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STUDY OF THE SHEAR STRENGTH OF CELLULAR CONCRETES

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ABSTRACT

Concrete structural elements are typically subjected to different stresses. Shear stress commonly occurs in concrete elements, potentially leading to failure, whether they are structural or not. Despite being an important mechanical property, there is a lack of specific standards for shear testing in concrete elements. Foamed cellular concrete (FCC) is a special lightweight concrete with low density, and its mechanical properties are inferior to those of normal density concrete (NDC). However, very little is known about its shear strength. This article evaluates the shear stresses of FCC with different densities. For this purpose, two types of FCC were obtained by varying the foam dosage (10% - FCC10 and 20% - FCC20). Specific mass and compressive strength (fc) were also determined. FCC10 and FCC20 showed a decrease in fc of approximately 44% and 60% compared to NDC, respectively. The decrease in shear strength was comparatively smaller, around 31% and 47% in relation to NDC, respectively.

KEYWORDS: *Density, compressive strength, shear stress, foamed cellular concrete.*

I. INTRODUCTION

Concrete plays a pivotal role in the modern world, serving as an essential product for civil construction, infrastructure, and various sectors. This industry is responsible for constructing residential and commercial buildings, bridges, dams, and tunnels [1]. The global production of concrete has been steadily increasing over the last few decades, in line with population growth and the development of the global economy. In 2020, global concrete production reached approximately 4.0 billion tons, marking an 8.1% increase [2].

In addition to its benefits as a structural material, normal density concrete (NDC) also presents challenges, one of which is its high self-weight, with a density ranging between 2300 kg/m^3 to 2500 kg/m^3 [3].

In an attempt to mitigate this drawback, various research studies involving lightweight concretes, with a density of less than 2000 kg/m^3 [3], emerge as an alternative, as they exhibit particular characteristics: lower self-weight, among others. These can be achieved by substituting coarse aggregates with different types of additions: aerogel [4]; foaming agents [5]; rubber aggregates [6]; expanded clay [7], [8], [9]; fly ash [10]; perlite [11]; expanded polystyrene [12]; expanded glass [13], [14], [15].

As it can be identified in the cited literature, there is a gap in studies regarding the production of lightweight concretes using foaming agent, referred to as foamed cellular concrete (FCC). This type of concrete is characterized by the absence of coarse aggregates, which are replaced by foam during its production to generate microbubbles distributed uniformly in the cementitious matrix [16].

Therefore, it is necessary to expand the knowledge about the mechanical properties of FCC. Among these properties is the shear strength that can occur in beams, slabs, and other support structures cast in place or in precast structures.

Pure shear is a specific type of transverse stress that occurs in concrete elements subjected to loads that do not generate bending moments and is one of the most critical failure modes in reinforced concrete elements, potentially leading to abrupt failure of the element [17]. The shear strength of concrete under pure shear is generally lower than the shear strength in elements subjected to bending moments, such as beams and slabs [18]. It is worth noting that the shear behaviour of structural concrete is complex, not well understood, and there is no accepted analytical solution to unify all factors influencing the shear behavior of reinforced concrete [19].

Over the years, numerous research studies have been conducted to determine the shear strength of concrete, and in each of these tests, different shapes, dimensions, and loading conditions have been employed [20]. Different testing techniques can lead to significant variations in shear strength values. These discrepancies occur due to factors such as the size of the samples used, the specific configuration of the test, and the speed of load application [21]. For this work, the test conducted on a cube supported by metal plates was adopted [22]. In this study, an analysis of the shear stress of lightweight FCC was developed and compared with the results of normal density concrete. The experimental methodology used, the results obtained, and the conclusions reached are presented below, along with the potential impact of this research in the field of civil engineering.

II. WORK ORGANIZATION

The article presents the study developed in the following stages: characterization of the materials of NDC and FCC concretes; composition of the concretes (NDC, FCC); production of the concretes and molding and quantity of test specimens for determination of properties in the hardened state; testing technique, procedures for determining shear stress; procedures for statistical analysis of the data obtained; results and analysis of the specific mass and compressive strength and shear stress obtained.

III. OBJECTIVES

The article aims to evaluate the shear stress in foamed cellular concreto, produced with the introduction of foams in two different proportions, 10% (FCC10) and 20% (FCC20). The study compares these measurements with the shear stresses found in concrete with normal density (NDC).

