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Design of interlocking masonry units and mechanical properties of masonry assemblages

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Abstract. This paper describes the design of a new interlocking masonry system, the production of designed interlocking units and mechanical properties of interlocked masonry assemblages with mortar. In this proposed system, units have horizontal and vertical locks to integrate the units to the wall and have a channel to enable the use of horizontal reinforcements in the wall. Using these units, unfilled, filled or reinforced walls can be constructed with or without mortar. In the production of the interlocking units, it was decided to use foamed concrete. 12 trial productions have been carried out at different mix proportions to obtain the optimum concrete mix. At the end of the mentioned productions, the units were produced with foam concrete which is selected as the most suitable in terms of compressive strength and specific gravity. Then, axial compression, diagonal tension and bed joint shear tests were carried out to determine the mechanical properties of the interlocked masonry assemblages with mortar. Results from the tests showed that interlocks designed to strengthen the system against shear stresses by creating discontinuity throughout the joints have been successful to achieve their aim. Obtained data will enable structural analysis of walls to be constructed with these new units.

Keywords: interlocking masonry; mechanical behavior; experimental study; foam concrete; mortared joints; masonry

1. Introduction

Masonry is a combination of units and mortar, which have different properties and is one of the oldest construction techniques. It is used widely around the world because of availability of materials, ease of construction, fire/frost resistance etc. But masonry structures cannot adequately resist seismic loads. After recent serious earthquakes in Turkey (for example, Kocaeli 1999, Duzce 1999, Van 2011), it has been observed that a lot of unreinforced masonry (URM) structures heavily damaged or collapsed because of their relatively higher mass, lack of ductility, energy absorbing capacity, poor-quality masonry materials, poor workmanship, poor connection between components etc. (Bayraktar *et al.* 2007, Dogangun *et al* 2008, Celep *et al.* 2010, Karaca *et al.* 2017, Oyguc and Oyguc 2017). Therefore, it is needed to improve their seismic performance and develop more effective masonry construction techniques. Damages to masonry structures under seismic effects include in-plane and out-of-plane wall failures. Out-of-plane failure, which is overturning of the URM walls, depends directly on the quality and strength of the connections (Oyguc and Oyguc 2017). In-plane failure mechanisms of URM walls, subjected to earthquakes, are characterized into three principal behavior i.e., a) diagonal shear cracking, diagonal cracks propagate as stair-stepped cracks along bed and head joints in the case of strong unit-weak mortar and across the units in the case of weak units-strong mortar, b) sliding on horizontal bed joints because of weak mortar joints, and c) flexural failure, subdivided into two types: rocking and toe crushing failure (FEMA 1998, Tomazevic 2000, Murthy *et al.* 2012, Khan *et al.* 2017, Leeanansaksiri *et al.* 2018,).

Rising population growth in developing countries has increased demand for residential houses. Early attempts were made to increase the size of masonry units and hence the number of mortar joints, which restrict on the number of layers to be constructed in a day, have been reduced (Anand and Ramamurthy 2000). Then, interlocking masonry units for low-rise buildings started to be used to eliminate the bedding mortar. Elimination of bedding mortar results in greater economy and accelerates construction speed (Anand and Ramamurthy 2000, Thanoon *et al.* 2008, Lee *et al.* 2017). Further, walls with these units can be assembled at much faster speed compared to conventional masonry construction due to self-aligning characteristics of interlocking units which enable them to be laid firmly on top of each other (Lee *et al.* 2017). Some researchers compiled the historical development of interlocking blocks and described their geometric properties, purposes and methods of construction until 2004 (Anand and Ramamurthy 2000, Ramamurthy and Nambiar 2004). Some other interlocking masonry units are also developed from 2004 to day. Some of them are hollow (Thanoon *et al.* 2008, Fay *et al.* 2014, Sokairge *et al.* 2017), some are solid (Ayed *et al.* 2016, Narayanan and Ramamurthy 2013) and others have holes for reinforcement (Ali *et al.* 2012, Lee *et al.* 2017, Mirandi *et al.* 2017). Some researchers have reported that interlocking keys of hollow block are not sufficient to resist the stresses of design load for an assembled wall in a

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structure due to elimination of mortar layers (Thanoon *et al.* 2008, Ali *et al.* 2012). To overcome this drawback, conventional reinforced concrete (RC) is used at regular intervals in the holes provided in hollow blocks (Thanoon *et al.* 2008, Sokairge *et al.* 2017). Furthermore, some researchers have used bed joint mortars (less mortar compared to conventional masonry) to improve the mechanical behavior of the interlocking masonry (Smith 2010, Narayanan and Ramamurthy 2013, Mirandi *et al.* 2017). The material used to product interlocking masonry units are stabilized earth (Nazar and Sinha 2006, Fay *et al.* 2014, Ayed *et al.* 2016, Mirandi *et al.* 2017), conventional concrete (Sokairge *et al.* 2017), fibre-reinforced concrete (Ali *et al.* 2012) and foamed concrete (Narayanan and Ramamurthy 2013).

