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Article

Strength analysis of structural concrete blocks with five mixture materials

Análisis de resistencia de bloques de concreto estructural con cinco dosificaciones de materiales

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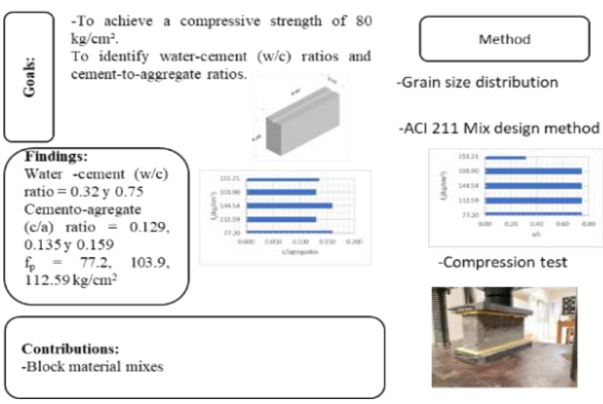
Abstract

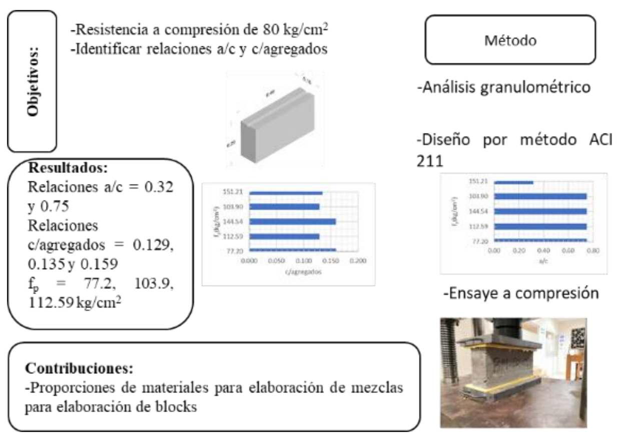
The structural system based on masonry walls is widely used in Mexico. Concrete block, one of its main components, exhibits significant variability in the material properties due to the frequent use of locally available resources for its production. Therefore, analyzing the physical properties of these blocks is essential. In this study, laboratory experiments were conducted considering five proposed mix designs. The water-cement ratios evaluated were 0.32 and 0.75, while the cement-to-aggregate ratios were 0.129, 0.135, and 0.159. The results indicate that both parameters significantly influence the compressive strength of the blocks, with higher strengths observed at lower water-cement ratios. Furthermore, the majority of the measured strengths exceeded the target value of 80 kg/cm².



Block, masonry, mixture materials

Resumen

El sistema estructural a base de muros de mampostería, es de uso frecuente en México. El block, es uno de los elementos que lo conforman y tiene la mayor variación en las propiedades de los materiales que lo componen, debido a que para su elaboración se utilizan generalmente materiales de la región. Por tal motivo, es importante analizar las propiedades físicas de estos. En el presente estudio, se presentan los resultados de experimentos de laboratorio considerando cinco dosificaciones propuestas, en las cuales se estudiaron relaciones agua-cemento de 0.32 y 0.75 y la relaciones cemento/agregados 0.129, 0.135 y 0.159. Los resultados indican, que ambos influyen en la resistencia a compresión de las piezas de blocks, presentándose la mayor resistencia a menores relaciones agua/cemento. La mayoría de las resistencias alcanzadas superan el valor objetivo de 80 kg/cm².



Block, mampostería, dosificaciones de materiales

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Introduction

Structural masonry is a widely used system in Mexico, so in addition to the existence of skilled labour, it is adapted to the different regions of the country. In an effort to standardise both the quality of the construction processes and the materials used, several standards have been established in Mexico, such as NMX-C-038 (2014), NMX-C-073 (2004), NMX-C-077 (1997), among others, as well as technical regulations including the NTC-DM (2023). These technical references include both procedures and minimum requirements for some masonry elements, including concrete blocks. Thus, for example, the NTC-DM (2017) updated the requirements for prismatic pieces made with materials available in the Valley of Mexico.