IV. METHODOLOGY

4.1. Main characteristics of the materials used

The materials used in the compositions of the concretes were: Portland cement type CPV ARI MAX, which presents a 28-day strength of 60 MPa [23]; density of 2.99g/cm^3 [24]; residue from marble and granite processing (RMGP) [25]; superplasticizer additive (SA) (polycarboxylate) with a specific mass between 1.067 to 1.107g/cm^3 and solids content between 28.5 to 31.5%, according to the manufacturer; air-entraining additive (IA) conventional/synthetic concentrated for foam generation, with a chemical base of sulfated ethoxylated fatty alcohol salt, with solids content of 5%, and density of 1.0 g/cm^3, according to the manufacturer; viscosity-modifying additive (VMA), with an apparent density of 0.4 g/cm^3. The fine natural aggregate (FNA) came from quartz sand with a specific mass of 2.45g/cm^3 and fineness modulus of 2.19. The coarse natural aggregate (CNA) of granitic origin with a specific mass of 2.64 g/cm^3 and maximum aggregate diameter of 9.6 mm.

4.2. Composition, production and molding of concrete

The compositions of normal-density concrete (NDC) and low-density foamed cellular concrete (FCC) are presented in Table 1, indicating the quantity of materials required for the production of 1 m^3 of concrete. The concretes were produced in the Laboratory of Structures and Materials (LEMA) at the Federal University of Alagoas (UFAL).

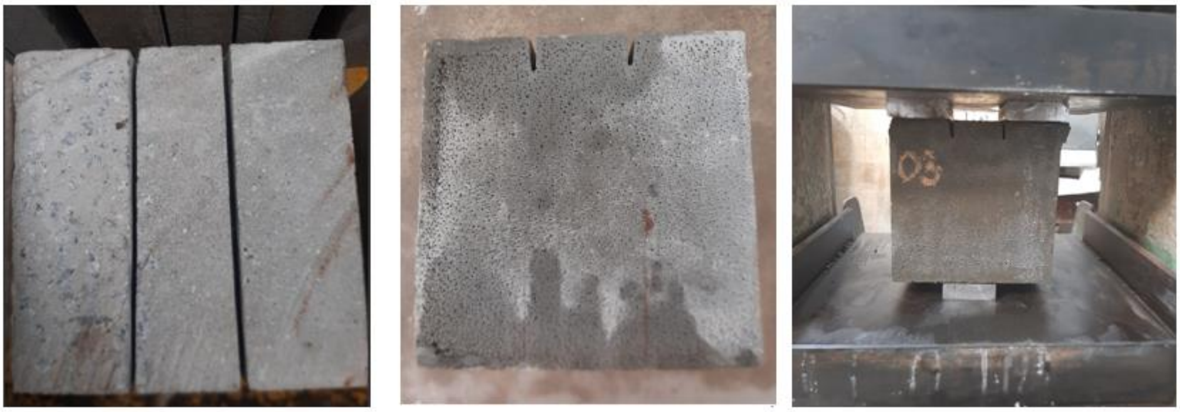
Table 1: Concrete composition (kg/m^3)

	Type of Concrete			
Materials	Unit	NDC	FCC10	FCC20
Cement	kg	409.30	673.41	598.41
RMGP		204.70	-	-
Water		184.20	256.29	225.1
SA		6.10	3.14	2.97
FNA		764.30	1009.71	897.2
CNA		764.30	-	-
VMA		-	4.52	9.04
Materials	%	-	10	20
Cement	-	0.45	0.38	0.38

The normal-density concrete (NDC), with a density ranging between 2000 kg/m^3 and 2800 kg/m^3, and the foamed cellular concretes (FCCs), with 10% foam (FCC10) and another with 20% foam (FCC20), have densities lower than 2000 kg/m^3 [3]. It is worth noting that, aiming to enhance result reliability, two productions of each concrete were carried out on two different days, using the same materials, proportions, and procedures. The first production is referred to as NDC 1^a; FCC10 1^a and FCC20 1^a, while the second is called a replica, denoted as NDC R; FCC10 R and FCC20 R. The production of NDC was done in a 120l capacity vertical axis concrete mixer, while FCC10 and FCC20 were produced using a 50l planetary mortar mixer. Prismatic specimens of 10 cm x 10 cm x 17cm and cubes of 10 cm x 10 cm x 10 cm [22].

