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Investigation of mechanical properties of masonry materials under compressive loading: experimental and numerical study

Yığma yapı malzemelerinin basınç yüklemesi altında mekanik özelliklerinin incelenmesi: deneysel ve nümerik çalışma

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Investigation of Mechanical Properties of Masonry Materials Under Compressive Loading: Experimental and Numerical Study

Highlights

- *Masonry structures*
- *Finite Element Modelling*
- *Material properties*
- *Stress-strain curve*
- *Concrete Damage Plastisity (CDP) Model*

Graphical Abstract

The mechanical behaviors of three types of masonry units (hollow brick, clay brick, aerated concrete) used in the construction of masonry structures were examined experimentally. A CDP (Concrete Damage Plastisity) model for clay-based baked brick material has been proposed.

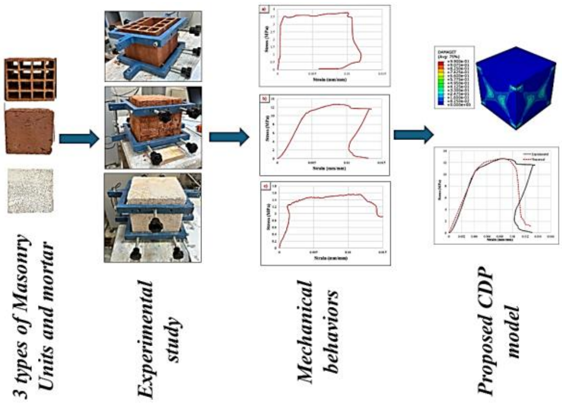

Figure. Graphical abstract

Aim

The aim of this study is to investigate mechanical properties of the frequently used masonry units.

Design & Methodology

In this study, the mechanical properties of 3 types of masonry units and normal strength mortar materials were determined experimentally.

Originality

In order to examine the structural behavior of existing masonry structures, stress-strain relationships under pressure loading of masonry units were revealed in order to provide data for finite element models created with micro modeling technique.

Findings

The mechanical properties and stress-strain curves of hollow brick, solid brick, aerated concrete and normal strength mortar materials were obtained. In the numerical verification study conducted for the CDP model proposed for clay-based baked brick material, the analysis results overlapped with the experimental results.

Conclusion

Using the data obtained in the study, micro finite element models can be created in which the in-plane and out-of-plane behaviors of masonry wall elements will be investigated.

Declaration of Ethical Standards

The authors of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Investigation of Mechanical Properties of Masonry Materials Under Compressive Loading: Experimental and Numerical Study

Research Article

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ABSTRACT

Masonry structures are buildings whose load-bearing system consists of vertical walls made of different units such as bricks, aerated concrete or natural stones. Masonry structures are quite common because they can be built quickly and economically with the use of local materials without requiring skilled labor. In the design of masonry structures and in the analyses of existing masonry structures, it is very important to determine the mechanical properties of the material accurately and to use them in the calculation models created with the micro model technique. In this study, the mechanical behaviour of hollow brick, clay brick and aerated concrete masonry units under uniaxial compressive loading was investigated experimentally for the purpose of masonry analysis. Using the experimental results, the concrete damage plasticity (CDP) model is proposed for the clay-based brick material for applications to be analysed by micro modelling technique in finite element software. The method used in the study will provide light for experimental studies to be carried out to determine the mechanical properties of different types of masonry units and to reflect them to the analysis models.

Keywords: Masonry structure, mechanical properties, brick, aerated concrete, CDP model.

Yığma Yapı Malzemelerinin Basınç Yüklemesi Altında Mekanik Özelliklerinin İncelenmesi: Deneysel ve Nümerik Çalışma

