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Properties of Foamed Concrete as Influenced by Air-Void Parameters

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ABSTRACT: The aim of this paper is to investigate the microstructure as a primary factor influencing the relationship between the density (a physical property) and the compressive strength (a structural property) of foamed concrete.

In order to evaluate these relationships, it was necessary to develop the air-void diameter and air-void spacing parameters to explain and quantify the microstructure of foamed concrete. A high-resolution monochrome camera connected to an optical microscope and computer with image analysis software, were used to develop these parameters.

It was found that for the mixtures with the lower densities (between 500 kg/m^3 and 1000 kg/m^3), the air-void size distribution has an influence on the 28-day dry density and the 28-day compressive strength of foamed concrete mixtures.

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TECHNICAL PAPER - FOAMED CONCRETE

PROPERTIES OF FOAMED CONCRETE AS INFLUENCED BY AIR -VOID PARAMETERS

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ABSTRACT

The aim of this paper is to investigate the microstructure as a primary factor influencing the relationship between the density (a physical property) and the compressive strength (a structural property) of foamed concrete.

In order to evaluate these relationships it was necessary to develop the air-void diameter and air-void spacing parameters to explain and quantify the microstructure of foamed concrete.

A high-resolution monochrome camera connected to an optical microscope and computer with image analysis software were used to develop these parameters.

It was found that for the mixtures with the lower densities (between 500 kg/m^3 and 1000 kg/m^3), the air-void size distribution has an influence on the 28-day dry density and the 28-day compressive strength of foamed concrete mixtures.

1. INTRODUCTION

The density of lightweight concrete is appreciably lower than the usual range of concretes made with normal weight aggregates. This study is only concerned with aerated concrete, in particular foamed concrete, which is produced by introducing air-voids into a cement paste consisting of cement, water and fly ash. The introduction of these voids is achieved by adding foam to the mix. A foaming agent consisting of hydrolized proteins is diluted with water and aerated to form the foam[1].

Since 1992 tests on the physical and structural properties of foamed concrete have been conducted at the University of Pretoria. The tests show that there seems to be an optimum mix for specific densities of the material. They also indicate that the relationship between the density (a physical property) and the compressive strength (a structural property) is influenced by the composition of the cement paste[2]. The aim of the research is to optimize the mix design and therefore other factors influencing the relationship between the density and the compressive strength of foamed concrete should be investigated.

The aim of this paper is to investigate the microstructure of the material as a primary factor influencing the relationship between the density and the compressive strength of foamed concrete. In order to evaluate these relationships it was necessary to develop parameters to explain and quantify the microstructure of foamed concrete. Therefore the air-void size distribution parameters and air-void spacing parameters are also discussed in this paper.

2. GENERAL BACKGROUND

The same values of porosity as well as density can be achieved for many small air-voids or for fewer larger air-voids in the mix; therefore the air-void structure may also influence the strength of foamed concrete.

Olorunsogo and Wainwright[3,4] stated that the pore structure of a cementitious material, predetermined by its porosity, permeability and pore size distribution, is a very important micro-structural characteristic as it influences properties of the material such as strength, fracture toughness and durability. The mechanical properties of a cementitious material are dependent mainly on the distribution of the pores within the hardened cement paste. The micro-properties could therefore be a primary factor influencing the material properties of foamed concrete.

The pore structure of air-entrained cement paste and therefore of foamed concrete consists of water-filled voids (gel and capillary pores) as well as air-voids (air-entrained and entrapped pores).

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According to Cebeci's[5] investigation air-entraining agents introduce the large air-voids and do not alter the characteristic fine pore structure of hardened cement paste appreciably. Therefore the assumption can be made that by comparing two foamed concrete mixes with the same cement paste composition and with the same mix preparations and curing conditions but with different percentages of foam, the air-void structure will be the main factor influencing the compressive strength.

3. EXPERIMENTAL PROCEDURE

3.1 Sample Preparation

Thirty different foamed concrete mixes were used in this investigation. See Table 1 for the *28-day dry densities* and 28-day compressive strengths of the mixtures. The foaming agent used is manufactured in South Africa and consists of hydrolyzed proteins. Rapid Hardening Portland cement from PPC, Herculus, Pretoria and fly-ash from Lethabo was used in the mixes[6].

