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Research Article

Relationship between Reinforcement Diameter and Bond Stress in High Performance Lightweight Concrete

Esra Tuğrul Tunç[1*], Kürşat Esat Alyamaç[2], Ragıp İnce[3], Zülfü Çınar Ulucan[4]

[1*] Firat University, Faculty of Engineering, Departmant of Civil Engineering, Elazığ, Turkey, (ORCID: 0000-0001-9071-774X), esratugrul@firat.edu.tr
[2] Firat University, Faculty of Engineering, Departmant of Civil Engineering, Elazığ, Turkey, (ORCID: 0000-0002-3226-4073), kealyamac@firat.edu.tr
[3] Firat University, Faculty of Engineering, Departmant of Civil Engineering, Elazığ, Turkey, (ORCID: 0000-0002-9837-8284), rince@firat.edu.tr
[4] Firat University, Faculty of Engineering, Departmant of Civil Engineering, Elazığ, Turkey, (ORCID: 0000-0003-3605-9728), zculucan@firat.edu.tr

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Abstract

High performance lightweight concrete (HPLC) is a new and original research in structural engineering. Due to the high risk of earthquakes, which is one of the biggest disasters today, the need for HPLCs has increased. The purpose of this study is to experimentally research concrete-reinforcement bond for the change parameters such as different reinforcement diameters and different embedded lengths. For this purpose, HPLCs with different mix ratios and different concrete components were prepared by using pumice aggregates. Within this scope, HPLC beam specimens of 100×180×800 mm dimensions were prepared and produced specimens were subjected to the Standard Belgium Hinged Beam (SBHB) test. There are limited studies in the literature on the investigation of the bond properties of HPLC beams with this test. The mentioned study draws attention with this aspect. In the present study, ribbed steel reinforcement bars with different diameters were used. The beam specimens were produced considering the different embedded lengths for each reinforcement diameter. The bond tests were performed. Using the load applied vertically and read with the help of the load cell in the experiment, the bond stress occurring in the reinforcement was calculated with the help of the force in the reinforcement indirectly found. As a result of the experiments, it has been determined that there is a significant relationship between bond stress and reinforcement diameter and embedded length. It has been determined that the bond stress decreases with the increase of reinforcement diameter and embedded length.

Keywords: High Performance Lightweight Concrete (HPLC), Beam, Bond stress, Reinforcement diameter, Embedded length.

Yüksek Performanslı Hafif Betonlarda Donatı Çapı ile Aderans Gerilmesi Arasındaki İlişki

Öz

Yüksek performanslı hafif beton (YPHB), yapı mühendisliğinde yeni ve güncel bir konudur. Kalıcı ve uzun ömürlü yapılar inşa edebilmek için YPHB'lere ihtiyaç vardır. YPHB ile kullanılacak toplam beton miktarı azaltılarak binaların hafiflemesi mümkündür. Günümüzde en büyük afetlerden olan deprem riskinin yüksek olması nedeni ile YPHB'lere olan ihtiyaç artmıştır. Betonarmenin varlığı, aderans olayına bağlıdır. YBHB'lerin aderans gerilmesi birçok parametreye bağlı olarak değişmektedir. Bu çalışmanın amacı, farklı donatı çapı ve farklı kenetlenme boyu gibi değişim parametreleri ile YPHB'lerin beton-donatı aderansı arasındaki ilişkinin deneysel olarak belirlenmesidir. Bu amaçla pomza agregaları kullanılarak farklı karışım oranları ve farklı beton bileşenlerine sahip

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[*] Corresponding Author: esratugrul@firat.edu.tr

YPHB’ler hazırlanmıştır. Bu kapsamda 100×180×800 mm boyutlarında YPHB kiriş numuneler hazırlanmış ve üretilen numuneler Standart Belçika Mafsallı Kiriş (BMK) deneyine tabi tutulmuştur. YPHB kirişlerin aderans özelliklerinin Standart Belçika Mafsallı Kiriş deneyi ile araştırılması konusunda literatürde sınırlı sayıda çalışma bulunmaktadır. Söz konusu çalışma bu yönü ile dikkat çekmektedir. Mevcut çalışmada Ø8 ve Ø10 çaplarında nervürlü çelik donatı çubukları kullanılmış ve her bir donatı çapı için 10Ø ve 20Ø kenetlenme boyları dikkate alınarak BMK numuneleri üretilmiş ve aderans deneyleri yapılmıştır. Deneyde düşey olarak uygulanan ve yük hücresi yardımı ile okunan P yükü kullanılarak dolaylı olarak bulunan donatıdaki F kuvvetinin yardımı ile donatıda meydana gelen aderans gerilmesi hesaplanmıştır. Yapılan deneyler sonucunda aderans gerilmesi ile donatı çapı ve kenetlenme boyu arasında önemli bir ilişki olduğu tespit edilmiştir. Aderans gerilmesinin beton basınç dayanımının artmasıyla arttığı, donatı çapı ve kenetlenme boyunun artması ile azaldığı belirlenmiştir.

Anahtar Kelimeler: Yüksek Performanslı Hafif Beton, Belçika Mafsallı Kiriş, Aderans Gerilmesi, Donatı Çapı, Kenetlenme Boyu.

1. Introduction

The bond between aggregate and matrix is stronger in the concretes with lightweight aggregate than in the concretes with normal aggregate. Cement paste is injected into the aggregate from the hollow structure of the light aggregate, causing a strong bond between aggregate and matrix. Thus, the formation of a weak point between the aggregate and the matrix is prevented and then a concrete with high durability is formed (Al-Khaiat and Haque, 1998; Hossain, 2004). Since the aggregates make up 70% - 80% of the concrete volume, the main way to produce lightweight concrete is to use aggregate with lower unit weight (Neville, 1995 and Aitcin, 1998). It is a fact that it has a significant effect on the mechanical properties and the other properties of concrete due to the high ratio of use of aggregates in the concrete composition (Ince and Çetin, 2019; Tunc and Alyamac, 2019). ASTM, ACI, TSE and European Concrete Standards define lightweight concrete with high strength as concrete with a dry unit weight of 1200 to 2000 kg/m^3 and a compressive strength of 50MPa or higher. The first use of lightweight concrete dates back to 3000 years ago. Romans in Europe built their temples and sculptures using lightweight concrete (Ulusu, 2007). After it was seen that lightweight concrete produced using lightweight aggregates at that time could be used safely, the use of lightweight concrete has become widespread in the past years and has continued to exist until today (El Zareef, 2010). For example; lightweight concrete was used in the bridge built in Italy between Sinigo and Avelengo cities with high traffic loads (Figure 1).

