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Effect of Additives, Cement Type, and Foam Amount on the Properties of Foamed Concrete Developed with Civil Construction Waste

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Abstract: The main objective of this study was to evaluate the use of additives in producing foamed concrete blocks, which were made by totally replacing natural sand with civil construction waste (CCW). The concrete blocks were developed in accordance with an experimental design that used the complete factorial statistical method, for which three factors with different levels were considered: cement type (CP-V, CP II-Z, and CP II-F); use of additive (without additive, plasticizer, air entrainment, and superplasticizer) and foam amount (5.7%, 7.7%, and 9.5% of the total mass). The influence of each factor and the interactions between them were assessed on the following response variables: compressive strength, dry and saturated density, air voids, water absorption, and thermal conductivity. The results show that all factors had a significant influence on the variable response. For example, the use of the superplasticizer additive resulted in higher compressive strength, lower density, lower air void, and lower thermal conductivity. Finally, the use of additives had little influence on the response variables in relation to the other factors.

Keywords: foamed concrete; civil construction waste; additives; properties

1. Introduction

Concern about the environment and sustainability has driven industries to research and rethink more sustainable methods with a view to minimizing impacts. For example, geopolymeric materials, which can be considered a cementitious material, have been developed with the purpose of replacing Portland cement and, consequently, reducing the environmental impacts caused by the cement industry through a decrease in energy consumption and CO_2 emissions [1,2]. Another way to minimize environmental impacts (generating excessive waste, littering public roads and streets because of irregular disposal and depleting natural resources) and achieve sustainability is to increase the use of construction civil waste (CCW) in the development of materials for civil construction. This has not yet been widely applied. For example, in Brazil, only, approximately 20% of CCW is reused [3–5].

From the perspective of sustainability, using this type of waste can reduce both the consumption of raw materials (for example, small and large aggregates) and the consumption of energy spent on extraction/comminution/finishing processes [6]. However, using these recycled aggregates in concrete and mortar can be hampered by the limitations imposed by the composition of CCWs, since recycled materials present high water absorption, lower specific mass, and lower mechanical resistance when compared to materials (concretes, adhered or bonded mortar) developed only with natural aggregates [7–9]. Therefore, using recycled aggregates becomes more attractive in cases where high mechanical resistance and low water absorption are not required. In addition, studies have shown that this type of aggregate obtained from CCW does not result in good durability when exposed to aggressive media [3,10].

A construction material that does not require a structural function is so-called "aerated" or "cellular" concrete, the apparent specific mass of which ranges from 320 kg/m^3 to 1920 kg/m^3 [11]. Cellular concretes can be obtained by introducing air bubbles into the mixture. Air bubbles may be generated in the mortar itself by chemical additives or by introducing preformed foam into the mortar. The aerated concretes prepared by incorporating the preformed foam into the mortar are known as foamed concrete (FC) [12]. Also, there are types of lightweight structural concretes that are obtained by totally or partially replacing conventional aggregates with lightweight aggregates, which have an apparent specific mass of between 900 kg/m^3 and 2000 kg/m^3 [13,14].

FCs present excellent performance in terms of thermal and acoustic insulation and fire resistance. For example, the study by Mydin et al. [15] evaluated the thermal performance of FCs developed with different additives (fly ash, lime, and polypropylene fiber) and densities, and found thermal conductivity values between 0.18 W/mK and 0.56 W/mK. Laukaitis and Fiks [16] analyzed the acoustic qualities of three types of aerated concrete (gas cement concrete; gas cement concrete with combined binder-Portland cement and lime; and foam cement concrete) and showed that the acoustic absorption coefficient values of normal materials depend on permeability and porosity and increase the coefficient of sound absorption by up to 0.6. Othuman and Wang [17] evaluated the thermal conductivity at high temperatures of FCs with different densities in order to obtain data on material properties to predict fire resistance and concluded that FCs may be an alternative that can replace gypsum in partition walls.

In spite of the positive properties of FC, due to the lack of the compressive strength of this type of material, its use becomes limited, which points to a need for studies on optimizing the mixtures that seek to improve this property of the material [18,19]. However, it should be noted that there is no Brazilian standard for foamed concrete. Therefore, a possible solution to improve the mechanical properties of FCs is to use additives that reduce the water/cement (w/c) ratio such as plasticizers and superplasticizers [20,21]. Another important factor that is directly related to the compressive strength of FC is the amount of foam added. Favaretto et al. [22] observed that by increasing the amount of foam in the mortar the compressive strength decreases. Falliano et al. [23] evaluated the effect of curing conditions, cement type, foaming agent, dry density, and presence of a superplasticizer on the development of the 28-day compressive strength, and concluded that all factors had a significant influence on the compressive strength; for example, the presence of the superplasticizer associated with the cellophane curing condition has led to an increase in the compressive strength as compared to the case without a superplasticizer. The highest strength values were measured for specimens that were wrapped within a cellophane sheet during the curing time, whereas the worst compressive strengths were observed in specimens cured in air; the different nature of the foaming agents contributes to a different arrangement of the void in the specimen microstructure and, consequently, changes to the resistance strength. According to the same authors, another significant factor is the water/cement ratio: when it is increased, the compressive strength decreases. Panesar [24] also evaluated three types of foam agents (one protein-based and two synthetic) on mechanical properties and thermal conductivity, and found that the foam agent type changes the amount and distribution of pores in the concrete structure, thereby changing the compressive strength and the thermal resistance.

The optimization of trace elements in FC mixtures should also encompass aspects related to the durability of this type of concrete. In general, concretes with less permeability are less prone to deterioration. One of the factors that controls the permeability of concrete is the cement used. Cements containing pozzolanic additions result in more durable concretes [25,26].

In view of the above, it can be observed that several works were and are being developed using CCW to substitute for a natural aggregate (river sand) in the production of civil construction materials (concrete, mortar, etc.); however, the authors did not find studies that relate the use of CCW (in total substitution to river sand) to cement type and different additives in foamed concrete. In addition, the CCW from Passo Fundo, a city in the south of Brazil, has not been fully studied yet and, consequently, we have not verified the possibility of its reuse. Therefore, the present paper sets out to evaluate the influences of different types of cement, the amount of foam, and different types of additive on the properties of foamed concrete in order to develop a foamed concrete using CCW to totally replace natural sand.

2. Materials and Methods

2.1. Materials

The following materials were used to undertake this study: cement, CCW, water, foam, and additives. Three types of Portland cement were used, which were designated according to the Brazilian standard (NBR 16697/2018): CP II-Z (made with the addition of fly ash); CP II-F (made with the addition of limestone filler); and CP V-ARI (which is a high initial strength cement, without pozzolanic addition). The physical and chemical properties of Portland cement are shown in Table 1.

Table 1. The properties of the cements.

Cement Type	Physical Properties									
	Setting Time		Blaine cm^2/g	#200%	#325%	Hot Expansion mm	Specific Gravity g/cm^3	Compressive Strength		
	Initial h:min	Last h:min						3 Days MPa	7 Days MPa	28 Days MPa
CP II-F	03:52	04:38	3.291	2.75	13.31	0.28	3.11	28.2	34.5	42.0
CP II-Z	04:15	05:03	3.583	2.54	9.57	0.22	2.96	25.8	33.3	42.0
CP V-ARI	03:19	04:01	4.448	0.08	0.52	0.25	3.05	38.4	44.9	53.6
Cement Type	**Chemical Properties**									
	Al_2O_3 %	SiO_2 %	Fe_2O_3 %	CaO %	MgO %	SO_3 %	L.O.I. %	Free CaO %	I.R. %	A.C. %
CP II-F	4.17	18.46	2.93	60.60	3.78	2.78	4.85	0.60	1.16	0.69
CP II-Z	6.01	20.14	3.10	54.60	3.45	2.69	5.51	0.57	10.96	0.84
CP V-ARI	4.22	18.80	2.95	60.27	3.91	3.14	3.33	0.68	0.75	0.69

L.O.I—Loss on ignition; I.R.—Insoluble residue; A.C.—Alkali content.

