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Novel Natural Bee Brick with a Low Energy Footprint for "Green" Masonry Walls: Mechanical Properties †

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Abstract: The present research delves into the experimental investigation of the mechanical properties of bee bricks, which serve as nesting habitats for solitary bees. The study aims to provide valuable insights into the efficacy of these bricks as eco-friendly alternatives emphasizing a low energy footprint. It is designed as a masonry unit to provide nest sites in urban or civil areas to order to protect and contribute to the reproduction of solitary (wild) bee pollinators. The invention concerns the solid structural and architectural material of masonry bricks, which have different sizes of cavities and constitute a natural habitat for various solitary bee species. It is an innovative material that can be used as a building material in both new constructions and existing masonry structures. At the same time, it can be used as a decorative material in gardens, nurseries, fields, the courtyards of houses, schools, and buildings in cities; it can even be used in "green" and sustainable buildings. To protect bees, it is necessary to address the threats mentioned above. The results indicate that the physical materials composed a high-performance product with a remarkable compressive strength of 12 MPa and 13 MPa in loading directions perpendicular and parallel to the bed joint, respectively. Simultaneously, despite the smooth surface, the bee brick presented respectable adhesive properties proving that this product is appropriate and can be proposed as a masonry unit for safe seismically designed structures. Furthermore, the direct shear results indicate that the low strength of the binder mortar as well as the bond strength of the masonry unit and the mortar play a significant role. Overall, this presents awareness about the reduction of biodiversity and, at the same time, a proposal of the dual use of the construction material for the construction of load-bearing masonry and a biotope needed for the reproduction and protection of pollinator bees.

Keywords: natural building material; bee brick; mechanical properties; green masonry walls; low energy footprint

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1. Introduction

It is worth noting that there exist more than 20,000 species of solitary bees globally beyond the well-known honey bee, with 1150 of these species inhabiting Greece. The main problem facing bees, as research has shown, is the dramatic decline in the solitary bee population in recent years due to disease. Saving bees is a priority for the protection of biodiversity and the well-being of our planet. To protect bees, it is necessary to address the threats mentioned above [1].

The review of the international literature outlines a minimal sample of research on brick bee hives [2]. Currently, available bee brick products are predominantly utilized for their decorative qualities and aesthetic value. Furthermore, the bee hives built so far contain a series of narrow openings where the solitary bees nest, so the holes are small, reducing the chances of larger solitary bee nesting. Furthermore, existing bee bricks have different sizes compared with ordinary bricks and, in addition, are made from concrete. This is also a disadvantage as concrete does not simulate the bee's natural environment. In addition, scientists are divided on the effectiveness of bee bricks, with some arguing that there are risks of attracting mites and increasing the spread of disease [3].

This innovative product is friendly to the environment and provides a natural ecosystem for developing and hatching solitary bees. These bricks have cavities (holes) that reach a depth smaller than the width of the brick and are of different sizes in diameter so that they can easily and safely form a nest for different types of solitary bees and allow them to reproduce. It is a natural brick consisting of the natural materials of lime and geo-mortar without cement. In this way, the bee's natural environment is simulated. In addition, the whole powdering and curing process is carried out without any heat treatment. This fact gives it the advantage of having as small a carbon footprint as possible during manufacturing, thus contributing to energy savings and, by extension, to protecting the environment.

An innovation of the bee bricks is the existence of microorganisms included in its composition. EMs consist of a wide variety of effective, beneficial, and non-pathogenic microorganisms that exist freely in nature, such as lactic acid bacteria, photosynthetic bacteria, various yeast species, and yeasts. When these microorganisms come into contact with organic material, they eliminate beneficial substances, such as vitamins, organic acids, mineral chemical compounds, and antioxidants, resulting in the creation of an environment in which microorganisms, through fermentation, contribute positively, excluding pathogens from the environment of the bee and activating the bee's reproductive process. To avoid the growth of pathogenic micro-organisms, the special provision of the design of the cylindrical axes of the cavities, with an upward slope from the entrance to their interior, is also recommended. The optical visibility of the slopes in question is limited as their incline remains below 10%. For this reason, to ensure the accurate installation of the brick, it is of utmost importance that a logo be visibly installed in the upper left corner of its face. Such a logo should indicate the upper and lower sides of the brick to maintain the correct placement of the holes with an upward incline. The construction of the cavities in this way helps to prevent the ingress of rainwater and moisture, which would allow the growth of harmful microorganisms and diseases.