4.3 Tests of the concrete in the hardened state

In the hardened state, the properties of specific mass [27], compressive strength [28], and pure shear stress [22] were determined, as shown in Figure 1. It is worth noting that a modification was made to the original test setup, as illustrated in Figures 4a and 4b. For each of the tests, three specimens (cp) were produced, totaling 27 specimens for each production, resulting in 54 specimens. All concretes were air-cured until the date of failure at 28 days. The equipment used for this test will be the Amsler press, which has a capacity of up to 200tf.



(a) (b) (c)

Figure 1: (a) Detail of the longitudinal notch, (b) depth of the notch, (c) positioning of the specimen for the test.

The modification made to the model proposed by [22] involved creating two notches on the specimens, each 15 cm in length (Figure 1-a), 0.4 cm in thickness (Figure 1-b), positioned at the top of the specimen to guide the failure to the other end (Figure 1-c). The calculation of shear stress was performed as follows:

τ: Shear stress (MPa);
F: Failure force provided by the machine in the shear test (N);
A= $150\,mm \times 135\,mm \times 2\ (mm^2)$

$$\tau = \frac{F}{A}\quad (MPa) \qquad \text{Equation (1)}$$

The original cross-sectional area would be 150 mm x 150 mm. However, in this study, it was 150 mm x 135 mm, where the loading was applied (top of the specimen).

4.4. Data processing

A statistical analysis using GraphPad Prism 5.01 software with one-way ANOVA and Tukey's multiple comparison test was applied to evaluate compressive strength and shear stress. Differences are considered significant when the p-value is less than 0.05, indicating that the results are statistically different, and for a p-value greater than or equal to 0.05, the results are statistically equal. Thus, to obtain the results, the mean values of three specimens from each test and their standard deviation were used.

V. RESULTS AND DISCUSSIONS

5.1. Specific Mass

The analyzed concretes exhibited specific mass with three distinct values (Figure 2): normal density concrete (NDC), with a value expected to be between 2.20 g/cm^3 and 2.40 g/cm^3, and the cellular concretes FCCE10 and FCCE20, which had densities lower than 2.00 g/cm^3 and are classified as lightweight concretes. The first three columns represent the values of the first production, and the last three columns represent its replica (Figure 1). The NDC recorded the highest densities, 2.38 kg/cm^3 and 2.37 kg/cm^3, respectively. In the lightweight concretes, it was observed that increasing the content of entrained air from 10% to 20% led to a decrease in density, evidenced in both the first production and the replica. The FCC10 varied from 1.72 kg/cm^3 to FCC20 of 1.49 kg/cm^3 in the first production and from 1.74 kg/cm3 to 1.53 kg/cm^3 in the replica. This represents a reduction of 14.36% in the first production and 12.06% in the replica. Furthermore, it was possible to observe that between the first production and the replica, all pairs of values were quite similar.

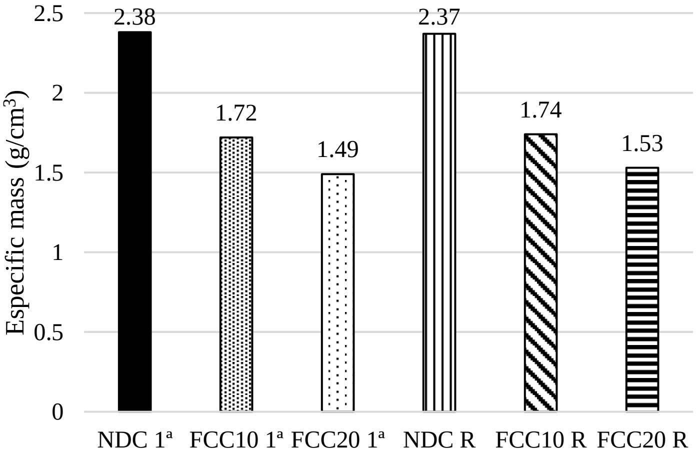


Figure 2: Average specific mass of concrete productions 1ª and Replica

5.2. Compression strength

The average compressive strength results are presented in Figure 3. For both the first production and the replica, three different levels of strengths were determined, with the NDC reaching the highest strengths of 47.08 MPa and 46.67 MPa, respectively. The cellular concretes FCC10 and FCC20, on the other hand, exhibited lower values of 26.05 MPa and 27.72 MPa for FCC10 and 18.22 MPa and 19.56 MPa for FCC20. The results indicate that increasing the addition of entrained air to the concrete results in a reduction in compressive strength.