Table 2 shows the composition of the cements, calculated from the Bogue equations [27].

Table 2. Estimated values of the potential composition for each cement using Bogue.

Cement Type	C_3S (%)	C_2S (%)	C_3A (%)	C_4AF (%)	$C_4AF + C_2F$
CP II-F	66.3	2.9	6.1	8.9	
CP II-Z	25.7	38.5	-	-	17.9
CP V-ARI	61.0	7.9	6.2	9.0	

CCW was used as an aggregate that totally replaces natural sand. This residue was collected in the region of Passo Fundo-RS-Brazil and characterized by Favaretto et al. [22]. Figure 1a shows the grain size curve for the CCW used and Figure 1b shows the CCW. Note that this granulometry falls within the usual ranges for the use of fine aggregates when producing concrete and is in accordance with the Brazilian standard NBR 7211 [28].

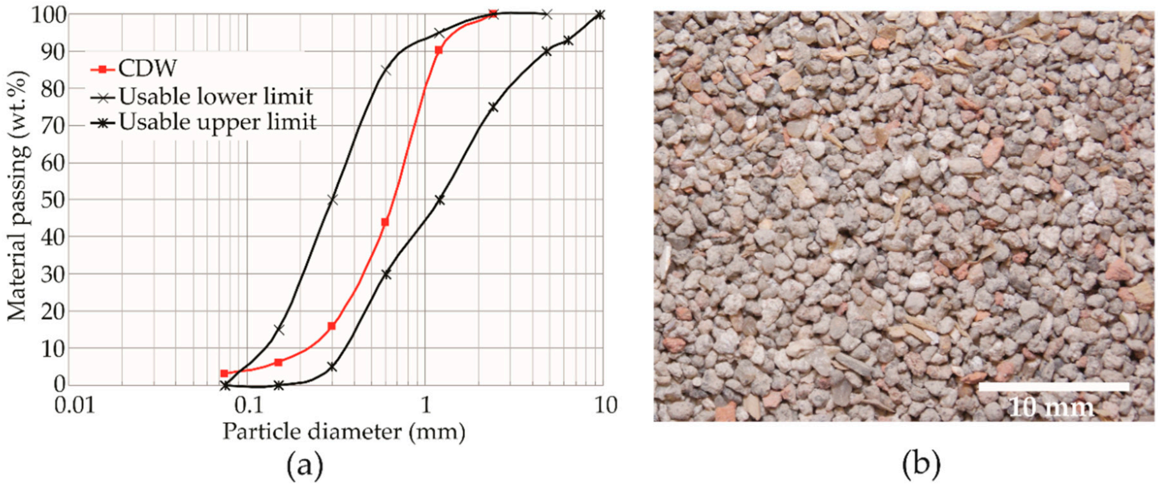

Figure 1. (**a**) Cumulative underflow distribution of CCW granulometries and normal upper and lower limits for concrete production according to NBR 7211 [28]; (**b**) CCW.

The agent used to produce the foam was amide 90 (diethanolamide 90% coconut fatty acid made by Asher (Produtos Químicos Ltda, Ribeirão Preto, Brazil) and water in a proportion of 1:30. This proportion was defined based on the results of prior studies [29]. A constant velocity mechanical stirrer was used to generate foam at a density of 100 kg/m^3.

Three different types of additive were used to produce test specimens, namely, plasticizer, air entrainment, and superplasticizer (polycarboxylate based). The amount of additive used, in accordance with the manufacturer's recommendation, was 0.5% of the weight of cement for all specimens that used additives.

2.2. Production of Foamed Concrete Specimens

The specimens were produced in accordance with NBR 5738 [30]. First, the CCW was mixed in a automatic planetary type mixer with water, cement, and the additive until the mixture was fully uniform, and it was then rested for 3 min at the speed of 140 RPM. Sequentially, the foam was produced and added to the homogeneous mixture and mixed for 3 min at a constant speed of 285 RPM until the concrete became fully homogeneous. The mixture was immediately deposited in cylindrical and parallelepiped molds (300 × 100 × 30 mm) that were to be used for the thermal conductivity tests. After 24 h the specimens were demolded and wrapped in plastic film for 28 days and 365 days (only for the compressive strength test) of concrete curing. After the curing time of the foamed concrete blocks had elapsed, tests were carried out to evaluate the characteristics of this concrete, for which output values were obtained, which were analyzed statistically.

2.3. Characterization of Foamed Concrete Specimens

The compressive strength test was performed as per NBR 5739 [31]. The foamed cellular concrete blocks were prepared for the compressive strength test, as determined by NBR 7680-1 [32]. The test was performed using a hydraulic press, model PC200C (Instron, Norwood, MA, USA).

The tests of densities (dry and saturated), air void, and water absorption were performed after the specimens had been cured for 28 days and followed the standards ASTM C 948-81 [33] and NBR 9778 [34].

The analysis technique described in British standard BS EM 480-11 [35] and by other authors [22,36,37] was used to determine the pore size. Two specimens of each sample were prepared, one specimen for the longitudinal section and another for the transverse section. The specimens were carefully polished, avoiding the creation of new pores that would cause measurement errors.

Macrographic images were taken with a microscope and imageJ software (National Institutes of Health, Bethesda, MD, USA) was used to process them.

Figure 2 shows the experimental apparatus used in the thermal conductivity tests, which were performed using the surface hot wire technique. The surface hot wire test is a direct method, which detects the transient temperature and has already been recognized as a variant of the parallel hot wire technique [38–44]. The experimental system consists of two multimeters that measure the intensity of the electric current and voltage, two parallelepiped concrete specimens, a hot wire (0.5 mm diameter, Kanthal—Kanthal Brasil, São Paulo, Brazil) connected to a power source, four temperature sensors, a data acquisition board and computer with Labview software (National Instruments, Austin, TX, USA). The temperature sensors were calibrated for a temperature range of 0 °C to 100 °C.

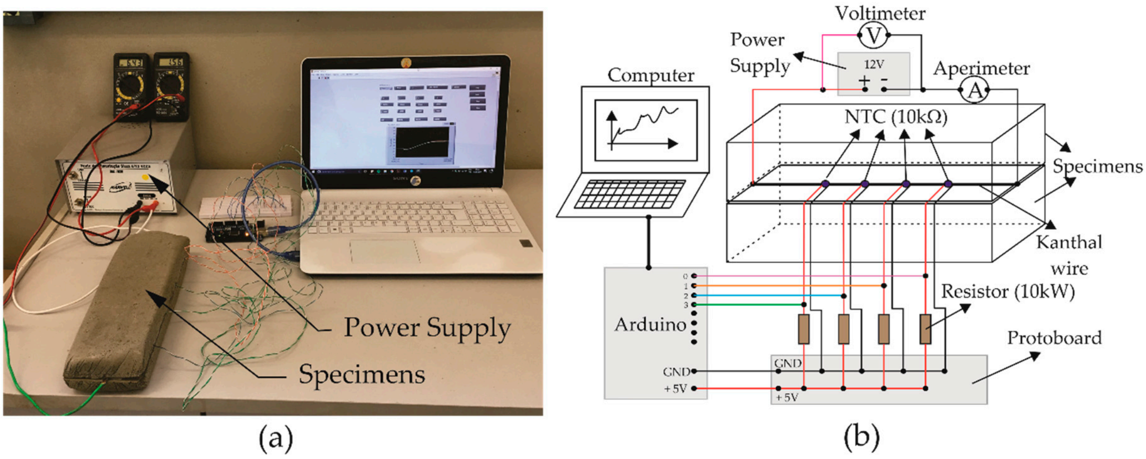

Figure 2. (**a**) Image of the experimental apparatus used to determine the thermal conductivity and (**b**) the schematic design of the apparatus.