Mix number	Water/ Binder ratio (mass / mass)	28-day Dry density (kg/m^3)	28-day Compressive Strength (MPa)	Air-void diameter parameters		Air-void spacing parameters	
				D_{50} (µm)	D_{10} (µm)	S_{50} (µm)	S_{90} (µm)
1	0.33	1223	22.0	175	439	190	7
2	0.33	892	9.4	135	252	60	11
3	0.33	831	7.2	131	279	30	0
4	0.33	741	4.5	151	341	40	2
5	0.33	661	3.3	169	392	70	2
6	0.33	536	2.0	305	707	70	10
7	0.29	1235	24.2	127	276	140	40
8	0.29	901	6.3	134	282	90	33
9	0.29	811	4.7	143	313	80	26
10	0.29	735	2.9	163	383	100	25
11	0.29	646	2.3	181	485	110	30
12	0.29	559	1.4	251	625	60	0
13	0.29	1230	20.5	130	258	150	36
14	0.29	958	5.8	111	240	180	26
15	0.29	790	3.8	146	373	120	46
16	0.29	713	2.5	200	423	110	43
17	0.29	612	1.5	230	518	90	30
18	0.29	555	1.0	210	492	100	41
19	0.28	1219	10.6	121	258	110	50
20	0.28	958	5.1	111	256	130	44
21	0.28	812	2.4	189	440	100	33
22	0.28	697	1.6	213	500	100	44
23	0.28	631	1.1	278	587	110	57
24	0.28	540	0.7	402	862	100	18
25	0.27	1168	6.6	129	217	280	143
26	0.27	941	3.5	137	233	120	41
27	0.27	771	1.7	156	291	80	31
28	0.27	726	1.3	225	534	140	49
29	0.27	689	0.8	203	430	110	0
30	0.27	518	0.5	319	711	130	54

Table 1: Material properties

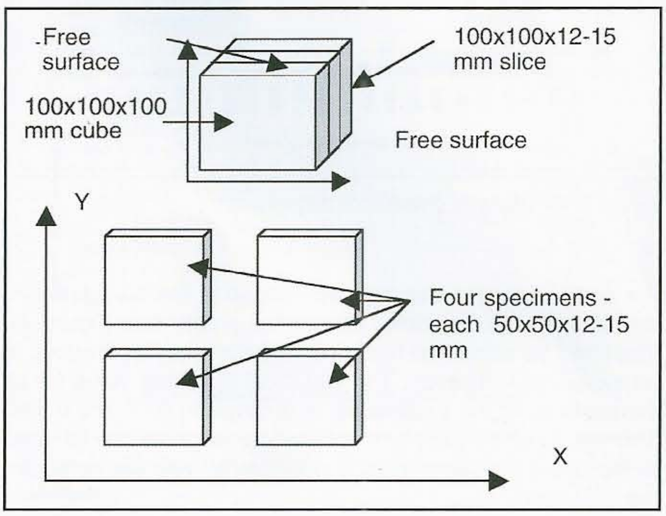

Figure 1: Preparation and orientation of specimens

For every mixture a 100 mm cube was cast for microscopic analysis purposes. The cubes were cut into slices of between 12mm and 15mm thick using a diamond saw. The slices were cut perpendicular to the original free surface after which every slice was again cut into quarters. The dimensions of the specimens were 50mm x 50mm x 12-15mm. The orientation of the specimens was kept the same throughout the work (See Figure 1).

The intended test surfaces were wet ground using sandpaper to produce a smooth flat surface. They were cleaned with compressed air and prepared in the oven at 50°C to ensure a dry surface for microscopic analysis.

3.2 Image Analysis

The image processing and analysis system used in this research consisted of a high-resolution monochrome camera connected to an optical microscope and computer with the image analysis software "Optimum 5.21". The microscope has a movable X, Y stage and by moving the sample manually in both the X and Y directions, representative images of the sample were collected.

