

COMPRESSIVE STRENGTH TEST OF INTERLOCKED BLOCKS MADE WITH HIGH-MECHANICAL-PERFORMANCE MORTARS

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ABSTRACT

Conventional masonry pieces are simple construction elements used to build houses for a long time. Nevertheless, the rapid growth in the demand for social and middle-class housing in developing countries has forced engineers to develop cheaper and new creation processes and systems with better features and qualities. In this sense, to obtain an optimization in masonry pieces, the following must be considered: 1) the material from which it is fabricated and 2) the design (shapes and geometry). As an alternative, in this work, we present the design of interlocked concrete blocks that measure 12.5 cm wide, 25 cm in height, and 40 cm in length, made with mortar mixtures with high mechanical performance, with which wall sections were built (masonry assemblies of 62.5 × 60 × 12.5 cm and prisms of 62.5 × 40 × 12.5 cm) and then characterized according to standards of the mechanical compression tests. The obtained mechanical compressive strengths were 177.72 kg/cm² in the unitary masonry pieces, 47.4 kg/cm² in prisms, and 3.98 kg/cm² in diagonal compression tests. This type of masonry materials and their assembly procedure can be useful for the manufacture of middle-income and social housing in developing countries.

1. Introduction

Nowadays, masonry units represent a large part of the constructed surroundings, it is estimated that 80% of the world's population lives in houses built with this type of construction material [1]. The fabrication of structural walls, made by assembling masonry pieces such as clay bricks and

concrete blocks using a mortar bed between 10 and 20 mm, is normally the most used system for the construction of low-income and social (middle-income) housing in the Metropolitan Area of Mexico.

The popularity of masonry construction is due, among other aspects, to its low cost, the local availability of the necessary materials, and the use of traditional construction techniques. Masonry blocks can be made from a variety of materials, types, and dimensions, and can be placed in different ways, normally using a thin mortar layer (≈ 2 cm) that allows linking the blocks. The union mortar can also be made with different types of conglomerates and sand, mixed with water. The mechanical properties of blocks and mortars are very different due to the components that constitute them, from its manufacturing process, their geometry, and size; therefore, when a set of masonry blocks united by a series of mortar layers is subjected to a compression load, a complex interaction appears in the transition zones.

Thus, lately, it has been decided the develop of new systems, methods, and procedures to build masonry, to try to eliminate some of the disadvantages of traditional methods in wall construction, for this, interlaced masonry blocks with dry piled system have been explored; it is well-known as mortarless masonry technology. This technology replaces conventional masonry construction by eliminating mortar layers, for masonry units with special characteristics in their geometry, which are mechanically interconnected through slots, unions, or tongue pieces that facilitate interlocking and load transfer [2].

Interlocked blocks have the advantage of accelerating masonry construction and/or improving the structural behavior of walls [3]. The interlaced masonry systems reported [4] are varied and adapted in terms of their mechanical performance, and most of these systems have being patented [5]. Currently, there are no specific construction regulations applicable to these systems, so they are governed by the constitutive laws of traditional masonry. Some masonry systems with interlocking blocks reported in the literature are the following: Mecano system [6], Sparfil [7], Haener [8], modified Hblock [9], Sparlock [10], WHD block [11], the Solbric and Hydraform systems [12], the Bamba, Auram, and Tanzanian systems [13], among others.

These systems have a series of advantages with respect to traditional masonry processes, such as the positioning of the blocks being simple and requiring less skilled labor. With this, the construction of the walls is faster, which leads to higher productivity [14, 15]. As they are done without a mortar bed, construction inaccuracies due to manual work are eliminated and problems associated with the specific properties of the mortar used to join the masonry blocks are also overcome [13]. In addition to facilitate the construction processes [16, 17], the technical use of these aids to promote sustainable construction [18] and the construction of structures with high mechanical resistance [19, 20, 21] that have been successfully investigated in areas of high seismicity [22, 23, 24, 25].

The constructive system based on the use of interlocking masonry blocks has been widely used in several developing countries in such a way that it has gradually replaced conventional masonry procedures [26]. On the other hand, in Mexico, many of the masonry pieces that are currently used in conventional constructive processes do not meet the minimum requirements related to mechanical performance established by the local norms, due to the lack of control in the manufacture of the pieces and the erroneous use of materials for its manufacture

[27, 28, 29, 30, 31]. Furthermore, interlocked block/based construction methods in Mexico are very few. In this sense, the intention of this investigation, in the first term, is to show the process to develop a high-mechanical-performance mortar and its implementation in the manufacture of interlocking masonry pieces, capable of being used in construction systems, and the second, the design, construction, and testing of the mechanical resistance of the manufactured blocks.

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2. Design and testing of the mortar used to manufacture the interlocked blocks

2.1 Materials used for the manufacture of mortars

The cement used was Portland 30 R type, which is widely commercialized in the center of the Mexican Republic, mainly in the State of Mexico, Mexico City, Puebla, Hidalgo, and Querétaro, which makes it one of the most used brands in the construction and auto-construction. The fine aggregates for the preparation of the mixtures were sands of “pink color” obtained from the quarries of the volcanic zone to the east of Mexico City, whose mineralogical composition is described in the reference (Table 1) [32].

Name of the Phase/Database of reference

Albita [30]

Low Albita [31]

Anortita sodiana [32]

Celedonita [33]

Cuarzo [34]

Richterita [35]

Sanidina [36]

Chemical formulas

$\text{Na}_{0.983}\text{Ca}_{0.012}\text{K}_{0.005}\text{AlSi}_3\text{O}_8$

$\text{NaAlSi}_3\text{O}_8$

$\text{Na}_{0.48}\text{Ca}_{0.52}\text{Al}_{1.52}\text{Si}_{2.48}\text{O}_8$

$\text{K}(\text{Mg}_{0.78}\text{Fe}_{1.22})\text{Si}_4\text{O}_{10}(\text{OH})_2$

SiO_2

$\text{Na}_{1.62}\text{Mg}_{6.19}\text{Si}_3(\text{O}_{22})(\text{OH})_2$

$\text{KFe}_{0.5}\text{Si}_{3.0}\text{Al}_{0.49}\text{O}_8$

Table 1.

Mineral identification of the aggregate – pink sand.

As reported by Muciño A. et. to. [32], the “pink” sand used in the elaborated mortar mixtures has the following mineralogical composition [32].

To make the mixtures, drinking water from the municipal network was used, a plasticizer additive, and finally, polypropylene microfiber, another additive, whose main function is to act as a secondary reinforcement of the mortar.

2.2 Sands characterization

A granulometric analysis was carried out on the sands, which is established in the ASTM- C 136 standard [30]. The process consisted of mechanically separating an aggregate sample (200 grams), previously dried in the oven at $110 \pm 5^\circ\text{C}$ [31], through a series of sieves with openings established progressively smaller than the norm, to determine the sizes and the gross weight of each size with respect to the total number of particles.

The data obtained from this analysis are represented in the form of a curve, where the percentage of weight that passes through the mesh is plotted on the ordered axis and the diameter of particles

on the abscissa. [Figure 1](#) shows the granulometric curve of the sand used in the experimentation.

