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INVESTIGATING THE FEASIBILITY OF IMPROVING PROPERTIES AND STRUCTURAL PERFORMANCE OF ECO-FRIENDLY COMPRESSED EARTH BRICKS

Eman O.Yehia [1*], Ahmed SH. Hashad [2], Ahmed G. Asran[1]

[1] Civil Department, Faculty of Engineering, Al-Azhar University, Nasr City, 11884, Cairo, Egypt,

[2] Construction Research Institute, National Water Research Center, Qalyubia, Egypt.

***Correspondence:** eman.omar2596@gmail.com

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ABSTRACT

This research aims to investigate the possibility of producing compressed earth bricks by utilizing a mixture of common available soil while enhancing its properties through the addition of a proportion of sand to meet Egyptian building specifications, while ensuring that the produced soil bricks are environmentally friendly. Additionally, the study examines the feasibility of incorporating brick hollows filled with grout to increase the overall brick compressive strength. The research also inspects the various failure patterns of the tested brick samples and determines the stress increments between the empty and filled brick hollows states. Furthermore, Numerical models were developed to represent different specimens of the brick prisms, allowing for the examination of their behavior under loading until failure, including the identification of failure modes. The experimental and numerical results demonstrate strong indicators that support the viability of utilizing the existing construction method for this type of brick to enhance its designed capacity beyond the current Egyptian specifications. Filling one hole of the brick with reinforced grout increased the efficiency of the prism by approximately 58%, and filling both holes with only just grout also increased the efficiency by approximately the same percentage. There is no point in filling both holes with reinforced grout because in this case the load depends directly on the reinforcement bars and not on the body of the prism. And The laboratory and analytical study achieved a compatibility exceeding 85%.

KEYWORDS: CEBs, Design Mixture, Failure Mode, Brick Hollows , Brick Modeling.

دراسة جدوى تحسين الخصائص والأداء الهيكلي للطوب الأرضي المضغوط الصديق للبيئة

إيمان عمر يحيي[1]*، أحمد شوقي حشاد[2]، أحمد جمعة عسران[1]

[1] قسم الهندسة المدنية، كلية الهندسة، جامعة الأزهر، مدينة نصر، القاهرة، مصر.

[2] معهد بحوث البناء، المركز القومي لبحوث المياه، القليوبية، مصر.

***البريد الاليكتروني للباحث الرئيسي :** eman.omar2596@gmail.com

الملخص

يهدف البحث الي دراسه امكانيه رفع الكفاءه و الخواص الميكانيكيه للطوب المضغوط من التربه الطبيعيه عن طريق الاستفاده من هندسه الشكل بملئ فجواته بحقين مسلح . تنقسم الدراسه الي ثلاث محاور اساسيه : المحور الاول وهو تصنيع الطوب من خلال دراسه عدد من الخلطات بنسب مختلفه من التربه الطبيعيه الي الاسمنت للحصول علي افضل خليط من حيث مقاومه الضغط ، المحور الثاني وهو استخدام طوب مصنع جاهز و اختبار خواصه ومن ثم تدعيم الفجوات بطرق عده للمقارنه بين المنشور الغير مدعم و المنشور المدعم و تاثيرتدعيم هذه الفجوات علي سلوك منحني الاجهاد – الانفعال و منحني الحمل –

الازاحه، المحور الثالث هو تمثيل هذه العينات المختبره علي برنامج التحليل اللاخطي ABAQUS لدراسه مدي التطابق بين النواتج المعمليه و التحليليه. قد اجريت دراسه عمليه علي نظام حائط من الطوب المضغوط المدعم احد فجواته بحقين مسلح لمقارنته بحائط من الطوب الطفلي التقليدي المستخدم في البناء لدراسه مدي العائد المالي من هذا الاسلوب الحديث علي التكلفه الاجماليه لاعمال المباني. وقد اظهرت الدراسه ان تصميم خلطه تحتوي علي نسبه تربه طبيعيه الي رمل 2.85 و محتوي اسمنتي 10% ينتج خليط ذات مقاومه متوسطه تبعا لمتطلبات الكود المصري لتصميم و تنفيذ اعمال المباني و ان استخدام طوب جاهز ذات مقاومه اجهاد متوسط ايضا و تدعيم فجواته يعمل علي رفع الكفاءه بالنسبه الي الاحمال الراسيه بما يقارب58%

الكلمات المفتاحية : الطوب المضغوط من التربة الطبيعية CEBs ، نمط الانهيار ، تجاويف الطوب ، نمذجة الطوب .

1. INTRODUCTION

Over the past few decades, there have been major modifications to the traditional construction system due to the high demand for fast, high-performance and cost-effective construction systems [1]. Therefore, researchers have made intensive efforts to develop a mortarless interlocking construction system, to make the building construction more cost-effective and sustainable than the traditional construction system [2]. For that Compressed earth Brick (CEBs) has gained significant attention in recent years as a sustainable alternative for traditional burned or concrete bricks. CEBs is a new generated building unit categorized as interlocking blocks in name Green Block or ECO Block [3], The word "Eco" is derived from the Latin "oeco," which means "household." These days, it frequently refers to "home," "habitat," or "Earth." Therefore, to be "Eco-friendly" is to be Earth-friendly. Eco-friendly is defined by the Cambridge Dictionary as "designed to have little or no damaging effect on the environment" [4]. This block is distinguished by reducing the carbon emissions, and containing a low percentage of cement with average 10% of mixture dry weight which reducing cement consumption used in construction industry [5].