ÖZ

Yığma yapılar, taşıyıcı sistemi tuğla, gaz beton veya doğal taşlar gibi farklı birimlerden üretilmiş düşey duvarlardan oluşan yapılardır. Nitelikli işçilik gerektirmeden yerel malzemelerin kullanımıyla hızlı bir şekilde ekonomik olarak inşa edilebilmeleri sebebiyle yığma yapılar oldukça yaygındır. Yığma yapı tasarımında ve mevcut yığma yapıların analizlerinde malzeme mekanik özelliklerinin doğru bir şekilde belirlenip mikro model tekniği ile oluşturulan hesap modellerinde kullanılması oldukça önemlidir. Bu çalışmada, yığma yapıların analizlerin kullanılması amacıyla boşluklu tuğla, dolu harman tuğla ve gazbeton yığma birimlerinin tek eksenli basınç yüklemesi altında mekanik davranışları deneysel olarak incelenmiştir. Deneysel sonuçlar kullanılarak kil bazlı tuğla malzemesi için sonlu eleman yazılımlarında mikro modelleme tekniği ile analiz yapılacak uygulamalar için beton hasar plastisite (CDP) modeli önerilmiştir. Çalışmada kullanılan yöntem, farklı tipteki yığma birimlerin mekanik özelliklerinin belirlenmesi ve analiz modellerine yansıtılması için yapılacak deneysel çalışmalara ışık tutacaktır.

Anahtar kelimeler: Yığma yapı, mekanik özellikler, tuğla, gaz beton, CDP model.

1. INTRODUCTION

Masonry structures are heterogeneous composite structures consisting of natural/artificial unit elements with different properties (e.g. bricks, adobe, aerated concrete or natural/irregular stones) and mortar material (e.g. clay, lime, cement) acting as a binder between these elements. The material-mechanical properties of masonry units can be defined in terms of surface pattern, unit volume weight, pore structure, thermal conductivity, fire resistance, modulus of

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elasticity, unit deformation properties, compressive and tensile strength parameters [1].

Today's masonry building stock consists of historical buildings (mosques, churches, temples, castles, bridges, caravanserais, etc.) that have the characteristics of cultural heritage and buildings used mostly in rural areas for shelter needs. These structures have been preferred for hundreds of years thanks to the reusability of the units that make up the masonry structure,heat /sound insulation, fire resistance, energy saving, economic and easily accessible production source. After the devastating earthquakes in the last 20 years (Kocaeli earthquake - Turkey 1999, Ağrı earthquake - Turkey 2004, Kashmir earthquake - Afghanistan 2005, L'Aquila earthquake - Italy 2009, Van earthquake - Turkey 2011, Emilia earthquake - Italy 2012, Lesvos earthquake - Greece 2017, Albania earthquake - Albania 2019, Sivrice earthquake - Turkey 2020, Kahramanmaraş earthquake - Turkey 2023), the damage conditions of masonry structures were evaluated in the investigations carried out in disaster areas. In these studies, the current conditions of the masonry structures were determined by taking into account the previous evaluations, and the importance of taking retrofitting/repair measures when necessary was emphasised in terms of both life safety and the protection of historical buildings, which are cultural heritage.


Sivrice earthquake [12]
Emilia earthquake [2]
L'Aquila earthquake [3]
Lesvos earthquake [6]

Figure 1. Damage situations of masonry structures


Kocaeli earthquake [31]
Sivrice earthquake [9]

Figure 1.Continue Damage situations of masonry structures

Researchers have shown that damage or complete collapse of masonry structures is generally caused by poor mortar quality [2-5], poor quality of masonry unit elements [6], inadequate workmanship [7,8], and design errors [9-12]. **Figure 1** shows masonry elements damaged in various earthquakes.

The structural behaviour of masonry structures is more difficult to simulate due to their inhomogeneous configuration, anisotropic structure, unsymmetrical building geometry (especially of historical buildings) and connections between elements [13-15]. Finite element analysis is considered to be the most appropriate calculation method for structural analysis of masonry structures [16]. Two modelling types, macro and micro, are used in the finite element method preferred for the solution of masonry structures [17]. The difference between micro modelling and macro modelling is that masonry unit elements and mortar material are considered separately in modelling [18]. In macro modelling, the unit is defined as a single homogeneous material including the effect of the element and mortar [19,20].

Masonry structures are constructed with unit elements and mortar material with different deformation properties due to the difference in the characteristics of the materials used. Regardless of the type of analysis, it is important to accurately determine the mechanical properties of the masonry unit elements and mortar material used and to reflect these properties in the analyses in terms of the consistency of the results obtained [21]. In masonry structures, although the volume of mortar material that provides the connection of masonry units to each other varies, this ratio is approximately 7%. Although the volume of mortar material is small, its effect on the performance of the structure is at a considerable level [1].

