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Hardened properties of foamed pastes with alternative foaming agents as function of porosity

Propiedades de las pastas espumadas endurecidas con agentes espumantes alternativos en función de la porosidad

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Abstract

Concrete is one of the most used materials in civil engineering. However, construction industry demands the use of lightweight materials. Cellular concrete is an alternative. This form of concrete is known for its low density, high workability, low thermal and acoustic conductivity and high fire resistance. In hardened state, properties of concrete such as density, compressive strength, permeability, shrinkage and thermoacoustic isolation are intimately related to its porosity and pore size distribution. Difference in pore structure is largely due to the foam type, water cement ratio and foam stability. Given the importance of porosity for the evaluation of the performance of a cellular concrete on hardened state, the present work aims to determine mathematical relationships between porosity and density and compressive strength, considering the effect of the type of foaming reagent used and the water/cement ratio.

Keywords: Foamed pastes; cellular concrete, porosity; density; compressive strength.

Resumen

El hormigón es uno de los materiales más usados en la ingeniería civil. No obstante, la industria de la construcción exige el uso de materiales de más livianos y el hormigón celular es una alternativa. Este tipo de hormigón es reconocido por su baja densidad, alta trabajabilidad, baja conductividad térmica y acústica y su alta resistencia al fuego. En estado endurecido, las propiedades del hormigón tales como la densidad, resistencia a la compresión, permeabilidad, retracción y aislamiento termoacústico se encuentran íntimamente relacionadas con su porosidad y distribución del tamaño de sus poros. La diferencia en la estructura de los poros se debe principalmente al tipo de espuma, razón agua-cemento y estabilidad de la espuma. Dada la importancia de la porosidad en la evaluación del comportamiento de un hormigón celular en estado endurecido, este trabajo busca determinar las relaciones matemáticas existentes entre la porosidad, densidad y resistencia a la compresión, considerando el efecto del tipo de reactivo espumante usado y la razón agua-cemento.

Palabras clave: Pastas espumadas; hormigón celular; porosidad; densidad; resistencia a la compresión.

1. Introduction

Cellular concrete is a type of lightweight concrete. American Institute of Concrete (ACI) in 523 defines the cellular lightweight concrete as a mixture of cement, water, and preformed foam. The purpose of the foam is to supply a production mechanism of a high ratio of air cells that when they are mixed with cement produce a porous solid (Gómez, 2015). Foamed concrete contains numerous pores inside the material, and these pores are a significant factor determining the material characteristics (Chung et al., 2017). There are several methods to accomplish the porosity in cellular concretes: chemical agents that include the air in the mortar, foaming agents that are added to the mixture or vacuum curing that manages to create pores due to the internal strains generated in the paste (Chica and Alzate, 2019). The pores in a foamed concrete might be generated in different configurations: interlayer (<1 nm), gel (1–10 μm), capillary (>10 μm) and from suction (1–2 mm). Properties of concrete such as density, compressive strength, permeability and shrinkage are intimately related to its porosity and pore size distribution (Chica and Alzate, 2019). Fine and close pores resulting in a compact in texture with high density and strength, but a low permeability (Yu et al., 2010). Some authors have proposed mathematical models to relate porosity with density and compressive strength, because both properties are very important in cellular concrete performance evaluation. On the pioneering studies about porosity influence on cellular concrete mechanical properties are results of Kearsley and Wainwright (Kearsley and Wainwright, 2001); (Kearsley and Wainwright, 2001a); (Kearsley and Wainwright, 2002). They found for aerated concrete with fly ash exits a strong relationship between dry density and porosity which is largely independent of ash type, ash content, or the inclusion of the foam.

Highlights

- *In foamed OPC pastes, porosity has a great influence on mechanical performance*
- *Equations used to relate porosity with density and compressive strength are founded*
- *Effect of foaming agent class, water content, superplasticizer and curing time could be considered on modelling*

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The relationship between porosity and dry density can best be described using the (Equation 1)

$$\gamma_d = 1149.37\, p^{-1.185} \qquad (1)$$

Where p is porosity [%] and γd dry density [kg/m3]. Also, about relationship between porosity and compressive strength, Kearsley and Wainwright (Kearsley and Wainwright, 2001a); (Kearsley and Wainwright, 2002) show a review with (Equations 2); (Equation 3); (Equation 4) and (Equation 5) to relate this properties:

$$f_c = f_{c,0}(1-p)^n \qquad \text{Balshin} \qquad (2)$$

$$f_c = f_{c,0}e^{-kp} \qquad \text{Ryshkevitch} \qquad (3)$$

$$f_c = k_s \ln\left(\frac{p_0}{p}\right) \qquad \text{Schiller} \qquad (4)$$

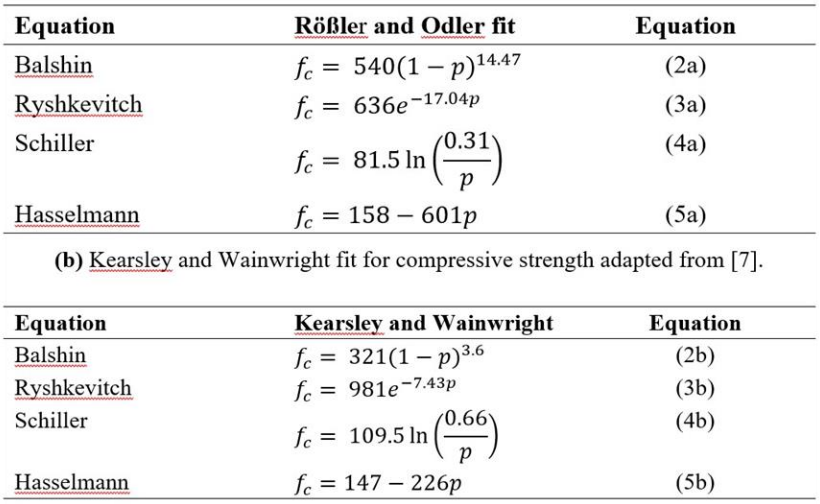
$$f_c = f_{c,0} - k_h p \qquad \text{Hasselmann} \qquad (5)$$

Where: fc compressive strength of concrete with porosity p; fc,0 compressive strength at zero porosity; p porosity (volume of voids expressed as a fraction of the total concrete volume); n a coefficient, which need not be constant; p0 porosity at zero strength; k, ks, kh empirical constants, t time since casting [days], $\bar{p}$ *mature porosity measured after 365 days.*

Rößler and Odler fitted a regression for their experimental data in (Equation 2) to (Equation 3), (Equation 4) and (Equation 5) as shown in (Table 1a). Their experimental data corresponds to a series of cement pastes with different water/cement ratios after different periods of hydration. They concluded for porosities between 5% and 28% that although all four of the strength–porosity equations shown above could be used, the relation between compressive strength and porosity can best be expressed in the form of a linear plot (Kearsley and Wainwright, 2002).

In (Table 1b) are presented the experimental results of Kearsley and Wainwright. In this experimental research, cement pastes had water/cement ratios of 0.3, 0.4 and 0.6; and the paste mixtures in which 50%, 66.7% and 75% of the cement (by weight) was replaced with fly ash (ash/cement ratios of 1, 2 and 3). Kearsley and Wainwright made foamed concrete mixtures of different casting densities (1000, 1250 and 1500 kg/m3). The relationship between measured porosity and the compressive strength was modelling. Haselmann fit the best for Rößler and Odler data, but Ryshkevitch fit the best for Kearsley and Wainwright data. The porosities of the cement pastes analysed by Rößler and Odler were below 30%, while the porosities of the Kearsley and Wainwright samples were as high as 66%.

Table 1. (a) Rößler and Odler fit for compressive strength adapted from (Kearsley and Wainwright, 2002)



Equation	Rößler and Odler fit	Equation
Balshin	$f_c = 540(1-p)^{14.47}$	(2a)
Ryshkevitch	$f_c = 636e^{-17.04p}$	(3a)
Schiller	$f_c = 81.5\ln\left(\frac{0.31}{p}\right)$	(4a)
Hasselmann	$f_c = 158 - 601p$	(5a)

(b) Kearsley and Wainwright fit for compressive strength adapted from [7].

Equation	Kearsley and Wainwright	Equation
Balshin	$f_c = 321(1-p)^{3.6}$	(2b)
Ryshkevitch	$f_c = 981e^{-7.43p}$	(3b)
Schiller	$f_c = 109.5\ln\left(\frac{0.66}{p}\right)$	(4b)
Hasselmann	$f_c = 147 - 226p$	(5b)

Some models for compressive strength prediction of aerated and foam concrete are either based on power model or Balshin model. Power model has an advantage that material behavior is related to its composition. Also, it is more correct to relate strength to the concentration of the solid products of hydration of cement in the space available for these products (Nambiar and Ramamurthy, 2008). Balshin equation provides a good fit to the plot of compressive strength against total porosity for slate based autoclaved aerated concretes and at all ages of foam concrete made of cement paste containing high percentage of ash (Nambiar and Ramamurthy, 2008). (Narayanan and Ramamurthy, 2001) based in Balshin model propose the (Equation 6a), (Equation 6b)(Narayanan and Ramamurthy, 2001).

$$f_c = 26.60\,(1-p)^{3.2} \qquad \text{Aerated with sand} \qquad \textbf{(6a)}$$

$$f_c = 24.28\,(1-p)^{1.8} \qquad \text{Aerated with fly ash} \qquad \textbf{(6b)}$$