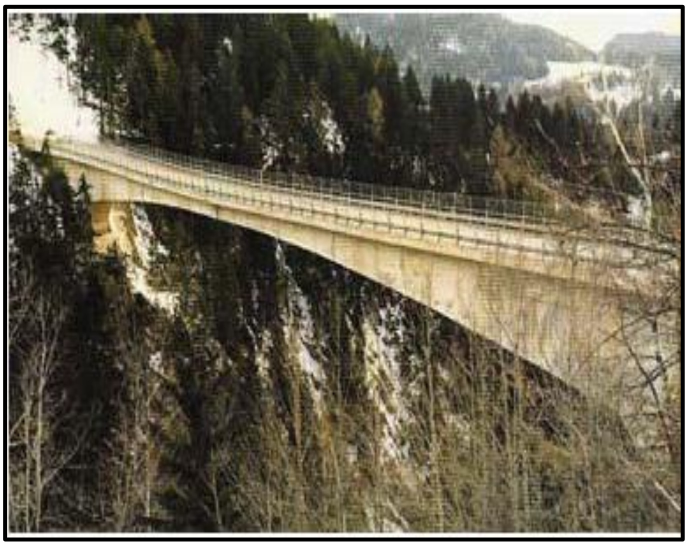


Figure 1. *Historical buildings produced with lightweight concrete: The bridge in Italy (El Zareef, 2010).*

It was produced high strength lightweight concrete with a unit volume weight of 2000 kg/m^3 and a compressive strength varying between 50 MPa and 60 MPa in the Hoff (1990)’s study. Wasserman and Bentur (1996) stated that the unit weight and water absorption values of the light aggregates used and the compressive strength of lightweight concrete produced using these aggregates are very important and that high strength lightweight concrete cannot be produced with every lightweight aggregate. In recent years, it has been observed that concrete can be produced in desired color, unit weight and strength. Unit weight of the concrete varies between 300 kg/m^3 and 3000 kg/m^3. While the thermal insulation of these concretes varies between 0.1 and 3 W/mk, their compressive strength varies between 1 and 100 MPa (Chandra and Berntsson 2003). Lightweight concretes are a versatile material due to their technical, economic and environmental advantages (Haque et al., 2004). It is extremely important to use high performance lightweight concrete (HPLC) as a bearing element. For this, it is necessary to know the properties of bearing systems such as beam, column, shear wall (Poon et al., 2004). Recently, statistical studies have increased to determine the most suitable lightweight concrete mix recipes. Tunç et al. (2018) conducted a detailed literature review on HPLCs containing pumice and obtained a formula that determines the compressive strength of HPLCs with high accuracy. Then, numerical research continued for lightweight concretes containing different lightweight aggregates. For this purpose; developed numerical methods with high accuracy that determines the compressive strength of lightweight concrete containing LECA aggregates and perlite aggregates (Saglam et al., 2019; Tunc et al., 2019). Finally, it was aimed to determine both the pre-concrete mix design and the tensile strength of lightweight concretes without testing. For this purpose, a numerical model was developed by using the tensile strength test results of structural lightweight concrete containing LECA aggregate belonging to previous studies (Tunc et al., 2020).

Since reinforced concrete is a composite material where concrete and reinforcement are combined, the bond between concrete and reinforcement must be strong, especially. To achieve this, deformed reinforcement should be used instead of plain reinforcement. The shear stresses that arise in deformed reinforcement are called bond stress. Bond stress is one of the most important features of reinforced concrete (Bingöl and Rüstem, 2009). Concrete-reinforcement bond is affected by many variables such as tensile strength of concrete, yield strength of steel, surface geometry of the bar, diameter of reinforcement, embedded length, thickness of concrete cover around the reinforcement (concrete cover), type of aggregate, and the additives (Ersoy, 1985). When the studies in the literature are utilized, the effect of these variables on the concrete-reinforcement bond has been investigated by many researchers from past to present. Diederichs and Schneider

(1981) examined reinforced concrete buildings using straight-deformed reinforcement to see the effect of surface geometry of reinforcement on concrete-reinforcement bond. Xiao and König (2004) found that the bond stress of straight reinforcements is less than that of deformed reinforcements, and rusty-rustless reinforcements exhibit a different bond behavior. Tanyıldızı and Yazıcıoğlu (2006) produced mineral-added concretes in order to examine the effect of straight-deformed reinforcements on concrete-reinforcement bond strength. Baena et al., (2009) investigated the effect of different types of reinforcements, including carbon fiber, glass fiber and steel fiber, on concrete-reinforcement bond stress, and new formulas were found depending on the diameter of the reinforcement. Arslan and Arslan, (2018) conducted the Belgium Hinged Beam test using different reinforcement diameters and different embedded lengths for each diameter in concretes produced with fixed cement content, and the concrete-reinforcement bond stress was examined experimentally under bending.

The way to minimize the building load without reducing the strength properties of buildings is to provide HPLC production by using lightweight aggregates. Pumice, a lightweight aggregate, can be preferred in HPLC production due to the abundant reserves in Turkey. The purpose of the present study; to examine the effect of different reinforcement diameter and different embedded length on the concrete-reinforcement bond of HPLC produced using pumice aggregates. The reason for choosing the mentioned change parameters is that they are the most important parameters affecting the concrete-reinforcement bond. For this purpose, Standard Belgium Hinged Beam (SBHB) samples for different mix ratios were produced and subjected to bond stress test. Different reinforcement diameters (Ø8 and Ø10) and different embedded lengths (10Ø and 20Ø) for each diameter were used in the produced BHBs. As a result of the experiments, higher stress values have been achieved in low diameter reinforcemenets for the same embedded length. In addition, it was determined that as the embedded length increased, the bond stress also increased.

2. Bond Stress

Various test methods are used to determine the bond stress and embedded length of concrete-reinforcement bond. The experiments conducted in this context are generally; it can be classified as pull-out and various beam tests. Usually; it was investigated related bond stress properties (embedded, lap joint, boundary stress) with pull-out experiments, it was investigated cracking properties with beam tests (Durmuş et al., 2006; Karatas et al., 2010; Tuğrul Tunç, 2020). There are also push-out experiments that have been investigated in fewer studies than others (Ersoy and Özcebe 2001; Beycioğlu et al., 2015).

2.1. Pull-Out Test

The pull-out test, which is simple to apply among bond stress tests, is the most preferred type of experiment in this respect. In this test, the reinforcements embedded in the cubic or cylinder concrete sample are pulled out by axial tensile force. Thus, the debonding of the reinforcement from the concrete is measured (Figure 2). Bond stress is based on the bond stress corresponding to the load where the debonding value is 0.25 mm for safety (Ersoy and Özcebe, 2001; Beycioğlu et al., 2015).