Recently, foamed concrete (FC), in different structural applications, has widely used because of its some favorable characteristics such as low density, better acoustic insulation (Zhang *et al.* 2015), low thermal conductivity (Chen and Liu 2013, Zhang *et al.* 2015, Liu *et al*. 2017), good fire resistance (Jones and McCharty 2005, Liu *et al*. 2017), good energy absorption (Chen and Liu 2013, Hadipramana *et al.* 2015). Furthermore, FC is used at a flowing consistency, fills up the molds easily and self levelling is achieved without any vibration (Narayanan and Ramamurthy 2013). Because of its low density, FC is used to reduce the risk of earthquake damages of structures because the earthquake forces influence the structures in proportions of their mass. FC consisting of entrapped bubbles is classified as lightweight concrete which is generally the combination of cement, sand, water, foam and lightweight aggregates. Despite the advantages, FC have low compressive, tensile strength and drying shrinkage resistance. Hence, some additives such as fibers, silica fume (SF), fly ash (FA) have begun to be used to improve the mechanical properties of FC. The use of fibers in FC has been reported to improve compressive strength (Bing *et al.* 2012, Awang *et al.* 2012, Hadipramana *et al.* 2013, Liu *et al.* 2017), tensile strength (Bing *et al.* 2012, Hadipramana *et al.* 2013, Rasheed and Prakash 2015), drying shrinkage resistance (Bing *et al.* 2012, Awang *et al.* 2015) and ductility (Rasheed and Prakash 2015, Afifuddin and Churrany 2017). It's also reported that the fibers can decrease formation of micro cracks and prevent propagation of cracks derived from micro cracks (Hadipramana *et al.* 2013, Rasheed and Prakash 2015). Many researchers have already examined the influence of the use of fly ash on properties of FC. According to them, fly ash in FC gives uniform distribution of air voids by providing uniform coating on each bubble and prevents bubbles from merging and overlapping (Kunhanandan Nambiar and Ramamurthy 2007, Chindaprasirt and Rattanasak 2011, Jitchaiyaphum *et al.* 2011, Awang *et al.* 2012). Since fly ash used as additive reduces the size and amount of air voids, FC will have better thermal properties (Awang *et al.* 2012, Jitchaiyaphum *et al.* 2011). Also, strength of FC with fly ash increases because of well-connected air voids (Chindaprasirt and Rattanasak 2011, Jitchaiyaphum *et al.* 2011). Moreover, incorporation of fly ash in FC has been found to reduce shrinkage and extend setting time of FC as it reduces heat of hydration (Chindaprasirt and Rattanasak 2011, Awang *et al.* 2012). Silica fume (SF) also helps to improve air-void distribution, making bubbles more uniform, closed circular and narrow size, hence addition of SF improves compressive strength and thermal insulation of FC (Bing *et al.* 2012, Hilal *et al.* 2015).

In this study, new type of interlocking masonry units which can provide to improve earthquake resistance of structures were designed and produced by considering failure modes of masonry walls. It was also aimed to reduce the cost of building by passing the reinforcement through the wall and not using any formwork in concreting. In the production of the units, it was used FC to reduce the mass. Trial productions were carried out at different mix proportions to obtain the optimum concrete mix and the units were produced with using the selected concrete mix. Finally, axial compression, diagonal tension and bed joint shear tests were carried out to determine the mechanical properties of the interlocked masonry assemblages with mortar. The obtained results will enable structural analysis of walls to be constructed with the units.

2. Experimental study

2.1 Production of foamed concrete

2.1.1 Materials

FC also known as cellular lightweight concrete were planned to be used in the production of masonry units. To obtain the optimum FC mix, with low density but high compressive strength, trial FC productions were made. Synthetic and resin-based organic liquid foam agents were used to product the foam. Synthetic based foam agent was used in the first 9 trial production. However, because of the foam consistency and hydration problems, the later productions were continued using organic resin-based liquid foam agent.

Conventional aggregate, coarse perlite, expanded perlite and pumice were used as aggregates in FC productions. Conventional aggregates with grain diameters ranging from 0.25 to 8 mm were used in different granulometric combinations. Saturated surface dry (SSD) specific gravity of the conventional aggregates is 2700 kg/m^3. The pumice with SSD specific gravity of 1380 kg/m^3 is in the lightweight aggregate class. The smallest and the largest pumice grain diameters used in the study was 1 mm and 16 mm, respectively. The expanded perlite, another aggregate used as a lightweight aggregate, has a grain diameter ranging from 0.3 to 0.6 mm. The coarse pearlite with a maximum grain diameter of 8 mm was also used in some lightweight concrete mixtures. In all lightweight concrete productions as cement, portland cement of CEM-I 42.5R type with a specific gravity of 3150 kg/m^3 produced in Turkey was used.

