

T.R.
GEBZE TECHNICAL UNIVERSITY
GRADUATE SCHOOL

**EFFECT OF CNT MODIFIED ADHESIVES IN INTERFACIAL
MECHANISM OF CFRP REINFORCED CONCRETE**



CAN MERT CISDIK

A THESIS OF MASTER OF SCIENCE
DEPARTMENT OF CIVIL ENGINEERING

ADVISOR: PROF. DR. FERİT ÇAKIR

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T.C.
GEBZE TEKNİK ÜNİVERSİTESİ
LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

CFRP TAKVİYELİ BETONUN ARAYÜZ MEKANİZMASINDA
CNT MODİFİYE EDİLMİŞ YAPIŞTIRICILARIN ETKİSİ

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To my family

ABSTRACT

Concrete is the most widely used construction material due to its compressive strength, availability and applicability. However, concrete structures can be exposed to effects that shorten their lifespan over time, such as cracking, corrosion of reinforcements and loss of durability due to various reasons, depending on loading and environmental conditions. As a result of these conditions, the need for strengthening structures has emerged and various methods have been developed in recent years to meet this need. The use of carbon fiber reinforced polymers (CFRP) has become one of the most frequently used structural strengthening methods among these methods. There are many studies in the literature on the application of carbon fiber polymers. Recently, studies have focused on both making existing strengthening methods more effective and innovative solutions that will increase interface performance. Nanotechnology-based material additives stand out with their potential to improve bond strength, especially in CFRP-concrete joints. In this context, the use of carbon nanostructures together with epoxy resins has become a new and interesting topic for structural engineering research.

In this study, the effects of carbon nanotube reinforcement on composite concrete interface behavior in unreinforced beams reinforced with CFRP plates were investigated. In the study, 2 different types of epoxy resins with different densities were used. It was aimed to increase the interface performance by adding carbon nanotubes to epoxy resins at 3 different rates (0.5%, 1.0% and 1.5%, respectively). First of all, 27 beams with dimensions of 150x150x600 mm were produced. In order to ensure a clear examination of the behavior at the composite-concrete interface and to eliminate the risks that may arise from concrete casting and production, a single type of cement-based, high-strength ready-mixed grout mortar was used in the production of the beams. The produced beams were strengthened using CFRP plates. The strengthened beams were subjected to 3-point bending tests. As a result of the experiments, the bending behaviors and collapse mechanisms of beams strengthened with epoxy resins of different densities and beams strengthened with epoxy resins reinforced with carbon nanotubes at different rates were investigated. The effects of carbon nanotubes on the interface mechanics were observed.

Keywords: Carbon Fiber Composite, Epoxy Resin, Three-Point Bending, Cement-Based Grout, Carbon Nanotube.

ÖZET

Beton, basınç dayanımı, bulunabilirliği ve uygulanabilirliği nedeniyle en yaygın kullanılan inşaat malzemesidir. Ancak beton yapılar, zaman içerisinde yükleme ve çevre koşullarına bağlı olarak çatlama, donatıların korozyonu ve çeşitli nedenlerle durabilite kaybı gibi ömrünü kısaltan etkilere maruz kalabilmektedir. Bu koşulların bir sonucu olarak yapıların güçlendirilmesi ihtiyacı ortaya çıkmış ve son yıllarda bu ihtiyaca yönelik çeşitli yöntemler geliştirilmiştir. Karbon fiber takviyeli polimer (CFRP) kullanımı, bu yöntemler içerisinde en sık kullanılan yapısal güçlendirme yöntemlerinden bir tanesi olmuştur. Literatürde karbon lifli polimerlerin uygulaması ile ilgili çok sayıda çalışma bulunmaktadır. Son dönemde ise hem mevcut güçlendirme yöntemlerinin daha etkin hale getirilmesi hem de arayüz performansını artıracak yenilikçi çözümler üzerinde çalışmalar yoğunlaşmıştır. Nanoteknoloji temelli malzeme katkıları, özellikle CFRP-beton bağlantılarında arayüz dayanımını iyileştirme potansiyeli ile öne çıkmaktadır. Bu bağlamda, karbon nanoyapıların epoksi reçinelerle birlikte kullanımı, yapı mühendisliği araştırmaları için yeni ve ilgi çekici bir konu haline gelmiştir.

Bu çalışmada, karbon nanotüp takviyesinin, CFRP plaka ile güçlendirilmiş donatısız kirişlerde kompozit beton arayüz davranışına etkileri araştırılmıştır. Araştırmada 2 farklı tipte, birbirinden farklı yoğunluklarda epoksi reçine kullanılmıştır. Epoksi reçinelere 3 farklı oranda (sırasıyla %0.5, %1.0 ve %1.5) karbon nanotüp katılarak arayüz performansının artırılması amaçlanmıştır. Öncelikle 150x150x600 mm ölçülerinde 27 adet kiriş üretilmiştir. Kompozit-beton arayüzündeki davranışın net olarak incelenmesini sağlamak ve beton dökümü ile üretiminden kaynaklanabilecek risklerin ortadan kaldırılması için kirişlerin üretiminde tek tipte çimento bazlı, yüksek dayanımlı hazır grout harcı kullanılmıştır. Üretilen kirişler CFRP plaka kullanılarak güçlendirilmiştir. Güçlendirilen kirişler 3 noktalı eğilme testine tabi tutulmuştur. Deneyler sonucunda farklı yoğunluklardaki epoksi reçinelerle güçlendirilmiş kirişler ile farklı oranlarda karbon nanotüp takviyeli epoksi reçineler ile güçlendirilmiş kirişlerin eğilme davranışları ve göçme mekanizmaları incelenmiştir. Karbon nanotüplerin arayüz mekaniğine etkileri gözlenmiştir.

Anahtar Kelimeler: Karbon Elyaf Kompozit, Epoksi Reçine, Üç Noktalı Eğilme, Çimento Bazlı Grout, Karbon Nanotüp.

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LIST OF SYMBOLS AND ABBREVIATIONS

CNT	: Carbon Nanotube
MWCNT	: Multi Walled Carbon Nanotube
SWCNT	: Single Walled Carbon Nanotube
DGBEA	: Diglycidyl Ether
FRP	: Fiber Reinforced Polymer
GFRP	: Glass Fiber Reinforced Polymer
CFRP	: Carbon Fiber Reinforced Polymer



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1. INTRODUCTION

In structural engineering, the concepts of sustainability, safety and longevity have become decisive factors in both new building designs and the protection of existing structures. Especially considering the increasing population, urbanization and natural disaster risk, improving the existing building stock and increasing its durability is a priority research area for engineering disciplines. In this context, structural reinforcement methods developed to increase the carrying capacity of structural elements and to eliminate existing damages have gained great importance in today's construction sector, both academically and practically.

Although reinforced concrete structures are the cornerstone of the construction sector with their high compressive strength and formability, serious decreases are observed in their mechanical performance due to micro cracks, reinforcement corrosion and environmental effects that occur over time. For this reason, reinforcement techniques should be selected correctly and applied effectively, especially in structures where the service life needs to be extended. In addition to traditional methods, reinforcements made with polymer-based composites have come to the fore in recent years due to their innovative and efficient solutions. One of the most striking of these systems is the use of carbon fiber polymer (CFRP).

CFRP materials have a wide range of applications from non-bearing walls to bridge beams thanks to their tensile strength, elasticity modulus, corrosion resistance and low specific gravity. However, the performance of CFRP systems is directly dependent not only on the quality of the material used, but also on the quality of the concrete-composite interface. This interface is of critical importance in terms of effectively transferring structural loads to the CFRP plate. Adhesion problems experienced at the interface can directly affect the collapse behavior of the system; this is one of the main factors limiting the success of CFRP applications.

In recent years, many studies have been conducted to improve the properties of polymer matrix adhesives in order to overcome these limitations. In particular, the use of nanotechnological additives has produced quite remarkable results in this context. The changes that nanomaterials create on the microstructure, their crack propagation inhibitory effects and their potential to increase bond strength have made them attractive solution partners in the field of structural engineering. Among these

additives, carbon nanotubes (CNT) are preferred especially in epoxy-based adhesives with their high surface area, extraordinary mechanical strength and electrical conductivity.

The inclusion of carbon nanotubes in the polymer matrix not only increases bond strength, but also ensures a more homogeneous distribution of stress accumulations in the interface region. In this way, crack formation and propagation are limited; therefore, it is possible for CFRP systems to become more durable and long-lasting. However, in order for such additives to work effectively, they must be combined with resins of appropriate viscosity, a smooth dispersion must be achieved, and they must exhibit behavior compatible with the interface mechanism.

All these developments have made it possible to go beyond classical structural reinforcement approaches and increase performance with improvements at the material level. In this context, each new experimental research conducted offers original contributions to the science of building materials and sheds light on field applications. Studies evaluating the effects of epoxy systems modified with carbon nanotubes on the composite-concrete interface behavior require both microstructural analyses and macro-level loading tests to be considered together. Thus, the behavior of not only the material but also the entire structural system can be interpreted more reliably.

