Compression Performance of Walls of Interlocking Bricks made of Iron Ore By-Products and Cement

Carrasco, E. V. M., Mantilla, J. N. R., Espósito, T., Moreira, L. E.

Abstract — This study deals with technical evaluation of the performance of walls constructed with interlocking bricks of iron ore by-products and cement under simple compressive loading. Three walls with dimensions of 150 cm width, 240 cm height and 15 cm thickness were built and tested. Testing was carried out according to the specifications of Brazilian standards. The first fissures arose with a stress of 0.56 MPa, corresponding to only 3.8% of the rupture stress of the brick alone. Horizontal displacement was negligible in all the walls and buckling was not observed. Rupture of the walls was through crushing; microfissures appeared first and evolved into fissures and then transformation into cracks. After generalized occurrence of cracks, rupture occurred. This behavior was similar to that of the bricks. Compressive load tests were also performed to determine the strength of the brick, of the prism (two overlaid bricks) and of the mortar. Results showed high compressive strength of 14.57 MPa for bricks, 9.82 MPa of the prisms and 25.2 MPa of the mortar. The walls showed good mechanical strength of 2.05 MPa, which represents 14% of the brick strength. Deformations were high, with axial deformation modulus of 420 MPa, which indicates a flexible behavior of the wall. Although the wall is flexible, the fissuration stress is relatively high, indicating excellent performance of the wall. Another very positive aspect is that this stress is only 13.6 % of the compressive strength of the wall and 1.9% of the brick, which indicates that there is a very large strength reserve.

Index Term — Wall performance; interlocking bricks; iron ore by-products.

I. INTRODUCTION

Great demand in the civil construction materials industry, and especially the need for utilizing ecologically correct material, is obliging designers and builders to use non-conventional materials. Production of conventional civil construction materials, such as cement, bricks and steel, consumes a great deal of energy and pollutes the air, water and soil [1]. A great deal of research is being developed throughout the world using solid residues generated by industry and by domestic and agricultural activities [2, 3]. Nevertheless, for solid residues from coal combustion and for aluminum, iron, copper and zinc tailings, few studies have been developed [4]. Research into these types of materials requires a great deal of time and effort when considering studies starting from the raw material, the tailings, the building component, the brick and, finally, the wall [5]. In the context of the present study, the raw material is the tailings of the iron ore mining process, a material of fine and coarse particle size. Stabilization was made with 10% cement. The brick design was conceived so as to allow an interlocking pattern and eliminate laying mortar. Building processes thus become cleaner and more efficient [6].

In regard to tests for determining the load capacity of a wall made with non-conventional materials, procedures developed for concrete block and ceramic brick testing are used. However, the suitability of these procedures has not been verified by scientific studies [7]. Contrary to other units of masonry, there is no consensus on the brick or block compressive load testing procedures for non-conventional materials. In this respect, some questions arise. For example, should wet or dry blocks be tested? How should three dimensional effects be considered in relation to form? How surrounding conditions should be evaluated in testing? [5]. The capacity of a wall under compressive loading is closely related to the compressive strength of the masonry units (stone, brick or block), as well as the strength of the laying mortar and type of interconnection of the units. Although other parameters also affect the load capacity of the wall (density, water absorption), compressive strength has become the standard, and it is a universal unit of measurement accepted for specifying the quality of masonry units [5].

This article analyzes the performance of walls made with interlocking bricks of iron ore tailings stabilized with cement. The standardized testing procedures for mortar and concrete blocks [8-10] and for masonry walls [11] were used.
II. MATERIALS AND METHODS

A. Materials

Bricks were made of a material consisting of a mixture of iron ore tailings with cement and water, and then compressed. A description of the materials and making of the bricks is provided below.

The tailings derived from iron ore were made uniform for undertaking all the characterization and strength tests. Results of particle size analysis allow classification of tailings as coarse, with percentages of 44% sand and 54% silt, and fine, with 14% sand and 79% silt, simply for differentiation.