In the study, silica fume and fly ash were used as additives. Their specific weights are 2200 kg/m^3 and 2390 kg/m^3, respectively. It has been observed that fly ash delayed the setting time (Chindaprasirt and Rattanasak 2011, Awang *et al.* 2012). It has also been observed that the

Table 1 Mix proportions of trial concrete productions (kg/m^3)

Production number	Cement	Silica fume	Fly ash	Conventional Aggregate				Pumice				Expanded perlite	Coarse perlite	Water		Foam agent	Hardening accelerator	Polypropylene fibers	w/c
				0.25-1 mm	1-2 mm	2-4 mm	4-8 mm	1-2 mm	2-4 mm	4-8 mm	8-16 mm			In foam	In mixing				
FC1	500	70	188	0	43	0	128	0	0	0	0	64	171	380	0	13	0	5	0.76
FC2	400	0	70	0	250	188	188	0	34	68	0	48	71	290	0	30	0	3	0.73
FC3	400	0	70	0	250	188	188	0	34	68	0	48	71	220	0	20	0	3	0.55
FC4	400	0	70	0	250	188	188	0	34	68	0	48	71	280	0	20	0	3	0.70
FC5	400	0	70	0	250	188	188	0	34	68	0	48	71	240	0	14	0	3	0.60
FC6	400	0	70	0	250	188	188	0	34	68	0	48	71	240	0	8	0	3	0.60
FC7	400	0	70	0	0	250	312	0	34	92	63	48	71	240	0	8	0	3	0.60
FC8	400	0	70	0	0	250	312	0	34	92	63	48	71	240	0	10	4	3	0.60
FC9	500	50	0	0	0	170	396	0	115	173	0	0	0	125	125	4	0	3	0.50
FC10	500	50	0	0	0	170	396	0	115	173	0	0	0	75	125	2.5	0	3	0.40
FC11	500	50	0	209	89	89	119	67	67	89	0	58	0	125	125	2.5	0	3	0.50
FC12	500	50	0	203	87	87	116	67	67	89	0	58	0	125	125	2.5	0	3	0.50

*FC: Foamed Concrete

fly ash causes foam to extinguish by reacting with the foam used in productions. Therefore, fly ash was not used in some trial productions.

In some trial productions, type C hardening accelerator according to ASTMC-494 was used. In addition, 20 mm long polypropylene fibers were used to improve properties of FC such as the tensile strength, drying shrinkage resistance etc. and to decrease micro cracks.

2.1.2 Mixing and casting

The absolute volume method specified in TS 802 was used in the mix design of the trial productions to find the optimum lightweight concrete mix. The calculated mix proportions of trial productions are given in Table 1.

The mixing of the concrete was carried out with a vertical concrete mixer of 75-liters capacity. In some trials, which is used pumice, the pumices were saturated with water the one day before. In the productions, firstly coarse aggregates were thrown into the mixer and mixed for about 5 minutes. Then, fine aggregates, cement and other binders were added to the mixture, respectively. Later on, all the dry ingredients in the composition were mixed. In the last stage, water required for concrete was completely added as foam in some productions, while in the others the mixing water and foam were separately added. The lightweight concrete prepared by this way was molded in cube samples of 150×150×150 mm. 10 cube samples were prepared for each production. In the study, the shaking table was used at a minimum level to prevent segregation.

The foam used in the production of lightweight concrete is a material formed by the combination of water and foam agent with compressed air. It was observed from the trial productions that optimum pressure for suitable foam consistency should be around 4-5 bar and optimum amount of foam agent should be 0.6-liter foam agent for per 30-liter water. If these conditions are met, density of the foam is between 80-90 g/l. Also, it was observed that the foam produced with the synthetic foam agent started to extinguish after about 90 minutes from being produced.

In the trial productions from FC1 to FC8, all the water in the concrete mix was used in foam production. This affected the consistency and workability of the concrete in the negative way. In FC2 and following trial productions, the pumices were saturated with water. Consistency of concretes were too dry in FC1, FC2 and FC3, relatively dry in FC6, FC7 and FC8 and fluid in FC4 and FC5. At the end of the production of the FC8, the only trial production used hardening accelerator, it was encountered with late setting problem as previous ones. It is thought that the reason for this is that the hardening accelerator and the foam agent are incompatible.

At the end of 8 trial productions, 3 main problems were encountered. These were insufficient foam consistency, late setting of concrete and foam extinction. It was thought that the problem of concrete consistency can be solved by adding some part of the needed water as foam and the rest as mixture water. Moreover, it was decided to use an organic resin-based foam agent instead of the synthetic one and not to use fly ash in next productions to solve the problems of foam extinction and late setting of concrete. FC9 and following trials were prepared with consideration of these information.

The optimum amount of foam agent for FC production is provided in the production of FC10. Also, the problem of foam extinction and late setting of concrete were solved by applying steps mentioned above. At the end of the productions until this point, the most suitable concrete in terms of consistency was FC10. Furthermore, in the next productions, it was decided to use the w/c ratio between 0.4-0.5.

The granulometry of conventional aggregate and pumice in FC11 were recalculated. FC11 production is almost recurrent in FC12 except for very small changes in the conventional aggregate granulometry. It was observed that FC11 and FC12 are the most suitable productions in terms of foam quality and concrete consistency.