(Kearsley and Wainwright, 2002) propose a new equation for compressive strength using Balshin fit, as follow (Equation 7a), (Equation 7b)

$$f_c = \ 321(1-p)^{3.6} \qquad \textbf{(7a)}$$

$$f_c = \ 39.6\,(\ln t)^{1.174}(1-p)^{3.6} \quad \text{changing } f_{c,0} \text{ to a function of time} \qquad \textbf{(7b)}$$

Nambiar and Ramamurthy (2008) presents other Balshin based equation (Equation 8a) and (Equation 8b):

$$f_c = 155.66\,(1-p)^{4.3} \qquad \text{Aerated with sand} \qquad \textbf{(8a)}$$

$$f_c = 105.14\,(1-p)^{2.68} \qquad \text{Aerated with fly ash} \qquad \textbf{(8b)}$$

The aim of this work is finding a mathematical model to fit density and porosity; and compressive strength and porosity, for different cellular concrete made with air entrainment agent and alternative foaming agent. The fit equations are compared with empirical models available in literature. Results will allow to analyze the effect of porosity on density and compressive strength on cellular concrete.

2. Experimental set up

Different foamed cement mixes were manufactured randomly. The variables of interest in the study are the water content (in terms of the water to cement ratio) and foaming agent employed. The materials used were ordinary Portland cement (OPC) and two types of reagents to incorporate a greater amount of air into the mix: commercially available air entrainment (AirToc D and SikaAer) and foaming alternative agents (nonylphenol and lauryl ether). In the dosages used, the cement content was kept between 400 and 500 kg for each m3 of mix. For the aerators, the reagent used was between 3 and 5%, and for the alternative foaming agents the dosages contain between 0.1 and 0.2%, in both cases, added with respect to the cement content. For water to cement ratio under 0.44, a superplasticizer was added to the mix. The manufacturing method of cellular concrete was in-mixing. In the in-mixing method, foaming agent is added to a mixer that creates bubbles due to its high rotating speed. The additive must trap air (encapsulate) and make it distribute uniformly. This method is easy to perform, standardized and widely used. For this experimental set up, the reactive it is incorporated at the same time with water and cement and mixed for 20 minutes. For the process, a Hobbart laboratory planetary mixer was used. A summary of the water content and type of reagent used is presented in (Table 2). With the mixtures, 5cm edge mortar cubes were melted and wet cured for 28 days. Likewise, measurements of dry density (ASTM C642), porosity (ASTM C642-13) and compressive strength (ASTM C109) were obtained experimentally at 28 days.

3. Results and discussion

The properties of hardened cellular concrete including porosity, density, and compressive strength are indicated in (Table 3).

3.1 Effect to porosity in density

To simplify the analysis of results, the problem was divided in three parts.

First, the analysis of global data base to understand the effect of porosity on density, including a comparation to Kearsley equation. Then, for the analysis filters the database results by foaming agent and finally, filter based to water to cement ratio to determining the influence of water content on dry density.

The relationship between dry density and porosity shown in (Figure 1) from which dry density is largely dependent on porosity, regardless the dosage.

A sample with high porosity is associated with its low density. Also, in this plot, are shown the data fit with Kearsley equation. In that sense, (Equation 1) do not fit properly the results in this experimental work as expected, because Kearsley equation was obtained fitting experimental data.

Table 2. Water/cement ratio and foaming agents used in experimental work

Sample	W/C ratio	Agent	Sample	W/C ratio	Agent
A1-1	0.3	Nonyl	G5-6	0.4	Laurylether
A1-2	0.3	Nonyl	G5-9	0.4	Laurylether
A1-3	0.3	Nonyl	G8-1	0.4	Laurylether
A2-6	0.3	Nonyl	G8-2	0.4	Laurylether
A2-7	0.3	Nonyl	L1	0.8	SikaAER
A2-8	0.3	Nonyl	L2	0.8	SikaAER
A2-9	0.3	Nonyl	L3	0.8	SikaAER
A3-6	0.3	Nonyl	L4	0.5	SikaAER
A3-7	0.3	Nonyl	M1-1	0.5	Air Toc D
G10-1	0.3	Laurylether	M1-2	0.5	Air Toc D
G10-2	0.3	Laurylether	M17	0.7	Air Toc D
G10-3	0.3	Laurylether	M18-1	0.7	Air Toc D
G10-4	0.3	Laurylether	M18-2	0.7	Air Toc D
G1-1	0.5	SikaAER	M2-1	0.44	Air Toc D
G1-2	0.5	SikaAER	M2-2	0.44	Air Toc D
G2-1	0.3	Nonyl	M24	0.7	Air Toc D
G2-2	0.3	Nonyl	M29	0.5	Air Toc D
G2-3	0.3	Nonyl	M3	0.35	Air Toc D
G2-4	0.3	Nonyl	M53	0.35	Laurylether
G2-5	0.3	Nonyl	M57	0.35	Laurylether
G3-1	0.8	SikaAER	U1	0.4	Nonyl
G3-2	0.8	SikaAER	U2-1	0.4	Nonyl
G3-3	0.8	SikaAER	U2-2	0.4	Nonyl
G3-4	0.8	SikaAER	U2-3	0.4	Nonyl
G3-5	0.8	SikaAER	U2-4	0.4	Nonyl
G4-0	0.6	Nonyl	U4-1	0.35	Nonyl
G4-1	0.6	Nonyl	U4-2	0.35	Nonyl
G4-2	0.6	Nonyl	U4-3	0.35	Nonyl
G4-3	0.6	Nonyl	U4-4	0.35	Nonyl
G4-4	0.6	Nonyl	U5-1	0.35	Laurylether
G5-1	0.4	Laurylether	U5-2	0.35	Laurylether
G5-2	0.4	Laurylether	U5-3	0.35	Laurylether
G5-3	0.4	Laurylether	U6-1	0.35	Laurylether
G5-5	0.4	Laurylether	U6-2	0.35	Laurylether