As an important reference in the update of the Mexican regulations, results of several studies were reported to improve the mixes to produce block pieces using aggregates available in the Valley of Mexico. Researchers analysed the properties of local materials and proposed optimal dosages that comply with current regulations, seeking to increase the compressive strength of the pieces. The studies included evaluation of the physical and mechanical properties of aggregates commonly used in manufacturing in the Valley of Mexico.

In addition, it was identified that aggregate properties can vary significantly even within the same region, which could affect the reproducibility of the proposed mixes in other regions. Important findings include that the implementation of the proposed mixes requires quality control during the manufacturing process, which represents a limitation for producers with limited resources and specifically for artisanal manufacturers (Tena *et al.*, 2017).

Similarly, another study identified the lack of a dosing method in the Ecuadorian industry for the production of hollow concrete blocks, they report that it is done empirically using lightweight aggregates such as pumice stone and fine sand. The study proposes the application of the ACI 211.2 (1998) method for lightweight structural concrete. The results allow improving the strength and quality of handmade products Villacís *et al*. (2020).

In the field of sustainability, results are reported that contribute both to the use of materials from the region and recycled materials, one of them is oriented to the use of recycled steel fibres from discarded tyres as reinforcement in soil-cement blocks. The results indicated that the addition of 1.5% fibre improved the compressive strength of the blocks by 20% compared to the non-fibre equivalent. In contrast, 0.75% showed no significant improvement. The study highlights the technical and environmental feasibility, proposing it as a sustainable alternative for the production of building materials from recycled materials. The researchers contribute with an alternative to improve building materials using recycled waste Oliveira *et al*. (2022).

Other contributions, including that related to the elaboration of a hybrid cement (Martínez-Gutiérrez *et al*., 2024) alkaline activated with sodium sulphate, indicate that replacing 10% of the fine aggregate with cork decreases compressive strength by 29%, but increases thermal conductivity by 32%, thus improving the thermal comfort of structural blocks. Studies have also been carried out concerning the use of construction waste (Molina *et al*., 2023) from demolition (CDW), which is a serious global environmental problem due to its high volume and impact.

The study discusses the manufacture of lightweight concrete blocks by incorporating CDW and ashes from thermoelectric power plants as an ecological and economical solution. Other researchers (Hossain *et al*., 2024) conducted an experimental test programme to measure parameters such as compressive strength and density, comparing blocks produced with different mixes of recycled and conventional aggregates. The results show that certain alternative aggregates allow the production of blocks with acceptable mechanical properties. They highlight that the use of recycled materials has the particularity that the quality and availability may vary according to the region, which could limit the standardisation or traceability of the results in terms of quality. Additionally (Guerra and Ruiz, 2024), other proposals include the incorporation of recycled glass fibres in concrete mixes for structural purposes, designed for an initial strength of 210 kg/cm², obtaining improvements in mechanical properties.

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Similar proposals (Soras, 2024) include aggregates of ground glass and expanded polystyrene, where it is observed that the strength decreased as the percentage of the latter material increased, due to its low density and adhesion in the mix.

Also noteworthy is the proposal that analyses the potential of oyster shell as a partial substitute or additive to reduce the exploitation of natural resources and promote recycling for concrete production. This study included percentages of crushed shell (5%, 10%, 15%, 20%) and as an additive (5%, 10%, 20%, 30%), in accordance with Mexican construction standards (De Dios-Suárez *et al.*, 2024). The results of this research are not focused on the use of concrete in the production of blocks, so it would be useful for other cases.

In addition to the use of recycled materials, studies are also reported on precast concrete blocks incorporating cabuya fibres and IP cement, considering five types of concrete blocks that consisted of adding 0.5%, 1.0%, 1.5%, 2.0% cabuya fibre. These studies indicate reduction of the thermal conductivity coefficient of the blocks, improvement of their thermal insulation capacity, as well as maintaining adequate mechanical properties (Laureano and Valladares, 2024).

