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INFLUENCE OF BOUNDARY CONDITIONS IN RESPONSE TO THE AXIAL COMPRESSION OF A CEMENT COMPOSITE

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Abstract. *This study aims to evaluate the mechanical behavior of a cement composite subjected to axial compression with different boundary conditions. These boundary conditions change the interfacial friction characteristics between the specimens and the test machine plates. These configurations modifies the mechanical behavior to axial compression, including maximum strength, stress-strain ratio and fracture mode of the material. For this work, axial compression tests were performed on cubic specimens with 10 cm in length in a cement composite material. The tests were performed with three boundary conditions. In the first one, which represents the minimum friction, grease was used between the plates and the specimens. For the second boundary condition, the tests were performed in the traditional manner, ie, direct contact between the sample and the metal plates of the test machine. The third boundary condition, which represents the maximum friction, forms bonded steel sheets on the specimens. Among the main results it can be highlighted that when comparing the data obtained in the tests with maximum friction and the traditional form, did not present great differences. On the other hand, the data obtained with minimum friction show a considerable reduction in the composite stiffness.*

Keywords: *Axial compression, boundary conditions, friction, fracture mode.*

1. INTRODUCTION

In axial compression tests, it is common that the friction generated between the specimen and the test machine plates result in boundary conditions, which may directly influence in the obtained results. In the case of concrete composites, this friction acting on the contact surfaces is responsible of considerable modifications in the compression strength (final resistance), ductility and rupture mode, promoting results that do not represent the real properties of the material under compression (Van Mier et al., 1997).

When the specimen reaches the maximum compressive load, it is observed a decrease of resistance with the increase of the deformation. Macro-cracks appears after the peak of tension. It is expected that the development of these macro-cracks will be in a direction parallel to the load application, but they show a certain inclination, as well as a random distribution close to the contour regions (Vieira, 2008). According to Mattei et al. (2007) this behavior occurs due to the friction between the specimen tested and the test machine, which causes shear stresses that modify the maximum compressive resistance and the stress-strain curve. In Figure 1 it is possible to observe the rupture modes of specimens subjected to axial compression (a) with friction and (b) without friction.

The friction generated between the test machine plates and the specimen results in confining transverse compression stresses generate a state of triaxial stress. This causes a default failure mode, which resembles an hourglass shape. Erdei (1980), Shah et al. (1996), Van Mier et al. (1997), Zisopoulos et al. (2000) and Carpinteri et al. (2001) among others, state that by reducing interfacial friction with the use of some lubricant, a reduction in the final strength and ductility of the specimens occurs when compared to test specimens that have restriction. Therefore, based on these arguments, to produce uniaxial loading tests, the friction stresses due to interfacial friction must be considerably reduced (Van Geel, 1998).

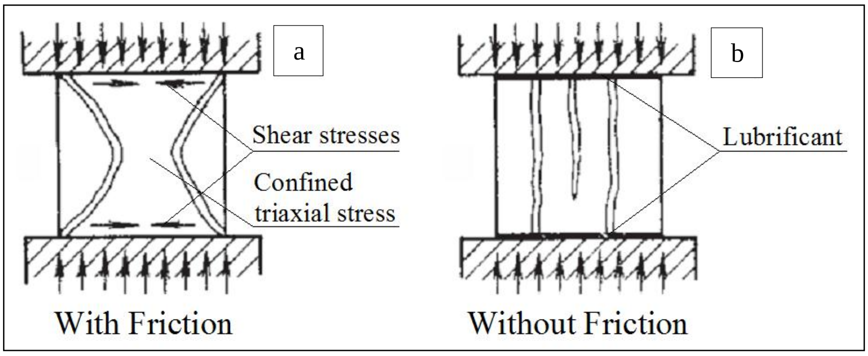


Figure 1. Failure mode of the sample according to the boundary conditions: (a) Test with friction; (b) Test without friction. (Adapted from Baykov e Sigalov 1983)

For reducing these interfacial tensions, compression apparatuses known as brush platens were developed by authors such as Kotsovos (1983), Van Mier (1986), Torrenti and Djebri (1995), Sagong et al. (2013), Tung and Tue (2015), Christiansen et al. (2016), Foltz et al. (2017) and Xu et al. (2017). However, even if friction reduction is sought in the execution of the tests, there has not yet been a consensus of the authors as to the best method to apply and what it can mechanically imply in a solid element.