1.1. Purpose of Thesis

The main purpose of this thesis is to experimentally investigate the effectiveness of CNT added epoxy resin systems in order to improve the composite-concrete interface performance in reinforced concrete structural elements reinforced with CFRP plates. Bond strength losses and bonding failures, especially in the interface region, negatively affect the overall strength performance and structural integrity of CFRP reinforced systems. Therefore, modification of epoxy-based adhesives with nano-additives stands out as one of the important solution proposals in this field.

This thesis aims to evaluate the mechanical effects of nano-modified adhesives at the concrete-composite interface and to reveal their effects on critical parameters such as bond strength, crack propagation and collapse mechanism in CFRP applications. The findings to be obtained will contribute to the development of more reliable, long-

lasting and performance-oriented reinforcement strategies not only at the laboratory level but also in real field applications.

In addition, the comprehensive evaluation presented in this study aims to provide a better understanding of the place of nanotechnological additives in structural engineering and to provide new scientific insights for the design of CFRP systems and engineering applications.

1.2. Scope and Content

This thesis aims to experimentally evaluate the performance of CNT added epoxy resin systems for the improvement of the interface mechanical behavior in reinforced concrete beam elements reinforced with CFRP plates. The study reveals the effects of nanotechnology-supported material modifications on the bond strength in concrete-composite joints and is carried out with an innovative approach that follows the developments in this field in construction materials science.

The scope of the research includes the application of adhesive systems prepared by adding 0.5%, 1.0% and 1.5% multi-walled carbon nanotube (MWCNT) to two types of epoxy resins with different viscosities to the interface of unreinforced reinforced concrete beams with CFRP plates and systematically examining the effects of these systems on the interface behavior. In the production process, a single type of cement-based, high-strength ready-mixed grout mortar was preferred in order to reduce the variability originating from concrete casting. In this way, it was aimed to observe the bond strength originating from the interface more accurately.

Three-point bending tests were performed on 27 beam samples prepared within the scope of the study and the crack development, failure modes, load carrying capacities and bond behaviors of the samples were evaluated in detail. In addition, the micro-level effects observed in the interface region were interpreted in terms of understanding the material-mechanical relationship.

The content of the thesis consists of the following sections:

1. General framework of CFRP applications and nanomaterial additives in construction materials,
2. Literature review of previous studies on CFRP-concrete interface behavior,

3. Distribution of carbon nanotubes in epoxy resin, their effects and experimental methods on sonication applications,
4. Detailing the sample production, materials used, experimental design and applied test procedures,
5. Analysis of experimental data obtained from bending tests and comparison of results,
6. Interpretation of results, suggestions and discussion of scientific contributions for future studies.

This thesis aims to evaluate the potential of new material combinations, especially in reinforcement applications with CFRP, by demonstrating the contributions of nanotechnological additives to increase the performance and safety of composite structural elements with concrete experimental data. Thus, both a contribution is made to the academic literature and new avenues are opened for engineering applications.

2. LITERATURE REVIEW

Concrete is the most widely used construction material due to its compressive strength, availability and applicability. However, concrete structures can be exposed to effects that shorten their lifespan over time, such as cracking, corrosion of reinforcements and loss of durability due to various reasons, depending on loading and environmental conditions. As a result of these conditions, the need to strengthen structures has emerged and various methods have been developed in recent years to meet this need. The use of CFRP composites, which emerged for this purpose, to strengthen concrete structures has attracted significant attention due to their high strength-to-weight ratio and corrosion resistance properties. CFRP has become a preferred material for strengthening reinforced concrete structures by offering long life and minimizing maintenance costs. Due to its high tensile strength, durability and lightweight structure, maintenance costs are very low. In addition, unlike traditional steel reinforcement, CFRP does not corrode and thus becomes quite suitable even for chemically aggressive environments [1]. In addition, it has been shown in various studies that bending, shear and axial load capacities can be increase and service lives can be extended significantly with CFRP applications without making significant changes in the dimensions of structures [2].

The effective application of CFRP composites in reinforced concrete structures is significantly dependent on the behavior of the bond at the composite-concrete interface. The interface must exhibit sufficient bond strength to resist shear and delamination under loading conditions. Despite significant improvements, problems such as delamination, poor adhesion, and interface failure are still encountered [3]. Lau et al. emphasized the importance of interface bond strength in determining the performance of CFRP reinforced concrete beams. Interface bond strength is affected by various factors such as the preparation of the application surface, the properties of the epoxy-based resin, environmental conditions, and the mechanical properties of the CFRP composite. It has been reported that techniques such as sandblasting, abrasion, or primer application increase the interface bond performance and delay the onset of delamination under loading [4].

Epoxy resins that bond the CFRP composite to the concrete surface determine the bond strength and durability of the composite-concrete interface. There are many types of

epoxy resins that differ from each other in their properties such as viscosity, density, curing time, and mechanical performance.

2.1. Cementitious Grouts

Cement-based grout mortars are specially formulated materials that have a wide range of applications in modern structural engineering, both in new construction applications and in the repair and reinforcement processes of existing structures. These mortars are especially preferred in load-bearing systems due to their critical engineering properties such as high fluidity, low shrinkage (and sometimes even expansion), and high early and final strength.

The development process of grout materials and the history of engineering applications can be traced back to the early 19th century [5]. In 1802, Charles Bering used mud slurry and lime slurry as injection materials and injected these mixtures into the formation with the help of a pulse pump and managed to effectively increase the soil bearing capacity. After this date, mud and lime-based slurry were used primarily as grouting materials. The invention of Portland cement in 1824 laid the foundation for the formation of cement-based grouts and their widespread engineering applications. In 1838, British scientist Thompson first used cement grout to strengthen rock and soil during tunnel excavations and achieved significant success. In 1845 and 1864, cement grout was used as an injection material in reservoir overflow channel foundations and in the reinforcement of mine shaft walls. Since these applications, cement grout has become the most important grout material and has been widely used in engineering areas such as ports, tunnels, mines and dams [6]. Today, cement-based grouts stand out with their high fluidity, non-segregation, light expansion, rapid early strength development, high final strength and good durability and durability properties when mixed with water [7]. Their application areas have also expanded over time; not only rock-soil injections, but also equipment foundation fixation [8], filling of tendon voids of prestressed concrete structures [9], special protection engineering applications, reinforcement of existing reinforced concrete structures and masonry structures [10] are widespread in many areas.

Grout materials basically consist of cement, fine-grained aggregate, water and various chemical additives that increase performance.

Cement: Portland cement or blast furnace slag cement is usually used. The type of cement affects the strength of the mortar, its setting time and its resistance to environmental effects.

Aggregate: Fine aggregate (sand) and sometimes very fine aggregate (pozzolanic materials such as silica fume or fly ash) are used. Aggregate increases the volumetric stability of the mortar and reduces shrinkage.

Water: Provides the consistency and workability of the mortar. The water/cement ratio directly affects the strength and permeability of the mortar. In ready-mixed grout mortars, water is added to the mixture last. Proper workability is achieved by adding it to the mixture at the rate determined by the manufacturers. The water/powder ratio usually varies between 12% and 17%. The amount of mixing water is determined according to the air temperature and the humidity and temperature of the surface to be applied.

Chemical additives: Various additives are used to improve the properties of grout mortars. These include superplasticizers (provide high fluidity), shrinkage inhibitors (reduce shrinkage), setting accelerators or retarders (adjust the setting time) and air entrainers (increase freeze-thaw resistance). In particular, the types of superplasticizers used significantly affect the amount of water required by the mixture. While the mixing water requirement drops to 12% in the use of polycarboxylic ether-based superplasticizers, this rate can go up to 17% in naphthalene formaldehyde-based superplasticizers. In addition, results such as different workability times and different separation rates can be encountered in the use of two different types of plasticizers.

Cement-based grouts generally have high fluidity, low shrinkage or expansion, high strength and good adhesion properties.

A large number of studies have investigated the structural behavior of cement-based mortar under uniaxial compression. The results show that cement-based mortar exhibits a larger peak stress, smaller elastic modulus, larger proportional limit and more pronounced brittleness compared to ordinary concrete [12].