However, the Earthen constructions have some limitations , which include the following: Non-standardised material, Non-resistant to water and less resilient as a construction material, Structurally limited, Suitable only for in situ construction [6].

Unit block performance dependents on the soil characteristics and the mix design. Some studied mixtures had compressive strengths ranged from 4.92 N/mm^2 to 15.72 N/mm^2 and recommended The optimal mix contained 10.91% cement and 11.40% water [7]. Some of the mixtures for this type of brick used some types of industrial wastes such as: cement slag, and straw ash [8]. This research aims to explore the feasibility of producing a Lego type of CEBs that comply with Egyptian specifications while utilizing the common available soil mixture. An essential aspect of this investigation is ensuring the environmental friendliness of the produced bricks. This means that the produced bricks should contain cement to soil ratio less than 10%. The study addressed improving the properties of the mixture by adding a proportion of sand. In addition to property enhancement, the research investigates the potential benefits of incorporating brick hollows filled with grout. The investigation quantifies the stress increments between the empty and filled states of the brick hollows, providing valuable insights into the behavior and performance of the brick wall designs. The research aspires to find the foundations for a technique used in developing the current Egyptian design code for this type of brick. This technique considers the expected increase in the brick compressive strength into the current standard designed criteria.

For examples to similar cases to this study , the unfilled and filled prisms of rubberized concrete interlocking bricks was given compressive strength 5.58 N/mm^2 and 10.82 N/mm^2 ,respectively, which means filling hollow bricks with grout raise the prism capacity about 50%[9].

When studying the compressive force of autoclaved aerated concrete (AAC) whose openings be suppored by plain concrete columns. it was explained that if the hole of block be at least 8.37% of the total area net and C25 grade concrete was used for core column : the compression force would be not less than the traditional construction force, which has been shown that construction can be widely used as load bearing walls in low-height storey buildings and as infill walls in structures of reinforced concrete or steel [10] .

Failure patterns of the tested brick samples were studied also to identify the most probably limitations of this technique. Furthermore, numerical models are developed to represent different brick prism specimens using ABAQUS [11, 12] program to support the experimental findings and gain a deeper understanding of the structural behavior. These models enable the examination of the bricks' response to loading until failure, including the identification of failure modes.

2. Experimental program

The experimental program was divided into three groups. The first group was involved in mixture design and used to test the optimal soil mixture based on the results of previous studies but with applying specific limitations. While the second group was developed to review various manufacturing process to ensure that by using the recommended mixture, there will be no negative effects on the brick units produced. The last group was carried out directly to study and determine the compressive strength for building units constructed in different methods. Their collapse patterns were also, inspected. The results of this group were used todemonstrate the feasibility of increasing the loading capacity that could be taking into account to develop the currently used design criteria. The following sections provide a detailed explanation for each group of the experimental program. From analyzing the test results mentioned in one of the previous studies, it was found that several tests were conducted on compressed brick mixtures after seven days and 28 days, but there was a percentage of more than 20% of the specimens tested after seven days giving a higher result than its result on day 28 [7]. To avoid the occurrence of an error percentage in the study values that may affect the accuracy of the results, all tests were standardized after 28 days of sample curing , as recommended by the code [13] .

2.1Mixture Design

Table1. MixtureDesign

No.	A	B	C	D	E	F	G
Soil /sand	2.31	2.85	2.00	2.31	2.40	0.20	0.44
Cement	9.1%	10%	9.10%	9.1%	9.10%	10%	10%
Water	20.2%	10.2%	11.5%	8.7%	9.10%	12%	10%

The first group of experimental tests was developed to determine a soil mix to produce bricks with compressive strength appropriate to the requirements of Egyptian specifications and acquires four features. The four features are: environmentally friendly, using local common soil, easy to mix and manufacture and economic.Based on the results of previous studies for many different mixtures [4] , seven mixtures were selected. The selected mixtures were subjected to modify their mixing ratios to meet the considered features requirements. The used natural soil is 75% retained on sieve NO.200 and classified as sandy clay loam soil according to (MIT) and textural (triangle) classification, as shown in the **Fig. 1**. The design mixture is displayed in **Table 1.**