According to Kumar et al. (2016) the investigations carried out on the influence of machine plate restraint are more concentrated on the compressive stress-strain behavior in biaxial and triaxial compression tests, highlighting the need for more work focused on uniaxial compression. The author developed his study using different means of reduction of friction, determining among these that the use of grease was the most efficient. It also concludes that the grease influences only the post-peak stress strain behavior, without modifying the final strength or modulus of elasticity.

The Kumar study was based on tests of cylindrical specimens with a height/diameter ratio (h/d) equal to two, but according to Van Mier et al. (1997) and Xu et al. (2017) the influence of machine plate restraints depends on the specimen aspect ratio (Fig. 2 (a)) in conjunction with the coefficient of friction imposed in the execution of the test (Fig. 2 (b)). Therefore, it is interesting to also use grease as a means of smoothing the friction in other geometries, such as cubic specimens, which represent a more marked confinement. Thus, it can be verified that the use of grease is actually the most efficient way to ease the confinfigement effect in uniaxial compression tests.

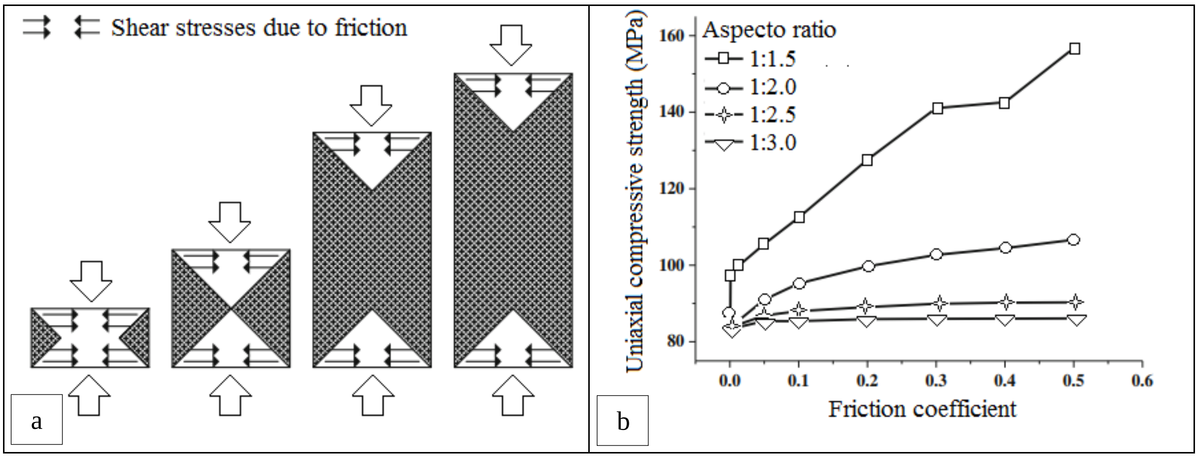


Figure 2. (a) Containment zones due to the friction restriction effect in the axial compression test (Adapted from Van Vliet and Van Mier 1996); (b) Relationship between uniaxial compressive strength and friction coefficients under different aspect ratios (Adapted from Gao et al. 2018)

Based on what was addressed, this work aims to analyze the influence of the boundary condition on the response to the axial compression of a concrete composite. Three boundary conditions were studied. The first one, which represents the minimum friction, grease was used between the plates and the specimens. For the second boundary condition, the tests were performed with traditional surface (reference), ie, direct contact between the sample and the metal plates of the test machine. The third boundary condition, which represents the maximum friction, forms bonded steel sheets on the specimens. The properties to be analyzed according to each boundary condition are the compression strength (maximum resistance), as well as stiffness and fracture mode.

