THE EFFECT OF EMBEDDING LENGTH AND CONCRETE COVER THICKNESS ON BOND STRENGTH IN BASALT AGGREGATE CONCRETE

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Abstract

This study investigated the effect of concrete cover thickness and embedding length on bond strength in concretes depending on the bonding properties of basalt aggregate in cement matrix. B420C construction steel with a diameter of 12 mm was centrally embedded in concrete samples for bond tests. CEM I 42.5 R cement and basalt aggregate were used for the production of concrete samples. 'Lollipop'-shaped reinforced concrete samples were prepared to make sure that concrete cover thickness is equal in the reinforcement circumference for the bond tests. These samples were prepared in nine different sizes with three different diameters and at three different height/diameter ratios. The results show that embedding depths of reinforcements in the samples with a diameter of 50 mm have no significant effect on bond strength. It has, therefore, been determined that the cylinder diameter of the concrete should be greater than 50 mm.

Keywords: Bond, pull-out, concrete cover thickness, embedding length.

BAZALT AGREGALI BETONDA KENETLENME BOYUNUN VE BETON ÖRTÜ KALINLIĞININ ADERANS GERİLMESİNE ETKİSİ

Özet

Bu çalışmada çimento matrisi içerisinde bazalt agregasının yapışma özelliğine bağlı olarak aderans dayanımına beton örtü kalınlığının ve kenetlenme boyunun etkisi araştırılmıştır. Aderans deneyleri için beton örneklerine 12 mm çapında B420C tipi inşaat çeliği merkezi olarak gömülmüştür. Beton örneklerin üretimi için CEM I 42.5 R tipi çimento ve bazalt agregası kullanılmıştır. Aderans testlerinde beton örtü kalınlığının

betonarme ortamda eşit olması için Lolipop şekilli beton örnekleri hazırlanmıştır. Bu örneklerde; üç farklı çapta ve üç farklı narinlik (boy/çap) oranlarında olmak üzere dokuz farklı boyutta hazırlanmıştır. Sonuç olarak 50 mm çaplı örneklerde donatıların gömülme derinliklerinin aderans gerilmelerinde kayda değer bir değişikliğe neden olmamalarından ötürü beton silindir çapının 50 mm üzerinde olması gerektiği belirlenmiştir.

Anahtar Kelimeler: Aderans, pull-out, beton örtü kalınlığı, kenetlenme boyu.

1. Introduction

Reinforced concrete is made of steel bars embedded in concrete and is the most widely used building material, today. There are many important issues in the design and use of this material, which can be defined as a preferred fibrous composite. Bond strength is one of these issues. Changes in the physical and mechanical properties of concrete and steel affect the bond strength. In this case, the use of different raw materials is a topic that needs to be considered again and again.

Bond between steel and concrete is one of the most interesting topics for many researchers studying reinforced concrete [1]. Many studies have been and continue to be conducted on this subject matter [1-7]. Today, concrete structures play a major role in the building industry. Therefore, the bond between steel and concrete is essential to ensure the structural behavior of reinforced concrete elements for both serviceability and ultimate boundary conditions [8].

Bond behavior is of great importance for the monolithic effect in concrete and reinforcement rods, and for the structural response of reinforced concrete members [9]. Bond force between reinforcement and concrete is a fundamental phenomenon [10], which enables reinforced concrete to function as a structural material, and the bond between concrete and steel directly affects the reinforced concrete [11, 12].

For a reinforced concrete structure to behave as expected, the reinforcement should be well anchored into the concrete [13]. The relative motion or shear stress between steel reinforcement and concrete providing embedding is defined as bond [11, 13].

The bond is due to the bonding resistance between materials and due to mechanical embedding in the case of use of ribbed reinforcement [13]. Forces between

two materials are transferred by two actions actuated by various stress states such as physicochemical and mechanical. The relative importance of these actions depends largely on surface texture and reinforcement geometry [10]. In addition to these two aspects, there are other factors affecting bond behavior, such as concrete quality. For example, an alteration or addition of a material to a concrete mix design may change the physical and mechanical properties of the concrete, which will, in return, affect the bond between reinforcement and concrete [10].