When the existing literature is examined, many experimental studies have been carried out to determine the mechanical properties such as compressive strength, tensile strength, modulus of elasticity, unit deformation property and material properties such as water absorption, unit volume weight, hardness and void structure of masonry unit elements of different sizes and mortar material acting as intermediate binder [22-26] In these studies, various loading types (static, cyclic, impact) and external environment effects such as high temperature effect [27,28]. are common research topics. In addition to experimental studies, numerical studies have also been carried out by creating finite element models for masonry unit elements, panels or masonry structures (bridges, houses,mosques, etc.) [20,29-30]. It is emphasised that the accuracy of the results obtained in these studies, which offer more economical solutions than experimental studies, depends on the established model and the mechanical properties of the materials [19].

This study was carried out to determine the mechanical behaviour of hollow brick, clay brick and aerated concrete masonry units used in the construction of masonry structures under uniaxial compressive loading. The stress-strain relationships obtained for 3 different masonry units with different mechanical properties can be used in the analysis and design of masonry structures.

2. MATERIAL AND METHOD

2.1. Masonry Units

Vertical hollow brick, clay brick and aerated concrete block are the main units used in the construction of masonry structures. Although masonry units of different sizes are used in the production of masonry structures, hollow bricks are 275×175×130 mm, clay bricks are 190×90×50 mm, and aerated concrete blocks are 600×250×150 mm in size. **(Figure-2)**

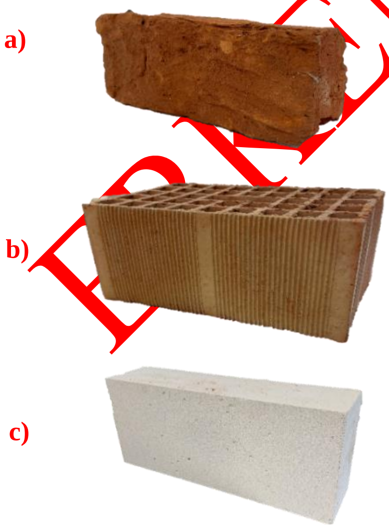

Figure 2. Units used in the production of masonry structures; a) clay brick, b) Vertical hollow brick, c) Aerated concrete block

In order to obtain the stress-strain behaviour of masonry units under compressive loading, the specimens to be tested were planned to be prepared in cube dimensions of 150 × 150 × 150 mm. Hollow brick and aerated concrete units were directly cut to 150 mm and cube specimens were obtained. However, the specimens could not be prepared by cutting because the dimensions of the filled clay bricks were not suitable. A different method was followed for the determination of the mechanical properties of clay bricks. As shown in **Figure 3**, wooden moulds with cube dimensions of 150 × 150 × 150 mm were produced and samples were taken during production from a brick factory where brick production is actively carried out. The clay-soil material used in the production of clay bricks was placed in wooden moulds and compacted. The prepared cube samples were dried in the open air for 1 week in the same condition as the bricks and then fired in an oven at 800 C^{0}.

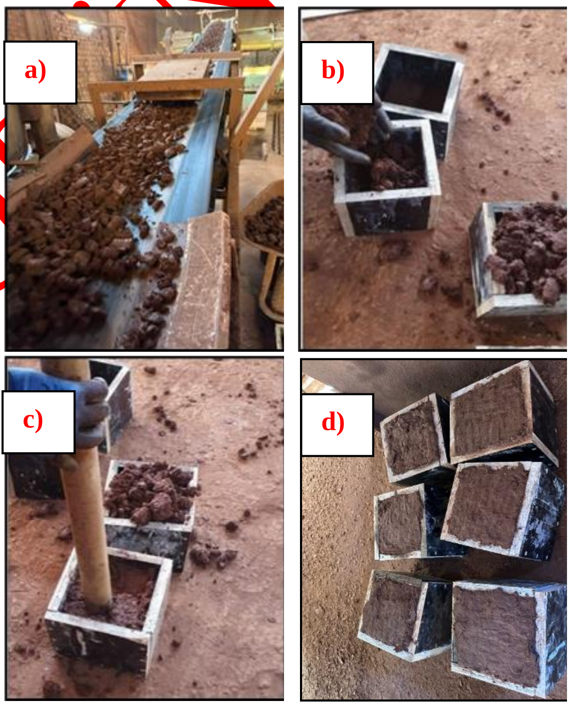

Figure 3. The process of taking samples from the brick factory for the determination of the mechanical properties of clay bricks: a) production line, b) placing the brick mixture in wooden moulds, c) compaction of the mixture, d) prepared cube samples