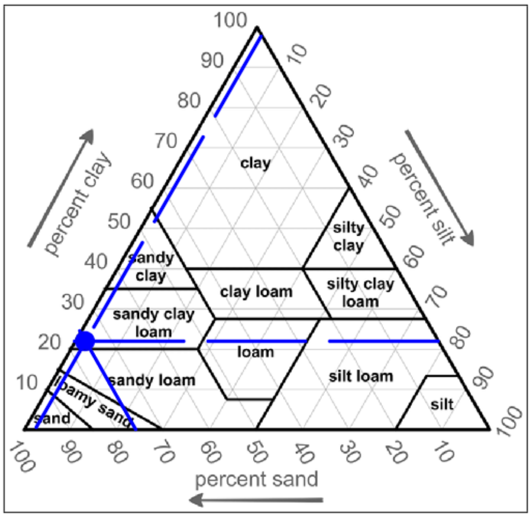


Fig. 1. Soil Texture

2.1.1 Sample Preparations

The samples were prepared in several steps. First step: both of soil and sand are sieved, the final size of particles was not more than 2.36 mm, as shown in **Fig. 2.(a)** Second step: mixing the ingredient and pour into cube form, as shown in **Fig. 2.(b)** Third step: the specimens were compacted to the same compressibility ratio for each specimen by applying pressure to make 50 mm settlement using wooden plate, as shown in **Fig. 2.(c)** While in step four and after mix hardening, the specimens cured with water to 28 days before testing, as shown in **Figs. 2.(d).**

a b c d

Fig. 2. Specimens Preparation

2.1.2 Mixtures Evaluation

The mixtures were evaluated using the results of compressive strength test sand the failure shape of the samples was also examined and crack pattern was recorded. At the age of 28 days, the specimens were tested using compression testing machine and the result presented in **Table 2.** The cracks patterns for tested mixture's samples are shown in **Fig. 3.**

Table 2. Compression Strength Results

N0.	A	B	C	D	E	F	G
Compressive Strength N/mm^2	2.73	4.85	3.34	1.52	2.69	2.25	2.70

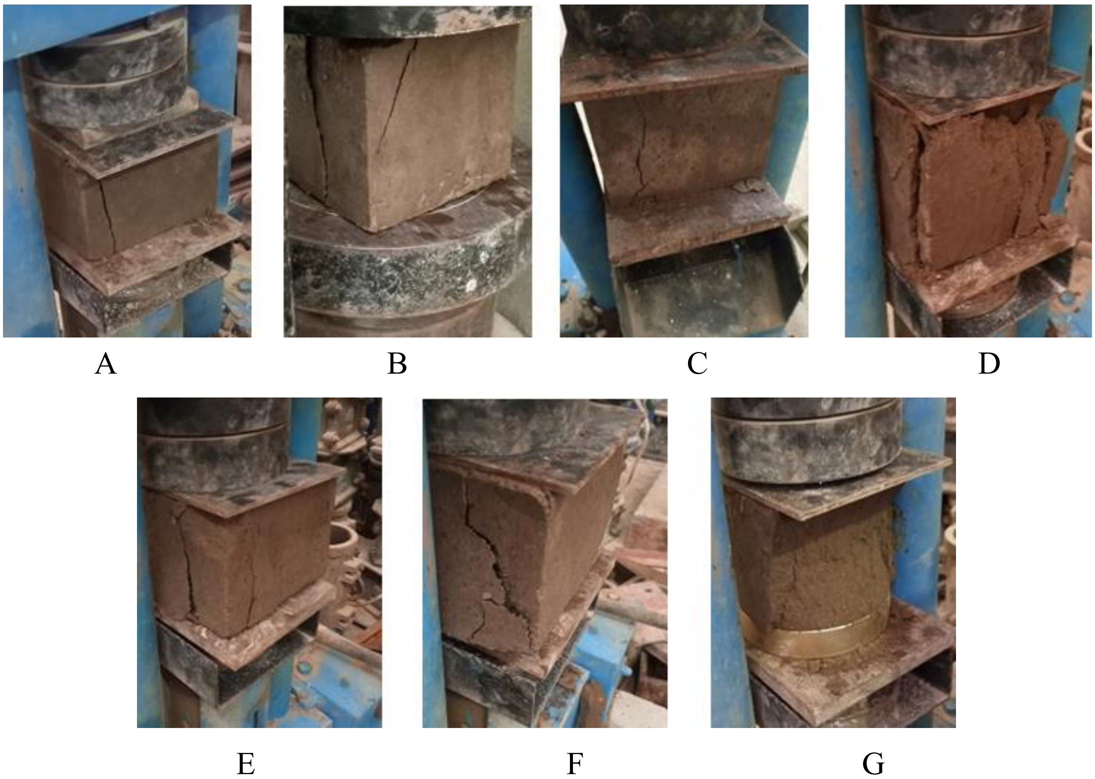


Fig. 3. Specimens during Compression Test

2.1.3 Mixture Selection

Egyptian code for building by Compressed Stabilized Soil Bricks [14] states that the wet compressive strength for unit is ranged from 3 to 4 N/mm^2 . That mean mixtures B, and C are accepted accordance to mentioned code. So, the mixture of sand /soil in ratio between 2 - 2.85 with cement content 10%, and water content with rang of 10.2% to 11.5% as a percentage of total weight, was generated an accepted CEB unit for building that comply with Egyptian standard. Mixture "B" was the chosen mixture for its higher strength results. In this stage the selected mixture has three of the required four features. While, the ease mix and manufacture feature was examined in the manufacturing process.

2.2CEBs Manufacturing Process

In the second group of the experimental program, the ability of the mixture to be manufactured easily and similar to the usual mixtures was reviewed by going through all the manufacturing stages and ensuring that a complete product is reached without any defects or resorting to introducing any special procedures than usual. The mixture was prepared to begin manufacturing a number of blocks and examining the final product.

