Düzce University Journal of Science & Technology, 12(2024) 264-278

Düzce University
Journal of Science & Technology

Research Article

Determination of Mechanical Properties of Walls Produced with Different Wall and Mortar Materials

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DOI: 10.29130/dubited.1374665

ABSTRACT

Walls produced using different masonry materials and mortars are among the structural elements that carry horizontal and vertical loads. In this context, the mechanical properties of walls produced with different wall and mortar materials have been investigated. In the production of wall samples, Harman Brick (HB), Masonry Brick (MB) and Bimsblok (BB) were chosen as the mesh material Reinforced Mortar (RM) and Polypropylene Fiber Added Mortar (PM) were used as binding materials in the construction of the walls produced in 900x900 mm dimensions. The volumetric mixing ratios of the mortar used were prepared as sand:cement:lime=6:1:1, according to the TSE 2510 standard. The bricked wall samples were subjected to diagonal loading tests after being kept in the laboratory environment for 28 days. Flexural and compressive strengths of the mortars used in wall building, displacement values of the walls, shear strength, rigidity modulus, energy absorption capacity and collapse patterns of the walls were determined. The graphs of the displacement values obtained by examining the behaviors observed in the test samples and the cracks formed were interpreted. It was observed that the shear strength of the walls built using PM was higher than the shear strength of the walls built using RM. The energy absorption capacity was highest in the fibrous specimen laid with masonry bricks. The average vertical load value of the wall specimens built with fibrous mortar, which is the BB of the masonry material, was 30% higher than the specimens built with non-fiber mortar.

Keywords: *Fiber, Mortar, Shear strength, Walls*

Farklı Duvar ve Harç Malzemeleri İle Üretilen Duvarların Mekanik Özelliklerinin Belirlenmesi

ÖZ

Farklı örgü malzemeleri ve harçlar kullanılarak üretilen duvarlar, yatay ve düşey yükleri taşıyan yapı elemanları arasında yer almaktadır. Bu kapsamda yapılan çalışmada farklı duvar ve harç malzemeleri ile üretilen duvarların mekanik özellikleri araştırılmıştır. Duvar numunelerinin üretilmesinde Harman Tuğla (HT), Yığma Tuğla (YT) ve Bimsblok (BB) örgü malzemesi olarak seçilmiştir. 900x900 mm boyutlarında üretilen duvarların örülmesi işinde bağlayıcı malzeme olarak, Takviyeli Harç (TH) ve Polipropilen Lif Katkılı Harç (PH) kullanılmıştır. Kullanılan harcın hacimsel olarak karışım oranları TSE 2510 standardına göre, kum:çimento:kireç=6:1:1 olacak şekilde hazırlanmıştır. Örülen duvar numuneleri laboratuar ortamında 28 gün bekletildikten sonra diyagonal yükleme deneyine tabi tutulmuştur. Duvar örülmesinde kullanılan harçların eğilme ve basınç dayanımları ile duvarların deplasman değerleri, kayma dayanımı, rijitlik modülü, enerji yutma kapasitesi ve duvarların göçme biçimleri

Received: 16/10/2023, Revised: 10/11/2023, Accepted: 16/12/2023

belirlenmiştir. Deney numunelerinde gözlenen davranışlar ve oluşan çatlaklar incelenerek elde edilen deplasman değerlerinin grafikleri yorumlanmıştır. PH kullanılarak örülen duvarların kayma dayanımı, TH ile örülen duvarların kayma dayanımına göre daha fazla olduğu görülmüştür. Enerji yutma kapasitesi ise yığma tuğla ile örülen lifli numunede en fazla meydana gelmiştir. Örgü malzemesinin BB olan lifli harçla örülen duvar numunesi lifsiz harçla örülen numunelerle göre % 30 oranında daha fazla ortalama düşey yük değeri alınmıştır.