2.1.3 Result and discussion

The samples were taken out from the curing pool while 7 days old for 14 days-strength and 21 days old for 28 days-

Table 2 Average compressive strength and specific weight for every production

Production Number	Dry unit weight (kg/m^3)	Saturated surface dry weight (kg/m^3)	Compressive Strength (MPa)		Standard Deviation (MPa)
			f_{cm14}	f_{cm28}	
FC1	1350	1441	5.20	7.30	0.20
FC2	1268	1340	1.54	2.43	0.14
FC3	1538	1629	9.66	10.37	0.23
FC4	1326	1390	0.56	0.85	0.04
FC5	1322	1380	0.95	1.26	0.06
FC6	1161	1406	2.14	2.60	0.18
FC7	1133	1445	1.38	1.57	0.08
FC8	1118	1468	1.11	1.34	0.06
FC9	1110	1157	1.26	1.49	0.09
FC10	1093	1096	0.42	0.62	0.05
FC11	1285	1357	9.22	9.69	0.29
FC12	1246	1313	9.01	11.43	0.16

strength. These samples were kept in laboratory environment which has relative humidity of 70% and temperature of 20±2℃. Half of the samples from each production were used to determine 14 days-strength and the other half were used to determine 28 days-strength. For every production; dry unit weights and saturated surface dry weight of samples are determined before axial compression test. Accordingly, average compressive strengths, specific gravity values and standard deviations of the compressive strengths at 28 days for each production are given in Table 2.

As it is seen from Table 2; dry unit weights of FC1, FC2, FC3, FC4 and FC5 productions are higher and in the first 5 productions compressive strengths of FC4 and FC5 are lower than the others. Dry unit weights and compressive strengths of FC6, FC7, FC8, FC9 and FC10 are lower than the others. Dry unit weights of FC11 and FC12 productions are 1285 kg/m^3 and 1246 kg/m^3, compressive strengths are 9.69 MPa and 11.43 MPa, respectively. It's obvious from Table 2, FC11 and FC12 are suitable to be used to produce interlocking masonry units considering specific weight and compressive strength. When FC11 and FC12 trial productions are compared, it was seen that FC12 has higher compressive strength and lower specific weight than FC11. Therefore, FC12 was selected to produce the interlocking units.

2.2 Design and production of interlocking masonry units

In this part, an interlocking masonry unit, which has a special geometry was designed to improve in-plane and out-of-plane behaviors of masonry walls under lateral loads. The geometry of the unit is shown in Fig. 1.

By using these units; grouted, ungrouted and reinforced walls can be built with or without mortar. As it is seen in Fig. 1 and Fig. 2 the unit has horizontal and vertical locks. The horizontal locks provide discontinuity in shear plane which is formed along the horizontal joints. Another damage caused by horizontal loads in masonry walls is the out-of-plane overturning. It is believed that the locks in the vertical axis of the masonry unit will contribute to the out-of-plane behavior of walls. Details of the joints of the interlocking masonry units are shown in Fig. 2.

In the literature, there are many studies regarding the use of reinforcement in masonry walls to improve the

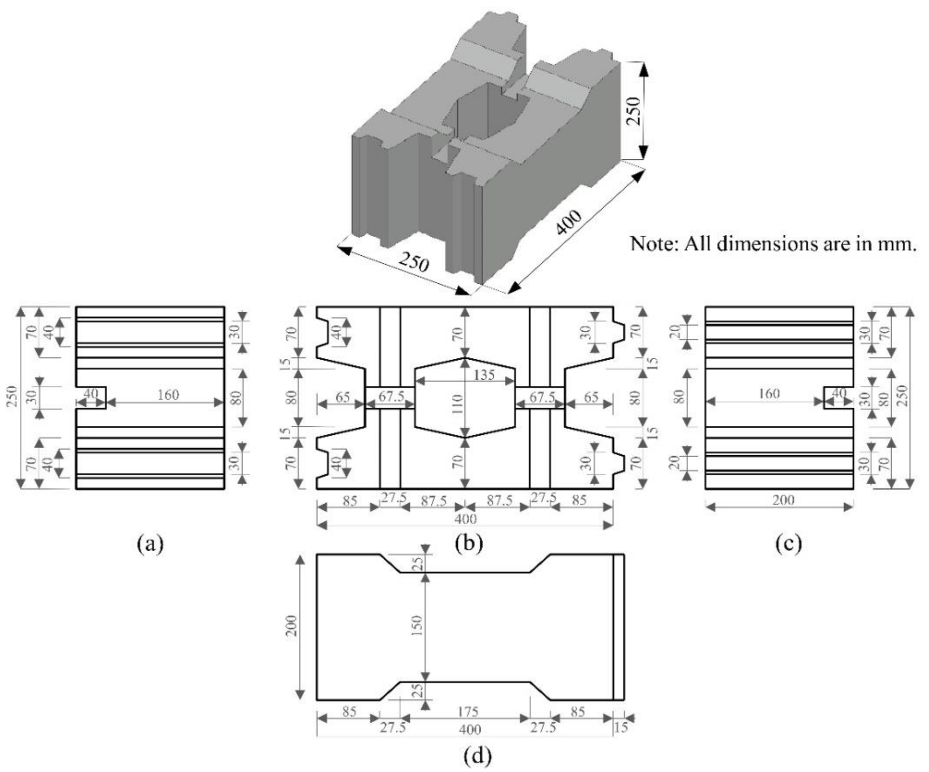

Fig. 1 The geometry of interlocking masonry unit, (a) left side view, (b) top view, (c) right side view, (d) front view