2.2.1 The CEBs Press Machine

Commonly used equipment in this type of industry was used and is called Semi-automatic CEBs machine, shown in **Fig . 4.** The moulds are filled manually and the pressing and extraction are done automatically. The unit dimension is 120 mm in width, 250 mm in length, and 60 mm in thickness with two holes 55mm diameter for each, where the net area is 25250 mm^2. CEBs were stored in showed place as shown in **Fig. 4 (f) ,** and curing by water for 28 days before testing.

2.2.2 The Manufacturing Process Evaluation

The chosen mixture was evaluated in terms of the manufacturing process through observations of the manufacturing processes up to the results of compressive testing for samples of produced bricks. There weren't any obstacles or defects noticed during manufacturing process of the chosen mixture. As the results, **Table 3.** show that the produced brick compressive resistance matching with the results of the mixture "B" as expected.

(a) CEBs press machine

(b) Mould form lower face

(c) Mould form upper

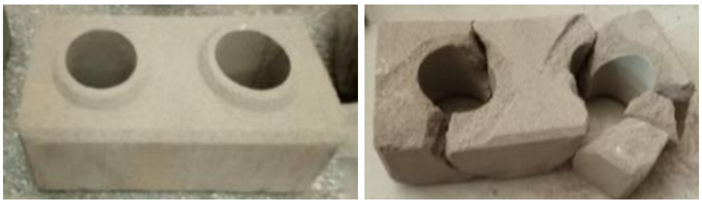
(d) The Compacting

(e) The Compacted Unit –Raised

(f) Manufactured Cebs

Fig. 4. CEBs Manufacturing Steps

Table 3. TheCompression Test Results and Failure mode

Test	Specimen - CEBs Unit	Compressive Strength
Compression test	 **Fig. 5.** CEBs- Before and After Testing	4.45 N/mm^2

2.3 Loading Capacity of Building Units

This part of the experimental program was designed to compare between four construction methods in which these blocks are used. The four building methods are building with or without filling the brick holes either partially or completely. Also, the holes could be reinforced. Another Ready CEB was used due to the lack of the required quantities and because the purpose of this part of the tests does not depend on the brick mixture as much as it depends on the construction method. A group of tests were conducted to determine the properties of the used brick before preparing the prism samples. The used bricks properties are displayed in **Table 4.**

Table 4. Brick Unit Specifications

Unit.		Weight(N)	Volume (mm^3)	Density(N/mm^3)	Failure load (KN)	Area(mm^2)	Compressive strength (N/mm^2)
CEBs	1	29950	1515000	0.197	142.5	25251	5.64
	2	30030		0.198	127.5		5.05
	3	30190		0.199	162.5		6.44
	Average	30056		0.198	144.17		5.71

2.3.1 Specimen Preparation

In each method, three prism specimens were prepared to confirm the results. In the first method, the brick is used as it is or without filling the holes with grout. The specimens were coded as (P-CEBs). In the second building method, a single hole in the specimen was filled with reinforced grout (P-1MC).While in the third method; both holes were filled with reinforced grout (P-2MC). The reinforced prisms were prepared by adding reinforcing bar with 12 mm diameter. The fourth method both holes were filled with grout but without reinforcing bars (P-2MG), as shown in **Fig.6.**

2.3.2 The Used Grout Specifications

Before preparing the specimen samples, it was necessary to determine the characteristics of the building mortar and grout in order to unify them among all the samples to ensure the neutrality of their effect. It was also necessary to ensure the ability of this mortar to penetrate into the holes without nesting. The grout mixture was: - cement: Sand: fine aggregate by volume 1: 1.25: 1.25, respectively. The water-cement ratio was 0.6, the grout slump was200 mm and the compressive strength was17.85 N/mm2. The cement grade was 25, and the fine aggregatesize was less than

3.75mm , according to EPC 204 [13]. The cylinder test of grout was carried out according to EPC 203[15] , as shown in **Fig. 7.(b, c).**

The mortar used was pure Portland cements (without sand).it's typically used to fill gaps or spaces between blocks with constant water-cement ratio. It was bedded between blocks with 5 mm thickness. The Mortar cubes was prepared and tested after 28 days accordance to Annex III - Laboratory Testing Manual for Concrete Materials [16], as shown in **Fig. 7.(a),** which resulted strength 32 N/mm2.

a-CEBs unit b- P-CEBs c- P-1MC, 2MC, 2MG

Fig. 6. Compressed Earth Block specimens test

a b c

Fig. 7. Compressed Earth Block specimens test

2.3.3 Test Results

All the groups were tested using universal machine. The strength for all prism types and the average strength of each type were presented in **Table 5.** Also, the load - displacement as well as the stress –strain relationships for each prism was plotted as shown in **Fig. 8,9.**

The load – displacement relationships for groups P-CEBs, P-1MC, P-2MC and P-2MG were plotted as shown in **Fig. 8.** By dividing the applied load by net area and dividing vertical displacement by original gage length, accordance to ASTM E111[17] , the corresponding stress – strain relationships were obtained. It was noted that filling a single hole with grout increased the load capacity by about 58.93% greater than that of the case of open holes. It was also noted that filling both holes with grout only increased the load capacity by about 58.22% greater than that of the case of open holes. In case of filling both holes with grout and reinforcing these holes with steel bars, the load capacity of the blokes increased with about 128.12%.