In order to determine the mechanical properties, 3 cube specimens each with a separation length of 15 cm were produced for three different masonry unit types **(Figure 4)**. Each sample was weighed with a precision balance and the unit volume weights of the materials were determined. Then, when the cube specimens were tested under compressive loading, the measurement setup shown in **Figure 5** was used to obtain the stress-strain relationship. The strain value corresponding to the load for each loading step was calculated by using the LVDT with a precision of 0.01 mm located vertically in the measurement setup.

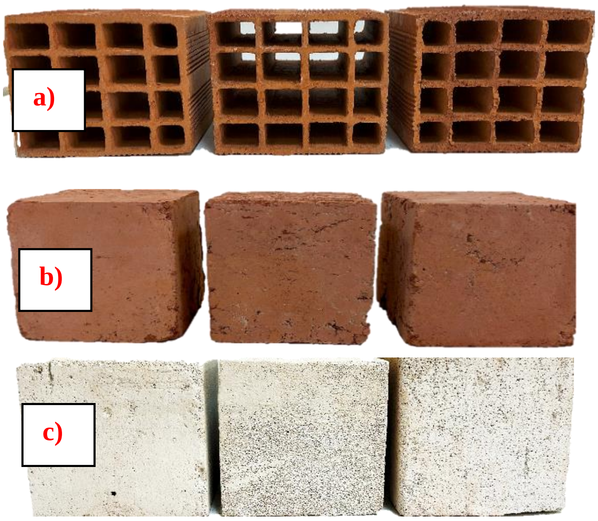

Figure 4. Cube specimens prepared for the determination of mechanical properties: a) hollow brick, b) clay brick, c) aerated concrete

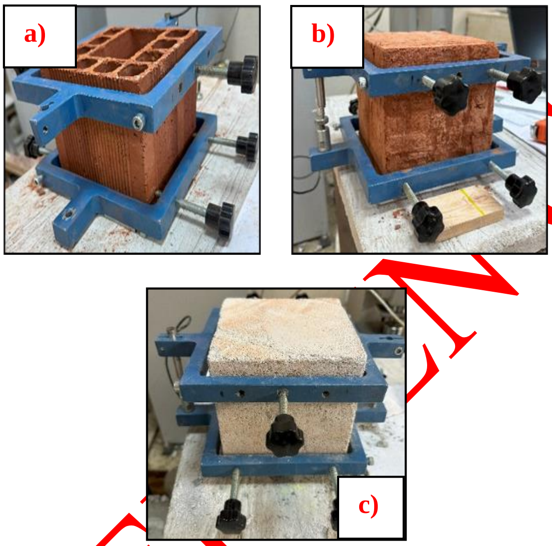

Figure 5. Mechanism used for the determination of stress-strain relations of masonry units: a)hollow brick, b) clay brick, c) aerated concrete

2.2. Mortar

The mortar layer that holds the units forming the wall of the masonry structures together also ensures the continuity of the wall. In TS-2848 standard [32] , mortars are divided into 5 classes according to their strength. 3:1 ratio of sand and cement mixture is defined as class A mortar and the compressive strength of this type of mortar is 15 MPa. Within the scope of the study, the mechanical properties of the cement-based ready-mixed mortar product, which is similar to the mechanical properties of the class A mortar specified in TS-2848 standard, were also determined. In order to determine the mechanical properties of the mortar material, 4 cube specimens with dimensions of 150 × 150 × 150 mm and 3 prism specimens with dimensions of 40 × 40 × 160 mm were prepared.

The prepared specimens were tested and the unit volume weight, 7 and 28-day compressive strength and 28-day flexural tensile strength of the mortar materials were obtained. In addition, the measurement setup shown in **Figure 6** was used to obtain the stress-strain relationship when testing 28-day-old cube specimens. In the measurement setup shown in **Figure 6**, in addition to the LVDT measuring the vertical deformation with an accuracy of 0.01 mm, a second LVDT was used to measure the lateral deformation. Thus, the Poisson's ratio for the mortar sample was also calculated experimentally.