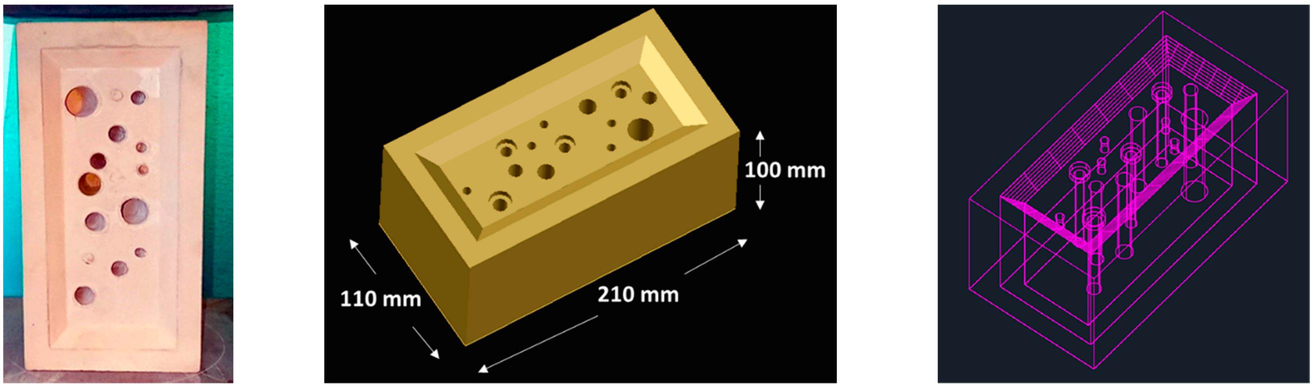
At the same time, the bee bricks are useful for educational purposes as they can be easily integrated into the educational process as an experiential activity. Simultaneously, they can be integrated as a structural material of the buildings or architecturally and decoratively integrated into the surrounding area of schools and/or other public institutions, effectively contributing to an awareness of the world to rescue solitary bees. The invention concerns a brick with holes as a structural and architectural-decorative material, constituting a natural habitat for attracting solitary (wild) bee pollinators. The bee brick has cavities of various sizes inside where the bees can lay their eggs and the eggs can hatch, then seal the unique entrance with mud. It is an innovative product that can be used as a construction material in new constructions made from load-bearing masonry and in existing constructions of buildings made from load-bearing masonry [4–8]. In particular, the masonry unit can be built or installed as a visible plinth on the exterior of structures. At the same time, it can be used as a decorative material in gardens, nurseries, fields, house yards, schools, and public buildings in cities, even in "green" and sustainable buildings [9]. The main goal is to save the different species of solitary bees, which are a vital part of the ecosystem as they contribute to the fertilization of plants through pollination.

2. Materials and Methods Section

All the materials of the bee bricks and binding mortars are environmentally friendly with natural antibacterial and antifungal properties that actively dilute pollutants. The bee brick is constructed from a fluid and breathable geo-mortar, which is a blend of natural NHL lime and geo-binder. This product has been certified to enhance the safety of buildings. A similarly composed material is the binding mortar produced by the same company, Kerakoll

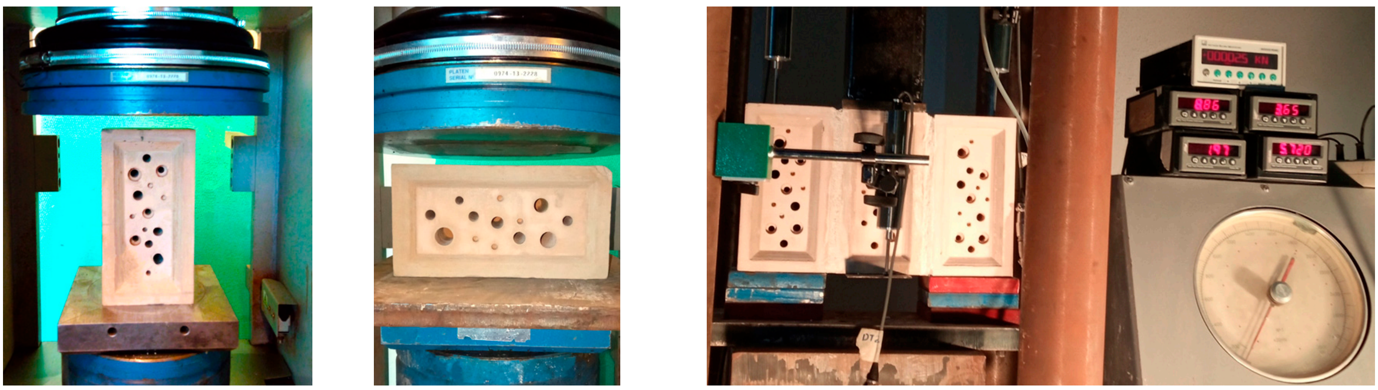
S.p.a. This is a type of geo-mortar that is finely crafted and breathable. It is made from pure natural NHL lime and geo-binder and has a resistance class of M15. This type of mortar is perfect for use on highly breathable masonry and concrete structures, making it ideal for green building and restoring monuments. The materials used in this mortar are all naturally derived and comprise recycled minerals, making them eco-friendly with low CO_2 and very low volatile organic compound emissions and a low energy footprint [9]. Additionally, a diverse group of microorganisms, including lactic acid bacteria, photosynthetic bacteria, various yeasts, and other non-harmful species found in nature, are added to the mortar mixture in liquid form after fermentation at a constant temperature for several days.