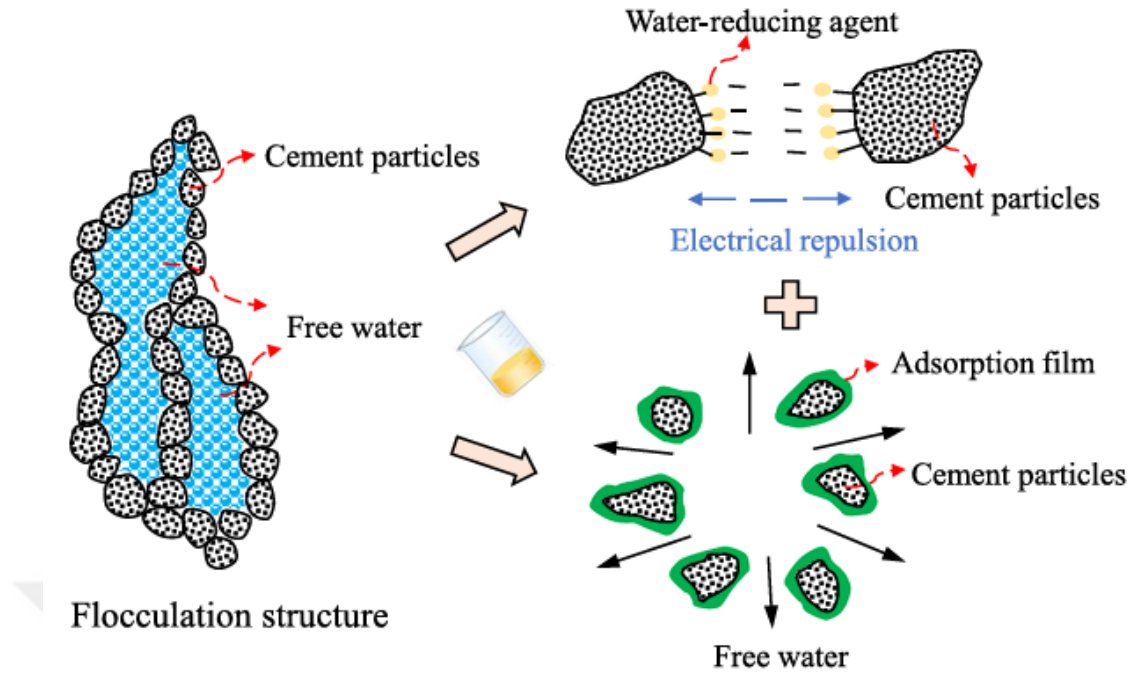


Figure 2.1: Working mechanism of water-reducing agents [11].

2.2. Carbon Fiber Reinforced Polymers

Reinforced concrete structures may be damaged and suffer structural performance losses during their service life or when exposed to aggressive environments. In such cases, structural elements must be strengthened to ensure that the load-bearing capacity reaches the original design value or higher levels. Corrosion is one of the main causes of deterioration in reinforced concrete and steel structures and can lead to various negative consequences, ranging from structural weakening such as cracking and section loss to sudden collapse. The high strength-to-weight and stiffness-to-weight ratios of composites make them attractive for infrastructure rehabilitation [13].

CFRP's are increasingly important in structural strengthening and repair applications in civil engineering. Thanks to their advantages such as high strength-to-weight ratio, corrosion resistance and ease of application, they offer an effective solution to increase the performance of reinforced concrete structures. Carbon plates, in particular, are widely used to increase the load-carrying capacity and stiffness of reinforced concrete elements by bonding them to the tension zone. Plates, which are widely used in the repair and strengthening of concrete beams, are usually bonded to the lower surface of the beam. Initially, steel plates were used, but later the use of CFRP plates became

prominent. CFRPs are preferred due to their higher strength/weight ratio, various advantages and higher durability compared to steel equivalents. In addition, thanks to the reduction in the costs of CFRP materials and the development of epoxy resin-based synthetic adhesives, these advanced composites are considered as an important alternative for reinforced concrete structures to replace traditional steel [14].

The mechanical properties of CFRP materials depend on the type, volume fraction, orientation of carbon fibers and the properties of the polymer matrix used. Carbon fibers can have high tensile strength (2000-7000 MPa) and elasticity modulus (200-600 GPa). Epoxy resins are generally used as polymer matrices; these resins hold the fibers together, provide load transfer and provide protection against environmental effects [15].

The performance of CFRP for the purpose of strengthening concrete elements has been investigated in many studies in terms of structural behavior, material properties and application method. The increase in the bending strength of reinforced concrete beams can be achieved by bonding CFRP plates with epoxy based on the fiber direction to the areas subjected to tensile stresses. When composite fibers are placed perpendicular to the cracks, a significant increase in bending strength and rigidity is achieved compared to cases where the fibers are placed parallel to the cracks. It is reported that an increase in bending strength of up to 200% can be achieved with CFRP [16].

Carbon plates are used in the reinforcement of reinforced concrete beams, slabs and columns. The plates are bonded to the concrete surface with epoxy-based adhesives.

Cleaning, roughening and applying a suitable primer (primer) to the concrete surface before the bonding process are of critical importance to ensure adhesion.

By applying carbon plates to reinforced concrete elements, the stresses in the tensile region of the element are reduced and the load-carrying capacity is increased. However, the effectiveness of CFRP plates depends on the establishment and preservation of the adhesion at the interface.

Debonding of CFRP plates from the concrete surface is a significant problem that limits the bearing capacity of reinforced elements. Debonding can generally occur as cohesive failure on the concrete surface, separation in the adhesive layer, or delamination within the CFRP laminate itself. Debonding of CFRP plates from the

concrete surface depends on the concrete performance, surface preparation, and plate placement, as well as the performance of the adhesive used at the interface.

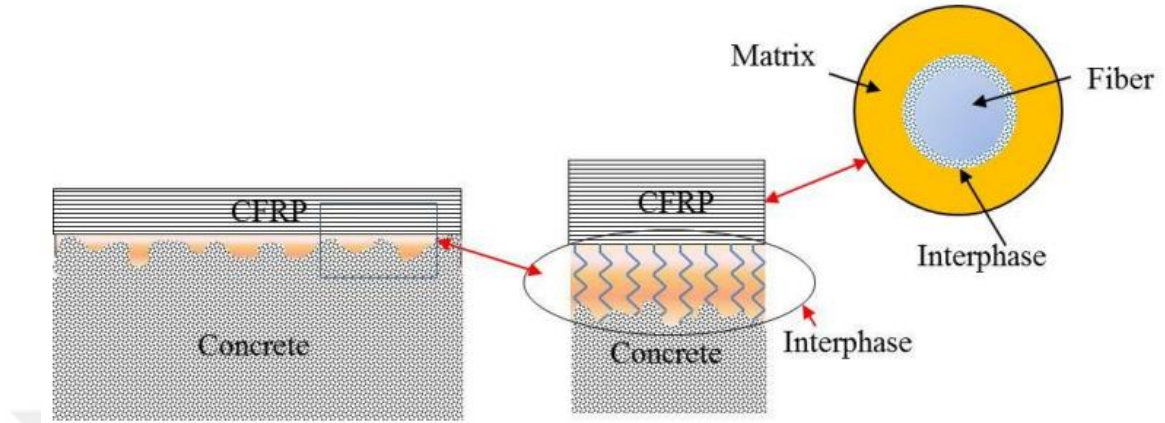


Figure 2.2: Theoretical scheme of interphases [13].

2.3. Epoxy Based Adhesives

Epoxy-based adhesives play a critical role in civil engineering, especially in the reinforcement and repair of reinforced concrete structures. They are widely used in bonding CFRP sheets, fabrics and plates to the concrete surface, in the assembly of steel plates and other structural reinforcement processes. These adhesives are of great importance in terms of the effectiveness and durability of the reinforcement systems due to their properties such as high adhesion strength, low shrinkage, good chemical resistance and appropriate viscosity [17], [18].

Epoxy adhesives used in reinforcement applications are generally two or three-component systems: [19], [20], [21].

Epoxy Resin: Epoxy resins based on bisphenol A (DGEBA) or bisphenol F are generally used. These resins can have high molecular weight and low viscosity. The type of resin affects the mechanical properties, chemical resistance and application properties of the adhesive.

Hardener: Various hardeners such as amines, polyamides, anhydrides or phenols can be used. The hardener reacts with the epoxy resin to cure and determines the final properties of the adhesive. The type of hardener affects the curing time, temperature resistance and chemical resistance.

Fillers: Silica, calcium carbonate, talc or other inorganic fillers can be used to reduce the cost of the adhesive, adjust its viscosity, improve its mechanical properties or bring its coefficient of thermal expansion closer to that of concrete.

Additives: Plasticizers, thixotropic agents, air entrainers, UV stabilizers and other additives can be added to improve the workability, durability or other properties of the adhesive.

One of the most important properties of epoxy adhesives is their high adhesion to concrete, steel, CFRP and other building materials. Adhesion ensures that the load transfer occurs effectively and the reinforcement system works successfully. In addition, the adhesive layer provides load transfer between the reinforced concrete element and the reinforcement material. The adhesive reduces the possibility of the reinforcement element detaching from the surface by counteracting the stresses on the concrete surface and increases the load-carrying capacity of the element.

In composite systems formed by bonding CFRP or steel plates to the concrete surface, ensuring and maintaining the adhesion at the interface is of critical importance. Loss of adhesion or debonding reduces the effectiveness of the reinforcement system and can even lead to structural damage [22].

Various studies have been conducted and continue to be conducted to reduce the possibility of debonding. Among these studies, a new concept called epoxy interlocking draws attention [23]. In this method, many holes were drilled on the concrete surface before the epoxy was applied, and this improved the bonding behavior and provided positive results of up to 89% in adhesion strength.

In another study [24], developed a new anchoring method for the epoxy/FRP interface. In this method, holes with diameters of 6 mm, 10 mm and 15 mm and a fixed depth of 20 mm were drilled into the concrete surface and then epoxy resin was injected into these holes to bond the FRP plates. With this technique, the bond strength and ultimate shear strength of CFRP to concrete increased by 77.5% and 78.1%, respectively. This increase was more pronounced in larger diameter holes.