Anahtar Kelimeler: *Lif, Harç, Duvar, Kayma dayanımı,*

I. INTRODUCTION

Walls are structural elements created by laying natural and artificial stones or blocks with a mineral binder, with or without mortar. In wall construction, mesh materials such as MB, HB, BB and aerated concrete and also mortars as binders are used. MB, which is among the masonry materials and is widely used in residences in rural areas, is generally constructed using binding materials called bricks and mortar. BBs, which are among the wall knitting materials, are a preferred material due to their fire resistance, high sound and heat insulation and low unit volume weight [1]. The mesh materials and mortars used in wall construction have significant effects on the strength of walls [2], [3]. Walls made of MB are sufficient in terms of pressure resistance, but insufficient in terms of shear resistance. The weak adherence between MB and mortar causes insufficient shear strength [4]. Insufficiency of shear strength of brick walls is one of the most important problems of brick applications [5]. Walls built with bricks in buildings generally carry lateral loads resulting from earthquakes. The expected durability of a brick wall subjected to seismic loads largely depends on the shear strength of the wall, and the shear strength of brick walls may also decrease over time [6]. In order to directly estimate the shear strength of walls, appropriate tests are performed on wall samples produced according to TS EN 1052-3 standard or diagonal loading tests according to ASTM 519-2022 [7]–[9]. However, in order to maintain the integrity of walls under various loading conditions, it is important to improve the properties of the mortars used as binders and ensure good adherence [10]. The mortar used as a binding material in wall construction, the amount of cement or lime in it, the grain distribution and properties of the aggregate, and the amount of mixing water are important factors that affect the mechanical and physical properties of the mortars. The mortars used in wall construction are to transfer the forces that the stones and bricks are exposed to from one row to another when they are in a horizontal or near-horizontal layer, and also to connect the stones and bricks to each other when the mortar is in a vertical or near-vertical state [11]. There are many studies on the shear strength of brick walls produced with different mortars [12]-[19]. The shear strength of walls depends on many factors such as brick material, strength of mortar, construction technology and curing conditions, as well as the bond strength between brick and mortar. It is known that the high mortar strength, which is among these factors, will also increase the adherence between brick and mortar. Various studies have been conducted by adding different fibers to cement mortars to reduce plastic shrinkage [20]. Homogenously distributed fibers in the mortar delay the formation of the first crack and control crack development. It strengthens the mortar against disintegration by reducing the expansion of initial cracks and preventing microcracks from turning into macrocracks [21], [22]. For this reason, various fibers are used to prevent cracks, protect the mortar-brick contact surface, and provide greater adherence between the mortar and brick surface [23].

In this study, it was aimed to determine the appropriate wall mesh material and binding material by finding out the mechanical properties of walls produced with different wall and mortar materials. In addition to the previous studies, masonry materials were selected as blend brick, masonry brick and pumice block and the shear strengths of the walls were investigated using fiber mortar. For the experimental study, 18 wall samples with the same geometric properties and dimensions of 900x900 mm were produced. RM and PM were used as binding materials in wall building. The volumetric mixing ratios of the mortar used are sand:cement:lime=6:1:1. HB, MB and BB were chosen as mesh materials in the production of wall samples. Wall samples produced with different wall and mortar materials were evaluated by subjecting them to shear strength testing and examining the test results.

II. MATERIALS AND METHODS

A. MATERIALS

CEMI-42.5/R type portland cement obtained from BASTAS Cement Factory, produced according to TS EN 197-1 (2012) standard, was used as a binder in the production of mortar samples [24]. The physical and chemical properties of cement are given in Table 1. Slaked lime with a specific gravity of 2.38 gr/cm^3 was used in the production of mortars used in wall building [25]-[28]. The physical and chemical properties of powdered lime are given in Table 2.

Table 1. *Physical and Chemical properties of CEM I 42.5 R type cement*

Chemical Analysis	**CEM I 42.5**
Al_2O_3 (%)	5.65
SiO_2 (%)	20.62
CaO (%)	62.08
Fe_2O_3 (%)	4.05
K_2O (%)	0.69
SO_3 (%)	2.57
MgO (%)	2.55
Na_2O (%)	0.27
Loss on ignition (%)	1.55
Physical Analysis	
Fineness (cm^2/g)	3400
Beginning of Set (min)	260
Ending of Set (min)	300

Tablo 2. *Physical and chemical properties of lime*

Chemical Analysis	**Analysis Results**
CaO (%)	85.78
R_2O_3 (%)	0.47
SO_3 (%)	1.47
MgO (%)	3.52
Loss on ignition (%)	22.51

In the production of mortar, river sand, whose 0-4 mm size granulometry is given in Figure 1, in accordance with TS 706 EN 12620+A1, was used [27]. The fineness modulus of the river sand used was calculated as 3.21. Water absorption percentages and densities of aggregates were found according to TS EN 1097-6 [28]. The surface dry water saturated density of the river sand is 2.67 g/cm^3, and its water absorption percentage is 1.15%. Drinkable city tap water was used within the scope of the experimental study [29].