Bond is not only affected by concrete characteristics but also by shear-bond interaction, concrete-steel strength, location of reinforcement in concrete, embedding length, reinforcement diameter and concrete cover thickness [9, 11, 13]. With a proper embedding of reinforcement at concrete, these two materials function like a single composite material [11, 12]. As stated earlier, stress transfer between reinforcement rods and surrounding concrete (concrete cover thickness) in this embedding is a very important issue for reinforced concrete [13].

During the period when conventional concrete steels were produced, reasons for and factors affecting bond were assumed to be fully known. With technological developments, it has been reasoned that the bond between concrete and steel should be at a maximum level in order to manufacture high-strength steels and use them in concrete in the most efficient way. In order to strengthen this bond, a new generation of concrete reinforcement with high-strength steels comprising embossments and indentations has been developed and put into practice [1].

Studies in the literature report that the bond becomes weaker when the fluidity of common concrete increases or when a sand-rich mixture is used. It is also stated that the filling capacity of concrete may increase the bond by allowing the mixture to cover the reinforcement more effectively. At the same time, local microcracks weakening the mechanical properties may develop in case of insufficient stability at the weak aggregate-cement paste [10].

Many studies have been carried out on bond in concrete structures with normal weight aggregates and some model equations have been developed by researchers [12]. It has been reported that lightweight aggregates have lower bond strengthes than normal weight aggregates [14]. Another study on concrete with volcanic pumice aggregate and

concrete with normal aggregate shows that normal concrete has 12% more bond strength than do lightweight aggregate concrete [15].

Studies were conducted in the mid-20th century on basalt aggregate concrete. They determined that the heat transfer and coefficient of thermal expansion of basalt are low. In addition, they also stated that cracks formed in parallel with increasing compressive strength appear at higher stress values in basalt aggregate concrete. Increasing the tensile strength in concrete, these cracks are observed to be allowed by the rough surface of the basalt aggregate [16]. 45 to 52% of the basalt composition used in the production of concrete is SiO_2 [17].

Basalt is a dark gray and black volcanic rock consisting mainly of feldspar. Having different features, it is widely found in Diyarbakır and Afyon provinces and in Trakya region in Turkey [18]. These rocks are particularly strong against water absorption, corrosion, frost, impact and friction. Basalt is also used as a building stone as it is a very hard, dense and high-strength rock [19].

Besides aggregate, bond strength of some mineral admixtures has also been studied by some researchers. In one of these studies, high performance concrete samples were prepared using silica fume, the effect of which on bond conditions was investigated. The results indicate that the effect of silica fume on bond mechanism depends on concrete cover thickness [20].

There are many studies conducted on bond strength in slag- and class F fly ash - based geopolymer concrete [21], recycled aggregate concrete [22], freeze-thaw exposed concrete [23] and fine recycled aggregate concrete [24].

Numerous types of tests have been developed to determine the parameters affecting embedding length. The simplest of these tests is central pull-out method. A central pull-out test is performed by casting reinforcements into cylindrical or prismatic concrete samples and pulling them by means of a central load and measuring the debonding/pull-out of the reinforcement [25]. Studies on bond generally address reinforcement types and reinforcing bar diameter [1, 12, 13]. Some studies investigated the effect of high temperature on bond strength [26]. Some other studies used normal and light aggregate concrete and conducted central pull-out tests to determine bond strength [1, 12-14, 27, 28]. However, the effect of concrete cover thickness and

embedding length on bond strengths has not been adequately investigated in the literature.