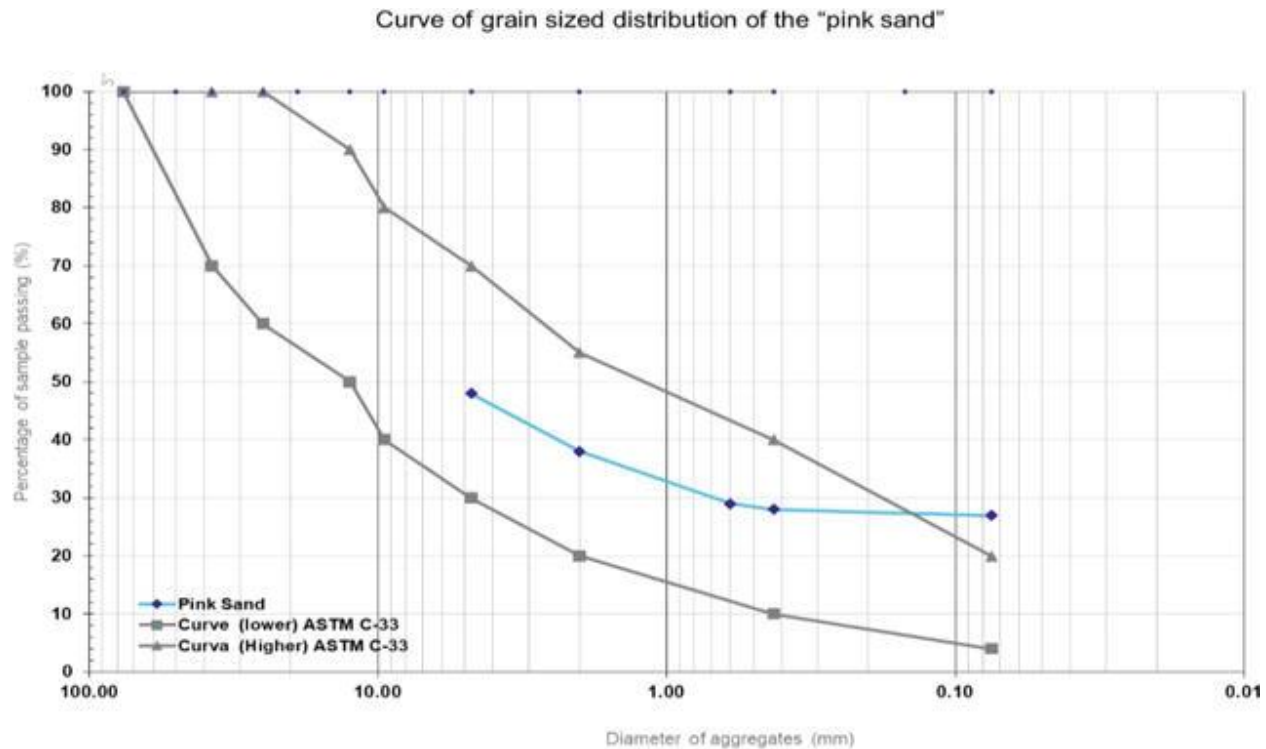


Figure 1.

Grain-sized distribution of the “pink” sand used in the manufacture of mortars.

2.3 Mortar mixtures

According to what is established for high-mechanical-performance concrete by the American National Institute of Science and Technology (NIST) and the American Concrete Institute (ACI), high-performance concrete is homogeneous, made with high-quality components, with good adherence, without segregation, and its mechanical properties must be stable and with high early strength [33].

Therefore, cement mixtures were made with water, sand, and additives following the ASTM C-109 standard trying to obtain the physical and mechanical properties of a high-performance mortar, by implementing best practices and mixing designs, based on the aforementioned definition. The ASTM C109 standard describes the test method and the necessary conditions for the determination of the compressive strength of hydraulic cement mortars in cubic specimens with a side of 2 inches [34, 35].

[Table 2](#) shows the quantities of the materials used for the preparation of five cubic specimens (5×5×5 cm) for each type of mixture (M1, M2, and M3), used for each day of the compressive strength test (1, 3, 7, 14, and 28 days). All the mixtures were prepared in a ratio of 1:2.75 (cement-sand), as follows: the first mixture, M1, was taken as a reference and was prepared with cement-sand and drinking water from the municipal network, while M2 mixture was added with a

superplasticizer as an additive, and M3 mixture, apart from the additive, was also added with polypropylene microfiber.

Type of mortar	Volume of cm3	Cement Grams	Sand Grams	Water Grams	Proportion - ASTM 109	Plasticizer C-w/c Grams	Polypropylene microfibers Grams
M1	3125.0	1641.5	4514.1	1477.4	1: 2.75	0.90 —	—
M2	3125.0	1641.5	4514.1	574.4	1: 2.75	0.35 528.8	—
M3	3125.0	1641.5	4514.1	574.4	1: 2.75	0.35 528.8	31.9

Table 2.

Mortar mixtures with additives (M2–M3) and without additives (M1).

For each mixture and by every day of the test five buckets were used, with a volume of 125 buckets of cm3, for 3125 a total volume of cm3 by the 25 buckets, for each type of mixture and by every day of the test (column 2), for this volume 1641.5 grams of cement (column 3) and 4514.1 grams of sand were used (column 4), the M1 mixture required 1477.4 grams of water so that the consistency was fluid and workable, for mixture 3 and 4, 574.4 grams of water was used to obtain the same workability and fluidity that the M1 mixture (column 5), obtaining a relation cementitious water of 0.9, 0.35, and 0.35 for mixes M1, M2, and M3, respectively (column 7), to the mixture M2 and M3 528,8 grams of superplasticization additive (column 8) was added, and finally to the M3 mixture, aside from the plasticizer, 31.9 grams of microfibers of polypropylene were added (column 9).

The amount of the materials used was established by employing a previous sampling of the mixtures to obtain the optimal quantity of additives in each one of them. Thus, in the fresh state, the parameters considered essential were fluidity and setting, while in the hard state, it was the compressive strength.

2.4 Compressive strength of mortar

The manufacturing process was as follows: the mortar materials were mixed manually and spilled into molds of established dimensions (50 mm by side). Subsequently, they were subjected to mechanical vibrations to guarantee the release of possible air bubbles. After 24 hours, the samples were removed from molds and left to stand at room temperature. To ensure the perpendicularity between faces, the samples were treated under a mechanical rectified process. So, the treatment guaranteed a homogeneous distribution of stresses during the compression tests. The compressive strength tests were carried out in an INSTRON hydraulic compression machine (model 400RD-E1-H2) at a load rate of 1 kN/second until rupture [34].

The compression at break was obtained from the average of 3–5 tested cubes, declaring the relationship between the total load supported during the test and the contact area of the cube section. [Figure 2](#) shows the compressive strength values at 28 days for the three mixtures.