2.4. Experimental Design

Three parameters were used as control factors: cement type, additive type, and amount of foam. Three levels were used for the type of cement; four levels for the additives, which used three types of additives and one concrete mix without additive; and three levels for the amount of foam. Other parameters were kept constant, especially the water/cement ratio (w/c). Six output variables (responses) were analyzed, namely: compressive strength, (saturated and dry) densities, air voids, water absorption, and thermal conductivity.

A complete experimental factorial matrix with 36 mixtures was drawn up in order to produce foamed concrete blocks. Eleven specimens of each test were produced, three of which were used for compressive strength tests; the remaining test specimens were used for the other tests. A total of 396 specimens was produced. Table 3 shows the experimental matrix with the values used.

An analysis of variance was used to determine the influence of the factors on the output variables. Factors were considered to be significant for p-values equal to or lower than 0.05 (the critical value adopted), which indicates a confidence level equal to or greater than 95% with respect to what is being stated. Also, the percentage contribution of each factor was estimated by the sum of the squares.

The p-value is a probability that measures the evidence against the null hypothesis. The lower the probability, the stronger the evidence against the null hypothesis. The F-value is a statistical test used to determine whether the term is associated with the response, i.e., the larger the F-value is, the more influential the factor is on the response [45].

Table 3. Experimental matrix.

Order	Cement Type	Cement (kg)	Additive	Foam (kg)	CCW (kg)	Water (kg)	w/c Ratio
1	CP V-ARI	1.8	No additive used	0.25	1.8	0.57	0.45
2	CP V-ARI	1.8	Plasticizer	0.25	1.8	0.57	0.45
3	CP V-ARI	1.8	Superplasticizer	0.25	1.8	0.57	0.45
4	CP V-ARI	1.8	Air entrainment	0.25	1.8	0.57	0.45
5	CP V-ARI	1.8	No additive used	0.34	1.8	0.48	0.45
6	CP V-ARI	1.8	Plasticizer	0.34	1.8	0.48	0.45
7	CP V-ARI	1.8	Superplasticizer	0.34	1.8	0.48	0.45
8	CP V-ARI	1.8	Air entrainment	0.34	1.8	0.48	0.45
9	CP V-ARI	1.8	No additive used	0.43	1.8	0.39	0.45
10	CP V-ARI	1.8	Plasticizer	0.43	1.8	0,39	0.45
11	CP V-ARI	1.8	Superplasticizer	0.43	1.8	0.30	0.45
12	CP II-F	1.8	Air entrainment	0.43	1.8	0.39	0.45
13	CP II-F	1.8	No additive used	0.25	1.8	0.57	0.45
14	CP II-F	1.8	Plasticizer	0.25	1.8	0.57	0.45
15	CP II-F	1.8	Superplasticizer	0.25	1.8	0.57	0.45
16	CP II-F	1.8	Air entrainment	0.25	1.8	0.57	0.45
17	CP II-F	1.8	No additive used	0.34	1.8	0.48	0.45
18	CP II-F	1.8	Plasticizer	0.34	1.8	0.48	0.45
19	CP II-F	1.8	Superplasticizer	0.34	1.8	0.48	0.45
20	CP II-F	1.8	Air entrainment	0.34	1.8	0.48	0.45
21	CP II-F	1.8	No additive used	0.43	1.8	0.39	0.45
22	CP II-F	1.8	Plasticizer	0.43	1.8	0,39	0.45
23	CP II-F	1.8	Superplasticizer	0.43	1.8	0.30	0.45
24	CP II-F	1.8	Air entrainment	0.43	1.8	0.39	0.45
25	CP II-Z	1.8	No additive used	0.25	1.8	0.57	0.45
26	CP II-Z	1.8	Plasticizer	0.25	1.8	0.57	0.45
27	CP II-Z	1.8	Superplasticizer	0.25	1.8	0.57	0.45
28	CP II-Z	1.8	Air entrainment	0.25	1.8	0.57	0.45
29	CP II-Z	1.8	No additive used	0.34	1.8	0.48	0.45
30	CP II-Z	1.8	Plasticizer	0.34	1.8	0.48	0.45
31	CP II-Z	1.8	Superplasticizer	0.34	1.8	0.48	0.45
32	CP II-Z	1.8	Air entrainment	0.34	1.8	0.48	0.45
33	CP II-Z	1.8	No additive used	0.43	1.8	0.39	0.45
34	CP II-Z	1.8	Plasticizer	0.43	1.8	0,39	0.45
35	CP II-Z	1.8	Superplasticizer	0.43	1.8	0.30	0.45
36	CP II-Z	1.8	Air entrainment	0.43	1.8	0.39	0.45

3. Results and Discussion

3.1. Compressive Strength

Tables 4 and 5 show the ANOVA results for compressive strength after curing times of 28 and 365 days, respectively. For test specimens with a 28-day curing time, it can be stated that the type of cement, the amount of foam, and the interaction between the factors showed a significant influence with 95% reliability. As for the type of additive, its influence cannot be quantified. Note that the amount of foam was the factor that most influenced compressive strength, its contribution being 39%. The type of cement also influences the compressive strength; its contribution is 13%. Also, note that there was an interaction between the factors, which corresponds to the difference in behavior of a given factor due to the different levels of another factor.

After the specimens had been cured for 365 days, it was observed that all the factors had a significant influence on the resistance to compression with 95% reliability, including the type of additive, which presented a contribution of 9%.

Table 4. Analysis of variance for compressive strength after 28 days of curing.

Factor	Sum of Squares	Degrees of Freedom	Mean of Squares	*F*-Value	*p*-Value	% Contribution
Cement Type (CT)	67.697	2	33.848	34.159	0.0000	13.4
Foam Amount (FA)	196.517	2	98.258	99.160	0.0000	39.0
Additive Type (AT)	5.425	3	1.808	1.825	0.1502	1.1
CT*FA	67.534	4	16.883	17.038	0.0000	13.4
CT*AT	18.880	6	3.147	3.176	0.0080	3.7
FA*AT	49.273	6	8.212	8.288	0.0000	9.8
CT*FA*AT	27.378	12	2.281	2.302	0.0151	5.4
Error	71.345	72	0.991			14.2
Total	504.048	107				100.0

* Interaction between factors.

Table 5. Analysis of variance for compressive strength after 365 days of curing.