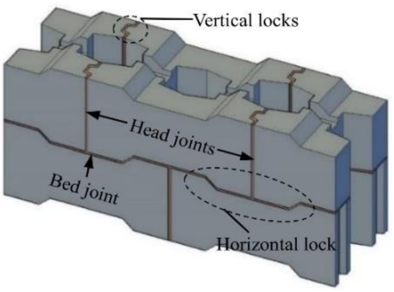

Fig. 2 Details of the joints of the interlocking masonry units

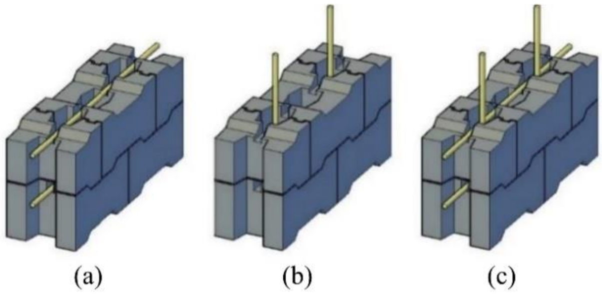

Fig. 3 The use of reinforcement in interlocking masonry units, (a) horizontal, (b) vertical, (c) horizontal and vertical reinforcements

Fig. 4 Assembly steps of the molds

behavior of walls under the lateral loads (Zhang *et al.* 2001, Voon and Ingham 2008, Haach *et al.* 2010, Cao *et al.* 2014). The use of reinforcements in masonry walls provides more ductile behavior under external loads. There are horizontal channels on the top middle part of designed units. It becomes possible to use horizontal reinforcements during construction of walls thanks to these channels (Fig. 3).

Also, in this part of study, a suitable mold system was designed for production of the masonry units. Each part in the mold system is designed to be independent and detachable to facilitate the removal of the units from the mold and minimize the damages of the units. Sheet iron plates with 5mm thickness were used for molds. Assembly steps of molds are given in Fig. 4.

After the molds prepared, FC produced with FC12 mix proportions was molded. At the end of 7 productions, a total of 70 interlocking units were produced for this study. The units were removed from the molds after 1 day and kept in the curing pool with a temperature of 23±2°C for 21 days. After 21 days, units were taken out of the pool and kept in laboratory environment with a temperature of 20±2°C and a relative humidity of 75%.

The minimum age of units used for interlocked masonry assemblages are 28 days old. The units are shown in Fig. 5.

Fig. 5 Interlocking masonry units

Required half units for assemblages were obtained by dividing the one unit into two halves.

Cube samples with 150×150×150 mm dimension were taken to determine strength differences between production series from each lightweight concrete production. The samples were kept in the exact same condition with the units. Compressive strength of a total of 42 cube samples, six samples taken from each lightweight concrete product, were determined by axial compression test on 28th day.

Minimum strength obtained from cube samples is 7.43 MPa and the maximum is 10.95 MPa. Average compressive strength and standard deviation of all samples were calculated as 10.15 MPa and 1.75 MPa, respectively. This indicates that there are no significant strength differences among the foam concretes used in the production of units. Average saturated surface dry weight of the samples was calculated as 1325 kg/m^3 and this value is approximately same with saturated surface dry weight (1313 kg/m^3) of FC12.

2.3 Mechanical properties of interlocked masonry Assemblages

In this section, axial compression, diagonal tension and bed joint shear tests were conducted to determine mechanical properties of interlocked masonry assemblages. The data obtained from these tests will be used in structural analysis of walls to be constructed with the interlocking units.

Axial compression, diagonal tensile and bed joint shear test specimens with different geometries were assembled with the same mortar, full and half masonry units. All masonry specimens were tested without reinforcements.

A hydraulic cylinder piston was used to load the masonry assemblages. A universal flat-type load cell with 1000kN capacity was placed on top of the hydraulic piston to determine the load values. The load cell was calibrated before the tests. Displacements were measured electronically by Linear Potentiometric Displacement Transducers (LPDT).

All assemblages prepared for tests were cured in laboratory environment at a temperature of 20±2°C and relative humidity of 75% for a period of 28 days.

