

ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

**EFFECT OF COARSE AGGREGATE CONCENTRATION ON BOND
STRENGTH AND BOND-SLIP BEHAVIOR BETWEEN REINFORCING
STEEL AND LOW AND MID-STRENGTH CONCRETE**



M.Sc. THESIS

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Department of Civil Engineering

Structure Engineering Programme

JUNE 2023

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

**İRİ AGREGA KONSANTRASYONUNUN DONATI ÇELİĞİ İLE
DÜŞÜK VE ORTA DAYANIMLI BETON ARASINDAKİ BAĞ DAYANIMI VE
SIYRILMA DAVRANIŞINA ETKİSİ**

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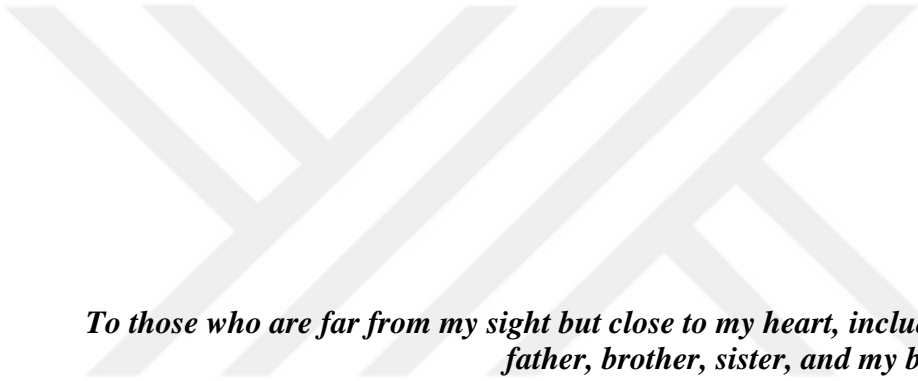
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*To those who are far from my sight but close to my heart, including my mother,
father, brother, sister, and my beloved daughter*



FOREWORD

I am honored to present my master's thesis entitled "Effect of Coarse Aggregate Concentration on Bond Strength and Bond-Slip Behavior between Reinforcing Steel and Low and Mid-Strength Concrete." The aim of this research was to investigate the impact of coarse aggregate concentration on the bond properties of reinforced concrete with different water to cement ratios.

This study provides a comprehensive understanding of the relationship between coarse aggregate concentration and the bond behavior of reinforced concrete. The results have important implications for better understanding the behavior of concrete structures, particularly those with low and medium strength. Furthermore, this research attempted to determine how changing parameters affect the characteristic properties of these types of concrete.

Throughout my research journey, I had the honor of being guided and supervised by Prof. Dr. Hakan Nuri ATAHAN, who has been a valuable mentor to me since our first meeting almost five years ago. I would also like to express my gratitude towards Dr. H. Nuri TÜRKMENOĞLU, Res. Asst. S. Nihat BIÇAKCI, and Res. Asst. Şervan BARAN for their unwavering support and assistance throughout this research project.

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ABBREVIATIONS

ASTM	: American Society for Testing and Materials
CEB	: Comité Euro-International du Béton
NS	: Natural Sand
FIB	: International Structural Concrete Federation
ITZ	: Interfacial transition zone
C.Sand	: Crushed Sand
CS1	: Crushed stone 1
CS2	: Crushed stone 2
LVDT	: Linear Variable Differential Transformer
W/Cm	: Ratio of water/total binder (by weight)
CA	: Coarse aggregate



SYMBOLS

Cm	: Centimeter
db, ϕ	: Rebar diameter
ϵ	: Deformation - strain
GPa	: Giga Pascal
Kg	: Kilogram
KN	: Kilo Newton
l	: Adherence length
m	: Meter
mm	: Milimeter
dm	: Decimeter
MPa	: Mega Pascal
N	: Newton
p	: Load
s	: Second
τ	: Bond strength



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EFFECT OF COARSE AGGREGATE CONCENTRATION ON BOND STRENGTH AND BOND-SLIP BEHAVIOR BETWEEN REINFORCING STEEL AND LOW AND MID-STRENGTH CONCRETE

SUMMARY

Concrete is currently the most consumed building material in the world. The 20th century saw a significant increase in the use of concrete in construction due to its high quality, speed, and ease of implementation. Reinforced concrete is one of the most commonly used load-bearing systems in buildings. However, despite the development of high-performance concrete, medium, and low-strength concrete is still widely used in ordinary residential buildings due to various factors. These factors include the use of substandard materials, insufficient details, lack of implementation based on clear scientific bases, and bad construction practices, such as pouring concrete on site without giving importance to increasing the water/cement (W/C) ratio or using aggregates with an inappropriate gradation. Such practices are responsible for most failures in reinforced concrete structures. While most modern buildings use deformed rods to improve the bonding between the rod and concrete, many older structures still rely on smooth rods. The increasing need to evaluate existing construction means that there is a constant need for information about its performance. The research on plain rebars was discontinued because they were not used in the first place when producing ribbed rebars, and ordinary bars have been surpassed in progress in understanding and behavior since the 1960s with the advent of ribbed rebars. The bond between concrete and reinforcement is an important factor in the evaluation of reinforced concrete structures. With the widespread use of reinforced concrete structures, it has become essential to understand the bonding properties between concrete and steel. For a structural element consisting of concrete and reinforcement to act as reinforced concrete, the bars must be clamped to the concrete. This interlocking is affected by many variables, such as the tensile strength of the concrete, the bond strength between reinforcement and concrete, and the concrete compressive strength. Other factors include the concrete reinforcement interface properties, geometric properties of the reinforcement, reinforcement production technique, reinforcement diameter, corrosion, embedment length, concrete confinement, concrete cover thickness, and the type and size of aggregate used. Therefore, the characteristic properties of concrete have a great effect on the bond between concrete and reinforcement. In areas that are located on the active seismic belt, in order to understand the behavior and performance of existing buildings, The worst implementation scenarios in addition to using two types of rebars that resemble the existing case were simulated. In the presented work, investigating the stress-strain properties and bond behavior of reinforced concrete with low and medium strength at different coarse aggregate concentrations was aimed. To achieve this, concrete mixtures with 3 different W/C ratios (0.6, 0.9, and 1.2) and 4 different coarse aggregate concentrations (0%, 20%, 40%, and 60%) were produced. The volume of aggregate and cement paste was kept constant in all mixtures. Pull-out tests were carried out to examine the bond properties between concrete and reinforcement. For this purpose, 12mm nominal diameter ribbed and plain steel rebar were used. The results showed that the compressive strength increased up to a certain

coarse aggregate concentration and then decreased, particularly in low-strength classes, with this trend decreasing as the W/C ratio decreased. The contribution of coarse aggregate concentration to compressive strength became more evident with a decrease in the W/C ratio. For instance, in concrete groups with W/C ratios of 1.2, 0.9, and 0.6, the strength increases percentages of concrete with a 40% coarse aggregate ratio compared to a 0% coarse aggregate ratio were 13.8%, 28.8%, and 70.2%, respectively. The study also found that the modulus of elasticity values increased with the increasing coarse aggregate ratio, and the slope of the post-peak region of the stress-strain curves became steeper. The bond strength of the concrete-reinforcement interface is affected by the W/C ratio. A decrease in the W/C ratio results in a denser concrete structure with reduced porosity, which positively affects the adherence between concrete and reinforcement. The bond strength values of mixtures with a W/C ratio of 0.60 were found to be higher than those with other dosages for both types of rebars. In summary, the type of rebar, water-cement ratio, and concentration of coarse aggregate affected the bond strength and bond-slip behavior between the concrete and reinforcement. Understanding these factors is crucial in designing and constructing safe and durable concrete structures.

İRİ AGREGA KONSANTRASYONUNUN DONATI ÇELİĞİ İLE DÜŞÜK VE ORTA DAYANIMLI BETON ARASINDAKİ BAĞ DAYANIMI VE SIYRILMA DAVRANIŞINA ETKİSİ

ÖZET

Dünya genelinde beton en çok kullanılan yapı malzemesidir. Yüksek kalitesi, hızlı ve kolay uygulanabilirliği nedeniyle 20. yüzyılda beton kullanımı inşaatта önemli ölçüde artmıştır. Betonarme ise binalarda en sık kullanılan yük taşıyıcı sistemlerden biridir. Ancak, günümüzde yüksek performanslı betonların geliştiriliyor olmasına rağmen, çeşitli faktörler nedeniyle orta veya düşük dayanımlı beton sıradan konut binalarında hala kullanılmaktadır. Ayrıca eski yapı stoğu içerisinde de önemli miktarda orta veya düşük beton dayanımına sahip binalar mevcuttur. Binalarda kullanılan betonun kalitesini etkileyen pek çok faktör bulunmaktadır. Bu faktörler arasında; beton üretiminde kalitesiz malzemelerin kullanımı, yapılan tasarım hesaplamalarının yetersiz olması, net bilimsel temellere dayalı uygulamanın yapılmaması, sahada betonun su/çimento oranına önem vermeden beton dökme işlemi yapılması veya kullanılan agrega gradasyonunun standarda uygun gibi etkenler yer almaktadır. Bu tür uygulamalar, betonarme yapıların çoğunun riskli duruma gelmesinden sorumludur. Bunlarla birlikte, günümüzde betonarme yapıların üretiminde, donatı ve beton arasındaki bağı iyileştirmek için nervürlü donatılar kullanılırken, birçok eski yapıda düz yüzeyli donatıların kullanıldığı bilinmektedir.

Mevcut yapıların değerlendirilmesi ihtiyacındaki artış, kullanılan malzeme ve sistemlerin performansı hakkında sürekli bir bilgi ihtiyacı gerektirmektedir. Düz yüzeyli donatıların kullanımı, nervürlü donatıların üretilmeye ve öncelikli olarak kullanılmaya başlaması ile birlikte azalmıştır. Beton ve donatı arasındaki bağı, betonarme yapıların deprem anındaki davranışına etki eden önemli bir faktördür. Betonarme yapıların yaygın kullanımıyla birlikte, beton ve donatı arasındaki bağı yapısı özelliklerinin anlaşılması esas haline gelmiştir. Nitekim, beton ve donatıdan oluşan yapısal bir elemanın betonarme olarak davranabilmesi için donatı ve betonun birlikte çalışabilmesi gerekir. Bu kenetlenme (bağı yapısı); betonun çekme dayanımı, donatı ile betonun aderansı ve beton basınç dayanımı gibi birçok parametreden etkilenmektedir. Diğer yandan, betonarme arayüz özellikleri, donatı geometrik özellikleri, donatı üretim tekniği, donatı çapı, korozyon, aderans boyu, betonun sıkıştırılması, beton pas payı kalınlığı, kullanılan agrega türü ve boyutu gibi parametreler de bu bağı yapısını etkileyen diğer faktörlerdir. Dolayısıyla, betonun karakteristik özellikleri, beton ve donatı arasındaki bağı dayanımının üzerinde büyük bir etkiye sahiptir.

Bu çalışmada, aktif deprem kuşağı üzerinde bulunan bölgelerde mevcut binaların davranış ve performanslarını anlayabilmek için, bu yapılarda kullanılmış olan betonlara benzer özelliklerde düşük ve orta dayanımlı beton karışımları tasarlanmıştır. Ayrıca iki farklı tip donatı (nervürlü ve düz yüzeyli) kullanılarak beton ile donatı arasındaki aderans ve sıyrılma özelliklerinin araştırılması hedeflenmiştir. Bu

doğrultuda, farklı iri agrega konsantrasyonlarına sahip, düşük ve orta dayanımlı betonların mekanik özellikleri, elastik özellikleri, tek eksenli basınç yüklemesi altındaki gerilme-şekil değiştirme davranışı ve donatı ile beton arasındaki bağ dayanımı ve donatının betondan sıyrılma davranışının incelenmesi gerçekleştirilmiştir.

Yapılan çalışmada, hedeflenen orta ve düşük dayanımlı betonları elde edebilmek için 0,6, 0,9 ve 1,2 olmak üzere 3 farklı su/çimento (S/Ç) oranına ve her bir S/Ç oranı için de 4 farklı iri agrega konsantrasyonuna (%0, %20, %40 ve %60) sahip beton karışımları üretilmiştir. Beton üretiminde CEM I 42,5R sınıfı çimento kullanılmış olup agrega karışımının maksimum tane büyüklüğü 16 mm'dir. Üretilen karışımların tamamında, toplam agrega (ince+iri) hacmi ve çimento hamuru hacmi sabit tutulmuştur. Bu sayede her bir S/Ç oranına sahip karışım grubunda çimento hamurunun hacim ve özelliklerini değiştirmeden, karışım içerisinde artan iri agrega konsantrasyonunun beton özellikleri, beton ile donatı arasındaki bağ dayanımı ve donatının betondan sıyrılma davranışı üzerindeki etkisinin belirlenmesi amaçlanmıştır.

Betonların üretimi gerçekleştirildikten sonra, her bir karışımdan 10 adet $\Phi 100 \times 200$ mm boyutunda silindir numune ve içerisine donatıların yerleştirildiği 8 adet $150 \times 150 \times 150$ mm boyutunda küp numune (4 adet nervürlü, 4 adet düz donatı), alınmış ve bir gün sonra kalıplardan çıkarılan numuneler 28. güne kadar $21 \pm 2^\circ\text{C}$ sıcaklığa sahip kür havuzunda bekletilmiştir. Silindir numunelerden 4 tanesi üzerinde basınç dayanımını belirleyebilmek için TS EN 12390-3 standardına uygun bir şekilde yük kontrollü basınç deneyi (yükleme hızı 5 kN/s) yapılmıştır. Diğer 4 adet numune üzerinde elastisite modülü, Poisson oranı değerlerini belirleyebilmek ve tepe yük öncesi ve sonrası gerilme-deformasyon grafiğini elde edebilmek için deplasman kontrollü basınç deneyi gerçekleştirilmiştir (yükleme hızı 0,75 $\mu\text{ε}/\text{dk}$). Deplasman kontrollü deneyler sırasında numunelerin üzerine ASTM C469 standardına uygun bir şekilde birbirinden bağımsız 2 farklı çerçeve bağlanmıştır. Bu çerçevelere bağlanan lineer değişken diferansiyel transformatörler (LVDT) aracılığıyla boyuna ve yanal deformasyon değerleri cihaz tarafından otomatik olarak kaydedilmiştir. Kalan 2 adet silindir numune ise ortadan 2'ye bölünmüş ve elde edilen 4 adet $\Phi 100 \times 100$ mm boyutundaki numuneler üzerinde TS EN 12390-6 standardına uygun bir şekilde yarmada çekme deneyi (yükleme hızı 1 kN/s) gerçekleştirilmiştir. Diğer yandan çekip-çıkarma deneyi için hazırlanan numunelerde kullanılan donatıların çapı 12 mm ve donatıların beton ile temas eden yüzeyinin uzunluğu donatı çapının 5 katı (60 mm) olarak seçilmiştir. Bunu sağlayabilmek için donatının beton içerisinde gömülü kalan 90 mm uzunluğundaki bölümün üzerine hortum yerleştirilmiş ve beton ile teması önlenmiştir. Çekip çıkarma deneyi ise özel olarak hazırlanan çerçeve sistemi universal çekme cihazına bağlanarak gerçekleştirilmiştir. Deney sırasında donatının sıyrılma miktarı donatı ucuna yerleştirilen lvdt aracılığı ile yük değerleri ise sisteme bağlanan yük hücresi vasıtasıyla eş zamanlı olarak otomatik bir şekilde kaydedilmiştir.