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Table 3. Experimental results

Sample	Porosity [%]	Density [kg/m^3]	Compressive strength [MPa]
A1-1	46	886	8.94
A1-2	44	911	8.35
A1-3	46	899	7.76
A2-6	55	823	3.56
A2-7	49	828	3.61
A2-8	51	859	2.71
A2-9	47	842	3.1
A3-6	35	1000	12.52
A3-7	35	970	12.45
G10-1	84	595	2.25
G10-2	80	609	2.26
G10-3	77	609	2.19
G10-4	84	594	2.15
G1-1	40	1014	13.08
G1-2	41	1014	12.4
G2-1	28	1154	17.9
G2-2	31	1120	21.3
G2-3	26	1164	16.19
G2-4	29	1118	18.45
G2-5	26	1183	23.87
G3-1	46	1078	8.93
G3-2	46	1055	10.57
G3-3	46	1053	10.6
G3-4	46	1041	9.89
G3-5	43	1109	9.04
G4-0	37	1317	27.52
G4-1	36	1292	27.66
G4-2	36	1303	27.86
G4-3	39	1268	27.18
G4-4	38	1278	27.54
G5-1	53	545	2.02
G5-2	61	583	2.02
G5-3	55	543	2.02
G5-5	55	556	2.02
G5-6	68	584	2.02
G5-9	62	577	2.02
G8-1	48	734	5.05
G8-2	50	712	5.05
L1	34	978	8.7
L2	33	980	9.11
L3	73	613	1
L4	25	1206	12.8
M1-1	25	1514	24.7
M1-2	24	1550	23.3
M17	48	838	3.1
M18-1	51	828	3.4
M18-2	55	739	2.9
M2-1	30	1414	13.2
M2-2	27	1440	14.6
M24	40	1017	9.7
M29	27	1293	16.1
M3	20	1636	37.9
M53	28	1251	8.9
M57	36	901	5.6
U1	69	702	2.87
U2-1	69	666	3.58
U2-2	63	667	3.02
U2-3	61	692	3.51
U2-4	67	666	3.03
U4-1	88	543	1.7
U4-2	89	509	1.57
U4-3	88	526	1.64
U4-4	88	525	1.52
U5-1	75	644	4.25
U5-2	70	630	3.51
U5-3	71	656	3.48
U6-1	33	862	7.37
U6-2	30	861	7.25

(Figure 1), show a relationship between dry density and porosity. Mathematical model to describe the relationship between porosity p and density γ_d *is as (Equation 9):*

$$\gamma_d = 496.5\, p^{-0.70} \tag{9}$$

Where γd is density [kg/m3] and p is porosity [%]