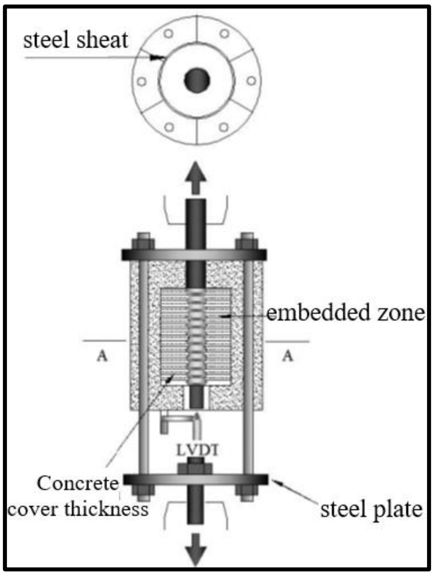


Figure 2. *Center pull-out test (Tuğrul Tunç, 2020).*

Using the pull-out load obtained in this experiment, the bond stress between concrete and reinforcement is calculated with Equation (1).

$$\tau_b = \frac{P}{\pi \emptyset l} \quad (1)$$

in which; τ_b is the bond stress (MPa), P is the force required to pull out the reinforcement (N), $\emptyset$ is the diameter of the reinforcement (mm), and l is the length of the reinforcement embedded in the concrete (mm).

2.2. Beam tests

In the previous studies, it is seen that alternative beam tests have been developed since the pull-out test cannot clearly the concrete-reinforcement bond trying to bend (Ersoy and Özcebe, 2001). Current major beam tests developed; Bureau of Standards test, Texas test, Standard Belgium Hinged Beam test and Beam Cracking test (Durmuş et al., 2006; Beycioğlu et al., 2015; Tuğrul Tunç, 2020). It has been observed that the beam cracking test is generally applied to large sized reinforced concrete beams.

Bureau of standards test; it is a test used to determine the bond strength in bending (Figure 3a). This test is used to determine the bond behavior in bending. For this purpose, in this test, the use of stirrups has been increased to prevent shear fractures. Since the stirrups used will affect the bond strength, this test makes it difficult to determine the embedded length accurately. For this reason, it is difficult to obtain realistic results (Benli et al., 2008). The fact that the reinforcement is embedded in a very large concrete in the Texas Beam test increases the disadvantages of this experiment (Figure 3b). In this beam test setup; it is important to avoid the local compressive stresses applied by the bearing that can scrape the reinforcement from the concrete. Otherwise, splitting of the reinforced concrete mass may occur (Beycioğlu et al., 2015).

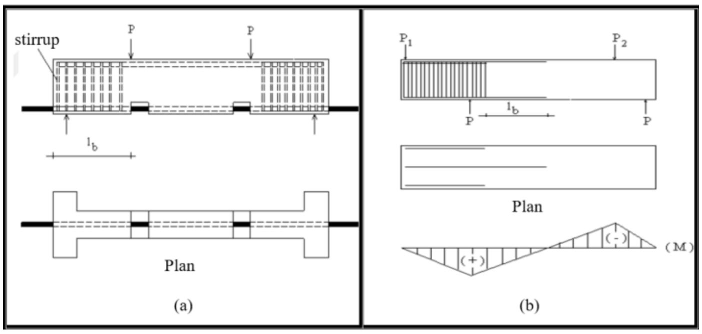


***Figure 3.** Beam test setups: **a)** Bureau of Standards test, **b)** Texas Beam test (Tuğrul Tunç, 2020).*

2.3. Standard Belgium Hinged Beam test (SBHB)

The standard Belgium Hinged Beam test is defined in BS 4449:2005+A2:2009 standard. This beam test is a test to examine concrete-reinforcement bond under bending. TS EN 12390-5 and ASTM C 293 describe the test method in which the concrete beam is loaded from the middle point (L/2 distance) of the distance between the supports. In this test, the vertical load applied to the specimen is recorded through the load cell. Based on the principle that the moment is zero at the joint point, the force "*F*" formed in the reinforcement is calculated by writing the isostatic equilibrium equations. The debonding values corresponding to the determined "*F*" forces are recorded with potentiometric scales placed at the beam ends.

The sketch of the Standard Belgium Hinged Beam test setup is presented in Figure 4(a). As can be seen in the free-body diagram, half of this test element is similar to the eccentric extraction test (Figure 4). However, the experiments conducted at Middle East Technical University in Turkey have shown that the results obtained from these two types of experimental elements are quite different. Since the difference in displacement with the support and load applied in the Belgium Hinged Beam test is too much compared to the eccentric pull-out test, the only difference between the two test types, the observed strength difference is connected to this test. In the beam cracking test, this reinforced concrete test beam, which is generally taken as a rectangular section, is placed on two supports at a certain "*L*" openning. Loading is done by means of two single loads that are vertical, symmetrical and within a certain range. The ability to measure mid-openning deflection during loading gives this test type a special importance. In this type of test, it is important that the test sample is large in size and therefore give more realistic results.

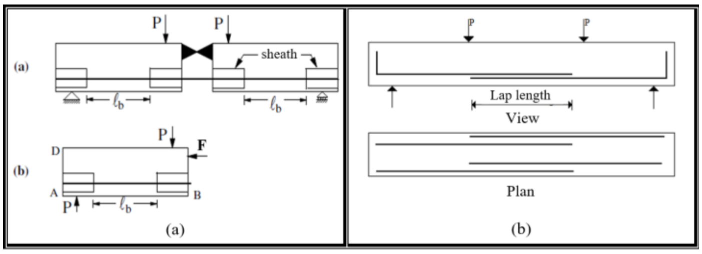


***Figure 4.** The beam test setups: a) Standard Belgium Hinged Beam test setup, b) Beam Cracking test setup (Tuğrul Tunç, 2020).*

It is also supported by the literature that the standard Belgium Hinged Beam test is more accurate than the pull-out test. De Larrard et al. (1993) conducted Belgium type bond tests for concretes with different strengths and examined the effect of the diameter of the bond reinforcement. Arslan and Durmus (2011) investigated the bond effect of steel reinforcement bars of different diameters in lightweight concrete beams with the Standard Belgium Hinged Beam test. Hosseini et al., (2015) prepared 12 Standard Belgium Hinged Beam test samples in order to determine the effect of stirrup density and number on concrete-reinforcement bond. Beycioğlu et al. (2015) experimentally investigated the relevant bond properties using Ø10 reinforcement bars in lightweight concretes containing pumice aggregate using the Standard Belgium Hinged Beam test method.

