

Comparative assessment of the mechanical behaviour of aerated lightweight concrete

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ABSTRACT

The present study aims to discuss the effect of air entrainment on the mechanical behavior and durability of molded concrete elements. The experiment was carried out using samples with 4 different masses (1500 kg/m³, 1700 kg/m³, 2000 kg/m³, and 2300 kg/m³) and 3 water/cement ratios (0.63-1:5, 0.50-1:4, 0.43-1:3) that were tested to determine compressive strength, water absorption, void index, and carbonation depth. The results showed significant decreases in performance and in the protection indicators of the armature (water absorption and carbonation), confirming the need for additional mitigation for the structure (protective paints, stainless steel bars), under penalty of premature loss of durability over its lifetime.

Keywords: lightweight concrete and entrained air; concrete wall; compressive strength; capillarity; absorption.

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Avaliação comparativa do comportamento mecânico de concretos leves com ar incorporado

RESUMO

O presente estudo visa discutir o efeito dos incorporadores de ar no comportamento mecânico e de durabilidade de elementos de concreto moldados no local. O experimento foi desenvolvido com a confecção de amostras com 4 diferentes massas específicas (1500kg/m³, 1700kg/m³, 2000kg/m³ e 2300kg/m³) e 3 relações água/cimento (0,63 – 1:5, 0,50 – 1:4, 0,43 – 1:3), ensaiados para determinação da resistência à compressão, absorção de água, índice de vazios e profundidade de carbonatação. Os resultados obtidos apontaram quedas expressivas no comportamento e indicadores de proteção da armadura (absorção de água e carbonatação), o que confirma a necessidade de utilização de meios adicionais mitigadores para a estrutura (pinturas protetoras, barras inoxidáveis), sob pena da perda prematura da durabilidade ao longo da sua vida útil.

Palavras-chave: concreto leve e ar incorporado; parede de concreto; resistência à compressão; capilaridade; absorção.

Evaluación comparativa del comportamiento mecánico de concretos ligeros con aire incorporado

RESUMEN

En el presente estudio busca discutir o efectuar dos incorporadores de comportamiento no mecánico y durabilidad de elementos de hormigón moldeado no locales. El experimento fue desarrollado con un conjunto de muestras con 4 masas específicas diferentes (1500 kg / m³, 1700kg / m³, 2000kg / m³ y 2300kg / m³) y 3 relaciones agua / alimento (0,63 - 1: 5, 0,50 - 1: 4, 0,43 - 1: 3), pruebas para determinar la resistencia a la compresión, absorción de agua, velocidad de profundidad y profundidad de la carbonatación. Los resultados obtenidos no son expresivos, no se comportan como indicadores de protección de armadura (absorción de agua y carbonatación), o que confirme la necesidad de usar suavizantes de agua adicionales para la estructura (tintas de protección, barras de acero inoxidable) debido a la pérdida prematura. Da durabilidad a lo largo de su vida útil.

Palabras clave: concreto ligero y aire incorporado; pared de concreto; resistencia a la compresión; capilaridad; absorción.

1. INTRODUCTION

Concrete made from Portland cement is the most important structural material in civil construction today. As described by Helene and Andrade (2007), concrete can be considered one of the most interesting discoveries in the history of human development and quality of life, even being the most recent of structural building materials.

The use of concrete walls molded onsite has become an option frequently used in Brazil in order to achieve the social goal of reducing the housing deficit. In hot climates, it becomes necessary to discuss the thermal discomfort caused by the use of this type of material, which can be minimized with concrete having lower specific mass obtained with the incorporation of air entrainment additives. This technique, however, can lead to a decrease in both mechanical performance and in protection against the entry of water and aggressive agents into the structure.

It is noteworthy that these systems have been used in buildings around the country for about 30 years and, according to Corsini (2011), are divided basically into two types, depending on the

concrete adopted: normal density concrete walls and light concrete walls. To regulate systems of conventional concrete walls, ABNT NBR 16055 (2012) was published in 2012. For wall systems made from light foamed concrete, there are standards dating from 1992 (ABNT NBR 12645 and NBR 12646, 1992), which are currently under review, with important discussions taking place regarding the improvement in thermal performance and the loss of reinforcement protection provided by the concrete itself. In this context, the current study evaluated, through experimental development, concrete having different levels of specific mass and its consequences on the principal mechanical properties (resistance to compression) and cement qualities (water absorption, void index, carbonatation depth, etc.) to prevent water entering into the interior of the structure.

1.1 Light concrete

As shown by Rossignolo (2009), lightweight concrete is characterized by a reduction of the specific mass in relation to conventional concrete, as a consequence of the substitution of part of the solid materials with air. According to Romano, R. C. O. et al. (2015), they can be classified as concrete with light aggregates, cellular concrete, and non-fine concrete. According to NBR 8953 (2015), these concretes should be classified by specific mass according to Table 1.

Table 1. Classification of specific mass. Source: (NBR 8953, 2015).

Nomenclature	Dry specific mass (kg/m ³)
Light concrete (CL)	< 2000
Normal concrete (C)	2000 to 2800
Heavy or dense concrete (CD)	> 2800

The analysis of the specific mass obtained for groups of concrete shows a correlation with the inclusion of voids. The relationship between intentionally entrapped air content and specific mass is quite straightforward; an increase in the volume of air causes a reduction in the value of specific mass, while maintaining the same proportion of materials. The specific mass of the concretes is reduced through the inclusion of voids in its interior.