Factor	Sum of Squares	Degrees of Freedom	Mean of Squares	*F*-Value	*p*-Value	% Contribution
Cement Type (CT)	26.618	2	13.309	9.28	0.0002	2.8
Foam Amount (FA)	362.858	2	181.429	126.43	0.0000	37.8
Additive Type (AT)	86.817	3	28.939	20.17	0.0000	9.0
CT*FA	69.851	4	17.463	12.17	0.0000	7.3
CT*AT	114.476	6	19.079	13.30	0.0000	11.9
FA*AT	68.998	6	11.500	8.01	0.0000	7.2
CT*FA*AT	127.327	12	10.611	7.39	0.0000	13.3
Error	103.318	72	1.435			10.8
Total	960.263	107				100.0

* Interaction between factors.

Figure 3a shows the relationship between compressive strength and cement types at different curing times (28 and 365 days). The CP II-Z cement, for curing times of 28 and 365 days, presented on average a higher compressive strength compared to other CP V-ARI and CP II-F cements. This behavior can be explained by the presence of fly ash in the CP II-Z cement. The results obtained for compressive strength are in accordance with those of Jitchaiyaphum et al. [46], who studied a foamed cellular concrete containing pozzolanic material. As is known, pozzolanic additions react chemically with the $Ca(OH)_2$ from the hydration reactions, thereby decreasing the porosity and the connectivity between pores (capillarity) [47] of the concrete, and, over time, increasing its compressive strength and durability against the action of aggressive agents, such as sulfate and chloride ions [48–50]. Also, the products formed when the cement is hydrated regulate the behavior of the matrices after hydration. Thus, initial mechanical strengths can be high if the cement contains large amounts of C_3S. However, at more advanced ages the greatest influence on mechanical resistance is given by C_2S [26].

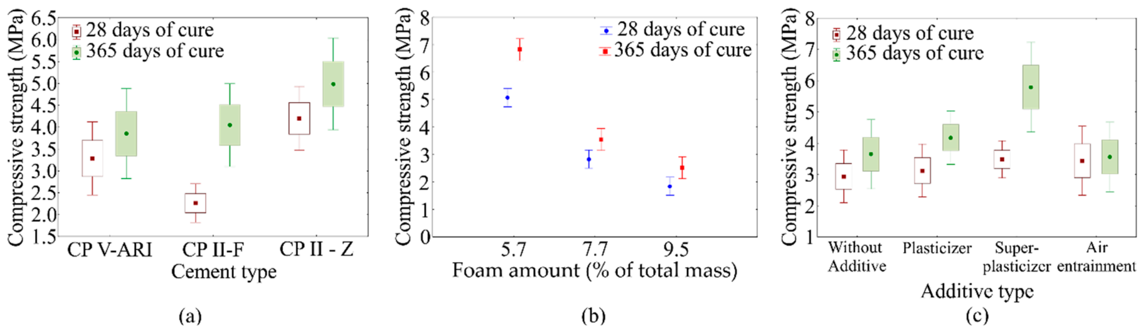

Figure 3. Compressive strength related to (**a**) cement type, (**b**) foam amount, and (**c**) additive type for different curing times, where the middle point is the mean, the box is the confidence interval (95%), and the whisker shows the standard deviation.

Figure 3b plots the compressive strength with respect to the amount of foam (% of total mass) for different curing times (28 days and 365 days). When increasing the amount of foam the compressive strength decreases. This occurs due to air being incorporated into the foam, as a result of which pores forms in the structure, decreasing the density and, consequently, the compressive strength [22,23]. Also, the compressive strength increases significantly when the curing time is increased, i.e., an average increase of approximately 40% in compressive strength can be obtained. This increase in compressive strength achieved by increasing the curing time occurs due to the interaction between the factors, especially the interaction between the types of cements and the amount of foam [51]. It is known that pozzolanic additions lead to a late gain in compressive strength, which explains the greater influence of the type of cement at more advanced ages.

The values observed in the graph that plots compressive strength for most of the specimens were higher than the minimum required by NBR 12646 [52], which determines the compressive strength for walls of foamed concrete. However, it is important to emphasize that there is no Brazilian standard to evaluate this property in blocks of foamed concrete. The lowest value for compressive strength was found for the test specimens developed with a foam content of 9.5% of the total mass and 28 days of curing time, the average value being compressive strength of 1.85 MPa.

Figure 3c shows that, for a 28-day curing time, the superplasticizer specimens had a mean compressive strength of 3.48 MPa; and that the air incorporator and the plasticizer presented lower compressive strength values than the superplasticizer, namely, 3.1 MPa and 3.4 MPa, respectively. The specimens made without additives had the lowest compressive strength, this being 2.9 MPa. There was little variation in the compressive strength due to the presence of additives, except for the specimens that used superplasticizer additive in their composition, which were evaluated after 365 days. This is because the presence of superplasticizer in the concrete mix leads to a higher strength due to the reduced void size and pore connectivity [53].

The results also show that using CCW to substitute natural sand may have influenced the compressive strength, since CCW absorbs more water than natural sand, which causes foam bubbles to coalesce and, consequently, increase in size, thereby reducing the homogenous distribution of CCW in the mixture [22,54]. Another observation is that the compressive strength results are smaller than the results obtained by Hanif et al. [55], Morales-Conde et al. [56], and Abbas et al. [57], but the materials these authors, used as aggregates have different characteristics to the CCW used in the present work.

3.2. Dry and Wet Bulk Densities

Tables 6 and 7 present the analysis of variance for the dry and the saturated density, respectively. For these properties, all factors and the interaction between them had a significant influence (significance of 95% or more). Note that the amount of foam was the factor that most influenced the dry density. This is because the higher the amount of foam, the greater the number of voids and the lower the density of the material.

Table 6. Analysis of variance for dry density (28 days of curing).

Factor	Sum of Squares	Degrees of Freedom	Mean of Squares	*F*-Value	*p*-Value	% Contribution
Cement Type (CT)	659,792	2	329,896	275.9	0.0000	19.4
Foam Amount (FA)	1,696,582	2	848,291	709.6	0.0000	50.0
Additive Type (AT)	40,996	3	13,665	11.4	0.0000	1.2
CT*FA	324,870	4	81,218	67.9	0.0000	9.6
CT*AT	50,929	6	8488	7.1	0.0000	1.5
FA*AT	314,349	6	52,392	43.8	0.0000	9.3
CT*FA*AT	219,660	12	18,305	15.3	0.0000	6.5
Error	86,077	72	1196			2.5
Total	3,393,255	107				100.0

* Interaction between factors.

Table 7. Analysis of variance for wet density (28 days of curing).

Factor	Sum of Squares	Degrees of Freedom	Mean of Squares	*F*-Value	*p*-Value	% Contribution
Cement Type (CT)	542,783	2	271,392	344.4	0.0000	29.1
Foam Amount (FA)	526,782	2	263,391	334.3	0.0000	28.2
Additive Type (AT)	52,151	3	17,384	22.1	0.0000	2.8
CT*FA	165,006	4	41,251	52.4	0.0000	8.8
CT*AT	86,025	6	14,337	18.2	0.0000	4.6
FA*AT	271,135	6	45,189	57.3	0.0000	14.5
CT*FA*AT	164,559	12	13,713	17.4	0.0000	8.8
Error	56,735	72	788			3.0
Total	1,865,175	107				100.0

* Interaction between factors.