Only basalt aggregate (no other chemicals) was used as coarse and fine aggregate and a central pull-out test was used to determine bond strengths of the concrete in this study. The aim of the study was to investigate the effect of concrete cover thickness and embedding length on bond strength depending on the adhesion property of basalt aggregate in cement matrix in order to determine sufficient concrete cover thickness and embedding length for bond regressions.

2. Material and Method

2.1 Materials

The reinforcement embedded in the concrete samples for bond tests is B420C grade construction steel with a 12 mm diameter produced in İskenderun-Turkey iron steel factory. Table 1 and Table 2 show the properties and chemical composition of B420C construction steel, respectively.

Table 1. Characteristic features of B420C grade construction steel.

Surface Texture	Class	Area (mm^2)	Yield Strength (MPa)	Tensile Strength (MPa)	Breaking Elongation (%)
Ribbed	B420C	113.04	475	587	24.1

Table 2. Chemical composition (%) of B420C grade construction steel.

Steel	C	Si	Mn	P	S	Cr	Cu	Ni	N	Fe
B420C	0.27	0.30	0.80	0.03	0.05	0.07	0.29	0.14	0.01	98.04

CEM I 42.5 R grade cement was used to produce the concrete samples. The basalt aggregate obtained from Afyonkarahisar – Turkey was mixed as 35% fine, 35% moderate and 30% coarse, according to TS 802 standard [29]. The gradation of the aggregate and the sample images are given in Figure 1 and Figure 2, respectively.
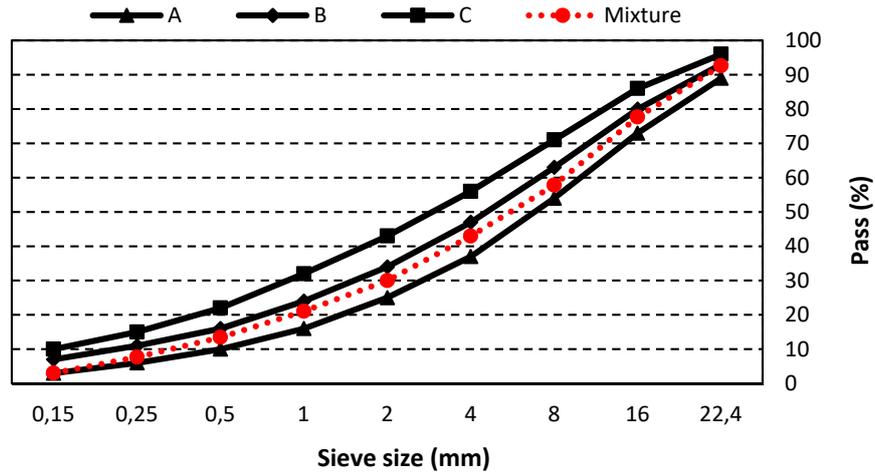
Figure 1. Sieve analysis of basalt aggregate mixture (d_{max} = 22.4 mm).

Figure 2. Basalt aggregate used in the production of concrete.

2.2. *Preparation of Samples*

The quality of concrete in which reinforcement will be embedded is important for bond strength tests. Therefore, the target compressive strength was taken as C30/37. Only basalt aggregate (no other chemicals) was used in the production of the concrete samples. Table 3 shows the materials and mix ratios used in the production of the concrete samples. The concrete samples were subjected to water curing in laboratory environment for 28 days. Reference concrete samples were prepared in dimensions of 150 x 150 x 150 mm. Water absorption and unit volume weight values of the reference samples were calculated using the water saturated weight and dry weight values of the concrete samples while the compressive strength values of the reference samples were determined according to TS 12390-3 [30].

Table 3. Properties of aggregates, and materials and mix ratios used for 1-m^3 concrete.