Elde edilen sonuçlardan bahsedilecek olursa, farklı S/Ç oranına sahip karışımların tamamında %40 oranına kadar artan iri agrega konsantrasyonu ile birlikte basınç dayanımlarının arttığı fakat %60'lık iri agrega konsantrasyonunda ise basınç dayanımlarının %40 oranında agrega içeren karışımlara göre azalma eğilimi gösterdiği görülmüştür. Örneğin, 1,2 S/Ç oranında, %0 iri agrega konsantrasyonu içeren karışıma göre %20 ve %40'lık karışımlardan elde edilen sonuçlar sırasıyla %13,2 ve %13,8 oranında daha yüksek iken %60'lık karışım için basınç dayanımı %23,6 oranında daha düşüktür. 0,9 S/Ç oranına sahip karışımlarda %0'lık karışıma göre %20, %40 ve %60'lık karışımlardan elde edilen basınç dayanımı artış oranları sırasıyla %14,1, %28,8 ve %23,6 iken bu artış oranları 0,6 S/Ç oranına sahip karışımlar için sırasıyla

%70,0, %70,2 ve %67,7'dir. Bu sonuçlar değerlendirildiğinde, öncelikle 1,2 S/Ç oranına sahip karışımlarda kapiler boşluğun daha fazla olması ve bunun sonucu olarak hamur fazı dayanımının çok düşük olmasına bağlı olarak agrega-hamur ara yüzeyi çok zayıftır. Bu nedenle kullanım oranı artmasına rağmen iri agreganın basınç dayanımına belirgin bir etkisi gözlemlenmemiştir. Diğer yandan 1,2 S/Ç oranına sahip karışımların aksine azalan s/ç oranı ile birlikte hamur fazının dayanımı daha da artmış ve ara yüzey özelliklerinin iyileşmesiyle birlikte iri agreganın basınç dayanımı değerlerine etkisi daha belirgin hale gelmiştir. Elastisite modülü sonuçları incelendiğinde ise, basınç dayanımı sonuçlarından farklı olarak, artan iri agrega konsantrasyonu ile birlikte elastisite modülü değerlerinin de sürekli arttığı bir eğilimin olduğu görülmektedir. Yukarıda bahsedildiği üzere, %60 iri agrega konsantrasyonuna sahip karışımlardan %40'luk karışımlara göre daha düşük seviyelerde basınç dayanımı değerleri elde edilmişti fakat elastisite modülü değerlerinde en yüksek sonuçların iri agrega konsantrasyonu %60 olan karışımlardan elde edildiği görülmüştür. Örneğin, 0,6 S/Ç oranına sahip karışım grubunda %0 iri agrega içeren karışımın elastisite modülü değeri 21,3 GPa iken bu değer %60 iri agrega içeren karışımdan 27,0 GPa olarak elde edilmiştir. Yani elastisite modülü %27 oranında artmıştır. Bunun nedeni olarak karışım içerisindeki en rijit taneler olan iri agregaların varlığı ve miktarının, betonun elastisite modülünü pozitif yönde etkilemesi gösterilebilir. Ayrıca S/Ç oranının azalmasıyla hamur fazının dayanımının artması ve böylece agrega-hamur arayüzeyi özellikleri iyileşmesi de elastisite modülünün belirgin bir şekilde artmasını sağlamıştır. Poisson oranı değerleri incelendiğinde karışıma iri agrega eklenmesi ile birlikte belirgin bir değişiklik meydana gelmediği ve Poisson oranının 1,2 S/Ç oranına sahip karışımların tamamında 0,20'ye eşit olduğu, 0,9 S/Ç oranına sahip karışımlarda 0,19-0,21 aralığında olduğu ve 0,6 S/Ç oranına sahip karışımlarda ise 0,22'ye eşit olduğu görülmüştür. Yarmada çekme dayanımlarına bakıldığında ise tüm beton gruplarında karışıma iri agrega eklenmesi ile birlikte yarmada çekme dayanımlarında bir artış meydana geldiği görülmüştür. Bununla birlikte, basınç dayanımı sonuçlarına benzer şekilde yarmada çekme dayanımındaki artış miktarı S/Ç oranı azaldıkça daha belirginleşmiştir.

Çalışma kapsamında üretilen betonların basınç yüklemesi altındaki davranışları incelendiğinde; 1,2 S/Ç oranına sahip betonlarda karışıma iri agrega eklenmesi ile tepe yük sonrası düşen kol eğrilerinde belirgin bir değişiklik olmadığı fakat 0,6 ve 0,9 S/Ç oranına sahip karışımlarda düşen kol eğiminin belirgin bir şekilde dikleşerek davranışın gevrekleştiği görülmüştür. Ancak, artan iri agrega konsantrasyonunun düşük basınç dayanımına sahip betonların davranışında belirgin bir farklılık oluşturmadığı gözlemlenmiştir.

Beton ile donatı arasındaki bağ dayanımı özelliklerinin ve farklı yüzey özelliklerine sahip donatıların sıyrılma davranışının incelenmesi amacıyla özel olarak hazırlanan numuneler üzerinde çekip-çıkarma deneyi gerçekleştirilmiştir. Deneylerden elde edilen sonuçlara bakıldığında, bağ dayanımı değerleri; düz donatılı numunelerde 3,4 ile 5,8 MPa aralığında iken nervürlü donatı içeren numunelerde 6,3 ile 21,1 MPa aralığındadır. Karışımların S/Ç oranı azaldıkça her iki donatı tipinde de bağ dayanımı değerlerinin arttığı gözlemlenmiştir. Düz donatı içeren karışımlarda iri agrega konsantrasyonunun etkisine bakıldığında, 1,2 ve 0,9 s/ç oranına sahip karışımlarda artan iri agrega konsantrasyonu ile birlikte bağ dayanımının arttığı fakat 0,6 S/Ç oranına sahip karışım grubunda bağ dayanımı değerlerinin birbirine oldukça yakın olduğu belirlenmiştir. Diğer yandan nervürlü donatı içeren karışımlara bakıldığında 1,2 S/Ç oranına sahip karışımda en yüksek bağ dayanımının 7,4 MPa ile %20 iri agrega

konsantrasyonundan, 0,9 S/Ç oranına sahip karışımında 13,0 MPa ile %40 iri agrega konsantrasyonundan ve 0,6 S/Ç oranına sahip karışımında ise 21,1 MPa ile %60 iri agrega konsantrasyonundan elde edildiği görülmüştür. Diğer yandan karışımların bağ dayanımı- sıyırılma davranışı incelendiğinde düz donatılı karışımlarda çok küçük sıyırılma değerlerinde bağ dayanımı değerine ulaşıldığı ve hemen sonrasında bağ gerilmesi-sıyırılma eğrisinin düşüğe geçtiği görülmüştür. Nervürlü donatı içeren numunelerde ise bağ dayanımına ulaşmadan önce sıyırılmanın başladığı, bağ dayanımına ulaştıktan sonra da bir plato bölgesi oluştuktadan sonra bağ gerilmesi-sıyırılma eğrisinin düşüğe geçtiği belirlenmiştir. Bu durum açık bir şekilde düz donatılı numunelerde sadece donatı ile beton arasında kimyasal bağdan kaynaklı bir mekanizmanın çalıştığını fakat nervürlü donatı içeren numunelerde ise kimyasal bağın yanında nervür ile beton arasında mekanik kenetlenme mekanizmasının da devreye girdiğini göstermiştir.



1. INTRODUCTION

Concrete is the main building material in the current era (Sims et al., 2019) since the French Louis Vicote succeeded in producing cement from limestone and fired clay in 1817, and in a similar way Joseph Aspden produced Portland cement in 1824. Despite the distinctive characteristics of Portland cement, it did not start a revolution in the construction world, where it was considered only an artificial stone. But after Lambot discovered reinforced concrete in 1847, the use of reinforced concrete in slabs was repeatedly patented. The first actual application on a building located in New York, America (1871-1875), here began the real revolution in the history of modern construction (Cruz, 2010) with reinforced concrete, which is defined as consisting of materials with different mechanical and physical properties, and its properties depend on the joint work between the concrete and the reinforcing bars. So, when different loads are applied to the reinforced concrete, the load is distributed between the concrete and the reinforcement, where they share the loads by an interaction between the internal surfaces through the bond strength, where we can describe the behavior of the bond as the relationship between the shear forces (parallel to reinforcement) and the rebars resulting in a change in forces and deformations between the rebar and concrete material and potentially causing slippage between the inner surfaces of the two materials (Sahi & Al-Zuhairi, 2009). On the other hand, concrete is a composite material composed of three phases; binding paste, coarse and fine aggregates, and interfacial transition zones (ITZ) (Sun et al., 2022). The ITZ found in concrete are situated between the matrix of mortar and the aggregate. This region is considered the weakest and most crucial link within the concrete structure due to the difference in specifications compared to the cement paste that is distanced from the aggregate, as well as the cement paste that envelops the aggregate. The thickness of ITZ ranges from 9 to 51 micrometers for normal concrete, and it is influenced by the characteristics of individual mixture components, such as (coarse aggregate, and the W/C ratio of the mixture) which plays a significant role in the properties and thickness of this zone. Moreover, ITZ is a key factor in determining the mechanical behavior of concrete. The

adhesion between the aggregate and the cement paste in the ITZ controls the strength of the concrete.(Akçaoğlu et al., 2004; Prokopski & Halbiniak, 2000; Nilsen and Monteiro, 1993; Zheng et al., 2005)

The W/C plays a major role in determining the mechanical properties of concrete. This ratio controls the microstructure of the ITZ and its thickness. In conventional concrete, where the W/C is greater than 0.4, the strength of the material is primarily determined by the mortar and its connection with the coarse aggregate. The coarse aggregate is the strongest phase, but its effect on strength is limited as micro cracks tend to form in the weaker ITZ during load transfer, which can lead to concrete failure.

However, in high-strength concrete with a W/C ratio less than 0.4, the properties of the mortar and the bonding behavior of mortar in the interfacial region are improved, making it comparable to the strength of the coarse aggregate, which in this case becomes the weakest phase. Therefore, the strength of the concrete is not solely dependent on the W/C ratio in this case. Other factors that must be considered for improving the strength of concrete include the use of aggregates with high mineral composition and strength, which can improve the overall strength of the concrete. Also, the effect of coarse aggregate with a different chemical composition also plays a key role in high-strength concrete. But, in conventional concrete, the main factor affecting concrete strength is the ITZ between the coarse aggregate and the paste phase of concrete (Elsharief et al., 2003; Vishalakshi et al., 2018). Akcaoglu et al (2004) examined how the W/C ratio and the size of coarse aggregates affect the formation of the ITZ and the consequent failure mechanism of concrete. The research investigated two different W/C ratios of 0.4-0.8 and utilized single spherical steel aggregates of varying sizes. Results showed that larger coarse aggregates and lower W/C ratios had a negative impact on the properties of the ITZ. This suggests that the adverse effect of rigid aggregates becomes more pronounced as the quality of the matrix and the size of the aggregate increase (Akçaoğlu et al., 2004).

Despite great developments in the construction industry and the development of high-specification building materials that enhance durability and sustainability, engineers still face challenges with older buildings that were constructed before the new codes were implemented. These buildings can pose a great danger to public life and property. Ensuring the safety and structural integrity of older buildings is a major concern for engineers. This issue highlights the importance of studying low-strength concrete,

which is a prevalent issue in many of these buildings, and a major contributor to potential hazards.

Reinforced concrete structures built before 1970 are vulnerable during earthquakes due to insufficient seismic detail to provide sufficient ductility. These structures often have a number of shortcomings, the most important of which are the use of plain rebars as longitudinal reinforcement, poor anchoring to strengthen the girders in the columns, low concrete strength, poor execution, and no design codes for earthquake hazard (Hertanto, 2005). The bond strength between the longitudinal reinforcement and the surrounding concrete is a crucial factor in the overall behavior of reinforced concrete components. One of the most important factors affecting this bond is the compressive strength of the concrete. The compressive strength can affect the efficiency of the concrete structure as a whole. In the United States, concrete is not graded based on strength like it is in Europe and other countries. However, for the purpose of understanding the relationship between microstructure and properties, it is useful to classify concrete into three categories based on compressive strength:

1. Low-strength concrete (less than 20 MPa)
2. Moderate-strength concrete (20 to 40 MPa)
3. High-strength concrete (more than 40 MPa) (ACI 408R-03, 2003 ; Mehta and Monteiro, 2013)

A country located on the active seismic belt, such as Turkey, has experienced many devastating earthquakes during the past decades. Despite advancements in concrete technology and access to high-strength concrete, most existing buildings do not meet current design specifications. A field study of three Turkish cities at risk of earthquakes found that 19% of public buildings had a concrete strength of less than 8 MPa, while 33% of buildings were between 8 MPa to 10 MPa, additionally, it was found that most of the collapsed and severely damaged buildings due to earthquakes had a low strength between 8 to 10 MPa, indicating the danger that low-performance concrete poses in the event of future earthquakes (Inel, 2008). Another study on buildings that collapsed or were severely damaged in the earthquakes in Adana and Izmit in 1998 and 1999, respectively, found that the catastrophic outcome resulted from poor execution during construction and low-strength concrete, specifically due to the design of the mixture and the absence of aggregate gradation (Kankam, 1997). Low-strength concrete plays

a major role in causing building collapse in an earthquake-damaged area, as seen in samples taken from a collapsed building in the 1998 Adana earthquake, where the strength of the concrete was found to be between 5.37-10.35 MPa (Çağatay, 2005). In order to accurately represent the behavior of low-strength concrete and approximate the reality under the influence of the total compressive and tensile forces, an experimental study was conducted and the experimental results were systematically analyzed and the data from previous literary studies in a comparative manner (Ispir et al., 2022). The study recommends that new models should be found that more accurately reflect the behavior of low-strength concrete under compression and tension. As previously discussed, the crucial stage in the characteristics of low-performance concrete is the stage of coarse aggregate and its impact on the development of cracks in the ITZ.