Figure 4a shows the dry density and the saturated density in relation to the type of cement used. Note that the specimens made with CP II-F cement have a lower dry and saturated density than CP II-Z cement. Probably this occurs due to 6-10% limestone filler being added to the CP II-F cement, which decreases the capillarity of mortars and concretes, while pozzolanic material ranging from 6% to 14% in mass being added to CP II-Z cement lowers its permeability and increases its density [48,49]. The CP V-ARI cement presented an intermediate value of dry and saturated density in relation to the other cements studied.

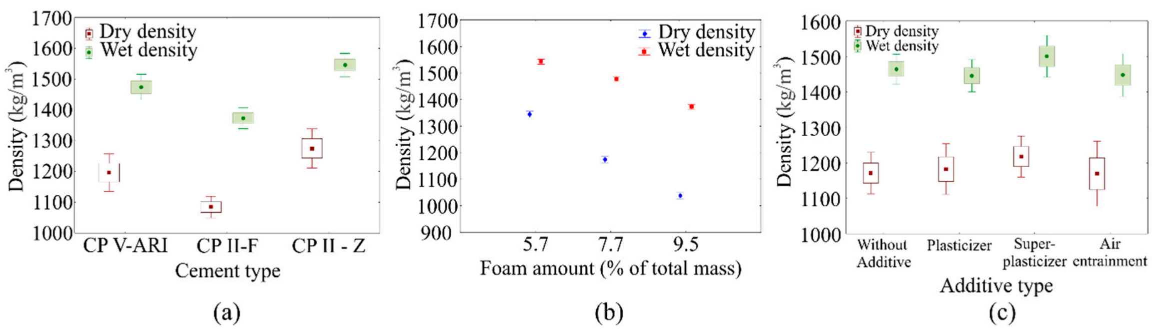

Figure 4. The dry and wet density related to (**a**) cement type, (**b**) foam amount, and (**c**) additive type for different curing times, where the middle point is the mean, the box is the confidence interval (95%), and the whisker shows the standard deviation.

Figure 4b shows the relationship between the density of the specimens and the amount of foam (% of total mass). The smallest amounts of foam are those with the highest densities, which is as expected [37]. When less foam is added, the air bubbles incorporated are grouped by dehydration, resulting in larger bubbles. Variations in density can also occur when bubbles collapse due to the hydrophilic film being reduced, thus making the bubbles less resistant, this being a consequence of using CCW instead of natural sand [58,59].

Figure 4c plots the dry and the saturated density relative to the type of additive. The specimens with the highest densities (dry and saturated) were those to which superplasticizer was added [23]. The air additive had an average dry density of 1270 kg/m^3 and a mean saturated density of 1580 kg/m^3. The plasticizer additive presented an average dry density of 1290 kg/m^3 and an average saturated density of 1590 kg/m^3. The specimens that did not have additives added had an average dry density of 1285 kg/m^3 and a mean saturated density of 1605 kg/m^3. Although there are differences between the specimens with and without additives, this is very small, i.e., the additives have little influence on this property.

High densities were obtained for foamed concrete compared with previous studies [22,29,60,61]. However, the density results are within the acceptable range for lightweight concrete density [11].

One possibility to reduce the density is to increase the amount of foam, which makes a greater contribution to the density variability.

3.3. Water Absorption

Table 8 presents the analysis of variance for water absorption, with 95% reliability. Note that the amount of foam has a greater influence on the absorption of water, as it makes a 50% contribution. The type of cement makes a contribution of 3% and while the type of additive has an influence, its contribution is 1%. The interaction between the factors, the type of cement, the amount of foam and the type of additive make a contribution of 12%. The interaction between the factors of cement type and additive type make a 12% contribution while the interaction between the type of cement and the amount of foam makes the lowest contribution among the factors, this being 8%. The amount of foam and the type of additive make a 9% contribution to the blocks of foamed concrete absorbing water.

Table 8. Analysis of variance for water absorption (28 days of curing).

Factor	Sum of Squares	Degrees of Freedom	Mean of Squares	*F*-Value	*p*-Value	% Contribution
Cement Type (CT)	347.91	2	173.95	32.59	0.0000	3.3
Foam Amount (FA)	5317.99	2	2659.00	498.20	0.0000	49.7
Additive Type (AT)	120.47	3	40.16	7.52	0.0001	1.1
CT*FA	901.98	4	225.49	42.25	0.0000	8.4
CT*AT	1314.68	6	219.11	41.05	0.0000	12.3
FA*AT	998.08	6	166.35	31.17	0.0000	9.3
CT*FA*AT	1310.15	12	109.18	20.46	0.0000	12.2
Error	384.28	72	5.34			3.6
Total	10,695.54	107				100.0

* Interaction between factors.

Note from the graph on water absorption due to the types of cement—see Figure 5a—that there was a change in the absorption in accordance with the cement used. The CP II-F showed an absorption of 27.0%, CP II-Z-22.5%, and CP V-ARI 24.5%. As expected, the cement to which pozzolanic material was added (CP II-Z), on average, was the one that absorbed the least water, because, according to the literature, when the amount of pozzolanic material is increased, the absorption of water tends to decrease [62].

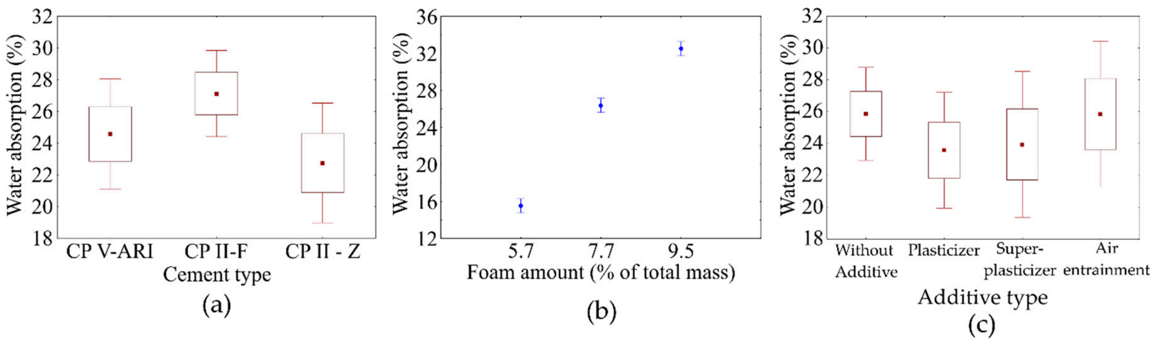

Figure 5. The water absorption related to (**a**) cement type, (**b**) foam amount, and (**c**) additive type for different curing times, where the middle point is the mean, the box is the confidence interval (95%), and the whisker shows the standard deviation.

According to Figure 5b, the more foam is added, the greater the water absorption. This occurs due to the increase in total voids and the connectivity between the pores (capillarity) [4,63].

What can be seen from Figure 5c is the amount of water absorbed due to the types of additives used; the plasticizer and superplasticizer additives present average water absorption of 23.6% and 24.0%, respectively, compared to the additive incorporating air and to the blocks of foamed concrete without addition of additive, both of which presented an average of 26% absorption of water. The results obtained for water absorption are similar to those found in the literature [64,65].

3.4. Air Void

Table 9 presents the analysis of variance for air void. From this analysis it can be affirmed, with 95% reliability, that the type of cement, the amount of foam and the type of additive have a significant influence on the number of pores present in the blocks of foamed concrete produced in the study. The factor that had the greatest influence on the air void was the amount of foam, its contribution being 41%. Note that the type of cement and the type of additive acting individually made a low contribution (0.6% and 1.4%, respectively) to the number of pores, but the interaction between these factors made a high contribution of approximately 17%. It is known that additives act to reduce the surface tension of water or the deflocculation via a change in the electric charge of the particles of the cement [66]. Therefore, the additives reduce the consistency of the mortar, thereby increasing its fluidity, and making the mortar more fluid, which may offer less physical resistance to maintaining the structure of the air bubbles incorporated by the foam [26,67].