Material	Specific weight	Water absorption (%)	Amount of material used (kg)
Fine aggregate (35%)	2.48	2.4	583
Moderate aggregate (35%)	2.69	1.0	632
Coarse aggregate (30%)	2.78	1.6	560
Cement	3.15	-	390
Water	1.00	-	195
TOTAL			2360

The 12-mm diameter B420C construction steels used for the bond tests were centrally embedded in the concrete samples with properties given in Table 4. 'Lollipop'-shaped reinforced concrete samples were prepared to make sure that concrete cover thickness is equal in the reinforcement circumference for the bond tests. These samples were prepared in nine different sizes (Table 5) with three different diameters (50 mm, 75 mm and 100 mm) and at three different slenderness (height/diameter) ratios (1.0, 1.5 and 2.0). Figure 3 shows the molds used in the preparation of the samples.

Table 4. Water absorption, unit volume weight and compressive strength values of concrete.

Water absorption (%)	Unit volume weight (kg/m^3)	Compressive strength (MPa)
0.55	2398	37.84

Figure 3. Molds specifically designed for bond tests.

Table 5. 'Lollipop'-shaped concrete samples for bond tests.

Series	Concrete diameter (mm)	Concrete height (mm)	Slenderness ratio
50/50	50	50	1.0
50/75	50	75	1.5
50/100	50	100	2.0
75/75	75	75	1.0
75/112	75	112	1.5
75/150	75	150	2.0
100/100	100	100	1.0
100/150	100	150	1.5
100/200	100	200	2.0

2.3 Determination of Bond strengths

Bond strengths of the lollipop-shaped reinforced concrete samples were determined using the pull-out method. A 100-kN capacity pull-out device was used with the help of the auxiliary apparatus (Figure 4) in order to be able to apply the test mechanism.
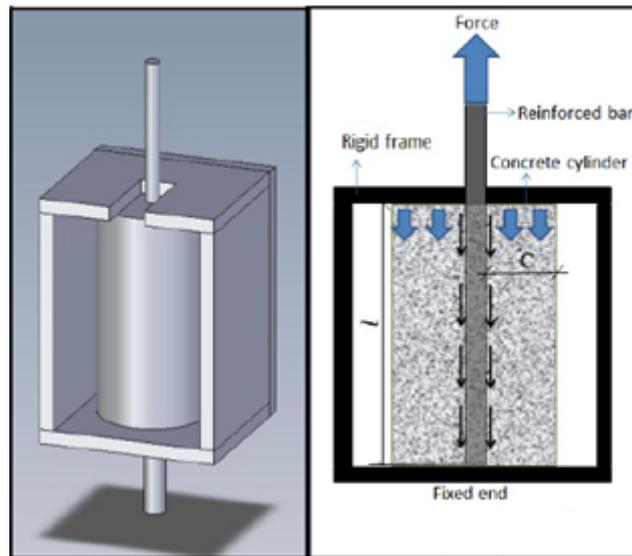

Figure 4. Bond test setup [31].

The maximum load was taken into account when calculating the pull-out strength. The bond strength values of the lollipop-shaped samples were calculated according to Equation 1. In this equation, T_{max} refers to the bond strength (MPa), P to

the pull-out force of the reinforcement obtained from the pull-out device, d to the reinforcement diameter (12 mm), and l to the embedding length of the reinforcement. At this stage, the reinforcements are embedded in the lowest levels of the cylindrical concrete samples, and therefore, the height of the cylindrical lollipop-shaped samples and the embedding depth represent the same length [11, 31].

3. Findings and Discussion

The bond strength values, which can be characterized as the resistance of the reinforcement surface area to the concrete interface, and the pull-out length values are given in Figure 5, which clearly demonstrates the effect of concrete cover thickness and embedding length on bond strength. Figure 5 indicates that the inadequate concrete cover thickness of the cylindrical concrete samples with a diameter of 50 mm did not contribute to the strength even when the embedding length was increased twofold. When this inadequate concrete cover thickness was increased by 50% to 75 mm, it made a significant contribution to the bond strength for reinforcement Ø 12 and the reflections of this contribution led to a certain increase in the bond strengths with an increase in the embedding length. The concrete cover thickness was increased by 100% to 100 mm in order to determine the optimum level of the thickness for the reinforcing bar diameter Ø 12. In this case, the highest bond strength was obtained at the embedding length of 100 mm. Although increasing the embedding length after this stage led to an increase in the tensile strength during the bond test, bond strengths decreased due to the rod surface area.