The lightweight concrete group, however, is broad and it is not adequate to simply classify it only by specific mass. Other qualities must also be taken into account. It is important to consider the production method, that is, what materials and processes are considered during preparation, such as mechanical resistance, workability, retraction, and fluency, among others.

1.2 Air entrainment additives

According to Du et al. (2005) and Whiting et al. (1999), air-entraining additives have the function of producing stable air bubbles evenly distributed throughout the concrete. According to Mehta and Monteiro (2014), the air-entraining additives are surfactants, usually consisting of wood resin salts, proteins and fatty acids, and some synthetic detergents. According to Kumaran et al. (2004), the air entrained by the additive takes the form of small bubbles having dimensions between 0.01 mm and 1.00 mm, spaced from 0.10 mm to 0.20 mm apart, that display elastic behavior.

According to Torres et al. (2014), the additive incorporated in the mixture promotes a reduction in the surface tension of the water. For Fujii et al. (2015) and Bauer (1994), it acts by involving the air bubbles already present and also involves the finest aggregate particles of the cement. The combination of the solid particles involved, and the air bubbles is more stable than the each is alone. Although it reduces the mechanical strength of the concrete, the incorporation of air improves workability, reduces exudation, and improves the behavior of the material during transportation, which can be done with less possibility of segregation.

2. EXPERIMENTAL DEVELOPMENT

The proportions used were determined by adapting the Ibracon dosing method (Helene and Terzian, 1992), using concrete samples with three cement:aggregate proportions: 1:3, 1:4, and 1:5, all having the same consistency (170 ± 30) mm, which required the use of three different water/cement ratios: 0.43, 0.50, and 0.63, respectively (Table 2). The mortar content ($\alpha\%$) of 0.65 was also fixed for all dosages, a percentage commonly adopted for the preparation of lightweight concretes.

For each of these dosages, samples were prepared with four levels of specific mass in the fresh state, obtained using polyfunctional additive Mira 93/Grace (density: 1.17 g/cm^3) and air entrainer SikaAer, (density: 1.01 g/cm^3 , nature: liquid, base: synthetic resin, pH (23°C) 10-12, solid content(%): 4-6) with proportions of 0.5% and 0.1% of the mass of the cement, respectively, totaling 12 test families. The increase in void content was obtained from increasing the mixing time of the concrete in the concrete mixer (between 3 and 15 minutes), since the amount of additive was kept constant.

Table 2. Groups and subgroups tested.

Group(1:m)	Subgroup	Approximate specific mass(kg/m^3)
A (1:5) w/c=0.63	1	2300
	2	2000
	3	1700
	4	1500
B (1:4) w/c=0.50	1	2300
	2	2000
	3	1700
	4	1500
C (1:3) w/c=0.43	1	2300
	2	2000
	3	1700
	4	1500

To carry out the study, 120 cylindrical (10 cm x20 cm) concrete specimens were molded for the tests to determine specific mass (fresh and hardened state), compressive strength (at 7 and 28 days), total and capillary absorption, and carbonatation depth, as shown in Table 3. All tests were performed according to their current standards, which are described in Table 4.

Table 3. Description of samples used per test.

Group	m	Subgroup	Specific mass	Rupture (7 and 28 days)	Absorption and dry sp. mass	Capillarity	Carbonatation	Total Specimens
A	1:5	1	2300	4	2	3	1	10
		2	2000	4	2	3	1	10
		3	1700	4	2	3	1	10
		4	1400	4	2	3	1	10
B	1:4	1	2300	4	2	3	1	10
		2	2000	4	2	3	1	10
		3	1700	4	2	3	1	10

		4	1400	4	2	3	1	10
C	1:3	1	2300	4	2	3	1	10
		2	2000	4	2	3	1	10
		3	1700	4	2	3	1	10
		4	1400	4	2	3	1	10
Total Specimens		-		48	24	36	12	120

Table 4. Tests and Normative Parameters.

TESTS:	Normative Parameters	International Equivalents
Determination of specific mass	ABNT NBR 9778:2009	ASTM C231/C231M:2017 ASTM C29/C29M:2017
Compressive strength	ABNT NBR 5739:2007	ASTM C39/C39M:2018
Cement consumption	ABNT NBR 12655:2015	ASTM C1084:2010
Water absorption, void index, and specific mass	ABNT NBR 9778:2009	ASTM C29/C29M:2017
Capillary absorption	ABNT NBR 9779:2012	ASTM C1585:2013
Carbonatation depth	RILEM CPC-18, 1988	-----

2.1 Laboratory production of concrete

For the production of the concretes in the laboratory, dry aggregates and pre-mixed large and small aggregates were used with type CP-V ARI cement, similar to type III of ASTM C150 (2017). Some of the principal characteristics of the aggregates used are described in Table 5.

Table 5. Description of physical characteristics of the aggregates used.