In soil-cement mixtures, the proportions of the fine and coarse fractions affect the strength characteristics and the properties of the brick made from the material, and it is known that soils with a greater percentage of sand in their composition usually lead to greater strength in the soil-cement composition (Silva, 2005). Thus, after various mixtures of different proportions of coarse and fine tailings, that which represented the best mixture in terms of particle size was defined, 75% of coarse tailings and 25% of fine tailings. To stabilize the tailings mixture, Portland cement - CP V - HES (High Early Strength) was used, at 10% cement content.

The load calculated to be applied in brick pressing for the cement CP V – HES was 400 kN.

The mixture of components and uniformity in making bricks is of great importance; in this respect, the sequence adopted was initially mixing the tailings, then the cement and, finally, little by little, the water in a mortar mixer. The mixture was then placed in the mold for application of load by a hydraulic press manufactured especially for this purpose and, finally, at the end of the process, the brick was extracted for curing.

It should be highlighted that the configuration of the brick, Fig. 1, was conceived as an interlocking building system, without the need for grouting and laying mortar for the bricks, i.e., only through fitting the bricks together. Fig. 2 shows a sequence which illustrates this building system.

B. Test specimens

The iron-ore-tailings brick wall (P) with dimensions of 150 cm width x 240 cm height and 15 cm thickness was defined as a test specimen. For compressive load tests, three walls were built with 35 courses of bricks, with two orifices at each end filled with mortar made from the tailings and cement materials themselves. Fig. 3 gives an overview of the wall building sequence.

The test specimens (TSs) for determination of strength by means of compressive load tests: the brick, the prism which consists of two overlaid bricks and the mortar are shown in Fig. 4.

C. Equipment for load application and preparation for wall testing

The loads transmitted to the walls were applied by a hydraulic jack attached to a test frame. The hydraulic jack,
with 1,500 kN capacity, has flow and return lines such that piston movement may be made in two directions. Fig. 5 provides a view of the test frame and the jack used.

![Fig. 5. View of the test frame, load application system and hydraulic jack.](image)

The values corresponding to the loads applied were measured by a load cell with 500 kN capacity, coupled to an activation pump for the piston of the hydraulic jack. This load cell was calibrated on a Universal Testing Machine, which, for its part, was calibrated in a laboratory accredited by INMETRO.

The walls were set up on the reaction slab of the Experimental Structural Analysis Laboratory. The entire construction process of the walls, including the dose of filling mortar, was controlled. After curing of the mortar (7 days), preparation and instrumentation of the walls began. A welded frame and a rubberized asphalt sheet were placed between the piston of the hydraulic jack and the top of the wall so as to uniformly distribute the forces on the upper surface of the wall. Front and side shields were placed in the test frame, consisting of angle irons and a metallic screen, to keep the wall from falling due to instability during the test or when its failure occurred. These shields were fastened to the test floor. (Fig. 6)

![Fig. 6. Detail of the protective shields of the walls.](image)

D. Equipment for measuring vertical displacement

For determination of longitudinal displacements of the walls, displacement transducers were used (DTs), placed parallel to the direction of the load and lateral to the wall, as shown in Fig. 7. That way, any tendency of shortening of the walls in the direction of the load would be registered. The reason for use of two DTs was to check whether there would be any differential in shortening between the two lateral faces of the wall. The DTs used were Kyowa brand, type DT 100A, model BA6872 and BA6875, 100 mm stroke and sensitivity of 0.01 mm.

![Fig. 7. Detail of wall testing: displacement transducer used for determination of vertical displacement.](image)

E. Equipment for measurement of horizontal displacements

For determination of horizontal displacements, a DT was used, placed in a perpendicular manner to the direction of the load and at 5/6 wall height [11], as shown in Fig. 8. That way, any tendency of bending and/or instability of the wall in the direction orthogonal to that of loading could be registered. The DT used was Kyowa brand, type DT 50A, model BA5687, 50 mm stroke and sensitivity of 0.01 mm.

![Fig. 8. Detail of wall test: displacement transducer (DT) used for determination of horizontal displacement.](image)

The Data Acquisition System (DAS) consists of a signal conditioner board which amplifies and conditions the signal, an A/D (analog/digital) conversion board, and control board which contains multiplexer and 16 channels, with their respective signal conditioners. The entire system is connected to a computer. The DTs and the load cell were each connected to a channel. The information collected can be obtained with very high frequency. In the test performed, a reading frequency of 10 Hz was used, i.e., 10 readings per second. The complete system is shown in Fig. 9.