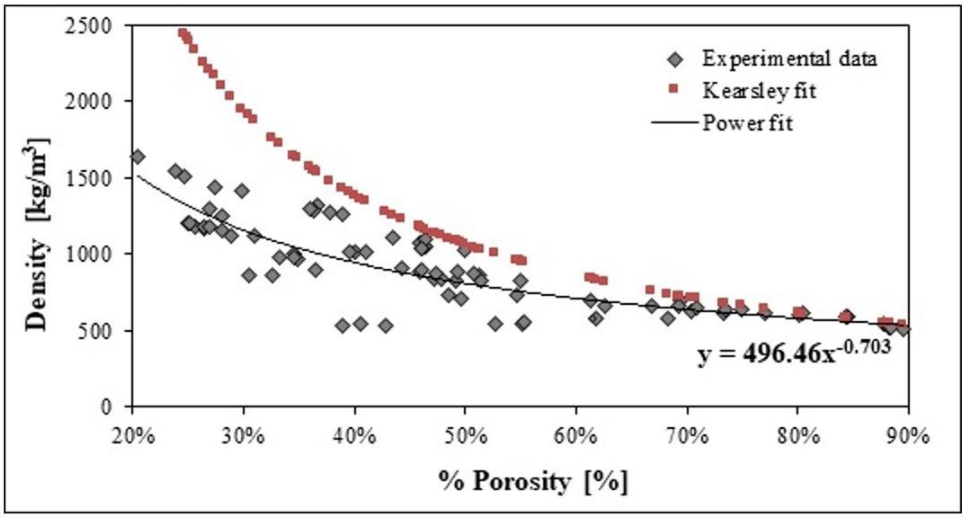

Figure 1. Porosity and density relationship for cellular concrete

In (Equation 9), it is observed the difference in the parameters respect (Equation 1a). Also, the correlation value R2 as 0.7 is an indicator for a low correspondence between all experimental results. For this reason, the second strategy, that is, to apply a filter by reagent class is consider. A resume for the behavior for separated data by reagent is exposed in (Figure 2). For AirToc-D and nonyl regression equations are like (Equation 9), but with small changes in coefficient that improves R2. However, for laurylether and SikaAer because due large data dispersion none fit applies correctly. The cause of high dispersion of experimental data is a poor pore distribution in the cement matrix or for some phenomenon associated to foam stability like bleeding or segregation. Finally, the data are filter in two ranges for water to cement ratio, as is shown in (Figure 3). The division in ranges was made considering the adding or not of superplasticizer into the mix. Experimental results plot in (Figure 3) clearly indicates the effect of superplasticizer on dry density, that is, samples without superplasticizer have more density. Probably, this effect is due because in plastic state, superplasticizer improves the foaming generation and its stability. A low water/cement ratio result in a stiff mix and breakage of bubbles during the mixing. Also, it bring a higher proportion of small pores with a larger surface area, finally resulting in thinner pore walls and more connected pores. Highest water/cement ratio result in too weak to hold the bubbles which lead to segregation [10]. Results for two water to cement ratio are fit in the same form that (Equation 9).

