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A review on different destructive methods to determine the compressive strength of an existing masonry

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Abstract:- Determination of the compressive strength of an existing masonry attracted the attention of many scientists and researchers around the world. Most of these researchers, scientists and engineers want to find the best way to obtain the compressive strength of masonry in situ with high accuracy, and less cost. There are many methods to determine the compressive strength of masonry. Some of these methods are destructive methods and others are non-destructive methods and others are partially destructive. Each one of these testing methods has advantages and disadvantages .this paper presents different destructive testing Methodsfor obtaining the compressive strength of an existing masonry. Testing procedure, the main advantages and the problems of each method are explored.

Keywords:- masonry, compressive strength, flat jack, core test method, masonry prism, standard test method

I. INTRODUCTION

Determination of the compressive strength of existing masonry constructions is not easy because of the variation of masonry materials properties; there are different building techniques, the knowledge about the existing damage in masonry construction throughout their life is absent and the lack of codes. In addition, restrictions in the inspection and the removal of specimens in buildings of historical value, as well as the high costs involved in the inspections and tests.

In recent years, large investments around the global were made in this field, leaded to discover some techniques which help to obtain masonry compressive strength with less cost and high accuracy and less damage in construction part where compressive strength is required to be obtained. Some of these methods are well known and introduced to codes.As an example flat jack testing method is well known in USA and introduced to American standards ASTM C 1996 and C 1997 while this method still unknown or not well known in Russia and other countries. On the other hand, some researchers attempted to discover other ways to obtain the compressive strength of masonry such as core testing methods which it has it aims and advantages. These methods need to be developed and solve their problems to find the optimum way to determine masonry strength. Also each method has it uses depending on the accuracy needed, the location of masonry part which need to obtain the strength of it and the cost of the test and other factors[1,2].

II. LITERATURE REVIEW

Methods for determination an existing masonry compressive strength are different and each one has it features and problems. Some of these methods are based on determination of mortar compressive strength and unit (brick, stone) compressive strength individually. But in order to obtain the compressive strength of the whole masonry in situ, the information about compressive strength of each mortar and unit (brick, stone) individually is not effective for the following reasons:

1- Any mistake in result of mortar strength or brick strength leads to mistake in the final strength of the whole masonry.**Steil et al.**[3] studied the influence of mortar strength on the compressive strength of masonry and found that an increase of 8.8% in the compressive strength of masonry prisms when increased 78% of the compressive strength of mortar. **Cunha et al.** [4] also investigated the relation between mortar strength and masonry strength and observed that increasing 400% of mortar compressive strength leads to obtain an increase of 20% in the compressive strength of the whole masonry.

2- There is no standard method to obtain the strength of mortar in situ. The American standard ASTM C 780 is based on testing normalized samples (referenced specimen) made from the same materials which the existing masonry made of. This method is not effective in term of existing mortar because the strength of mortar is challenging depending on many factors such as w/c ratio, mix proportion, aggregate ratio, sand type and

others. Furthermore, compressive strength is only one of several important mortar properties. Workability often has a greater impact on the quality of the masonry constructed. Other properties such as shrinkage characteristics and resistance to freeze-thaw deterioration can also affect the long term performance of the masonry. Also Field determined compressive strength test results of mortar do not correlate well with the structural properties of the in-place masonry [5].

Nwofor, T.C. [6] studied the effect of varying water/ cement ratio on the compressive strength of masonry. Different samples were prepared with different w/c ratio. Samples were tested after (7, 14, 28) days. Result showed that the compressive strength of mortar was decreased when increased w/c ratio values. **Appa Rao**[7] studied the influence of constituent materials and various mix proportions on compressive, splitting and tensile strength of the mortar. The study clearly showed that different mix proportion effect on the mortar strength and the strength was ranged from high strength to low strength depending on the mix proportion and water/cement ratio which was used in the experiment. Furthermore **Neville** [8] investigated the effect of aggregates on the mechanical properties of fresh and hardened mortar. Result showed that aggregates have a significant influence in both rheological and mechanical properties of mortar. Mineralogical composition, toughness, particle size distribution, shape and surface texture of aggregates are properties which effect on the behavior of mortars in fresh and hardened status and finally effect on mortar strength.
That means the properties of mortar prepared as normalized specimen according to American standard ASTM C780 might not be as the same as it is in the existing masonry and this lead to in accuracy of mortar strength obtained and lead to in accuracy in the result of the masonry strength even assuming that have a correlation to combine the strength of masonry component to obtain the compressive strength of the whole masonry.
3- The homogeneity of masonry component during working together in construction is important factor effect on masonry strength. Thus, it is impossible to predict the compressive strength of masonry using mortar and brick compressive strength individually [9].