![Fig. 9. The complete system is shown in this figure.](image)
F. Test for determination of compressive strength of the bricks and prisms

For determination of compressive strength of the bricks and prisms a sample was selected which consisted of seven bricks and six prisms. As for the filling mortar used in constructing the walls, cylindrical TSs was fashioned. The bricks, prisms and TSs were tested in the Wood and New Material Mechanical Characterization Laboratory (CPAM) in a hydraulic press controlled by hydraulic servo, EMIC brand, with 2,000 kN capacity. All the tests were performed according to standard requirements [8-10]. Fig. 10 shows details of testing, and a brick and a prism after rupture.

G. Tests for determination of wall load capacity

The walls were tested after complete curing of the filling mortar of the orifices (12 days). The load applied on each wall was performed in three cycles (loading and unloading), the first and the second up to 50% of predicted load, and the third up to failure. Load application was controlled in such a way that the force applied, calculated in relation to gross area, rose progressively at the rate of 0.25 N/cm²/s. The walls were loaded in a continuous manner; the measurements of loads, vertical displacements and horizontal displacements were registered by the DAS. When the load in the second cycle reached 180 kN, the pieces of equipment for reading horizontal displacements were removed to avoid damage to them, and then load application was continued until the wall reached the point of failure. In Fig. 11, failure of the wall W1 is shown, and details of the appearance of the first fissures in the bricks.

III. RESULTS AND DISCUSSION

A. For the compressive load tests of bricks, prisms and mortar

The results of the compressive load tests, the compressive strength of the TSs of the bricks, prisms and the mortar, are shown in Table I. The modes of rupture observed were crushing for the brick, and crushing at the brick interface for the prism.

<table>
<thead>
<tr>
<th>TS</th>
<th>Brick</th>
<th>Prism</th>
<th>Mortar</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>15.13</td>
<td>10.52</td>
<td>24.32</td>
</tr>
<tr>
<td>02</td>
<td>15.84</td>
<td>10.77</td>
<td>25.03</td>
</tr>
<tr>
<td>03</td>
<td>12.08</td>
<td>9.81</td>
<td>26.07</td>
</tr>
<tr>
<td>04</td>
<td>13.53</td>
<td>10.57</td>
<td>24.29</td>
</tr>
<tr>
<td>05</td>
<td>12.15</td>
<td>9.91</td>
<td>26.05</td>
</tr>
<tr>
<td>06</td>
<td>16.40</td>
<td>7.31</td>
<td>---</td>
</tr>
<tr>
<td>07</td>
<td>16.86</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Mean</td>
<td>14.57</td>
<td>9.82</td>
<td>25.15</td>
</tr>
<tr>
<td>S.D.</td>
<td>1.99</td>
<td>1.29</td>
<td>0.88</td>
</tr>
<tr>
<td>C.V.</td>
<td>13.6%</td>
<td>13.1%</td>
<td>3.5%</td>
</tr>
</tbody>
</table>

Key: S.D. = Standard deviation and C.V. = coefficient of variation.

Upon analyzing the values of Table I, it may be seen that the bricks show high compressive strength, on average 14.57 MPa, with a relatively small coefficient of variation, 13.6%, for the number of test specimens analyzed. All the bricks failed in the same manner, through crushing. In other words, under both aspects analyzed, compressive strength and manner of rupture, there is regularity in the results, which is always a positive factor. The prisms likewise exhibited high compressive strength, 9.82 MPa, with a relatively low coefficient of variation, 13.1%, although with a high loss of strength of 33% in relation to the brick alone. The prisms also failed through crushing, however, at the brick interface. The mortar had high mean mechanical resistance of 25.15 MPa and a coefficient of variation of only 3.5%.

B. For compressive load tests of the walls

In Fig. 12, the graphs of load x vertical displacement (DT-1 and DT-2) and of horizontal displacement of wall W1 are presented as examples. Note that the horizontal DT curve ends at the load of 320 kN, for the DT was removed at that time to keep it from being damaged. The stress x deformation graph of each one of the walls is presented in Fig 13.
In table 2 are shown the failure of the wall, rupture load, rupture stress and the stress at which the first fissure appears, for each wall.