Aggregate Characteristics	Fine Aggregate	Coarse Aggregate
Fineness modulus	1.71	5.51
Maximum diameter (mm)	2.36	12.5
Dry specific mass (g/cm ³)	2.63	2.77
Apparent specific mass (g/cm ³)	2.73	2.72
Bulk density (kg/m ³)	1620	1470

Soon after the initial mixing of the materials, the polyfunctional additive and kneading water were added (reserving approximately 500ml of water from the concrete to add the air entrainer). After initial mixing of the concrete, its subsidence and specific mass were determined. Subsequently, the air entrainer was added along with the remainder of the water, as shown in Figure 1. After completing production, the specific mass of the fresh concrete was measured until reaching the approximate values intended and initially stipulated.



Figure 1. Mixing of materials in concrete mixer. Without air entrainment additive (a) and with air entrainment additive (b).

3. RESULTS

After reaching the ages planned after molding and wet curing, samples were divided among the tests planned for the hardened concrete. Figure 2 displays a graph with the specific masses according to ABNT NBR 9778 (2009), with their respective equivalences (ASTM C231/C231M and ASTM C29/C29M, 2017), obtained from the fresh concretes for the different study groups evaluated.

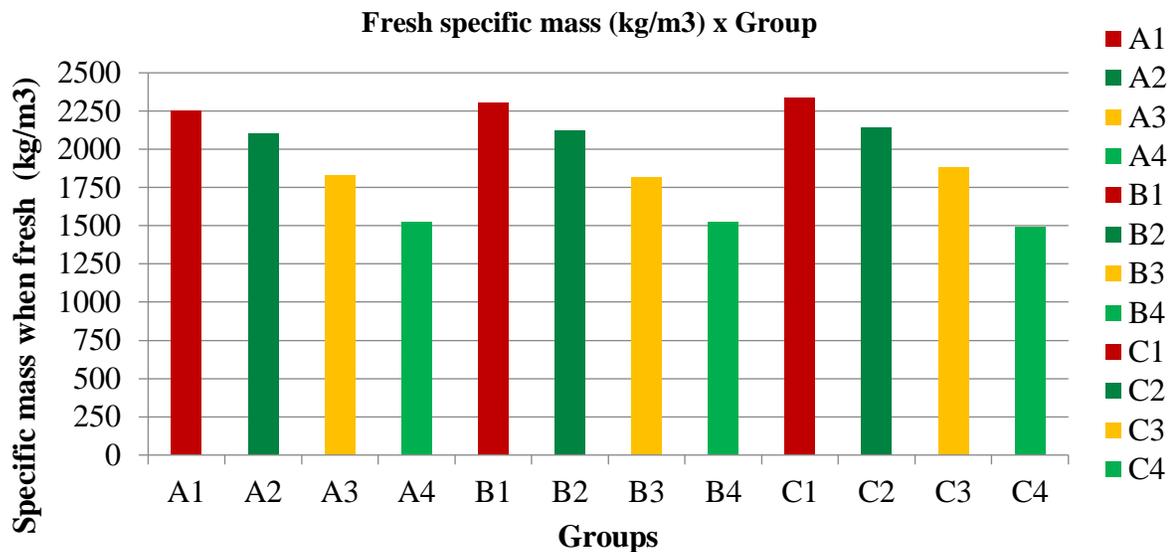


Figure 2. Specific mass x test groups

Fig. 3 shows the entrained air contents obtained from the fresh concrete for the different study groups evaluated.