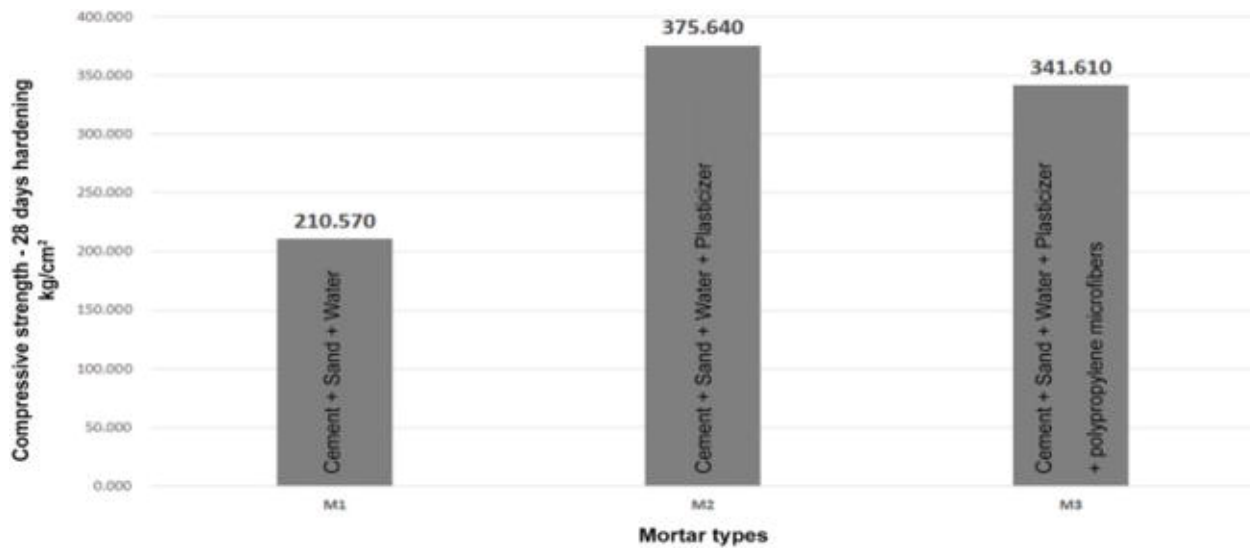


Figure 2.

Maximum breaking strength in compression test for mixtures M1, M2, and M3 at 28 days of hardening.

In this research, for the manufacture of the blocks, the M3 mixture (cement, sand, water, plasticizer, and micro polypropylene fibers) was selected, due to the ductile behavior of the material, when reaching the breaking point, the mortar bucket was not disintegrated, as the M1 and M2 mixtures (Figure 3a and b), and the time to reach its last state of failure was greater, being an important aspect in the performance of a structural element.

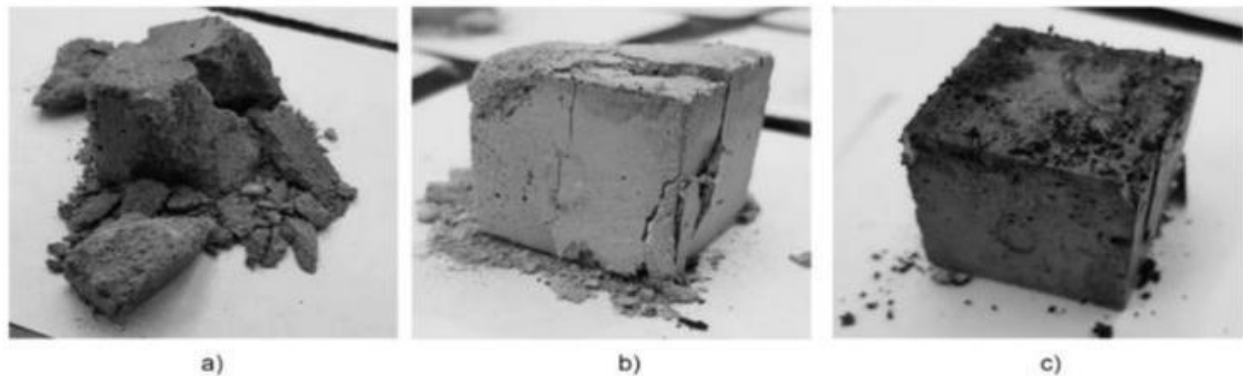


Figure 3.

Samples after the compressive strength test. Mixtures: a) M1; reference mortar, b) M2; mortar with plasticizer, c) M3; mortar with microfibers and plasticizer.

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3. Interlocking block system design

The block designed with high mechanical resistance to compression mortar is a solid piece since

it has a net area $>75\%$ of the gross area and its internal and external walls have a thickness of 30 mm (Figure 4a), fulfilling the requirements established in NMX-C-404-ONNNCCCE norm [36]. The block is prismatic in shape and has a smooth face, is made up of two pieces, a female piece, and a male piece (Figure 4b) that allow mechanical union, in such a way that the use of impact mortar to join them is avoided.

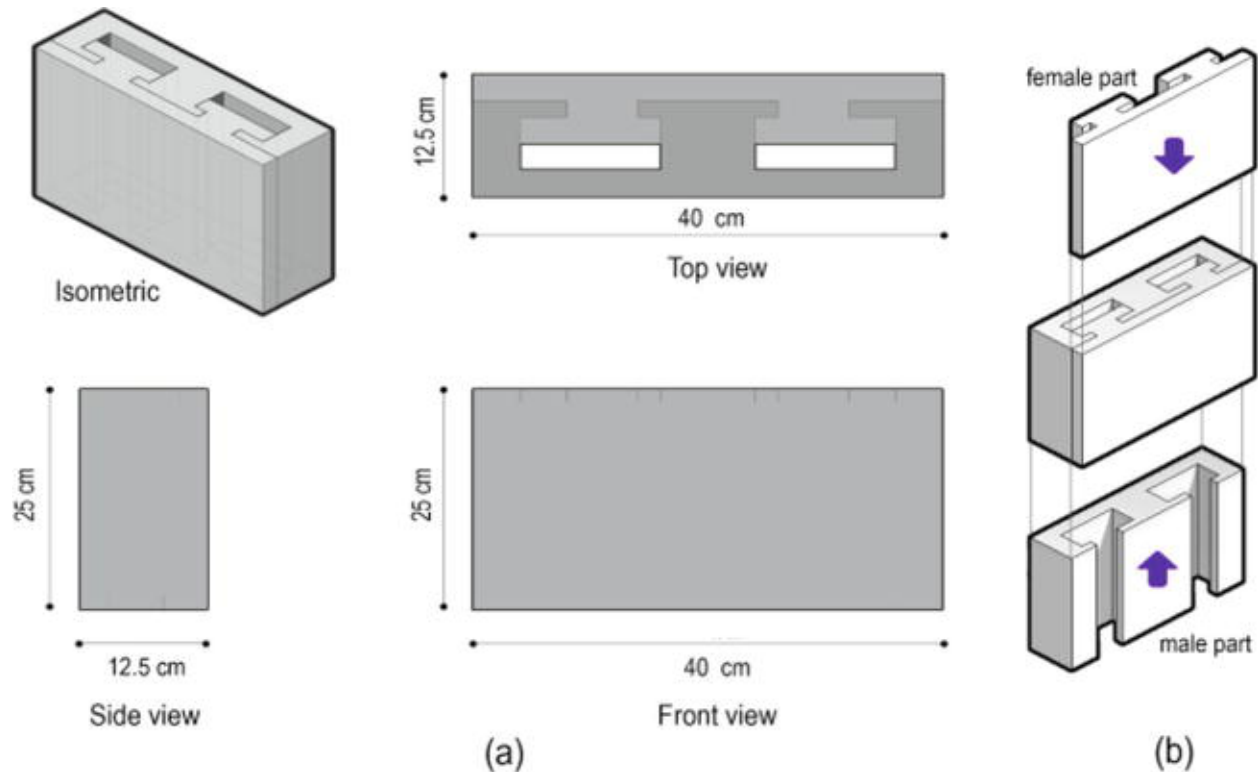


Figure 4.

a) Isometric and plans of the designed block, with dimensions of 40 centimeters long, 25 centimeters high, and 12,5 centimeters wide. b) Form of union of the block that consists of two pieces, a female piece, and a male piece.

