Building constructions characteristics and mechanical properties of confined masonry walls in San Miguel (Puno-Peru)

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ABSTRACT

House self-construction and self-management are very common in different cities in Peru, which is the case in several areas in the district of San Miguel (Puno). This is due to the lack of financial resources to hire professionals to design and construct their houses. Therefore, many residents build without technical guidance and materials without quality standards. As a result, the buildings in the area have various construction pathologies that demonstrate their high seismic vulnerability, which indicates that the guidelines established in the Peruvian Masonry Design Code NTE 070 are not followed. Therefore, as a first step towards evaluating the seismic vulnerability of the houses in San Miguel, it was decided to evaluate the construction pathologies and typologies by conducting a survey. Subsequently, to characterize and evaluate the physical-mechanical properties of the masonry walls, 24 piles and 24 small walls were built and tested. The materials tested were obtained from the urban area of the same study place. According to the experimental tests, it was observed that the axial compression and diagonal shear values of the prisms are lower than the minimum values specified in the Peruvian Construction Code, and this would increase the seismic vulnerability of the constructions. Therefore, many of the houses in the district could suffer significant damage and even collapse in a seismic event.

Keywords: non-engineering buildings; construction pathologies; masonry prisms; experimental tests, seismic vulnerability; damage survey, Puno

1. INTRODUCTION

In some Peruvian cities, there has been an exponential increase in population, consequently increasing the need for housing. In addition, there is a lack of resources to acquire a finished house or hire professionals to design and build confined masonry structures. As a result, many residents are forced to build informally, that means, without technical supervision and with cheap materials of questionable quality (Flores et al. 2019, Yacila et al. 2019, Blondet et al. 2006).

The confined masonry (CM) buildings are characterized by masonry walls (fired clay units) enclosed with reinforced concrete (RC) elements along the four edges. These RC elements may avoid out-of-plane failure and improve the shear in-plane behaviour of the walls. Unlike unreinforced masonry buildings (URM), where kinematic failure modes may be analyzed (i.e. Micelli et al. 2016), CM walls are more likely to fail in-plane. Also, some reseachers have studied the use of confine elements to strength URM walls built with other unit types (Khan et al. 2021, San Bartolomé et al. 2009).

The CM walls (built with fired caly units) are the main structural elements that provide lateral stiffness to the dwellings against the action of earthquakes and transfer the loads coming from the slab to the foundation (Varela-Rivera et al. 2019, Marques and Lourenco 2019). An appropriate density of CM walls in a structure and both directions allows the building to perform well in seismic events. Therefore, it is necessary to know the constructive flaws of the walls, the characteristics and mechanical properties of the masonry, the variability in the mortar thicknesses (Reddy et al. 2009), and the quality of its materials to estimate the structural safety of the assembly. Based on data from national censuses and annual measurements that CAPECO (2018) conducted on the formal housing market, it is estimated that the percentage of informally built housing in Peru between 2007 and 2014 in Lima is 68.5%. In addition, it is inferred that the percentage of informal housing would be equal to or greater than 70% in the rest of the country (Zavala et al. 2019).

Seismic vulnerability is represented by the susceptibility of a structure to suffer damage (Vatteri and D'ayala 2021, Preciado et al. 2020, Ranjbaran and Kiyani 2017). Vulnerability reflects the lack of strength of a building to earthquakes, as indicated by Bommer et al. (1998), and depends on the building design characteristics, the quality of materials and the construction technique (Kuroiwa 2002).

Blondet et al. (2004) conducted a study on analyzing the seismic vulnerability of informal CM dwellings in the Peruvian coastal area. It is determined that if a house is average but the quality of construction is poor (e.g. use of low-quality materials), then the seismic vulnerability can be assessed as high. Likewise, these houses are built in stages, depending on the inhabitants' availability of economic resources. According to Sánchez et al. (2019), the progressive construction and the use of low quality materials may infer in a high seismic vulnerability since there is not engineering building planning for the future. Also, Hadzima-Nyarko et al. (2016), and Parammal and D'Ayala (2021) studied the vulnerability of confined masonry buildings and agree that the seismic capacity may decrease when there are more deficiencies in the construction (e.g. poor wall-column connection, low wall density, unconfined walls, spacing of cross walls, etc). This is why houses with severe structural, architectural and construction deficiencies make them vulnerable to natural phenomena such as earthquakes (Ruiz-García and Negrete 2009, Sánchez et al. 2019, Zavala et al. 2019).

Vulnerability usually manifests itself through various pathologies that appear in buildings. Many researchers have studied the seismic vulnerability of masonry buildings on a local and large scale demonstrated the necessity for understanding the seismic behaviour of those buildings and their relationship to their mechanical material properties (Ahmad et al. 2010, Blondet et al. 2006, Flores et al. 2019, Hadzima-Nyarko et al. 2016, Lovón et al. 2018). González et al. (2008) understand pathology as a systematic deficiency that occurs in most constructions because of the poor quality of materials used in construction, construction errors that are not identified that way by the builders, the lack of a culture of quality in the supervision, the lack of regulations and legislation in construction, among others. Consequently, it is necessary to determine the quality of the CM constructions and the properties of the materials that the houses are built with.

As in other cities in Peru, in the district of San Miguel in Puno, the application of construction standards appears to be still incipient. Nevertheless, the population makes a considerable investment in constructing their housing, even saving several years. Therefore, the houses must be safe in the event of a seismic event.

Puno has gone through several experiences of earthquakes, such as those that occurred in 1928 (6.9*Ms*) and 2016 (6.3*Mw*), which caused damage to homes (making them uninhabitable) and even caused collapses. Therefore, to predict the seismic response of residential masonry walls, it is essential to study their physical-mechanical characteristics and properties (Quiroz et al., 2014). Furthermore, to evaluate the mechanical behavior of a masonry wall, it is necessary to know its mechanical properties through experimental tests (Perez-Gavilán et al. 2019, Almeida et al. 2014, Binda et al., 2014). For this reason, this study evaluated the mechanical characteristics of piles and walls built with typical bricks from the San Miguel area to verify whether they meet the requirements of Peruvian standard NTE 070 (2006) and thus infer their seismic vulnerability.

2. EVALUATION OF THE HOUSES

2.1. Surveys in the study area

The study was carried out in the district of San Miguel, which belongs to the province of San Román in the department of Puno and is home to approximately 65,500 people. Figure 1 shows the location map of San Miguel at the national, departmental and provincial levels. In Puno, the buildings have grown without specific planning due to the spontaneous union of neighbourhoods and urbanizations in its surroundings. This uneven and disorganized growth had different consequences in several aspects, such as the heterogeneity in the variety and uses of housing. Likewise, the lack of a political organization and the lack of attention to basic needs and services forced the population of the northern area to create the district of San Miguel in 2016. Approximately 12 340 out of 16 130 dwellings in San Miguel are made of clay brick (INEI 2018). In this research, 92 dwellings were chosen to be evaluated and intended to represent the construction typology of the area. Unfortunately, it was impossible to have a more significant number of surveys because many villagers were afraid that this study was part of the local government's tax data update campaign. Nevertheless, figure 2 shows some of the surveyed dwellings, where it can be noticed how these dwellings grow without an adequate architectural order.