By using the "*P*" load applied vertically in the test and read with the help of the load cell, the indirectly found "*F*" force in the reinforcement and the corresponding loss of bond to this force can be determined. With these "*F*" forces, the bond stress (τ_b) that will occur in the reinforcement is calculated with the Equation (2).

$$\tau_b = (\sigma_s \times \emptyset)/4\ell_b \tag{2}$$

in which; σ_s is the strees in reinforcement (MPa), τ_b is the bond stress (MPa), $\emptyset$ is the diameter of reinforcement (mm), and ℓ_b is the embedded length (mm).

3. Materials and Methods

3.1. Material Properties

In the present study, pumice aggregates brought from Organized Industry in Elazig in Turkey were used as lightweight aggregate for HPLC production. Pumice aggregates with D_{max}=8 mm were laid to dry in the area in front of the Construction and Building Materials Laboratory of Fırat University, Faculty of Engineering, Department of Civil Engineering (Figure 5). The granulometry of the dried the mixture pumice aggregates with maximum compactness in accordance with TS 802 was determined according to the Fuller parabola. The saturated dry surface specific gravity of the said mixture aggregates was 1.35 g/cm^3, the water absorption ratio was 20.8% and the Los Angeles abrasion loss value was 40%. In this respect, the usability of pumice aggregates in HPLC production is suitable.

***Figure 5.** Pumice aggregates to be used in HPLC production: a) Drying of pumice aggregates for sieve analysis, b) Pumice aggregates remaining on each sieve in accordance with TS EN 933-1.*

CEM I 42.5R Portland cement was used in this experimental study. All kinds of physical-mechanical tests and chemical analysis results related to this cement are presented in accordance with TS EN 197-1. The features of the cement type in question are given in Table 1 in detail.

Table 1. *Physical, chemical and mechanical properties of Cem I 42.5R cement*

Chemical properties	Percent by mass (%)	Physical properties	
SiO_2	21.4	Specific gravity (g/cm^3)	3.12
Al_2O_3	3.95	Initial set (min.)	168
Fe_2O_3	3.60	Final set (dk)	200
CaO	62.4	Fineness module (cm^2/g)	3490
MgO	3.80	**Mechanical properties**	
SO_3	2.98	**Compressive strength (MPa)**	
Ignition loss	1.00	2-day	29.5
K_2O+Na_2O	0.80	7-day	38.1
Insoluble matter	0.58	28-day	61.5
Free Cao	1.20		

When the previous studies in recent years are utilized, it is seen that the fine aggregate ratio should be 50% or more for HPLC production (Neville, 1995 and Aitcin, 1998). In this study, marble powder obtained from the waste of cherry marble extracted in Elazig province in Turkey, which has the feature of filling the gap, was used. Silica fume (SF) is an important component of high performance concretes. It has properties such as increasing workability, bond, strength and durability in concrete. For this reason, silica fume was used as a mineral additive in the study. In the study in question, a new generation polycarboxylate supported super plasticizer was used to ensure workability and prevent segregation due to low water-to-cement ratios (*w*/*c*). It is known that chemical additive content increases concrete strength (Tugrul Tunc, 2019). The physical/chemical properties of the waste marble powder and silica fume used in this study and the characteristic properties of the chemical additive are presented in Table 2.

Table 2. *Properties of waste marble powder, silica fume and chemical additive used in this study*

Waste marble powder	Silica fume	Chemical additive
Density (g/cm^3)=2.70	Density (g/cm^3)=2.50	Appearance =liquid
Specific surface area (cm^2/g)=3924	Blaine surface (cm^2/g)=296000	Colour=brown
SiO_2 (%)=28.35	Ignition loss (%)=1.68	Density (g/cm^3)=1.075
Fe_2O_3 (%)=9.70	SiO_2 (%)=91.92	pH=4.00 ± 1
$CaCO_3$ (%)=60.48	MgO (%)=3.69	Chloride content<% 0.1

In this experimental study, two different deformed reinforcement bars with 8 mm and 10 mm diameter were used to determine the bond stress of concrete-reinforcement. The mechanical properties of the reinforced concrete reinforcements in question were determined as the yield strength 530 MPa, tensile strength 565 MPa and rupture elongation rate 24% for Ø8-S420. Also, it was determined yield strength 515 MPa, tensile strength 575 MPa and rupture elongation rate 22% for Ø10-S420.

3.2. Production of High Performance Lightweight Concrete

In this study, 4 concrete mix recipes were prepared to obtain a set of Belgium Hinged Beam (BHB) samples with a cement content of 600 kg/m^3 and a water-to-cement ratio of 0.30 using different sized pumice aggregates. In this study, 8% silica fume and 16% waste marble powder were added to cement in order to increase the amount of fine powder material. Later, a new generation super plasticizer additive 1.2% of cement weight was added (Table 3). In this study, in order to understand the effect of change parameters such as different reinforcement diameter and different embedded length on the concrete-reinforcement bond, the amount of aggregate, silica fume and marble powder ratios entering the mixture were kept constant. Pumice aggregates in the mixture were saturated with water one day before due to its lightness.

Table 3. *Concrete mixture prescriptions for HPLC beams using Ø8 and Ø10 diameter steel reinforcement*

Samples	*w/c*	Cement content (kg/m^3)	Silica fume ratio (%)	Marble powder ratio (%)	Chemical additive ratio (%)	Air content (%)	Aggregate content (kg)					Diameter of reinforcement	Embedded length
							0 – 1 mm	1 – 2 mm	2 – 4 mm	4 – 8 mm	8 – 16 mm		
BMK-1	0.30	600	8	16	1.2	2	216.5	156.8	112.0	74.6	186.6	Ø8	10Ø
BMK-2	0.30	600	8	16	1.2	2	216.5	156.8	112.0	74.6	186.6	Ø8	20Ø
BMK-3	0.30	600	8	16	1.2	2	216.5	156.8	112.0	74.6	186.6	Ø10	10Ø
BMK-4	0.30	600	8	16	1.2	2	216.5	156.8	112.0	74.6	186.6	Ø10	20Ø

A 125 dm^3 capacity and horizontal axis laboratory type mixer (Figure 6a) was used to obtain the BHB samples whose mixture content is given in Table 3. First, coarse and fine aggregates were put into the mixer and mixed, then cement and silica fume and marble powder were added and mixed. Then, two-thirds of the mixing water was added to the mixture while the mixer was running. Finally, the remaining water was mixed with the super plasticizer and put into the mixer, and the mixer was stopped after ensuring sufficient homogeneity. For BHB production, 100×180×800 mm beam samples were prepared by using 5mm thick steel molds. Plastic sheats are used in the reinforcement to limit the embedded lengths. The ends of the sheats are sealed with silicone to prevent concrete from entering into them. Care has been taken to ensure that the molds are properly filled. The concrete mixes were poured in two layers and subjected to vibration in the shaking table. After all the beams produced were kept in the mold for 24 hours, the molds were removed. BHB samples removed from the mold were cured for 28-days in the laboratory using wet sacks (Figure 6b).