In a previous study, it has been reported that bond strength decreases with an increase in reinforcement diameter and in embedding depth/reinforcing bar diameter [27]. In this study, the bond strengths increased with a decrease in the embedding depth/reinforcing bar diameter in the lollipop concrete samples with a 100 mm diameter and the highest bond value (6.6 MPa) was obtained from the 100/100 series (Figure 5). The test results indicate that of all samples with similar content of concrete mix ratios, those with larger reinforcing bar diameter and embedding depth have lower bond strengths [27]. Here, the amount of water between the concrete and reinforcement surface increases as the diameter and length of the reinforcement contacting the concrete increase, which increases the voids and reduces the concrete area. Thus, as the

surface area and bond length between the two materials increase, the average bond strength transmitted to the concrete covering the reinforcement decreases [27]. In light of this information, the values obtained from the lollipop samples with a diameter of 100 mm are consistent with the literature.

Contrary to the literature, the bond strengths increased with an increase in the embedding depth/reinforcing bar diameter ratio in the lollipop samples with a diameter of 75 mm. The embedding depths of the reinforcements did not cause a significant change in the bond strengths of the samples with a diameter of 50 mm. However, the bond strengths increased with an increase in the diameters of the lollipop concrete samples and pull-out length values decreased in direct proportion with the concrete volume. The pull-out length values in the concrete samples ranged from 7.6 to 0.7 mm (Figure 5).
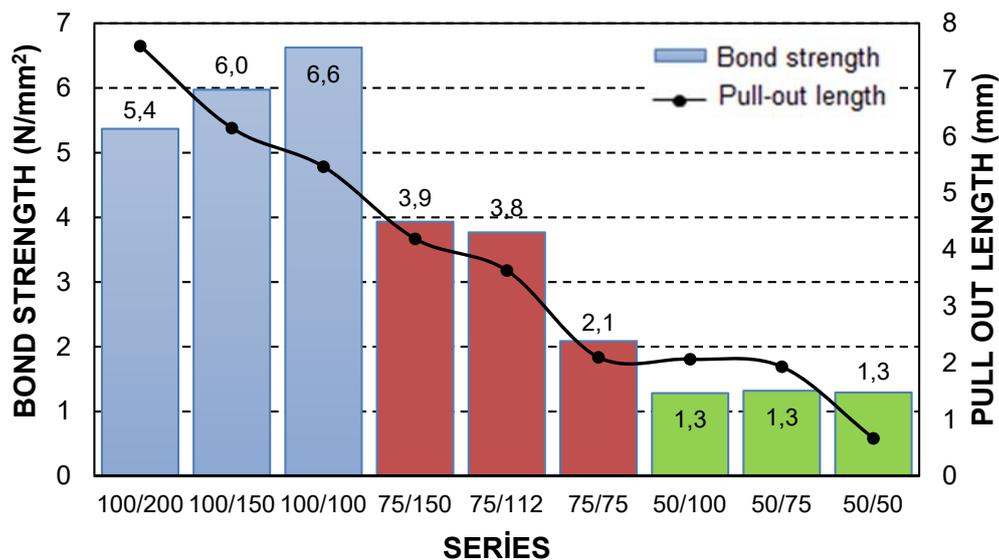

Figure 5. Bond strengths and pull-out length values of samples

The aim of the bond test was for the reinforcement not to debond and displace and the bond tests were expected to end with a concrete split. Therefore, it has been concluded that no further increase in the cover thickness is necessary for the present experimental setup. The tensile stresses are shown in Figure 6 to better understand the effect of the concrete mass on the tensile states resulting from the interpretation of the bond strength graph and the resistance of these reinforcements against this effect.