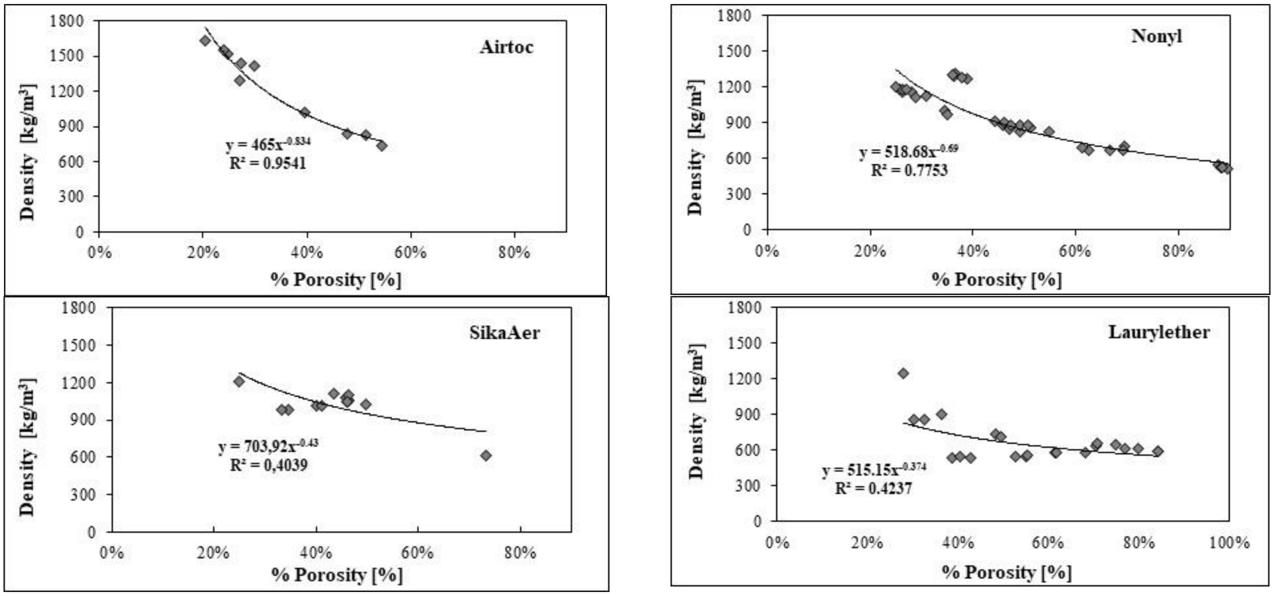

Figure 2. Power fit for data by foaming agent

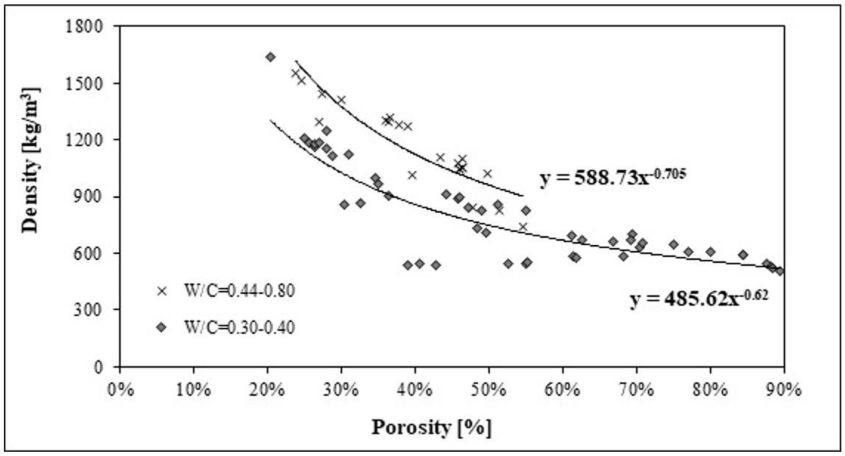

Figure 3. Power fit for data by water/cement ratio

2.2 Effect to porosity in compressive strength

For analysis the relationship between porosity and compressive strength, the global results data base is compared to Rößler and Odler, and Kearsley and Wainwright specific models. In all equations, fc is compressive strength at 28 days of curing [MPa] and p is porosity in [%]. About Schiller model (Equation 4), this only apply for porosity under 31% (Rößler and Odler) and 66% (Kearsley and Wainwright). The global data base was filtered to find the samples that accomplish the porosity condition. (Figure 4) present a plot of Schiller model equation to fit our experimental data. The equations obtained are given by:

$$f_c = 64.06 \ln\left(\frac{0.35}{p}\right) \text{ Porosity below 31\%} \qquad \textit{(10a)}$$

$$f_c = 21.72 \ln\left(\frac{0.65}{p}\right) \text{ Porosity below 66\%} \qquad \textit{(10b)}$$

Correlation value R2 are over 0.7, explaining the variability in compressive strength. In Schiller model the logarithmic parameter is associated to maximum porosity condition permitted. For this experimental research, this parameter fit as it expected. Also, in both cases, the adjusting parameter is very different because the cellular concrete samples are made with different conditions, and it is m mechanical performance it is evaluated only at 28 days of curing.

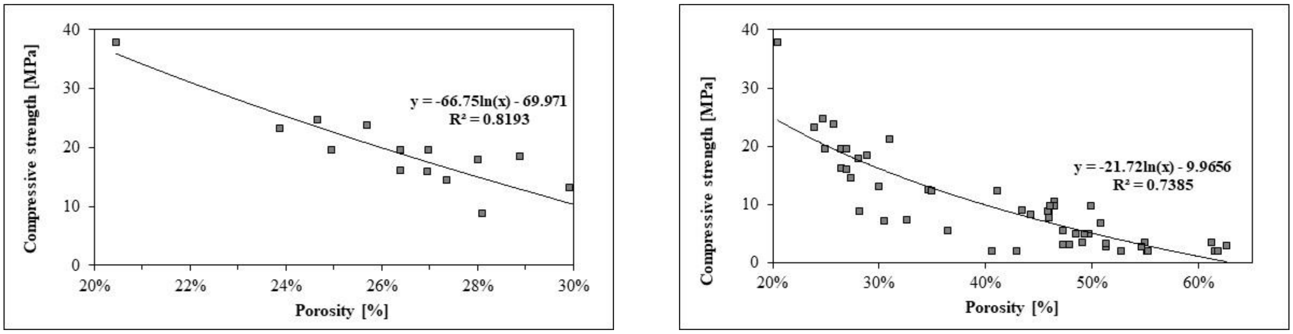

Figure 4. Regression of Schiller model (logarithmic)

Another fit model is related to Ryshkevitch model (Equation 3), that is an exponential adjust. (Figure 5) shows a regression. The Ryshkevitch equation for experimental data with R2 = 0.8, is: (Equation 11)

$$f_c = 41.687e^{-3.769p} \tag{11}$$

The fit parameters do not match with Rößler and Odler or Kearsley and Wainwright models because differences in casting conditions. In this experimental research, the water to cement ratio and foaming agents are not the same, and samples do not contain fly ash or sand.