Table 9. Analysis of variance for air void (curing time of 28 days).

Factor	Sum of Squares	Degrees of Freedom	Mean of Squares	*F*-Value	*p*-Value	% Contribution
Cement Type (CT)	57.18	2	28.59	4.85	0.0105	0.6
Foam Amount (FA)	3697.69	2	1848.84	313.80	0.0000	40.7
Additive Type (AT)	124.85	3	41.62	7.06	0.0003	1.4
CT*FA	987.53	4	246.88	41.90	0.0000	10.9
CT*AT	1578.10	6	263.02	44.64	0.0000	17.4
FA*AT	961.67	6	160.28	27.20	0.0000	10.6
CT*FA*AT	1243.12	12	103.59	17.58	0.0000	13.7
Error	424.20	72	5.89			4.7
Total	9074.343	107				100.0

* Interaction between factors.

Figure 6a shows the air void graph in accordance with the type of cement, where the mean values of the air voids were very close, these being 28.9% for CPII F, 27.8% for CPV-ARI, and 27.1% for CPII Z.

Likewise, little variation was observed in the number of pores when the additive used changes, even if they perform different functions in the mixtures. The results observed in the present study are in agreement with the studies carried out by Chandni and Anand [68], who evaluated the effect of superplasticizers on the properties of foamed concrete. The relationship between the air void and the additives tested can be seen in Figure 6c. In general, the additives have little influence on air being incorporated into the mortar. Note that the test specimens without and with additives had a very similar air void, with a mean that ranged from 26.3% to 29.3%.

Figure 6b shows that the amount of foam is the factor that has the greatest influence on the air void, precisely because it accounts for how many pores form in the structure of the blocks. The blocks to which 9.5% foam was added had a mean air void of 33.5%; blocks to which 7.7% foam were added resulted in a mean air void of 30.4%; and, finally, adding 5.7% foam to blocks resulted in an average air void of 19.9%. Comparing with a previous work [22], the value for air voids found was lower. This is possibly because the water/cement (W/C) ratio used in this work was lower, that is, in the present work a W/C ratio of 0.48 was used and in the previous work a W/C ratio of 0.64 was used. The W/C ratio is a factor that significantly influences all responses [29].

Figure 7 presents macrographic and typical binary images (*) of transversal sections of the 36 specimens in sequence, following the order of Table 3. Average porosity values were: (1*) 13%, (2*) 20%, (3*) 28%, (4*) 15%, (5*) 29%, (6*) 28%, (7*) 34%, (8*) 29%, (9*) 31%, (10*) 31%, (11*) 47%, (12*) 33%, (13*) 29%, (14*) 29%, (15*) 20%, (16*) 19%, (17*) 34%, (18*) 33%, (19*) 45%, (20*) 34%, (21*) 33%, (22*) 32%, (23*) 18%, (24*) 35%, (25*) 26%, (26*) 27%, (27*) 17%, (28*) 17%, (29*) 34*, (30*) 17%, (31*) 31%, (32*) 36%, (33*) 33%, (34*) 32%, (35*) 36%, and (36*) 39%.

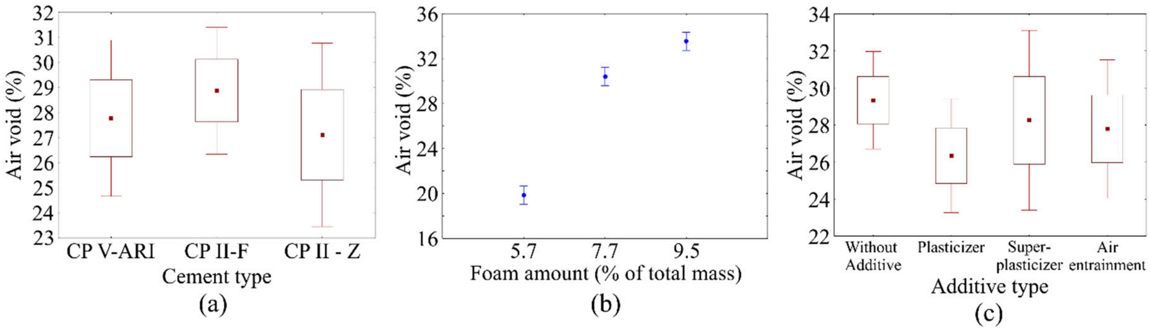

Figure 6. The air void related to (**a**) cement type, (**b**) foam amount, and (**c**) additive type for different curing times, where the middle point is the mean, the box is the confidence interval (95%), and the whisker shows the standard deviation.