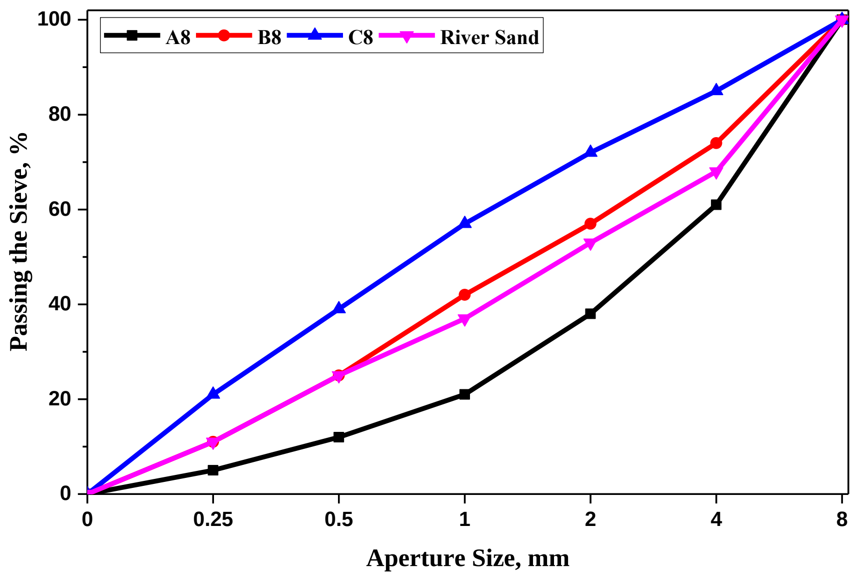


***Figure 1**. River sand sieve analysis*

In the process of knitting the wall samples, commercially available 90x190x50 mm sized HB (Figure 2a), 190x290x135 mm sized MT (Figure 2b) and 190x390x185 mm sized BB (Figure 2c) were used. The technical specifications of HB, MB and BB used in the experimental study are given in Table 3. The technical properties of Sika fiber brand polypropylene fiber added to the RM mixture are given in Table 4.

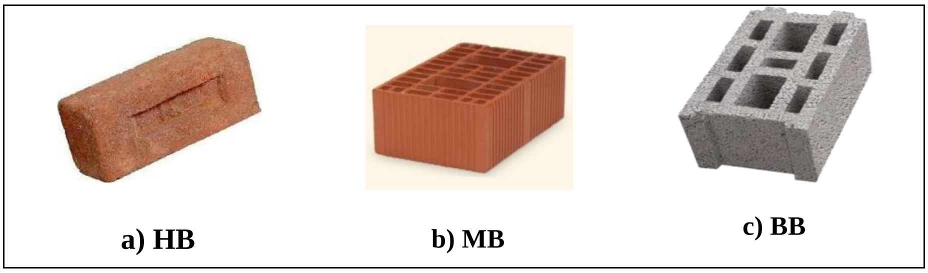


***Figure 2.** The appearance of **(a)** HB, **(b)** MB and **(c)** BB used*

***Table 3.** HB, MB and BB technical properties*

Technical Specifications	HB	BB	MB
Unit volume weight (kg/m^3)	1420	733	700
Compressive strength (MPa)	16	1.82	10
Amount of use (m^2)	98	12-13	22-25
Weight (kg)	2.15	8.5	4.5
Size (mm)	90x190x50	190x390x185	190x290x135

***Table 4.** Technical properties of polypropylene fiber*

Technical Specifications	**Description**
Specific gravity	0.91 g/cm^3
Length	12 mm
Diameter	18 mikron-nominal
Specific surface area	250 m^2/kg
Tensile strength	300-400 MPa
Elastic modulus	~4000 MPa

B. METHOD

In the construction of the wall a sample produced in the study, HB, MB and BB, and as binder reinforced and fibrous mortar was used. Flexural and compressive strengths of the mortars used were determined. In order to determine the shear strength of wall samples, diagonal loading tests were performed on the samples. Horizontal and vertical displacement values were recorded from the front surfaces of the samples. Experimental results were interpreted by drawing various graphs and tables. The names of the walls included in the study, the masonry material and the type of mortar used are given in Table 5.

Table 5. *Symbols and names of wall samples*

Sample Names	Wall Materials	Mortar Type
HB1- HB2- HB3	Harman Brick	Reinforced Mortar
HF1-HF2-HF3	Harman Brick	Fiber Added Mortar
MB1- MB2- MB3	Masonry Brick	Reinforced Mortar
MF1-MF2-MF3	Masonry Brick	Fiber Added Mortar
BB1-BB2-BB3	Bimsblok	Reinforced Mortar
BF1-BF2-BF3	Bimsblok	Fiber Added Mortar

B.1. Preparation of Mortars

The volumetric mixing ratios of the RM used in wall building are sand:cement:powdered lime=6:1:1. RM production was carried out by adding cement into the lime mortar in accordance with the relevant standard, and then it was mixed by adding 1.5 volume of water into the dry RM [30]. Polypropylene fiber was included in the mixture as 600 g, as recommended by the manufacturer, into the RM with a volume of 1 m^3. The amounts of materials used in the mortars prepared as binders are given in Table 6.