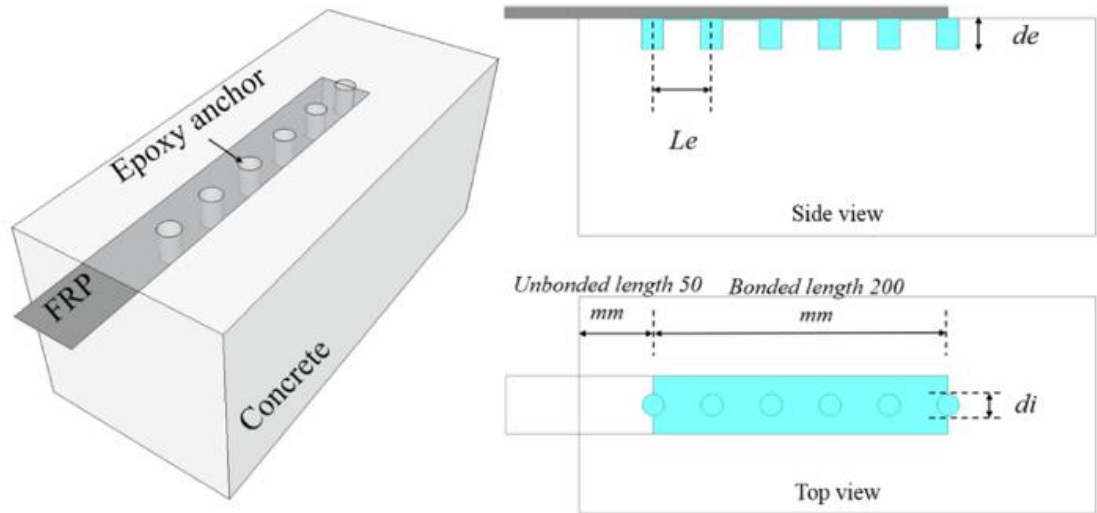


Figure 2.3: Theoretical application scheme of epoxy anchor [24].

2.4. Carbon Nanotubes

The carbon atom is found in nature in several different forms, called allotropes. They are all made up of carbon atoms, but these atoms come together in different ways to form carbon allotropes with different properties, such as coal or diamond. In addition to the carbon allotropes found in nature, different forms of carbon have been synthesized in the laboratory over the years. An example of this is graphene, which consists of a single layer of carbon atoms. Like graphene, carbon nanotubes consist of carbon atoms in a cage that is only one atom thick. Unlike graphene, carbon nanotubes are formed as long, hollow tubes. Carbon nanotubes can be described as a series of tubes intertwined. They may resemble the rings of a tree or a telescopic antenna folded inward. The theoretical image is shown in **Figure 2.4** [25].

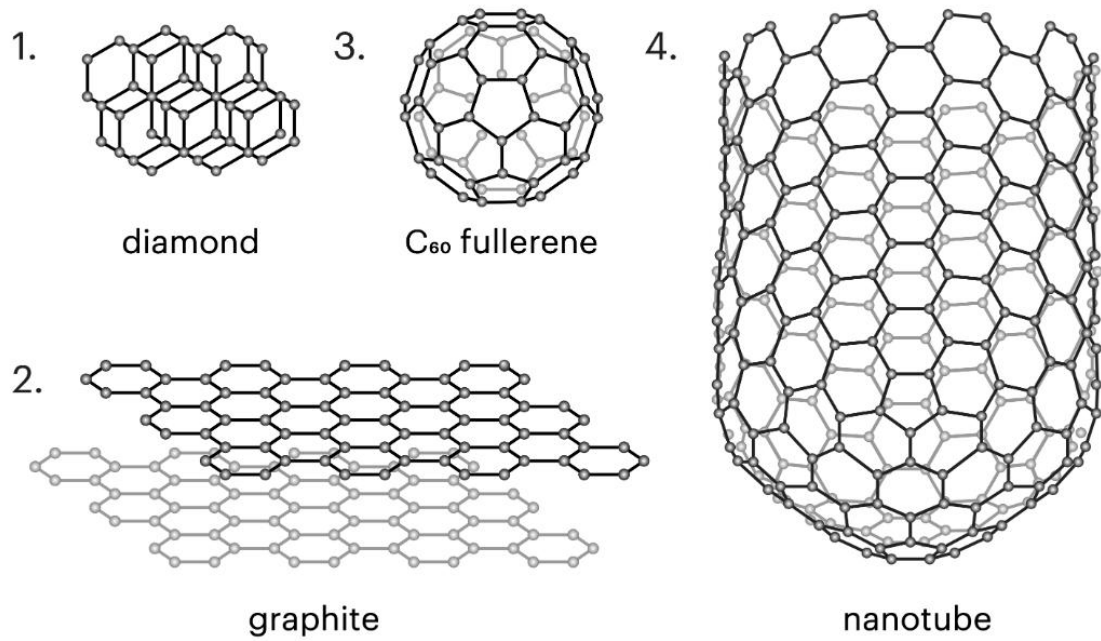


Figure 2.4: Examples of different forms (allotropes) of carbon materials [25].

CNTs are hollow, cylindrical in shape with nanoscale dimensions and are divided into two groups according to the layers of the cylindrical shape: single-walled carbon nanotubes (SWCNT) and multi-walled carbon nanotubes (MWCNT) [26].

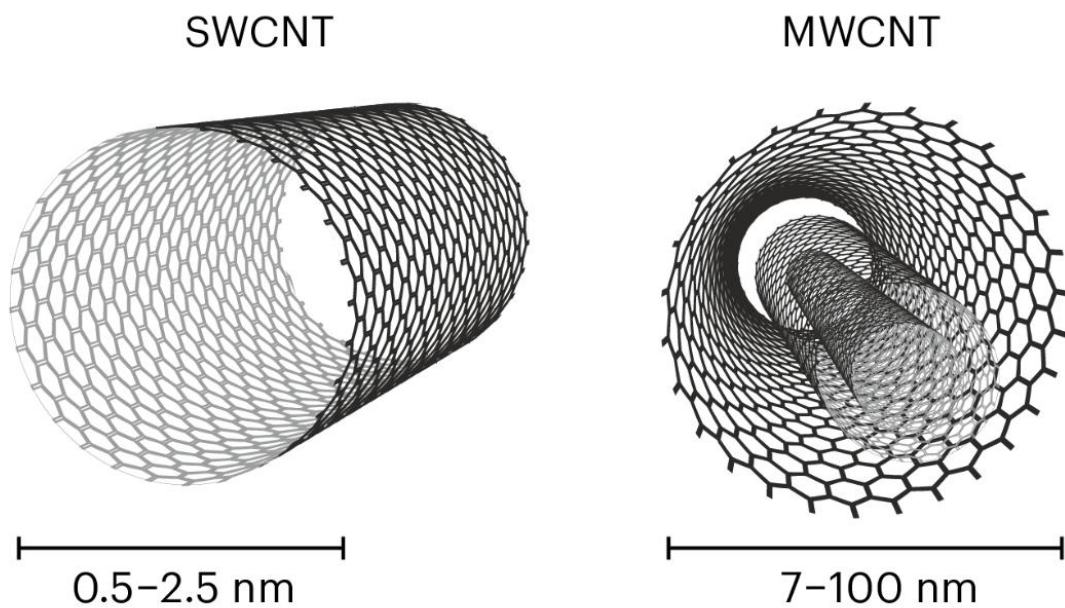


Figure 2.5: Schematic representation of a SWCNT and a MWCNT [26].

MWCNT's are materials with superior properties such as high strength, high elastic modulus, high electrical conductivity and large surface area. Thanks to these properties, they are widely used to improve the mechanical, electrical and thermal properties of polymer composites, especially epoxy resins. Various studies have shown that various mechanical properties of epoxy modified with CNT reinforcement are improved, and that it positively affects flexural strength [27], tensile strength [28], Young's modulus [29] and elongation at fracture [30].

In many studies, these improvements offered by CNT-modified epoxy resins have also been investigated for the purpose of strengthening reinforced concrete structures. Rousakis et al. [28] investigated the confinement efficiency obtained by wrapping concrete columns with glass fiber reinforced polymer (GFRP) fabric using CNT-modified epoxy. Irshidat et al. [31] investigated the effect of CNT-reinforced epoxy on the structural performance of reinforced concrete columns and beams strengthened with CFRP sheets. According to the results of the experimental study, it was revealed that the ultimate load carrying capacity of the elements strengthened with CNT-reinforced epoxy increased significantly. In another study [32], the effect of epoxy modification with MWCNTs on the bond-slip relationship between FRP sheets and concrete was investigated by shear test and it was shown that the ultimate creep and bond strength increased depending on the type of FRP (carbon or glass) and epoxy used. It was also stated that additional increases in this strength were observed as the width of the FRP sheet and the bond length increased.

3. EXPERIMENTAL STUDY

3.1. Material Property Tests

3.1.1. Cementitious Grouts

The grout mortar used in the study is a product known in the industry as “high strength non-shrink grout” and produced in accordance with the TS EN 1504-6 standard. The reasons for choosing this material includes minimizing surface cracks thanks to its low shrinkage rate, providing surface stability of CFRP laminates with its high early and final strength capacity, and contributing to adhesion strength thanks to its closed pore surface structure. The cement-based mortar used was supplied by Fosroc Construction Chemicals. The product is called Conbextra TS. The technical specifications of the grout mortar used are as follows [34].