According to the findings obtained from the produced samples, it was determined that an increase in the concrete volume led to an increase in the stresses on the reinforcement (Figure 6). When the tension on the reinforcement is more than the

concrete cover, the bond is affected by the concrete content and the mineral materials added to the concrete change the friction between the side surface and the concrete. In such cases, the bond force, which is perpendicular to the reinforcement, rises, so tensile stress increases [26]. As a matter of fact, it was observed that an increase in the volume of the concrete samples led to an increase in the friction forces, which resulted in an increase in the stresses on the reinforcement (Figure 6). As stated in the literature, it was determined that the bond shape in the lollipop samples exhibited a fracture type and the spread of transverse cracks around the reinforcement accelerated as a result of an increase in the tensile stress [26].
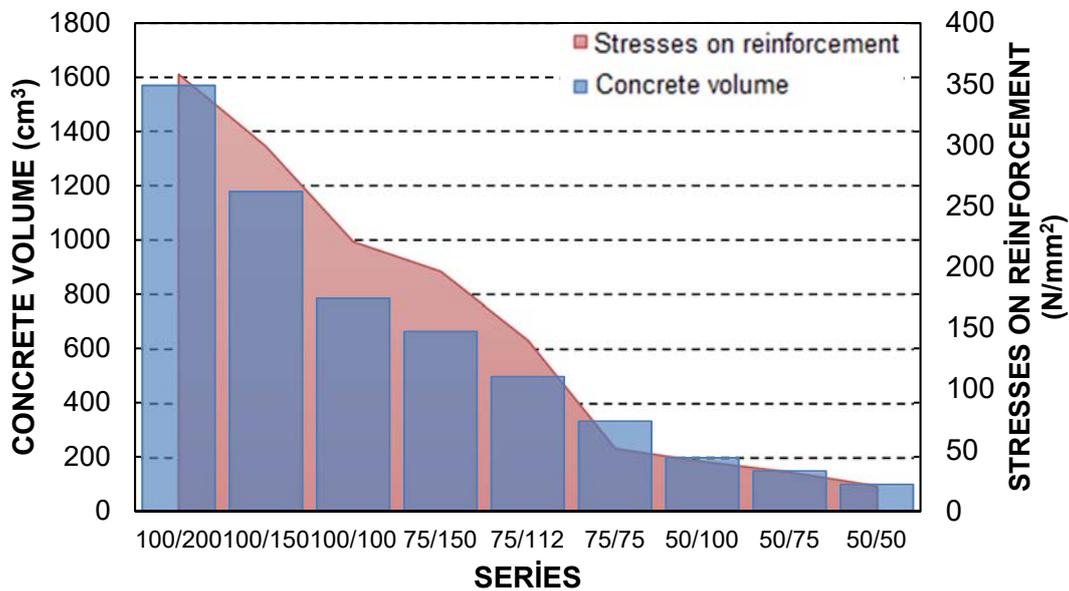

Figure 6. Concrete volume of samples and stresses on reinforcement

In reinforced concrete, reinforcement is embedded in the concrete mass in sufficient length. Otherwise, it is not possible to remove the reinforcement from the concrete. If the embedding length is not sufficient, the rod may slip out in connection with the surface geometry of the reinforcement. The length of the reinforcement embedded in the concrete is referred to as embedding length [32].

In the reinforcement embedded in the concrete, bond forces affecting the reinforcement along the embedding will be formed. These bond forces must balance the applied tensile strengths. In order to ensure adequate embedding, the total bond forces in the reinforcement circumferences must be equal to the tensile force of the rod. Experiments have shown that bond strengths do not spread uniformly along the

embedding and that the actual distribution depends on many variables. The distribution of bond strengths is not uniform and it is indicated that this distribution changes according to the level of stress in the rod as well as other variables [32]. The effect of the embedding length of the reinforcements on bond strengths is shown in Figure 7. As noted in the literature, it has been observed that bond strengths are at higher levels when stresses on the reinforcement is more and that bond strengths do not exhibit linear behavior. Bond changes depending on embedding length, however, bond strength is not proportional to embedding length [11].