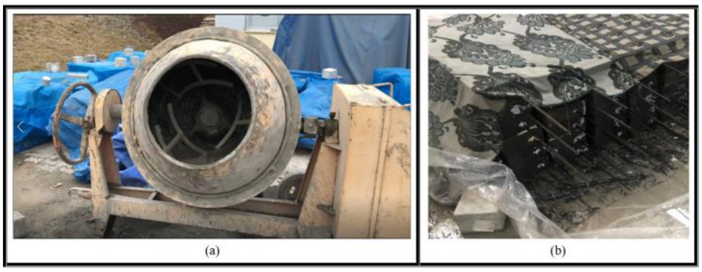


Figure 6. *Production of high performance lightweight concrete: a) Concrete mixer, b) Curing application of Belgium Hinged Beam test samples.*

3.3. Standard Belgium Hinged Beam test

In order to determine the concrete-reinforcement bond properties of the produced BHB samples, the Standard Belgium Hinged Beam test setup has been designed in accordance with BS 4449:2005+A2:2009 standard. Vertical load was applied to BHB samples through a 2500 kN capacity concrete test press operating with the hydraulic loading principle and the beams were forced to bending. BHB samples are placed on two supports, one fixed and the other movable. Loading was applied from the midpoint. The vertical loads applied to the beams were read with the help of the load cell. Potentiometric scales were used to measure the stripping amount of the reinforcement from the concrete at both ends of the beam sample subjected to experimental loading. The loads applied vertically and their corresponding debonding values were recorded simultaneously with the help of the data collection unit. A steel hinge is placed in the middle of the beam in order to reset the moment and calculate the loads on the reinforcement (Figure 7).

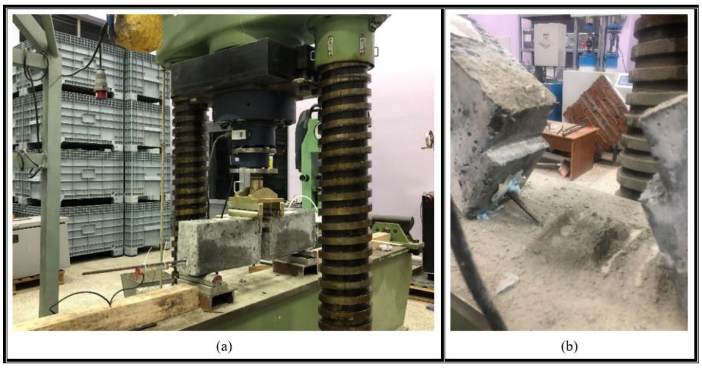
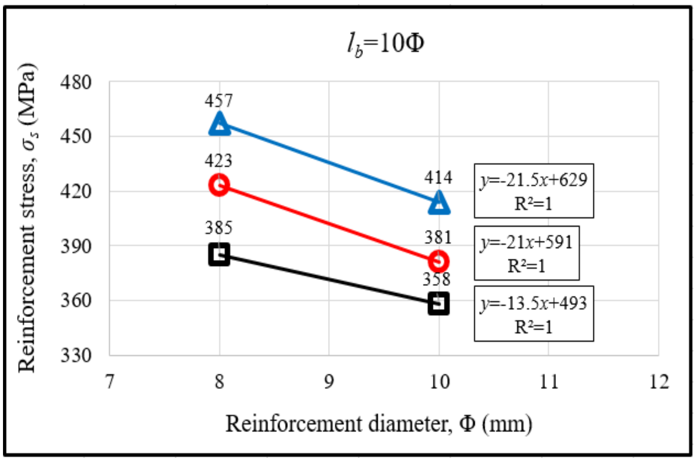


Figure 7. *Standard Belgium Hinged Beam test: a) placing the reinforced concrete beam sample on the test loading device, b) rupture of the reinforcement as a result of the bond test.*

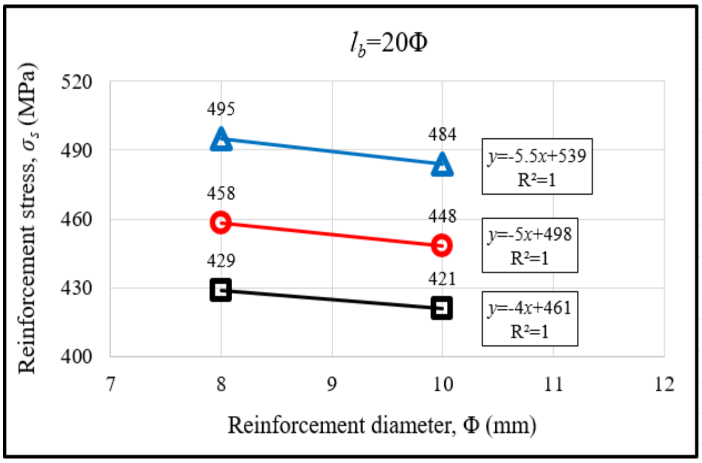
4. Experimental Results and Discussion

In the present study, the concrete-reinforcement bond of the BHB samples exposed to loading in accordance with the BHB test was investigated. Here, reinforcement bar diameters of Ø8 and Ø10 and embedded lengths of 10Ø and 20Ø are tested. It was observed that the experimental error margin was low in the beam tests performed for three control samples in each series. In addition, it can be said that the effect of reinforcement diameter and embedded length on both the bond stress and the stress in the reinforcement is great. It has been observed that both the bond stress and the stress in the reinforcement decrease as the diameter of the reinforcement increases. It has been observed that with the increase in the embedded length, both the bond stress and the stress in the reinforcement increase. From here, it was concluded that the diameter of the reinforcement changes inversely with both the bond stress and the stress in the reinforcement, and the embedded length changes in direct proportion to both the bond stress and the stress in the reinforcement. Considering that the bond stress is calculated by Equation (1), it can be said that it is directly related to the stress in the reinforcement.