1.1 Scope

In the performance evaluation phase of existing structures, collecting information on the material properties of the structure from the examined building can be considered an important step. The collection of such information from the building (such as determining the existing concrete strength, reinforcement amount, type, diameter, and corrosion status) can be practically achieved with damaged and undamaged measurement techniques. On the other hand, the quality of concrete used in buildings dating back to the pre-1990 period, when the ready-mixed concrete industry was not widespread enough in our country, shows a significant distribution in terms of both strength and coarse aggregate content. Compressive strength values may fall below 10 MPa levels and may move away from an ideal or balanced aggregate mixture in terms of composite material properties. This situation significantly affects the elastic properties of the concrete, as well as the bond strength between the concrete and the reinforcement and, the slip properties of the reinforcement from the concrete. There are empirical relations/models and regulations available in the literature that predict the bond strength between the reinforcement and the concrete and also the slip behavior of the reinforcement from the concrete. These models are generally obtained from studies carried out on concrete mixtures designed to mix in appropriate constituent material proportions, taking into account concrete design rules. So, it can be argued to what extent they represent the behavior of old structures with very

different (low) strengths and poor design properties. In this respect, this study, it is aimed to investigate the mechanical properties and the slip behavior of "ribbed" and "plain" steel reinforcements embedded in low and moderate-strength concrete mixtures (in the range of 10 to 40 MPa) with varying coarse aggregate contents

1.2 Literature Review

1.2.1 Effect of coarse aggregate on concrete properties

The use of large coarse aggregates in concrete has become more popular for economic and environmental reasons, such as reduced energy consumption and increased production rates. However, it is crucial to keep in mind the trade-off between these benefits and the performance of the resulting concrete. This is particularly important when considering the outdated practice of using concrete poured in place without proper quality control measures, as was the case in the construction of many old buildings. This method often involved manually mixing the concrete or using small batches, and increasing the amount of coarse aggregate to cut costs and increase volume, which resulted in poor-quality constructions (Tumidajski and Gong, 2006). Both coarse and fine aggregates are essential components of concrete, making up approximately 60-80% of its total volume. In the past, aggregate particles were viewed as inert materials, but they are now recognized for their physical properties such as shape, size, texture, and mineral composition, as well as microstructural characteristics such as density and porosity, which can affect the properties of the concrete in both its solid and fresh states, including strength, corrosion resistance, durability, dimensional stability, and consistency. Aggregates are typically classified by particle size, with coarse aggregates ranging from 4.75 to 50 mm and fine aggregates falling within the range of 75 μm to 4.75 mm (Mehta and Monteiro, 2013). The use of larger size aggregate in concrete leads to a lower total surface area in a given volume of concrete, which in turn reduces the water requirement for a given workability, resulting in higher strength at a given W/C ratio. However, later research found that using larger size aggregate did not lead to increased strength as expected. This is because larger aggregate size reduces the development of gel bonds, which are responsible for the strength of the concrete. Additionally, larger aggregate size creates a more heterogeneous concrete, preventing the uniform distribution of load when stressed. Additionally, the use of larger size aggregate can lead to internal bleeding and the

development of micro-cracks in the transition zone, resulting in lower compressive strength. It is important to note that while the use of larger-size aggregate can negatively impact high-strength concrete, its influence is reduced in lean mixes or weaker concrete. In fact, in lean mixes, a larger aggregate can result in the highest strength, while in rich mixes, it is smaller aggregates that yield higher strength (Neville, 2011) . Due to the importance of the physical properties of aggregates, and the relationship between coarse aggregate shape and concrete strength, granite coarse aggregates were divided into flaky and oversized stones, and three aggregate groups with different shape characteristics were generated. The compressive and splitting tensile strengths of the concrete were tested at different intervals with different W/C ratios. The results showed that the compressive strength of concrete with a W/C ratio of 0.33 was affected by the shape of the aggregates, due to the strength of the concrete matrix, where the strength decreased. But, this relationship was not significant with a ratio of 0.41 and 0.50. The splitting tensile strength of concrete was not significantly affected by the form of aggregate for any of the W/C ratios tested (Huang et al., 2021) 144 samples were studied, where different mixtures of steel fibers were adopted, and here was the trend to use recycled aggregates as a kind of sustainable green concrete material. Recycled coarse aggregate was used instead of 30% of natural aggregate with maximum grain sizes (9.5-19-31.5) mm. The compressive strength and tensile strength increased by splitting and the impact resistance of concrete until it reaches the highest mechanical properties with a maximum particle size of 19 mm and then decreases with the increase in the size of the coarse aggregate used. On the other hand, the addition of fibers led to an increase in all of the mechanical properties where the optimum ratios ranged between (1- 1.2%) of steel fiber in the mixture (Xia et al., 2021) The mineral composition of coarse aggregates can greatly affect the mechanical properties of concrete. By selecting specific types of high-strength coarse aggregates, such as granite the performance of the high-strength concrete can be improved. A study on the effects of using basalt and limestone coarse aggregates with diameters of 12-19 mm on both high-strength and normal concrete was investigated. It was found that the size of the coarse aggregate did not significantly impact the compressive strength, but the use of basalt aggregate increased the compressive strength in both normal and high-strength concrete. In contrast, the use of limestone aggregate only increased the compressive strength of normal concrete and had no effect on high-strength concrete. These findings highlight the importance of carefully considering the mineral

composition of coarse aggregates in the design of concrete mixes (Kozul and Darwin, 1997; Scheiden and Oneschkow, 2019). In two separate studies, the effect of coarse aggregate size on the properties of self-compacting concrete (SCC) and normal and high-strength concrete was examined. In the first study, eight concrete mixes were tested using coarse aggregate sizes of 20mm, 16mm, 12.5mm, and 10mm. The effect on the mechanical properties of the concrete was evaluated. The results showed that the compressive strength, splitting tensile strength, and flexural strength were highest at 20mm size, all strengths increased with an increase in the size of the coarse aggregate (Rao, 2010). In the second study, a similar result was also found where the effect of maximum size for coarse aggregate (MSCA) on the compressive strength of normal and high-strength concrete was examined. The American design method ACI 211.1 was used for normal concrete and ACI 211-4R for high-strength concrete. The MSCA ranged from 9.5 to 50 mm for normal-strength concrete and from 9.5 to 25 mm for high-strength concrete. The results showed that the compressive strength increased with increasing MSCA for both types of concrete, with the effect on normal concrete being greater than on high-strength concrete (Mohammed and Al-Mashhadi, 2020). In order to study the effect of the size of coarse aggregate and its effect on the nominal strength of concrete (in which all concrete components and their proportions are specified in standard specifications to achieve a certain strength, where the numbers indicate the mixing ratios "1 (cement): 2 (fine aggregate): 3 (coarse aggregate), while the number after the mixture symbol M indicates the strength of the concrete after 28 days). Maruthachalam et al. (2022) used concrete grade with mixing ratios: M7.5 (1:4:8) &(1:4:7) &(1:4:6) and M5 (1:5:10) &(1:5:9) &(1:5:8) by using 100% of 40 mm coarse aggregate. They also studied the effect of using 40% of 20 mm size aggregate and 60% of 40 mm aggregate. The results were as follows: Using 100% of 40 mm of aggregate, the mixture (1:5:8) was about 3.5 times stronger than the mixture (1:5:10). Also, the mixture (1:4:6) gave 5 times stronger results than the mixture (1:4:8). By comparing the use of 100% aggregate with the ratio (60% of 40 mm and 40% of 20 mm), there was a significant increase in the strength of concrete by 35.8% to 52.8% in the mixture and M5. However, the percentage of increase in strength in the M7.5 mixtures is much larger. The increase ranged between 174% to 287%, all of which are compared to 100% of 40 mm coarse aggregate.

1.2.2 Types of reinforcement and the bond properties between the concrete and rebar

The discovery of reinforced concrete in the mid-18th century marked the beginning of a revolution in construction. Reinforced concrete was known by various names, such as ferrous concrete, iron concrete, and new steel and concrete. Companies held patents on their products and reinforced concrete was often referred to as Hennibique, Thacher, Milan, or Mounir systems. Reinforcement in the early stages of construction used plain round or square bars with sizes ranging from ¼ inch to 1.25 inches. The strength of reinforcement has gradually increased through a better understanding of metallurgy and improved manufacturing technology. Square twisted and twisted deformed bars were strain-hardened to improve their tensile strength. In 1983, the process was changed to quenching and self-tempering to achieve improved strength, durability, and weldability. For high seismic applications, micro-alloy bars, alloyed mainly with vanadium and nickel, provide strength with improved ductility. Since its introduction, there have been significant advances in the manufacture and properties of rebar. We can see in the table the evolution of reinforcing bars with pictures.



Figure 1.1 : Evolution of reinforcing bars (Munter, 2017).

Currently, most buildings utilize ribbed reinforcement bars as they provide better bonding between the rebar and cement, resulting in improved concrete performance.

However, there are many older buildings that still exist and are currently in use, reinforced with plain rebar. As a result, it is crucial to have information about these buildings to assess their current condition and safety. This has become an increasingly pressing concern, particularly as research on plain rebar has halted due to the widespread use of ribbed rebar. Reinforced concrete structures built in the 1950s until the 1970s often employed plain round bar reinforcement, which has lower bond strength compared to the newer deformed bar reinforcement. The bond between the longitudinal reinforcement and the surrounding concrete is crucial for the overall behavior of reinforced concrete components. Old construction codes did not take into account potential issues with the bond strength and used conventional theory for flexure and shear. This can lead to discrepancies between the predicted seismic behavior of structures using plain round bars and their actual behavior. Using data from tests on structures with deformed reinforcement to assess the seismic performance of structures with plain round bars may not be accurate (Cairns, 2021; Hertanto, 2005).

Understanding the transfer of forces between the reinforcement (rebar) and concrete in reinforced concrete construction is essential for optimal design. This transfer occurs through:

1. Chemical adhesion,
2. Friction,
3. Mechanical anchorage between the deformed bars and the concrete.

Chemical adhesion and mechanical anchorage are the primary methods of force transfer after the initial slip, but friction also plays a significant role, especially between the concrete and the bar deformations (ribs). However, in old buildings, where the plain bars were used, there are no lugs but rather a smooth surface exists. Therefore, it is not possible to transfer loads and forces to the concrete surrounding these bars through mechanical interaction, and this is what the scientist Abrams (1913) showed.

- 1- Chemical adhesion between concrete and bars before slips begin to form,
- 2- Mechanical friction resulting from the wedge action between the bars and the small parts scattered when slip occurs.

These two mechanisms are affected by the Poisson effect, which reduces the contact area by expanding the tensile region around the plain bars with low allowable bond stresses, which were commonly used in North America and are still used in some regions of the world (Sahi and Al-Zuhairi, 2009; Abrams, 1913; ACI 408R-03, 2003).

As the bond between concrete and reinforcing bars is responsible for transferring and distributing loads, there are various factors that play a role in its behavior, including:

- The volume of concrete surrounding the bars, which is related to the concrete cover and bar spacing.
- The adhesion between the concrete and reinforcing elements.
- The gripping is created by the drying shrinkage of the surrounding concrete and the shear interlock between the ribs and the surrounding concrete.
- The frictional resistance to sliding and interlock when the reinforcing element is subjected to tensile stress.
- The influence of the quality and strength of the concrete in tension and compression.
- The mechanical anchorage effect of the ends of bars through development length, splicing, hooks, and crosshairs.
- The diameter, shape, and spacing of the reinforcement and their effect on crack development.

It can be challenging to individually quantify the contributions of these factors to bond strength. However, the shear interlock, shrinking forces, and quality of the concrete are generally considered significant factors.

Generally, a bond stress-slip relationship can reflect the bond behavior between reinforcement and concrete. According to ACI 408R (2003), four test methods are used to describe the bond strength-slip relationship and evaluate bond properties between steel and concrete. These methods are called i-pull-out, ii-beam end, iii-beam anchorage, and iv-beam splice. Among these methods, pull-out test is the most popular method for determining the bond properties of steel and concrete because it is practical, inexpensive, and quick. Other methods for determining bond properties do exist, but the pull-out test is the most commonly used due to its convenience (Pishro and Feng,

2018; Naway, 2009). Pull-out testing is the most commonly used due Click here to enter text. ease of fabrication and testing procedure. Various factors such as the influence of bonded length, bar shape, and size, concrete strength, and pull-out loading rate (ACI 408R, 2003; Mo and Chan, 1996), The pull-out test is a method of evaluating the bond between rebar and concrete, which can be carried out according to various standards and references. During the test, a rebar is embedded in concrete samples such prism or cylinder and subjected to a static loading rate, while a tension force is applied to pull out the rebar from the concrete. The test is performed using a confined test setup, where the reaction is applied directly to the specimen. Throughout the test, the force applied and the corresponding relative displacement between the rebar and the concrete, known as bond slip, are continuously measured and recorded. Standards and references recommend different setups, including variations in concrete specimen dimensions, bond length, rebar location, and loading rate for the pull-out test (Sadeghi and Sharma, 2019). Bond stress distribution along the length of the bar in concrete (Feldman and Bartlett, 2007), lateral loading (Zhang et al., 2016), and bonding characteristics of the plain bar in low-strength concrete (Ahmad et al., 2018) have been studied using pull-out test. There are four stages to the interaction between concrete and a bar under a pull-out force:

1. The first stage (free cracks concrete): For low bond stress value, the bond is mostly due to chemical adhesion and there is no band slip, but there is an elastic behavior as there are high local stresses occur near the ends of the ribs. Chemical adhesion is also aided by the rough surface of the steel, but overall chemical and physical adhesion play a minor role, as seen in the low bond strength of plain bars, where chemical adhesion and micro interlocking are quickly followed by bar sliding (dry friction). Also note that the relative displacement of the bar is always measured in relation to the undisturbed concrete and consists of two parts: i- The relative slip at the inner surfaces between (the rebar - concrete) and ii- The shear deformations in the concrete. Therefore, even if there is no bar slip, a certain displacement occurs owing to the localized strains close to the interface. This explains the slip at this stage.

2. The second stage (first cracking): As the bond stress increases, the role of chemical adhesion in the ribbed and plane bars ends, but it is noticed that at the ribs, the transfer of forces to the concrete and small transverse cracks begin around the ribs, which allows the bars to slide. At this stage, there is no destruction of the concrete split.

3. The third stage: With the continuation of higher bond stress values and the breakdown of chemical adhesion, the longitudinal cracks (splitting cracks) begin to spread due to the wedging action of the ribbed rebar, as this movement resists crushed concrete as it gathers in front of the ribs in the ribbed bars. This stage is described as the stage of mechanical adhesion. This mechanical resistance continues until a fracture occurs in the concrete, where the cracks reach the outer surface of the concrete, and then the sudden pull-out failure occurs.

4. The fourth stage: This applies to plain bars. This stage begins immediately following the failure of the adhesive bond. The transfer of force in this stage is primarily due to friction and is heavily influenced by transverse pressure. Factors that contribute to increased friction include concrete shrinkage and roughness on the surface of the bar. On the other hand, wear on the interface along the sliding plane results in a reduction of radial compressive stresses and ultimately a decrease in bond stress (FIB, 2010; Ernst and Sohn, 2013).

The interest in the bond between tie bars and concrete began a long time ago by engineers and experts. It is said that "Thaddeus Hayatt" conducted a test to determine this bond since 1879. He was one of the first to study this bond extensively and with different samples. Where Abrams found that there is no slip in the rod until reaching the bond stress of about 60% of the bond resistance and assumed that the distribution of the bond stress is irregular along the length of the rod. He found that the average bond stress decreases when the slip increases in the other unloaded end (Abrams, 1913).

This was confirmed by Feldman and Bartlett (2007) on bond stress in plain bars in pull-out experiments to understand how various factors such as embedment length, surface type of reinforcing bars, bar diameter, and impact bond strength. Through experiments, it was found that the maximum pull-out resistance occurs just before slip initiates at the unloaded end of the bar and that the bond resistance subsequently reduces as slip increases. Additionally, he found that bond stress magnitudes vary along the length of the bar at all applied loads, with the location of peak bond stress shifting from the loaded end toward the unloaded end as the applied load increases. He also concludes that the bond strength of plain bars is significantly lower than that of deformed rebars and that increasing the compressive strength of the concrete can improve the bond properties.

Xing et al. (2015) examined the bond behavior between reinforcing bars and concrete. Pull-out tests were conducted on six groups of specimens with plain steel bars and two groups of specimens with deformed steel bars as a reference. The main parameters examined were embedment length, surface type of reinforcing bars, and bar diameter. The results showed that the bond strength of plain steel bars was significantly lower than that of deformed bars, with an average of 18.3% of the bond stress. (Xing et al., 2015).