3.3 Identification of air-voids

The focus of the optical microscope was adjusted until the cement paste was in focus and all the air-voids were blurred on the computer monitor. This contrast was considered to be sufficient to distinguish between air-voids and cement paste.

Figure 2 shows the typical images produced by the camera. The air-voids can easily be identified. Each image was digitized and stored by the computer.

Each photograph represented an area of 1954 mm by 1872 mm. Twenty photos of each mixture were analyzed resulting in more than 250 air-voids counted per mixture.[7]

According to Uchikawa[8] the minimum diameter of an air-void are approximately 30 um and the maximum diameter of air-voids is 1 mm. The pores with diameters greater than 1 mm is defined as large entrapped air and the pores smaller than 30 um are defined as gel- and capillary pores. Air-voids with diameters between 10 ?m and 1000 ?m were counted. By setting these boundaries it was ensured that entrained air-voids were counted.

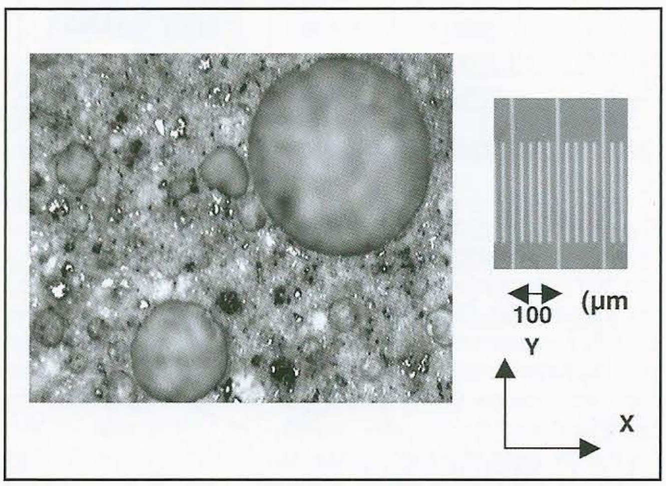

Figure 2: Optical Microscope Image of Air-Voids [6]

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3.4 Image Analysis - Output data

The data of every defined area (air-void) in the image was stored and analyzed separately. The output data was presented and stored in an ASCII file for use by any data processing computer program. An extract of the file is shown in Table 2. The count is the number of air-voids counted in a specific photo. The area is the area of a specific air-void in mm2 units. The perimeter is the length in mm of the circumference of the void. The next two columns are the x- and y coordinates of the centroid of each air-void.[7]

With this output data the parameters for the air-void size distribution and the air-void spacing were developed.

4. AIR-VOID SIZE DISTRIBUTION PARAMETERS

4.1 Development of parameters

Assuming that air-voids are perfect spheres and circular in section, an effective air-void diameter can be calculated using the measured area from the software output data[7,8]:

$$\text{Air-void diameter} = \sqrt{\frac{4A}{\pi}} \quad \text{where A = area of void}^{(7)}$$

Count	Area	Perimeter	X - Position	Y - Position
4	20991.37	577.19	64.3	1117.08
	30543.43	685.76	977.05	758.38
	12658.85	463.64	557.97	755.42
	34692.92	789.81	1267.8	593.96
8	4481.82	271.67	700.51	1132.35
	7015.42	368.07	512.13	1082.13
	9109.98	366.93	985.75	1042.1
	26092.1	641.91	704.35	954.54
	2847.63	227.92	922.69	821.08
	17543.11	512.65	1415.72	703.62
	137915	1567.1	281.09	600.62
	40711.36	761.77	1402.32	199.35
2	2091.51	184.93	267.94	375.39
	21116.37	586.9	798.62	151.87
6	15786.97	503.82	1179.44	912.46
	8347.76	352.81	1429.51	917.84
	12594.82	444.64	1374.66	720.46
	27064.69	651.57	1183.64	689.18
	5756.24	296.34	1177.62	130.71

Table 2: Extract of software output data from "OPTIMUM 5.21"

The distribution of the air-void diameter sizes was determined by plotting a histogram for the calculated air-void diameters counted in each mixture. Typical air-void diameter distributions are indicated in Figure 3. The distributions shown are not actually representative of void diameters as the calculated air-void diameters are not necessarily the maximum diameters of each void (since the probability of 'slicing' a sphere at its maximum diameter is very small). The percentage of the number of voids is plotted on the vertical axis and the air-void diameters are plotted on the horizontal axis. The cumulative percentage distribution is also plotted on this graph. The cumulative distribution values on the graph show the percentage of the voids with diameters smaller than this specific value. The size distribution of air-void diameters for all the mixtures follows a log normal distribution[7].