2. METHODOLOGY

For current study, a cement composite with characteristic resistance equivalent to 50 MPa was used, the proportions of the materials constituting this material are: 43% course aggregate, 14% sand type 1, 17% sand type 2, 18% cement, 0.24% superplasticizer and 8% (water / cement ratio 0.44). The cement is from CP-V ARI. The course aggregate has a maximum aggregate diameter of 12.7 mm. The granulometry of the sands can be considered average, with its characteristic diameters and granulometry modulus respectively of 0.425 mm and 1.16 for sand 1 and 0.6 mm and 1.38 for sand 2. The superplasticizer additive (MC-PowerFlow, a company MC-BAUCHEMIE) has a density of 1.05 g/cm.

Cubic samples (10x10x10cm) were molded by means of NBR 5738 (ABNT, 2015), according Fig. 3 (a). After 28 days, before being submitted to the axial compression test, the specimens were rectified in order to regularize the surface of the composite in contact with the plates of the test machine, as shown in Fig. 3 (b).

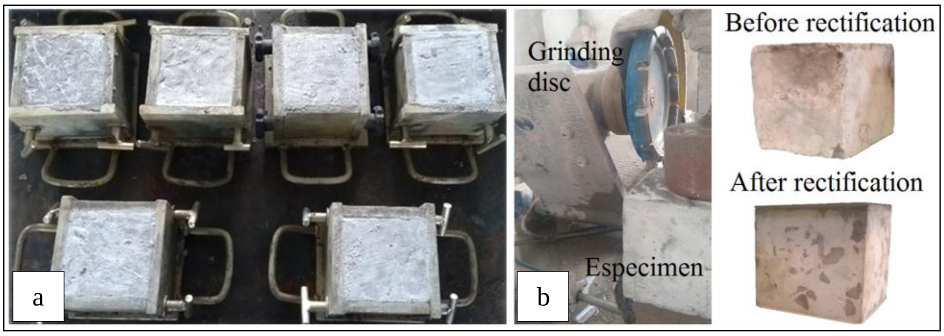


Figure 3. (a) Steel shapes for cubic specimens and (b) Rectification of specimens

The first boundary condition was designed to simulate a minimum friction, which is obtained by applying grease to the surfaces of the specimen in contact with the machine, minimizing friction between the materials during the test. The second boundary condition used was a traditional test, that is, no modification was made to the contact surface between the composite and test machine, providing a usual friction. The third boundary condition was based on the principle of achieving maximum friction, for which metal sheets were glued on both sides of the test piece in contact with the test equipment. The Figure 4 shows the boundary conditions used to perform the axial compression test.

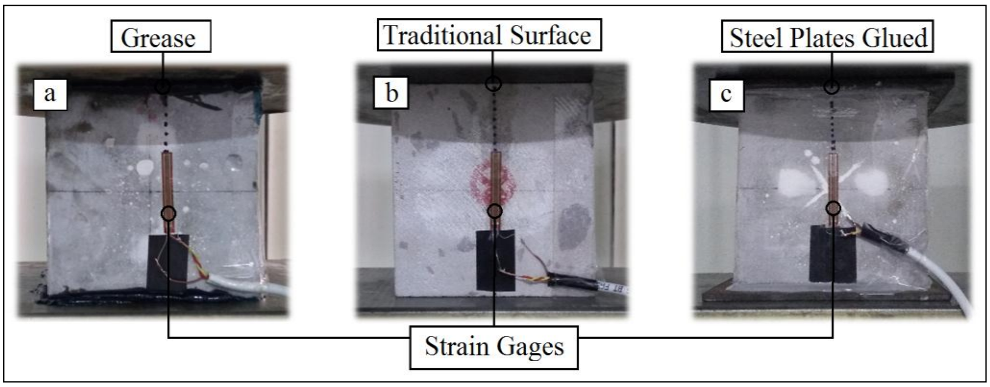


Figure 4. Test bodies: (a) minimum friction condition - grease; (b) traditional condition; (c) maximum friction condition - bonded metal sheets

The cubic solid composites were tested based on NBR 5739 (ABNT, 1994) through the INSTRON brand hydraulic press, SATEC series, model 5590-HVL, with a capacity of 1500 kN at a displacement rate of 0.05 mm/min. Thus, in order to determine the deformation that occurred in the material during loading, use was made of electric resistance strain gages, which consisted of the bonding of a sheet-like strain gage near the central region of the specimen for the three conditions of contour shown, it is possible to analyze the compressive stress-strain behavior of the concrete.