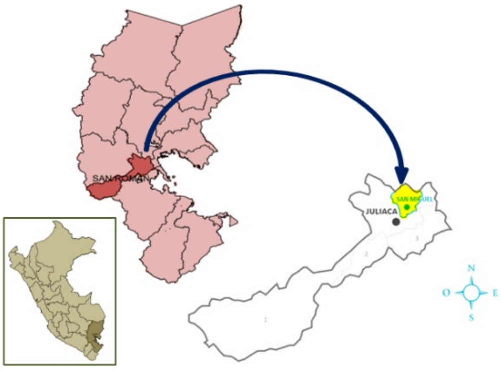
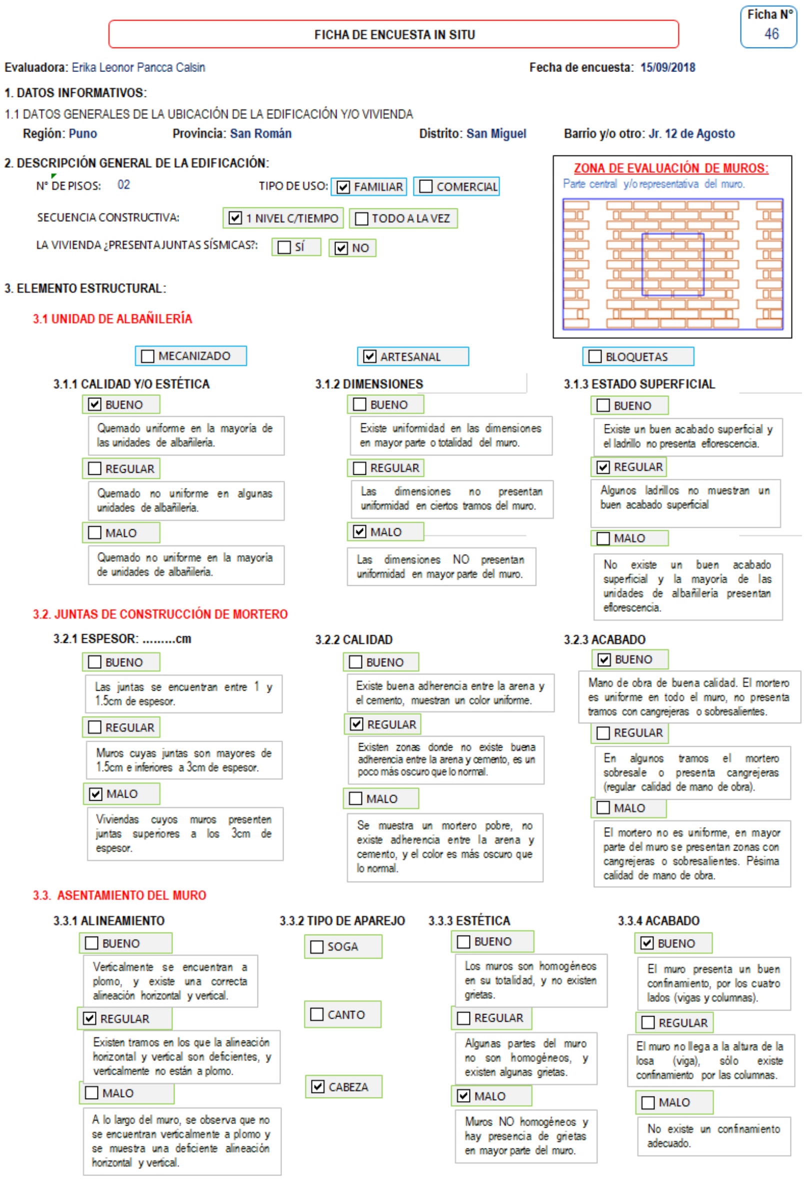


Figure 1. Location map of the district of San Miguel, Puno.

Figure 2. Some surveyed households in the district of San Miguel (Puno).

Fieldwork, office work and experimental trials were carried out. The fieldwork consisted in obtaining information using survey sheets from one wall of the first level per dwelling. As shown in Figure 3, the sheets consist of 2 pages whose format was divided into general data on the house, structural characteristics and wall construction. The latter includes the evaluation of the masonry unit (quality and aesthetics, dimensions and superficial condition), mortar construction joints (thickness, quality and finish) and wall settlement (alignment, type of rigging, aesthetics, and finish). Additionally, existing pathologies were noted: unconfined walls, non-uniform mortar joint thickness, cracks in the walls, presence of salinity in the overlying walls, poor horizontal and vertical alignment of masonry units, cracks in columns and confining beams, efflorescence in walls, low-quality masonry units, poor mortar-unit interaction, cracks in the mortar, poor column-wall interaction, wall construction at different times, exposed steel, existence or not of seismic joints, among others. Moreover, observations, comments, construction schemes and photographs of masonry walls were also added to the file. Finally, the sheets were filled out by hand at the time of the home visit.



FICHA DE ENCUESTA IN SITU

Ficha N° 46

Evaluadora: Erika Leonor Pancca Calsin

Fecha de encuesta: 15/09/2018

1. DATOS INFORMATIVOS:

1.1 DATOS GENERALES DE LA UBICACIÓN DE LA EDIFICACIÓN Y/O VIVIENDA

Región: Puno Provincia: San Román Distrito: San Miguel Barrio y/o otro: Jr. 12 de Agosto

2. DESCRIPCIÓN GENERAL DE LA EDIFICACIÓN:

N° DE PISOS: 02

TIPO DE USO: ☑ FAMILIAR ☐ COMERCIAL

SECUENCIA CONSTRUCTIVA: ☑ 1 NIVEL C/TIEMPO ☐ TODO A LA VEZ

LA VIVIENDA ¿PRESENTA JUNTAS SÍSMICAS?: ☐ SÍ ☑ NO

ZONA DE EVALUACIÓN DE MUROS:

Parte central y/o representativa del muro.

3. ELEMENTO ESTRUCTURAL:

3.1 UNIDAD DE ALBAÑILERÍA

☐ MECANIZADO ☑ ARTESANAL ☐ BLOQUETAS

3.1.1 CALIDAD Y/O ESTÉTICA

☑ BUENO
Quemado uniforme en la mayoria de las unidades de albañileria.

☐ REGULAR
Quemado no uniforme en algunas unidades de albañileria.

☐ MALO
Quemado no uniforme en la mayoria de unidades de albañileria.

3.1.2 DIMENSIONES

☐ BUENO
Existe uniformidad en las dimensiones en mayor parte o totalidad del muro.

☐ REGULAR
Las dimensiones no presentan uniformidad en ciertos tramos del muro.

☑ MALO
Las dimensiones NO presentan uniformidad en mayor parte del muro.

3.1.3 ESTADO SUPERFICIAL

☐ BUENO
Existe un buen acabado superficial y el ladrillo no presenta eflorescencia.

☑ REGULAR
Algunos ladrillos no muestran un buen acabado superficial

☐ MALO
No existe un buen acabado superficial y la mayoria de las unidades de albañileria presentan eflorescencia.