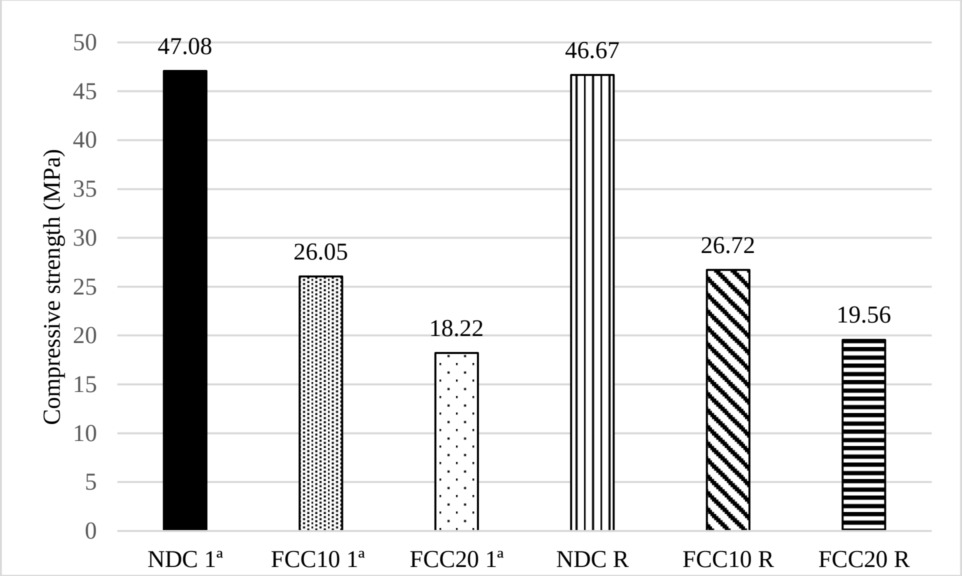


Figure 3: Average value of compression strength for the productions of the concretes 1ª x Replica

To validate the results, one-way analysis of variance (ANOVA) and Tukey's multiple comparison test, with 95% confidence, were used. It was possible to determine that the produced concretes and their replicas exhibit similar characteristics when compared to each other, namely: NDC 1ª and NDC R, FCC10 1ª and FCC10 R, and FCC20 1ª and FCC20 R. This implies that the production, molding, and curing procedures were consistent, leading to very close results between the two castings, thus strengthening the null hypothesis related to the applied treatment, as shown in Table 2.

Table 2: ANOVA with the results of the compression strength test (MPa) (n=3)

Concrete	1ª production	Replica
NDC	47.08 ± 0.93	46.67 ± 1.16
FCC10	26.05 ± 0.54	26.72 ± 1.51
FCC20	18.22 ± 0.44	19.56 ± 1.19
p-valor	> 0.05	> 0.05

5.3. Test Procedures

The pure shear test was conducted by modifying part of the methodology of the original test [22], as mentioned earlier. In Figure 4, the emergence of cracks can be observed precisely at the notch produced.

Figure 4: Failure exiting the notch.

5.4. Shear stress

From the analysis of the results obtained, it was possible to verify that the shear stress of the replicas of the individual concretes was similar to the results of the tests on the concretes from the 1st production, as shown in Table 3. Examining the graph in Figure 4, it can also be highlighted the decrease in shear strength with the incorporation of air in the concrete. In the NDC, without entrained air, the shear strength is higher than in lightweight concretes, and FCC20, the concrete with the highest content of entrained air, is the model with the lowest shear strength.