<table>
<thead>
<tr>
<th>Wall</th>
<th>Failure of the wall</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Rupture load = 400.24 kN</td>
<td>The beginning of fissuration occurred with a load near 100 kN, at the 5th upper right course. Subsequent fissures appeared after the application of a load of 200 kN. The fissures on the lateral parts of the wall arose with a load of 260 kN. The failure of the wall was not explosive nor fragile.</td>
</tr>
<tr>
<td></td>
<td>Rupture stress = 2.22 MPa.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Stress of the first fissure = 0.57 MPa.</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Rupture load = 345.75 kN</td>
<td>The beginning of fissuration occurred with a load near 100 kN, at the 1st upper course at the center part of the wall. Subsequent fissures appeared after the application of a load of 210 kN. Fissures on the lateral parts of the wall appeared with a load of 240 kN. The failure of the wall was not explosive nor fragile.</td>
</tr>
<tr>
<td></td>
<td>Rupture stress = 1.92 MPa.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Stress of the first fissure = 0.54 MPa.</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Rupture load = 362.68 kN</td>
<td>The beginning of fissuration occurred with a load near 100 kN, at the 12th upper course at the center part of the wall. Subsequent fissures appeared after the application of a load of 180 kN. Fissures on the lateral parts of the wall appeared with a load of 230 kN. The failure of the wall was not explosive nor fragile.</td>
</tr>
<tr>
<td></td>
<td>Rupture stress = 2.01 MPa.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Stress of the first fissure = 0.56 MPa.</td>
<td></td>
</tr>
</tbody>
</table>

Mean Rupture load = 369.56 kN
Rupture stress = 2.05 MPa.
Stress of the first fissure = 0.56 MPa.

S.D. Rupture load = 27.88 kN
Rupture stress = 0.15 MPa.
Stress of the first fissure = 0.015 MPa.

C.V. Rupture load = 7.5%
Rupture stress = 7.5%.
Stress of the first fissure = 2.7%.

The values of table II show that the wall exhibits good mechanical strength, taking brick strength into account. Nevertheless, the loss of strength is considerable in relation to the brick alone. The strength limit of 2.05 MPa is only 14% of the brick strength. However, the results are also regular, indicated by the relatively low coefficient of variation of 7.6%. An even greater loss of strength occurs for the beginning of observation of visual damage – appearance of the first fissures, which corresponds to the mean stress of 0.56 MPa, with a low coefficient of variation of 2.7%. In other words, the first visual damages would appear for stresses that are only 3.8% of the rupture stress of the brick alone.

In Fig. 12, it may be observed that horizontal displacement was practically negligible and the failures occurred through crushing of the wall by widespread occurrence of cracks. In other words, microfissures opened up into fissures and finally into cracks. Thus, the wall had the same mode of failure as the bricks, once more exhibiting regularity in behavior. The fact that horizontal displacement is negligible in the collapse means that there was no buckling, a phenomenon which would lead to a progressive increase in horizontal displacement as load increased. This was not observed. Only wall 1 had a
displacement of 6 mm for a load of 25 kN, undoubtedly representing a lateral adjustment of the system. Soon afterwards there was no increase in lateral displacement with the increase in load. It remained a vertical straight line up to removal of the DT.

Dividing the total load by the area of the cross section of the wall of 150 cm x 15 cm, the actual compressive stress is obtained. In Fig. 13 it may be observed that the wall stress x deformation curves may be adjusted by straight lines in the initial segment, thus drawing near to Hooke’s law, a favorable factor in terms of analysis. For low stresses of 2.05 MPa, on average, at the rupture limit, relatively high deformations of 0.6% are seen. That means that the wall is flexible. The tangent of the angle of the straight line with the horizontal is called the axial deformation modulus, and shows the mean value of 420 MPa. Fired ceramic brick walls and concrete block walls exhibit axial deformability moduli of 1,170 MPa and 720 MPa, respectively.