When testing the prisms in group P-2MC under loading, it was noted that the load - displacement relationship in **Fig. 8.** was divided to two stages. In the first stage, up to about 130 KN, all the prism elements work together as a single unit. In the second stage up to 160 KN the prism started to fail gradually followed by the grout and finally the steel reinforcement. on the other hand the P-2MG gives a more stability behavior in failure with near load value to first step of P-2MC, as shown in **Fig. 9.**

Table 5 . Prisms Strength

Group		Failure load (KN)	Area (mm^2)	Compressive strength (N/mm^2)
P-CEBs	1	78.44	25248.34	3.11
	2	68.2		2.70
	3	67.8		2.69
	Average	71.48		2.83
P-1MC	1	100.35	27625.63	3.63
	2	127.5		3.84
	3	113.4		4.10
	Average	113.6		3.86
P-2MC	1	179.98	30000.25	6.00
	2	149.14		4.97
	3	153.24		5.11
	Average	160.78		5.36
P-2MG	1	106.2	30000.25	3.29
	2	116.95		3.90
	3	116.1		3.87
	Average	113.1		3.69

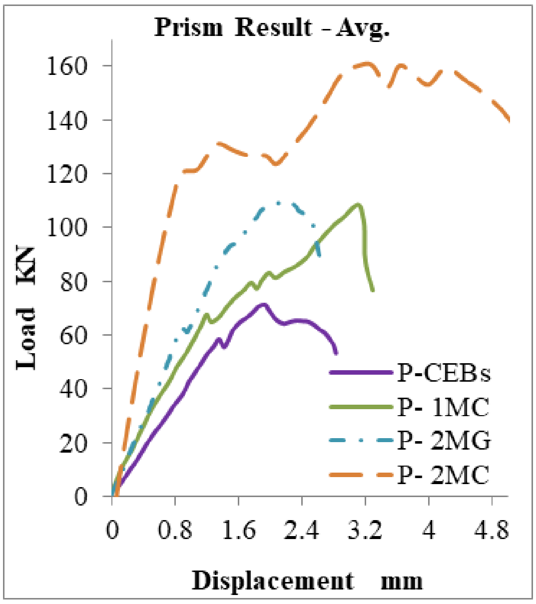


Fig. 8. Load-displacement curve

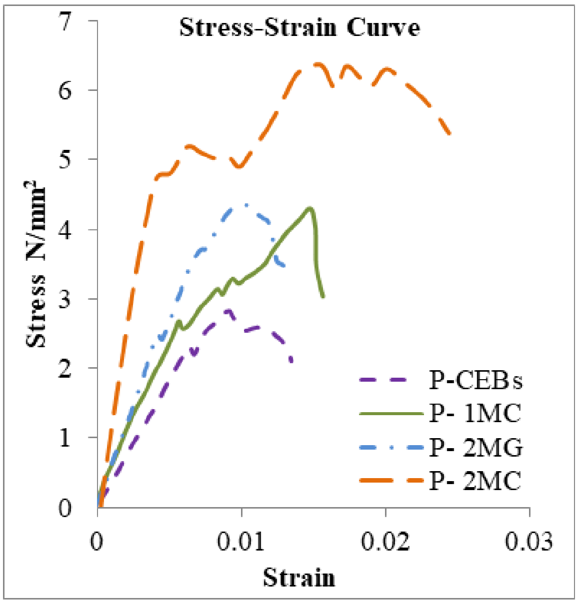


Fig. 9. Stress-strain curve

2.3.4 Failure Pattern Inspection

The failure crake of specimens P-CEBs, P-1MC, P-2MC, P-2MG are shown in **Fig. 10.(b), Fig. 11.(a-1), Fig. 11.(a-2),** and **Fig. 11.(a-3)**, respectively.

Fig. 10. CEBs Unit and Prism

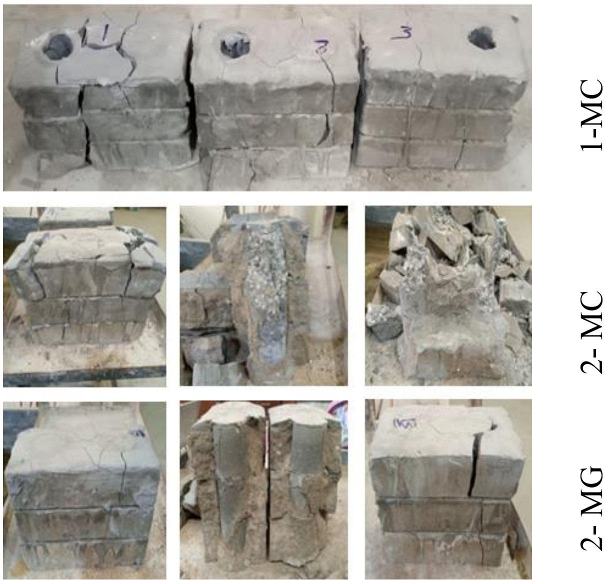


Fig. 11. Grouted Prisms

3. Numerical Modelling

The major structural elements of masonry building are the brick unit and the mortar .These materials are classified as non- homogenous materials, which makes their modeling is difficult. The numerical modeling difficulty is increased especially when studying the behavior of brick with mortar together and considering the effect of continuity of materials at the joints between brick and mortar. The ABAQUS structural analysis software program is one of the effective programs in representing such problems. Five numerical models were built to simulating the laboratory tested prisms P-CEBs, P-1MC, P-2MC, P-2MG as shown in **Fig. 12. (a, b, c, d)** respectively.