Recently, the influence of both hollow and solid blocks was studied, considering the bonding mortar for masonry, for which the researchers (Rafi and Khan, 2024), carried out experimental tests of the mechanical properties of masonry prisms subjected to uniaxial compression. The tests considered specimens with solid and hollow prismatic geometry of 100 mm and 150 mm thickness, using five ratios of 1:2, 1:3, 1:4, 1:5 and 1:6 by weight. The results indicate that the failure mode and compressive behaviour is not significantly affected by the type of mortar, although there were differences between the solid and hollow block prisms in the post-peak region of the stress-strain curve of the tested specimen.

As can be seen, the literature review suggests that the use of recycled materials or materials from the region leads to diverse results, so that even though their use cannot be standardised or regulated, specific studies are required for materials from the region if the use of available materials is to be promoted.

In the absence of a database to try to generalise recommendations, the regulations in Mexico encourage further regional or local studies to be carried out in order to have results that broaden the current regulatory scope. Based on the above, the following results of studies of available materials in the Municipality of Carmen, Campeche are presented.

Methodology

The process of elaboration of concrete blocks requires previous steps, which start with the selection of the material based on previous experiences that have led to favourable results. However, the selection requires the availability of economic resources that are generally available at the industrial level. Another scenario to be solved is to propose dosages considering the material in the region.

The first step in the final design of the block pieces consists of selecting the material to be included in the mix, obtaining physical properties and carrying out the granulometric analysis of the fine and coarse aggregates. This analysis provides the general classification of the gradation of the material. In parallel, parameters including loose volumetric weight, loose volumetric weight, moisture percentage, absorption, fineness modulus and others are obtained.

The next step is to make the mixture from the proposed dosages. After the blocks have been produced, they must be cured for subsequent testing to verify the design strength parameters, which are generally considered to be the compressive strength, shear strength and absorption of the pieces. Thus, the values obtained are compared with the limits established in the design standards, in Mexico included in the standard NMX-C-441 (2013) for non-structural use with a minimum design strength of 35 kg/cm^2 and NMX-C-404 (2012) for structural use 60 kg/cm^2.

Material selection

In the municipality of Carmen, Campeche, there is no identified material bank that meets the technical requirements needed to produce the blocks. Therefore, the material used for the tests and the elaboration of specimens was purchased from a commercial establishment specialised in construction materials.

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These suppliers offer the inputs required for the manufacture of concrete blocks, including cement, sand, gravel, stone dust and granules.

Geometry of the block pieces

According to NTC-DS (2023), solid pieces are considered to be those with a net area of at least 75 % of the gross area in their most unfavourable cross-section, and whose outer walls have a thickness of not less than 20 mm. Hollow parts are those with a net area of at least 50 per cent of the gross area; also, the thickness of their outer walls is not less than 15 mm. For hollow parts with two to four cells, the minimum thickness of the inner walls is at least 13 mm. For multi-perforated parts, whose perforations are of the same dimensions and evenly distributed, the minimum thickness of the inner walls of 10 mm for concrete parts. In addition, the requirements for the thickness of the outer and inner walls indicated in NMX-C-404 (2012) for hollow and multiperforated pieces shall be complied with.

The geometry of the blocks that make up the masonry structural system is a key factor, since their various shapes and configurations directly influence the final strength of the pieces. For this reason, in the present investigation, specimens with rectangular geometry were elaborated, which allowed focusing the analysis on the influence of the proposed mix proportions. Previous studies by Lastra *et al*. (2021), Álvarez-Arellano *et al*. (2023) and Álvarez-Arellano *et al*. (2024) have examined aspects such as geometry, strength values of commercial parts manufactured with materials from different regions of the country, as well as the increase in strength when incorporating a commercial additive.

In the present study, the geometrical data shown in Figure 1 were considered, resulting in the parts shown in Figure 2.