3.1 Manufacture of interlocking blocks

The elements of the interlocking blocks (Figure 5) made by manual draining of the M3 mixture described in Table 2 were made in wooden molds with the appropriate dimensions (Figure 6). After 10 days of air drying under ambient conditions (temperature and humidity), the units were demolded (Figure 7) to be subjected to compression tests after 28 days of hardening.

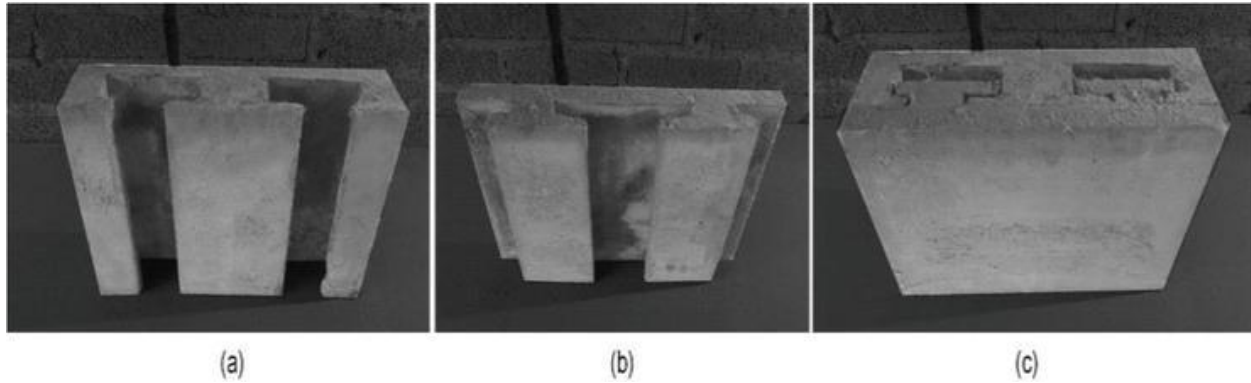


Figure 5.

a) Male piece, b) female piece, c) assembled block.

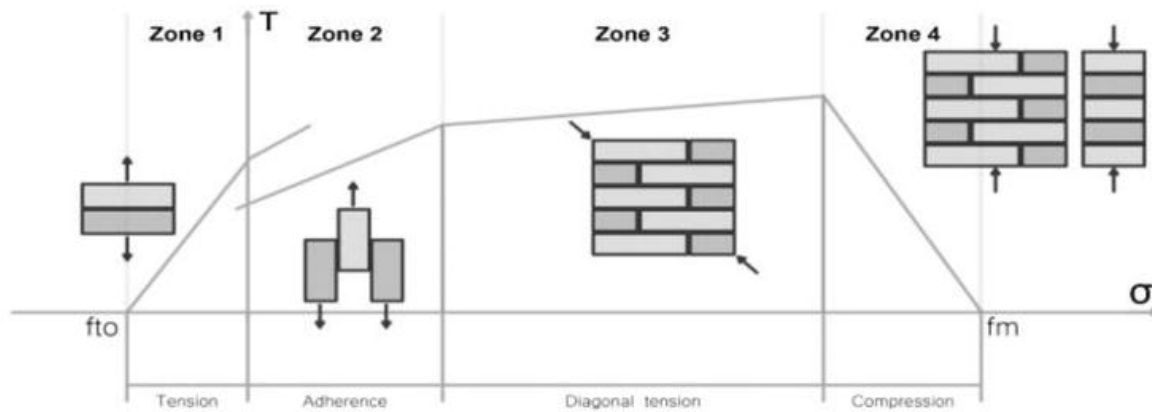


Figure 6.

Types of tests in masonry specimens made with blocks adhered with mortar a) Zone 1 – Tension, b) Zone 2 – Court, c) Zone 3 – Diagonal Compression, d) Zone 4 – Vertical Compression [37].

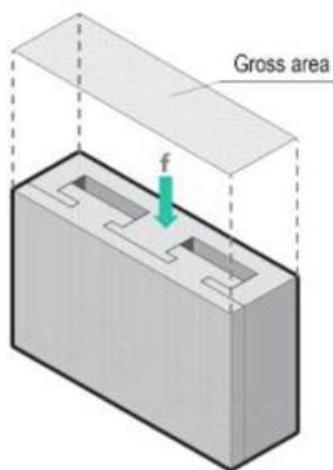


Figure 7.

Diagram of the simple compressive strength test for interlocking concrete blocks.

3.2 Compressive strength test of the proposed system

The characterization of the mechanical performance of masonry elements made with blocks adhered by mortar bed is made from four tests: adhesion between blocks by traction and shear, resistance to a vertical compression fracture in block prisms and diagonal compression masonry assemblies (Figure 7) [38]. In this case, due to the type of union of the designed blocks and the construction process of the masonry, only the mechanical performance was considered from the last two tests, that is, axial compressive strength in prisms and diagonal compressive strength in masonry assemblies (Figure 8).

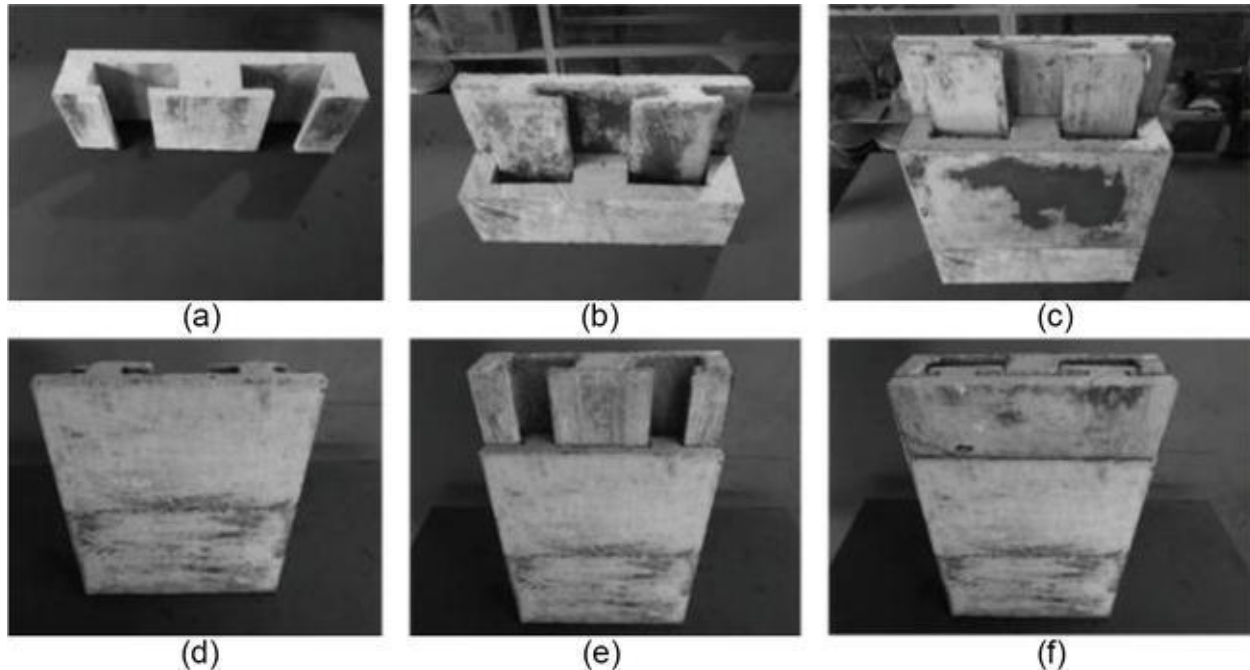


Figure 8.