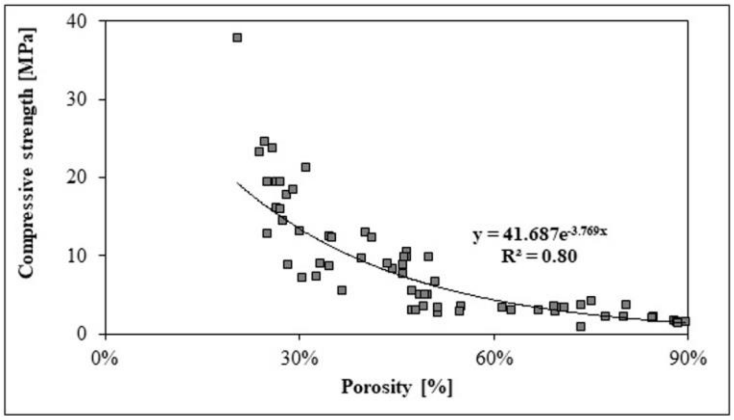

Figure 5. Regression of Ryshkevitch model (exponential)

For lineal fit, that is related to Hasselmann equation, in (Figure 6) it is shows the linear regression for experimental data with R2 value of 0.6, indicates that this model does not fit the experimental data base. The equation for Hasselman model is:

$$f_c = 23.518 - 29.156p \tag{12}$$

In this regression model, the main problem is for samples with porosity over 80% because are not fit into a lineal form. About power fit or Balshin equation, (Figure 7) show a plot for all data regression. The (Equation 13) represents the global fit with R2 = 0.7:

$$f_c = 18.303(1-p)^{1.31} \tag{13}$$

However, in (Figure 8), the plots of data filtered by reagent type show the influence of this variable on relationship between porosity and compressive strength. For all reagents when are individually treated, the R2 value improves significantly because dispersion of the data is related to nature to each foaming agent.

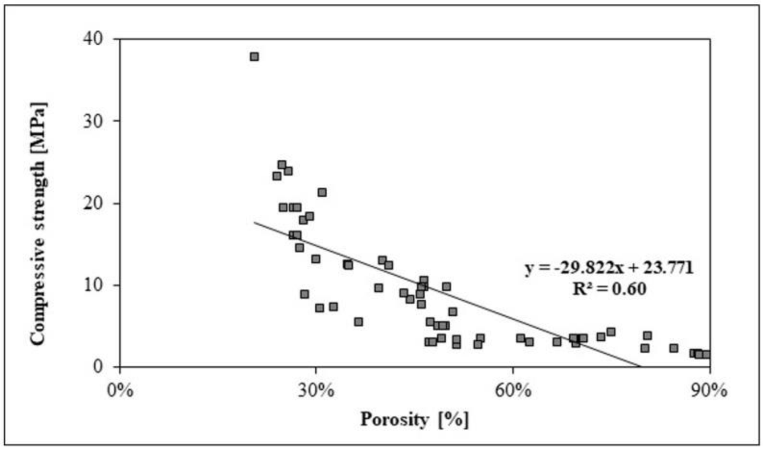

Figure 6. Regression of Hasselmann model (lineal)

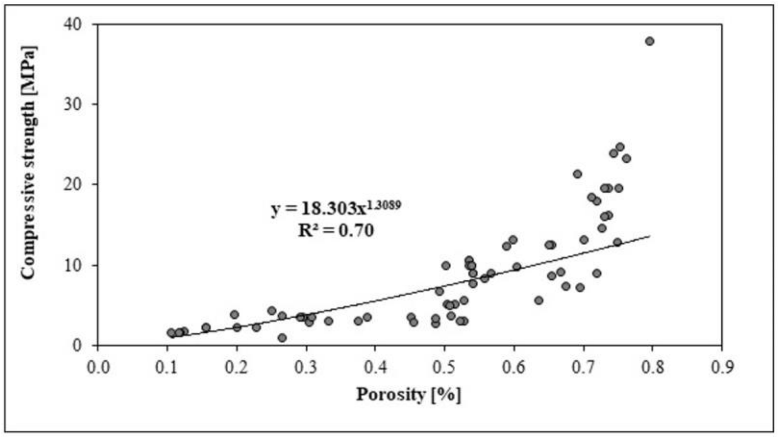

Figure 7. Regression of Balshin model (Power (1- p))