The mechanical strength of brick specimens that have undergone a 28-day ageing process was determined through compression and direct shear tests. These tests were conducted after the specimens had been cured at a relative humidity level of 95% and a temperature of 20 °C. The mix proportions used in this research were 3500 gr water, 110 gr mortar, 50 gr microorganisms, and 25 gr colour powder. The nominal dimensions of the bee bricks are 210 mm (length) × 100 mm (width) × 110 mm (height) (Figure 1). Uniaxial compression tests follow the European standard EN 772-1 (2000) [10]. Twelve solid blocks were tested, six in uniaxial compression vertically and six parallel to the horizontal joint. The compression tests were performed by applying a compressive load in an ELLE press machine, with a loading rate of 0.01 mm/s (Figure 2a,b). The compressive load was applied uniaxially and monotonically [7,8].



(**a**) (**b**) (**c**)

Figure 1. Bee brick (**a**) front view; (**b**) AutoCAD 3D-designed; (**c**) solid 3D-designed.



(**a**) (**b**) (**c**)

Figure 2. Experimental test setup of (**a**) compression test of solid brick with the loading direction perpendicular to bed joints; (**b**) compression test of solid brick with the loading direction parallel to bed joints; (**c**) direct shear test of brick triplet with Kerakoll binding mortar.

To investigate the properties of the brick interface and, in particular, the bond to the binder material proposed for use in the construction of load-bearing masonry, three triplet specimens consisting of three bee bricks and two mortar joints with a layer thickness of 10 mm were constructed and subjected to a direct shear test without lateral compression, as indicated by EN 1052-3 [11] specifications (Figure 2c). Triplet tests took place in an Avery Dennison servo-hydraulic press machine with a 3000 kN capacity and a loading rate of 0.01 mm/s.

3. Experimental Process

Six bricks were tested under compressive stress to fracture failure with the axial vertical load perpendicular to the bed joints. The results of these tests are presented in Table 1. In the first column are the codes of the brick specimens, with the letters B, C, and V from the initial letters of the words "Brick", "Compression", and "Vertical", respectively. In the second column are the volumes, V_{tot}, of the bricks removing only the indentation volume; in the third column are the percentage ratios of the holes' volumes, V_{holes}, to the total volumes, V_{tot}; and in the fourth column the values of the ultimate loads are stated. In the fifth column, the areas of the loaded surfaces, A, are shown, while the compressive strengths, σ, of the bricks are defined in the sixth column. The last row averages all the values in each column. The nominal average axial compressive strength of bee bricks appears to be about 12 MPa [7,8,12–14].

Table 1. Mechanical properties of bee bricks subjected to compression loading perpendicular to bed joints.

Vertical Bee Brick	V_{tot} mm^3	V_{holes}/V_{tot} %	Load N	A mm^2	σ (N/mm^2)
BCV_1	2160.000	3.38	123,700.00	10,560.00	11.71
BCV_2	2147.400	3.40	125,200.00	10,660.00	11.74
BCV_3	2145.300	3.40	113,500.00	10,650.00	10.66
BCV_4	2124.510	3.43	123,500.00	10,551.00	11.71
BCV_5	2099.100	3.47	140,300.00	10,430.00	13.45
BCV_6	2105.400	3.46	133,300.00	10,460.00	12.74
Average	2130.285	3.42	126,583.33	10,551.83	12.00