Mo and Chan (1996), conducted pull-out tests on short lengths of plain and deformed bars embedded in concrete, and the effects of rebar type, diameter, embedment length, concrete strength, and loading rate on bond behavior were examined. The results showed that the bond strength of plain bars was only 28.6% that of deformed bars, and the slip at failure was greater for plain bars than for deformed bars. The study also suggested that increasing the compressive strength of the concrete can improve the bond properties (Mo and Chan, 1996).

Purnomo et al. (2022) studied the bond strength of plain rebars embedded in concrete made from polypropylene plastic waste that has been coated with sand as a lightweight aggregate. The paper reports on a pull-out test of nine group specimens that were used to study the bond strength of plain rebars with diameters of 10mm, 12mm, and 16mm in the polypropylene plastic waste coarse aggregate lightweight concrete (PWCAC), failure mode, and bond stress-slip relationship. The results suggest that the bond strength and bond-slip relationship depend mainly on the bar diameter for PWCAC and the failure mode observed was a pull-out failure. The goal of the research is to investigate the potential use of recycled plastic waste as an aggregate in concrete mixtures and its effect on the bond strength between the concrete and reinforcement to reduce the building weight and have a beneficial effect on the environment (Purnomo et al., 2022)

Since there is a tendency to overcome the dissolution of reinforcing steel and the resistance of different weather conditions, three types of fiber-reinforced polymer bars (carbon-glass) covered with sand and deformed reinforcing bars were studied using different diameters (Ahmed et al., 2008). It gave results for GFRP and CFRP carbon fibers with 64% and 71% of the bond strength of reinforcing steel bars. For FRP fiber-reinforced bars, the bond stress corresponding to 0.05 mm of slippage at the free end can be considered as the design bond strength of this type of rebar. To show the

importance of stress-strain behavior, they proposed a model for normal and low-strength concrete and created a database of previous experimental studies by previous researchers. The target compressive strength values ranged between 5-52 MPa, and this data was used to generate relationships that represent the global behavior of normal and low-performance concrete. The similarity of the descending parts and the ascending parts in the stress-strain curve, and gave compatibility with the concrete in this range (Erdem and Bıkçe, 2021).

Iqbal et al. (2018), investigated the effect of maximum aggregate size on the bond strength of reinforcements in concrete. Four mixes of concrete with different maximum aggregate sizes 25.4mm, 19.05mm, 12.7mm, and 9.53mm, and similar compressive strengths were used with a bar size of 16mm. The compressive strength, splitting tensile strength, and bond strength for each concrete mix were tested and analyzed. The results showed a slight increase in compressive and splitting tensile strength with a decrease in maximum aggregate size, but the bond strength remained relatively stable except at a maximum aggregate size of 9.53mm, where a drop in bond strength was observed (Iqbal et al., 2018).

In addition, the effect of adding coarse aggregate to the concrete mixture on the shear behavior between concrete and reinforcement is also significant. In the literature, there are many models that attempt to predict the slip behavior between concrete and reinforcement. The International European Commission on Concrete (CEB) - International Federation of Structural Concrete (FIB) model code has proposed separation models for both ribbed and plain reinforcement. (Tang and Cheng, 2020) estimated the bond strength of ribbed reinforcement and proposed a model. A comparison with the CEB-FIB model and other models was also presented in the literature. On the other hand, Cairns (2021) developed a model to predict the bond strength and slip behavior between normal and concrete reinforcement. In these studies, it has been suggested that the bond strength of the models may be exaggerated or one may try to stay on the safe side to describe slip behavior.

In the experimental studies presented in this thesis, the bond strength and bond-slip behavior between the "low and moderate strength concrete mixtures with different varying coarse aggregate contents" and "plain and ribbed reinforcement" were investigated. Moreover, the mechanical (compressive strength and splitting tensile strength) and elastic and inelastic properties (modulus of elasticity, poissons ratio, and

stress-strain relations before and after the peak load) of this concrete and, also the effect of coarse aggregate concentration on these parameters, were investigated. For this purpose, 12 different mixtures with W/C of 0.60, 0.90, and 1.20 and with 4 different coarse aggregate concentrations (60%-40%-20%-0%) were produced. The total aggregate volume fraction was kept constant in all mixtures.





2. MATERIALS AND MIXTURE DESIGN

2.1 Materials Used

To produce concrete mixtures, coarse and fine aggregates, cement, and water were used.

2.1.1 Aggregates

While defining the aggregate particle size, sieves with specific dimensions are used. The particle size of the aggregate is determined by the smallest sieve through which it can pass. In this study, an aggregate mixture consisting of limestone-based crushed stone, crushed sand, and natural sand with the largest aggregate particle size of 16 mm was used. Density values of aggregates used are presented in Table 2.1. The gradation curves of the aggregates that were obtained and compared with the curves specified in the Turkish code (TS802, 2016). Although these obtained curves do not meet the standards in normal cases, we have decided to accept them based on our experience, as our goal is to simulate reality where the gradation of the aggregates was not taken into account during construction (Figure 2.1).

Table 2.1: Material density.

Material	Density (g/cm³)
Crushed Stone No.2 (CS2)	2.70
Crushed Stone No.1 (CS1)	2.69
Crushed Sand (C.Sand)	2.67
Natural Sand (NS)	2.69
Cement	3.15

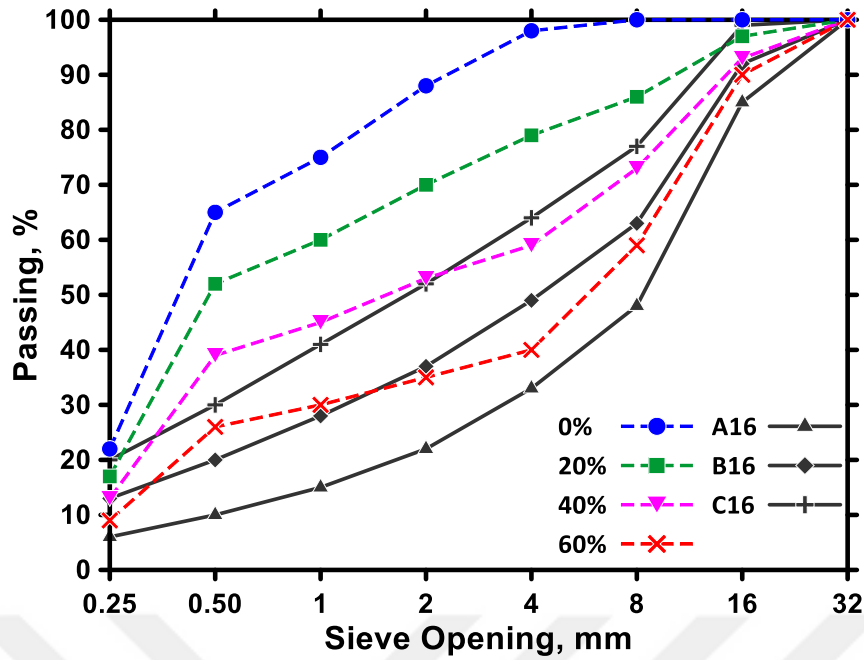


Figure 2.1: Aggregate mixture gradation curves.

Table 2.2: Sieve analyzes and mixed aggregate gradations.

Sieve Size (mm)	% passing										
	CS1	CS2	C. Sand	NS	A16	B16	C16	Mix (60%)	Mix (40%)	Mix (20%)	Mix (0%)
32	100	100	100	100	100	100	100	100	100	100	100
16	34	99	100	100	85	92	99	90	93	97	100
8	1	43	100	100	48	63	77	59	73	86	100
4	0	1	97	100	33	49	64	40	59	79	98
2	0	1	77	99	22	37	52	35	53	70	88
1	0	0	55	96	15	28	41	30	45	60	75
0.5	0	0	38	92	10	20	30	26	39	52	65
0.25	0	0	17	26	6	13	20	9	13	17	22

2.1.2 Chemical admixture

In some of the the mixtures with W/C of 1.20, a viscosity modifying admixture was used to raise the viscosity, maintain a homogeneous texture and prevent from severe segregation.

2.1.3 Cement

A commercially available Portland cement CEM I 42.5-R was used.

2.1.4 Mixing water

Standard tap water was used as mixing water.

2.2 Concrete Mixtures

To achieve the targeted low and medium-strength concrete mixes, 3 different W/C were identified in the mix design: 1.20, 0.90, and 0.60. Furthermore, in order to assess how coarse aggregate concentration impacts concrete properties and bond-slip behavior, 4 different concentrations of coarse aggregate (0%, 20%, 40%, and 60%) were used in the production of concrete mixtures for each of the aforementioned W/C (Table 2.3).

Table 2.3 Mixture properties (kg/m³).

Mixture Code	W/C	Coarse Aggr. (%)	Cement	Water	Natural Sand	Crushed Sand	Crushed Stone 1	Crushed Stone 2
					(0-2mm)	(0-4mm)	(4-12mm)	(12-20mm)
MIX1.2_%0	1.20	0	224	268	855	884	-	-
MIX 1.2_%20		20			684	708	271	90
MIX 1.2_%40		40			513	531	542	181
MIX 1.2_%60		60			342	354	813	271
MIX 0.9_%0	0.90	0	279	251	855	884	-	-
MIX 0.9_%20		20			684	708	271	90
MIX 0.9_%40		40			513	531	542	181
MIX 0.9_%60		60			342	354	813	271
MIX 0.6_%0	0.60	0	370	222	855	884	-	-
MIX 0.6_%20		20			684	708	271	90
MIX 0.6_%40		40			513	531	542	180
MIX 0.6_%60		60			342	354	813	271

As seen in Fig. 2.2, although the W/C changed, the aggregate amounts in the mixture did not change for each coarse aggregate concentration. In other words, the total aggregate volume and the volume of the paste phase were kept constant in all mixtures. Thus, it is aimed to determine the effect of increasing coarse aggregate concentration in the mixture on concrete properties without changing the volume and properties of the paste phase in each mixture group.

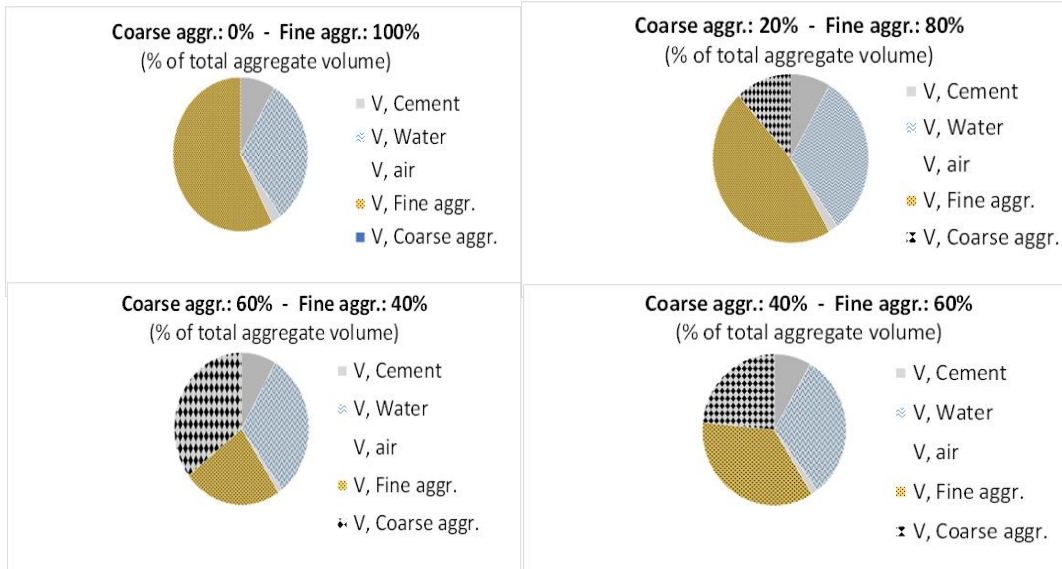


Figure 2.2: Coarse aggregate concentration of total aggregate volume.

2.3 Concrete Production

A mixer with a capacity of 50 dm³ in Istanbul Technical University, Civil Engineering Faculty, Construction Materials Laboratory was used for concrete production. A total of 12 different concretes mixtures were produced based on three different W/C (1.20, 0.90 and 0.60) for 4 coarse aggregate (CA) concentrations. The codes of the produced samples are given in Table 2.4.

Table 2.4: Coding of samples.

Mixture Code	Description of the Code
MIX1.2_%0	W/C =1.2 and CA concentration 0%
MIX 1.2_%20	W/C =1.2 and CA concentration 20%
MIX 1.2_%40	W/C =1.2 and CA concentration 40%
MIX 1.2_%60	W/C =1.2 and CA concentration 60%
MIX 0.9_%0	W/C =0.9 and CA concentration 0%
MIX 0.9_%20	W/C =0.9 and CA concentration 20%
MIX 0.9_%40	W/C =0.9 and CA concentration 40%
MIX 0.9_%60	W/C =0.9 and CA concentration 60%
MIX 0.6_%0	W/C =0.6 and CA concentration 0%
MIX 0.6_%20	W/C =0.6 and CA concentration 20%
MIX 0.6_%40	W/C =0.6 and CA concentration 40%
MIX 0.6_%60	W/C =0.6 and CA concentration 60%

These productions were repeated several times according to the number of samples to be used in the experiments. From each mixture, 4 cubes (15 cm³) with plain reinforcement, 4 cubes (15 cm³) with ribbed reinforcement and 10 cylindrical samples (10x20 cm) were produced. In total, experiments were carried out on 96 cube samples

and 120 cylindrical samples. All of the samples were cured in lime saturated water at $22\pm 2^{\circ}\text{C}$ until the test days. At the end of 28 days, pull-out, compressive strength, split-tensile strength and displacement-controlled uniaxial compressive strength tests were applied to these samples.





3. TESTS AND EXPERIMENTAL METHODS

3.1 Compressive Strength Test

In order to determine the mechanical properties, 4 of 10 cylindrical samples produced from each mixture with a diameter of 100 mm and a height of 200 mm were used for this experiment. The samples were cured in saturated lime water at $22\pm 2^{\circ}\text{C}$ until the 28th day. Both surfaces of the samples arriving on the test day were abraded by the Utest brand automatic surface abrasion device and the samples were made ready for the test. In order to obtain the compressive strength of the concrete, Load-controlled pressure test (loading speed 5 kN/s) applied in accordance with TS EN 12390-3 standard on 3 samples using Besmak brand 3000 kN capacity pressure device.

3.2 Displacement Controlled Uniaxial Compression Test

In order to determine the elasticity modulus and Poisson's ratio values and to obtain the stress-strain graph before and after the peak load, 4 out of 10 cylinder samples of 100 mm diameter and 200 mm height produced from each mixture were used for this test. The samples were cured in saturated lime water at $22\pm 2^{\circ}\text{C}$ until the test days. The tests were done on the 28th day. A displacement-controlled pressure test was performed using an Instron brand 5000 kN pressure device (loading speed $0.75 \mu\text{ε}/\text{min}$). During the displacement controlled experiments, 2 different independent frames were attached to the samples in accordance with the ASTM C469 standard. Longitudinal and lateral deformation values were recorded automatically by the device by means of linear variable differential transformers (LVDT) connected to these frames. The experimental system is given in Figure 3.1.