Bond strengthes can be evaluated in three categories depending on embedding lengths; ≥150 mm, ≥100 mm and ≤75 mm. Based on this classification, bond strengthes range from 4.95 to 5.37 MPa in ≥150 mm embedding lengths, from 3.77 to 3.95 MPa in ≥100 mm embedding lengths and from 1.29 to 1.70 MPa in ≤75 mm embedding lengths. With this information, it was determined that bond strengths increase with an increase in embedding length (Figure 7). It has been previously stated that bond strengths decrease with an increase in embedding length [27]. However, the samples used in this study were prepared in dry-plastic consistency and no additives of plasticizers were added. Therefore, it is estimated that there would be no surface reduction due to water between the concrete surface and the reinforcement.
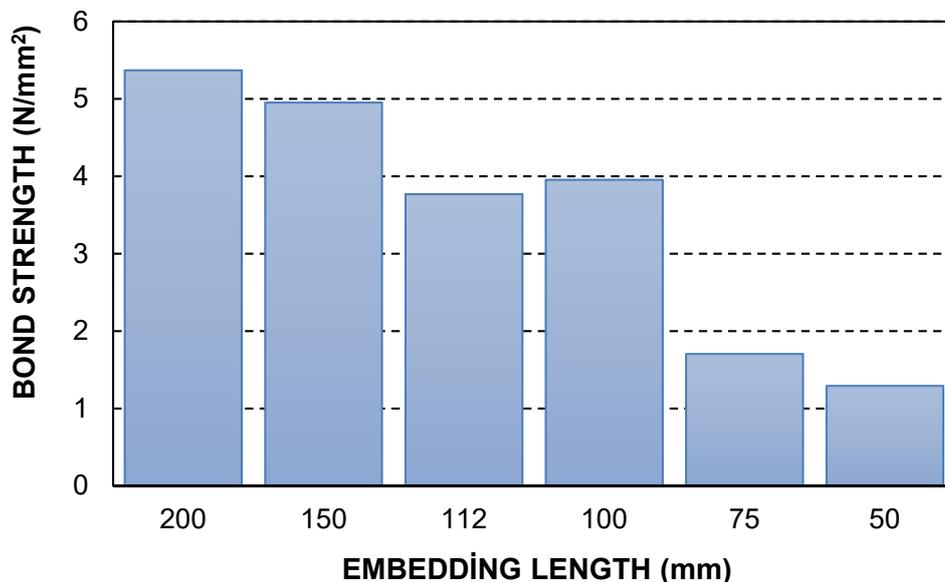

Figure 7. Bond strengths depending on embedding length.

Concrete cover thickness is important for elements in which ribbed reinforcement is used. It is stated that tensile strength is inversely proportional to

concrete cover thickness. However, the type of aggregate used also affects the bond. The bond of light aggregate concrete is lower than that of normal aggregate concrete [11]. There are also studies indicating that bond between reinforcement and mineral reinforced concrete decreases as a result of an increase in concrete cover thickness [26].

As with normal concretes, more concrete cover thickness helps the development of bond behavior. Bond strengths in partially recycled aggregate concretes were reported to be similar to those in normal concretes [27].