The 3D 8-node linear with reduced integration which is defined in the program manual as the C3D8R type element was selected. This structural element is an eight-node solid element with three translational degrees of freedom per node was used for block, mortar, grout, and a (beam element) for the reinforcement bar[18], and [12].

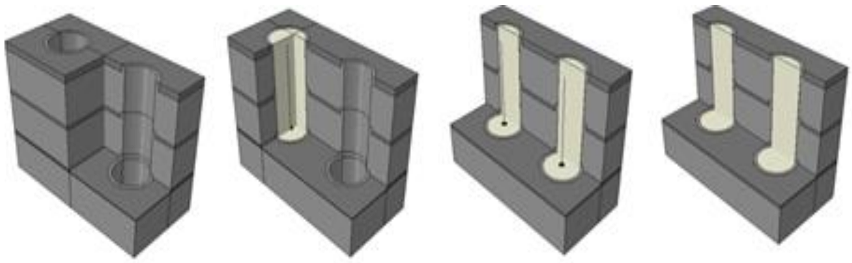


Fig.12. ABAQUS 3D-Simulated Prisms

To simulate the nonlinear behavior and studying the bricks failure patterns, the concrete damage plasticity model (CDP)[19] , which is an indicator of material degradation in post-peak rang, was applied to predict the behavior of concrete and other brittle materials , the CDP requires define the values of density, the modulus of elasticity, and Poisson's, as shown in **Table 6.** In addition to using the results of compressive strength tests to define the material compressive strength while its tensile strength was used as 10% of its peak compressive strength [19].

Table 6 the used material Properties

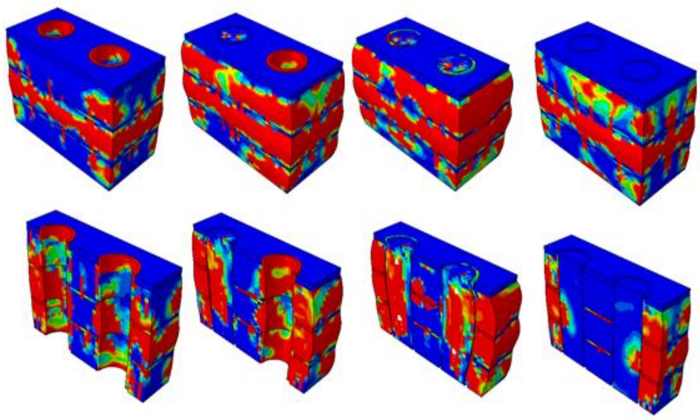
Elastic Property					
Elasticity parameter	CEBs	Brick	Mortar-1	Grout	Steel
Mass density (N/mm^3)	1.98-E9	1.54-009	1.5E-9	2.2E-9	7.8-E9
Young modulus (N/mm^2)	307.28	688.35	2013.7	1557.1	200000
Poisson ratio	0.2	0.2	0.2	0.2	0.3
Concrete Damage Plasticity (CDP)					
Dilation angle	Eccentricity	fb0/fc0	K		Viscosity
30	0.1	1.16	0.67		0

A perfect bond between the steel reinforcement and grout was achieved using the embedded regions. Cohesive elements used to model the complex contact behavior between two deformable surface, which enables the study of the cohesive behavior and the damage for the interlocking bricks, with consider the surface coefficient friction interaction which range between is (0.3 to 0.7) for bricks, based on the Mohr-Coulomb failure criterion. For the brick prism, the axial and horizontal degrees of freedom at the base are restrained and set a coupling reference point at the middle span to apply the displacement load.

A mesh convergence study conducts by gradually reducing the mesh size, and it is worth noting that by reducing mesh size the computational time increases substantially. Therefore, a 7 mm mesh size is adopted for the acceptable accuracy with time saving numerical modeling study [12, 18].