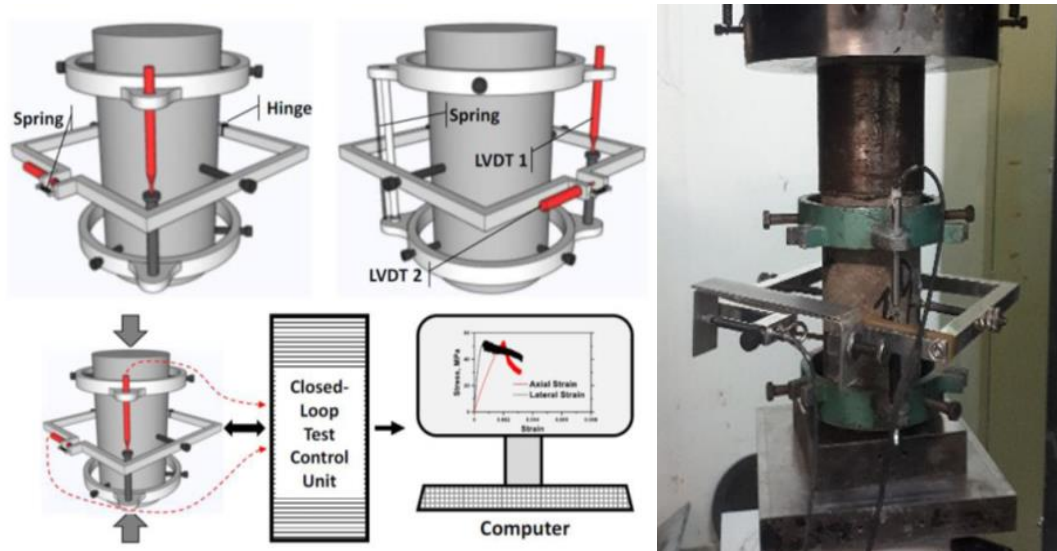


Figure 3.1: The displacement controlled uniaxial compression test system.

3.3 Splitting Tensile Test

Two cylinder samples produced from each mixture were used for this experiment. After the samples were kept in curing pools for 28 days, the test was applied. Before the experiment, the cylinders were divided into two, 100 mm in diameter and 100 mm in height. Thus, 4 samples were obtained for a mixture. The experiments were carried out in accordance with TS EN 12390-6 standard using an uniaxial pressure device, which was also used in the pressure test. The loading rate was set to 1 kN/s for this experiment

3.4 Pull-Out Test

12 different concrete mixtures prepared to determine the bond-slip properties between concrete and reinforcement were placed in specially designed molds (Figure 3.2). In this formwork system, the reinforcements (plain and ribbed) are pre-fixed. Thus, samples with a size of 15 cm³ and with reinforcement in the middle were obtained. From each mixture, 4 plain-reinforced cubes and 4 rib-reinforced cubes were obtained. Pull-out test was carried out on 96 cube samples in total.



Figure 3.2: Photos showing the used molds.

The diameter of the reinforcement used is 12 mm. According to the studies in the literature, the embedment length was chosen as 60 mm (5ϕ) for the optimum value. To ensure a 60 mm embedment length, 90 mm of the reinforcement in the concrete is covered with plastic hoses. The destruction of the concrete-reinforcement contact of the area outside the adherence length in this way prevented sudden cracking or splitting of the concrete and provided more accurate data at the time of slip. In addition, the mechanical properties of plain and ribbed reinforcement are shown in Table 3.1

Table 3.1: Mechanical properties of the reinforcing steel used in the tests.

Specimen	Nominal Diameter (mm)	Average Yield Strength MPa (St. Deviation)	Average Tensile Strength MPa (St. Deviation)	Average Displacement % (St. Deviation)
Plain	12	288 (1.9)	403 (1.4)	45 (0.3)
Ribbed	12	476 (19.0)	609 (10.9)	29 (1.5)

The rib spacing was measured as 6 mm and the rib pitch angle was 45° . The samples were removed from the mold 24 hours after casting and kept in curing tanks for 28 days. Pull-out tests were performed on the samples produced for both plain and ribbed rebar.

A specially designed frame shown in Figure 3.3 was used with a displacement-controlled tensile test machine to conduct the bond-slip test. A layer of rubber was added between the sample and the metal frame to ensure an even distribution of the load and prevent stress concentration. A load cell with a capacity of 100 kN was attached to the frame to measure the load, while a linear variable differential transformer (LVDT) was placed at the free end of the rebar to track its displacement in relation to the concrete and collect slip values.

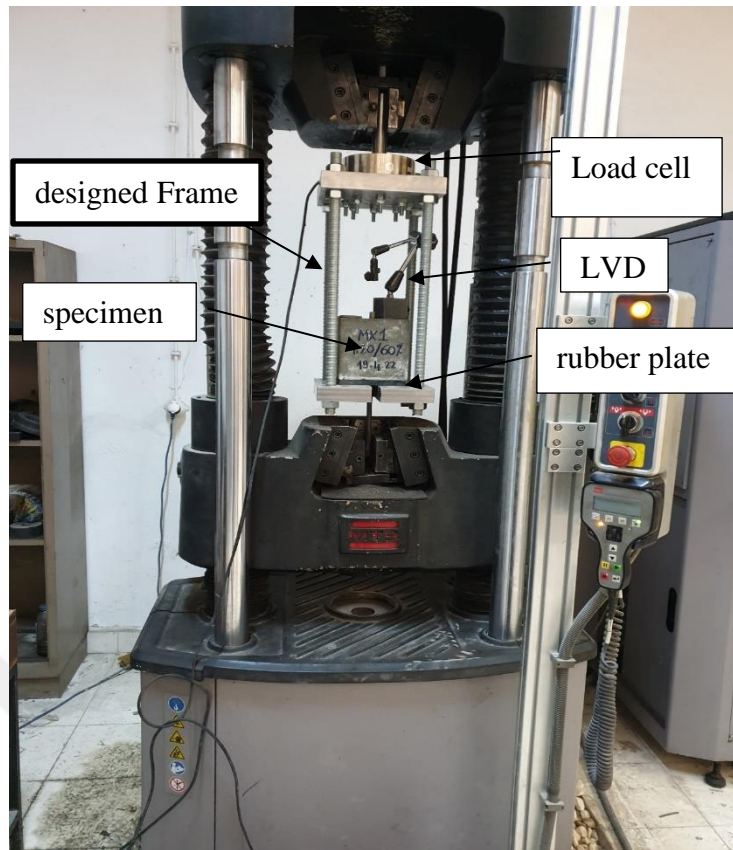


Figure 3.3: System for pull-out test.

In both types of reinforcement, the slip of reinforcement occurred in the form of pure stress. Therefore, splitting did not occur in the concrete cube samples. The bond strength was calculated according to the obtained load-displacement relationship. Bond strength values were found using the formula 3.1. P , d , and l in this equation correspond to the maximum load (N), the diameter of the reinforcement (mm), and the embedded length of the reinforcement (mm), respectively.

$$\tau = P_{max}/(\pi dl) \quad (3.1)$$

4. TEST RESULTS

In this chapter; compressive strength, splitting-tensile strength, modulus of elasticity, Poissons's ratio and bond-slip values of the reinforcements in the concrete sample are presented in tables.

4.1 Compressive Strength Test Results

Two different compressive tests were carried out within the scope of the study, namely displacement-controlled and load-controlled. The average results of the compressive strength test applied to 8 (120 samples in total) out of 10 cylinders produced for each mixture are shown in Table 4.1 with their standard deviations.

Table 4.1: Compressive strength test results for 28 days (displacement-controlled and load-controlled).

Mixture Code	Compressive Strength- Displacement Controlled MPa (St. Deviation)	Compressive Strength- Load Controlled MPa (St. Deviation)
MIX 1.2_%0	9.9 (0.53)	11.1 (0.54)
MIX 1.2_%20	11.1 (0.64)	12.6 (0.46)
MIX 1.2_%40	11.2 (0.72)	12.7 (0.74)
MIX 1.2_%60	8.9 (1.65)	7.9 (1.96)
MIX 0.9_%0	16.6 (0.97)	18.2 (0,55)
MIX 0.9_%20	19.5 (0.47)	20.8 (0,57)
MIX 0.9_%40	20.1 (0.36)	23.4 (1,63)
MIX 0.9_%60	18.5 (0.29)	22.5 (1,77)
MIX 0.6_%0	21.5 (0.22)	22.8 (0.42)
MIX 0.6_%20	35.9 (0.55)	38.8 (0.92)
MIX 0.6_%40	34.9 (0.63)	38.8 (0.59)
MIX 0.6_%60	35.1 (1.25)	38.3 (1.09)

4.2 Results of Modulus of Elasticity and Poisson's Ratio

The elastic modulus values obtained from the results of the displacement-controlled uniaxial compression test (applied to 4 cylinders in each mixture and 48 samples in total), the mean value of the Poisson ratios, with their standard deviations, are shown in Table 4.2 and Table 4.3.

Table 4.2: Modulus of elasticity values for 28 days.

Mixture Code	Modulus of Elasticity, GPa (St. Deviation)
MIX 1.2_ %0	13.15 (0.77)
MIX 1.2_ %20	15.78 (0.79)
MIX 1.2_ %40	15.45 (0.80)
MIX 1.2_ %60	17.66 (0.09)
MIX 0.9_ %0	17.49 (0.42)
MIX 0.9_ %20	19.74 (1.13)
MIX 0.9_ %40	20.14 (1.10)
MIX 0.9_ %60	20,21 (1.20)
MIX 0.6_ %0	21.31 (1.23)
MIX 0.6_ %20	24.93 (1.37)
MIX 0.6_ %40	25.80 (1.51)
MIX 0.6_ %60	27.00 (1.39)

Table 4.3: Poisson's ratio values for 28 days.

Mixture Code	Poisson Ratio, (St. Deviation)
MIX 1.2_ %0	0.20 (0.019)
MIX 1.2_ %20	0.21 (0.011)
MIX 1.2_ %40	0.20 (0.023)
MIX 1.2_ %60	0.20 (0.015)
MIX 0.9_ %0	0.21 (0.009)
MIX 0.9_ %20	0.21 (0.022)
MIX 0.9_ %40	0.19 (0.021)
MIX 0.9_ %60	0.19 (0.012)
MIX 0.6_ %0	0.22 (0.011)
MIX 0.6_ %20	0.22 (0.023)
MIX 0.6_ %40	0.22 (0.028)
MIX 0.6_ %60	0.22 (0.017)

4.3 Splitting Tensile Test Results

The average test results of the splitting tensile test applied to the remaining samples are shown in Table 4.4, together with their standard deviations. For this test, two cylindrical samples were cut to obtain four 10 cm diameter and 10 cm height samples. The results presented in Table 4.4 are represents the average of 4 test results for each mixture.

4.4 Pull-Out Test Results

In this experiment, 8 cubic samples (96 samples in total) produced for each mixture were used. Half of these samples have plain reinforcement and half have ribbed

reinforcement. The samples were kept in curing pools for 28 days. During the experiment, the force was applied to the samples until the reinforcements were displaced 10 mm in the concrete. The bond (adherence) strength values obtained as a result of the pull-out test are given in Table 4.5 for both rebar type, with their standard deviations.

Table 4.4: Test results for splitting tensile strength for 28 days.

Mixture Code	Splitting Tensile Strength, MPa (St. Deviation)
MIX 1.2_%0	1.61 (0.19)
MIX 1.2_%20	1.79 (0.33)
MIX 1.2_%40	1.86 (0.28)
MIX 1.2_%60	1.84 (0.16)
MIX 0.9_%0	2.30 (0.23)
MIX 0.9_%20	2.68 (0.21)
MIX 0.9_%40	3.02 (0.36)
MIX 0.9_%60	2.93 (0.27)
MIX 0.6_%0	2.52 (0.14)
MIX 0.6_%20	3.64 (0.11)
MIX 0.6_%40	3.66 (0.19)
MIX 0.6_%60	3.90 (0.35)

Table 4.5: Bond strength between reinforcement and concrete.

Mixture Code	Bond Strength (MPa)	St. Dev.	Bond Strength (MPa)	St. Dev.
	Ribbed Rebar		Plain Rebar	
MIX 1.2_%0	6.30	0.14	3.45	0.10
MIX 1.2_%20	7.43	0.20	3.95	0.28
MIX 1.2_%40	6.92	0.53	4.52	0.46
MIX 1.2_%60	6.38	0.44	4.20	0.44
MIX 0.9_%0	8.52	0.46	3.46	0.07
MIX 0.9_%20	10.51	0.45	4.44	0.27
MIX 0.9_%40	12.99	0.43	5.10	0.60
MIX 0.9_%60	12.10	1.00	5.08	0.21
MIX 0.6_%0	17.70	1.05	5.39	0.30
MIX 0.6_%20	20.93	0.82	5.76	0.45
MIX 0.6_%40	20.52	1.33	5.82	0.32
MIX 0.6_%60	21.07	0.52	5.48	0.45



5. EVALUATION OF TEST RESULTS

In this chapter; compressive strength, splitting tensile strength, modulus of elasticity, Poisson's ratio, bond strength of concrete mixtures and bond-slip behavior of the reinforcements in the concrete sample are reported and the results are discussed.

5.1 Discussion of the Compressive Strength Test Results

Compressive strength values for all mixtures are shown in Table 4.1. As mentioned earlier in section 3, two different compression tests were carried out within the scope of the study, namely displacement-controlled and load-controlled. The compressive strength values were obtained from the load-controlled compression test in accordance with the standard method. The average compressive strength values obtained from the displacement-controlled test are also shared in Table 4.1.

When the compressive strength results given in Table 4.1 are examined, it is seen that the compressive strength values obtained from the load-controlled test (except for the MIX1,2_60% mixture) are between 6% and 18% lower than those obtained from the displacement-controlled compression test. This is due to the fact that the loading rate in the displacement-controlled experiment is significantly slower, and the experimental control mechanism operates based on the displacement per unit time. Therefore, although the results obtained from the load-controlled test are taken into account as compressive strength, the values obtained from the displacement-controlled test are used in the calculations in the section where concrete behavior is discussed.

Compressive strength test results are also presented in Fig. 5.1 as bar graphs. By looking at Fig. 5.1 in general, it is seen that compressive strength increases with increasing concentration of coarse aggregate by up to 40% in all mixtures with different W/C ratios.

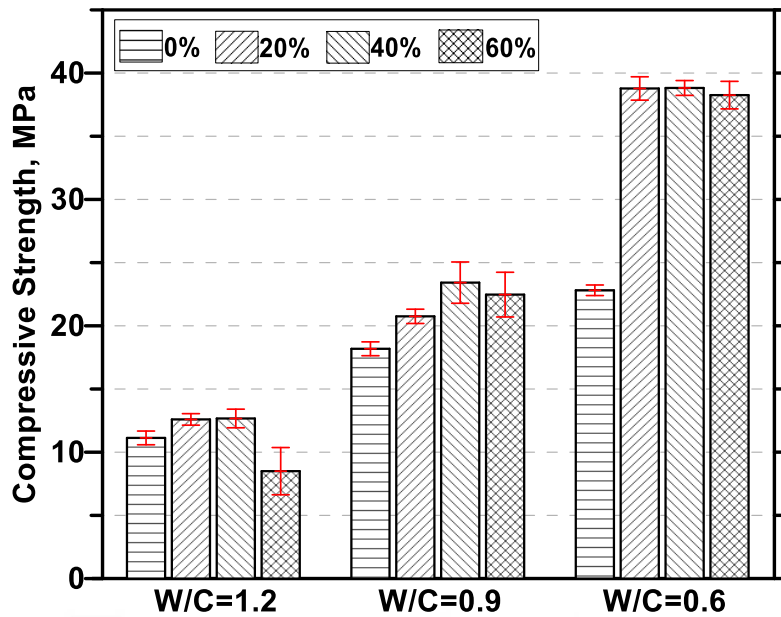


Figure 5.1: Compressive strength results (*error bars indicate ± 1 standard dev.*).