Table 6. *Materials and Sample names and weights in Experiment (1 m^3)*

Type of Mortar	River Sand (kg)	Cement (kg)	Lime (kg)	Polypropylene Fiber (g)
RM	2025	395	300	-
FM	2025	395	300	600

Within the scope of the experimental study, plain knitting type as shown in Figure 3 was preferred in knitting the wall samples. Plain knitting is formed by stacking straight rows on top of each other and half blocks are used to connect the corners. The wall samples were produced with a vertical joint spacing of 10 mm and a horizontal joint spacing of 12 mm [30]. The appearances of wall samples built using HB, MB and BB are shown in Figure 3. The samples were produced in dimensions of 900x900mm, not wider than 1.2x1.2 m^2 specified in the standard [8]. Wall thickness varies depending on the type of wall mesh material tested.

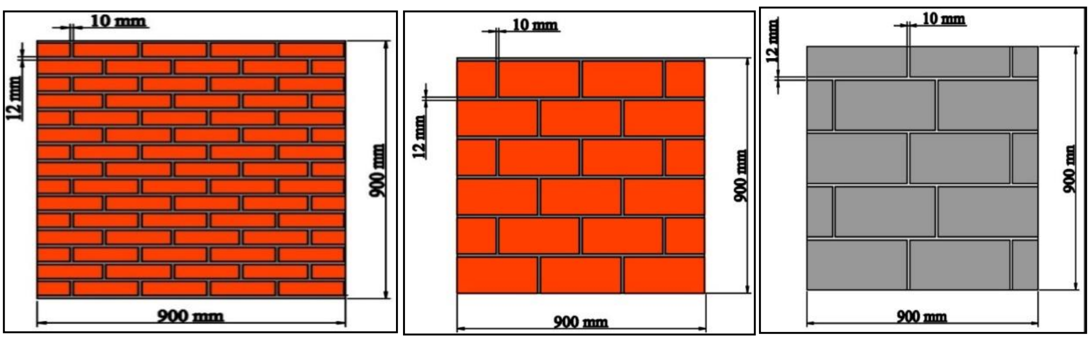


Figure 3. *Schematic views of wall specimens*

B.2. Experimental Studies

Flexural and compressive strength tests were carried out according to TSE 196-1 standard [31]. TS EN 196-1, 2016 on all mortar samples that were kept in the standard curing pool for 28 days. In order to apply vertical load to the wall sample, an experimental setup was created as shown in Figure 4a. During the preparation of the wall sample for the test, the sample was first rotated 45° and placed into the steel cap specially produced for the test. Care was taken to ensure that the sample placed inside the steel caps was in a vertical direction and that there was no gap between it and the cap. The loading mechanism is shown in Figure 4 by placing a hydraulic jack and load meter between the steel caps that are placed at the top and bottom of the sample and the loading frame. The load meter device is placed on the top of the loading device to measure the load acting on the wall. Strain gauges with a measuring length of 50 mm and a sensitivity of 0.001 mm were used to measure cracks in wall samples. To place the strain gauges in the experiment, holes were drilled at points 300 mm away from the intersection of the diagonals of the wall samples and the corner points. Then, anchor rods were placed at these points. Strain meters were installed so that one of these rods can be measured horizontally and the other vertically. Strain gauges were placed on the side surfaces of the produced test samples. A total of 2 channels were connected to the data cell for measuring cracks. Figure 4 shows the installation of strain gauges and the shear strength test setup. Shear strength, shear deformation and shear moduli of the samples were found with the help of ASTM 519 standard [8].

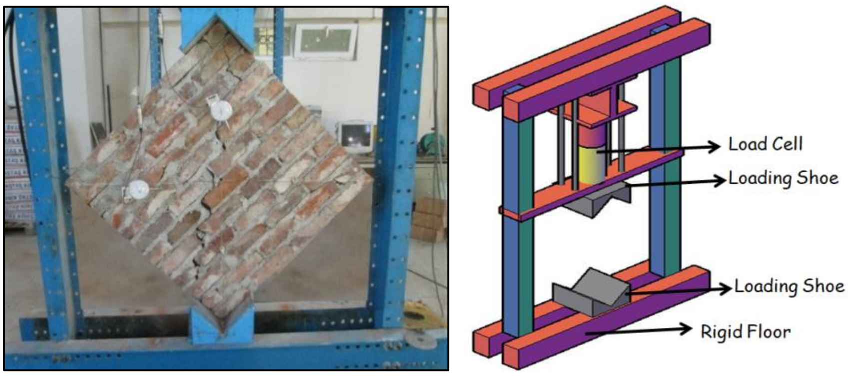


Figure 4. *Test setup*

III. RESULTS AND DISCUSSION

In this study, it was aimed to determine the mechanical properties of walls produced with polypropylene fiber RM and different masonry materials. In this context, the results obtained from the experiments performed on the walls are included in this section. With the flexural and compressive strengths of the mortars used as binders, the load/displacement graphs of the walls were interpreted by determining the collapse patterns of the walls, shear strength, stiffness modulus and energy absorption capacity.