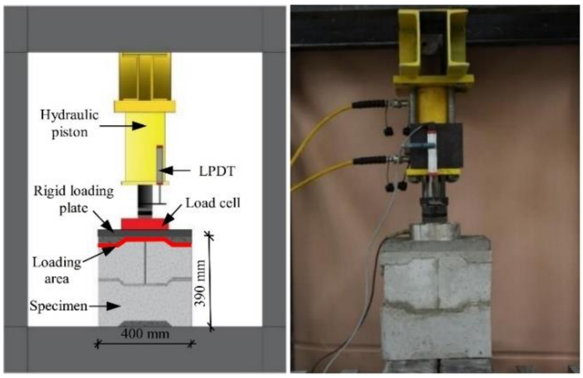

Fig. 6 The test specimen and loading system

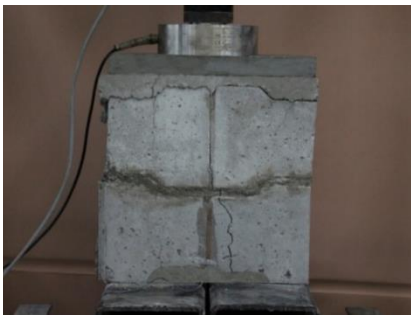

Fig 7 Typical failure mode of the specimen

2.3.1 Properties of masonry materials

Axial compression test was conducted to determine compressive strength of a unit according to ASTM C140/C140M-17a. The average compressive strength was obtained as 10.15 MPa. According to Turkish Earthquake Regulation (TEC 2007), artificial masonry units (adobe, brick, briquet, concrete block etc.) must have the minimum 5 MPa compressive strength. Calculated value is approximately twice of the value given in the Regulation.

All specimens were prepared with C2 type mortar which is identified in Turkish Standard TS 2510. In the production of mortar, CEM-II 32.5R type Portland cement produced in Turkey was used. Proportions by volume of cement and sand (0-4mm) for mortar were 1:5 following TS 2510. The average compressive strength of the mortar was determined as 8.73 MPa at the end of the tests carried out on 5 cm cube samples.

2.3.2 Axial compression test

In the axial compression test performed according to ASTM C1314-14, every specimen consisting of mortar between joints had an interlocking unit and two half interlocking units. Tests were carried out on a total of four specimens with height-to-thickness ratio of 1.56. One of the test specimens and loading system are shown in Fig. 6.

In the axial compression tests, it was observed that first damage appeared as a vertical crack in the nearly middle of the bottom unit, and then the crack propagated to the head joint. Also, at the later stages of the tests, vertical cracks were formed in the middle regions of the half units. The stress-strain relationship was calculated by using the load-displacement relationship obtained from the experiments. The stresses were calculated by dividing the applied load by the net loading area (without holes) and strains were calculated by dividing the displacements by the total length of the specimen. Table 3 shows compressive strength results of test specimens. Typical failure observed during the tests and average stress-strain relationship are shown in Fig. 7 and Fig. 8, respectively.

Table 3 Compressive strength of test specimens

Specimen No	Compressive Strength (MPa)		
	Individual	Average	Std. Deviation
1	9.68	8.40	1.04
2	7.84		
3	8.76		
4	7.31		

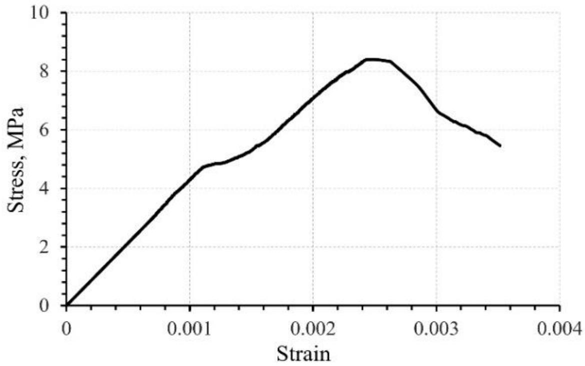

Fig. 8 Compressive stress-strain curve

In the axial compression tests, it was observed that first damage appeared as a vertical crack in the nearly middle of the bottom unit, and then the crack propagated to the head joint. Also, at the later stages of the tests, vertical cracks were formed in the middle regions of the half units. The stress-strain relationship was calculated by using the load-displacement relationship obtained from the experiments. The stresses were calculated by dividing the applied load by the net loading area (without holes) and strains were calculated by dividing the displacements by the total length of the specimen. Table 3 shows compressive strength results of test specimens. Typical failure observed during the tests and average stress-strain relationship are shown in Fig. 7 and Fig. 8, respectively.

The results of the axial compression tests revealed that the average compressive strength and standard deviation of the specimens are 8.40 MPa and 1.04 MPa, respectively. Also, modulus of elasticity of interlocked masonry obtained from the curve in Fig. 8 is 4270 MPa.

2.3.3 Bed joint shear test

Bed joint shear tests was conducted to determine shear strength of joints according to BS EN 1052-3. Two different test procedures (A and B) with or without pre-compressions are recommended in BS EN 1052-3. In the procedure A, test specimens must be tested at different pre-compression levels with at least three specimens for each level. In procedure B, the test is carried out without pre-compression with at least six specimens. In this study, procedure B was carried out with six specimens. Loading system and a test specimen are shown in Fig. 9.