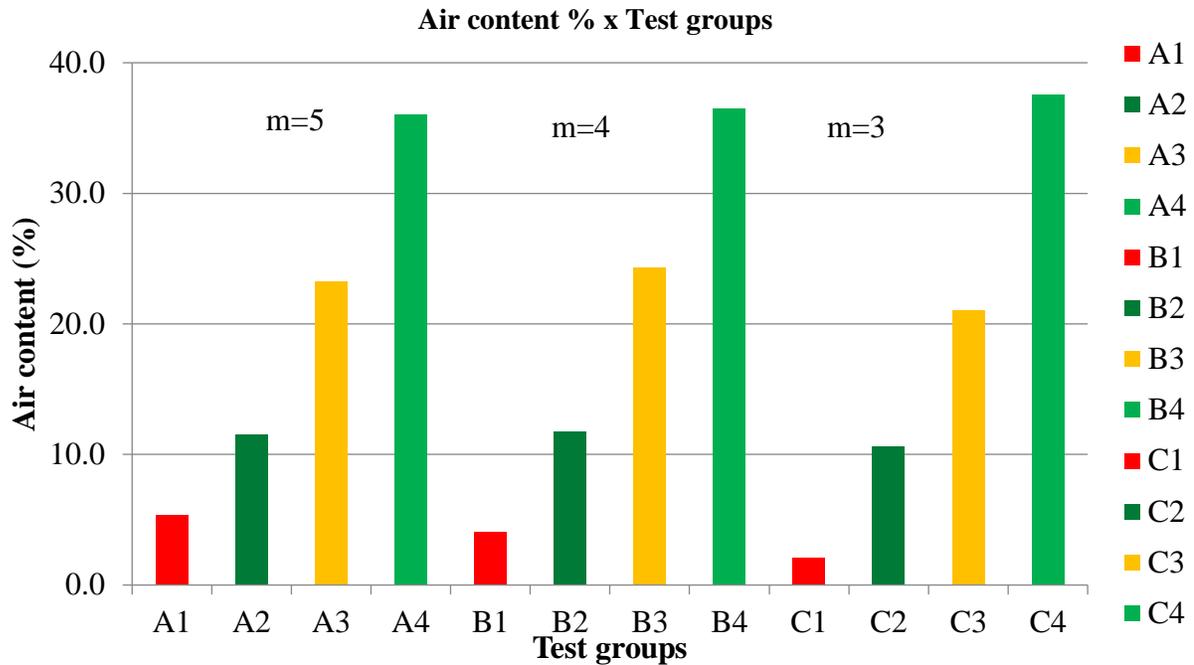


Figure 3. Air content x groups

3.1 Relationship between specific mass in the fresh state and compressive strength

Table 6 presents the results found from the compressive strength tests at 7 days and 28 days according to ABNT NBR 5739 (2007), equivalent to ASTM C39/C39M (2018), compared to the specific mass initially defined. For each concrete family, two cylindrical specimens were used, and the highest value found for the tested pair was considered to be representative of the sample.

Table 6. Results of compressive strength tests

Group	Specific mass (kg/m ³)	Compressive Strength (MPa)	
		7 days	28 days
A (1:5) w/c = 0.63	2300	32.6	40.8
	2000	18.4	23.3
	1700	7.7	9.8
	1500	1.8	2.1
B (1:4) w/c = 0.50	2300	43.2	54.6
	2000	20.7	29.2
	1700	7.6	11.0
	1500	1.1	1.8
C (1:3) w/c = 0.43	2300	50.0	65.4
	2000	22.1	28.7
	1700	14.7	18.0
	1500	1.6	2.2

Figures 8, 9, and 10 were generated from the compressive strength test data (Table 4) and the analysis of the influence of the water content of the concrete (Table 3). The water/cement ratio and the compressive strength for each specific mass group was evaluated.

The correlation between the water/cement ratio and strength, a determining factor in the study of concretes and verified by the Abrams model, is clearly observed for concrete of the conventional

class (specific masses of 2300 kg/m³ and 2000 kg/m³). For the concrete of the lightweight class contemplated in the study (specific masses of 1700 kg/m³ and 1500 kg/m³), the w/c ratio alone is not the only determining parameter of compressive strength behavior.

Once the air-entrainment additive was added to the blend, an improvement in the cohesion of the materials was visually observed, but there were no variations in the subsidence values of the concretes with specific masses of 2300, 2000, and 1700 kg/m³. Concretes with specific mass of 1500 kg/m³ showed small increases in subsidence values, varying between 190 mm and 210 mm. According to ABNT NBR 12655 (2015), equivalent to ASTM C1084 (2010), cement consumption of concrete having a lower specific mass is, in general, lower than for those of higher mass, as expected by Romano, et al. (2017), due to the inclusion of the air-entrainment additives, for similar consistency levels. In addition, for a larger "m" value, smaller cement consumption took place. The curves obtained for cement consumption for each specific mass is shown in Figure 4.

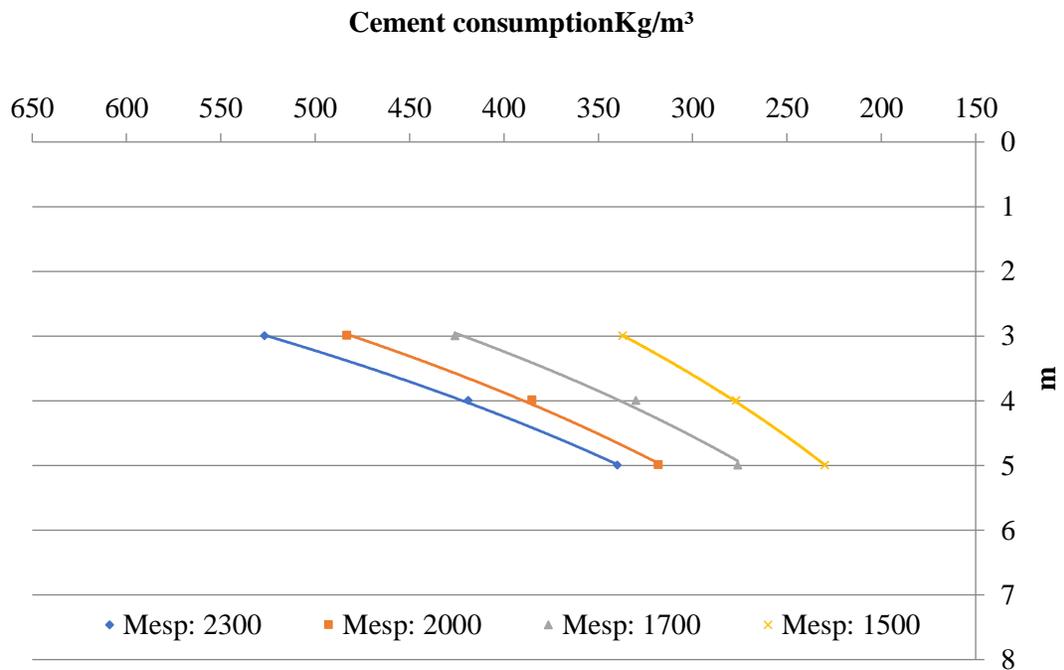


Figure 4. Cement consumption by specific mass

3.2 Relation between specific mass in the fresh state, water absorption, void index, and dry specific mass.

The dry specific mass values obtained from the hardened concrete test showed variations from the initial values and those stipulated for the specific mass bands of the study. This is due to the different losses of water to which the concretes are submitted once the hardening process begins. The values obtained from the void index tests corroborate the idea that concrete with lower specific mass has a higher void index. It also presents higher values of water absorption. A visualization of these three properties is shown in Figure 5.