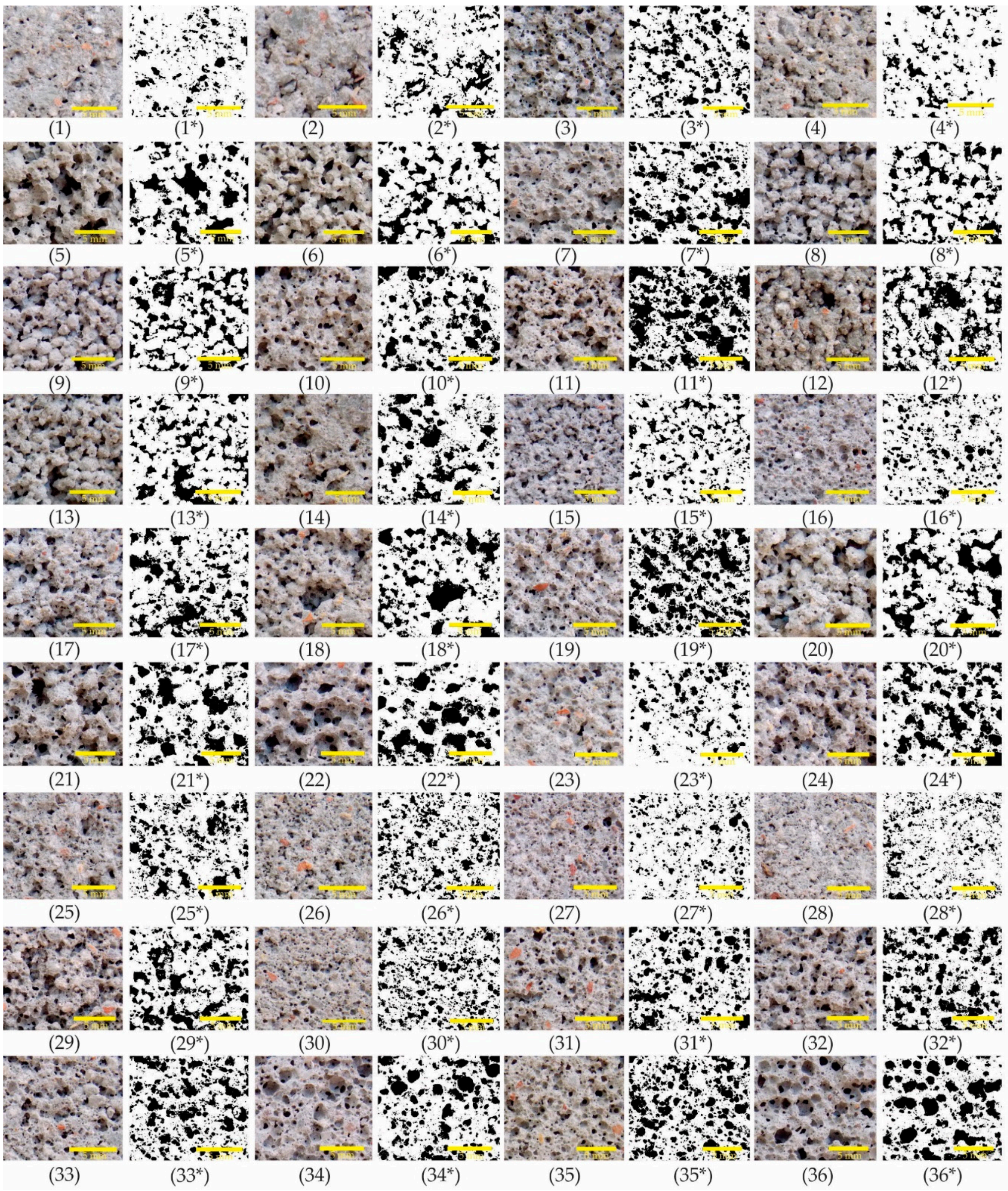

Figure 7. Macrographic and typical binary images for different mixes.

Through the macrographs we observe an increase in air void size with an increasing amount of foam. Also, this can be observed in Figure 8, which shows the mean diameter of air voids based on D10, D50, and D90 (which are used to represent the mean and ranges of particle sizes).

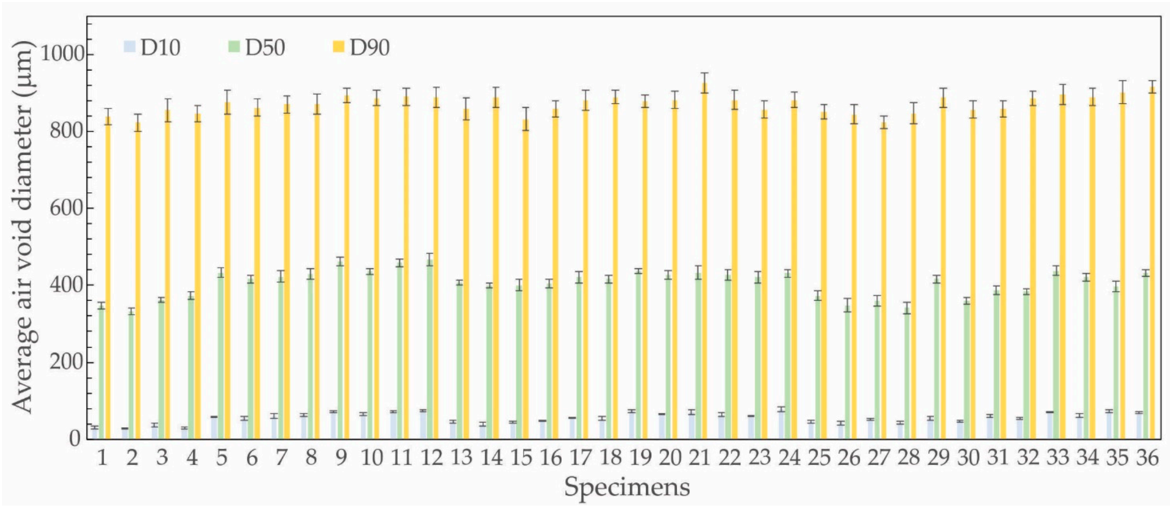

Figure 8. Average air void diameter based on D10, D50, and D90 for all specimens.

On average, small differences in air void size were observed: the average D10 was 55.8 μm, D50 was 406 μm, and D90 was 871 μm. These results are similar to the results found in the work of Favaretto et al. [22].

3.5. Thermal Conductivity

The analysis of variance for the thermal conductivity, is presented in Table 10. Note that the amount of foam makes a greater contribution to this property, followed by the type of cement and the type of additive. The interaction between the type of cement and the amount of foam exerted a greater influence on the thermal conductivity of the foam blocks.

Table 10. Analysis of variance for thermal conductivity (28 days of curing).

Factor	Sum of Squares	Degrees of Freedom	Mean of Squares	*F*-Value	*p*-Value	% Contribution
Cement Type (CT)	0.43250	2	0.21625	15.9986	0.0000	7.0
Foam Amount (FA)	1.59326	2	0.79663	58.9368	0.0000	25.7
Additive Type (AT)	0.33054	3	0.11018	8.1513	0.0000	5.3
CT*FA	1.91944	4	0.47986	35.5013	0.0000	31.0
CT*AT	0.21060	6	0.03510	2.5968	0.0246	3.4
FA*AT	0.27106	6	0.04518	3.3423	0.0058	4.4
CT*FA*AT	0.46158	12	0.03846	2.8457	0.0029	7.5
Error	0.97320	72	0.01352			15.7
Total	6.192	107				100.0

* Interaction between factors.

In Figure 9a, the thermal conductivity can be observed in relation to the types of cements. The higher the number of pores observed in the blocks made with CP II-F, the lower the thermal conductivity.

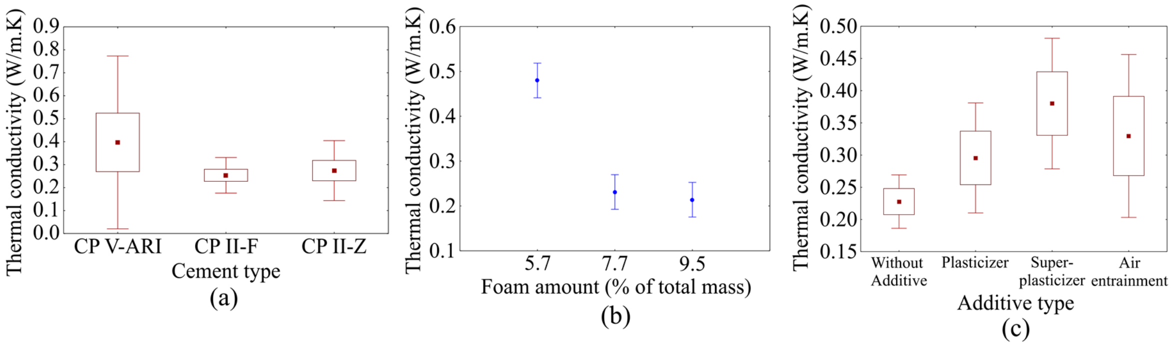

Figure 9. Thermal conductivity related to (**a**) cement type, (**b**) foam amount, and (**c**) additive type for different curing times, where the middle point is the mean, the box is the confidence interval (95%), and the whisker shows the standard deviation.

Figure 9b shows that increasing the amount of foam reduces the thermal conductivity, as expected, since, during low humidity, the air inside the pores behaves like thermal insulation.

The isolated influence of the additive type on the thermal conductivity can be seen in Figure 9c. The results show that the best thermal performance was obtained in the specimens made without additives.