3.2. JUNTAS DE CONSTRUCCIÓN DE MORTERO

3.2.1 ESPESOR: ....cm

☐ BUENO
Las juntas se encuentran entre 1 y 1.5cm de espesor.

☐ REGULAR
Muros cuyas juntas son mayores de 1.5cm e inferiores a 3cm de espesor.

☑ MALO
Viviendas cuyos muros presenten juntas superiores a los 3cm de espesor.

3.2.2 CALIDAD

☐ BUENO
Existe buena adherencia entre la arena y el cemento, muestran un color uniforme.

☑ REGULAR
Existen zonas donde no existe buena adherencia entre la arena y cemento, es un poco más oscuro que lo normal.

☐ MALO
Se muestra un mortero pobre, no existe adherencia entre la arena y cemento, y el color es más oscuro que lo normal.

3.2.3 ACABADO

☑ BUENO
Mano de obra de buena calidad. El mortero es uniforme en todo el muro, no presenta tramos con cangrejeras o sobresalientes.

☐ REGULAR
En algunos tramos el mortero sobresale o presenta cangrejeras (regular calidad de mano de obra).

☐ MALO
El mortero no es uniforme, en mayor parte del muro se presentan zonas con cangrejeras o sobresalientes. Pésima calidad de mano de obra.

3.3. ASENTAMIENTO DEL MURO

3.3.1 ALINEAMIENTO

☐ BUENO
Verticalmente se encuentran a plomo, y existe una correcta alineación horizontal y vertical.

☑ REGULAR
Existen tramos en los que la alineación horizontal y vertical son deficientes, y verticalmente no están a plomo.

☐ MALO
A lo largo del muro, se observa que no se encuentran verticalmente a plomo y se muestra una deficiente alineación horizontal y vertical.

3.3.2 TIPO DE APAREJO

☐ SOGA

☐ CANTO

☑ CABEZA

3.3.3 ESTÉTICA

☐ BUENO
Los muros son homogéneos en su totalidad, y no existen grietas.

☐ REGULAR
Algunas partes del muro no son homogéneos, y existen algunas grietas.

☑ MALO
Muros NO homogéneos y hay presencia de grietas en mayor parte del muro.

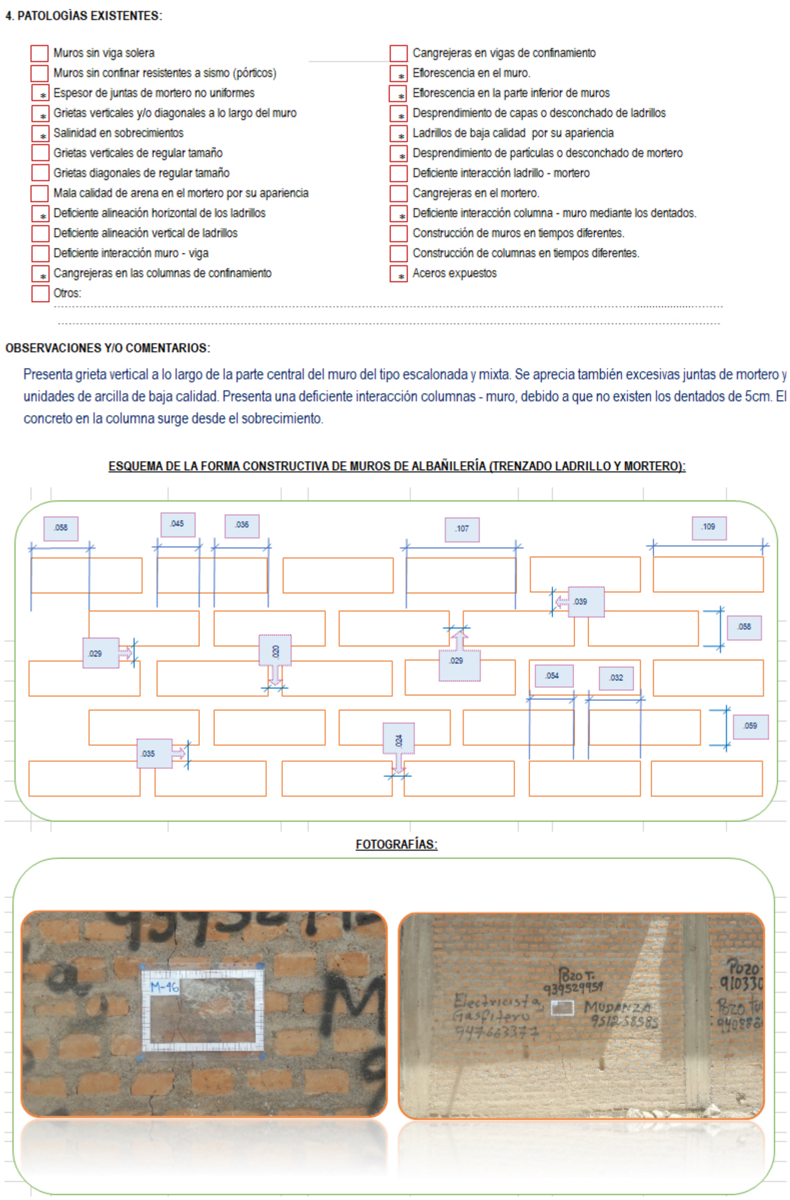
3.3.4 ACABADO

☑ BUENO
El muro presenta un buen confinamiento, por los cuatro lados (vigas y columnas).

☐ REGULAR
El muro no llega a la altura de la losa (viga), sólo existe confinamiento por las columnas.

☐ MALO
No existe un confinamiento adecuado.

Figure 3. Household survey sheets, in Spanish.



4. PATOLOGÍAS EXISTENTES:

- [ ] Muros sin viga solera
- [ ] Muros sin confinar resistentes a sismo (pórticos)
- [x] Espesor de juntas de mortero no uniformes
- [x] Grietas verticales y/o diagonales a lo largo del muro
- [x] Salinidad en sobrecimientos
- [ ] Grietas verticales de regular tamaño
- [ ] Grietas diagonales de regular tamaño
- [ ] Mala calidad de arena en el mortero por su apariencia
- [x] Deficiente alineación horizontal de los ladrillos
- [ ] Deficiente alineación vertical de ladrillos
- [ ] Deficiente interacción muro - viga
- [x] Cangrejeras en las columnas de confinamiento
- [ ] Cangrejeras en vigas de confinamiento
- [x] Eflorescencia en el muro.
- [x] Eflorescencia en la parte inferior de muros
- [x] Desprendimiento de capas o desconchado de ladrillos
- [x] Ladrillos de baja calidad por su apariencia
- [x] Desprendimiento de partículas o desconchado de mortero
- [ ] Deficiente interacción ladrillo - mortero
- [ ] Cangrejeras en el mortero.
- [x] Deficiente interacción columna - muro mediante los dentados.
- [ ] Construcción de muros en tiempos diferentes.
- [ ] Construcción de columnas en tiempos diferentes.
- [x] Aceros expuestos
- [ ] Otros:

OBSERVACIONES Y/O COMENTARIOS:

Presenta grieta vertical a lo largo de la parte central del muro del tipo escalonada y mixta. Se aprecia también excesivas juntas de mortero y unidades de arcilla de baja calidad. Presenta una deficiente interacción columnas - muro, debido a que no existen los dentados de 5cm. El concreto en la columna surge desde el sobrecimiento.