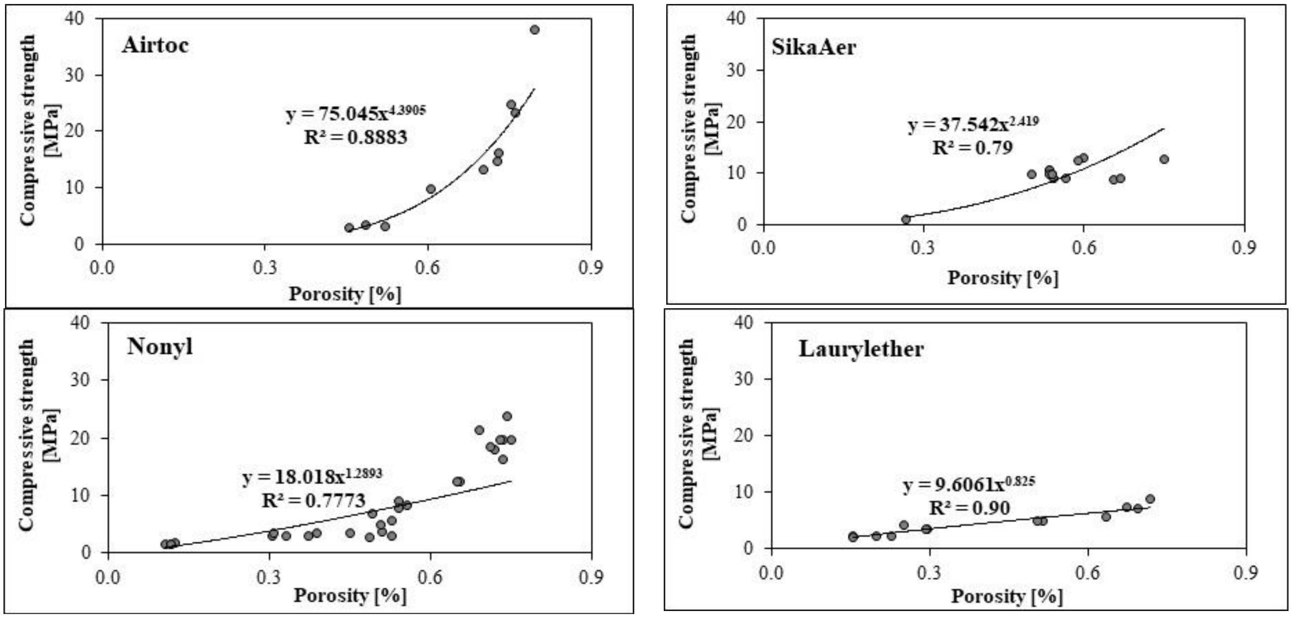

Figure 8. Regression of Balshin model filter by reactive (Power (1- p))

To conclude the discussion, the best fit to global data base for compressive strength as porosity function was achieved by Ryshkevitch model that corresponds to exponential regression (Equation 11). Clearly, this adjust correspond to experimental conditions employed in this research. These results are according to Kearsley and Wainwright results. However, if on the analysis the foaming agent is consider individually Balshin model present an improve fit.

4. Conclusions

Density and compressive strength are largely dependent on porosity. Kearsley model for density as porosity function was adjust to experimental results. The fact that data base contains data with a larger spectrum of porosities as well as higher strengths could explain the difference with Kearsley regression coefficients. Also, the effect of foaming agent class, water content, superplasticizer and curing time could be considered. About compressive strength and porosity relationship, Ryshkevitch and Balshin models present better fit than other models. Main contribution of this research are mathematical models to apply for non-conventional foaming agents in cellular concretes casting. The prediction relations developed in this study can serve as a simple tool for predicting the strength and density of foam concrete.

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6. References

Chica, L.; Alzate, A. (2019). Cellular concrete review: New trends for application in construction. Construction and Building Materials [Internet]. 200:637–647. Available from: https://doi.org/10.1016/j.conbuildmat.2018.12.136.

Chung, S-Y; Lehmann C.; Abd Elrahman, M. et al. (2017). Pore Characteristics and Their Effects on the Material Properties of Foamed Concrete Evaluated Using Micro-CT Images and Numerical Approaches. Applied Science, 7:550.

Gómez M. (2015). An Introduction to cellular concrete and advanced engineered foam technology.

Kearsley, E.P.; Wainwright P.J. (2001). Porosity and permeability of foamed concrete. Cement and Concrete Research, 31:805–812.

DOI: 10.7764/RIC.00029.21

Kearsley, E.P.; Wainwright, P.J. (2001). The effect of high fly ash content on the compressive strength of foamed concrete. Cement and Concrete Research, 31:105–112.

Kearsley, E.P.; Wainwright P.J. (2002). Effect of porosity on the strength of concrete. Cement and Concrete Research, 32:233–239.

Nambiar E.K.K.; Ramamurthy, K. (2006). Models relating mixture composition to the density and strength of foam concrete using response surface methodology. Cem Concr Compos [Internet]. [cited 2018 Jan 30];28:752–760. Available from: https://ac.els-cdn.com/S0958946506001107/1-s2.0-S0958946506001107-main.pdf?_tid=c65622a0-05c2-11e8-bf4e-00000aab0f26&acdnat=1517319654_08d697d97ae7965e6cf39caef3adc434.

Nambiar E.K.K.; Ramamurthy, K. (2008). Models for strength prediction of foam concrete. Materials and Structures [Internet]. [cited 2017 Nov 22];41:247–254. Available from: https://link-springer-com.ezproxy.unal.edu.co/content/pdf/10.1617%2Fs11527-007-9234-0.pdf.

Narayanan, N.; Ramamurthy, K. (2000). Prediction models based on gel-pore parameters for compressive strength of aerated concrete. Concrete Science and Engineering, 2:206–212.

Yu, X.G.; Luo, S.S.; Gao, Y.N. et al. (2010). Pore Structure and Microstructure of Foam Concrete. Adv Mater Res [Internet]. 2010 [cited 2018 Jul 30];177:530–532. Available from: www.ttp.net.