3. RESULTS AND DISCUSSION

3.1 Mechanical properties

Figure 5 present the compressive stress-strain curve for the three boundary conditions analyzed. These curves describe the characteristic behavior for the concrete composites tested under axial compression, the influence of the friction between the specimen and the test machine can be verified also through Fig. 1. It should be noted that the maximum stress of the specimens is a correction of damaged surface cracks in strain gages preventing them from being captured as post-peak deformations.

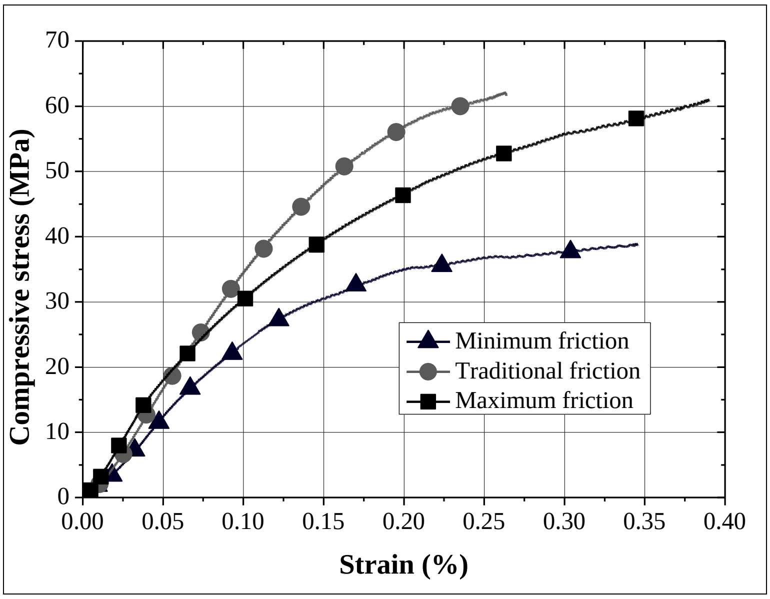


Figure 5. Compressive stress-strain curve for the three boundary conditions analyzed

Due to the inability to read the post-peak deformations, it is not possible to analyze the compressive stress-strain behavior after the maximum resistance of the specimens, so an important data is lost to compare with other authors. In Figure 6 the way the strain gages were damaged during the compression test is demonstrated.

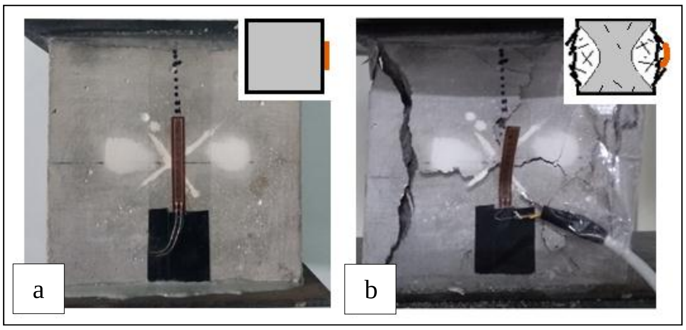


Figure 6. Interrupted strain gage reading after maximum specimen resistance: a) before applying the load, b) After reaching the peak resistance

Kumar et al. (2016) verified that the contour condition provoked by the use of grease modifies only the compressive stresss-train behavior after the resistance peak. As already discussed, this study did not verify this behavior, but it is clear that the typical curves for each boundary condition demonstrate that the rigidity of the material is also influenced as well as the final resistance. Thus, the present work complements other studies related to properties such as stiffness and strength, stating through tests that according to the imposed contour condition, mechanical properties of extreme importance for a structure can be modified.

Analyzing Figure 5, the composite sample tested for minimum friction has the smallest angle of inclination in the elastic regime. The Young's modulus of the material was around to 24 GPa. The axial compression strength is 40 MPa in this case. The sample submitted to traditional conditions present a Yong's modulus of 32 GPa, 25% bigger than the frictionless boundary condition. The axial compression strength found in the traditional test was

63MPa, 35% bigger than the first analyzed condition. This can be explained by the concentration of axial stresses due to the friction between the composite and the machine plates, which is practically zero with the use of grease.