ESQUEMA DE LA FORMA CONSTRUCTIVA DE MUROS DE ALBAÑILERÍA (TRENZADO LADRILLO Y MORTERO):

FOTOGRAFÍAS:

Figure 3. (Continuation) Household survey sheets, in Spanish.

The desk work consisted of the analysis of the survey sheets. The information collected in the field was processed in report forms for each dwelling. The surveyed dwellings' characteristics (structural, constructive, pathologies and typologies) were grouped, and a database was created. Subsequently, to characterize and evaluate the physical-mechanical properties of the masonry walls of the houses, laboratory work was carried out, which consisted of building and testing piles and walls. Before this, control tests (classificatory and non-classificatory) were carried out on the masonry units and the mortar. The tested materials were obtained from the same study site.

2.2. Construction typologies

Confined masonry (CM) walls are composed of clay brick walls surrounded by reinforced concrete (RC) elements. Some walls may have only on the ground floor an RC plinth. Typically, the longitudinal steel bars of the RC elements are composed of four bars of *Φ* ½", with stirrups of *Φ* ¼". Details of typical dimensions of CM walls and their CM elements are shown in Figure 4.

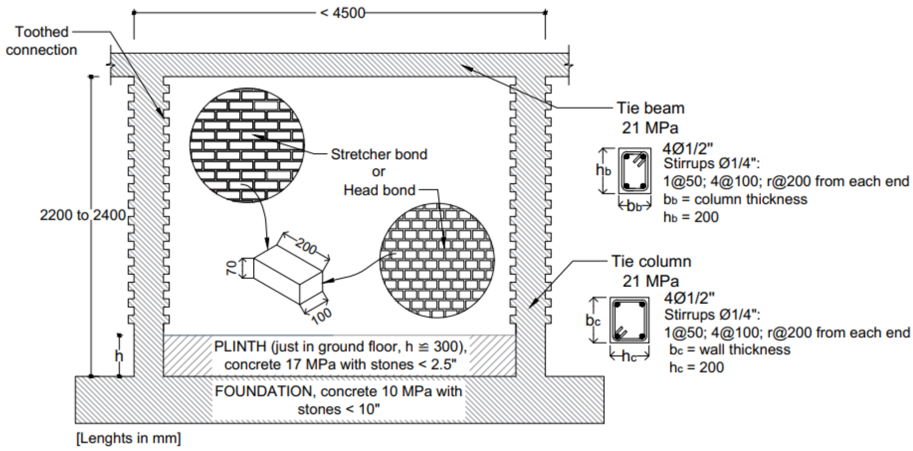


Figure 4. Typical confined masonry wall's configuration.

From the 92 houses evaluated, six typologies of walls were obtained, defined according to the thickness of the vertical (J.V.) and horizontal (J.H.) mortar joints. The three most predominant pairs (J.V. - J.H.) were selected to be characterized in the masonry prisms. Typology 01 (T1) with mortar thickness (J.V. and J.H.) of 20*mm*, typology 02 (T2) with a thickness of 30*mm* and typology 03 (T3) with a thickness of 40*mm*. These results are shown in Figure 5: T1 represents 25% of dwellings, T2 represents 58% of dwellings, and T3 represents 12%. An additional typology was considered a reference standard (TP), with mortar thickness between 10 to 15*mm* as indicated in NTE 070 (2006).

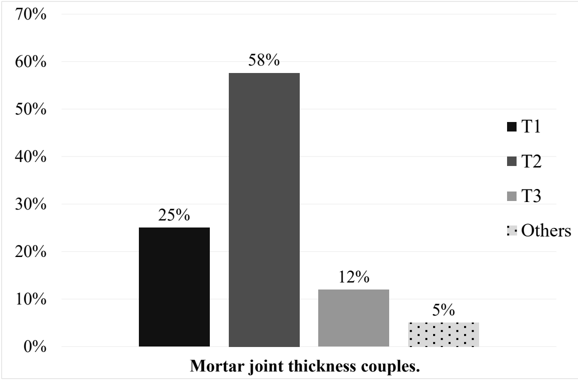


Figure 5. Distribution of walls according to the thickness of their joints.

2.3. Masonry wall pathologies

Vulnerability usually manifests itself through various pathologies that appear in buildings, ranging from minor damage and inconvenience to the occupants to significant failures that can cause the collapse of the dwelling or part of it (Astorga and Rivero 2009). Figure 6 shows the different pathologies found in the studied dwellings. For example, Figures 6a and 6b show an inadequate connection of the masonry units with the confining element since both elements have cracks or separations. In addition, figures 6c and 6d show that some houses have cracks in their walls. These cracks usually appear when there are differential settlements in the foundation due to low-strength concrete or the deficient use of reinforcing steel in the confining elements (Mosqueira and Tarque 2005). Likewise, Figures 6e and 6f show mortar joint thicknesses more significant than 15 *mm* (value recommended by NTE 070).

Moreover, these thicknesses are not homogeneous. Figures 6g and 6h show walls with efflorescence damage, a crystalline deposit (saltpetre) generally white colour that develops in the masonry or on the surface of the concrete, which, if not repaired, can increase and weaken the wall (Sathiparan and Rumeshkumar 2018, Annila et al. 2018). Figures 6i and 6j show no confining beam for the wall, and the columns are short due to the existence of windows. Finally, Figures 6k and 6l show the poor quality of the workmanship used in the construction of many houses, which, according to Mosqueira and Tarque (2005), can cause a reduction of up to 40% in the shear strength of the walls.

Figure 6. Existing pathologies in analyzed dwellings.

Figure 7 shows the percentage of incidence of various pathologies observed, the most predominant being the construction of walls with non-uniform mortar joint thickness (95%), houses with exposed steel (92%), with efflorescence in the lower part of walls (64%), with poor vertical alignment of bricks (63%), with the presence of cracks in mortars (62%), with the existence of salinity in overlays (62%), with the poor horizontal alignment of bricks (61%), with lack of good brick-mortar interaction (62%), with lack of good brick-mortar interaction (62%), with the presence of cracks in the mortar (62%), with the existence of salinity in the overlay (62%), with the poor horizontal brick alignment (61%), with lack of good brick-mortar interaction (59%), with deficient column-wall interaction through notching (54%), with cracks in confining columns (53%), among others.