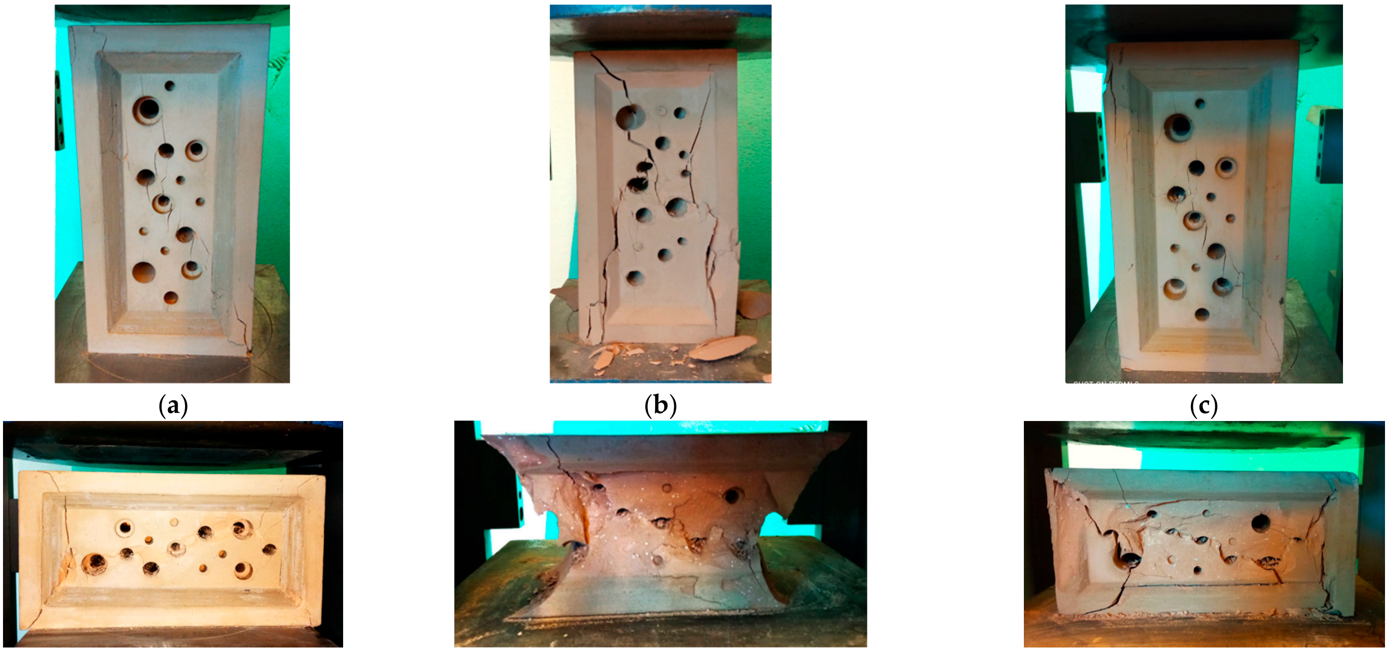
Additionally, six bricks were tested under compressive stress to fracture failure in the axial loading direction parallel to the bed joint. The test results are presented in Table 2. In the first column are the codes of the plinths, with the letters B, C, and L from the initial letters of the words "Brick", "Compression", and "Lateral", respectively. The last row averages all the values in each column. The nominal average axial compressive strength of bricks with vertical holes appears to be about 13 MPa [7,8,12–14]. It is worth noting that both compressive strength values exceed 5 MPa, thereby rendering them suitable for use in earthquake-resistant constructions as per the guidelines outlined in EC6 [15].

Table 2. Mechanical properties of bee bricks subjected to compression loading parallel to bed joints.

Lateral Bee Brick	Volume mm^3	V_{holes}/V_{tot} %	Load N	Area mm^2	σ (N/mm^2)
BCL_1	2157.400	3.38	261,600.00	20,660.00	12.66
BCL_2	2145.300	3.40	255,600.00	20,550.00	12.44
BCL_3	2168.400	3.36	269,400.00	20,760.00	12.98
BCL_4	2162.900	3.37	273,200.00	20,710.00	13.19
BCL_5	2156.850	3.38	276,400.00	20,655.00	13.38
BCL_6	2145.300	3.40	273,900.00	20,550.00	13.33
Average	2156.025	3.38	268,350.00	20,647.50	13.00

4. Evaluation of Results

From the compressive test results, it is evident that the novel product provides significant mechanical strength. The characteristic failure modes of the solid bricks during the compression test are shown in Figure 3. Particularly, in Figure 3a–c the failure modes of the vertical specimen with loading direction parallel to the bed joint are depicted where the brittle diagonal cracks forming a cone-shaped fracture mode are visible [16,17]. Furthermore, the cone-shaped failure mode is more prominent with a load direction perpendicular to the long side of the optical brick in the compression test (Figure 3d–f). A general note is that the failure of all bricks was not explosive at all and the specimen remained in place with existing cracks. The locations and diameter of the cracks affect the pattern of the failure mode, a matter that is to be under investigation at a later stage.