Joint or manufacture of the prisms of interlaced blocks.

3.3 Compressive strength test of interlocking blocks

The compressive strength tests of the interlocking blocks were based on the NMX-C-404-ONNCCE standard. The NMX C404 is a Mexican standard that evaluates masonry pieces for structural use, describing dimensions, shape, test methods, classification, specifications in the way of placing the pieces, and the values of compressive strength by type of piece [36]. Five blocks made with the M3 mixture (polypropylene sand, cement, water, fluidizer, and fiber) reported in Table 2 were tested applying the load between the upper and lower face of each one of the blocks. In all cases, the specimens that did not present visible cracks and with good parallelism between their upper and lower faces were chosen, making sure to align vertically, horizontally, and the center of the block with the steel plate of the testing machine (ELE, 36-3088/02, series 040700000005), at a loading rate of 180 kg/cm²/min, according to the standard [36].

The compression of the blocks was obtained by dividing the fully factored load recorded by the

total cross-sectional area of the sample (gross area) of a perpendicular section to the direction of the load, without discounting the gap (Figure 7), using the Formula 1, established in the NMX-C-036-ONNCCE standard [39].

$$f_p = P/A \quad f_{p1} = P/AE_1$$

Where f_{p1} is the compressive strength, P is the total factored load supported by the block, and A is the cross-section of the gross or total area of the specimen.

Nevertheless, for design processes and calculations, the compressive design resistance (f^*_{p1}) must be obtained using Formula 2, established by the NMX-C-404-ONNCCE standard [36].

$$f^*_{p1} = f_p / (1 + 2.5C_p) \quad f^*_{p1} = f_p / (1 + 2.5C_p E_2)$$

Where f_{p1} is the average compressive strength of five pieces using Formula 1, and C_p is a coefficient of variation of the compressive strength of the pieces, established in the NMX-C-404-ONNCCE standard, which will be taken as 0.35 for manufactured pieces or artisanal production and that do not have a quality control system, 0.30 for machining plants that do not have a quality control system, 0.20 for machining plants that demonstrate having a quality control system [36]. The results are shown in Table 3.

Test	Norm	Sample	Area cm	Maximum load kgf	Individual compressive strength (fp) kg/cm²	Medium compressive strength (f* p) kg/cm²
Compressive strength of pieces of block of concrete	NMX-C-404- ONNCCE- 2012	1	496.17	92130	186.68	177.72
		2	498.75	88780	178.01	
		3	498.33	85720	172.01	
		4	497.5	118100	237.39	
		5	456.5	118100	223.79	
Promedio:				193.27		

Table 3.

Results obtained from the compressive strength of concrete block pieces.

3.4 Fabrication of interlocked concrete block masonry and prism assemblies

For the compression test of prism and masonry assemblies made by joining and mechanical joining of the designed blocks, a total of three panels thick were made with specific dimensions, 40 centimeters in long, 62.5 centimeters stop, and 12.5 centimeters of thickness, in the case of the prisms (Figure 9a), and three panels with dimensions of 60 centimeters in length, 62.5 centimeters of stop, and 12.5 centimeters of thickness (Figure 9b), for the case of masonry assemblages, following that established in NMX-C-464-ONNCCE standard (Figure 10) [40].

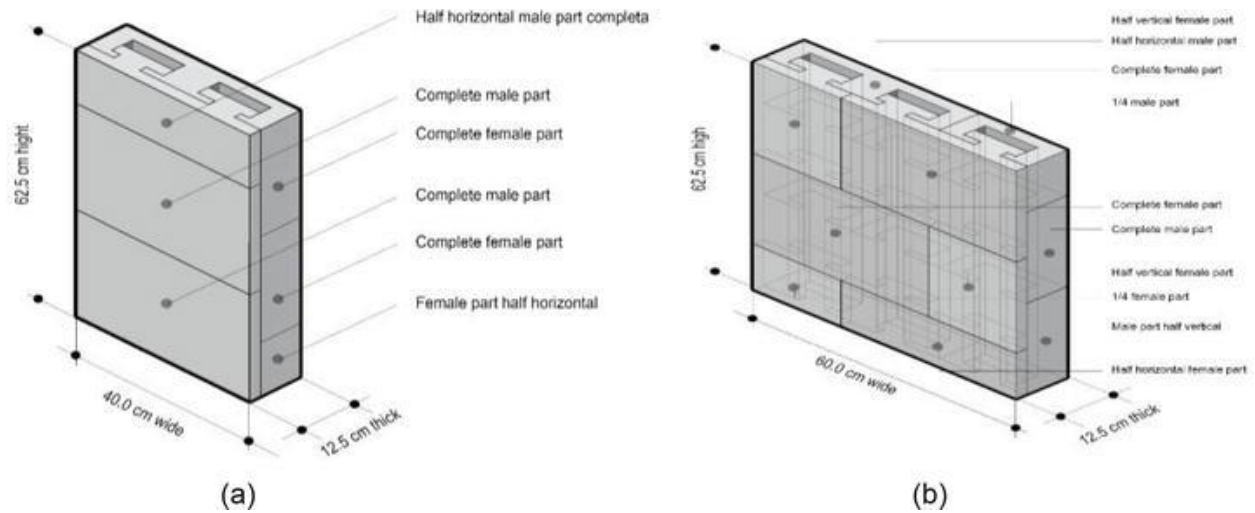


Figure 9.

Diagram of armed and dimensions of prisms and masonry assemblies made with interlocked mortar blocks.