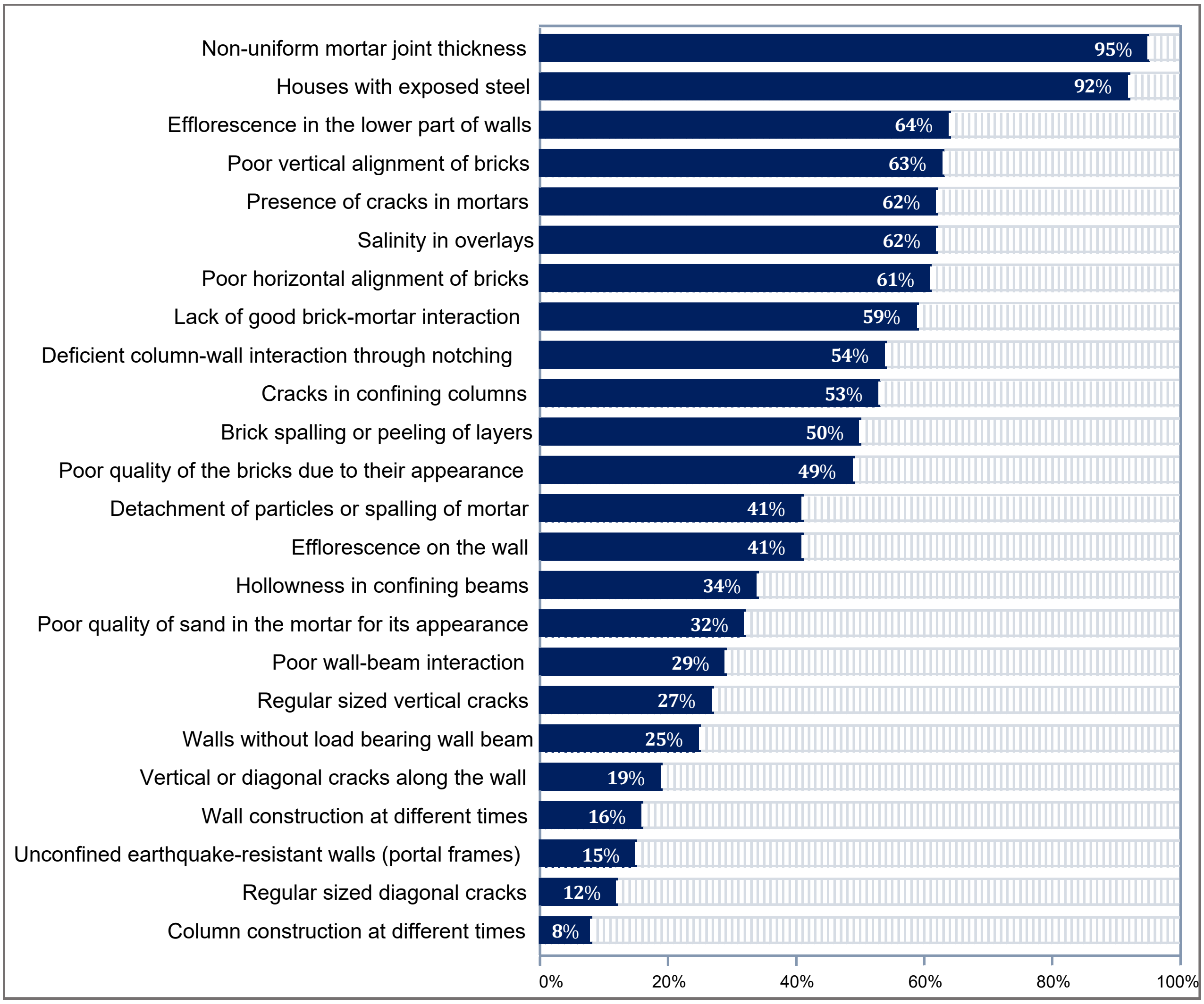


Figure 7. Existing pathologies in evaluated dwellings.

3. EXPERIMENTAL TESTS

A total of 100 control trials were performed on masonry units (20 samples of dimensional variation, 20 of warping tests, 20 of compressive strength tests, 20 of suction tests and 20 of absorption percentage tests) and 48 tests on prisms (24 of axial compression in piles and 24 of diagonal shear in walls). The masonry units (average dimensions 0.20*m* x 0.10*m* x 0.07*m*) were obtained from the exact study location, handmade and produced by two different producers, here named as F1 and F2.

3.1. Control tests on the units

The objective of the tests was to classify and determine the properties of the masonry units used in this study. The control trials included both classificatory and non-classificatory tests.

3.1.1. Qualifying tests

For the tests, two random groups of 10 masonry units were taken per producer (a total of 20). The properties related to the classification of the masonry units, according to NTE 070 (2006), are the dimensional variation, warping and compressive strength tests, which were performed according to the NTP 399.613 Standard.

The percentage of dimensional variation defines the height of the mortar courses, since the greater the variation in the heights of the units, the need arises to increase the joint mortar thickness beyond what is strictly necessary to achieve good adhesion (Gallegos and Casabonne 2005). The standard joint thickness should be around 10 *mm*. NTE 070 (2006) indicates that for every 3 *mm* increase in joint thickness, the compressive strength of the masonry and shear strength decreases by 15%. Therefore, it is essential to know the dimensional variation. The test was performed on 20 units (F1 and F2) and consisted in measuring with a millimetre graduated ruler the three dimensions of the unit (length, width and height) from the midpoints of the edges that limit each face. The warpage is used to determine how concave or convex a masonry unit is. Values greater than 2 *mm* of warpage can cause horizontal mortar joints to have hollows, hence, a poor bond between the unit and mortar and lower shear strength of the wall. A total of 20 units (F1 and F2) were tested. The test consisted of placing the surface of the unit on a flat table. Then, a metal ruler was placed on the diagonal of the seating surface to measure the most bending part (concave or convex) using a graduated wedge. Gumaste et al. (2006) indicate that the compressive strength of the brick can contribute between 25 to 50% of the shear strength of masonry walls. Twenty bricks (F1 and F2) were tested. The compressive strength of the brick was obtained by dividing the breaking load by the gross area of the brick.

3.1.2. Non-classificatory tests

These tests are more related to the construction procedure of masonry walls (Manchego and Pari 2016). For the tests, two random groups of 10 masonry units were selected, one group for each producer of F1 and F2 masonry units. The suction measures the initial water absorption rate from the bearing face of the masonry unit, a significant property to achieve adequate contact between the mortar and the unit. For the present study, all 20 samples (F1 and F2) were tested. This property was calculated as the relation between the unit's dry weight and the unit's weight after having placed it for one minute inside a tray with a constant height of 3 *mm* of water to fill the voids of the seating face of the unit with water.

The absorption percentage was performed to determine the amount of water contained in a masonry unit, calculated through the weight of the masonry unit in dry conditions and the weight in saturated conditions (after being immersed in water for 24 hours). This property is essential because the higher the absorption percentage, the more porous the unit is and, therefore, the less resistant to weathering (San Bartolomé 2008).

3.2. Tests on mortars

The compressive strength of the mortar influences masonry strength. Then, significant variability in mortar strength causes variability in masonry strength (Jessop and Langan 2005). Mortar is made of a mixture of fine aggregate and binders, to which a certain amount of water is added to provide a workable and adhesive mixture (Manchego and Pari 2016). The mortar specimens were obtained from the same mixture used for the construction of the prisms. Twelve cubes of approximately 50 *mm* on each side were formed. They were cured with water for 28 days and then tested in axial compression.