(**a**) (**b**) (**c**)

(**d**) (**e**) (**f**)

Figure 3. Failure modes of characteristic bee bricks with the loading direction (**a**–**c**) perpendicular to the bed joints and (**d**–**f**) parallel to the bed joints.

Figure 4 illustrates the failure modes of the triplets according to EN 1052-3 specifications. The characteristic patterns follow the four different failure modes (A1, B, C, D) with or without lateral compression for the shear tests. There are two distinctly categorized failure modes, namely A1 and A2, which fall under the purview of the A mode. A1 failure mode entails the failure resulting from the shear test in the bond area between a unit or mortar, either on one unit or between two units. Similarly, the A2 mode defines the failure that occurs only in the mortar faces due to the shear test. It is pertinent to note that shear failure in B mode is confined solely to the mortar, whereas C mode is employed to describe shear failure in the unit. Furthermore, D mode denotes the situation wherein the units exhibit crushing and/or splitting failure.

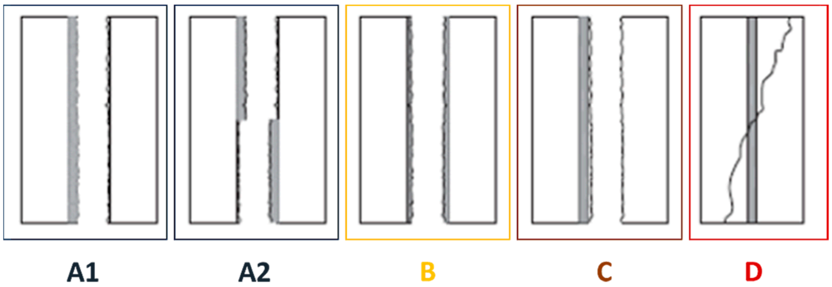


Figure 4. Shear failure mode types.

Figure 5 shows the three triplets of bee bricks with their binding mortars. The three specimens failed through different brittle failures. In Figure 5a, the failure occurs with the separation of the mortar from the brick due to the weakness of the interface between the two materials. In Figure 5b, it is evident that the use of low-strength mortar to create a joint provides failure in the mortar layer (failure mode B), while the shear failure is divided between two-unit faces in the third triplet. For each specimen, its failure mode is detailed, which is type A1, B, and A2, as shown in Figure 5a, b, and c, respectively. Significantly, despite the extremely smooth surface of the solid brick, it was demonstrated to be expected that the interface would fail with the complete detachment of the mortar from the surface of the brick. Nevertheless, the results indicate that the low strength of the binder mortar plays an important role. Further analyses and results of direct shear values will shed light on the assessment of the compatibility of the two interfaces of the bricks and the masonry. Additionally, future exploration into using green materials and sustainable technologies could be applied to assessing bee bricks' mechanical performance [18–20].

(**a**) (**b**) (**c**)

Figure 5. Failure modes of brick triplet subjected to shear testing for types (**a**) A1, (**b**) B, and (**c**) A2.

5. Conclusions

In this research, a novel and "green" masonry bee brick is presented as a hive and simultaneously as a masonry unit and the mechanical properties are experimentally investigated. The aim is to protect and help the different species of solitary bees, which are a vital part of the ecosystem as they contribute to the fertilization of plants through pollination. The utilization of materials in bee bricks and binding mortars comprises natural antibacterial and antifungal properties as well as a breathable geo-mortar, with natural NHL lime, geo-binder, and microorganisms also aiding in reducing pollutants, rendering them environmentally sustainable. Twelve bee bricks with horizontal holes were subjected to compressive loads, with six perpendicular and six parallel to the bed joints. The results reveal significant mechanical strength of about 12 MPa and 13 MPa in parallel and perpendicular loading directions to the bed joint, respectively, rendering it a suitable masonry unit for constructing secure and earthquake-resistant structures. Furthermore, the direct shear results indicate that the low strength of the binder mortar as well as the bond strength of the masonry unit and the mortar play a significant role. Nevertheless, further analyses and results of direct shear values will shed light on assessing the compatibility of the two interfaces of the bricks and the binder mortar. Moreover, in the next steps to follow, analyses using 3D finite element models will validate the masonry units' mechanical performances in comparison with the real experimental results. It presents a distinct solution that addresses the dual need for biodiversity and the benefits of utilizing construction materials for both load-bearing masonry and as an abode for pollinator bees.

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