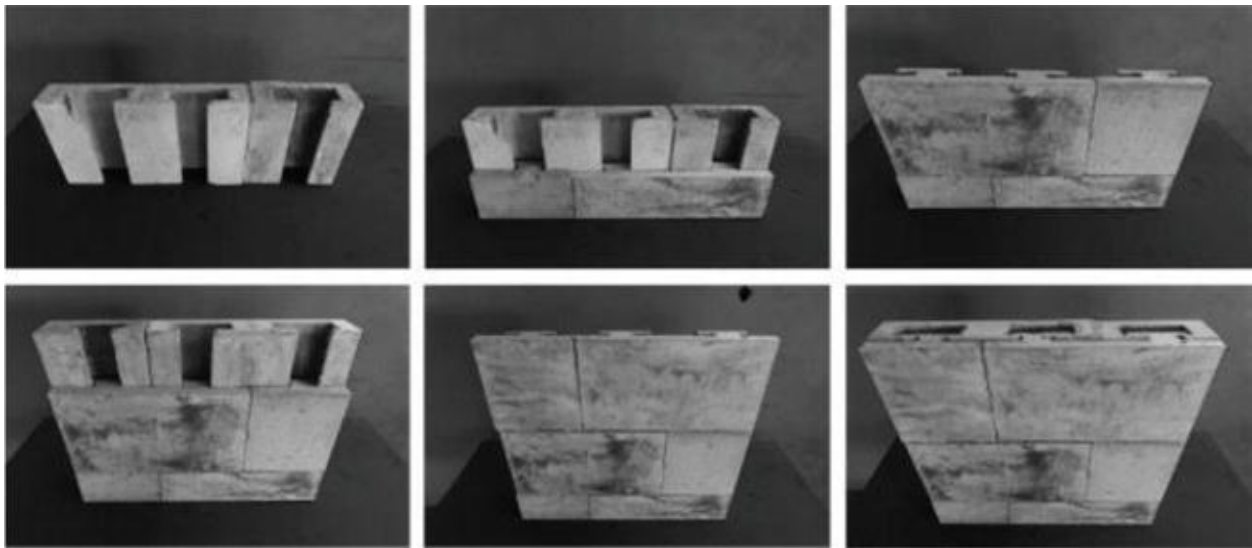


Figure 10.

Joint or manufacture of the masonry assemblages of interlaced blocks.

3.5 Axial compressive strength test of interlocking concrete block prisms

The determination of compressive strength of masonry was by testing three prisms of the same dimensions, which are built with the same type of pieces and technique. For this test, an ELE compression machine (model 1987AFE-X1) was used. This machine has a cushion made of steel plates. The female-male interlocking concrete blocks were placed edge to the steel plate with a thickness equal or greater than a third of the distance of the load-bearing block to the farthest corner of the sample, guaranteeing uniform distribution of the load according to the standard used

[40]. The loading rate was 1.5 kg/cm²/seg [40].

The compressive strength of the prism was calculated according to the stipulated in NMX-C-464-ONNCCE standard [40], dividing the total factored load supported during the test by the gross load area of the prism (Figure 11), determined as an average of at least three of the pieces of the prism (Formula 3). The result is expressed to an approximation of 0.01 MPa (0,1 kg/cm²), and the resistance obtained is multiplied by the correction factor for slenderness indicated in Table 4 [40].

$$f_m = P / (b \times t \times \text{slenderness factor})$$

Where f_m is the compressive strength of the prism in MPa (kg/cm²), P is the total applied load in N (kg), t is the thickness of the prisms in mm (cm), and b is the width of the prisms in mm (cm), the slenderness factor is indicated in Table 5.

Test	Norm	Sample	Large de la pila (mm; cm)	Prism thickness (mm; cm)	prism height (mm; cm)	Area	Slenderness ratio	Correction factor	Maximum load (N; kgf)	Compressive strength (kg/cm ²)	Design Compressive strength (kg/cm ²)
Compressive strength concrete block piles	NMX-C-464-ONNCCE-2012	1	40	12.5	62.5	500	5.00	1.0521	30972.9	65.17	
		2	40	12.5	62.5	500	5	1.0521	27498.3	57.86	47.4
		3	40	12.5	62.5	500	5	1.0521	25939.3	54.58	

Table 4.

Results obtained from the compressive strength in prisms made with concrete block of interlaces.

Stack slenderness ratio	Corrective factor
2	0.750
3	0.900
4	1.000
5	1.050
6	1.060

Table 5.

Correction factors for slenderness of the prisms obtained from [40].

The design compressive strength is calculated with Formula 4, established in the standard [40]:

$$f^*m = f_m / (1 + 2.5C_m) \quad f_m^* = f_m / (1 + 2.5C_m)$$

Where f^*m is the compressive strength for design purposes in MPa (kg/cm²), f_m is the average of the resistant efforts of the tested prisms; referred to the gross area give MPa (kg/cm²), and C_m is the coefficient of variation of the resistant efforts of the tested prisms, calculated as the quotient of the standard deviation between the average, and that should not be taken less than 0.10 in the case of verifying the quality control in work, nor that 0.15 in the other cases, according to what is established in the Mexican standard: NMX-C-464-ONNCCE [40]. The results are

summarized in [Table 4](#).

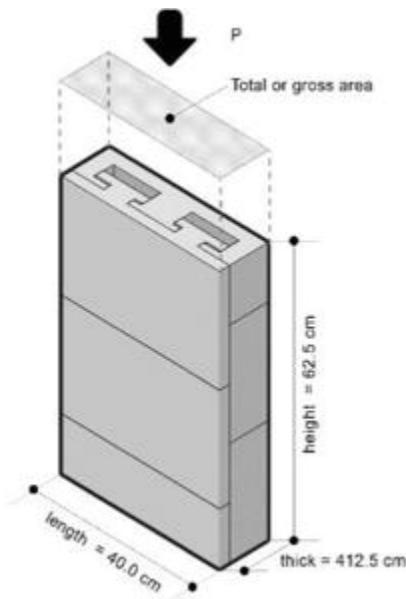


Figure 11.

Diagram of compressive strength in prisms made with blocks of concrete interlaces.

3.6 Diagonal compressive strength on the panel made with interlocking concrete blocks

[Figure 12](#) shows the diagonal compressive strength test system for masonry assembly. For this test, a load was applied along with one of the diagonals of the specimen. This process is established by NMX-C-464-ONNCCE [\[40\]](#). Briefly, before the total load, masonry assemblies are carefully aligned to the axis of the machine with the axis of the sample. According to the same standard [\[40\]](#), three cycles of preload with 15% of the total load should be applied (20 kg/cm^2). Finally, the loading rate was of $1.5 \text{ kg/cm}^2/\text{seg}$ [\[40\]](#). These tests were done in an ELE compression testing machine (model 1987AFE-X1). Three masonry assemblies were tested, as established by the NMX-C-464-ONNCCE standard [\[40\]](#).



Figure 12.

Diagonal compressive strength test system for masonry assemblies made with interlocking concrete blocks, obtained, and adapted from the NMX-C-464-ONNCCE standard [40].

The diagonal compression resistance was obtained using Formula 5 established in the NMX-C-464-ONNCCE standard [40], which defines the resistance of each wall as the ratio between the total factored load and the gross area of the masonry assemblies. The latter is obtained from the product of the thickness of the masonry assemblies (t) by the length of the compression diagonal (L_c) (Figures 13 and 14) measured before the test.

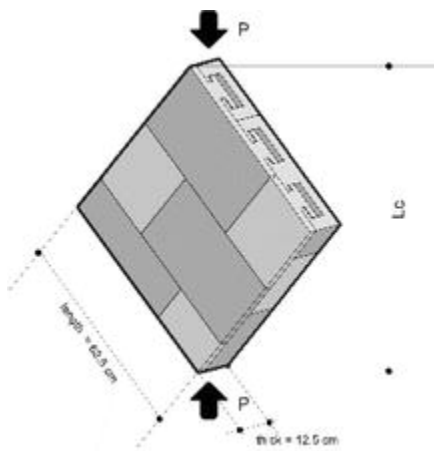


Figure 13.