Figure 8 shows the bond strengths of the samples depending on the concrete cover thickness according to the data obtained from the basalt aggregate concrete samples. The graph clearly indicates that the bond strengths increased with an increase in the concrete cover thickness in parallel with the information in the literature. It is, therefore, clear that increasing the concrete cover thickness surrounding the concrete will lead to higher bond strength values in samples.
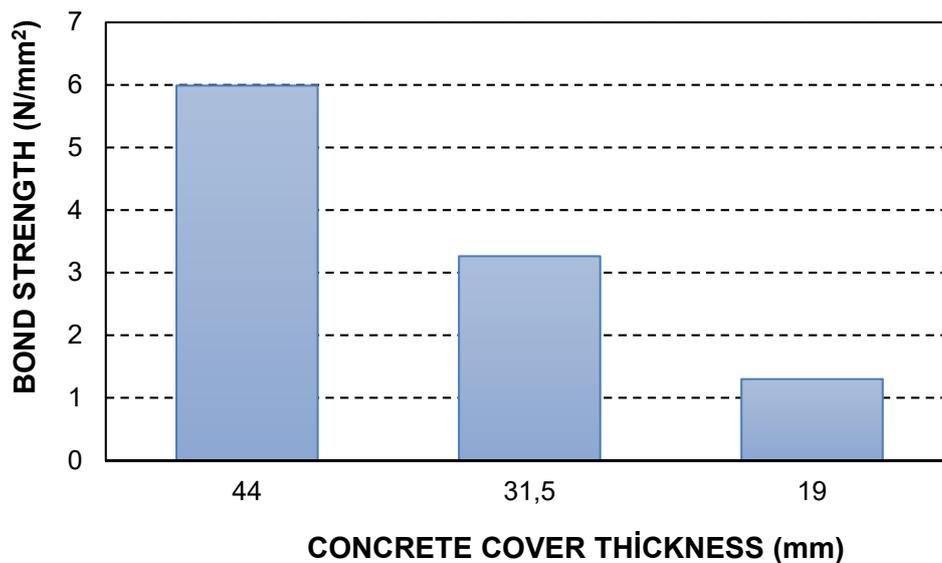

Figure 8. Bond strengths depending on concrete cover thickness.

Depending on the data on the reinforced concretes, Table 6 demonstrates the mathematical equations showing the relationship between the stresses on the reinforcement and the concrete volume and concrete cover thickness, and the relationship between the embedding length and bond strengths.

On the basis of the obtained data (Table 6), it was determined that the thickness of the concrete cover and the depth of the steel bar embedding are linearly related to the bond strength.

Table 6. Mathematical equations of findings.

Correlation between stresses on reinforcement (x) and concrete volume (y)	y = 3,9644x + 6,3982	R² = 0,9677
Correlation between concrete cover thickness (x) and bond strength (y)	y = 0,1877x - 2,3942	R² = 0,9913
Correlation between embedding length (x) and bond strength (y)	y = 0,0288x + 0,2115	R² = 0,8592

4. Results

The findings obtained from the tests indicate that in the event of inadequate concrete cover, increasing embedding length does not make any contribution to bond strengths. In parallel with the information available in the literature, it has been clearly shown that bond strengths increase with an increase in concrete cover thickness. Therefore, bond strengths are increased by increasing the concrete cover thickness surrounding the reinforcement.

It has been determined that a decrease in embedding depth/reinforcing bar diameter in the lollipop concrete samples with a diameter of 100 mm led to an increase in the bond strengths while, contrary to the literature, an increase in embedding depth/reinforcing bar diameter in the lollipop concrete samples with a diameter of 75 mm led to a decrease in the bond strengths, and embedding depths of the reinforcements did not cause any significant change in the bond strengths of the samples with a diameter of 50 mm. For this reason, it is considered that the cylinder diameter of the concrete should be over 50 mm.

It has been found that the bond strengths increase with an increase in the diameters of the lollipop concrete samples and that the pull-out length values decrease in direct proportion with the concrete volume.

Bond strengths ranged from 4.95 to 5.37 MPa in ≥150 mm embedding lengths, from 3.77 to 3.95 MPa in ≥100 mm embedding lengths and from 1.29 to 1.70 MPa in ≤75 mm embedding lengths.

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