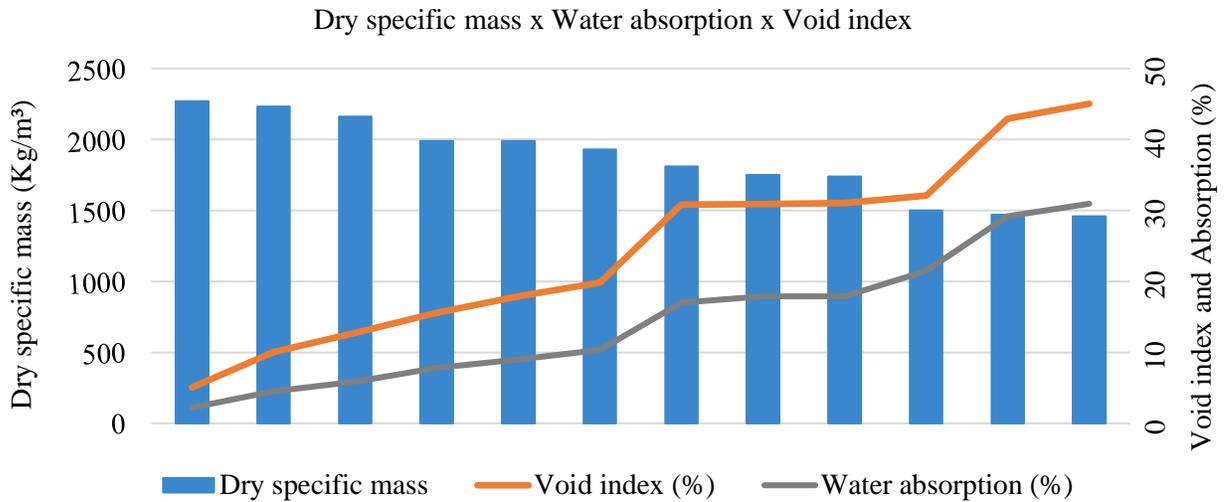


Figure 5. Relationship between dry specific mass, void index, and water absorption

Figure 6 shows the relationship between the specific mass and the void index for the samples, according to NBR 9778 (2009), with equivalent international standard ASTM C29/C29M (2017).

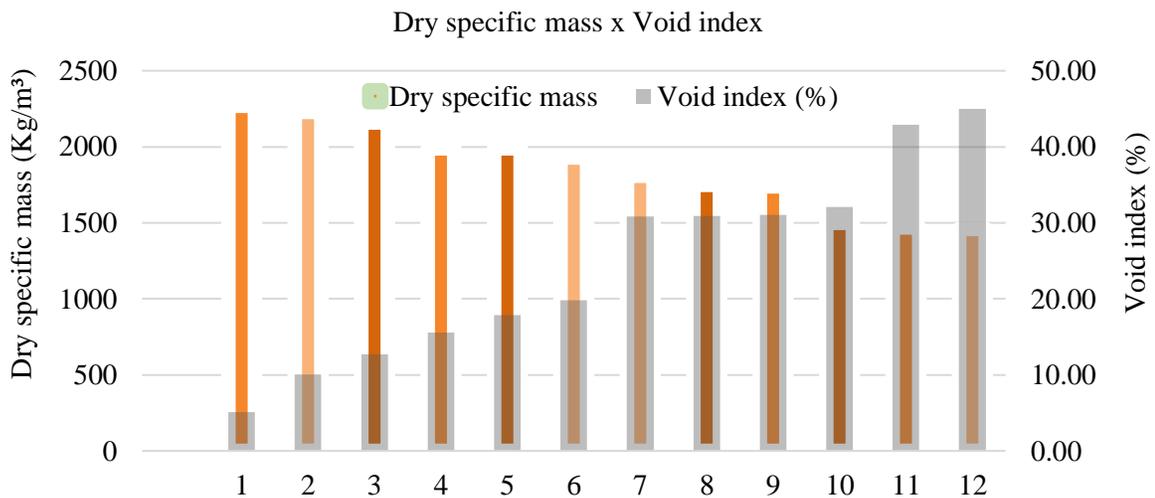


Figure 6. Relationship between specific mass and void index.

3.3 Relationship between specific mass in the fresh state and capillary absorption

The study also sought to evaluate the capillary absorption rates of the concretes prepared, in order to verify the effect of their properties on capillarity. To achieve this, the 12 concrete dosages used in the study were tested according to standard ABNT NBR 9779 (2012), equivalent to ASTM C1585 (2013).

In the specific case of capillary absorption, the relationship observed to have the greatest influence was still the specific mass of the concrete (obtained through the entrainment of air), but in addition, the water/cement ratio was much more influential than in the absorption, void index, and specific dry mass tests.