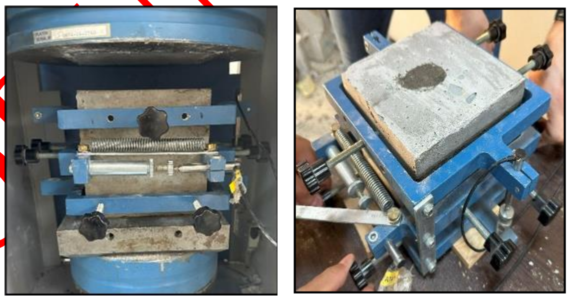

Figure 6. Determination of stress-strain relationship of mortar material

3. EXPERIMENTAL RESULTS

3.1. Masonry Units

Within the scope of the study, cube specimens with dimensions of 15x15x15 cm, 3 of each unit and 9 in total, were produced. After the production stage, the unit volume weights (g/cm^3) of the specimens of each masonry unit type were calculated. Then, compressive loading was applied to all specimens and their strengths (MPa) were determined. The compressive strength and unit volume weight of the tested specimens and the average results of each group are given in **Table 1.**

Table 1. Mechanical properties of the masonry units

Unit	Weight of per unit (gr/cm^3)	Compressive strength (MPa)
Hollow brick-1	0.68	2.78
Hollow brick-2	0.70	2.62
Hollow brick-3	0.69	2.20
Hollow brick- Average	**0.69**	**2.53**
Clay brick-1	1.68	11.80
Clay brick-2	1.68	12.45
Clay brick-3	1.67	12.82
Clay brick- Average	**1.68**	**12.36**
Aerated concrete -1	0.49	1.96
Aerated concrete -2	0.48	1.56
Aerated concrete -3	0.46	1.87
Aerated concrete **- Average**	**0.48**	**1.80**

Strain values were determined for one specimen from each masonry unit type group under compressive loading using the test setup shown in **Figure 5** and stress-strain relationships were obtained. The experimental findings obtained as a result of axial compressive loading test of masonry units are given in **Table 2** and stress-strain curves are given in **Figure 7**.

Table 2. Experimental results of the masonry units.

Masonry unit	Compressive strength (MPa)	Strain at max load (mm/mm)	Mod. of elastisity (MPa)	Energy dissipation capacity (N/mm^2)
Hollow brick	3.76	0.0096	5048.89	0.0371
Clay brick	12.68	0.0085	2439.32	0.1285
Aerated concrete	1.56	0.0101	576.49	0.0178

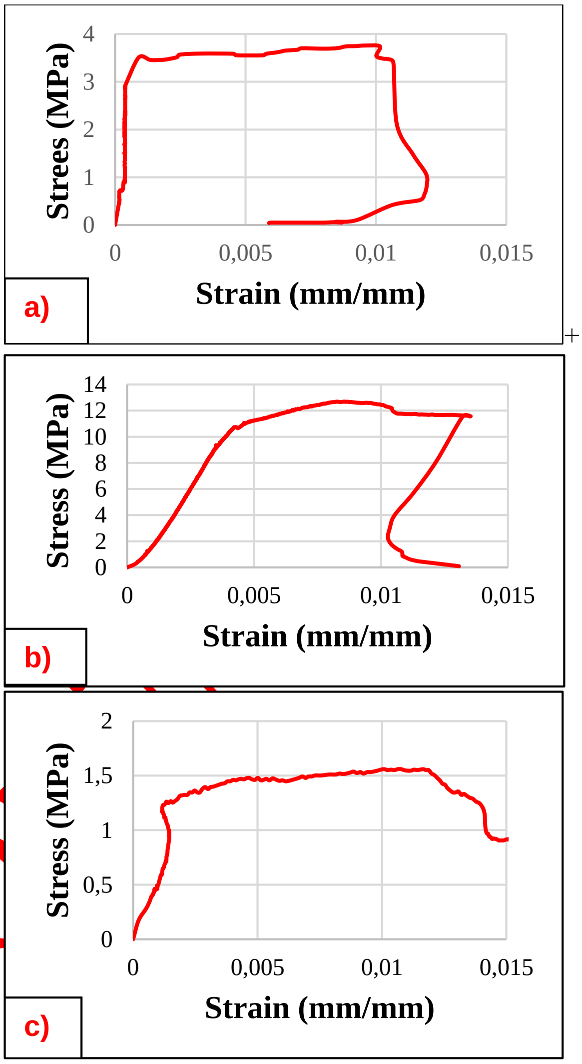

Figure 7. Stress-strain relationships of the masonry units: a) hollow brick, b) clay brick, c) aerated concrete