From Figure 3 it appears that for lower densities (Mix 5) there is an increase in the number of larger voids. Parameters had to be developed, in order to quantify these differences in air-void sizes and to compare the mixtures with each other. These parameters will also be used to evaluate the influence of air-void size distribution on the properties of foamed concrete.

By plotting the value (100-y) where y is the value of the cumulative distribution, *the cumulative % oversize air-void diameter distribution* is obtained as shown in Figure 4. The *cumulative % oversize air-void diameter distribution* values on the graph show the percentage of the voids with diameters larger than this specific value. Provision was made for statistical outliers by not taking the five percent smallest diameters and five percent largest diameters into account. A cumulative plot as shown in figure 4 was drawn for each mixture[9].

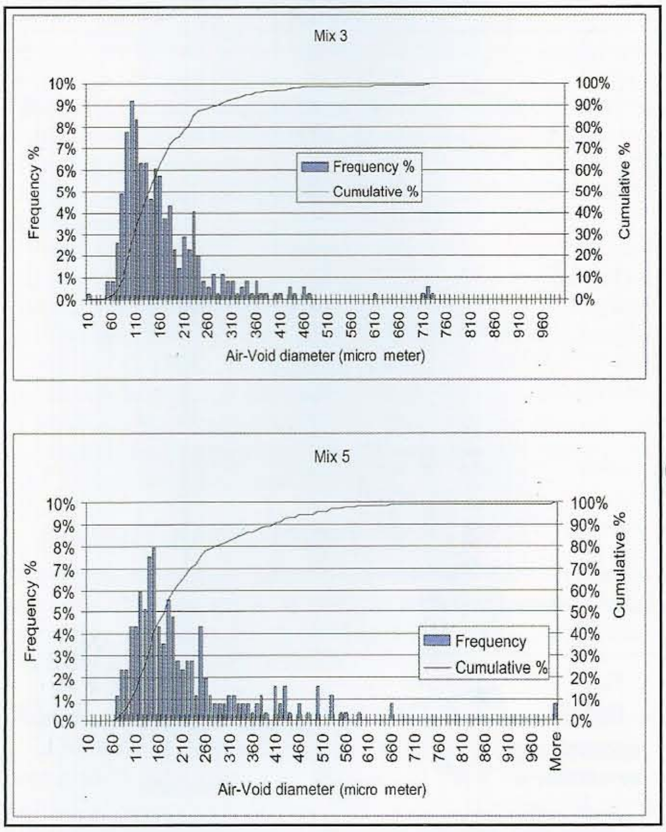

Figure 3: Air-void size distribution histograms[6]

For each mixture a trendline was added to the *cumulative % oversize air-void diameter distribution* graph (see Figure 4). The fitted trendline that best describe the measured values is an exponential function. The statistical R-square value for all the mixtures of the exponential fit is between 0.96 and 0.998. The values of the exponential equation can therefore be used to represent the *cumulative % oversize air-void diameters* for the mixtures[9].

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The corresponding 50 % oversize air-void diameter (D_{50}) in mm can be read from the exponential fit graph (see Figure 4). This diameter gives an indication of the median void size of each mixture. In the same way the 10 % oversize air- void