3.3. Tests on masonry prisms

Piles and walls (prisms) are used to calculate the axial compressive strength and diagonal shear strength of clay masonry, respectively. The prisms have to represent the walls as well as possible, so they should be exposed to similar conditions and have the same variables (unit type, mortar dosage, joint mortar thickness, rigging, workmanship, etc.) as the walls. To characterize the behaviour of the handmade masonry walls, 48 prisms (24 piers and 24 walls) were built. In these prisms, 4 construction typologies were represented, the 3 typologies (T1, T2 and T3) that best represent the walls of the houses (joint mortar thickness and cement dosage: sand), and the standard typology (TP) with the characteristics indicated by NTE 070 (2006). For each typology, 3 specimens were built, and each group was for handmade masonry units of the two producers (called F1 and F2).

Depending on the typology, the piles were built with 3 or 4 courses (heights between 0.30 and 0.38 *m*) and the slenderness was between 2.5 and 4. According to the NTP 399.605 (2013), the pile slenderness should be between 1.3 and 5.0.

The small walls (called also wallets) were between 6 and 7 courses. The approximate dimensions of the wall's assemblies were 0.60 x 0.60 *m*, as suggested by the NTP 399.621 (2004). The ASTM E519 (2021) standard suggests a minimum dimension of 1.20 x 1.20 *m*, but also permit walls with less dimension if the testing equipment may not accommodate bigger walls. RILEM TC 76-LUM (1994) considers small walls built with at least 4 courses and keeping as much as possible a squared shape. Then, the adopted dimension here agrees with the revised standards.

The construction characteristics of the specimens of the standard typology (TP) were as follows: joint mortar thickness between 10 to 15 *mm* and a mortar dosage of 1:4 (cement: sand). This typology was built respecting the indications of NTE 070 (2006). Regarding typologies T1, T2 and T3, these were built with a joint mortar thickness of 20*mm*, 30*mm* and 40*mm,* respectively, the three of them with a mortar dosage of 1:7 (cement: sand), the dosage most commonly used in housing construction in the study area. To analyze the influence of these variables, the following parameters were kept constant: the type of rigging (head bond), which represents almost 95% of the walls of the houses studied, the workmanship, the age of the specimens (28 days) and the testing technique. Regarding the workmanship, the prisms were made by a local master builder to replicate the construction reality as closely as possible. The construction procedure was as follows: before construction, the units were wetted by immersing them in a bucket of water for one minute to avoid too much water absorption of the mortar, prisms verticality was controlled with a plumb line and a level, heights were controlled with a scantling (wooden ruler), the prisms were cured by watering during the first 3 days as this is what is commonly done in the construction of informal dwellings. The axial compressive tests and the diagonal compression tests were force-controlled due to limitations in the laboratory. The load was applied trying to keep a rate velocity of 10 *kN/min*. Since no LVDTs were placed on the samples to measure deformations, just the maximum strength in each test was computed.

3.3.1. Masonry piles

Masonry piles are prisms composed of bricks laid one on top of the other and joined with mortar, as shown in Figure 8. 28 days after their construction, the piles were tested in axial compression. Only forces were measured, but deformation was not measured. This test made it possible to determine the strength of the walls to vertical loads, whose stress depends on the quality of the units, mortar and unit-mortar interaction.

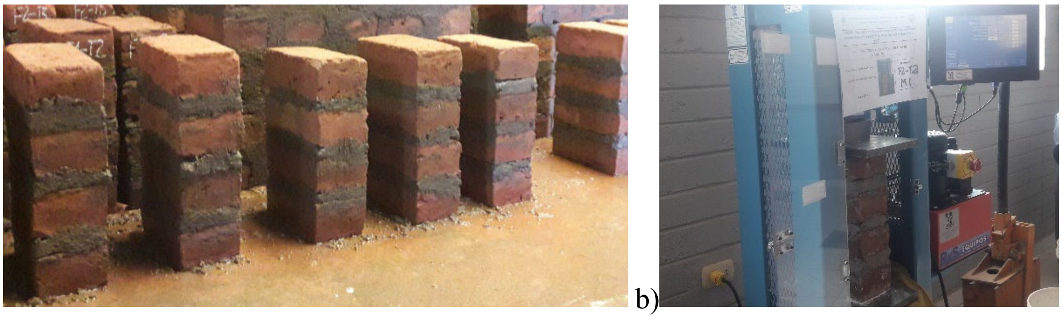
a)  b)

Figure 8. Masonry piles, a) samples, b) test set up

Figure 9 shows that failure in the piles was the development of vertical cracks through the units and mortar.

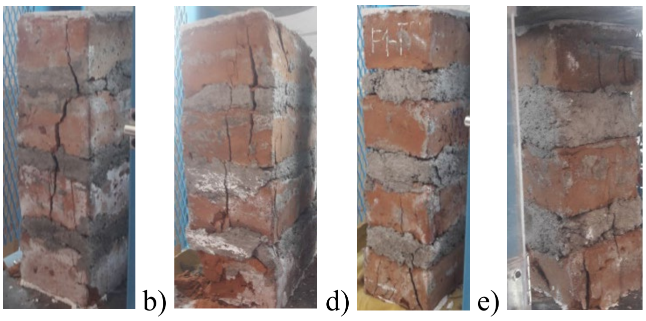
a) b) d) e) 

Figure 9. Failure mode of the tested piles, a) TP, b) T1, c) T2, and d) T3.

The average pile dimensions and maximum compressive loads recorded during the tests are detailed in Table 1.

Table 1.- Average pile dimensions by type and maximum supported load.

Typology	Dimensions in *mm*			*Pmax*
	Length	Width	Height	(kN)
TP	201	102	325	71.86
T1	201	104	348	74.42
T2	200	103	376	56.44
T3	200	102	292	61.62

3.3.2. Masonry walls

One of the most critical situations in which a wall can be subjected to shear is in the event of a seismic effect, hence the importance of knowing the mechanical behaviour of the masonry under this type of stress (Tena and Miranda 2003). The test to determine this behaviour consists in applying a diagonal tension to a squared wall. Two steel loading shoes were used to apply the machine load to the specimen (ASTM E-519 2021). Figure 10 shows the walls constructed in this research. The construction process was similar to that of the piles. During the tests, only the acting forces were measured, but not the deformation of the diagonals on the wall faces.

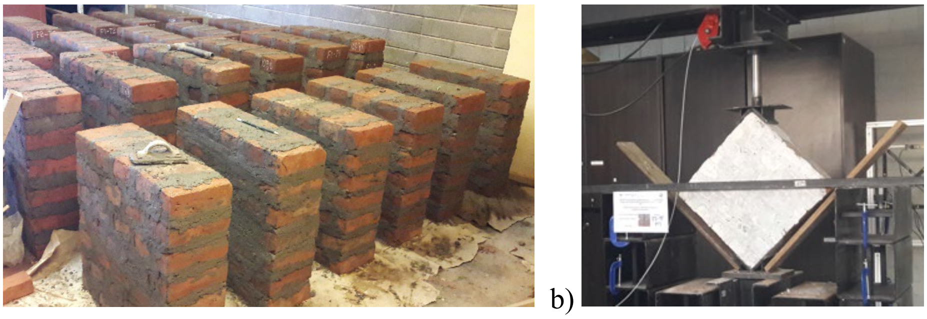
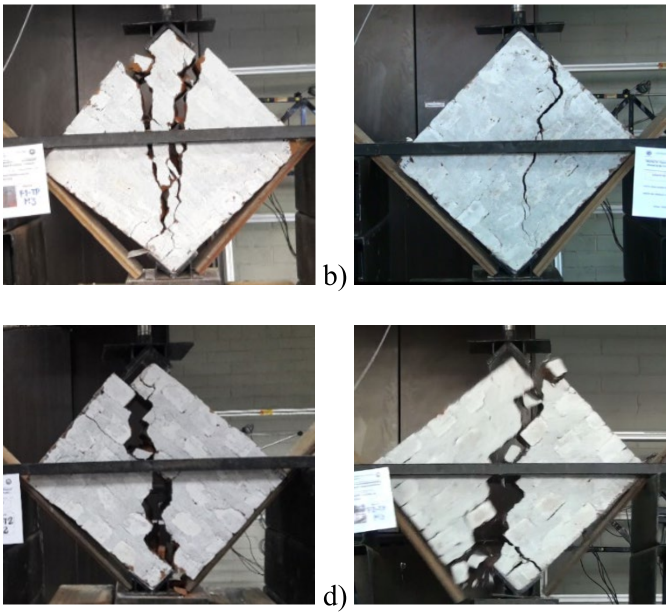
a)  b)