However, at a concentration of 60% coarse aggregate, it is seen that the compressive strength tends to decrease compared to mixtures containing 40% aggregate, and this trend becomes more significant with the increase of the W/C ratio. The W/C ratio plays a major role in determining the mechanical properties of concrete. This ratio controls the microstructure of the ITZ and its thickness. The strength of the material is primarily determined by the paste and its connection with the coarse aggregate. The coarse aggregate is the strongest phase, but its effect on strength is limited as microcracks tend to form in the weaker interfacial transition zone during load transfer, which can lead to concrete failure (Elsharief et al., 2003; Vishalakshi et al., 2018). So, for the 1.2 W/C ratio, the compressive strength of the mixture with 60% coarse aggregate concentration was obtained lower than the mixture with 0% coarse aggregate concentration. At 1.2 W/C ratio, the results obtained from the 20% and 40% mixtures are higher by 13.2% and 13.8%, respectively, compared to the mixture containing 0% coarse aggregate concentration, while the compressive strength for the 60% mixture is % 23.6 percent lower when these results are examined. It can be said that, the aggregate-paste interface is very weak due to the very low adhesive phase strength in the mixtures with a ratio of 1.2 W/C and, as a consequence, the larger capillary area and micro internal bleeding occurs in the concrete. For this reason, despite the increased utilization rate, no significant effect of coarse aggregate on compressive strength was observed.

In addition, during the concrete production stage, the tendency to decompose gradually increased as the concentration of coarse aggregates in the mixtures increased for 1.2 W/C ratio. Also, partial decomposition was observed especially in the 60% mixture.

The increase in the concentration of coarse aggregates in the mixture, leads to a decrease in the specific surface area for the development of continuous gel bonds from the originally weak putty at 1.2 W/C ratio, and this undoubtedly affected negatively the compressive strength. In order to obtain the effect of increasing the concentration of coarse aggregate on the compressive strength, we note that in the mixture W/C = 0.9 when comparing mixtures that contain concentrations of 20%, 40%, and 60% with the same mixture that contains a concentration of 0% of coarse aggregate, we find that the rate of increase in compressive strength was 14.1%, 28.8%, and 23.6%, respectively. As for the mixture with W/C=0.60, and by conducting the same comparison between mixtures of 20%, 40%, and 60% with the mixture containing 0% concentration, the increase in compressive strength was 70.0%, 70.2%, and 67.7%. %, respectively, When these results are examined, it can be seen that the strength of the paste phase has increased even further with a decreasing W/C ratio compared to mixtures with a W/C ratio of 1.2. Along with the improvement of interfacial properties, the effect of coarse aggregate on compressive strength values has become more pronounced. On the other hand, if the compressive strength values for each concentration of coarse aggregate are compared with 1.2 W/C ratio; for the W/C =0.9, the compressive strength values for 0%, 20%, 40%, and 60% coarse aggregate concentrations are respectively 63%, 65%, 85%, and 164% higher. For W/C=0.6, these increase rates were obtained as 105%, 208%, 206%, and 350%, respectively. These results clearly show that compressive strength values increase much more significantly with decreasing W/C ratio and increasing coarse aggregate concentration. The reason of that is the decrease in the void ratio of the paste phase which has constant volume and increase of mechanical properties with a decreasing W/C ratio, which leads to an increase in its strength. This increase in the strength of the paste phase improved the interfacial properties between the cement paste and the aggregate, making the transfer of load to the aggregate more effective. Thus, an increase in the concentration of coarse aggregate resulted in higher compressive strength values for lower W/C ratio.

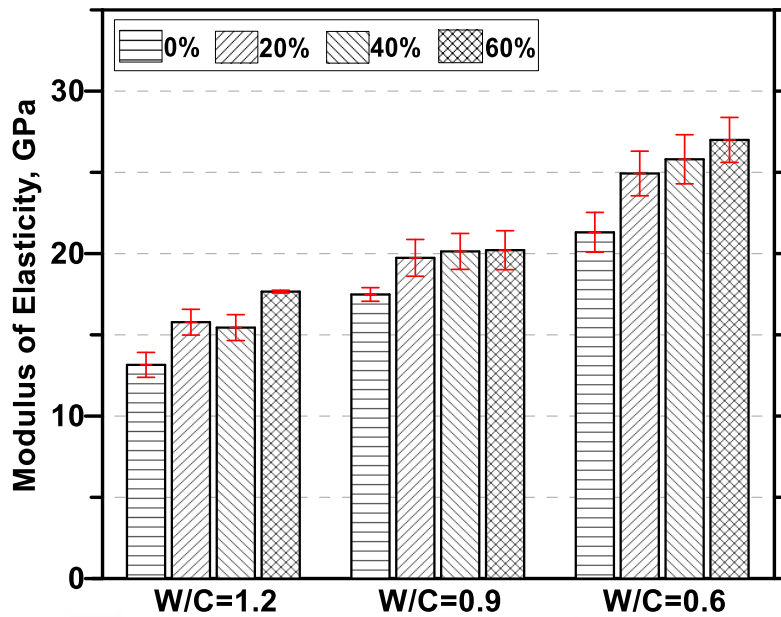


Figure 5.2: Modulus of elasticity (*error bars indicate ± 1 standard dev.*).

Fig. 5.2 presents the modulus of elasticity test results. Upon general examination of the graph provided in Fig. 5.2, it can be seen that there is a trend where the modulus of elasticity values increase with an increasing concentration of coarse aggregates even with the 60% coarse aggregate, which is different from the results obtained for compressive strength. It was previously noted that mixtures with a 60% concentration of coarse aggregates resulted in lower levels of compressive strength compared to mixtures with a 40% concentration. However, it can be observed that the mixtures with a 60% concentration of coarse aggregates had the highest modulus of elasticity values.

The percentage increase in modulus of elasticity values obtained from mixtures containing 20%, 40%, and 60% coarse aggregate concentrations, compared to mixtures with 0% coarse aggregate concentration, were 20.0%, 17.4%, and 34.3%, respectively for mixtures with a 1.2 W/C ratio; 12.9%, 15.2%, and 15.6%, respectively for mixtures with a 0.9 W/C ratio, and 17.0%, 21.1%, and 26.7%, respectively for mixtures with a 0.6 W/C ratio. Upon examination of the graph presented in Figure 5.2, it can be seen that increasing the concentration of coarse aggregates from 0% to 20% in low or medium-strength concrete mixtures led to a significant increase in the modulus of elasticity. On the other hand, increasing the concentration of coarse aggregates from 20% to 40% and 60% did not have a significant effect on mixtures with a 1.2 and 0.9 W/C ratio (it is thought that the increase in mix1.2_%60 mixture was due to interlocking of aggregates caused by segregation that has been mentioned before), while the modulus of elasticity values increased with an increasing

concentration of coarse aggregates in mixtures with a 0.6 W/C ratio. This is attributed to the increase in strength and compaction of the paste phase, which improves the interfacial properties between the aggregate and paste, and therefore, provides more efficient load transfer between the paste phase and the aggregates. In other words, the presence and quantity of the most rigid particles in the mixture, which are the coarse aggregates, positively affect the elastic modulus of the composite (concrete). Consequently, increasing the concentration of coarse aggregates results in an increase in the modulus of elasticity values.

5.2 Discussion of Displacement-Controlled Uniaxial Compression Test Results

When uni-axial load was applied to the cylindrical specimens, cracks spread significantly in both the matrix and aggregate-matrix interface regions after a certain stress limit. These cracks are affected by the transverse and longitudinal displacements that occur in the sample. Therefore, the absolute ratio of the transverse unit elongation to the longitudinal unit contraction that occurs when the concrete specimens are subjected to compressive stresses in the elastic range was calculated using the data obtained from the test. This ratio is Poisson's ratio. When the Poisson's ratios given in Table 4.3 are examined, it is seen that there is no significant change with the addition of coarse aggregate to the mixture. The Poisson's ratio values are equal to 0.20 in all the mixtures with a 1.20 W/C ratio. It is seen that it is in the range of 0.19-0.21 in mixtures with W/C ratio, and it is equal to 0.22 in mixtures with a 0.60 W/C ratio. This study showed that the coarse aggregate with different ratios in the mixtures did not affect Poisson's ratio.

In order to determine how the behavior of low and medium-strength concrete changes under compressive load with increasing coarse aggregate concentration, loading was continued after peak load for the specimens produced within the scope of the study. The "stress (σ) - strain (ϵ)" and "normalized stress (σ/σ_{\max}) - normalized strain (ϵ/ϵ_{cu})" curves obtained from these experiments are given in Figure 5.3.

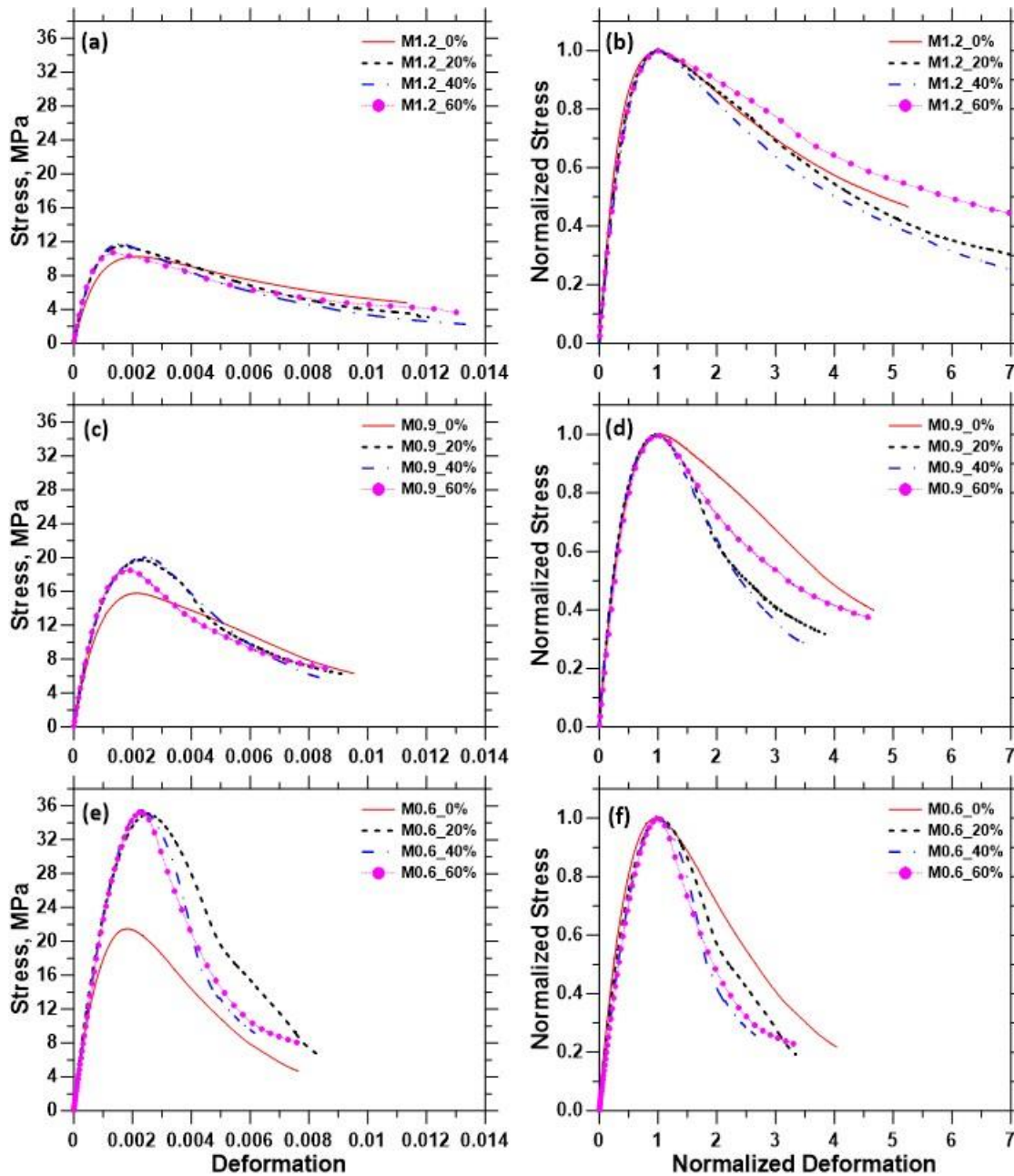


Figure 5.3: Sample stress-strain (left column) and normalized stress-normalized strain curves (right column) of mixtures.

Normalized stress values were obtained by normalizing each stress data to the maximum stress (σ_{max}), and normalized strain values were obtained by normalizing each strain data to the strain value corresponding to the maximum stress (ϵ_{cu}). Firstly, looking at the stress-strain curves given in the left column of Figure 5.3, there is no significant change in the descending branch curves after adding coarse aggregate to the mixes with a 1.2 W/C ratio after peak load, but a significant increase in the descending branch slope is observed in the mixes with 0.6 and 0.9 W/C ratios. These changes can be observed more clearly in the normalized stress-normalized strain

curves given in the right column of Figure 5.3. When the curves in Figure 3(b) are examined, the lowest descending branch slope belongs to the mix1.2_%60 mix, while the highest descending branch slope is obtained from the mix1.2_%40 mix. The descending branch curves of the other two mixes are very similar to each other.

When the graph in Figure 5.3(d), representing the 0.9 W/C ratio mixes is examined, it can be seen that the lowest descending branch slope belongs to the mix containing 0% coarse aggregate, followed by the Mix0.9_%60, and the steepest dropping branch curves are obtained from the Mix0.9_%20 and Mix0.9_%40 mixes, which are very similar to each other. When the curves of the mixes with 0.6 W/C ratio are examined, it can be seen that the lowest descending branch slope also belongs to the mix containing 0% coarse aggregate, and the difference between the descending branch slopes of the other mixes decreases and becomes closer to each other. As a result of this study, it has been determined that increasing the coarse aggregate concentration does not create a significant difference in the behavior of concrete with very low compressive strength, but it loosens the behavior of concrete as the compressive strength increases.

5.3 Discussion of the Results of Splitting Tensile Test

The results of the splitting-tensile test, which was conducted on four samples (100 mm diameter and height) for each mixture cured for only 28 days, are presented in Figure 5.4. When the results obtained for both W/C concrete groups are examined, it is observed that the splitting tensile strengths increased with the addition of coarse aggregate to the mixture. However, the increase in splitting tensile strength was more prominent as the W/C ratio decreased, similar to the compressive strength results. Compared to mixtures containing 0% coarse aggregate, mixtures with 20%, 40%, and 60% coarse aggregate concentrations showed increase rates of 11.0%, 15.5%, 14% for 1.2 W/C ratio; 16.5%, 31.2%, 27.3% for 0.9 W/C ratio, and 44.5%, 45.4%, and 54.8% for 0.6 W/C ratio.