The results show that, due to air being trapped in the structure of foamed concrete, there is a reduction in the transfer and absorption of heat in relation to traditional concrete, thus altering its thermal properties. For example, its thermal conductivity is reduced [69]. According to Kim et al. [70], the thermal conductivity of the material decreased linearly as the porosity in the concrete matrix increased, regardless of the location of the pores. The pore structures of the lightweight concrete with incorporated air become better with thermal insulation when compared to the conventional concretes, because thermal conductivity is directly related to the number and distribution of the pores in the concrete. The values of thermal conductivity are directly influenced by the specific mass of the material, that is to say, light concretes, which have a specific mass varying between 250 and 800 kg/m^3, provide excellent thermal insulation. Another factor that can influence thermal conductivity is humidity, because the lower the saturation of the concrete in the hardened state, the lower the thermal conductivity. However, an increase in moisture content in lightweight concrete results in an increase in thermal conductivity [49].

3.6. The Relationship between the Response Variables

For a better understanding of the results, relationships were set up between the response variables, such as: compressive strength with dry density (Figure 10a); compressive strength with air void (Figure 10b); thermal conductivity with dry density (Figure 11a); water absorption with air void (Figure 11b); and air void with dry density (Figure 11c). As expected, the compressive strength increases with increasing density and an increase in the number of pores (air void) reduces the compressive strength [22,23,29,36,51,71–73]. Also, the thermal conductivity depends on the density, i.e., by increasing the density the thermal conductivity increases, in accordance with other studies on this type of material [15,74–77]. Another observation is that the values of thermal conductivity for densities above 1300 kg/m^3 have greater dispersion. This dispersion is explained by the dispersions observed in experiments with CPV-ARI cement and with the addition of additives.

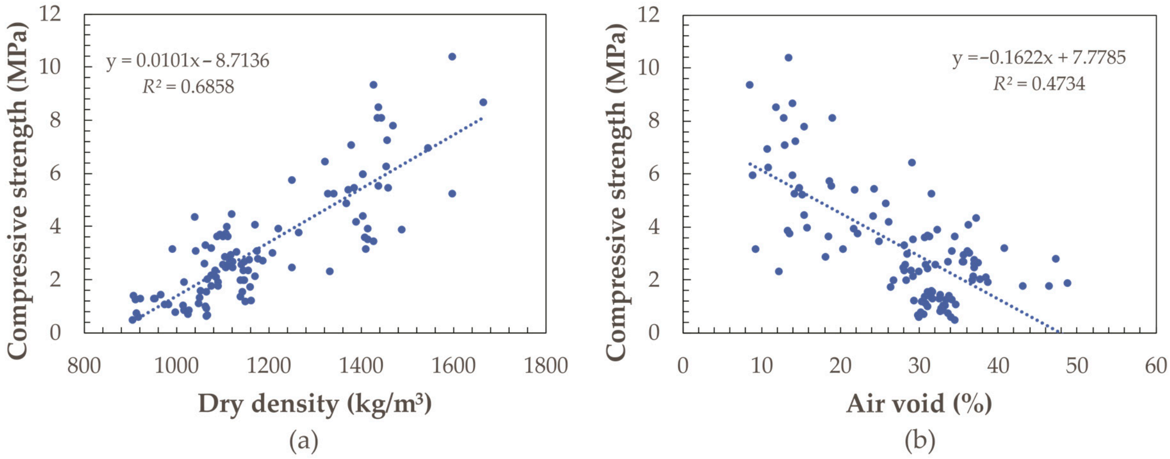

Figure 10. Compressive strength as a function of (**a**) dry density and (**b**) air void.

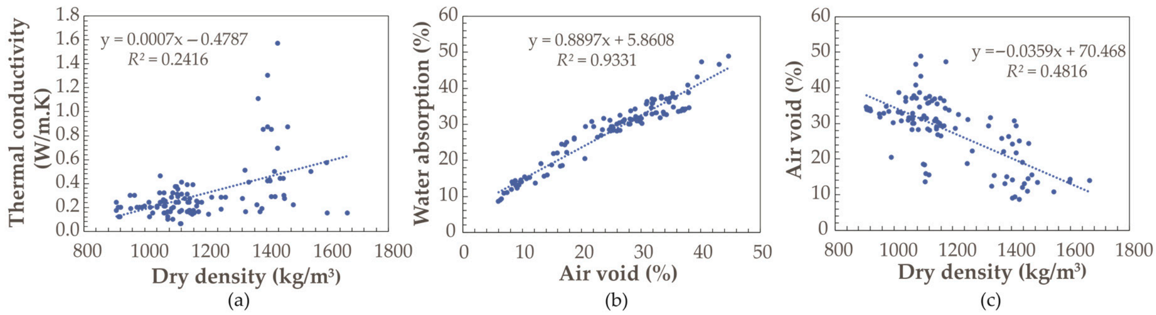

Figure 11. (**a**) Thermal conductivity as a function of dry density, (**b**) water absorption as a function of air void, and (**c**) air void as a function of dry density.

For the factor levels studied, it can be observed that the water absorption increases linearly with the increase in air voids and that the air voids decrease with an increase in the density. These results are also in agreement with the results found in the literature [64,73,78–80].

4. Conclusions

In this study, foamed concrete blocks were developed by adding civil construction waste (CCW), which totally replaced the conventional fine aggregates (natural sand). Based on our analysis, the following conclusions could be made:

- CCWs can be used integrally as aggregates in the production of foamed concrete blocks, thereby reducing civil construction companies' liabilities and reducing environmental impacts due to the irregular disposal of waste. In addition, by using this residue, the consumption of natural sand can be reduced. Sand is a finite aggregate and its extraction causes environmental damage, especially in rivers and lakes;
- The additives have little influence on the properties of foamed concrete blocks. Different additive proportions can be evaluated in future works to seek the optimization of the use of additives in concrete foam;
- For the specimens studied it is possible to obtain compressive strength of specimens higher than the minimum value of 1.4 MPa required by ASTM C869/C869M—11, but the values of compressive strength found are still low when compared with other studies on lightweight concrete that used other aggregate types. Therefore, studies should be conducted to try to increase the compressive strength of these materials, for example, studying the use of different curing processes to decrease the connectivity between the pores;

- As expected, the dry density and saturated density decrease when the amount of foam in the structure of the blocks increases. However, the densities are still high for lightweight concrete. Increasing the amount of foam in the fabrication of the blocks and experimenting with other foam agents could be a solution to decrease the density of these materials;
- The air void and the water absorption are strongly influenced by the amount of foam added to the structure, i.e., as the amount of foam increases, the number of pores increases. To minimize the water absorption, the connectivity between the pores must be reduced. For this reason, the foam stability should be studied in more detail;
- Specimens developed with CP II-Z cement showed, on average, the highest compressive strength, the highest densities, the highest thermal conductivity, the lowest air void, and the least absorption of water. Specimens developed with CP II-Z cement showed, on average, the lowest compressive strength, the highest densities, the highest air void and absorption of water, and the lowest thermal conductivity. The cement with pozzolanic addition presented the best results. So, to further improve the results, other materials, under replacement of the cement, can be added in new studies;
- The thermal conductivity found for foamed concrete blocks is in accordance with what NBR 15220 determines, namely that the thermal conductivity must be below 2 W/(m.K). To minimize the thermal conductivity, studies of foamed concretes with the addition of thermal insulation materials (wood, Styrofoam, etc.) can be carried out.

Author Contributions: P.F. performed the tests, analyzed the results, and wrote the paper. G.E.N.H. and R.M.C.T. assisted in the characterization of CCW and analysis of the results. R.d.A.S., R.T.L., and F.T. planned the study and assisted in the analysis of the results and with writing the paper.

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Conflicts of Interest: The authors declare no conflict of interest.

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