Table 3.1: Material Mixture Properties of Cementitious Grout [34]

Material Mixture Properties	Supplier Declaration
Aggregate grain diameter	0 - 5 mm
Application thickness	75-500 mm
Mixing water / powder ratio	< 0,14 %
Application temperature	2 - 35 °C

Table 3.2: Fresh Mix Properties of Cementitious Grout [34]

Setting time (EN 196-3:1996)	Initial set: 6 hours
Expansion ratio (EN 445)	% 0-1
Flowability (EN 13395-2)	> 450 mm
Density (EN 12350)	2280 kg/m ³

Table 3.3: Mechanical Properties Of Cementitious Grout [34]

Compressive Strength	> 14 N/mm ² , 1 day
100x100x100 mm cube 20 °C (EN 12190:1999)	> 42 N/mm ² , 7 days > 60 N/mm ² , 28 days
Shrinkage (28 days) (ASTM-C157-93)	< 600 micro tension
Flexural strength (BS 6319 Pt 3:1990)	6.7 Mpa, 28 days

3.1.1.1. Fresh Mortar Experiments

These are the tests carried out during the production phase, that is, while the mortar is still fresh. Unit weight and spreading tests were carried out on the mixtures.

3.1.1.1.1. Cement Spreading Test

Cement Spreading Table is used in spreading (fluidity) tests of mortar, lime, cement samples (TS EN 1015-3). It is aimed to determine the fresh consistency and spreading value of mortar containing mineral binder and dense aggregate or light aggregate immediately after mixing. The fresh sample placed on the spreading table with standard shape and size with the help of a mold with standard shape and size is subjected to vibration by turning the arm of the device. The arm lifts the spreading table upwards and drops it by releasing it from a certain height [33].



Figure 3.1: Cement spreading table according to TS EN 1015-3 [33].

The spreading value of the fresh mortar sample is determined by measuring the average diameter of the spreading mortar sample. A truncated cone-shaped mold made of stainless steel or brass, 60 mm high, with a bottom inner diameter of 100 mm and a top inner diameter of 70 mm is lubricated with a fluid mineral oil. The funnel is placed centered on the surface of the spreading table. The lifting arm is turned to check whether it works.

Each layer of mortar is hit with a mallet for at least 10 short strokes until it is evenly distributed on the mortar surface. The excess mortar is scraped off with a leveling knife or spatula, and the parts that overflow onto the table are wiped clean. After waiting for 15 seconds, the mold ring is removed in a vertical direction. The table is lowered 15 times at a rate of 1 per second. The diameter of the spread mortar mass is measured in mm in two perpendicular directions and the average is taken.

The test is carried out for two samples. If a deviation of more than 10% is observed between the spreading values of the two tests, the tests are repeated, the tests are repeated.

3.1.1.1.2. Unit Weight Test

A container with a certain volume is filled with mortar and its weight is measured by taking the tare of the container. Then, the weight is divided by the volume of the container to obtain the unit weight of the mortar. In the unit weight test, when the

container is filled with mortar, care should be taken to ensure that the surface is full and flat to the top.

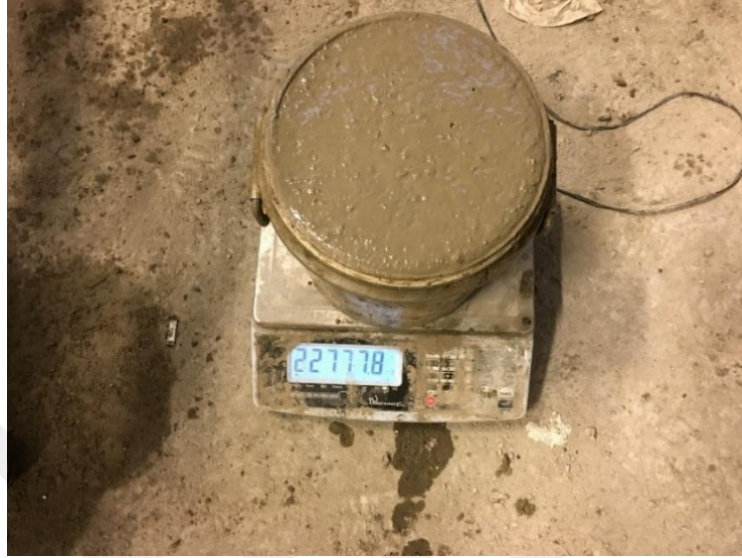


Figure 3.2: Unit weight test.

3.1.1.2. Hardened Mixture Experiments

3.1.1.2.1. Compressive Strength Test

The purpose of the pressure test is to determine the compressive strength of concrete. A sample of certain dimensions is placed in the press machine and the maximum load it can carry is determined. Then, the maximum load is divided by the area in contact with the press machine and the strength of the material is calculated [39]. In the study conducted in accordance with the TS EN 12390-3 standard, a pressure test was applied on cube samples with a side of 100 mm to determine the strength of materials on a certain day.

3.1.2. Carbon Fiber Reinforced Polymers (CFRP)

CFRP composite materials have been widely preferred in structural engineering applications in recent years due to their superior qualities such as high strength-to-weight ratio, excellent mechanical performance and corrosion resistance. CFRP plates, which are used especially for the reinforcement of reinforced concrete structural elements, offer lighter, more durable and easy-to-install solutions compared to

traditional methods. The CFRP plate used in this study consists of unidirectional carbon fibers and serves as an effective reinforcement function in elements with weak bending and shear strength thanks to its high elastic modulus and tensile strength.

The technical specifications of the CFRP plates in question are important in terms of correctly evaluating their mechanical performance and determining the parameters to be used in modeling. The CFRP plate used has an elasticity modulus of 165,000 N/mm² and a tensile strength of 3,000 N/mm² and allows a certain level of deformation before breaking with a 1.50% elongation at break. This plate, which has a thickness of 1.2 mm and a width of 30 mm, was applied by gluing it to the lower surface of the beam elements in the axial direction with a cross-sectional area of 36 mm². The CFRP plates used in the study were supplied by Master Builders Solutions Construction Chemicals. The product name is MasterBrace LAM.

Within the framework of these features, the mechanical behavior of the CFRP plate is summarized in **Table 3.4**, and the load transfer and structural reinforcement effect on this material were examined in detail in experimental applications.

Technical information and sample placement of the CFRP plate [37] used in the study are shown in **Table 3.4**.

Table 3.4: Mechanical Properties Of CFRP Plate [37]

Modulus of elasticity	165,000 N/mm ²
Tensile strength	3,000 N/mm ²
Elongation at break	1,50%
Thickness	1,2 mm
Width	30 mm
Cross-sectional area	36 mm ²

3.1.3. Epoxy Based Adhesives

One of the most critical components in the effective application of CFRP to reinforced concrete structural elements is the epoxy-based binders that perform the bonding process. Epoxy resins exhibit superior performance in the integration of FRP systems into the concrete surface thanks to their high bonding strength, chemical resistance, low shrinkage rate and controlled curing behavior. In this context, the effects of these parameters on the reinforcement system were evaluated comparatively by using two separate epoxy-based adhesives with different physical and mechanical properties in the study.

The epoxy-based adhesives used in the study were supplied by Master Builders Solutions Construction Chemicals and Fosroc Construction Chemicals. The epoxy adhesive with a density of 1.08 g/cm^3 used in the study is called MasterBrace SAT 4500 and is referred to as Product 1 in the study. The adhesive with a density of 1.30 g/cm^3 used in the study is called Fosroc Encapsulation Resin and is referred to as Product 2 in the study. The epoxy resins used in the study are distinguished from each other in terms of their mixing densities: Product 1 has a density of 1.08 g/cm^3 , lower viscosity and shorter working time (pot life); while Product 2 has a density of 1.30 g/cm^3 , higher viscosity and longer working time. Both products offer high compressive and flexural strength at the end of the 7-day curing period, and the adhesion strengths are declared by the manufacturer as $>3.00 \text{ N/mm}^2$ and $>4.00 \text{ N/mm}^2$, respectively.

In addition, the curing times of the products differ: While the full curing time of Product 1 is 7 days, Product 2 cures faster and reaches its full strength in 5 days. These differences are important factors that can affect the material selection depending on the environmental conditions and time during the application. The technical and mechanical properties of both adhesives are presented comparatively in **Table 3.5.** [35], [36].

The performance of these epoxy systems was particularly decisive in terms of the adhesion of CFRP sheets to the concrete surface and their effectiveness in load transfer and was considered as an important parameter in the experimental design of the study.

Table 3.5: Mechanical Properties Of Epoxy Resins [35], [36]

	Product 1	Product 2
Colour	Dark Blue	Blue
Mixture Density	1,08 g/cm ³	1,30 g/cm ³
Viscosity	1500-2500 mPa.s	100 P ± 20%
Compressive Strength /7 days)	> 60,00 N/mm ²	> 80,00 N/mm ²
Flexural Strength (7 days)	> 50,00 N/mm ²	> 40,00 N/mm ²
Bonding Strength	> 3,00 N/mm ²	>4,00 N/mm ²
Pot Life	30 min	70 min
Fully Curing Time	7 days	5 days

3.1.4. Carbon Nanotubes (MWCNT)

In recent years, with the development of nanomaterial technologies, nanometric additives such as CNT's have been widely used to improve the performance of structural materials. In this study, MWCNT additives were added to epoxy-based adhesives at certain rates and their effects on fiber-concrete interface behavior and general mechanical performance were investigated. It is known that MWCNTs produce remarkable results in composite systems due to their potential to delay crack propagation, act as micro-reinforcement, increase energy absorption capacity and improve load transfer mechanisms between fiber and matrix.