In Figure 8(a), it was determined that by increasing the diameter of the reinforcement from 8 mm to 10 mm, the stress in the reinforcement decreased from approximately 421.7 MPa to 384.3 MPa. In Figure 8(a), by increasing the reinforcement diameter from 8 mm to 10 mm, a decrease of approximately 9.4%, 10% and 7% was observed in the stress values in the reinforcement for the BHB samples, respectively. This situation is the same for only changing embedded length l_b=20Ø in Figure 8(b). However, the ratio of decrease in the stress values in the reinforcement is lower than in Figure 8(a). In Figure 8(b), it has been determined that by increasing the diameter of the reinforcement from 8 mm to 10 mm, the stress values in the reinforcement decreased from approximately 460.7 MPa to 451.0 MPa. In Figure 8(b), by increasing the diameter of the reinforcement from 8 mm to 10 mm, a decrease of approximately 2.2%, 2.2% and 1.9% was observed in the stress values in the reinforcement for the BHB samples, respectively. This situation shows that as the diameter of the reinforcement increases, the stress in the reinforcement decreases. This decrease ratio was determined to be lower for higher embedded length.



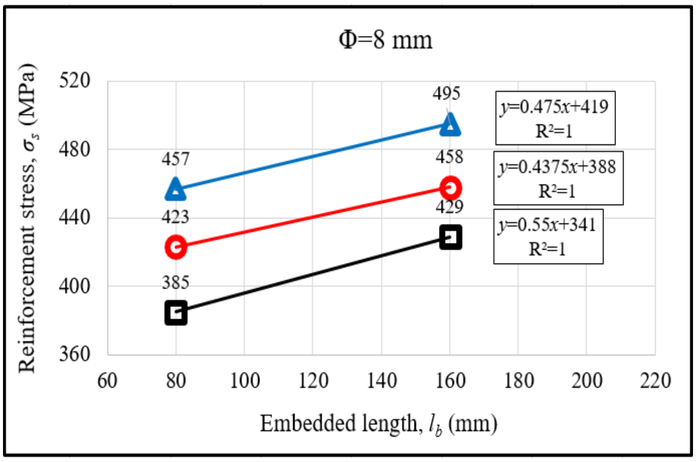
(a)



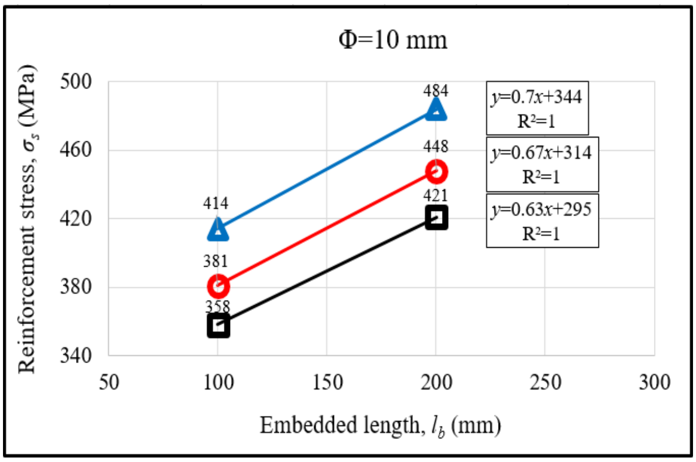
(b)

Figure 8. *Change of stress in reinforcement with reinforcement bar diameter: a) for l_b=10Ø, b) for l_b=20Ø.*

In Figure 9(a), it was determined that by increasing the embedded length from 10Ø=80 mm to 20Ø=160 mm, the stress values in the reinforcement increased from approximately 421.7 MPa to 460.7 MPa. In Figure 9(a), by increasing the embedded length from 10Ø=80 mm to 20Ø=160 mm, an increase of approximately 8.3%, 8.3% and 11.4% was observed in the stress values in the reinforcement for the BHB samples, respectively. This situation is the same for only changing reinforcement bar diameter Ø=10 mm in Figure 9(b). However, the ratio of increase in the stress values in the reinforcement is higher than in Figure 9 (a). In Figure 9(b), it was determined that by increasing the clamping length from 10Ø=80 mm to 20Ø=160 mm, the stress values in the reinforcement increased from approximately 384.3 MPa to 451.0 MPa. In Figure 9(b), by increasing the clamping length from 10Ø=80 mm to 20Ø=160 mm, an increase of approximately 16.9%, 17.6% and 17.6% was observed in the stress values in the reinforcement for the BHB samples, respectively. This situation shows that the stress in the reinforcement increases as the diameter of the reinforcement bar increases. This increase ratio has been determined to be higher for high reinforcement bar diameter.



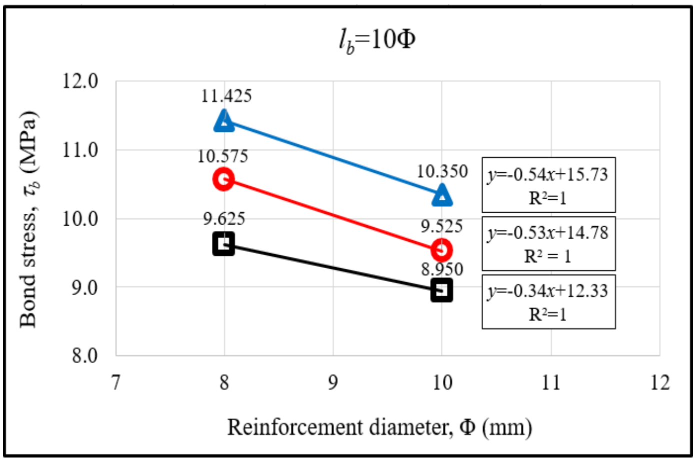
(a)



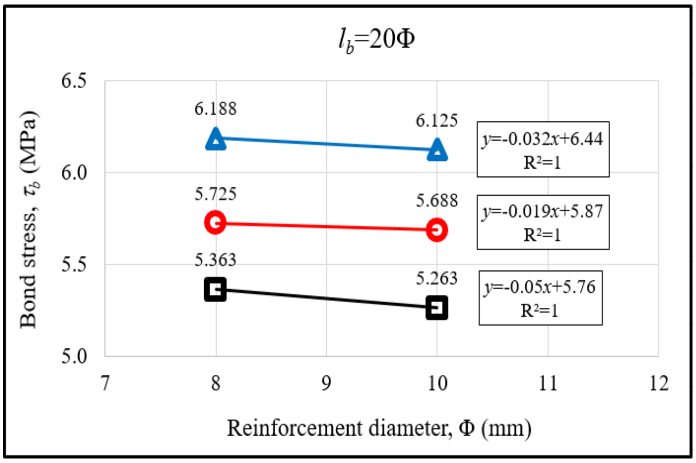
(b)

Figure 9. *Change of stress in reinforcement with embedded length: a) for Ø=8 mm, b) for Ø=10 mm.*

In Figure 10(a), it was determined that by increasing the reinforcement bar diameter from 8 mm to 10 mm, the bond stress values decreased from approximately 10.54 MPa to 9.61 MPa. In Figure 10(b), it was determined that by increasing the reinforcement bar diameter from 8 mm to 10 mm, the bond stress values decreased from approximately 5.76 MPa to 5.69 MPa. The change ratios of the bond stress values in Figure 10 are very close to the change ratios of the stress values in the reinforcement in Figure 8. This situation indicates that the stress in the reinforcement and the bond stress is directly related. It is observed that the bond stress decreases as the diameter of the reinforcement bar increases. This decrease ratio was determined to be lower for higher embedded length. It was concluded that the bond stress increases with the increase in the diameter of the reinforcement bar.