The pieces evaluated are considered solid blocks, since their net area, defined as the effective cross-section of the material, is equal to their gross area, which implies the absence of voids or significant perforations that affect their structural classification. In a subsequent stage, the pieces were classified according to their mechanical strength, following the parameters and specifications defined by the current NMX-C-038 (2014) standard.

Box 1

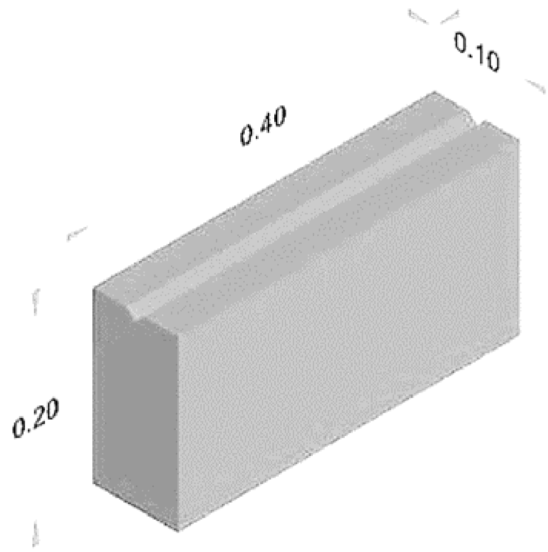

Figure 1

Nomenclature defining the dimensions of the studied concrete block

Box 2

Figure 2

Geometry of manufactured parts.

The compressive strength shall be evaluated in accordance with the current NMX-C-036 (2013) standard. For this purpose, the reference values indicated in Table 1, which establishes the minimum values of the masonry structural system, shall be taken as reference values.

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Box 3

Table 1

Minimum Allowable Compressive Strength Values

Type of part and material	f'_p	$\bar{f}_p$
Handmade solid clay partition walls	6(60)	9(90)
Solid or perforated clay or concrete partition walls	10(100)	15(150)
Clay or concrete hollow partition wall	6(60)	9(90)
Solid or multi-drilled clay or concrete block	10(100)	15(150)
Clay or concrete hollow block	6(60)	9(90)

Source: NTC-DM (2023)

Material particle size

The granulometry of the material is fundamental for the design of the mix, these aspects are included in the NMX-C-073 (2004) standard which refers to the determination of the volumetric mass of fine and coarse aggregates or a combination of both; standard NMX-C-077 (1997) refers to the method for the granulometric analysis of fine and coarse aggregates, in order to determine the distribution of particles of different sizes by means of sieves; standard NMX-C-164 (2014), establishes the test method for the determination of the relative density and absorption of coarse aggregate. In the results reported, the recommendations included in these standards were followed. It should be noted that the mixtures carried out include commercial material available to the general public, which is usually used for the production of block pieces by artisanal means.

The granulometric analysis of the sand for the production of the blocks provided the results shown in Table 2. The analysis considered tare mass (Mt) of 40 gr, tare mass plus sample (M_t+M_{mi}) of 3400 gr and initial sample mass (M_{mi}) of 3000 gr. From the same process, the values indicated in Table 2 for the percentage of gravels of 0.91%, 99.09 of sands and zero percent of fines were calculated.

From Table 2, the values of the effective diameters D_{10} = 0.42, D_{30} = 0.51, D_{60} = 0.68 were calculated using the interpolation expression suggested by Bardet (1997). Subsequently, the uniformity coefficients defined by $C_u = D_{60}/ D_{10}$ were estimated with a value of 1.609, $C_c = (D_{30})^2/(D_{60}xD_{10})$ curvature coefficient equal to 0.91.

According to the results, the material corresponds to the classification of poorly graded material.