A.1. Flexural and Compressive Strength Values of Mortars

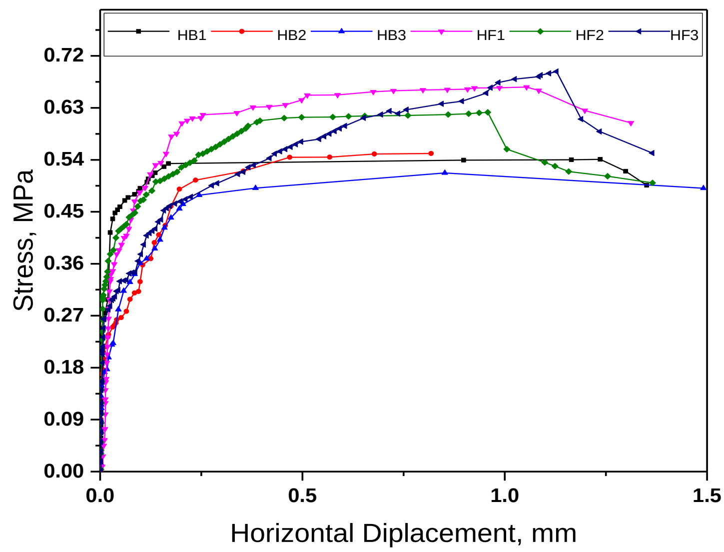
The flexural and compressive strengths of the mortars used in the knitting process of the knitting materials are shown in Table 7. It is seen that polypropylene fiber substitution causes a decrease in compressive strength, but an increase of approximately 15% in flexural strength. The compressive strength of reinforced mortars varies between 8 and 15 MPa [32]. The addition of slaked lime to cement mortars appears to provide less compressive strength but significantly higher flexural strength [33].

__Table 7__. Flexural and Compressive Strength of mortar samples, (MPa)

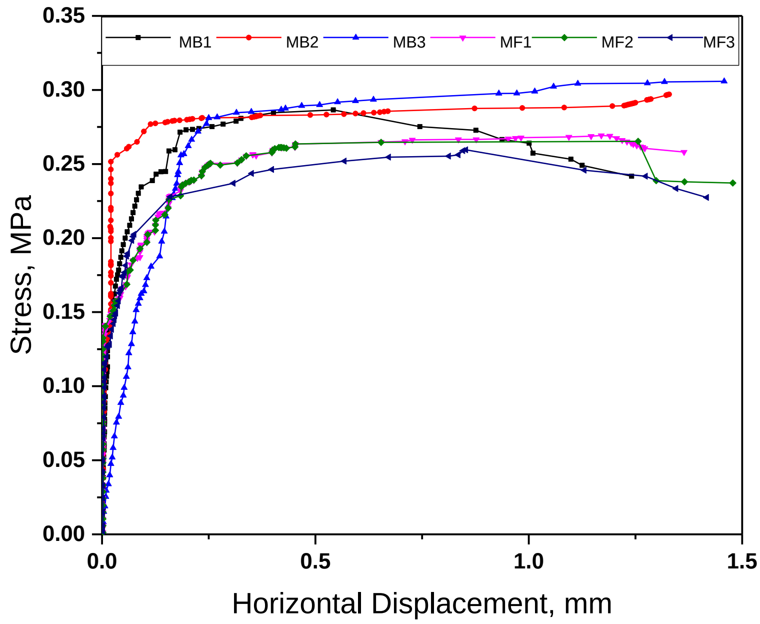
Type of Mortar	Flexural Strength	Compressive Strength
RM	6.7	9.5
FM	7.8	8.2

A.2. Stress-Horizontal Displacement Values

Stress-horizontal displacement graphs of wall samples are shown in 5. When the stress-horizontal displacement graphs of all wall samples were examined, the highest stress was seen in the wall samples built with FM, as 0.67 MPa. The lowest stress value was determined as 0.16 MPa in the sample knitted with BB. The addition of polypropylene fiber to the mortar used in wall knitting caused an increase in stress values in all samples.



(a)



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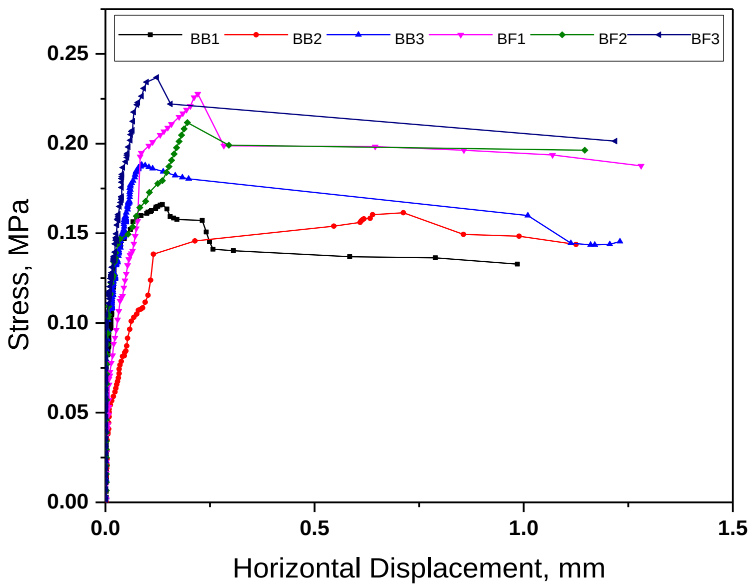