3.2. Mortar

In order to determine the mechanical properties of Class A mortar material used in the construction of masonry structures, a total of 7 mortar specimens, 4 cube and 3 prismatic specimens, were produced.Firstly, unit volume weight (gr/cm^3) were determined on the manufactured cube specimens. These specimens were tested under compressive and flexural load at the end of 7 and 28 days curing periods. The unit volume weight, compressive strength and flexural tensile strength of the tested specimens are summarised in **Table 3**.

Table 3. Mechanical properties of the mortar

Cure time	Weight per unit of volume (g/cm^3)	Compressive strength (MPa)	Bending tensile strength (MPa)
7	1.62	14.04	-
28	1.66	17.80	1.30
28	1.62	18.00	1.60
28	1.62	19.50	1.50

Using the experimental setup shown in **Figure 6**, strain values were obtained for a mortar specimen under compressive loading and stress-strain relationships were obtained. The experimental results obtained from the axial compressive loading test are summarised in **Table 4** and the stress-strain curve is shown in **Figure 8.**

Table 4. Experimental results of the mortar

Masonry unit	Compressive strength (MPa)	Strain at max load (mm/mm)	Mod. of elastisity (MPa)	Energy dissipation capacity (N/mm^2)
(A) class mortar	17.98	0.0040	25602.56	0.0320

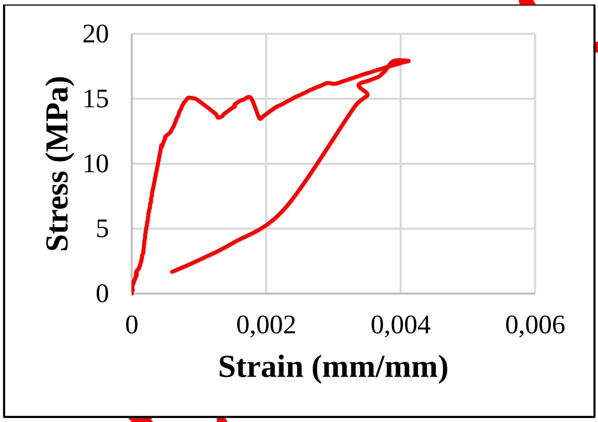

Figure 8. Stress-strain relationship of the mortar

3.3. Modelling Clay Brick Material In ABAQUS

The material's mechanical characteristics demonstrate that, similar to concrete, it possesses distinct tensile and compressive behaviors as well as non-linear behavior and plastic deformations under compressive stress. As a result, the concrete damage plasticity (CDP) model, which was extensively employed in ABAQUS, characterized this material used in the construction of bricks [33]. The damage mechanism, plastic behavior, and compressive and tensile behavior of materials are all covered by the CDP model. It can converge findings to precision when compared to other models. The two material failure processes identified by the CDP model are compressive crushing and tensile cracking, as seen in **Figure 9**. The present study used the stress-strain equations established via experimentation to calculate the plastic strain (εpl), inelastic strain (εin), and damage parameter (dc) for the clay-based soil material. **Table 5** lists the yield stress, inelastic strain, plastic strain values, and associated damage factors that were utilized to define the CDP model.