Figure 7 shows the graph of specific mass and capillary absorption for the 12 dosages, sorted into descending order of specific mass.

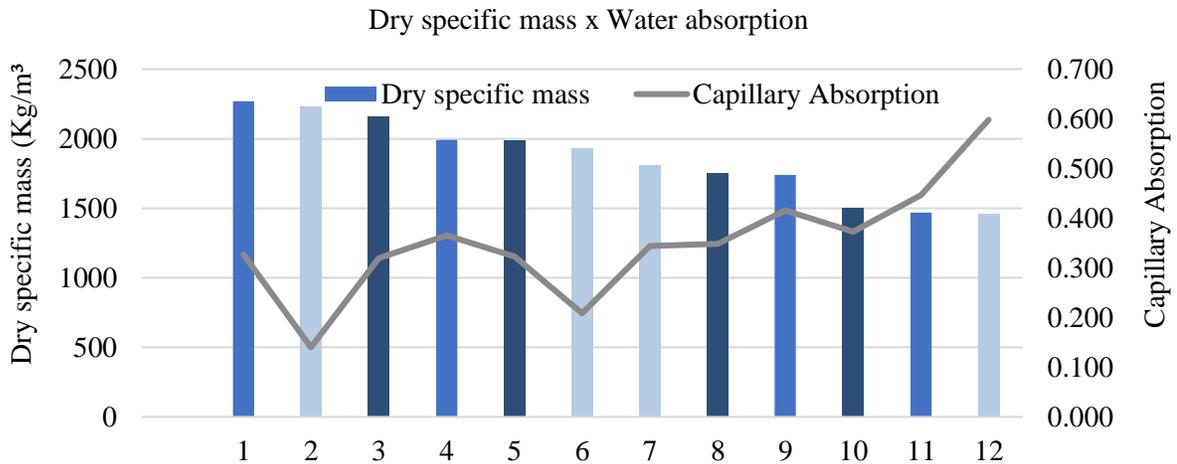


Figure 7. Relationship between specific mass and capillary absorption

It can also be observed that, for concretes without the use of the air entrainment additive, the capillary absorption followed variation in the water/cement ratio quite closely. For the other concretes, there were variations in the results. It is still possible, however, to visualize the tendency of the absorption curve to grow as the values of specific mass decrease. It can be said that the w/c ratio influences but is not the only source of influence on the absorption behavior.

3.4 Relation between dry specific mass and compressive strength

Figures 8, 9, and 10 show the relationship between the specific mass values of the concretes in the dry state and their respective compressive strengths, demonstrating the strong correlation between the properties.

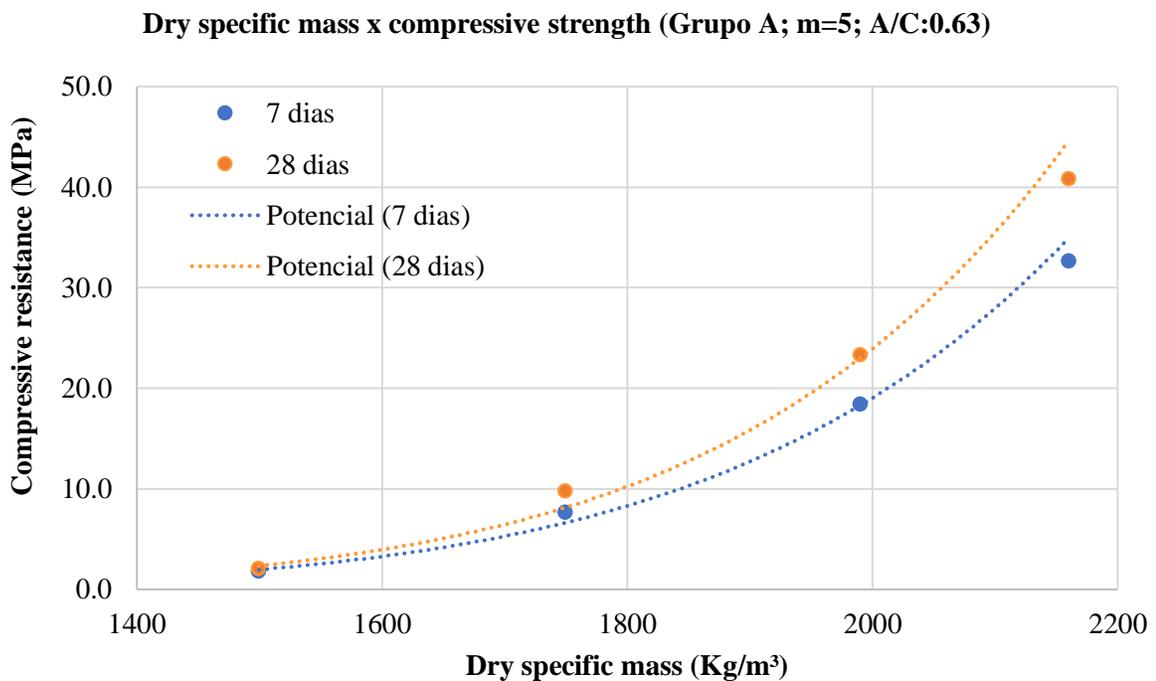


Figure 8. Compressive strength and specific mass - m=5

Dry specific mass x compressive resistance (Grupo B; m=4; A/C: 0.50)