(c)

Figure 5. *Stress-horizontal displacement graphs of wall Samples* ***(a)****: HB,* ***(b)****: MB,* ***(c)****: BB*

A.3. Shear Strength

The shear stress corresponding to the greatest load in the wall samples is calculated and given in Table 8. The shear stress corresponding to the highest load (74.4 kN) among the samples was calculated as 0.216 N/mm^2 in the MF03 sample. More shear strength occurred in samples knitted with PH. The shear strengths of the test samples corresponding to the highest load are shown in Table 8. The maximum shear modulus corresponding to a load of 72.25 kN was calculated as 0.00256. The reason why the shear modules are different is that the vertical and horizontal displacements vary between the samples. It is seen that the average vertical load values are higher in the test samples knitted using polypropylene fiber. The average vertical load value of the wall sample built with FM, where the knitting material is HB, was approximately 20% higher than the samples built with fiberless mortar. The average vertical load value of the wall sample built with PH, where the knitting material is MB, was approximately 12% higher than the samples built with fiberless mortar. The average vertical load value of the wall sample built with polypropylene fiber-infused mortar, where the mesh material is BB, was approximately 30% higher than the samples built with fiber-free mortar. The mesh material also contributed to the walls produced using FM reaching the highest load at different values.

Table 8. *Modulus of shear of test specimens*

Samples	Highest Load (kN)	Average Load (kN)	Shear Stress (MPa)	Shear deformation (γ)	Vertical Displacement ΔV (mm)	Horizontal Displacement ΔH (mm)
HB01	34.48	34.70	0.21	0.00172	0.953	1.236
HB02	36.69		0.22	0.00207	0.985	1.651
HB03	32.93		0.20	0.00109	0.529	0.852
HF01	42.05	41.95	0.26	0.00176	1.152	1.084
HF02	39.65		0.24	0.00173	1.242	0.958
HF03	44.15		0.27	0.00198	1.395	1.128
MB01	65.17	64.04	0.19	0.00184	1.168	1.170
MB02	64.18		0.18	0.00167	0.864	1.256
MB03	62.78		0.18	0.00216	1.891	0.853
MF01	69.31	71.86	0.20	0.00075	0.411	0.542

MF02	72.25		0.21	0.00256	1.891	1.365
MF03	74.04		0.21	0.00193	0.803	1.657
BB01	40.18		0.11	0.00047	0.457	0.136
BB02	39.05	41.58	0.11	0.00091	0.450	0.712
BB03	45.52		0.13	0.00045	0.486	0.087
BF01	55.08		0.16	0.00046	0.368	0.221
BF02	51.20	54.52	0.15	0.00052	0.470	0.196
BF03	57.28		0.16	0.00032	0.279	0.123

A.4. Stiffness Module

The stiffness module values of the wall samples were calculated using vertical load-vertical strain values. Table 9 gives the calculation results of the stiffness modules of the samples. The highest stiffness modulus is seen in the HB03 sample with a value of 337.20 MPa, and the lowest is seen in the MB02 sample with a value of 82.57 MPa.

Table 9. Modulus of rigidity of the samples

Samples	Highest Load (kN)	Modulus of Rigidity (MPa)	Samples	Highest Load (kN)	Modulus of Rigidity (MPa)
HB01	34.48	222.73	HF01	42.05	265.92
HB02	36.69	196.81	HF02	39.65	254.85
HB03	32.93	337.20	HF03	44.15	247.45
MB01	65.17	103.72	MF01	69.31	270.63
MB02	64.18	112.65	MF02	72.25	82.57
MB03	62.78	85.14	MF03	74.04	112.00
BB01	40.18	252.13	BL01	55.08	347.98
BB02	39.05	125.05	BL02	51.20	286.11
BB03	45.52	295.61	BL03	57.28	530.25

A.5. Energy Depletion Values

The amounts of energy absorption capacity by the samples during the experiment were calculated from the areas under the vertical load-strain curves of the samples. While calculating the area, the area under the part up to 0.85 of the highest vertical load level on the falling arm of the vertical load and strain curve, where the highest load level begins to decrease, was taken into account for each sample [34]. Energy absorption capacity of wall samples are given in Table 10. The highest energy absorption capacity was calculated in the MB02 sample as 122.11 kNmm, and the least in the HF03 sample as 43.20 kNmm. It is seen that the addition of polypropylene fiber to the produced mortars causes an increase in the energy absorption capacity of the samples.