The MWCNT product used in the study is highly purified (> 92%) and has a modified structure to include certain surface functions (-OH group at a rate of 1.5%) and supplied by Nanografi Nanotechnology Company. The outer diameters of the nanotubes are in the range of 8–28 nm and their inner diameters are in the range of 5–10 nm; they have lengths ranging from 10 to 35 µm. These dimensional properties directly affect the dispersibility and surface interactions of nanotubes in the epoxy matrix.

The specific surface area of the MWCNTs used is 120 m²/g and has the potential to form a good interface with the resin thanks to its high surface activity. This material,

which has a real density of 2.20 g/cm³, was produced by the Chemical Vapor Deposition (CVD) method, which ensures that the nanotubes have homogeneous morphology and controlled structural properties. MWCNTs, whose electrical conductivity is measured at a high value such as 98 S/cm, can also be evaluated as a functional additive element in addition to mechanical reinforcement.

In this context, the basic physical and chemical properties of the MWCNT product used in the study are summarized in **Table 3.6**, and the performance changes obtained by adding this additive to the epoxy resin at different rates are analyzed in detail with experimental data [38].

Table 3.6: Properties of MWCNT [38]

Purity	> %92
(-OH) content	1.5 wt%
Colour	Black
Outer diameter (nm)	8,0 - 28,0
Inner diameter (nm)	5,0 - 10,0
Length (μm)	10,0 - 35,0
Tapped density (g/cm ³)	0,15
True density (g/cm ³)	2,20
Specific surface area (m ² /g)	120
Ash content (wt%)	9 wt%
Electrical conductivity (S/cm)	98
Production method	Chemical vapor deposition (CVT)



Figure 3.3: Picture of MWCNT [38]

3.2. Three Point Bending Test

3.2.1. Specimen Preparation

Beam samples were prepared to be 150x150x600 mm long. First of all, sample molds with dimensions of 150x150x1220 mm were prepared, cleaned and lubricated with mold release agent. The molds were divided with a 20 mm thick separator element and 2 beams were produced from one mold. The images of the prepared samples are as follows.



Figure 3.4: Sample Molds with Dimensions of 150x150x1220 mm.

All beam samples were produced from a single type of cement-based grout mixture. The cement-based ready-mixed grout mortar used was stacked in a closed environment at 20 °C and kept until use.



Figure 3.5: Storage of cement-based grout used in the mixture.

For the grout mixture, large containers were used in which 50 kg of ready grout mortar could be mixed at a time. A hand mixer with 400-600 rpm was used for mixing. Mixing water was added to the product at a water/powder ratio of 13.50%. The mixture to which water was added was first mixed at 400-600 rpm for 4 minutes, then waited for 1 minute and mixed again at 400-600 rpm for 4 minutes before being taken into the sample container. In this way, the homogeneity of the grout mixture was ensured.



Figure 3.6: Placing the prepared mixture into molds.



Figure 3.7: Samples placed in molds and kept for 24 hours.

In addition, cube samples with dimensions of 100x100x100 mm and cylindrical samples with dimensions of 100x200 mm were taken from the prepared mixture in order to measure the compressive and splitting tensile strengths, respectively.



Figure 3.8: Samples removed from the mold.

All of the produced samples were kept in the concrete curing pool at 25 °C for 28 days.



Figure 3.9: Samples removed from the cure pool on day 28.

Before reinforcement applications, the surface to be applied must be cleaned of dust and dirt, dry (moisture ratio $<4\%$) and as smooth and even as possible. In addition, it

is expected that the plaster and grout on the surface will be wiped off and removed. The samples removed from the mold were wiped to ensure adhesion with the adhesive and the application surface was prepared.



Figure 3.10: Beam sample surface after grinding.

The samples that were surface grinded and cleaned were made ready for CFRP plate bonding application. One of the issues that should be considered in CFRP plate bonding application is to keep the adhesive at +15-25 °C. In this way, epoxy-based resin shows optimum performance.

In the application of epoxy-based adhesives, first component A should be mixed for 30 seconds. Then, component B should be added to component A and mixed with a mixer with a capacity of at least 300 rpm. This process should continue for at least 3 minutes and a homogeneous mixture should be provided.

In addition, the part where the plate will be placed on the beam was marked before the bonding application and the possibility of test error was prevented.



Figure 3.11: Preparation of epoxy-based adhesive before application.

The prepared epoxy-based resin should be applied in equal thickness and homogeneously to both the plate surface and the concrete beam surface.



Figure 3.12: Applying the prepared resin homogeneously to both surfaces.

After applying the epoxy adhesive equally to both surfaces, the CFRP plate was bonded to the concrete beam. In order to avoid any gaps between the concrete surface and the CFRP plate, full adhesion is achieved by pressing with a roller parallel to the fiber direction.



Figure 3.13: Ensuring full adhesion of the CFRP plate to the concrete.

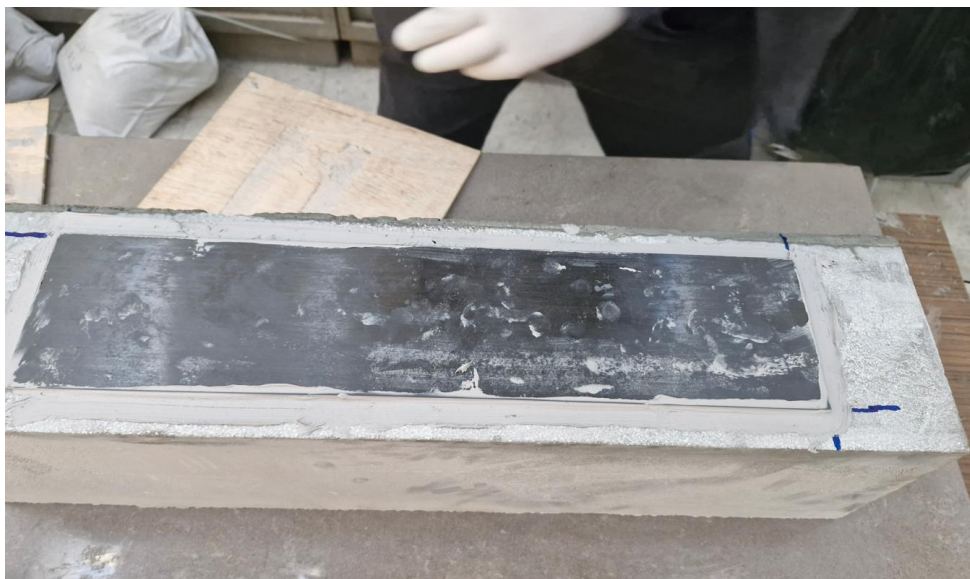


Figure 3.14. Reinforced beam specimen.

In the preparation of samples containing MWCNTs, the primary concern was to ensure that carbon nanotubes were distributed homogeneously in the epoxy resin. In the preparation of CNT-modified epoxy, CNTs were first added to the A component of the epoxies and mixed with a mechanical mixer for 15 minutes. Then, this mixture was sonicated in an ultrasonic device for 30 minutes.



Figure 3.15: Sonicator used for mixing of MWCNT.



Figure 3.16: MWCNT-epoxy resin component A mixed in sonicator.

The MWCNT/resin component A mixture was then mixed with the epoxy component B (hardener) at low speed for approximately 4 min. The process continued until the mixture reached a homogeneous consistency.

The prepared adhesive mixtures were applied to the concrete beam samples by spreading them evenly on the CFRP plate and concrete beam as detailed above. Before application, clearly marking the area where the CFRP plate will be bonded and passing over the bonded plate with a roller is extremely critical for the success of the application.

In addition, the MWCNT ratio in the epoxy resin significantly affected the appearance of the final mixture. As shown in **Figure 3.16**, the dosage increased, the color of the mixtures darkened, turning from light blue to dark navy blue, nearly black.



Figure 3.17: Samples produced with adhesive containing MWCNT (At top left; 0%, top right 0.5%, bottom left; 1.0%, bottom right; 1.5%, respectively.)

The width of the CFRP sheets used in the experiments were determined by tests conducted during preliminary studies. In this context, firstly, epoxy-based adhesives with 3 different densities (1.08, 1.30, 1.60 gr/cm³, respectively) were strengthened with 100 mm wide CFRP sheets as shown in **Figure 3.17** and subjected to three-point bending tests. As a result of the bending tests, it was observed that all of the samples underwent shear type deformation. The fracture types are shown in **Figure 3.18**. Afterwards, beams strengthened with 50 mm and 30 mm wide CFRP sheets were tested, respectively. In order to see the debonding effect more clearly, the experiments were carried out with 30 mm wide CFRP sheets. The placement of CFRP sheets on concrete beams is shown in **Figure 3.19**. In addition, since MWCNT did not disperse in the epoxy adhesive with a density of 1.60 gr/cm³ and a homogeneous mixture was not formed, this density epoxy was removed from the study program.