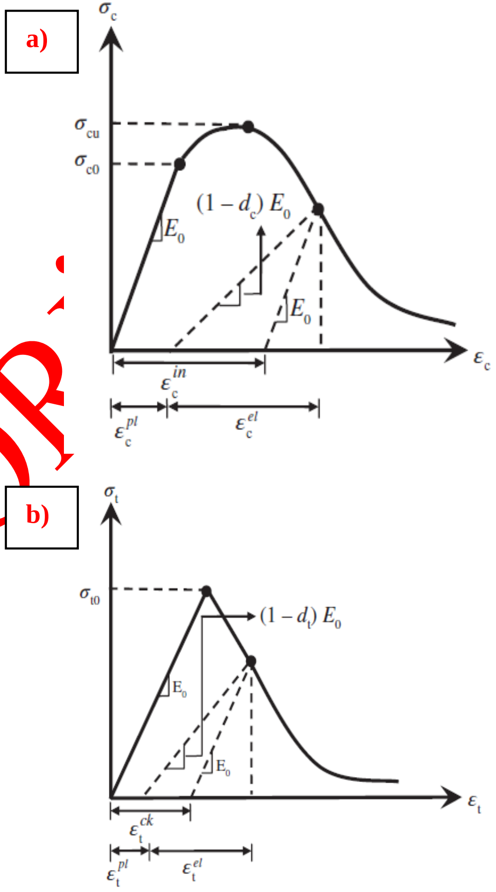

Figure 9. CDP a) Compression model, b) Tension model

Table 5. CDP model parameters

Stress	Inelastic Strain	Plastic Strain	Damage C
Compression			
10.97	0.00000	0.00000	0.00000
11.59	0.00014	0.00014	0.00000
12.64	0.00274	0.00274	0.00000
11.76	0.00579	0.00542	0.06929
11.56	0.00863	0.00818	0.08512
8.80	0.00992	0.00831	0.30395
6.03	0.01121	0.00844	0.52278
3.27	0.01250	0.00857	0.74160
0.50	0.01379	0.00870	0.96043
Tension			
Stress	**Inelastic Strain**	**Plastic Strain**	**Damage T**
1.36	0.00000	0.00000	0.00000
0.97	0.00131	0.00119	0.23016
0.68	0.00262	0.00238	0.46032
0.39	0.00394	0.00357	0.69048
0.10	0.00525	0.00476	0.92063

Using the CDP model parameters found in **Table 5**, ABAQUS was used to describe the baked soil material that was based on clay. The following plasticity parameters were input when the CDP model was defined: Shape factor (K), 1, fbo/fco, 1.16, dilation angle (ψ), 30, flow potential eccentricity (e), 0.1, and viscosity parameter (μ), 0.001.

A cube component with dimensions of 15x15x15 cm was modeled and analyzed under compressive loads in ABAQUS finite element software to verify the correctness of the CDP model behavior set in the program. **Figure 10** displays the stress-strain curve that was produced as a consequence of the investigation. It was shown that, during compression, the numerical stress-strain curve of the cube specimen modeled using the CDP model approach closely matched the curve obtained experimentally.

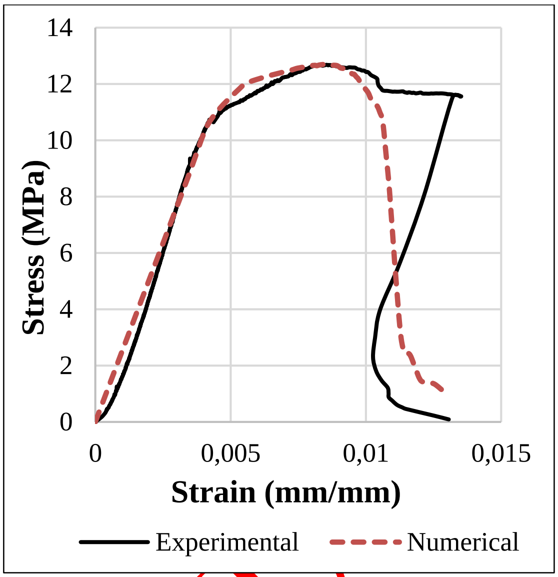

Figure 10. Comparing experimental and numerical stress-strain curves

The compressive and tensile damage distributions of the cube element as a result of the analysis were shown in **Figure 11-a** and **Figure 11-b**, respectively. Also, the damage distribution obtained experimentally is given in **Figure 11-c.**