3.1Determine Structural Behaviour

Fig. 13. Displays two shots, one of them is externally general view while the other is an internal vertical section in the prism centerline were used to explain the failure patterns of the four specimens resulting from the numerical analysis. The four prisms behaviors were also analyzed numerically under loading and represented in **Fig. 14.** as the force-displacement relation as displayed.



a b c d

Fig. 13. Failure Pattern

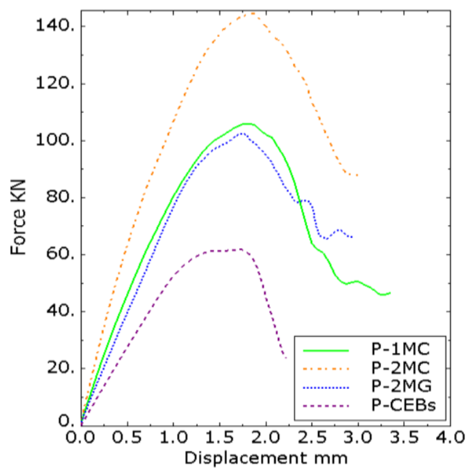


Fig. 14. Force-Displacement Curve

4. Experimental Results

4.1 Load Carrying Experimental Results

By comparing the results of this study with previous studies in the same field, we find a great agreement in the average results gained from the concrete element filling the brick holes in raising the overall efficiency of brick posts despite the difference in the study brick [9].

In this study , When analyzing the experimental results of the tested prisms to determine the load capacity for each building method, the following is noted:-

- The compressive strength results of P-CEBs, P-1MC, P-2MC, and P-2MG are 71.98, 113.6, 160.78, and 113.1N/mm^2, respectively.
- The results showed that, the effect of filling prism holes with reinforced grout participate in raising overall strength by approximately 58.93%.
- The participation of load carrying in 2MCand 2MG samples are approximately 128.12%, and 58.22%, respectively.

4.2 Failure pattern analysis

The failure pattern type of un-grouted prism is categorized under type 3 (cone and split), and the grouted prism is categorized under type 7 (face shell separation), as shown in **Fig. 15.** according to ASTM C39/C38M [20] . When analyzing the failure behavior of prisms, it was noted that the P-2MC gives high failure load, but the load-displacement curve in **Fig. 8.** presents that its failure happen in two stages, the first one approximately at 130 KN where prism works until this load as one unit, and the second step at 160 KN where the remaining resistance in this level depends on reinforcing bars only because the blocks body is already cracked from the first stage, on the other side the P-2MG gives a more stability behavior in failure with near load value to first step of P-2MC, as shown in **Fig. 11 (a).**

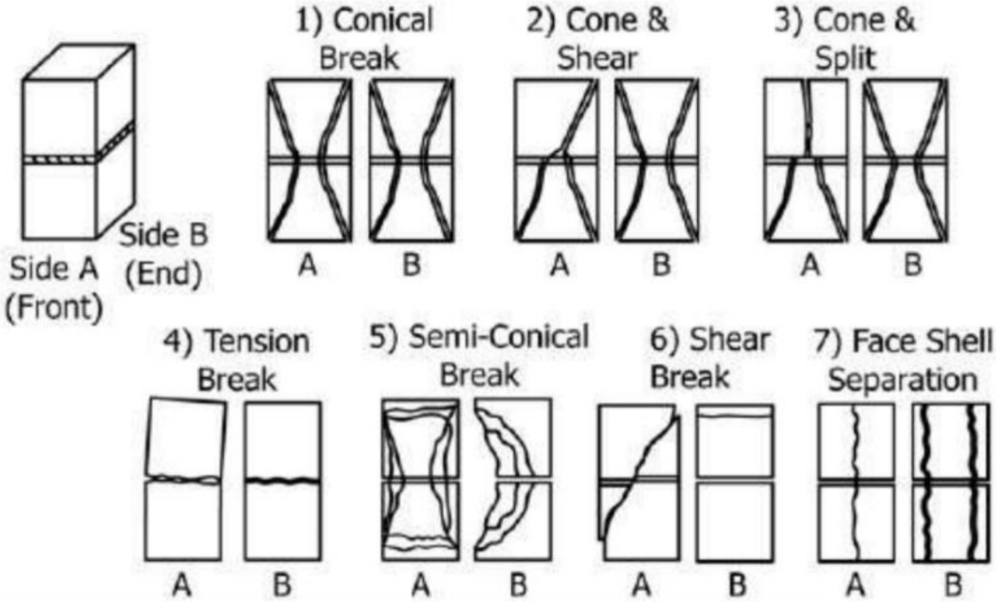


Fig. 15. ASTM C1314-14 Sketches of Mode of Failure

5. Numerical Results

The Compressive strength results of the numerical models that represent P-CEBs, P-1MC, P-2MC, and P-2MG are 60.89, 105.92, 144.7, and 102.5 N/mm2,respectively.The failure capacity results show convergence between the numerical analysis and the experimental result, as shown in **Fig. 16.** the load – displacement behavior between the experimental and numerical specimens**.** The degree of convergence in the range of zero to maximum load in prisms P-CEBs, P-2MC and P-2MG is much more than P-1MC, After maximum load the numerical behavior is divergent the experimental one in all cases.

The Failure pattern, especially, for grout prisms where the P-2MC and P-2 MG have different behavior. The P-2MC was cracked completely as shown in **Fig. 11.(a),** and this what appearance in program as shown in **Fig. 13.(c),** and in case of P-2MG the grout remained unbroken after the cracking in laboratory and in program too , this is shown in **Fig.(11.(a), 18.(d)).**

Accordingly, the agreement between the laboratory and analytical results of the prisms specimens ranged from 85% to 93%.