Furthermore, based on the data provided in Tables 4.1 and 4.4, the ratio of splitting tensile strength values to compressive strength was calculated. These ratios in the range of 0.142-0.147, 0.126-0.130, and 0.094-0.110 for 1.2, 0.9, and 0.6 W/C ratios, respectively. The calculations revealed that the ratio of splitting tensile strength to compressive strength decreased as the compressive strength increased, indicating an increase in the brittleness of concrete. Upon examining the effect of coarse aggregate

concentration on the tensile/compressive strength ratio, it was found that there was no significant effect in concretes with 1.2 and 0.9 W/C ratios. However, for mixtures with 0.6 W/C ratios and approximately 20% and 40% coarse aggregate concentration, there was a decrease of 15%.

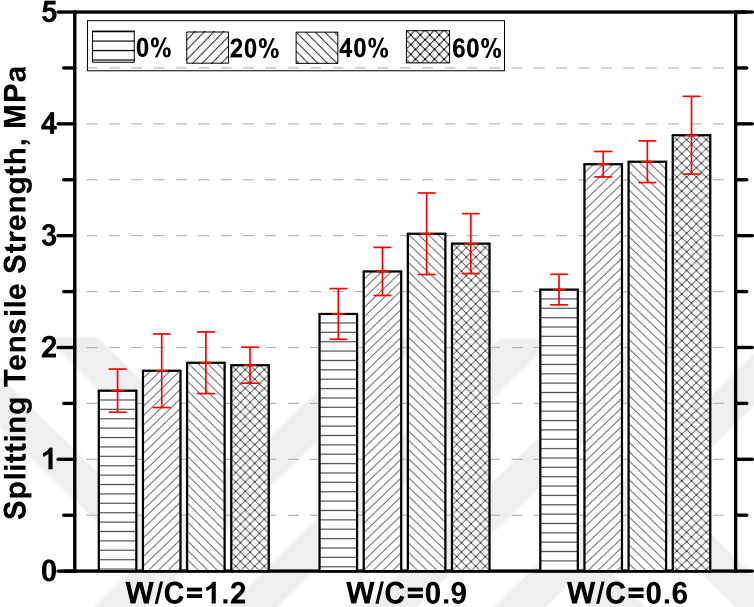


Figure 5.4 : Splitting tensile strength results (*error bars indicate ± 1 standard dev.*).

5.4 Discussion of the Results of Pull-Out Experiment

As mentioned earlier in section 3, 4 plain reinforced cubes and 4 ribbed reinforced cubes were produced from each of the 12 mixtures. The embedded length was equal to 60 mm which is equivalent to $5 \times \phi$ recommended by (RILEM, 1970). These samples were cured for 28 days. A total of 96 cubes were subjected to a pull-out experiment. As a result of the experiment, load and corresponding displacement data were obtained. Based on these data the average bond strength was calculated. In this experiment, any concrete splitting was not observed during the pullout test due to the low-strength concrete produced. In this section, the results of bond strength will be discussed.

5.4.1 Evaluation of the bond strength between concrete and reinforcement

The bond strength values between concrete and reinforcement are given in Table 4.5 for both ribbed and plain rebars. The graph obtained based on these results is shown in Figure 5.5. Bond strengths were obtained using the formula given in 3.1.

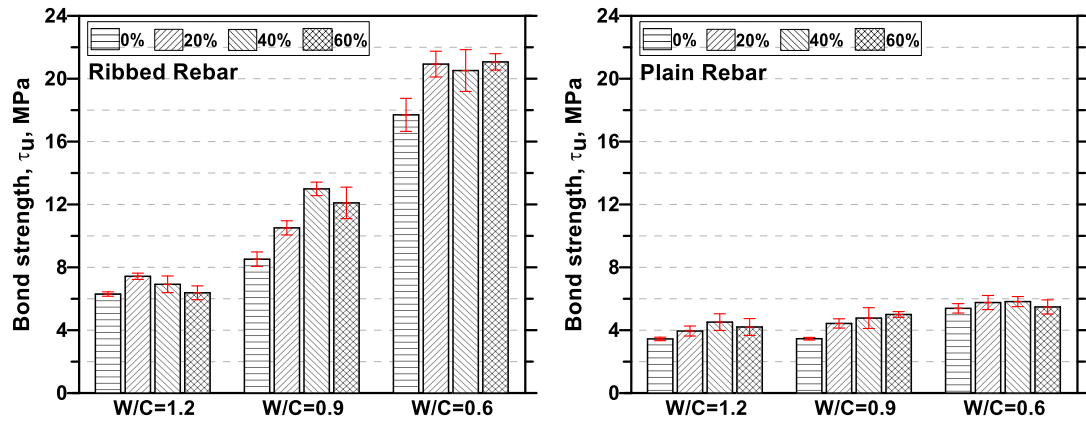


Figure 5.5 : Bond strength results of plain (left) and ribbed (right) rebar embedded mixtures (*error bars indicate ± 1 standard dev.*).

Comparative pull-out testing on plain and deformed reinforcing bars can provide insight into the relative bond strength of the two types of reinforcing steel and the different mixtures. Based on the test conditions presented in this study and when the graphs are examined, the bond strength of plain rebars was clearly lower than that of the ribbed rebars. The results will appear in detail with the study of the various factors affecting the bond strength.

5.4.1.1 Influence of the shape of the reinforcement used in the experiment

The bond strength developed by the ribbed rebars is higher than the one developed by plain rebars, that range between (3.40 to 5.82 MPa) for plain rebars and (6.30 to 21.07 MPa) for ribbed rebars. This is consistent with the references (Sahi and Al-Zuhairi, 2009; Abrams, 1913; ACI 408R-03, 2003). The initial chemical adhesion occurs concurrently with the micromechanical interaction that arises from the microscopic roughness of the steel surface (friction) for both types of rebars. On the other hand, the mechanical anchorage between the ribbed rebars and the concrete, assuming all other properties remain unchanged, the two phenomena, chemical adhesion and mechanical interaction, work together in a synergistic manner. They complement and enhance each other, resulting in stronger adhesion between the two surfaces (rebars and concrete). For this reason, it requires more force to slide off the concrete.

5.4.1.2 Influence of the water to cement ratio

In this experiment, three different W/C ratios were selected to simulate the worst concrete mixture that could be poured on-site. The graphs showed that the bond strength values of mixtures with a W/C ratio of 0.60 were higher than those with other dosages for both types of rebars. This improvement can be attributed to the concrete's

denser structure and reduced porosity resulting from a decrease in the W/C ratio, which positively affects the adherence between concrete and reinforcement. This corresponds to the literature (Elsharief et al., 2003; Vishalakshi et al., 2018). The W/C ratio plays a crucial role in determining the mechanical properties of concrete, especially in normal and low-strength concrete with high W/C ratios. This ratio controls the microstructure of the ITZ and its thickness, where the strength of the material is primarily determined by the mortar and its connection with the coarse aggregate. The coarse aggregate is the strongest phase, but its effect on strength is limited because micro-cracks tend to form in the weaker interfacial transition zone during load transfer, leading to concrete failure and a decrease in bonding strength.

On the other hand, when the W/C ratio is decreased, the properties of the mortar and the bonding of mortar in the ITZ are improved. This effect is evident in the rise in bond strength values for W/C ratios of 0.9-0.6 compared to a W/C ratio of 1.2.

5.4.1.3 The influence of coarse aggregate concentration

Upon examining Figure 5.1 and closely observing the compressive strength behavior, it was found that the bond strength tends to act in the same manner, increasing with an increase in the concentration of coarse aggregate, as mentioned by Chan (1996). This confirms the relationship between compressive strength and bond strength. This behavior can be attributed to plain rebars, as the bond strength is not affected by the additional mechanical interlock present in ribbed rebars that friction with coarse aggregate. In plain rebars, it is found for the 1.2 W/C ratio that, the bond strength increased with an increase in coarse aggregate concentration up to 40%, where the bond strength peaked at 4.24 MPa. However, at a concentration of 60%, the bond strength decreased slightly to 4.09 MPa. For the 0.9 W/C ratio, the highest bond strength was observed as 5.06 MPa at a concentration of 60% coarse aggregate. However, at lower concentrations (0%, 20%, and 40%), the bond strength varied, with a peak at 4.83 MPa for 40% concentration. For the 0.6 W/C ratio, the bond strength did not show a clear trend with changing coarse aggregate concentration, the highest bond strength observed as 5.82 MPa at a concentration of 40%. However, the bond strength for all concentrations tested (0%, 20%, 40%, and 60%) was relatively similar. On another hand, for the ribbed rebars, it is found that, the bond strength results higher than plain rebars due to the additional mechanical interlock so the results show the following: For the 1.2 W/C ratio, the highest bond strength was observed at a value of

7.43 MPa for 20% concentration of coarse aggregate. However, at higher concentrations (40% and 60%), the bond strength decreased slightly, with values of 6.92 MPa and 6.38 MPa, respectively. For the 0.9 W/C ratio, the highest bond strength was observed at the value of 12.98 MPa for 40% concentration of coarse aggregate. Again, at higher concentration (60%), the bond strength decreased slightly, with a value of 11.70 MPa. For the 0.6 W/C ratio, the highest bond strength was observed as 21.1 MPa for 60% concentration of coarse aggregate. However, at a concentration of 20%, the bond strength was considerably lower as 20.9 MPa, suggesting a non-linear relationship between bond strength and coarse aggregate concentration. In general, for all three ratios of W/C tested (1.2, 0.9, and 0.6), an increase in coarse aggregate concentration resulted in an increase in bond strength, with some variation between concentrations.

5.4.2 Evaluation bond-slip behavior between concrete and reinforcement

One of the ways to evaluate bond behavior is to apply pull-out tests, which provide information on the overall relationship between average bond stress and slip. This relationship is influenced by both the properties of the concrete and the geometry of the reinforcing bars (Leibovich, 2022). Fig 5.6 and 5.7 illustrates the average bond stress-slip curves for W/C ratios of 0.6, 0.9 and 1.2.

When analyzing the graph for 1.20 W/C ratio with ribbed rebars, it can be seen that the bond stress initially increases with increasing slip until it reaches a peak. After that, there is a plateau region where the bond stress remains relatively constant. As the slip continues to increase, the bond stress decreases gradually. That is because after the bond stress reaches its peak, the role of chemical adhesion (which is weak due to the high W/C ratio) diminishes whereas mechanical friction persists and the curve shows a slow decline after the peak.

The graph (W/C=1.2) shows that, as the concentration of coarse aggregate increases, there is a general increase in the maximum bond stress. For instance, at a slip of 0.6 mm, the mixture with 20% coarse aggregate concentration has the highest maximum bond stress, measuring around 7.4 MPa. Conversely, the mixtures with 0% and 60% coarse aggregate concentrations have the lowest maximum bond stress, at approximately 6.2 MPa and 6.3 MPa, respectively, with slip values of 0.5 mm and 0.7 mm. The mixture with 40% coarse aggregate concentration has a maximum bond

stress of around 6.9 MPa at a slip of 0.6 mm, which is slightly lower than the value for the mixture with 20% coarse aggregate concentration.

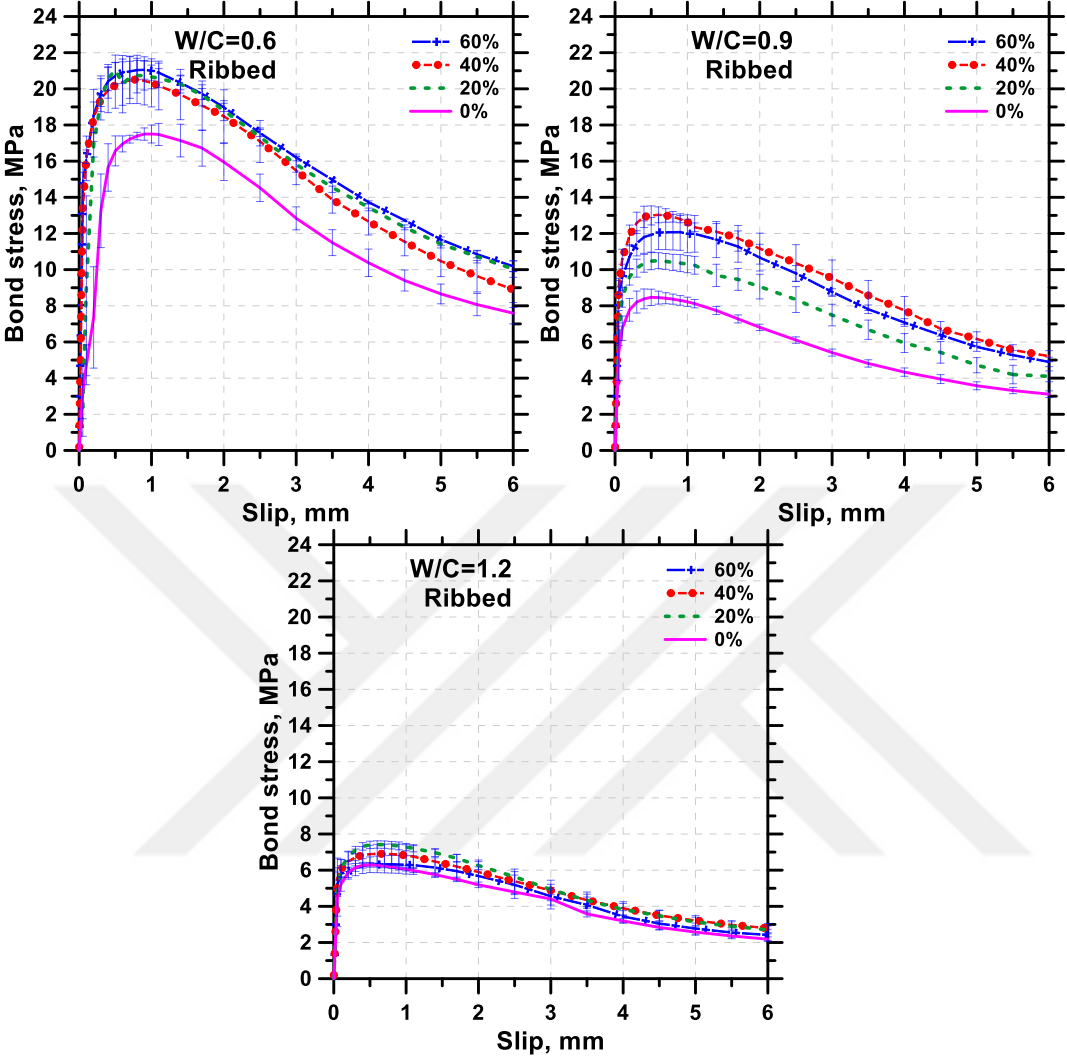


Figure 5.6: Average bond stress-slip graphs of ribbed rebar embedded mixtures (error bars indicate ± 1 standard dev.).

Although there was some variability in the results, the concentration of coarse aggregate led to an improvement in the bond stress compared to the mixture with 0% coarse aggregate. This can be attributed to the increased friction between the lugs of the ribbed rebars and the coarse aggregate.

When analyzing the graph for 0.90 W/C ratio for ribbed rebars, as the concentration of coarse aggregate increases to 20%, the graph shows a sharper increase in the bond stress value, with the maximum value observed at a slip value of around 0.6 mm. At a concentration of 40%, the bond stress value is slightly lower at a slip value of 0.9 mm, while at 60%, it remains slightly lower than the maximum value.