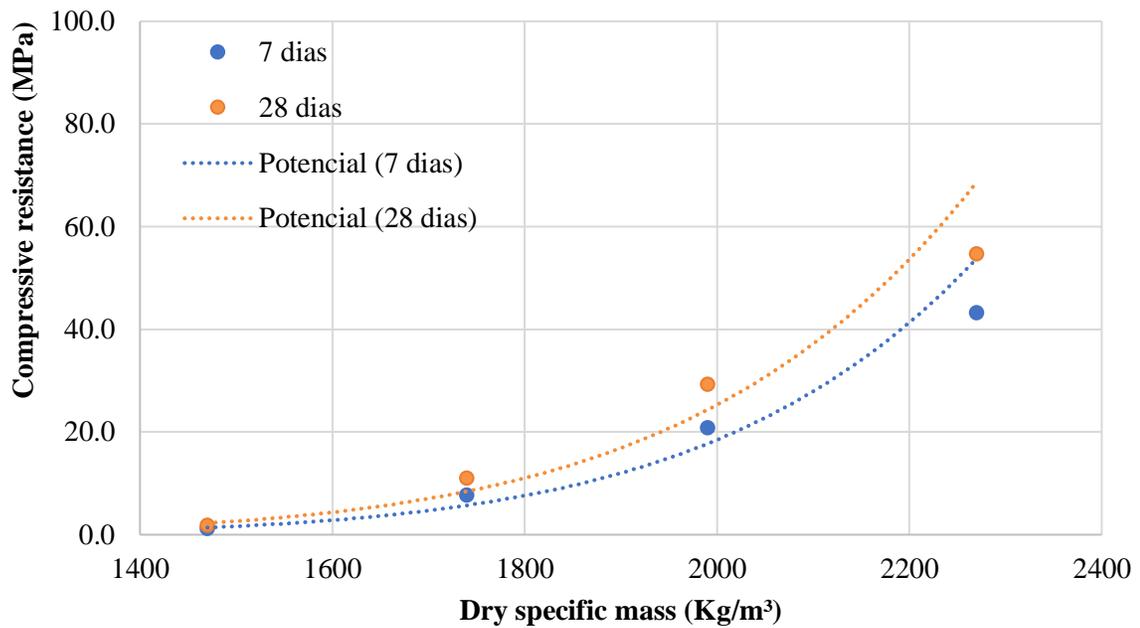


Figure 9. Compressive strength and specific mass - m=4

Dry specific mass x Compressive resistance (Grupo C; m=3; A/C:0.43)

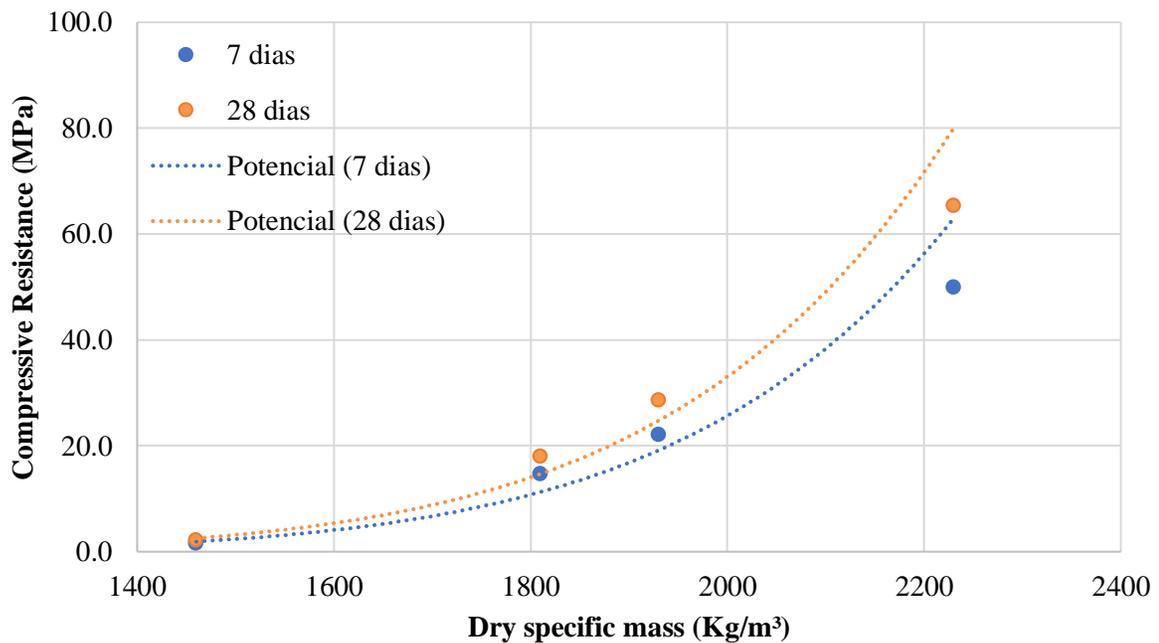


Figure 10. Compressive strength and specific mass - m=3

The results show that higher values of compressive strength were found for higher densities. An increase in voids within the concrete causes both lower specific mass and a reduction in mechanical strength. According to NBR 12646 (1992), compressive strength values for of cellular concrete must meet a minimum value of 2.5 MPa.