Figure 10. Masonry walls, a) samples, b) test set up

The wall failure mode was mostly by diagonal cracking and breaking bricks and mortar, as shown in Figure 11. The two wooden tables along two wall sides were placed to avoid the fall of the broken pieces, but they did not have interaction with the walls during the tests.



a) b) c) d)

Figure 11. Failure shape of the tested walls, a) TP, b) T1, c) T2, and d) T3.

Table 2 shows the dimensions of the tested walls and the average maximum load values for each type.

Table 2.- Average dimensions of the walls by type and maximum load capacity.

Typology	Dimensions in *mm*			Pu (*KN*)
	Length	Width	Height	
TP	578	543	200	68.76
T1	548	610	200	56.35
T2	578	583	200	50.68
T3	630	632	200	39.67

4. RESULTS

4.1. Control tests (classificatory and non-classificatory)

From the results of the classification tests, F1 bricks are classified as Type IV according to their dimensional variation of 3.41%, and F2 bricks as Type III with a dimensional variation value of 4.17% (NTE 070 2006). Standard ITINTEC 331.017 (1978) indicates that Type IV bricks are high strength and durability, suitable for rigorous service conditions and subjected to moderate exposure to the elements. Type III bricks are medium strength and durable, suitable for use in low exposure to weathering conditions.

On the other hand, according to their warping, the masonry units of both producers F1 and F2 are classified as Type V, according to NTE 070 (2006). The average values for F1 were 1.40 *mm* convex and 1.20 *mm* concave, and F2 bricks were 1.40 *mm* convex and 1.50 *mm* concave. ITINTEC 331.017 (1978) states that Type V bricks are high strength and durability, suitable for use in very rigorous service conditions, and can also be subjected to moderate exposure to weathering conditions in contact with heavy rain, soil and water.

Regarding the characteristic strength to axial compression ($f'b$) of the masonry units, NTE 070 (2006) considers 4.90 *MPa* as the minimum value to be considered as type I brick. The F1 bricks do not classify at this minimum since their $f'b$ was 4.61 *MPa* on average. On the other hand, F2 bricks (6.16*MPa*) do classify as Type I. Type I are bricks with meagre strength and durability, which can only be used under minimum requirements (1 or 2-story houses) and avoiding direct contact with rain or soil, according to ITINTEC 331.017 (1978).

From the non-classifying tests, which are more related to construction procedures, the suction values must be between 10 and 20 *gr/200cm2-min*. From the values achieved in the tests, none of the units is in this range. Therefore, it is recommended to water the units before setting, since, otherwise, adverse effects could be generated when the unit absorbs water from the mortar. Regarding the absorption test, the masonry units had values lower than the maximum value of 22% indicated by NTE 070 (2006). About the saturation coefficient, units with values greater than 0.85 are too porous and, therefore not very durable (San Bartolomé 1994). According to the results of the test, the masonry units do not exceed the limit, which means that they are durable and, since they have a low absorption percentage, they could also be exposed to the outdoors.

Despite the fact that the results of the qualification tests could be good in some aspects, the structural quality of the units is poor given their low *f'b* value, whose result varies even from one producer to another (F1 and F2).

4.2. Compression tests on mortars

To compare the quality of the mortar used to construct the masonry prisms, cubic specimens of mortar with two different dosages were made and tested. For the 1:4 dosage (cement: sand), which was used for the TP standard typology, a compressive strength (*f'c*) of 14.4 *MPa* was obtained. For the 1:7 dosage commonly used for housing construction in San Miguel (T1, T2 and T3), an *f'c* of 8.2 *MPa* was obtained (43% lower than TP). San Bartolomé (1994) mentions that the poor quality of the mortar can influence the compressive strength of the masonry by 10%. Therefore, the compressive strength of the mortar should be similar to that of the unit. This is to avoid its failure by crushing and giving homogeneity to the masonry.

4.3. Axial compression tests on piles

The axial compressive strength (*fm*) of the piles was calculated using the following equation:

$$fm = C * \frac{Pmáx}{área}$$

where *C* represents the coefficient of correction for slenderness that varies according to the height of the pile and *Pmax* is the maximum load applied on the prism. The value of *C* in this study was 0.92 for TP and T1; 0.94 for T2; and 0.88 for T3. The characteristic strength to the axial compression of the masonry (*f'm*) was obtained as the average value of the samples tested (by typology) minus one times the standard deviation.

Figure 12 shows a summary of the 24 results obtained from the axial compressive strength tests on masonry piles. As can be seen, the *f'm* values obtained for TP did not reach the recommended value by NTE 070 for handmade bricks (3.40 *MPa*), even though an adequate mortar was used in this typology. It can be pointed out that this typology is the closest to the value recommended by the Peruvian standard. The *f'm* results obtained for the other typologies (T1, T2 and T3) are lower than the minimum recommended value. Therefore, the poor construction quality of the masonry walls in San Miguel is demonstrated.

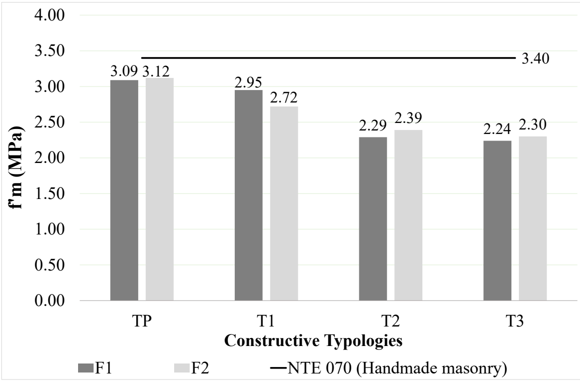


Figure 12. Characteristic strength to axial compression in TP, T1, T2 and T3 piles.