For all of these reasons other methods were developed and used to determine the compressive strength of masonry. As stated in**LuigiaBinda**[10] Flat-jack testing originates from the field of rock mechanics. The first attempt of using the flat jack in masonry structure was by Italian researcher (Paolo Rossi) in the early 1980s and, since then, many researchers worldwide started paying attention to this technique, as example **C. Abdunur**[11] implemented tests with very small semi-circular flat-jacks, and conducted idealized photo elastic stress analyses on plastic models. **Atkinson-Noland &Associates** [12] used the flat jack testing method for evaluation compressive strength and deformability of an existing old masonry building in United States. The result has shown that this test method is accurate, straightforward, and suitable for using in old masonry structures. **Qinglin and Xiuyi**[13] developed a thick flat-jack with large displacement capabilities for use on very soft masonry materials typically found in China. **John C Scrivener** [14] carried out different type of tests on old masonry buildings. Results of this test showed that a correction factor is required to take account the effect of the flat jack. Usually the calibration factor is supplied with device. However, the device should be calibrated each 4-5 times of using it. Two separate standards for masonry evaluation with flat-jacks were developed in the United States by the ASTM and approved in 1991.**ASTM Standard Test Methods C 1196-91**, In-Situ Compressive Stress within Solid Unit Masonry Estimated Using Flat-jack Measurements [15] and **C 1197-91**, In Situ Measurement of Masonry Deformability Properties Using the F1at jack Method [16]. European practice follows RILEM standards **LUM.D.2 and LUM.D.3** [17], which were first introduced in 1990.

Alejandre[18] studied the estimation of Portland cement mortar compressive strength using small micro cores. The study was based on extracting small diameter core samples of mortar from masonry using cutting tools. On the other hand, normalized samples (referenced specimen) with the same parameters and same properties were prepared in laboratory. Samples from different shapes (cylindrical, prismatic), sizes and types were tested under compression to determine the compressive strength of the mortar and subjected to statistical analysis in order to find the difference value of compressive strength while changing these factors. Result showed that different parameters, shape and properties lead to different result of compressive strength. Conversion factors were found range from 0.53 to 0.86. Author stated that these conversion factors are allowed to be used for any mortar made of same parameters and properties.**Enrico Sassoni**[19] Studied different methods to determine the compressive strength of clay brick masonry in situ. Samples were taken from a multi-span masonry arch bridge in Bologna (Italy), the bridge works since (1852) for railway traffic crossing the Reno River. Large cylindrical (diameter =100 mm) core samples were extracted from the bridge and tested under compression to obtain compressive strength of masonry. On the same time masonry prisms were extracted from the same bridge part and tested according to masonry prism standard. Also, small cores from bricks and mortars were tested individually and the result of compressive strength of mortar and brick were combined using a

correlation. The result of masonry prism test and core test showed agreement with (fcm=13.2) for small cores and masonry prism method and (fcm=13.1) for large cores testing method.
In summary, there are different methods to obtain the compressive strength of an existing masonry. These methods are destructive and non-destructive methods (NDT).The destructive methods are standard testing method, masonry prism testing method, core testing method and flat jack testing methods.

III. METHODS REVIEWING

3.1 Determination of masonry compressive strength using core testing method:

There are two methods of core testing to determine the compressive strength of an existing masonry:

1. Small diameter core testing method for brick and mortar individually. Figure (1) shows an example of mortar small cores.
2. Large diameter core testing method (cylindrical cores) for the whole masonry brick and mortar together. This method is applied more in (splitting testing) to determine thetensile strength of masonry. (Unfortunately, the information about it in compressive strength determination is seldom).

Small core testing method is based on withdrawn small diameter core specimens of brick and mortar separately and testing the mortar and the brick individually under compression. The result of mortar compressive strength and the brick compressive strength should be combined using special formulas to determine the total compressive strength of masonry. This method is useful for historical buildings and some buildings where using small cores lead to reduce the destructionof masonry part where samples are taken while big samples cause more deformation in masonry and may reduce bearing capacity of the masonry construction or the element. That is the main advantage of using this methodfor obtainingmasonry compressive strength. However, there are some other advantages of using small core testing method such as:

1. Using small cores required less powerful machines or sampling probes and this lead to reduce the cost due to less purchase and/or amortize
2. The ability of obtaining more samples.
3. The small core samples are easier to handle.
4. It is impossible to extract big samples in some masonry construction parts such as masonry columns because of the small area of that part. Small core testing method offers a solution for this problem.