Table 10. *Energy absorption capacity of wall samples*

Specimens	Highest Load (kN)	Energy Absorption Capacity (kNmm)	Specimens	Highest Load (kN)	Energy Absorption Capacity (kNmm)
HB01	34.48	57.86	HF01	42.05	58.29
HB02	36.69	62.20	HF02	39.65	41.32
HB03	32.93	53.35	HF03	44.15	43.20
MB01	65.17	113.57	MF01	69.31	85.32
MB02	64.18	106.78	MF 02	72.25	122.11

MB03	62.78	89.45	MF 03	74.04	168.91
BB01	40.18	54.25	BL01	55.08	62.80
BB02	39.05	55.43	BL02	51.20	59.12
BB03	45.52	74.16	BL03	57.28	63.48

A.6. Immigration of Samples Formats

As a result of the observations made on the wall samples built with TH fibrous mortar, where HB was used as the masonry material, the collapse generally occurred with the formation of diagonal cracks along the joint and the vertical separation of the sample into two at the interface of HB and mortar. As a result of the crack propagating vertically and along the joint, it ended by splitting into two with a brittle fracture at the interface of HB and mortar. During the experiment, no crushing occurred on the upper and lower headings of the wall built with HB. The cracks formed after loading in wall samples built with HB and FM are shown in Figure 6.

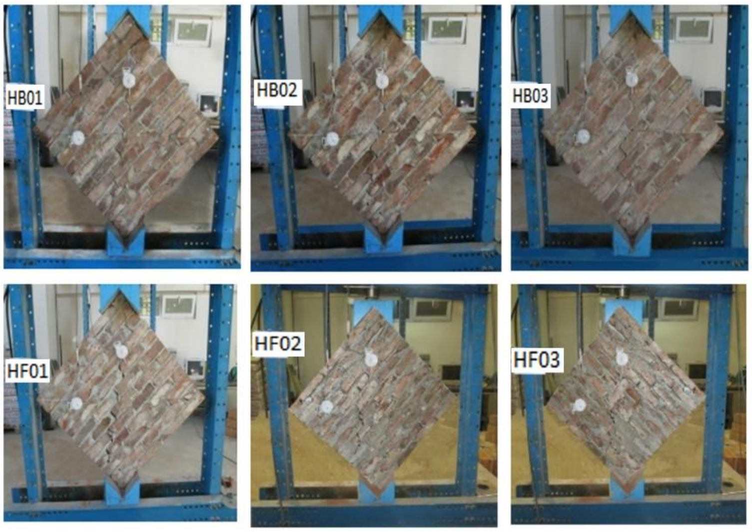

Figure 6. *Failure patterns of wall samples built with HB*

As a result of the observations made on the wall samples built with MB as a masonry material, the collapse pattern started with the formation of small cracks in the vertical direction. As a result of the crack propagating along the joint, the masonry brick and mortar interface separated from each other. A diagonal crack occurred in the MB element located on the upper side of some wall samples, but no crushing occurred in the upper and lower headings of the masonry brick walls. In some samples, cracks occurred due to the breaking of MBs. The cracks formed in the wall samples after loading are shown in Figure 7.

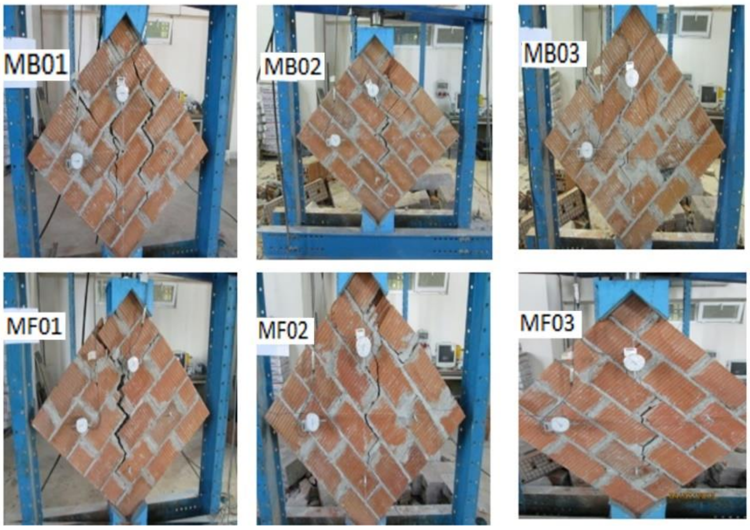

Figure 7. *Failure patterns of wall samples built with MB*

The collapse happening as a result of the observations made on the wall samples built with BT and FM as the masonry material occurred due to the formation of diagonal cracks along the joint and the vertical separation of the sample into two from the BB and mortar interface. A diagonal crack occurred in the middle area of the wall. During the experiment, no crushing occurred on the upper and lower heads of the wall built with BB. With the sudden increase in the crack width, the BT02 wall sample suddenly separated in the vertical direction due to the increasing load effect. The cracks formed in the wall samples after loading are shown in Figure 8.

