/m^3. For a similar mix proportion yet with foam volume (V_F = 20%), the compressive strength increased further to reach 26 MPa; corresponding a density of 1641 kg/m^3. Thus, a compressive strength value of conventional concrete can be reached, however at density values in the range of 1400 to 1600 kg/m^3.
- **Mineral Additives' Incorporation (Compressive Strength):** Several partial replacement proportions/percentages of filler with fly ash and/or microsilica were considered. The compressive strength of foam concrete

augmented from 26 MPa to values exceeding 38 MPa, on partial replacement of filler by 75% and 7.5% for fly ash and microsilica, respectively; due to pozzolanic effect, pore distribution improvement and increasing paste phase

- **Mineral Additives' Incorporation (Density):** Partial replacement of filler (75% and 7.5% for fly ash and microsilica, respectively) resulted in a minor reduction in density of 5% approx. (compared to original/control sample; a result of reduction in specific gravity as well as the improving in pore distribution and bubble loss.
- **Thermal Conductivity (λ):** The obtained λ values for the total of (232 batches) yielded values ranging from 0.2 to 0.7 W/m.k (10 to 40% approx. of conventional concrete). For the tested samples within this study, a density reduction of 100 kg/m^3, for foamed concrete, results in 0.04 W/m.k reduction of λ. This comes in agreement with earlier similar efforts.
- **Ultrasonic Pulse Velocity (UPV):** On applying UPV to hardened foamed concrete specimens, a strong/linear correlation is found between wave velocity and density. In turn, the density of foamed concrete can be predicted in situ using non-destructive testing.
- **Multi-linear Regression versus ANN results:** A multi-linear regression approach was used to obtain empirical models for mix design; mainly for density and compressive strength; given the three main input parameters (cement/filler ratio, sand/filler ratio and foam volume). On comparing the "Normalized Root Mean Square Error" (NRMSE) obtained to that of the ANN model, it is discovered that the empirical model is equally adequate (on estimation of foamed concrete compressive strength). The machine learning approach (based on ANN), however, could be more reliable when further data collection takes place.

- **The purpose of Machine Learning (ANN based):** This effort serves as a starting point for an extensive data base regarding foamed concrete,

ultimately leading to generalized models for physical and mechanical properties.

Key words: Foamed concrete, Compressive strength, Analysis of means (ANOM), Analysis of variance (ANOVA), Thermal conductivity, Artificial neural networks (ANN).

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