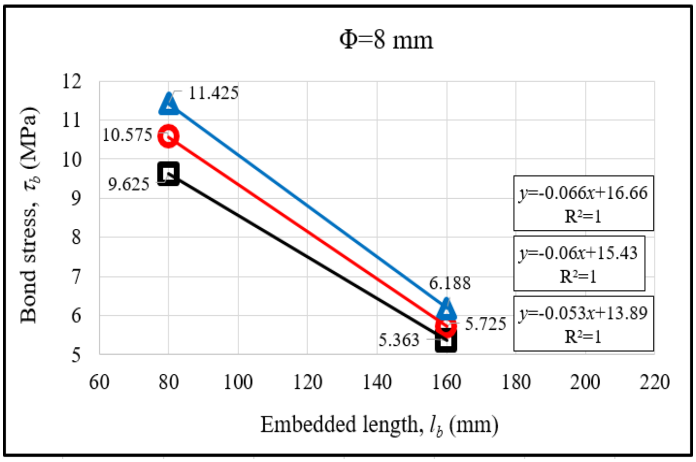
(a)



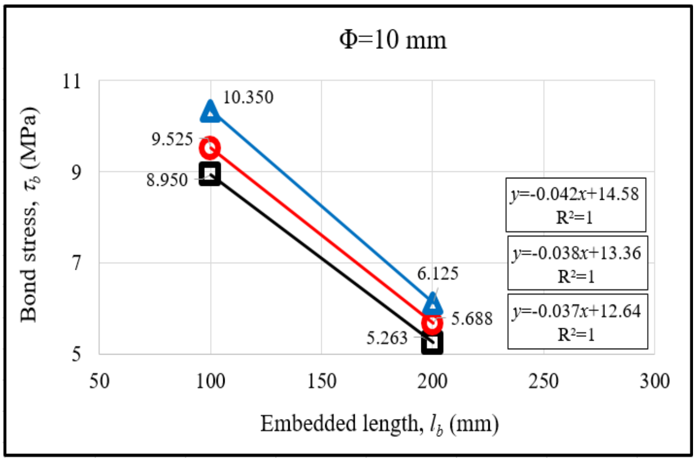
(b)

Figure 10. *Change of the bond stress with reinforcement bar diameter: a) for l_b=10Ø, b) for l_b=20Ø.*

In Figure 11(a), it was determined that by increasing the reinforcement bar diameter from 8 mm to 10 mm, the bond stress values decreased from approximately 10.54 MPa to 5.76 MPa. In other words, approximately 45.4% decrease in the bond stress was determined. In Figure 11(b), it was determined that by increasing the reinforcement bar diameter from 8 mm to 10 mm, the bond stress values decreased from approximately 9.61 MPa to 5.69 MPa. In other words, approximately 40.8% decrease in the bond stress was determined. The change ratios of the bond stress values in Figure 11(a) are very close to the change ratios of the stress values in the reinforcement in Figure 11(b). This indicates that the bond stress is inversely proportional to the embedded length and there is a similar decreasing trend for higher reinforcemenet bar diameter. As a result, it was observed that the bond stress decreased significantly with the increase in the embedded length. This decrease ratio was determined close to each other for high reinforcement bar diameter.



(a)



(b)

Figure 11. *Change of the bond stress with embedded length: a) for Ø=8 mm, b) for Ø=10 mm.*

5. Conclusions and Recommendatios

In the present study, the Belgium Hinged Beam test, which is a present test for the investigation of concrete-reinforcement bond properties under bending, has been experimentally investigated for the effect of reinforcement bar diameter and embedded length on both bond stress and stress in the reinforcement. The results of this study are summarized below:

- Since it is aimed to build an earthquake-resistant structure with the production of HPLC, it is thought that this study will benefit the sustainable environment and the national economy.
- In this study, using pumice aggregate in the production of HPLC will contribute to the economy in terms of Turkey having high pumice reserves.
- The stress values in the reinforcement determined in the BHB tests were obtained by breaking the reinforcement bar. This is due to testing relatively low reinforcement bar diameters (Ø= 8 and 10 mm).
- In the performed experiments, the maximum value of the stress in the reinforcement was determined as 495 MPa and the minimum value of the stress in the reinforcement as 358 MPa. The maximum value of the bond stress was determined as 11.425 MPa, and the minimum value of the bond stress was determined as 5.263 MPa.
- It has been observed of the stress value in the reinforcement that it decreases with increasing reinforcement bar diameter and increases with increasing embedded length.
- It has been observed of the value of bond stress that it decreases with the increase of both reinforcement bar diameter and embedded length.
- It is recommended that HPLC specimens are subjected to relevant tests for different mix ratios.
- It is recommended to test different embedded lengths and different reinforcement diameters.

Especially in recent times considerably occurrence of damage in the structures because of the severe earthquake in Turkey shows that earthquake-resistant the production of HPLC should be given more importance.

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References

Aitcin, P. C. (1998). High performance concrete. CRC press.

Al-Khaiat, H and Haque, M. N. (1998). Effect of initial curing on early strength and physical properties of a lightweight concrete. Cement and Concrete Research, 28(6), 859-866.

Arslan, M. E. and Arslan, T. (2018). Investigation of Development Length and Rebar Diameter Effects on Bond Strength by Using Hinged Beam Test. Science and Engineering Journal of Firat University, 30(2), 1-11. (in Turkish).

Arslan, M. E. and Durmus, A. (2011). Investigation of bond behavior between lightweight aggregate concrete and steel rebar using bending test. Computers and Concrete, 8(4), 465-472.

ASTM C 293, 1994. Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Center-Point Loading), Annual Book of ASTM Standards.

Baena, M., Torres, L., Turon, A. and Barris, C. (2009). Experimental study of bond behaviour between concrete and FRP bars using a pull-out test. Composites Part B: Engineering, 40(8), 784-797.