Figure 3.18: Beams produced during preliminary studies (with 100 mm wide CFRP plate and epoxy resin of 3 different densities)



Figure 3.19: Deformation of the beams produced in the preliminary studies

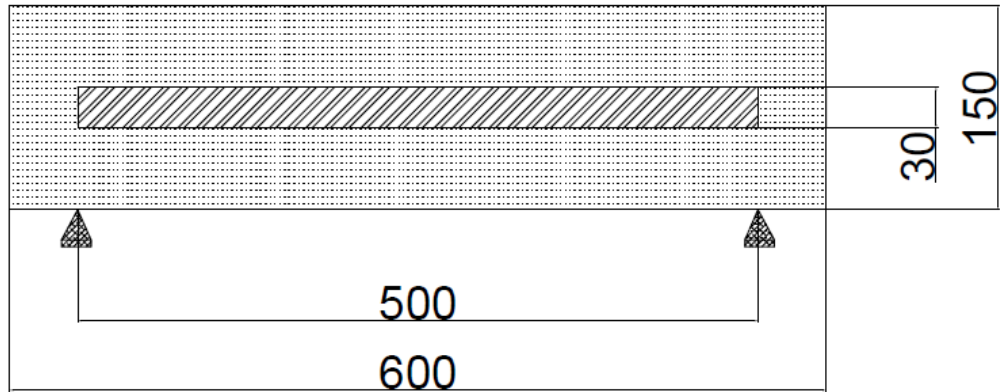


Figure 3.20: Theoretical placement of CFRP sheets on concrete beams

After the preliminary studies are completed and the experimental program is determined, it is aimed to see the effects of 2 different epoxy resins with 3 different MWCNT doses on reinforcement performance.

First of all, reference samples were prepared for this purpose. Reference samples are plain concrete beams that are not subjected to any treatment, are produced without reinforcement with cement-based grout mortar and no reinforcement application is made. They are coded as REF.

Afterwards, reference samples of 2 different types of epoxy resins were prepared. These samples are CFRP plate reinforced samples produced using epoxy-based adhesives with 1.08 gr/cm³ and 1.30 gr/cm³ densities. MWCNT reinforcement was not used in these samples. They are coded as EP1,XX_CNT0,0.

Finally, samples reinforced with epoxy adhesive reinforced with 3 different doses of MWCNT were produced. Since this is the purpose of this study, the performance of beams reinforced with different doses of MWCNT reinforced epoxy adhesive was examined. Samples are coded as EP1,XX_CNTYY.

Sample codes and descriptions are detailed in the table below.

Table 3.7: Coding of Samples

Sample Code	Explanation
REF	Unreinforced, CFRP plate-free samples
EP1,08_CNT0,0	Reinforced plates using 1.08 density epoxy resin
EP1,08_CNT0,5	Reinforced plates using 1.08 density epoxy resin and 0.5% MWCNT
EP1,08_CNT1,0	Reinforced plates using 1.08 density epoxy resin and 1.0% MWCNT
EP1,08_CNT1,5	Reinforced plates using 1.08 density epoxy resin and 1.5% MWCNT
EP1,30_CNT0,0	Reinforced plates using 1.30 density epoxy resin
EP1,30_CNT0,5	Reinforced plates using 1.30 density epoxy resin and 0.5% MWCNT
EP1,30_CNT1,0	Reinforced plates using 1.30 density epoxy resin and 1.0% MWCNT
EP1,30_CNT1,5	Reinforced plates using 1.30 density epoxy resin and 1.5% MWCNT

3.2.2. Three Point Bending Test Setup

The 3-point bending test is a test method used to evaluate the bending strength, elasticity modulus and other bending properties of a material. It is often used to determine the properties of bars, plates and similar plane materials. The sample is placed in a 3-point support device. This device involves three support points: 2 under the two extremities of the sample and 1 over a point in the middle of the sample. The test device applies a load to the upper surface of the sample. This load makes the sample bend under the support point in the middle of the sample. As the load gradually increases, one notes the bending behaviour of the sample.



Figure 3.21. Three point bending test set up at Istanbul Technical University



Figure 3.22. Placing the specimen in the equipment for the three-point bending test

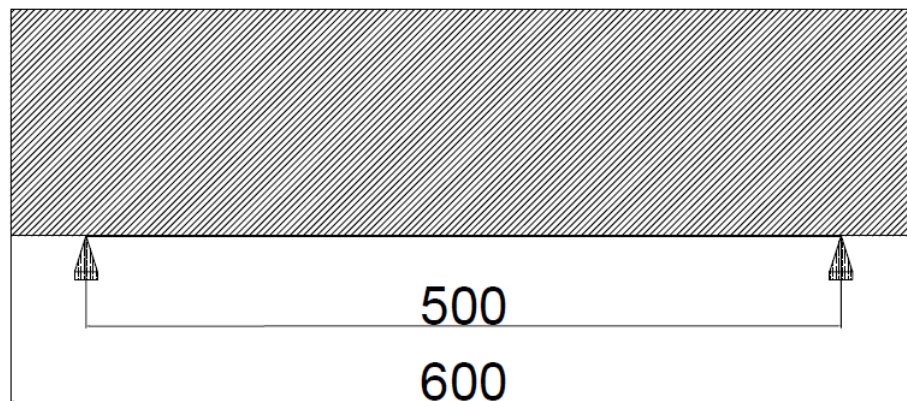


Figure 3.23: Theoretical layout of concrete beam for three-point bending test (CFRP plate is shown at the bottom of the beam, between the supports.)

4. RESULTS AND DISCUSSIONS

4.1. Material Property Test Results

4.1.1. Fresh Mortar Test Results

4.1.1.1. Cement Spreading Test

The spreading (consistency) test, which is conducted to evaluate the workability of fresh mortars, is a critical preliminary assessment test, especially in terms of material homogeneity, water/binder ratio and consistency control. This test allows the determination of rheological properties that directly affect the behavior of the mixture during the placement and application stages. In this test, which is conducted in accordance with the TS EN 1015-3 standard, after a certain volume of mortar sample is placed on the spreading table, the table is released for a standard number of blows, and the extent to which the mortar spreads with its own weight is measured.

The spreading diameters of the cement-based mortar mixtures produced within the scope of this study were measured on three replicate samples and the results obtained are presented in **Table 4.1**. The values obtained show the fluidity level and workability of the mixtures, and confirm that homogeneous and suitable consistency mixtures were obtained for advanced mechanical tests.

Table 4.1: Cement Spreading Test Results

	Sample 1	Sample 2	Sample 3
Spreading (TS EN 1015-3)	320 mm	315 mm	330 mm

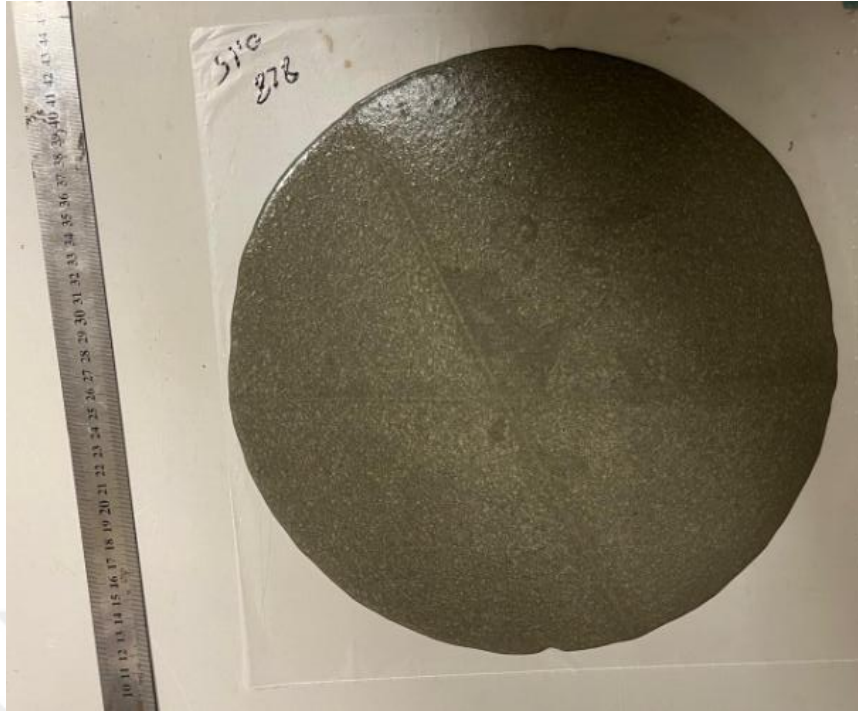


Figure 4.1: Cement spreading test according to TS EN 1015-3 [33]

4.1.1.2. Unit Weight Test

Determination of the physical properties of fresh and hardened mortars is of great importance in terms of evaluating the strength and performance criteria of the material. In this context, the unit weights of the mortar mixture used in the experimental study were determined in fresh and hardened states and compared with the manufacturer's declaration. Unit weight tests performed in accordance with the EN 12350 standard on fresh mortar samples provide information about the homogeneity and density level of the mixture. In addition, the physical stability of the material over time was evaluated with control measurements performed on the hardened mortar. The obtained data are presented in **Table 4.2** below.