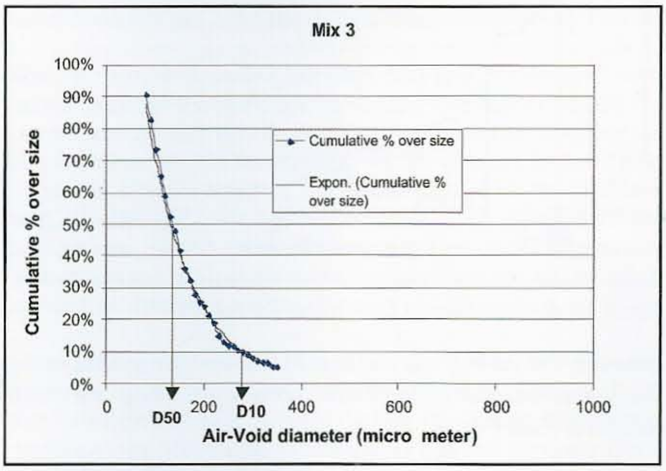

Figure 4: Oversize air-void diameter distribution

diameter (D_{10}), which shows the difference in number of larger voids in each mixture, can be read from this graph. The values of *the oversize air-void diameter distribution parameters* (D_{50}) and (D_{10}) can be seen in Table 1. These parameters can be used to compare the air-void size distribution of the different mixtures[(9)].

4.2 Discussion of Results.

Table 1 shows the values of the air-void diameter parameters for all the mixtures. To evaluate the influence of the air-void size distribution on the 28-day dry density, the 28-day dry density was plotted as a function of the air-void diameter parameters (D_{50} and D_{10}) (see Figure 5).

As the *28-day dry density* increased the median void diameters became smaller. At higher densities the 10 % largest voids in the mixtures also became smaller. It is interesting to note that the distribution curves converge, indicating that the voids become smaller and more uniform in

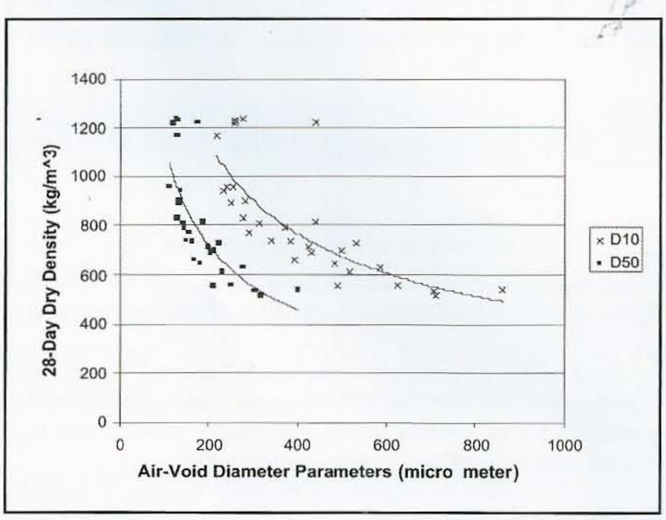

Figure 5: 28-Day Dry Density versus Air-Void Size Distribution Parameters.

sizeat higher densities. A limit is reached at a *28-day dry density* of approximately 1000 kg/m³, as the data obtained at higher densities do not display any clear pattern. It seems that the air-void size distribution do not have an influence on dry densities higher than 1000 kg/m³ because the air-voids are far apart in the paste and therefore do not have the ability to merge before setting of the paste around the bubbles.

To evaluate the influence of the air-void size distribution on the 28-day compressive strength, the 28-day compressive strength was plotted as a function of the air-void diameter parameters (D_{50} and D_{10}) (see Figure 6). The graph displays a decrease in the 28-day compressive strength with an increase in void diameter. Figure 6 indicates that smaller air-voids in a mixture ensure higher *28-day compressive strengths.* Larger air-voids in a mixture give rise to lower 28-day compressive strengths. If the size distribution of the air-voids increases it leads to lower *28-day compressive strengths* for mixtures with 28-day dry densities lower than approximately 1000 kg/m³.