Benli, A., Türk, K. and Calayır, Y. (2008). Numerical and Experimental Investigation of Bond Strenght of Beams Produced from Self-Compacting Concrete. Science and Engineering Journal of Firat University, 20(4), 599-607. (in Turkish).

Beycioğlu, A., Arslan, M. E., Bideci, O. S., Bideci, A., Emiroglu, M. 2015. “Bond behavior of lightweight concretes containing coated pumice aggregate: Hinged beam approach” Computers and Concrete, 16(6), 911-920.

Bingöl, A. and Gül, R. (2009). A Reassessment on the Bond Strength Between Reınforcement and Concrete and the Effect of High Temperatures on the Concrete and on the Bond Between Concrete and Reinforcement. Turkish Science-Research Foundation, 2(2), 211-230. (in Turkish).

BS 4449:2005+A2:2009.Steel for the reinforcement of concrete—Weldable reinforcing steel—Bar, coil and decoiled product.

Chandra, S. and Berntsson, L. (2003). Lightweight Aggregate Concrete. Noyes Publications, USA, 1-430.

De Larrard, F., Shaller, I. and Fuchs, J. (1993). Effect of the bar diameter on the bond strength of passive reinforcement in high-performance concrete. Materials Journal, 90(4), 333-339.

Diederichs, U. and Schneider, U. (1981). Bond strength at high temperatures. Magazine of Concrete Research, 33(115), 75-84.

Durmuş, A., Dahil, H. and Arslan, M. E. (2006). Comparative Investigation of High Performance Concrete-Reinforcement Adherence. Turkey Engıneerıng News, 441. (in Turkish).

El Zareef, M. (2010). Conceptual and Structural Desıgn of Buıldıngs Made of Lıghtweıght And Infra-Lıghtweıght Concrete. Master of Science. Von der Fakultät VI – Planen Bauen Umwelt der Technischen Universität Berlin.

Ersoy, U. and Özcebe, G. (2001). Reinforced concrete: basic principles. Calculation According to TS500 and Turkish Earthquake Code. Ankara. (in Turkish).

Ersoy, U., 1985. Reinforced concrete. Evrim Publishing. ,(in Turkish).

Haque, M. N., Al-Khaiat, H. and Kayali, O. (2004). Strength and durability of lightweight concrete. Cement and Concrete Composites, 26(4), 307-314.

Hoff, G.C., 1990. High-Strength Lightweight Aggregate Concrete. ACI SP(121), 619- 644 p.

Hossain, K. M. A. (2004). Properties of volcanic pumice based cement and lightweight concrete. Cement and concrete research, 34(2), 283-291.

Hosseini, S. J. A., Rahman, A. B. A., Osman, M. H., Saim, A. and Adnan, A. (2015). Bond behavior of spirally confined splice of deformed bars in grout. Construction and Building Materials, 80, 180-194.

Ince, R. and Çetin, S. Y. (2019). Effect of grading type of aggregate on fracture parameters of concrete. Magazine of Concrete Research, 71(16), 860-868.

Karatas, M., Turk, K. and Ulucan, Z. C. (2010). Investigation of bond between lap-spliced steel bar and self-compacting concrete: the role of silica fume. Canadian Journal of Civil Engineering, 37(3), 420-428.

Neville, A. M. (1995). Properties of concrete (Vol. 4). London: Longman.

Poon, C. S., Shui, Z. H. and Lam, L. (2004). Compressive behavior of fiber reinforced high-performance concrete subjected to elevated temperatures. Cement and Concrete Research, 34(12), 2215-2222.

Saglam, R.N., Tunc, E. T., Demir, T., Ulucan, M. and Alyamac, K.E. (2019). Structural Lightweight Concrete Produced With Perlite Aggregate – A Preliminary Mix Design. International Civil Engineering and Architecture Conference (ICEARC 2019).

Tanyıldızı, H. and Yazıcıoğlu, S. (2006). Effect of Mineral Admixtures on Bond Strength of Concrete and Reinforcement. Science and Engineering Journal of Firat University, 18(3), 351-357. (in Turkish).

TS 802, 2016. Concrete Mix Calculation Principles. Turkish Standardization Institute (in Turkish).

TS EN 12390-5, 2002. Hardened Concrete Tests, Chapter 5: Determination of Flexural Strength of Test Samples, Turkish Standards Institute, Ankara. (in Turkish).

TS EN 197-1, 2002. General cements-Composition, properties and suitability criteria. Turkish Standards Institute, Ankara. (in Turkish).

TS EN 933-1: 2012. Experiments for the geometric properties of aggregates part 1: Determination of grain size distribution-Sieving method. Turkish Standards Institute, Ankara. (in Turkish).

Tugrul Tunc, E. (2019). “An Experimental Study Based on the Strength Properties of Concrete Containing Chemical Admixture.” European Journal of Science and Technology, 17, 901-908.

Tugrul Tunc, E. (2020). “Determination of Bond Properties in High Performance Lightweight Concrete.” Ph. D. thesis, Firat University, Elazığ. (in Turkish).

Tugrul Tunc, E. and Alyamac, K. E. (2019). “A preliminary estimation method of Los Angeles abrasion value of concrete aggregates.” Construction and Building Materials, 222, 437-446.

Tugrul Tunc, E., Alyamaç, K. E. and Ulucan, Z. C. (2020). “A Numerical Approach to Estimate the Tensile Strength of Structural Lightweight Concrete.” El-Cezeri Journal of Science and Engineering, 7(2), 690-699.

Tugrul Tunc, E. Alyamac, K. E., Ince, R. and Ulucan, Z. C. (2018). “Investigation of mechanical properties of high-performance lightweight concrete with pumice aggregate.” Engineering Sciences, 13(4), 344-353.

Tugrul Tunc, E., Saglam, R. N., Ulucan, M., Demir, T., Ulucan, Z. C. and Alyamac, K. E. (2019). “A Preliminary Mix Design For Structural Lightweight Concrete Produced With LECA.” International Civil Engineering and Architecture Conference (ICEARC 2019)

Ulusu, İ., 2007. “Investigation to production of high strength light weight concrete with using raw perlite aggregate.” Ph. D. thesis, Atatürk University, Erzurum. (in Turkish).

Wasserman, R. and Bentur, A. (1996). Interfacial interactions in lightweight aggregate concretes and their influence on the concrete strength. Cement and Concrete Composites, 18(1), 67-76.

Xiao, J. and König, G. (2004). Study on concrete at high temperature in China—an overview. Fire safety journal, 39(1), 89-103.