Diagonal compressive strength diagram for masonry assemblies made with interlocking concrete blocks.

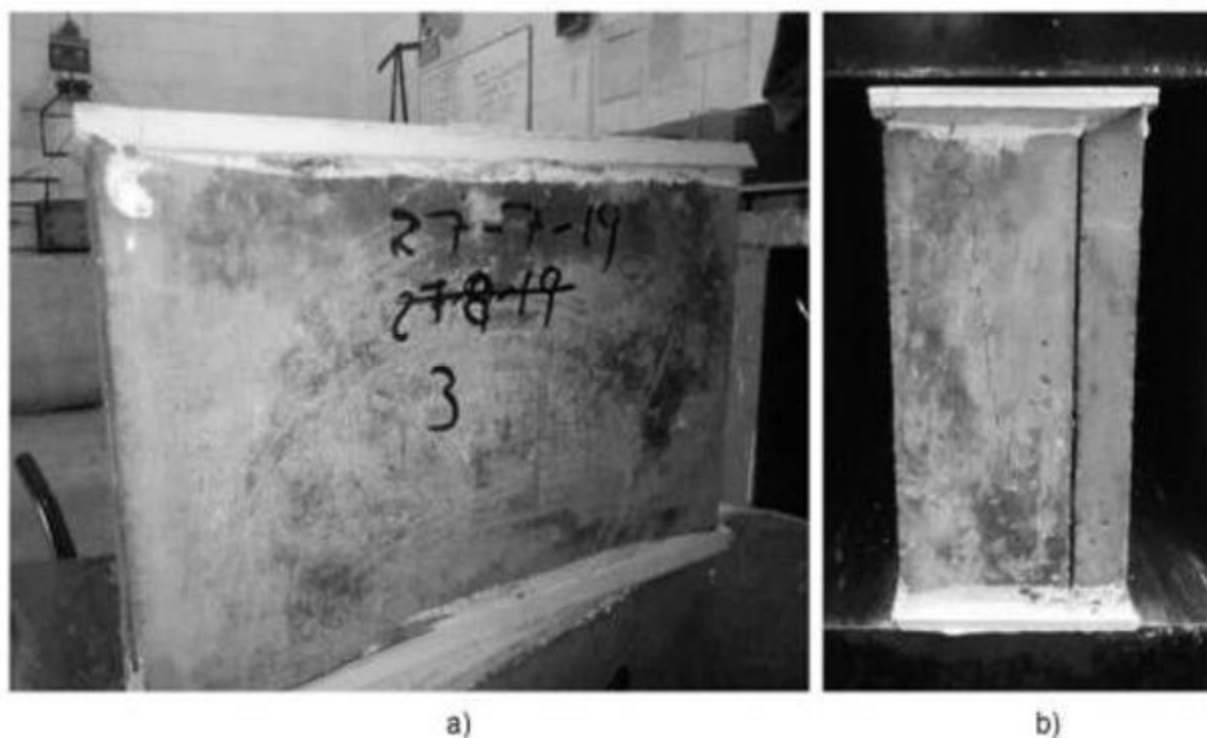


Figure 14.

a) Female-male concrete block after the compressive strength test, b) typical cracking on the lateral faces of the female-male concrete blocks after the compressive strength test.

$$v_m = P / t L_c \quad v_m = P / t L_c E_5$$

Where V_m is the diagonal compressive strength of the masonry assemblies in MPa (kg/cm^2), P is the total applied load in N (kgf), t is the thickness of the masonry assemblies in mm (cm), and L_c is the length of the compression diagonal in mm (cm).

The compression resistance due to diagonal traction for design purposes is calculated using Formula 6 established in Standard NMX-C-464-ONNCC [40]:

$$v^* m = v_m / 1 + 2.5 C_v \quad v^* m = v_m / 1 + 2.5 C_v E_6$$

Where $v^* m$ is diagonal compressive strength for design purposes in MPa (kg/cm^2), V_m is the average of the resistant stresses of the tested masonry assemblies referred to the gross area in MPa (kg/cm^2), C_v is the coefficient of variation of the resistant efforts of masonry assemblies tested, calculated as the quotient of the standard deviation between the average and which should not be taken less than 0.10 in the case of verifying the quality control on-site, nor than 0.20 in other cases [40], obtaining the results in Table 6.

Test	Norm	Sample	Maximum load (N; kgf)	Die thickness (mm; cm)	Diagonal length (mm; cm)	Diagonal compressive strength (kg/cm ²)	Diagonal compressive strength (kg/cm ²)
Diagonal compression of dies manufactured with tongue-and-groove block	NMX-C-404-ONNCCE-2012	1	5233.7	12	86	5.07	3.98
		2	4835.3	12	87	4.63	
		3	5445.7	12	87	5.22	

Table 6.

Results obtained from the compressive strength in masonry assemblages diagonal made with concrete block of interlaces.

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4. Discussion of results

4.1 Mortar mixtures

High-performance mortars must have the following characteristics [41, 42, 43, 44]:

1. In their fresh state, they must be able to flow with good adhesion, to be placed without segregation or stratification, and must have an excellent performance on construction sites.
2. Hard mortars must have high mechanical resistance to compression.
3. In the hardened state, they must have high volume stability, i.e., low shrinkage and low warpage.
4. They must have discharge durability.

To obtain these benefits, new technologies have been developed: On the one hand, a meticulous selection of the particle size of the high-quality stone aggregates achieving the adequate packing of these elements in the prepared mixtures. The uses of additives allow to adjust the physical-chemical properties of hydrated calcium silicates (CSH) that constitute the binder that provides the mechanical properties to concrete and mortar [45].

Figure 4 shows the effect that the additives have on the compression fracture of the mixture M3 (plasticizer and polypropylene microfibers (Figure 4c), concerning the mixtures M1 (Figure 4a) and M2 (Figure 4b). In the M1 mortars, used as a reference, made with sand, cement, and water, the almost total disintegration of the material is observed when the fracture point is reached. In the remaining cases, samples M2 and M3, the disintegration is partial. In the case of M2 samples (mixture with fluidizer), the shape of the piece is maintained, and multiple cracks only appear at the moment of rupture. In the case of M3 samples (mixture with fluidizer and polypropylene microfibers), the piece integrity is almost total with some cracks. These results clearly show the effect of fluidizers and polypropylene microfibers on the structural integrity of mortars. The effect of these additives is also observed in the mechanical performance of the mixtures, with the

maximum breaking strength being 210.57 kg/cm² for the mixture M1. In the case of mixtures M2 and M3, these values were 375.64 and 341.64 M3 kg/cm², respectively, showing an increase of >60% of the mechanical resistance when the additives are added, this is mainly due to the reduction of the water-cement ratio [46]. As a reference and for the case of Mexico City, fracture resistance values in compression of a type 1 structural mortar are 180 kg/cm², with mixture M1 and mixture M2 between 180% and 200% above the accepted value by this standard [37]. Although the mechanical resistance to fracture of the M2 mix is higher than that of the M3 mix (around 9% less than M3), the structural integrity observed in the latter (Figure 4c) makes it a candidate to be used in masonry constructions in areas of high seismicity. Moreover, there is the greatest possible ductility so that the structure can dissipate the greatest amount of energy in the event of an earthquake.