In the maximum friction condition, the found Young’s modulus was 34 GPa, a similar value respect to the reference. 64 MPa of compression strength was found for this boundary condition. This maximum resistance is very close to the traditional test as well. Furthermore, no significant difference between the glued and traditional conditions were found at the peak stress and Young’s modulus.

This way, connected to the mechanical properties, from this study it is possible to verify that according to the modification of the contour condition imposed in an axial compression test the resistance can vary by approximately 1/3 depending on the friction imposed during the test. It is therefore of importance to tighten the norms in relation to the execution of the test, since in the practical scope of the execution of structures, the axial compression test is of utmost importance to verify if the strength of the concrete used in construction is equivalent to that used in design of structure. If the laboratory verification test is influenced by the imposed contour conditions, an imprecise result of the final concrete strength can be obtained, which can compromise the structure in execution without the knowledge of the technical personnel, a fatal error. Therefore, more studies that address this theme should be developed.

3.2 Failure mode

In Figure 7 the characteristic failure mode presented by the composite can be observed by varying the boundary conditions for the axial compression test.

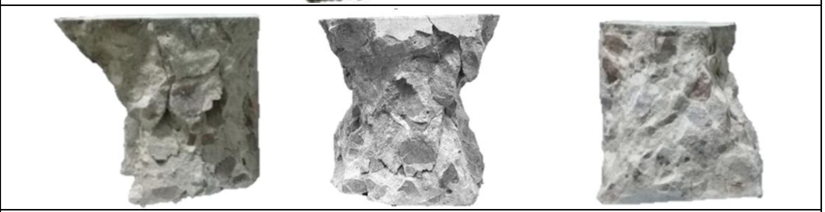
Minimum Friction (grease)	
Intermediate Friction (reference)	
Maximum Friction (glue)	

Figure 7. The characteristic failure mode according to each boundary condition: (a) test using grease, (b) with a traditional surface and (c) with steel sheets glued

Analyzing the rupture form of the specimens, it becomes apparent that for traditional confinement tensile tension occurs, which causes an hourglass-shaped rupture mode. However, by minimizing friction, there is a greater stress distribution in the composite, promoting multiple cracks and greater deformation in the composite.

In addition, from the rupture mode verified for condition of maximum friction, it is noticed that the hourglass format is predominant. Comparing the reference test to that one of maximum friction, it is observed that the rupture mode tends to approximate that verified when imposed at maximum friction, in some tests until reaching the apparent conical trunk shape. Therefore, confinement was present in both traditional and high-friction tests, which leads us to observe that in the usual tests of axial compression, the obtained resistance is actually a triaxial effort, which according to Carpinteri et al. (2001) is considerably larger than the uniaxial stress, thus raising the load of the specimens tested.

The norm NBR 5739 (ABNT, 1994) defines the methodology that the axial compression tests of concrete cylindrical specimens should follow, but it is not mentioned the fact of the possible influence of the restriction in tests of axial compression, nevertheless are exposed modes of rupture that the specimens may present in this type of test and their respective nomenclatures, as shown in Fig. 8.

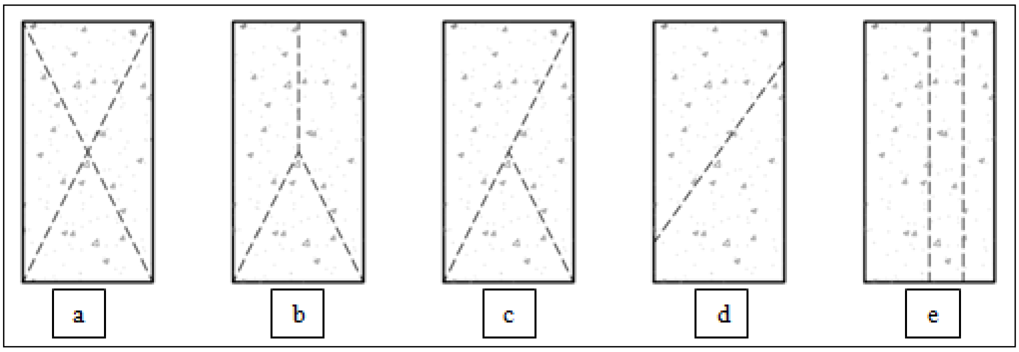


Figure 8. Modes of rupture: (a) Conic, (b) Conic and bipartite, (c) Conic and shear, (d) Shear, (e) Columnar (Adapted from NBR 5739 (ABNT, 1994))