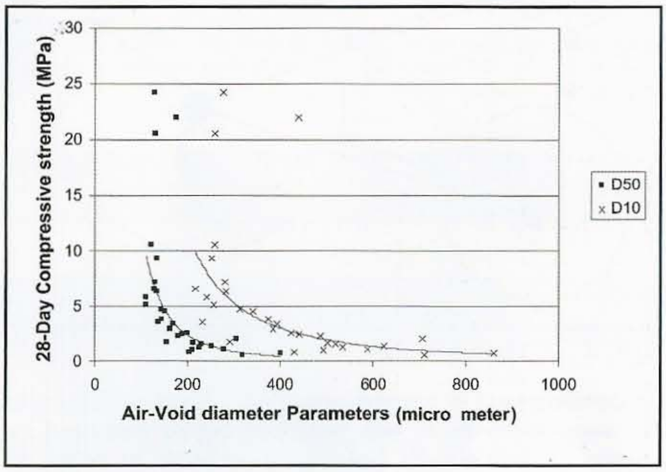

Figure 6: 28-Day compressive strength versus Air-Void Distribution parameters

The air-void size distribution does not seem to have an influence on the *28-day compressive strength* for the mixtures with *28-day dry densities* higher than 1000 kg/m³.

5. AIR-VOID SPACING DISTRIBUTION PARAMETERS

The direct distance through the cement paste from one air-void to the next nearest air-void in the vicinity is used to describe the spacing of the air-voids (see Figure 7)[(9)].

The X and Y coordinates of the centroids of the air-voids as found in the output data is used to determine the spacing of air-voids (see Figure 8)[(9)].

The distance between voids can be calculated using the following equation[(9)]:

$$S_{1,2} = \sqrt{\left((x_1 - x_2)^2 + (y_1 - y_2)^2\right)} - R_1 - R_2$$

$S_{1,2}$ = Minimum direct distance between air-voids.

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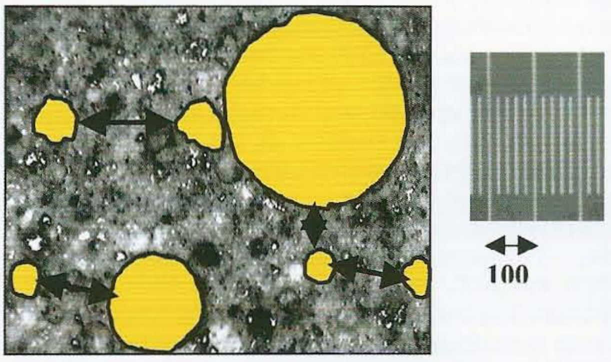

Figure 7: Distance between air-voids

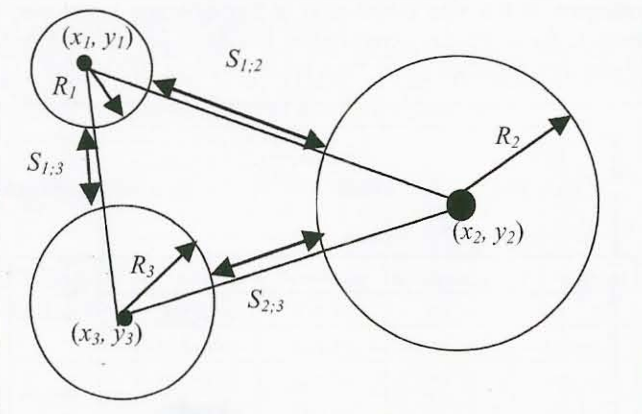

Figure 8: Spacing of air-voids.

5.1 Development of parameters.

The same methods as was described before was used to develop parameters for spacing of air-voids in order to compare mixtures[9].

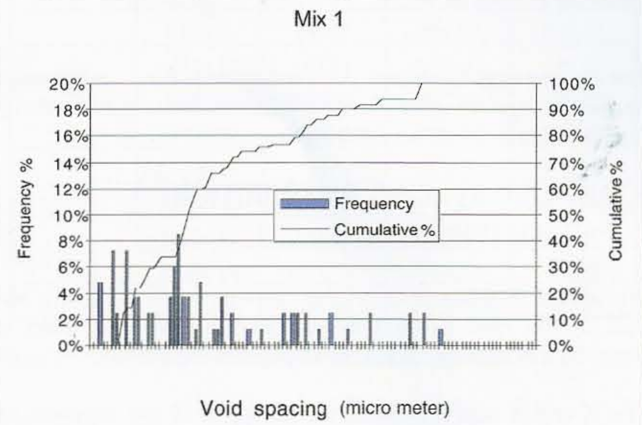

Figure 9: Air-Void spacing Distribution

A histogram and the cumulative frequency % distribution for the minimum distances between air-voids were plotted for each mixture (See Figure 9)[9].