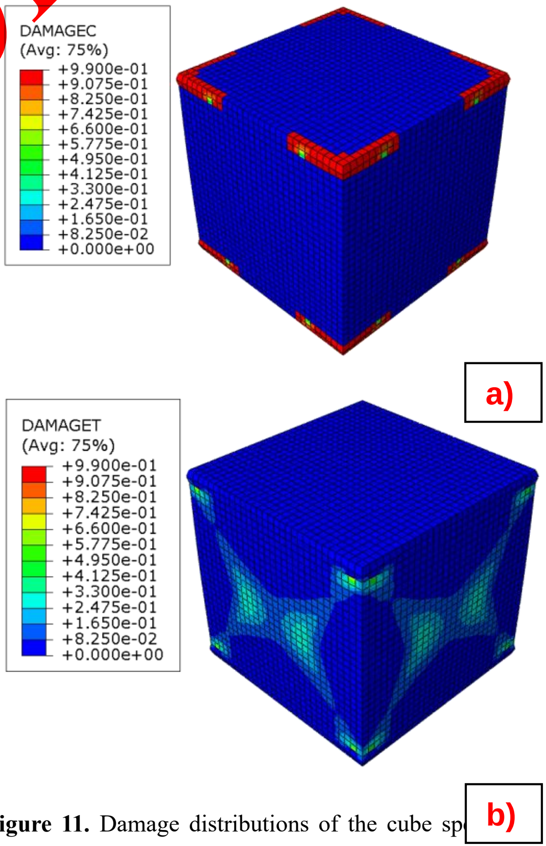

Figure 11. Damage distributions of the cube sp a) Compression damage, b) Tension damage, c) Experimental damages

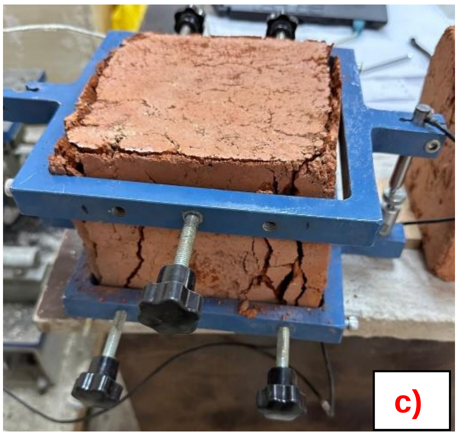

Figure 11. Continue Damage distributions of the cube specimen a) Compression damage, b) Tension damage, c) Experimental damages

The numerical analysis using the CDP model shows that the damage distributions are very similar to the experimental results. Thus, the proposed CDP model can be used in future numerical studies with clay-based brick material.

4. RESULTS and CONCLUSIONS

Hollow bricks, clay brick, and aerated concrete were frequently used in the production of the masonry structures. These unit elements are connected to each other with mortar elements with different strength properties and masonry walls are constructed. In this study, an experimental study was carried out to determine the mechanical properties of three different types of masonry units and normal strength mortar material. In addition to the experimental studies, a numerical validation study was also carried out. The results obtained from the experimental and numerical studies are summarised below;

- When the masonry units were compared in terms of compressive strength, the masonry unit with the highest strength was clay brick, followed by hollow brick and aerated concrete, respectively.

- The hollow brick unit has the highest modulus of elasticity and the unit with the lowest modulus of elasticity was determined as aerated concrete. Considering that hollow brick and clay brick units are produced from the same material type, it is thought that the approximately 2-fold difference in the modulus of elasticity may be due to the void configuration in the hollow brick unit or the difference in the firing process involved in the production process of the bricks.

- When masonry units are compared in terms of energy consumption, clay brick has the highest capacity, while the second and third ranked units are hollow brick and aerated concrete, respectively.

- A general CDP model for clay-based fired bricks is proposed by utilising the experimental results of clay brick material. The stress-strain behaviour and damage distributions obtained in the numerical validation study carried out with the proposed material model were compared with the experimental results and it was found that the results overlapped with each other. This proposed material model can be used in the analysis models of masonry structures consisting of clay-based bricks with different void types or with different geometric dimensions.

ACKNOWLEDGEMENT

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DECLARATION OF ETHICAL STANDARDS

The authors of this article declare that the materials and methods used in their studies do not require ethics committee approval and/or legal-specific permission.

AUTHORS CONTRIBUTIONS

Alper ÇELİK: Conducted the experiments, performed numerical modeling and analysis, and wrote the manuscript.

Özgür ANIL: Provided supervision.

Ömer MERCİMEK: Contributed to the writing of the manuscript.

Sercan Tuna AKKAYA: Assisted with layout design and contributed to the writing of the manuscript.

Ahmet İhsan TURAN: Contributed to the execution of the experiments.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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