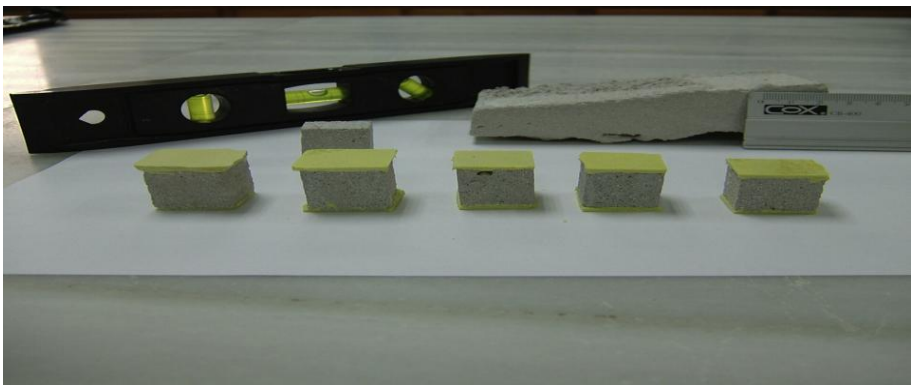

Figure (1)- Cubic micro cores of mortar capped with sulfur used in (Alejandre) experiment [18]

3.1.1 Size and shape of samples:[18,19,20,21]

a) For small core testing: Cores size recommended range from (15-60) mm for all lengths. Samples shape can be cubic or cylindrical.

b) For large core testing: Cores diameter should be 150mm. However the recommended diameter ranges from (100-150) mm. Samples shape is cylindrical.

3.1.2 Test procedure:[22,23,24,25,26]

For small diameter core testing:

Cores of mortar and brick should be extracted from masonry using the drill machine. In some cases, to take brick core we may extract the brick from masonry and then extract cores from the brick. After that, shaping and fixing samples and cutting them to the final size required using the saw. Samples surfaces should be smooth and empty of meandering. Then, mortar samples should be capped with sulfur or gypsumto ensure smoothness of the surface. Finally, testing cores under compression using the compression testing machine with specific load till failure to obtain the compressive strength of each mortar and brick separately. In order to have the whole masonry strength, some correlations should be used to combine the compressive strength of brick and

mortar together. The following equation is an example of correlation formula for masonries made of good quality of brick and mortar withfbc>fmc (cf. §3.1) as stated in [17].

Fwc,bm= [1−0.8 α^ (1/3)] × [fmc+ 0.4 (fbc−fmc)]

Where:
Fwc,bm: masonry compressive strength (brick and mortar)
fmc: mortar compressive strength
fbc: brick compressive strength
α: the ratio of mortar joint thickness to brick height (α≈10 mm/50 mm, on the average).

While the equation used in Russia is:
$R_u = AR_1 [1- a / (b+R_2 /2R_1)] \gamma$
Where:
R_u: masonry compressive strength;
R_1: compressive strength of unit;
R_2: compressive strength of mortar;
γ:Coefficient for masonry made with weak mortar (less than 2,5 MPa);
$A= [(100+R_1) / (100m+nR_1)]$
m, n, a, b: coefficients depending on the type of masonry units.

For large diameter core testing:
Cores should be extracted from masonry including brick and mortar together using drill machine. After that, cores should be treating to obtain the final shape and size of and surfaces should be smooth. Then samples should be casted with mortar to ensure the smoothness of surfaces and for load distribution while testing. Finally, testing samples under compression using the compression testing machine to determine the compressive strength of masonry.

3.1.3 Conclusion and Results of core testing method: [27, 28]

Masonry compressive strength results obtained using large cores (cylindrical cores) method is accurate. However, small cores diameter testing results might not be very accurate comparing with other methods such as masonry prism or flat jack depending on many factors. The shape of the sample, the size and the correlation used to combine between brick and mortar strength as well as the amount of samples tested plays an important role on the accuracy of the method.

3.1.4Technical difficulties of core test method to obtain masonry strength:[28,29]

In case of using small core test the usual Technical difficulties are:

1. Difficulties of mortar sampling.
2. The obtaining strength is the strength of brick and mortar individually.
3. There is not standard correlation to combine the compressive strength of the brick and the mortar together to determine the compressive strength of the whole masonry. There are different correlations from different resources and this lead to different results.
4. The direction of sampling effect on the value of the compressive strength of the sample. Samples which are taken in different directions lead to different results.