In practice, materials should be below determined limit states, both for strength and for utilization. In this case, the stresses should not under any circumstances reach the value of 0.56 MPa because at that point visible damages would already appear, the first fissures. Normally, along with this value, a coefficient of safety is introduced. Supposing that this coefficient were 2, then, in practice, the walls could bear a load such that the maximum stress would be 0.28 MPa. Such a stress for the wall area tested corresponds to a load of 63 kN. Observing the load x displacement curves for this load, we would have shortening of the walls of less than 3 mm, a relatively low value, which is a favorable result. This load of 63 kN would correspond to a distributed load per linear meter of 4.2 kN/m. In other words, the dry blocks as they were tested would allow safe construction of two-story buildings, i.e., a ground floor and an upper floor with a roof.

A large load reserve would remain until rupture, which is one more favorable aspect. In other words, these walls, in not having shown fragile rupture or buckling, would provide warning that they were going to fail. If the load exceeded the fissuration limit, small fissures would arise and, from that point on, larger cracks would arise and so on in a consecutive manner until final collapse of the wall. Working with a stress of 0.28 MPa is only 13.6% of the rupture load of the wall and 1.9% of the rupture load of a brick.

C. Comparison of results of ceramic brick masonry walls and concrete block walls

In this item a comparison of the results obtained in compressive load tests on the interlocking brick walls with results of ceramic brick walls and with non-structural concrete blocks is presented [12]. In Fig. 14, 15 and 16, the graphs of stress x deformation, rupture stress and fissuration stress are presented, respectively, of these three types of walls.

It may be observed in Fig. 14 that the curves of the iron-ore-tailings brick walls have greater slope than the ceramic brick walls and concrete block walls. That indicates that they are more flexible, with a lower deformation modulus. In Fig. 15, it may be observed that the rupture stress of the iron-ore-tailings wall is greater than the concrete block walls and even more if compared to ceramic brick walls. In Fig. 16 it may also be observed that the fissuration stress of the iron-ore-tailings walls is greater than the ceramic brick walls and concrete block walls.

IV. Conclusions

The regularity of the results in terms of low coefficients of variation of the mechanical tests and of the modes of rupture,
of the bricks and of the wall as a whole, is a positive aspect of the behavior of the wall.

The bricks exhibited high mean compressive strength of 14.57 MPa, with a relatively low coefficient of variation, 13.6%, for the number of test specimens analyzed in a total of 7. All the bricks failed in the same manner, through crushing. Under both aspects analyzed, compressive strength and rupture mode, the results show regularity, which is a positive factor.

The two overlaid bricks, called a prism, likewise showed high compressive strength, a mean of 9.82 MPa, also with a relatively low coefficient of variation, 13.1%, although a loss of strength in the order of 33% was observed in relation to the brick alone. The prisms also failed through crushing, in the same manner as the bricks.

The wall exhibited good mechanical strength, in spite of its loss in relation to the brick alone being considerable. The stress limit was 2.05 MPa, on average, which represents 14% of the brick strength. The results are also regular, as indicated by the relatively low coefficient of variation of 7.6%. The fissuration stress was 0.56 MPa, corresponding to only 3.8% of the rupture stress of the brick alone.

In relation to vertical and horizontal wall displacements, it was observed that horizontal displacement was practically negligible in all of them. Taking vertical displacement into account, it may be concluded that the walls exhibit ductile and not fragile behavior, likewise a positive result from the structural point of view. In regard to wall deformation, it was observed that for the stress limit of 2.05 MPa, the mean of the three walls, there were relatively high deformations, of 0.6%. That means that the wall is flexible, with the mean axial deformation modulus of 420 MPa, relatively low, and less than that of ceramic bricks and concrete blocks.

A very positive aspect is that the calculated stress of 0.28 MPa is only 13.6% of the stress limit (2.05 MPa) of the wall and 1.9% of the mean compressive strength of the brick (14.57 MPa), i.e., there is a very large reserve in terms of strength.

Studies that may be conducted in this area are – in regard to the interlocking bricks, evaluate performance in a fire situation, combustibility and durability; in regard to the walls, and evaluate structural performance to impact loads, thermal and acoustic performance, water tightness and durability.

ACKNOWLEDGMENT
To the SAMARCO S.A. mining company for providing the tailings and for financial assistance.

LITERATURE REFERENCES