By plotting the values (100-y) where y is the value of the cumulative distribution, the cumulative frequency % distribution air-void spacing was obtained and an exponential function was fitted for each mixture. The median distance

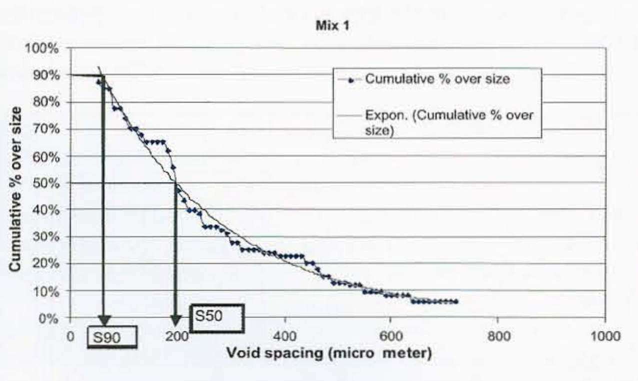

Figure 10: Air-Void Spacing Distribution Parameters

between the voids (S_{50}) and the 90 % over size void-spacing (S_{90}) was calculated for each mixture by using the fitted functions (See Figure 10)[9].

5.2 Discussion of results

The effect of the air-void spacing on the *28-day dry density* can be seen in Figure 11. For mixtures with dry densities lower than 1000 kg/m³, 90 % of the spacing distances are larger than approximately 35 µm and 50% of the spacing distances are larger than approximately 100 µm. Spacing distances increase for the higher dry densities.

There is no clear relationship between the *28-day dry densities* and the air- void spacing. The higher *28-day dry densities* may have an influence on the air-void spacing but the data obtained in this investigation is not enough to determine if there is a relationship or not.

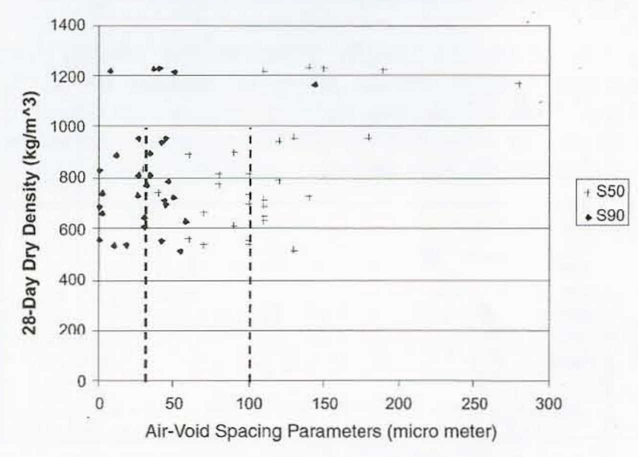

Figure 11: 28-Day Dry Densities versus Air-Void Spacing Parameters

No clear relationship between the air-void spacing parameters and the compressive strength could be found. These results indicate that it is only the density and size of the air-voids that has an influence on the compressive strength.

6. CONCLUSIONS

The air-void diameters have an influence on the *28-day dry*

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densities between 500 and 1000 kg/m^3. The void diameters became smaller as the dry density increases. For their part the air-void diameters for mixtures with dry densities between 500 and 1000 kg/m^3 have an influence on the 28-day compressive strength of foamed concrete. The compressive strength decreases with an increase in void diameter.

The 28-day dry densities between 500 and 1000 kg/m^3 have no influence on the spacing of air-voids. The higher *28-day dry densities* may have an influence on the air-void spacing but the data obtained in this investigation is not enough to determine if there is a relationship or not. It seems that for the mixtures with *28-day dry densities* higher than 1000 kg/m^3 it is the composition of the paste that determines the compressive strength of the mixture because the air-voids are too far apart to have an influence on the compressive strength.

The spacing of the air-voids does not seem to have any influence on the 28-day compressive strength. The results of this investigation thus indicate that by minimizing the air-void diameters the compressive strength of foamed concrete (for a given dry-density) can be optimized.

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