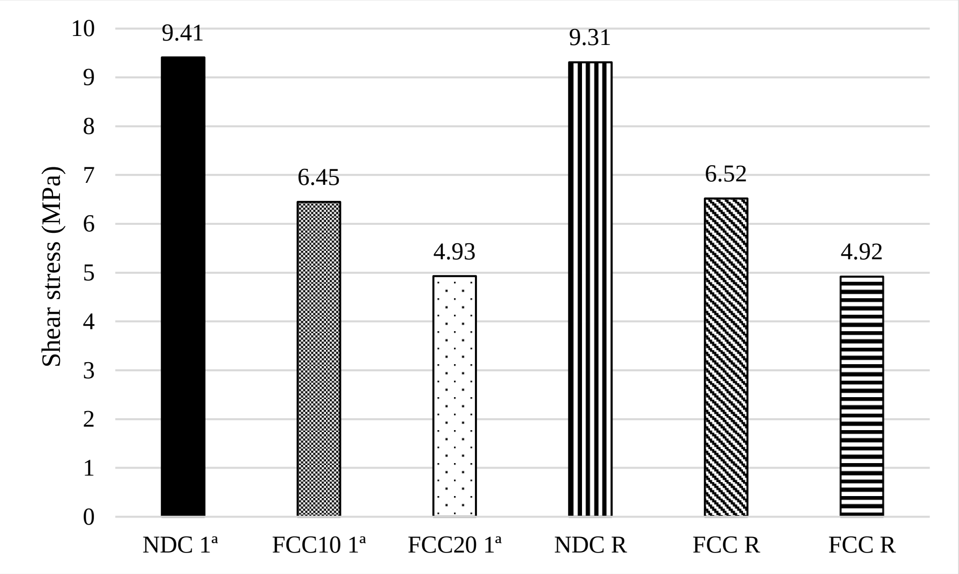


Figure 5: Average shear stress value of the 1st production vs. Replica

The average shear strength value of NDC was 9.41 MPa and 9.31 MPa for the 1st production and replica, respectively (Figure 5). The addition of 10% entrained air reduced the shear strength to 6.45 MPa and 6.52 MPa (1st production and replica, respectively), representing a reduction of 32%. In the last case analyzed, the 20% entrained air caused an even greater reduction in shear strength to 4.93 MPa and 4.92 MPa (1st production and replica, respectively), with a reduction of approximately 47%.
Analyzing only the results of the concretes with added entrained air, FCC10 vs. FCC20, it was observed that FCC20, which had 50% more foam compared to FCC10, however, the shear stress result did not occur in the same ratio, reducing only by 25% compared to FCC10.

Table 4: ANOVA table for the shear stress data (MPa) of the concretes (n = 3)

Concrete	1ª production	Replica
NDC	9.41 ± 0.23	9.31 ± 0.20
FCC10	6.45 ± 0.10	6.52 ± 0.55
FCC20	4.93 ± 0.06	4.92 ± 0.04
Summary of the analysis of variance		
F Value	664.60	
Treatment (between columns)	60.76	
Residual (within columns)	0.2194	
p - value	> 0.05	

The one-way analysis of variance (ANOVA) and post hoc Tukey's multiple comparison test, with 95% confidence, showed that the original concretes and their replicas are similar. This finding was obtained by comparing the produced pairs (NDC 1ª and NDC R), (FCC10 1ª and FCC10 R), and (FCC20 1ª and FCC20 R). These results indicate that the production, molding, and curing procedures were uniform, resulting in similar responses between the two sets of castings, confirming the null hypothesis of the treatment.

VI. CONCLUSIONS

This study addressed the evaluation of normal density concretes compared to cellular foamed concretes. The results reveal significant variations in the mechanical properties of the different types of concrete, emphasizing the importance of considering specific mass as an influential factor.

The concretes exhibited distinct specific masses, with NDC measuring 2.38 g/cm³, while FCC10 and FCC20 recorded considerably lower values, around 27% and 36% lower compared to NDC, respectively. This difference in specific mass values directly reflects on the materials' density, indicating a clear trend of decreasing density with the introduction of foam into the concrete matrix.

The compressive strength was notably affected by the variation in specific mass. NDC exhibited an average compressive strength close to 47 MPa, comparing the values with NDC, FCC10 and FCC20 showed 44% and 60%, respectively. This inverse correlation between specific mass and compressive strength suggests that the introduction of foam impacts the concrete's ability to withstand compression loads. However, when the analysis is done only between the two lightweight concretes FCC10 and FCC20, the difference is only 28%, demonstrating that the addition of 10% more foam in FCC20 had a lesser impact on reducing compressive strength.

Furthermore, the influence of specific mass was observed in shear stress. NDC exhibited a shear stress of 9.41 MPa, while FCC10 and FCC20 registered lower values around 31% and 47%, respectively, compared to NDC. This trend suggests that the presence of foam cells in the concrete not only affects compressive strength but also compromises the material's ability to withstand shear forces. Again, comparing only FCC10 and FCC20, the difference between them was only 23%, indicating a lesser impact on this property when compared to compressive strength.

Thus, it was possible to observe the impact caused on compressive strength and shear stress when reducing the specific mass of the concrete. While reducing specific mass may be desirable in certain applications, it is vital to consider the impacts on mechanical properties, such as compressive strength and shear stress.

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