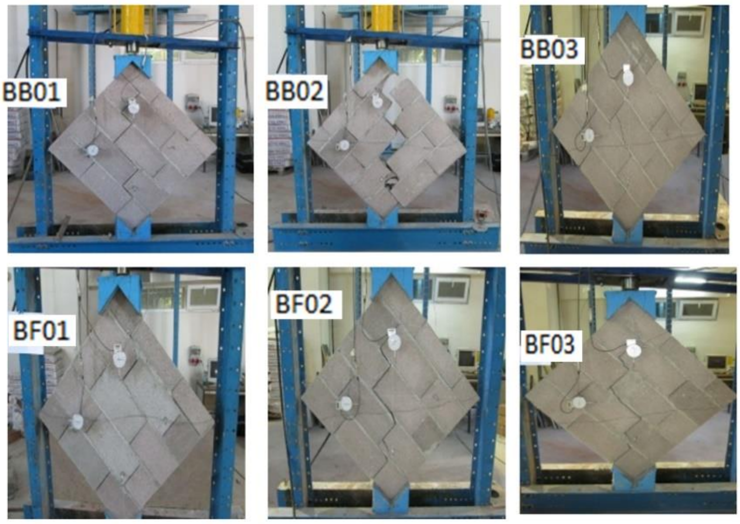

Figure 8. *Failure patterns of wall samples built with BB*

Cracks that occur as a result of shear strength tests performed on wall samples may occur predominantly through mortar joints or through blocks [35]. It was observed that they split into two at the brick and mortar interface [36]. In addition, there are other factors that affect brick wall strength, such as mortar thickness and bond strength between mortar and brick [37]. It is observed that the collapse of wall samples built with mortars with insufficient bond strength is caused by the insufficiency of the bond between the mortar and brick units, but in mortars with stronger adherence, the bricks crack [38].

IV. CONCLUSION

The mechanical properties of walls produced with different wall and mortar materials were determined experimentally. Experimental results were obtained by producing 18 wall samples of 900x900 mm in size with the same geometric features. The binding material used in the masonry was TH and PP fiber mortar, and HB, MB and BB were used as the masonry material. The test results performed on wall samples are given below.

• It is observed that substituting polypropylene fiber in mortars causes a decrease in compressive strength, but an increase of approximately 15% in flexural strength.

• When the stress values of all wall samples were examined, it was seen that the highest stress value was 0.67 MPa in the wall sample knitted with FM, and the lowest stress value was 0.16 MPa in the sample knitted with BB. The addition of polypropylene fiber to the mortar used in wall masonry caused an increase in stress values in all samples.

• When the shear stresses of the samples were examined, the shear stress corresponding to the highest load (74.4 kN) was calculated as 0.216 N/mm^2 in the MF03 sample. The reason why the shear modules are different is that the vertical and horizontal displacements that occur vary between samples. It is seen that the average vertical load values are higher in the test samples knitted using polypropylene fiber. It is seen that the wall samples built with fibrous mortar, where the mesh material is HB, MB and BB, receive 20%, 12% and 30% more average vertical load values, respectively, compared to the samples built with non-fibrous mortar. The mesh material also contributed to the walls produced using PH reaching the highest load at different values.

• It was observed that the shear strength value was highest in the samples knitted with MB. It is thought that the reason for this is the high adhesion of mortar and masonry bricks and that the mortar enters the holes in the brick and increases the slip resistance.

• It has been determined that wall samples built with PH contribute to the shear strength of the wall. Wall samples built using FM showed higher shear strength than wall samples built using RM.

• The collapse that occurred in almost all of the wall samples occurred due to the formation of diagonal cracks along the joint and the vertical separation of the wall sample into two at the interface of the mesh material and mortar. It has been determined that samples knitted with BB have more brittle fractures than other samples.

• It has been observed that MB wall samples knitted using polypropylene fiber have a higher ability to deform and carry the highest load than other samples.

The fact that the walls used in masonry structures are load-bearing for the structure increases the importance of masonry materials. For this reason, the addition of polypropylene fibers to mortars in masonry masonry work with mortar bricks, masonry bricks and pumice block will make the structures safer.

ACKNOWLEDGEMENTS: This work is supported by Gazi University Scientific Project (Project no: 07/2012-58).

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