Box 4

Table 2

Sand granulometry

Soil Type	Sieve No.	Opening (mm)	Retained weight (gr)	Percentage retained (%)	Percentage passing (%)
Records	4	4.76	27.00	27.00	99.09
Arenas	10	1.68	65.00	65.00	96.90
	10	1.68	65.00	65.00	96.90
	20	0.84	420.00	420.00	82.72
	40	0.42	2160.00	2160.00	9.82
	60	0.25	275.00	275.00	0.54
	100	0.149	15.00	15.00	0.03
	200	0.074	1.00	1.00	0.00
Finos	Fund		0.00	0.00	0.00
		Mmf =	2963.00	2963	

The granulometry of the granules gave the results shown in Table 3. Tare mass (M_t) was 40 gr, Tare mass plus sample (M_t+ M_{mi}) was 3400 gr and Initial sample mass (M_{mi}) was 3000 gr. Applying the same procedure as for sand, the values shown in Table 3 were calculated for the percentage of gravels of 0.91%, 99.09 of sands and zero percent of fines.

Box 5

Table 3

Granulometry of granules

Soil Type	Sieve No.	Opening (mm)	Retained weight (gr)	Percentage retained (%)	Percentage passing (%)
Records	1"	25.4	0.00	0.000	100.00
Arenas	3/4"	19.05	0.00	0.000	100.00
	1/2"	12.7	10.00	0.335	99.66
	3/8"	9.52	315.00	10.553	89.11
	4	4.76	1770.00	59.296	29.82
	10	1.68	810.00	27.136	2.68
	1"	25.4	0.00	0.000	100.00
	3/4"	19.05	0.00	0.000	100.00
Finos	Fund		80.00	2.680	0.00
		Mmf =	2985.00	100	

From Table 3, the values of the effective diameters D_{10} = 2.22, D_{30} = 4.77, D_{60} = 6.77 were calculated. Subsequently, the uniformity coefficients defined by $C_u = D_{60}/D_{10}$ were estimated with a value of 3.04, $C_c = (D_{30})^2/(D_{60}xD_{10})$ curvature coefficient equal to 1.51. According to the results, the material corresponds to the classification of poorly graded material, since $C_u > 4$ and $1 < C_c < 3$. It is observed that the C_u value of 3.04 is close to 4, which represents better uniformity of the material.

From the particle size analysis of the stone dust and gravel provided characteristics of poorly graded materials.

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Proportions used in the mix design

The proportions considered for the elaboration of the bocks were estimated from the dimensions of Figure 1 corresponding to 10x20x40 cm, with a volume of 0.10x0.20x0.40 m = 0.008 m^3, target strength of 80 kg/cm^2. With this data, 1 m^3 of concrete for blocks was batched according to the ACI 211.2 (2022) method, and the results shown in Table 4 were obtained.

Box 6

Table 4

Proposed dosage for 1 m^3 solid block.

Material	Quantity
Cement (kg)	273.33
Coarse aggregate (kg)	696.85
Fine aggregate (kg)	1020.85
Water (lt)	205

The dosage considered water specific gravity of 1000 kg/m^3, cement specific gravity of 3150 kg/m^3, fine aggregate (stone dust) of 1454 kg/m^3, coarse aggregate (gravel) of 1454 kg/m^3, MF(fineness modulus) of 3.0, maximum aggregate size of 3/8", slump of 2.5 cm, fine aggregate (stone dust) absorption of 0.75%, coarse aggregate (gravel) absorption of 0.67%, moisture content of fine aggregate (stone dust) 27.66%, moisture content of coarse aggregate (gravel) 4.89%, compact unit weight of fine aggregate (stone dust) 1664 kg/m^3, compact unit weight of coarse aggregate (gravel) 1584 kg/m^3, loose unit weight of fine aggregate (stone dust) and coarse aggregate (gravel) 1454 kg/m^3.

Compression testing of parts

The compression test requires the prior verification that the surface of the specimens to be tested remains flat, therefore, the block pieces were pitched with sulphur, within the tolerance of ± 0.05 in a length of 150 mm taken in two orthogonal directions. Figure 3 shows one of the cases studied. The tests were carried out on the Shimadzu universal machine with a capacity of 100 Ton.