It was verified that, for the same concrete, the increase of the entrainment of air provoked a reduction in the specific mass, and consequent reduction in the mechanical resistance. This behavior was influenced principally by two properties: the increase of the voids in the concretes and the water/cement ratio used.

It was observed that the concretes with specific mass near 1500 kg/m^3 , that is, those with more air entrainment, had compressive strength performance determined almost completely by the quantity of voids, taking into account the water/cement ratio adopted.

The results found agree with those obtained by Teixeira Filho (1992), where one of the observed results was the distinction of the influence of the water/cement ratio when different specific mass classes were observed. For concrete with specific mass of 1100 kg/m^3 and 1300 kg/m^3 , increasing the water/cement ratio from 0.5 to 0.6 resulted in an increase in strength. For concrete classes with specific mass of 1700 kg/m^3 and 1900 kg/m^3 , the same increase in the water/cement ratio, from 0.5 to 0.6, resulted in lower values of compressive strength.

In this study it is also observed that, for example, for dosages with specific masses of 1500 kg/m^3 , a water/cement ratio of 0.63 had higher axial compressive strength than for a water/cement ratio of 0.50. For the results obtained, it is possible to consider that the changes in the influence of w/c ration on the axial compressive strength are justified by the reduction of specific mass and increase in voids in the concrete (Teixeira Filho, 1992).

In addition, it was observed that concrete with a specific mass of 1900 kg/m^3 has interesting mechanical properties, with values of compressive strength in the range of 20 MPa, combined with the possible benefits of air entrainment, such as reduced consumption, lower weight, and improvements in thermal and acoustic comfort compared to conventional concrete.

In the case of capillary phenomena, the evaluated concretes showed an increase in capillary absorption as specific mass decreased.

It is known that the permeability of concrete is a crucial factor for its durability. The more permeable the concrete, the more susceptible to the deleterious actions of agents present in the environment. Thus, special attention must be given when using concretes that have high void indices and high capillarity, as is the case in the present study.

3.5 Relationship between specific mass in the fresh state and carbonatation depth.

In order to evaluate the concretes studied from the point of view of carbonatation, 12 specimens were separated to be used in the evaluation. Because the previous test was non-destructive, it was possible to evaluate these concretes submitted to the atmospheric action of the laboratory environment, where they remained for a period of 110 days of exposure.

To perform the test, the procedure described in Rilem (1988) was used, and the 10x20 cm test specimens were sectioned at 1/3 of their length.

After sectioning, the specimens were sprayed with a solution of phenolphthalein (2%) for pH identification. A transition zone occurs along the advance of the carbonatation front, having pH below 9 and tending to be colorless in the presence of the solution. The zone with pH higher than 9 tends to be violet in color.

In this way, it was possible to identify the carbonatation front formed by observation, as shown in Figures 11 and 12.



Figure 11. Measurement of carbonation depth for concrete with specific mass of 1500 kg/m³



Figure 12. Measurement of carbonation depth for concrete with specific mass of 1700 kg/m³

Table 7. Average carbonatation depth values

Group	W/C	1:m	Subgroup	Specific mass (kg/m ³)	Carbonatation depth (mm)
A	0.63	1:5	1	2300	0.97
			2	2000	1.87
			3	1700	3.54
			4	1500	18.75
B	0.50	1:4	1	2300	0
			2	2000	1.27
			3	1700	1.59
			4	1500	18.92
C	0.43	1:3	1	2300	0
			2	2000	0.84
			3	1700	1.6
			4	1500	10.68

It was found that the lightweight concretes have a carbonation front that is much more advanced than that of the conventional concretes. Even those concrete with a reduced water/cement ratio, such as group C (w/c: 0.5), presented significant carbonation depths for the lower specific masses (1500 and 1700 kg/m³) over the 110 days of the test.

4. CONCLUSION

The current study evaluated the repercussions of a reduction in specific mass of concrete on its mechanical properties and durability. The interest in using concrete with an air entrainment additive has grown, especially for walls poured in place, that usually are repeated. This solution stands out for its tendency to improve thermal behavior, when compared to concrete of normal density, which is indispensable in regions of high temperatures, such as in the Brazilian northeast. Associated with this is a marked reduction in cement consumption insofar as the concrete density is reduced, despite the possible cost due to the inclusion of the air-entraining additives. However, it is essential that these benefits are weighed against the possible compromise in durability, due to the greater ease of entry for aggressive agents, especially chloride ions and carbon dioxide.

The tests demonstrated the strong influence that the reduction of the concrete's specific mass had on its mechanical behavior, in particular, its durability. Reducing the specific mass also provoked significant increases in water absorption (3% to 30%), void index (5% to 50%), capillary absorption (0.2 g/cm² to 0.6 g/cm²) and carbonation depth (0 mm to 18.9 mm).

These results point to the need to adopt measures of surface protection for the concrete when used in regions with an aggressive environment, in order to reap the benefits (especially financial and economic) of the technique, without compromising the concrete's durability. It is also necessary to assess the need for maintenance in order to ensure adequate performance behavior over the years.

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