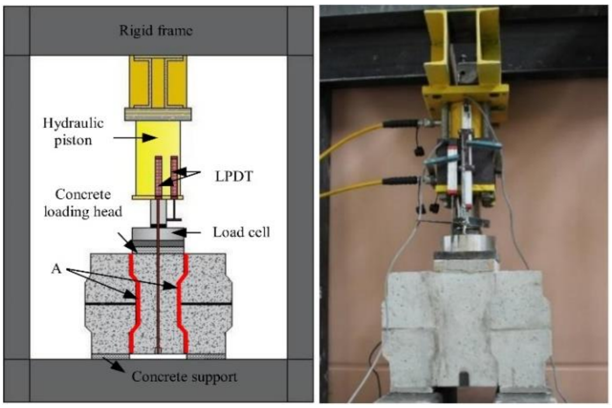

Fig. 9 Loading system and a test specimen of bed joint shear test

Table 4 Bed joint shear strength of test specimens

Specimen No	Shear Strength (MPa)		
	Individual	Average	Std. Deviation
1	0.45	0.44	0.07
2	0.50		
3	0.46		
4	0.34		
5	0.53		
6	0.38		

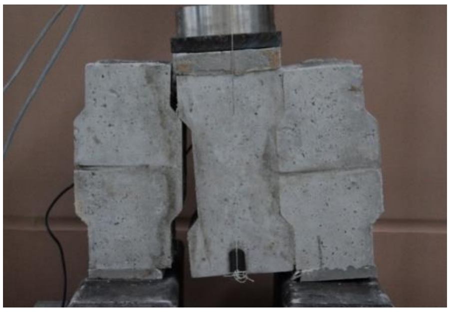

Fig. 10 Typical failure mode of shear test specimen

Bed joint shear tests were carried out under monotonic increasing load with constant load-rate. All specimens were separated along vertical joint (Fig. 10). Shear strength of the specimens is shown in Table 4. Average shear stress-strain curve obtained from the tests is shown in Fig. 11. The curve was calculated by using experimental load-displacement data obtained from the test.

Bed joint shear strength (τ_s) is calculated as

$$\tau_s = \frac{P}{2A} \tag{1}$$

where P is the applied shear load and A is the cross-sectional area without holes of a specimen parallel to the head joint as seen in Fig. 9.

Average shear stress, corresponding strain and standard deviation of the results are 0.44 MPa, 0.00023 and 0.07 MPa, respectively.

2.3.4 Diagonal tension test

Diagonal tension test is a method that tensile and shear strength of a masonry are determined by using diagonal

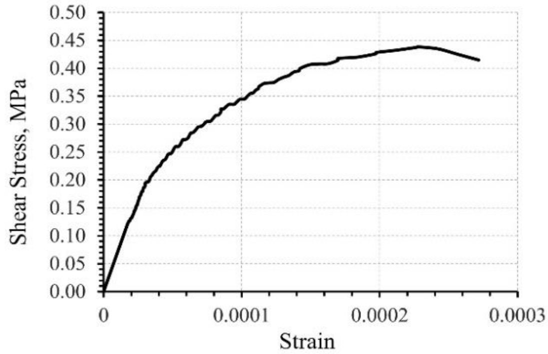

Fig. 11 Shear stress-strain curve

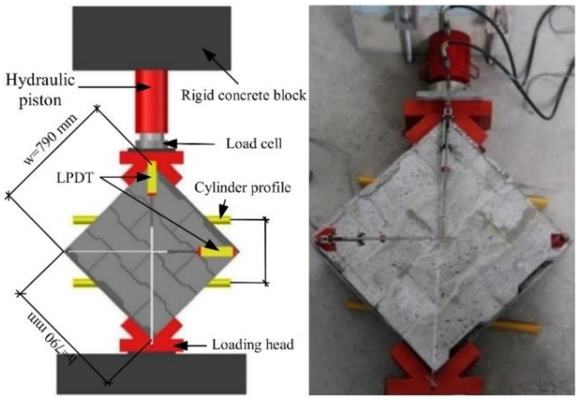

Fig. 12 Loading system and test specimen of diagonal tension test

shortening and elongation values under compression along one diagonal of specimen. According to ASTM E519/E519M-15, the nominal size of each specimen shall not be less than 1200×1200 mm. In this study, however, dimensions of the specimens were 790×790 mm due to experimental limitations such as symmetry problem and test setup. Scheme of loading system, positions of displacement transducers (LPDT) and a specimen for the tests are shown in Fig. 12.

Three specimens were tested under monotonic increasing load by rotated 45 degrees horizontally. According to ASTM E519/E519M-15, if the test carried out horizontally, rigid steel rollers shall be provided at a spacing no greater than 400 mm, allowing for unimpeded movement of test specimen under in the plane of the direction of loading. This was ensured with 2 steel circular profiles with diameter of 50 mm and length of 1000 mm placed at interval of 400 mm. Two LPDTs were placed on one side of the wall diagonally and perpendicular to each other.