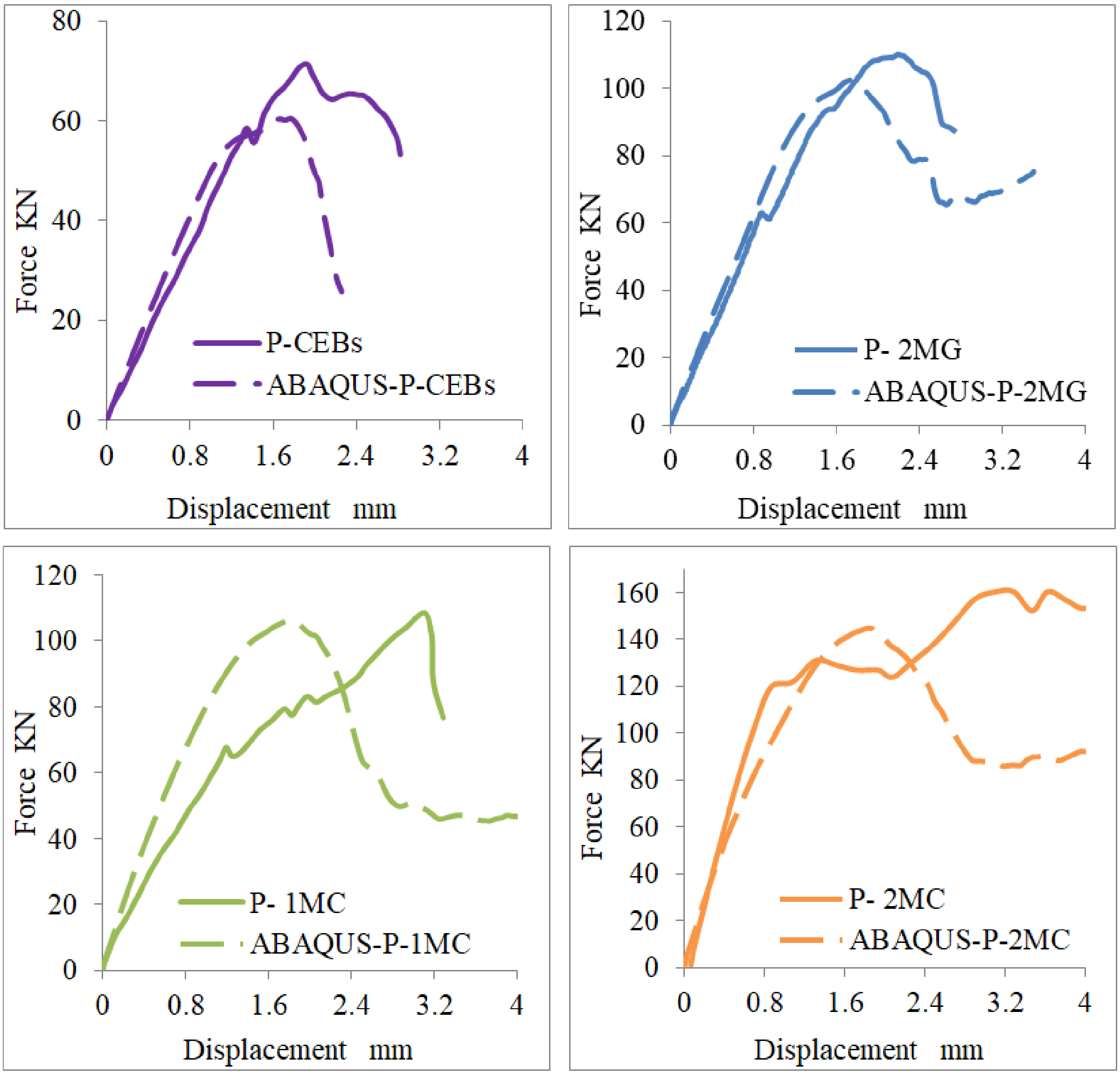


Fig. 16. The Compatibility of Experimental & Numerical Results

Conclusion

The study included all the steps of manufacturing the compressed earth bricks to obtain an economical and environmentally friendly brick. The study extended to examine the possibility of exploiting current construction methods to reach the peak of economic and environmental exploitation of this technology in construction.

The results showed that current construction methods, in which usage of some grouted hollow, contribute significantly to raising the overall bearing capacity of bricks. The results showed the following:-

1. Recommending a practical and environmentally friendly mixture that meets the requirements of the Egyptian Building Code, economically and easy for production.
2. The cracking pattern caused by compression loading can be categorized accordance to ASTM C1314-14 as present for ungrouted prisms a cone and split type, and for grouted prism as a face shell separation.
3. Using one reinforced grouted hole or two grouted holes without steel reinforcement are the optimum.
4. The high strength in the P-2MC is coming from loading the reinforcement bars individually after prisms failure.
5. The mathematical representation of brick samples was very successful in predicting their actual behavior.
6. To avoid the limitations observed by studying , the prepare of compressed bricks near the workplace due to its relatively heavy weight compared to traditional bricks is must. The exterior face apperance of the blocks is affected over time by the surrounding atmosphere, for that it is recommend to paint the exterior face of the wall with a layer of varnish.

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