While in case of using large core testing method usual Technical difficulties are:

1. Compressive strength obtained by this method is represented to the compressive strength in the location of extracting. However, other locations in masonry part may have different compressive strength due to producing issue. It means that bricks of the same masonry parts have different values of compressive strength while producing. The same issue is for the mortar.
2. The amount of samples extracted is limited because extracting many samples with big size may effect on the strength of the existing masonry after extracting.
3. it is impossible to extract samples In some construction parts which have small areas such as columns or construction parts where extracting samples from masonry lead to deformation or reduce the bearing capacity in that part.
4. Direction of samples testing plays a significant role on the value of masonry strength. Different direction testing lead to different results.

3.2 Determination of masonry compressive strength using masonry prism testing method:

There are two ways of masonry prism testing method to determine the compressive strength of masonry.

1- The first way (normalized prisms) is the testing procedure According to American standard **ASTM C1314** [30] which it is based on build up masonry prisms consist of unit (bricks, blocks, others) and mortar together. Constructed prisms should be similar to those used in the construction. At least three samples should be prepared andthe minimum length of prisms shall be 4 in. (100 mm).then, surfaces of samples should be capped with sulfur-filled capping or with high-strength gypsum cementand samples should be tested under compression to determine the compressive strength of masonry.

2- The second way is based on extracting masonry prisms consist of unit (brick, block, others) and mortar from an existing masonry using saw-cut machine. Same testing procedure above is followed except that the specimen should be extracted from the existing masonry using a saw-cut machine [31].

The main advantage of this method is it uses for all masonry types (block, silicate brick, clay brick and others) and it uses for solid and hollow masonry units.

3.2.1 Results of masonry prism test method:[10,32,33]

The second way of masonry prism testing method is similar to large core testing method. The result is accurate and shows the real compressive strength of the existing masonry. However, the compressive strength result taken from the first way of this test (normalized prisms) doesn't express the real strength of the existing masonry for the following reasons:

1. The mortar compressive strength prepared in laboratory is not representative to the actual strength of mortar used in the existing masonry because the properties of mortar prepared in laboratory might not be as the same as it is in the existing mortar.
2. Also, the compressive strength of masonry is affected by the time. It means the compressive strength of masonry which was built before 50 or 100 years has a different compressive strength with the fresh sample prepared (normalized specimen) due to the durability, and the environment around the masonry.
3. Environment around the masonry play important role on masonry strength. the erosion of the mortar and masonry corrosion and the humidity percentage and other factors can reduce the compressive strength of masonry while the fresh masonry prisms prepared do not affected by these factors.
4. The homogeneity of masonry component duringbuilding the masonry construction is important factor effect on masonry strength. The homogeneity of component of the existing masonry might not be as the same as it is in the prisms prepared.

3.2.2 Problems of masonry prism testing method:[34,35]

Problems of the first way of masonry prism testing method (normalized specimen):

1. Compressive strength obtained by this method is not representative to the real compressive strength of the existing masonry for the reasons Annotated above in the point 3.2.5.
2. The test required good curing and handling during prisms construction and transportation.
3. The cost of this test is high due to the materials used to construct the prisms (units, mortar)
4. In some buildings especially the historical buildings need to find materials similar to which it used in the existing buildings. That means in some buildings which was built long time ago, masonry materials which was used in construction is unique and there are no similar materials nowadays.

Problems of the second way of masonry prism (extracted specimens):

1. The amount of samples extracted is limited because extracting many samples with big size may effect on the strength of the existing masonry after extracting.
2. Difficulties of samples extracting. While extracting the sample, different factors should be taken into account such as the location of the sample in masonry part, safety requirements and others.
3. it is impossible to extract samples In some construction parts which have small areas such as columns or construction parts where extracting samples from masonry lead to deformation or reduce the bearing capacity in that part.
4. Extracted samples should be avoided from fractures or damages while extracting, transportation and handling, Otherwise samples should be neglected.