According to values obtained for typologies T1, T2 and T3, it can be deduced that the characteristic strength to axial compression in piles is inversely proportional to the joint mortar thickness; that is, as the mortar joint thickness increases, the axial compression strength decreases. As shown in Figure 13, the *f'm* value of TP (thickness e= 10 *mm* and mortar 1:4) is 90% of the standard *f'm*; of T1 (e= 20 *mm*), between 80 and 88% of the standard; of T2 (e= 30 *mm*), between 67 and 70% of the standard; and T3 (e= 40 *mm*), 68% of the minimum specified value in the standard. It is also indicated that the mortar used in TP had a compressive strength of 14.4 *MPa*, and in the others of 8.2 *MPa*.

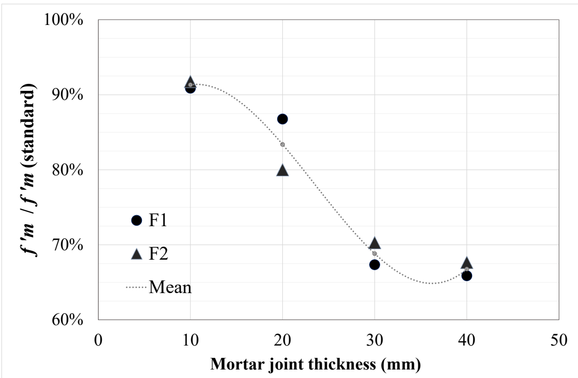


Figure 13. Variation of *f'm* according to TP, T1, T2 and T3 mortar joint thickness.

4.4. Diagonal compression tests on walls

ASTM E-519 (2021) and the NTP 399.621 (2004) standards defines the test method for determining the diagonal tensile strength (*vm*) assuming uniform shear stress conditions. In this case, the diagonal tensile and shear strength are the same. These standards recommends the following equation for evaluating the diagonal tensile (shear) strength:

$$vm = 0.707 * \frac{P_u}{A_n}$$

where *Pu* is the maximum force supported by the wall and *An* is the area of one side of the specimen. The characteristic strength of the masonry to shear obtained from diagonal compression wall tests (*v'm*) was obtained as the average value of the tested specimens (by typology) minus one time the standard deviation.

It is important to mention that RILEM TC 76-LUM (1994) stablishes that the stress state is not uniform along the diagonal of the wall. Then, there are different equations to compute the tensile and shear strength. The first is obtained as 0.5 P_u/A_n, and the second as 0.88 P_u/A_n (Brignola et al. 2008). As Crisci et al. (2020) mention, the tensile strength of masonry walls is lower than the one computed with ASTM E-519 (2021), while the pure shear strength is higher.

Figure 14 shows the results obtained from the diagonal tensile strength tests on masonry walls following the ASTM E-519 (2021) and NTP 399.621 (2004), no deformation gauges were used. Even though the TP walls were built with a good quality mortar and respecting the thickness of the joints, their *v'm* value did not reach the minimum value recommended by NTE 070 (2006) for handmade bricks (0.50 *MPa*). The diagonal tensile (shear) strength values of the other typologies are well below the recommended minimum. This situation is of concern since *v'm* is a direct value to evaluate the seismic capacity of confined masonry housing. It is essential to mention that the *v'm* for industrial bricks is 0.80 *MPa* according to the standard. In case to use RILEM TC 76-LUM (1994) standard, the computed tensile strengths will be less than the ones reported in Figure 14.

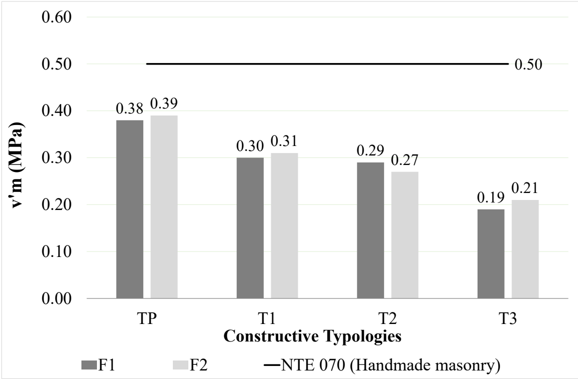


Figure 14. Diagonal tensile (shear) strength characteristic for TP, T1, T2 and T3 walls computed with ASTM E-519 (2021) and NTP 399.621 (2004).

Similar to piles, it can be deduced that the characteristic strength to diagonal shear in walls is inversely proportional to the thickness of the mortar joint; that is, as the thickness of the joint mortar increases, the diagonal shear strength decreases. Figure 15 shows that the *v'm* value of TP (e= 10 *mm*) is around 77% of the *v'm* of the standard; of T1 (e= 20 *mm*) 60% of the standard; of T2 (e= 30 *mm*) between 54 and 58% of the standard; and T3 (e= 40 *mm*), between 38 and 42% of the minimum value specified in the standard.

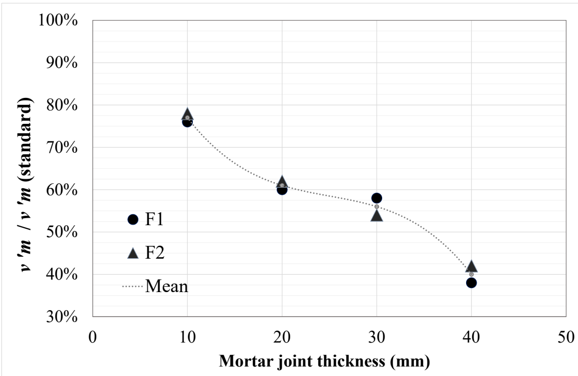


Figure 15. Variation of *v'm* according to TP, T1, T2 and T3 mortar joint thickness.

5. CONCLUSIONS

Of all the surveyed houses, 25% have walls with joint thicknesses of 20 *mm*, 58% with 30 *mm*, 12% with 40 *mm*, and 5% variable. In addition, the inhabitants use handmade bricks for construction. The 10 most common construction problems in these houses are walls with non-uniform mortar joint thickness, exposed steel, efflorescence in the lower part of walls, poor horizontal and vertical alignment of bricks, presence of hollowness in mortar, salinity in overlays, lack of good brick-mortar interaction, deficient column-wall interaction through notching, and hollowness in confining elements. This demonstrates the lack of professional counselling during the design and construction of housing in San Miguel and Puno in general.

From the results of axial compression in piles and diagonal compression in walls, it can be concluded that the strength values are inversely proportional to the thickness of the mortar joints; this means that the greater the thickness of the joint, the lower the strength value of the masonry. In axial compression, masonry built with handmade bricks and joint thicknesses of 20, 30 or 40 *mm* reduces its axial strength by 15, 32 and 35%, concerning the minimum value of 3.40 *MPa* specified by the Peruvian standard. For diagonal compression, the same joints show a shear strength reduction in the walls of 40, 45 and 60%, concerning the standard's minimum value of 0.50 MPa. Although in masonry with a joint thickness of 10 *mm* and a mortar with a cement:sand ratio of 1:4, the masonry strength values are below the minimum values recommended by the standard. In addition to the construction problems identified during the surveys, it can be deduced that the houses in San Miguel have a high seismic vulnerability and could fail and even collapse in case of an earthquake. These results demonstrate the high seismic vulnerability of buildings in San Miguel and the urgent need to implement training campaigns for the proper construction of seismic-resistant housing, study massive forms of seismic reinforcement, and improvement of existing housing, thus mitigating the seismic risk in Puno.

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