It's important to note that when the properties of the cement paste are improved by reducing the W/C ratio, there is a clear enhancement in the bond stress and overall bond strength when using coarse aggregate, compared to using a mixture with 0% concentration due to the improved properties of the bonding paste there is an improvement in the chemical adhesion before reaching the peak. So, the slope of the descending branch of the graph line increases because after reaching the peak, the bond stress value decreases in the descending branch due to the loss of an important part of adhesion which is "the chemical adhesion" and the continuation of "mechanical friction".

When analyzing the graph for 0.60 W/C ratio for ribbed rebars, the bond stress values generally increase as slip values increase for each coarse aggregate concentration. However, the rate of increase varies depending on the concentration of coarse aggregate. In the 0% mixture, slippage begins with small values of bond stress, unlike in other concentrations where slippage doesn't occur until shortly before reaching the peak. The slope of the graph increases as the W/C ratio decreases, indicating a stronger bond between the concrete and the reinforcing steel. Additionally, the plateau length decreases after reaching the peak.

The results of bond stress converge in all mixtures, indicating that increasing the concentration of coarse aggregate improves bond stress compared to the 0% mixture. However, after reaching a maximum at a coarse aggregate concentration of 20%, increasing the concentration of coarse aggregate does not increase bond stress. In the 0% mixture, the peak is delayed to 1.1 mm. This delay is due to the improvement in mechanical bond strength and homogeneity in the mixture without coarse aggregate.

In Fig. 5.7, when analyzing the graph for 1.20 W/C ratio, for 0% coarse aggregate concentration, the descending branch of the graph is the steepest. This means that the bond stress values decrease rapidly as the slip increases. This could be because there is less resistance to sliding between the two surfaces without the coarse aggregate.

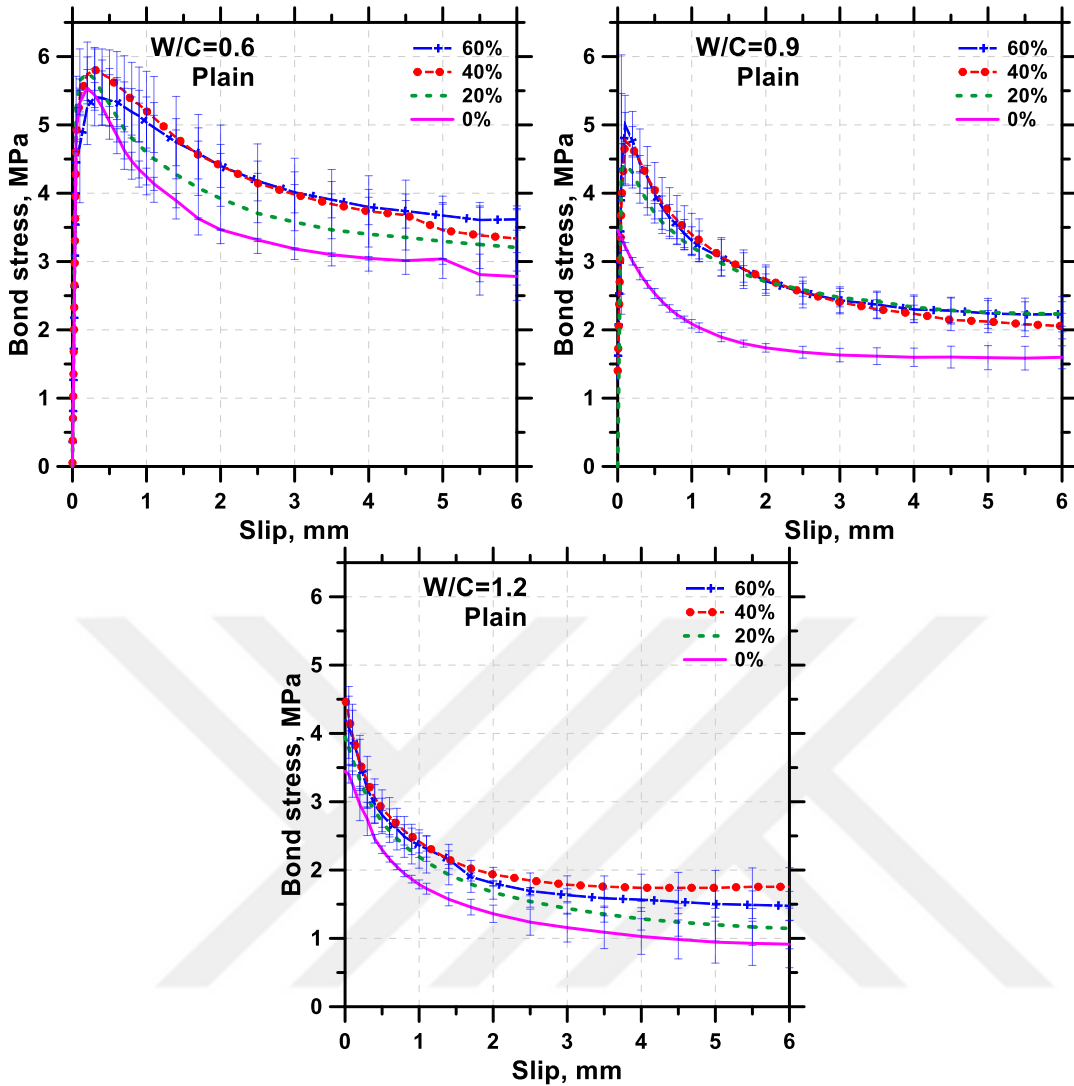


Figure 5.7: Average bond stress-slip graphs of plain rebar embedded mixtures (error bars indicate ± 1 standard dev.).

For 20%, 40% and 60% coarse aggregate concentrations, the slope of the graph is less steep compared to the 0% concentration. This indicates that the bond stress values decrease at a slower rate as the slip increases. This could be because the presence of coarse aggregate increases the resistance to sliding, resulting in a slower decrease in bond stress values. The mixture with 60% coarse aggregate concentration has a maximum bond stress of around 4.2 MPa at a slip of 0 mm, which is slightly lower than the value for the mixture with 40% coarse aggregate concentration which has the maximum bond stress in this mixture around 4.5 MPa and also slips 0 mm.

It was observed in the mixture that slip did not occur until the bond strength reached its "peak". This can be attributed to the inadequate mechanical bond and the absence of effective friction, unlike in ribbed rebars. Consequently, there was no efficient transfer of loads between the concrete and the plain rebars.

When analyzing the graph for 0.90 W/C with plain rebars, for the case of 0% aggregate concentration, it is observed that, a similar behavior to a previous case where the maximum bond stress value occurs at 0 mm slip and then decreases rapidly for higher slip values. However, due to the increased strength of the mixture, a higher value for the plateau can be observed at around 1.8 MPa compared to 1 MPa for the previous case.

For 20% coarse aggregate concentration, the bond stress increases rapidly with slip until it reaches a peak of 4.43 MPa at a slip of 0.1 mm, after which it decreases gradually with a further increase in slip. This behavior can be attributed to the fact that the coarse aggregate provides interlocking with the steel reinforcement, resulting in higher initial bond stress. However, as slip increases, the interlocking effect decreases, leading to a decrease in bond stress.

At 40% coarse aggregate concentration, the bond stress increases with slip until it reaches a peak of 5.00 MPa at a slip of 0.1 mm, after which it decreases with a further increase in slip. The peak bond stress is higher than that of 20% coarse aggregate concentration, which can be attributed to the higher interlocking effect provided by the increased coarse aggregate concentration.

At 60% coarse aggregate concentration, the bond stress increases rapidly with slip until it reaches a peak of 5.00 MPa at a slip of 0.1 mm, after which it decreases gradually with a further increase in slip. The behavior is similar to that of 40% coarse aggregate concentration, but the peak bond stress value is the same as that of 40% coarse aggregate concentration, suggesting that further increase in coarse aggregate concentration does not provide significant improvement in bond strength.

Additionally, a longer plateau can be observed compared to the previous case. This effect may be related to the increased surface area of the coarse aggregate, which allows for more points of contact with the rebar and therefore higher mechanical friction.

When analyzing the graph for 0.60 W/C with plain rebars, the peak bond stress value is observed at a slip value of around 0.2 mm for all concentrations. After this point, the bond stress decreases as the slip increases.

The shape of the graph changes as the coarse aggregate concentration increases. At 0% and 20% coarse aggregate concentrations, the graph has a concave-upward shape.

At 40% coarse aggregate concentration, the graph is nearly linear, and at 60% coarse aggregate concentration, the graph has a concave-downward shape.

At 0% and 20% coarse aggregate concentrations, the bond stress values are relatively high and decrease rapidly as the slip increases. At 40% coarse aggregate concentration, the bond stress values are higher than 0% and 20% concentrations and also decrease more slowly as the slip increases. At 60% coarse aggregate concentration, the bond stress values are the lowest of all the concentrations until a slip value of 2 mm after which it shows the longest plateau.

5.5 Evaluation of the Compressive Strength–Bond Strength Relationship

The relationship between compressive strengths and bond strengths are illustrated in Fig. 5.8.

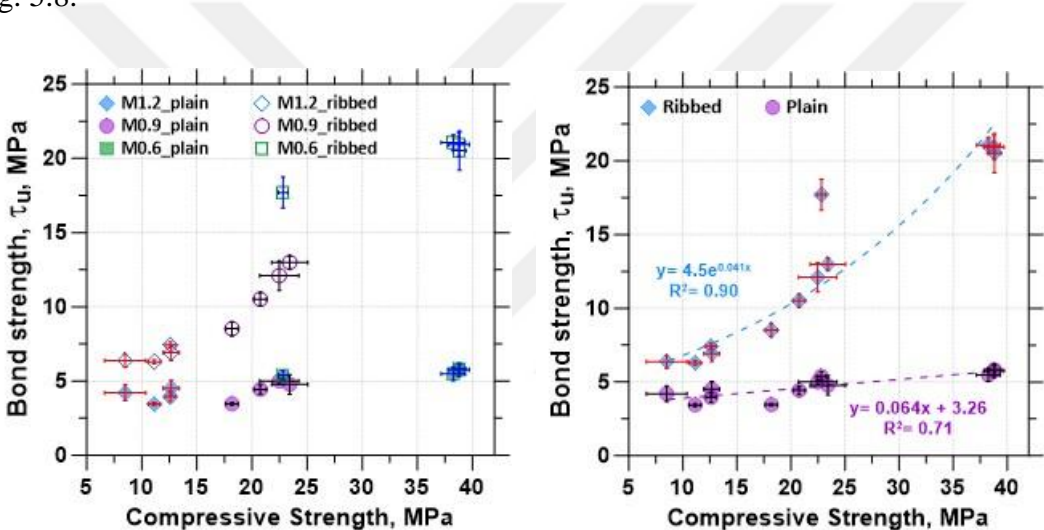


Figure 5.8: Bond strength vs compressive strength relations (*error bars indicate ±1 standard dev.*).

In these figures, two cases are distinguished: plain rebars and ribbed rebars. A clear correlation between bond strength and compressive strength is shown in both cases, where, on average, concrete with higher compressive strength exhibits higher bond strength. However, as seen before, the increase in bond strength is much higher for ribbed rebars compared to plain ones when compressive strength is increased. The surface area and mechanical interlock are much higher for ribbed rebars, translating to higher bond strength when chemical adhesion is increased, i.e., when compressive strength is increased. When fitting the data, it is seen that an exponential curve better represents the data for ribbed bars with ($R^2=0.9$) compared to a linear curve for plain bars with ($R^2=0.71$). If a more detailed look is taken into the points for each W/C ratio, the following observations could be made. Firstly, the mixtures containing coarse

aggregates are grouped together and separated from the mixture containing 0% coarse aggregate concentrations. More precisely, mixtures with 0% coarse aggregate show significantly lower compressive strength for comparable bond strength with mixtures containing higher coarse aggregate concentrations. Secondly, this separation becomes higher as the W/C ratio decreases whereas the points for mixtures containing coarse aggregates become closer to each other.





6. CONCLUSIONS

The results of this study can be summarized as follows:

1. Increasing the coarse aggregate concentration in concrete mixtures up to 40% positively affected the compressive strength, while increasing the concentration to 60%, resulted in lower values compared to 40% concentration.
2. With the addition of coarse aggregate to the mixture, the increase in compressive strength becomes more apparent with decreasing W/C ratio due to the improved aggregate-mortar interface properties. This allows for more effective load transfer to the aggregate.
3. The addition of coarse aggregate to low-strength concrete ($W/C = 1.2$) has very little effect on compressive strength. In fact, when the coarse aggregate concentration is increased to 60%, the compressive strength decreases by 24% compared to a mixture with 0% coarse aggregate concentration.
4. Unlike compressive strength, the highest values for elasticity modulus are obtained from mixtures containing 60% coarse aggregate at all W/C ratios and have increased with increasing coarse aggregate ratio in almost all mixtures.
5. As the W/C ratio decreases to 0.6, the difference in elasticity modulus between each coarse aggregate concentration becomes more apparent. This can be explained by the improved aggregate-mortar interface properties. The elastic modulus value of the mixture with 0% coarse aggregate concentration is 21.3 GPa, while the value obtained from the mixture with 60% coarse aggregate concentration is 27.0 GPa, representing a 27% increase in elasticity modulus.
6. When examining the stress-strain curves of the mixtures, it is observed that as the compressive strength increases, the slope of the descending branch of the curve becomes steeper.
7. When looking at the effect of coarse aggregate concentration on the descending branch of the curve, there is no significant difference between the mixtures at a W/C ratio of 1.2. However, as the W/C ratio decreases and coarse aggregate

is added to the mixture, it is found that the slope of the curve increases significantly, leading to more brittle behavior of the concrete.

8. It has been observed that the splitting tensile strengths increase with the addition of coarse aggregate to the mixture and the effect of the increased amounts and different coarse aggregate concentrations becomes more pronounced as the W/C ratio decreases.
9. When considering bond strength, ribbed rebars have a higher bond strength than plain rebars due to better chemical adhesion and mechanical interaction.
10. Bond strength is higher in mixtures with a W/C ratio of 0.60 than in other mixtures with higher W/C ratios for both types of rebars. Decreasing the W/C ratio improves the adherence between concrete and reinforcement.
11. An increase in bond strength is observed for W/C ratios of 0.9-0.6 compared to a W/C ratio of 1.2.
12. In addition, bond strength increases with an increase in coarse aggregate concentration for all three W/C ratios tested. Plain rebars' bond strength is not affected by mechanical interlock, which is present in ribbed rebars. For ribbed rebars, the highest bond strength was observed at a lower concentration of coarse aggregate than for plain rebars.

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- Civil engineer (2013-2016)
- Workplace Lattakia health directorate - engineering section: construction branch
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PUBLICATIONS, PRESENTATIONS AND PATENTS ON THE THESIS

- **Kaf O.A., Bıçakçı S.N., Baran Ş., Türkmenoğlu H.N. and Atahan H.N.** 2022. The Effect of Coarse Aggregate Concentration on the Bond Stress vs. Slip Relation between Low-Strength Concrete and Reinforcing Steel, *IGRS'22, International Graduate Research Symposium*, 1-3 June 2022, Istanbul, Türkiye.
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