3.3 Determination of masonry compressive strength using flat jack test method:

3.3.1 What is the flat jack?

Flat jack is an instrument made to be inserted into a typical mortar joint where slot is formed. It uses to determine the existing stress (in-situ stress), the deformability and the compressive strength of masonry

structures. Flat-jack is a "thin envelope-like bladder with inlet and outlet ports which may be pressurized with hydraulic oil". A flat-jack produces in many shapes and sizes as shown in figure (2). When the device works, it exerts pressure on the surrounding masonry and by measuring surface deformations; information about the existing state of stress as well as the stiffness and strength of masonry can be obtained.[36]

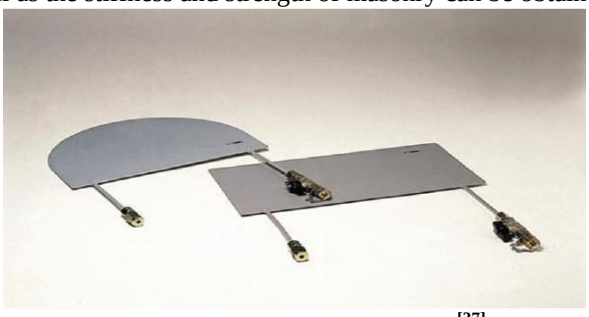

Figure (2)-flat jack equipment [37]

3.3.2 In-situ deformability test (Double flat-jacks):[12,37,38,39]

This test is similar to the single flat jack testing (in situ stress testing). The difference is that it is performed in-situ and two flat-jacks are used to exert the load. By digging two parallel slots, part of the wall is isolated from the surrounding masonry forming a "specimen". Masonry between the flat-jacks is assumed to be unstressed. Flat-jacks are then inserted into both slots, and the initial distances between gauge points are measured. By pressurizing flat-jacks, the load is applied to the "specimen" creating an approximately uniaxial state of compressive stress. Increasing the pressure in the device lead to decreasing the distances between gauge point pairs decrease. By gradually increasing the pressure, the stress-strain relationship can be determined. Loading-unloading cycles can also be performed. Based on an experimental stress-strain curve, the value of Young's compressive modulus can be calculated. Furthermore, compressive strength of masonry can be determined if extend damage in masonry is acceptable. Obviously; this can only be done if the maximum pressure of flat-jacks is higher than the strength of the masonry tested. Also, appearing of cracks while testing can be a sign of failure state in masonry and the result of compressive strength testing at the point of cracks appearing is acceptable. During testing, the load-displacement diagram is monitored and, when it becomes highly nonlinear (indicating imminent failure), loading is usually terminated. Even in this case, it is possible to estimate peak compressive strength by extrapolation of the stress-strain curve.

3.3.3 Accuracy of the flat-jack technique:

J.L. Noland [12] conducted an experiment on a masonry wall built in a simple load frame in United States. The wall was subjected to a uniform stress of 250 psi. A stress of 280 psi was measured during this test, which is reasonably close to the applied stress of 250 psi. In-situ deformability tests were also implemented on walls and provided similarly favorable results. For the modulus of elasticity, the result obtained by test 433ksi while the result by testing prisms constructed with the tested wall was 445ksi.the flat jack test showed error with the range of 15-20% in different experiments. **Authors of reference**[40] carried out some experiments .results of laboratory testing has shown that the in-place stress test has a margin of error of up to 20%.[1]conducted two Laboratory studies on two masonry specimen to evaluate the existing stresses using flat jack method. The stresses obtained from the tests are close to the applied stress with error is less than 15%. For practical applications such error in the stress estimation is reasonable and represents valuable information.

3.3.4 Technical difficulties of flat jack test method: [40,41]

1. In order to determine the compressive strength of masonry, the part of masonry tested (specimen) must be damaged to reach the failure status of the specimen.
2. In some constructions parts which have small area such as columns, it is impossible to use this method due to the damage of the part which may reduce the bearing capacity or lead to damage it totally.
3. Difficulties in the interpretation of results when the cutting and recovery of distances are not successful. Also, the reliable interpretation of the results when the material is too weak or non-homogeneous.
4. Cost issue. Flat jack device and other equipment need for the test are expensive.
5. Needing of repairing the construction part tested after using this method.

IV. CONCLUSION

There are different ways to determine the compressive strength of an existing masonry. Standard testing according to codes uses to obtain the strength mortar and brick individually and there is no correlation to

combine them in order to obtain masonry strength. Also, according to American standard ASTM C780, mortar strength obtained using this method is not representative to mortar strength in the existing masonry for the reasons explained in this article. Other methods are applied to determine the compressive strength of masonry in situ. These methods are flat jack testing method, masonry prism and core testing method. The using of each method, test procedure, advantages and problems of each method are demonstrated in the article. Authors suggested that combining between methods is the best way to determine the compressive strength of masonry in situ with high accuracy. That means using more than one method for the same part of masonry to obtain the compressive strength with high accuracy.

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