As can be seen in Fig. 8, if different forms of rupture occur, it is because in fact the specimens tested do not break for the same reasons and circumstances. Figure 8 (a) shows a rupture mode with vertical cracks along the entire sample. Figure 8 (e) shows a rupture mode with vertical cracks along the entire sample, in the case of a columnar fracture that is strongly identified with the mode of rupture of the specimens with reduced friction with grease. Therefore, the NBR 5739 (ABNT, 1994) norm should deal more clearly and specifically with respect to the test environment, especially as regards the friction presented by the test machine plates, how this can be minimized and how it can affect the reliability of the test results.

Even if the norm deals with cylindrical specimens with h/d = 2 ratio commonly used in laboratory tests, which suffer less from the restriction due to their slenderness, yet according to Fig. 9, the compressive strength is affected by the factor friction.

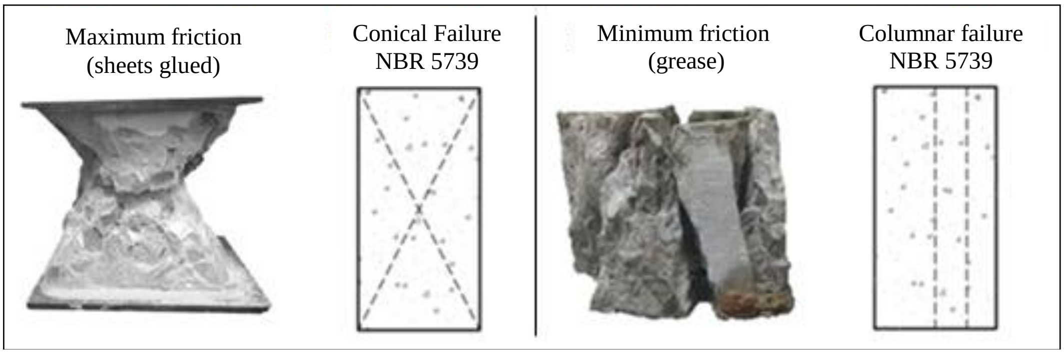


Figure 9. Comparison between experimentally found rupture modes with those presented in the norm NBR 5739 (ABNT, 1994)

4. CONCLUSIONS

The performance of this work allowed to evaluate, through a solid concrete composite, that according to the boundary condition imposed in an axial compression test, mechanical properties such as maximum strength and stiffness can vary considerably, which reveals the influence of interfacial friction between test material and the plates of the compression test machine.

Among the results, it may be outlined that for tests with grease use, a reduction of 25% in the Young's modulus was observed in relation to the reference test, as well as a reduction of 35% in the compressive strength. When comparing the test with the use of steel sheets glued to the reference, a Young's modulus and resistance was obtained very close to that one of reference. However, this one presented greater ductility after the beginning of the plastic regime. Comparing the tests with the use of grease and steel sheets glued, it was verified that when the friction was maximized, the resistance increased by around 37%, just as the Young's modulus rises 30% higher than the specimen with minimum friction.

Regarding the fracture mode, it was observed that when the friction is minimized, the cracks occur vertically and there is an expressive deformation of the material. Thus, when there was friction, a confinement of triaxial tensions was generated which caused the characteristic failure mode in hourglass format. Therefore, the rupture mode becomes a simple way of analyzing the tensions that led the material to disrupt, being able to verify if there was influence of the plates of the machine in the surfaces of contact. In addition, it is worth mentioning that the norm that governs the axial compression tests, NBR 5739 (ABNT, 1994) presents different rupture modes, being a same test, making it important to review these concepts.

Based on these results, more focus should be given to studies on laboratory test procedures, such as the case of axial compression, since the environment in which they are performed can significantly influence the final results. This fact harms not only the academic sector, in relation to research on the mechanical behavior of materials, but also in the practical field of engineering, since axial compression tests are usually performed to check if what is being carried out on site is compatible with the project carried out by a professional.

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