Box 7

Figure 3

Laying of blocks for compression testing

The calculation of the compressive strength (fp, in kg/cm^2) was calculated according to NMX-C-036 (2013) where the maximum load P (kg) and substituted into equation (1), considering as A (cm^2) the gross cross-sectional area of each 400 cm^2 block.

$$fp = \frac{P}{A} \quad (1)$$

The corresponding values for each proposed dosage are indicated in the Table 5.

Box 8

Table 5

Summary of five proportions for block making

Dosage	Cement (kg)	Fine aggregate (kg)	Coarse aggregate (kg)	Water (lt)	a/c	c/ aggregates	f_p(kg/cm²)
D1	2.19	8.17	5.57	1.64	0.75	0.159	77.20
D2	1.92	6.28	8.57	1.44	0.75	0.129	112.59
D3	2.19	7.75	5.97	1.64	0.75	0.159	144.54
D4	1.92	5.85	8.98	1.44	0.75	0.129	103.90
D5	2.02	8.99	5.97	0.64	0.32	0.135	151.21

Discussion of results

The present study is focused on the use of material from the region of the Municipality of Carmen, Campeche. The elaboration of mixtures includes the use of materials available in material shops and they are usually considered in the mixture to elaborate handmade blocks. Therefore, they were considered as the basis for the design. Mix D1 consisted of fine aggregate (stone dust), coarse aggregate (granzón); mix D2 consisted of fine aggregate (stone dust), coarse aggregate (gravel); mix D3 consisted of fine aggregate (sand-stone dust), coarse aggregate (granzón); mix D4, was made up of fine aggregate (sand-stone dust), coarse aggregate (gravel).

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Mix D5, was made up of fine aggregate (sand), coarse aggregate (gravel); and all with cement and water with the same physical properties and corresponding proportions. Table 5 shows the dosages corresponding to a 10x20x40 cm block, the water/cement ratio designated as a/c and the cement/aggregate ratio designated as c/aggregate.

Table 5 shows w/c ratios of 0.32 and 0.75, for the first case the range of calculated compressive strength varies between 77.2 to 144.54 kg/cm^2 corresponding to D1, which was made with fine aggregate (stone dust), coarse aggregate (granzón) and D3 which was made with fine aggregate (sand-stone dust) as well as coarse aggregate (granzón), respectively.

The variables that influenced the differences in compressive strength are attributed to the moisture content of 27.66% for fine aggregate for D1 and 1.35% for D2. D2 and D4, correspond to similar compressive, w/c, and c/aggregate strengths.

It should be noted that the fine aggregate that corresponds to stone dust, in general, does not have a quality control that allows standardising its properties or maintaining a granulometry that complies with the graduation of controlled materials. However, this material is very frequently used, as it provides the mix with a consistency that allows the mixture to be worked and improves the finish.

Design D5, on the other hand, is characterised by having the lowest w/c ratio, but not the lowest c/aggregate ratio. In this case, the w/c ratio is predominant, being the lowest of all the cases, as shown in Table 5 and visualised in Figure 4. Likewise, according to Figure 5, it is verified that the aggregate cement ratio, with the materials used, could be considered in the interval 0.129 to 0.159 with water-cement ratios of 0.75.

Box 9

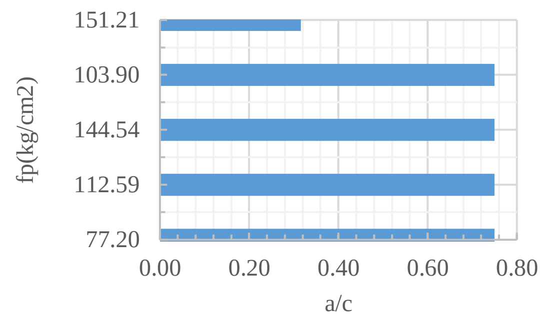

Figure 4
Ratio f_p vs. a/c.