In the tests, load was applied by a hydraulic jack and values are measured by a load cell. Loading rate was kept constant with 10 kN steps as far as possible. Typical failure of the specimens and average load-displacement curves of opposite diagonals can be seen in Fig. 13 and Fig. 14, respectively. In the literature (Sousa *et al.* 2013, Bolhassani *et al.* 2015), in the diagonal tension tests carried out with concrete masonry units, the failure modes were characterized as step-wise cracks at the joints between units and mortar. In this study, however, typical failure plane progressed through the joints and interlocking units. As

Fig. 13 Typical failure of the specimen

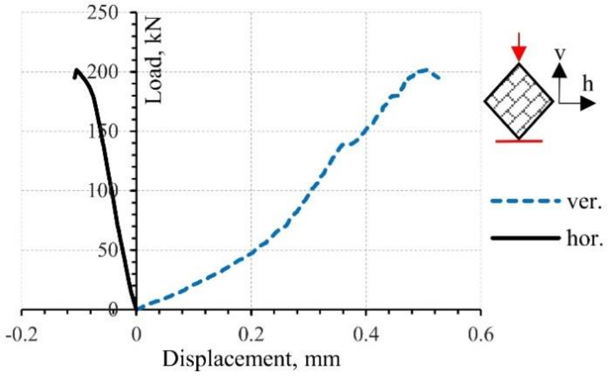

Fig. 14 Load-displacement curves

Table 5 Tensile strength of test specimens

Specimen No	Tensile Strength (MPa)		
	Individual	Average	Std. Deviation
1	0.84		
2	0.68	0.76	0.08
3	0.75		

shown in Fig. 13, typical damages occurred at the joints near the supports and at the interlocking units in the middle areas of the specimens. This indicates that the interlocks have changed failure modes and are effective against shear stresses as aimed.

According to ASTM E519/E519M-15, horizontal diagonal tensile strength (τ) at the center of specimen can be calculated as

$$\tau = \frac{0.707P}{A_n} \quad (2)$$

where P is applied load. Net diagonal cross-sectional area of specimen, A_n, is was calculated as

$$A_n = \frac{(w+h)}{2}\, t\,.n \quad (3)$$

In Eq. (2), w, h, t and n are width, height and total thickness of specimen and percent of the gross area of the unit that is solid, respectively. Table 5 presents test results of the specimens. Relationship between diagonal tensile stress and strain, obtained from the equations, is shown in Fig. 15. Average diagonal tensile strength of the masonry specimens and standard deviation were calculated as 0.76 MPa and 0.08 MPa, respectively.

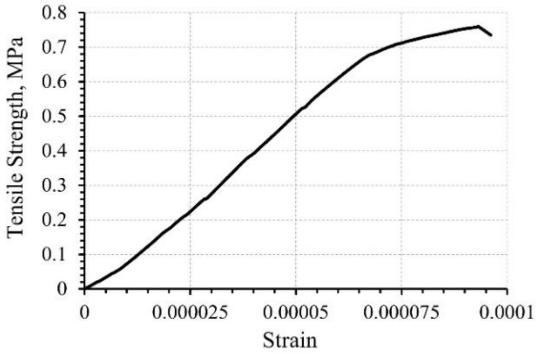

Fig. 15 Relation between horizontal tensile stress and strain

3. Conclusions

This paper presents design and production of new type of interlocking masonry units and identification of the mechanical properties of interlocked masonry assemblages.

Observations and results obtained at the end of FC trial productions are summarized below.

- It has been observed that the foam produced with the synthetic foam agent started to extinguish before the setting of concrete. This problem has been solved by using an organic resin-based agent which allows the foam to extinguish later. Thus, it is seen that using organic based foam agents gives better results than synthetic based one in FC production.
- For homogenous FC mix, the foam density should be approximately 80-90 g/l. For the appropriate foam consistency, it has been determined that, required optimum pressure should be between 4-5 bar, and the optimum amount of foam agent should be approximately 0.6 liters for every 30 liters water.
- It has been observed that, fly ash delays the setting time of FC and causes foam to extinguish by reacting with foam used in production.

The results of the tests conducted on the interlocking masonry units which is designed and produced with FC in the scope of this study are summarized below.

- The designed interlocking mechanism is sufficient to interlock the assembled units in different directions and suitable for use with mortar.
- The interlocked system provides a self-aligned, practicable, fast construction. This system also allows the use of horizontal and vertical reinforcements together.
- The average compressive strength of an interlocking masonry unit is 10.15 MPa. This value is approximately twice of the minimum compressive strength value given in the Turkish Earthquake Regulation.
- Volume and saturated surface dry weight of a single unit are 0.0013 m^3 and 1325 kg/m^3, respectively.
- It's obtained that the average compressive strength of the interlocked masonry is 8.40 MPa and modulus of elasticity is 4270 MPa.
- Average shear and tensile strength of the masonry are obtained as 0.44 MPa and 0.76 MPa, respectively.
- Interlocks designed to strengthen the system against shear stresses by creating discontinuity throughout the

joints have been successful to achieve this aim.

This study is the first step towards to define behavior of interlocked masonry walls with or without reinforcements under cyclic lateral loading. If these units are used in the low-rise masonry structures to be built in rural areas, the possible loss of life and property due to the earthquakes may decrease.

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