4.2 Concrete blocks

As already mentioned, M3 mix was chosen to build the interlocking concrete blocks, under the hypothesis that resilient masonry systems with good mechanical performance could be made with them, manufacturing blocks with dimensions of 40 cm long x 25 cm high x 12,5 cm wide and taking them to compressive strength tests after 28 days, and for both pieces, the wall, and the prism systems. Table 7 compares the design resistance to compression of the blocks, masonry assemblies, and prisms made, referring to the compressive strength requirements of common masonry with concrete blocks and cement mortar, required by the Complementary Practical Standards of Masonry of Mexico City.

Test	Design (kg/cm ²) NORMATIVE	strength Design (kg/cm ²) PROJECT	strength
Block	150	180	✓
Prims	25–100	47.4	✓
Assemblage	2.0	3.98	✓

Table 7.

Comparison of results obtained from the compressive design resistance of blocks, prisms, and interlocking concrete block masonry assemblies vs. the resistance established in the NMX-C-464-ONNCCE and NMX-C-036-ONNCCE standards for pieces, prisms, and masonry concrete block assemblies.

The results of Table 7 show that the average compressive strength of the interlocking blocks exceeds the established on the NMX-C-036-ONNCCE standard (150 kg/cm²) by almost 30 kg/cm², although for some individual cases from these blocks, values close to 200 kg/cm² were obtained, i.e., 50 kg/cm² above what was established. This indicates that it is possible to increase the mechanical performance of the blocks made with the M3 mixture.

Another advantage of manufacturing the blocks with this type of mixture is that the fracture process did not lead to high fragmentation. This is because the polypropylene fibers act as a three-dimensional reinforcement in the mortar since they help to distribute internal tensile stresses and flexion of homogeneous compression and bending during compression tests, in addition to

reducing microcracks and cracks induced by temperature changes and plastic contraction during the mortar setting process during block manufacture.

The failure of the fiber-reinforced blocks occurs gradually, and the cracks derived from the test are visible extending through the lateral faces of the specimen. The fibers allow the blocks to resist a small increase in load after cracking and increase the toughness of the units.

On the other hand, and as we have already seen, the compressive strength in prisms made with interlocking blocks was 47.4 kg/cm^2 , higher than the average design strength required by the standard for prisms made with higher strength concrete blocks at 60 kg/cm^2 together with type 1 mortar that establishes a resistance of 25 kg/cm^2 , and lower prisms made with blocks with a resistance of 150 kg/cm^2 and joined with type 1 mortar where the required resistance is 75 kg/cm^2 , but very close prisms made with blocks with a resistance of 100 kg/cm^2 and type 1 mortar, where the minimum design resistance required by the standard is 50 kg/cm^2 .

During the application of the load, cracks were originated in the front faces of the prisms (long side in the female type pieces). Failure usually occurs from compression cracking or vertical cracking. This type of failure is produced by the difference in the deformable cross section between the pieces, generating tensile stresses in the latter. The fibers added to the concrete blocks help to withstand the stresses, thereby reducing and controlling the propagation of crack opening. As there are no lines of fragility as it is with a prism where the mortar intervenes suddenly, the concrete blocks work at their maximum capacity, generating a longer rupture or failure time compared with a prism adhered with mortar.

On the other hand, in the design resistance to diagonal compression of the masonry assembly, an average load of 3.9 kg/cm^2 was obtained, complying with the requirement established by the Mexican standard, which is 2 kg/cm^2 for solid pieces with the structural application; however, in the individual behavior of masonry assemblies, the highest resistances were obtained at 5 kg/cm^2 .

According to [47], masonry assemblies are the specimens that best capture the failure modes of structural masonry, since they consist of blocks joined by mortar through the aligned, continuous, or horizontal bed, and stepped vertical bed. This arrangement allows the polypropylene fibers to exhibit their explosion effect in the best way, since, although there is no encounter with the mortar, the stresses developed in the units are greater than in the blocks and prisms. This is basically due to two factors: first, the larger sample size, being less bound by the test device than the other samples. Second, the presence of dry or staggered butt joints results in higher stresses compared with prisms. Under these conditions, the fibers act as an effective reinforcement and can effectively contribute to improving the strength of the structural element.

In the test, the vertical load generates increasing tensile stresses that are oriented perpendicular to the load direction. This tensile stress field leads to the failure of masonry assemblies along a crack approximately perpendicular to the diagonal between the two loaded corners.

During the tests carried out on the masonry assemblies, it was observed that the fault was combined, since the pieces slipped due to lack of adhesion between them; however, when the pieces reached their maximum comfort of the displacement due to the system, the force that interacts on the overlaps between the blocks causes them to work as if it were normal masonry,

generating diagonal tensions where the cracks cross the pieces indistinctly. On the other hand, a form of ductile failure occurs since the adherence of the fiber-matrix allows the parts of the cracked elements to remain united, generating advantages for structural systems in seismic zones by having more ductile elements that give time to react to a total collapse. According to Mehta and Monteiro [46], fiber-reinforced concrete will suffer increasing loads after the first cracking of the matrix due to the resistance to fiber extraction. As the load increases, the fibers tend to transfer the additional stress to the surrounding matrix through the bonding stresses until fiber failure occurs or until the accumulated slip locally leads to fiber breakage.

5. Conclusions

In this study, an interlocking procedure of blocks made with structural class mortars with high mechanical resistance to compression is proposed as a construction method according to the Mexican standard. The resistances obtained in the experimentation of the compression of prisms (axial compression) and masonry assemblies (diagonal compression) made with those blocks comply with the values required by the standard for common masonry systems of ordinary structural blocks adhered to common concrete with hitting mortar. Therefore, the system developed in this research can be used in compression forces as an alternative to the conventional construction system, with the additional advantage that it represents the simplicity of the assembly for the manufacture of mechanical elements, the physical problem of the walls, and the reduction of and manufacturing between the stick mortar and the masonry, accelerating the production and reducing costs, as it does not require specialized equipment or labor.

The results obtained in the experimental process suggest that the construction method with load-bearing walls made with the type of blocks developed in this research can generate more efficient housing construction methods. Nevertheless, before establishing general conclusions about the mechanical behavior of masonry made with these blocks, additional studies and exhaustive tests related to the elastic constants of the wall sections must be carried out, to establish design criteria (failure limit state, serviceability limit state), design for durability, resistance factors, evaluate masonry walls through their confinement or interior reinforcement, to have elements that allow the foundation of structural calculation principles and ensure the performance of the masonry units or pieces in the present structural masonry systems, complying with the structural mechanical performance assumptions, such as the capacity for deformation and ductility, to guarantee the stability of a structure built with this system, according to normative annex A, “number of acceptance of defects of construction systems with masonry designed for earthquakes,” established in the complementary practical standards for the masonry of Mexico City. However, the acceptance or rejection of the new system will be the responsibility of the competent authority of Mexico City, which is the Construction Safety Institute, this unit will assess if the system complies with the current standard in force under the scientific, technical, and technological aspects.

Finally, a stress concentration analysis must be carried out to optimize the geometry of the interlocking blocks to avoid mechanical failure in weak areas, as well as generate a mixture of semi-wet or dry mortar to be able to optimize their industrial production.

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