The results obtained indicate that it is possible to obtain resistances that comply with the minimum values of the current standards in Mexico, the reference standard being the NTC-DM (2023). In the absence of local regulations, the designs of masonry structures are based on this technical standard, having the disadvantage that the properties of the materials included in the document to nearby areas of Mexico City, with their own characteristics, as reported by Tena *et al*. (2017), who made a proposal to improve mixtures to produce concrete masonry pieces using materials commonly available in the Valley of Mexico.

Box 10

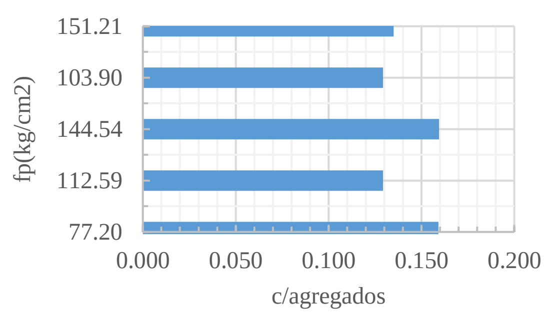

Figure 5
Relation f_p vs. c/ aggregates

Conclusions

Five dosages were proposed for concrete mixes considering the properties of the materials available in the Municipality of Carmen, Campeche, highlighting the following:

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1. The 5 proposed dosages are formed by the available materials. Dosage D1 consisted of fine aggregate (stone dust), coarse aggregate (granzón); D2, fine aggregate (stone dust) and coarse aggregate (gravel); D3, fine aggregate (sand-stone dust) and coarse aggregate (granzón); D4, fine aggregate (sand-stone dust) and coarse aggregate (gravel); D5, fine aggregate (sand) and coarse aggregate (granzón).

2. The analysis of the cases studied indicates that the w/c ratio is the most influential factor on the strength achieved.

3. The w/c ratio of 0.75 gives higher values than the target strength of this study of 80 kg/cm^2.

4. The cement/aggregate ratio values of 0.129 and 0.159 generate strengths close to the target strength, however, the water/cement ratio of 0.134 significantly modifies the compressive strength.

5. The materials used in the different dosages are generally classified as poorly graded. This represents the actual conditions under which the block pieces are made by artisanal methods.

6. The five proposed dosages were carried out using the ACI 211 method, which represents an alternative for the mix required for the production of concrete blocks.

7. The dosages studied correspond to materials available in the region, these could be implemented to propose the local technical standard for masonry.

Recapitulating conclusions

In relation to the study carried out, the proposed dosages make it possible to achieve acceptable compressive strengths using material from the region. The authors hope that the results will form part of experimental references for the standardisation of the design and construction practice of masonry structures, especially in the elaboration of pieces through artisanal methods.

Declarations

Conflict of interest

The authors declare that there is no conflict of interest. They have no competing financial interests or personal relationships that could have influenced, or appear to influence, the content presented in this article.

Authors' contribution

The first author conducted experimental studies and drafted the paper, the first co-author contributed to the analysis of results and comparison with existing standards, the second co-author conducted the literature review, and the third co-author conducted the comprehensive review of the full paper.

Availability of data and materials

The data presented in this research are available for consultation if required.

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Abbreviations

NMX	Mexican Standard
NTC	Complementary Technical Standard

NTC-DM	Complementary Technical Standard for masonry design and construction
NTC-DS	Complementary Technical Standard for earthquake design
ACI	American Concrete Institute
RCD	Demolition product material
Cemento IP	High durability multi-purpose cement
f'_p	Average compressive strength of block
$\bar{f}_p$	Design compressive strength of block
f_p	Experimental compressive strength of the block piece
Mt	Tare mass
M_{mi}	Sample mass
C_c	Coefficient of curvature
C_u	Uniformity coefficient
P	Axial load applied
A	Gross cross-sectional area of the block part
D1	Material dosage 1
a/c	Water/cement ratio

References

Background

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