Table 4.2: Unit Weight Test Results

	Sample 1	Sample 2
Fresh Mortar Unit Weight (EN 12350) (kg/m ³)	2281 kg/m ³	2278 kg/m ³
Hardened Mortar Unit Weight	2284 kg/m ³	2281 kg/m ³
Supplier Declaration (EN 12350) (kg/m ³)	2280 kg/m ³	

**Figure 4.2.** The unit weight measurements of the hardened samples

4.1.2. Hardened Mixture Test Results

4.1.2.1. Compressive Strength Test

One of the most decisive indicators of the mechanical performance of cement-based materials such as mortar and concrete is compressive strength. In this context, the compressive strength of the mortar mixture used in the study was measured in a laboratory environment at the end of 1, 7 and 28 days of curing periods on 100×100×100 mm cube samples in accordance with the EN 12190:1999 standard. The results obtained were evaluated in order to monitor the early age and final strength development of the material and to compare it with the minimum performance criteria

declared by the manufacturer. In this context, the experimental data obtained and the manufacturer's declarations are presented comparatively in **Table 4.3**.

Table 4.3: Compressive Strength Test Results

Compressive Strength 100x100x100 mm cube (EN 12190:1999)	1 day	7 days	28 days
Laboratory Test Results	18 N/mm ² , 1 day	44 N/mm ²	63 N/mm ²
Supplier Declaration	> 14 N/mm ²	> 42 N/mm ²	> 60 N/mm ²



Figure 4.3. The compressive strength results of the hardened samples (On the left, the test result of the 28-day cylindrical sample with dimensions of 200x100 mm, on the right, the test result of the cubic sample with dimensions of 100x100x100 mm)

4.2. Three Point Bending Test Results

Evaluation of mechanical performance of reinforced concrete elements reinforced with composite materials is of critical importance in terms of structural safety and durability. In this context, the bending behaviors of beam samples strengthened with epoxy-based adhesives and systems containing different amounts of MWCNT reinforcement were investigated with three-point bending tests. Epoxy resins used as the reinforcement system were selected at two different densities (1.08 g/cm³ and 1.30

g/cm³) and samples containing 0.0%, 0.5%, 1.0% and 1.5% MWCNT additives were prepared for each density. The maximum bearing capacity, bending strength, displacement behavior and energy absorption capacities of each sample group were evaluated in detail in comparison with the reference samples.

The maximum breaking loads obtained as a result of the three-point bending tests are presented in **Table 4.4**; the averages, standard deviations and calculated bending strength values of these values are presented in **Table 4.5**. According to the results obtained, it was observed that the samples without MWCNT additive but reinforced with epoxy reached approximately three times higher flexural strength compared to the reference samples. In both epoxy densities, the mixtures without MWCNT exhibited the highest strength, and a slight decrease in strength occurred with the addition of MWCNT. It was evaluated that this decrease occurred as a result of the epoxy matrix becoming brittle with the addition of MWCNT.

The experimental study was not limited to the bearing capacity only, and the load-displacement curves of the samples were also examined to reveal their deformation capacities. The maximum displacement and load values of the samples reinforced with epoxy with 1.08 and 1.30 g/cm³ density are detailed in **Table 4.6** and **Table 4.7**, and these data are visualized graphically in **Figure 4.7** and **Figure 4.8**. Although the MWCNT additive caused a partial decrease in the bearing capacity, an increase in the displacement capacity was observed. Specimens prepared with 0.5% MWCNT addition in particular showed ductile behavior by reaching the highest displacement values. However, it was observed that this increase became stable or decreased with the increase of MWCNT ratio to 1.0% and 1.5%.

Energy absorption capacities calculated from the areas under the load-displacement curves are presented in **Table 4.7** and compared in **Figure 4.9**. The effect of MWCNT addition took a different direction here. Specimens prepared with 0.5% MWCNT addition, especially in the epoxy group with a density of 1.08 g/cm³, weakened in terms of flexural strength but showed a significant increase in energy absorption capacity. On the other hand, although MWCNT addition generally reduced the energy absorption capacity in systems with a density of 1.30 g/cm³, these values approached the level of the mixture without MWCNT again at a 1.5% additive ratio. This shows that the MWCNT additive affects not only the load-bearing capacity but also important parameters such as ductility and energy absorption.

Finally, the fracture modes that occurred during the tests were also observed and examples are presented in **Figure 4.10** and **Figure 4.11**. It was determined that the strengthened beams generally cracked under the bending-shear effect and the CFRP sheet broke together with the debonding behavior. These observations revealed the direct effect of the bonding quality and fiber-matrix interaction on the performance of the system.

Table 4.4: Three Point Bending Test Results – Loads

Sample Code	Sample 1 (N)	Sample 2 (N)	Sample 3 (N)	Average (N)
REF	24797,0	14119,0	12854,0	17256,7
EP1,08_CNT0,0	36962,0	39915,0	40340,0	39072,3
EP1,08_CNT0,5	34848,0	36394,0	38550,0	36597,3
EP1,08_CNT1,0	32763,0	35566,0	36593,0	34974,0
EP1,08_CNT1,5	30553,0	34757,0	36234,0	33848,0
EP1,30_CNT0,0	44266,0	40385,0	41726,0	42125,7
EP1,30_CNT0,5	29250,0	33817,0	37142,0	33403,0
EP1,30_CNT1,0	31885,0	34279,0	32482,0	32882,0
EP1,30_CNT1,5	40907,0	34335,0	33247,0	36163,0

Table 4.5: Three Point Bending Test Results – Flexural Strength

Sample Code	Average (N)	Standard Deviation (N)	Flexural Strength (Mpa)	Standard Deviation (Mpa)
REF	17256,7	6560,7	3,451	1,312
EP1,08_CNT0,0	39072,3	1839,9	7,814	0,368
EP1,08_CNT0,5	36597,3	1859,4	7,319	0,372
EP1,08_CNT1,0	34974,0	1982,4	6,995	0,396
EP1,08_CNT1,5	33848,0	2947,6	6,770	0,590
EP1,30_CNT0,0	42125,7	1971,1	8,425	0,394
EP1,30_CNT0,5	33403,0	3962,3	6,681	0,792
EP1,30_CNT1,0	32882,0	1246,1	6,576	0,249
EP1,30_CNT1,5	36163,0	4144,3	7,233	0,829

Table 4.6: Load-Displacement Values of Three Point Bending Test

Sample Code	Sample 1			Sample 2			Sample 3		
	Load (N)	Max. Disp. (mm)	Energy (Joule)	Load (N)	Max. Disp. (mm)	Energy (Joule)	Load (N)	Max. Disp. (mm)	Energy (Joule)
REF	24797,0	1,32	16,30	14119,0	0,76	5,34	12854,0	0,78	5,03
EP1,08_CNT0,0	36962,0	1,87	34,49	39915,0	1,94	38,78	40340,0	1,98	39,98
EP1,08_CNT0,5	34848,0	2,41	41,99	36394,0	2,38	43,33	38550,0	2,28	43,89
EP1,08_CNT1,0	35566,0	2,08	36,97	32763,0	1,83	29,95	36593,0	2,01	36,79
EP1,08_CNT1,5	34757,0	1,90	32,93	30553,0	1,87	28,63	36234,0	2,25	40,84
EP1,30_CNT0,0	44266,0	2,45	54,20	40385,0	1,99	40,20	41726,0	1,74	36,24
EP1,30_CNT0,5	29250,0	2,21	32,32	33817,0	2,05	34,68	37142,0	2,26	41,97
EP1,30_CNT1,0	31885,0	1,92	30,66	34279,0	2,34	40,04	32482,0	2,12	34,37
EP1,30_CNT1,5	40907,0	2,59	53,04	34335,0	2,28	39,18	33247,0	2,18	36,27

Table 4.7: Energy Absorption Capacity

Sample Code	Sample 1	Sample 2	Sample 3	Average Displacement (mm)	Average Load (N)	Average Energy (Joule)	Std. Dev. (Joule)
	Energy (Joule)	Energy (Joule)	Energy (Joule)				
REF	16,30	5,34	5,03	0,95	17256,7	8,89	6,42
EP1,08_CNT0,0	34,49	38,78	39,98	1,93	39072,3	37,75	2,89
EP1,08_CNT0,5	41,99	43,33	43,89	2,36	36597,3	43,07	0,97
EP1,08_CNT1,0	36,97	29,95	36,79	1,97	34974,0	34,57	4,01
EP1,08_CNT1,5	32,93	28,63	40,84	2,01	33848,0	34,13	6,19
EP1,30_CNT0,0	54,20	40,20	36,24	2,06	42125,7	43,55	9,44
EP1,30_CNT0,5	32,32	34,68	41,97	2,17	33403,0	36,32	5,03
EP1,30_CNT1,0	30,66	40,04	34,37	2,13	32882,0	35,02	4,72
EP1,30_CNT1,5	53,04	39,18	36,27	2,35	36163,0	42,83	8,96

Generally, the strengthened samples achieved almost 3 times higher flexural strength results than the reference sample. Also, considering the standard deviation values, it can be said that there is no significant difference in flexural strengths of the beams strengthened with the epoxy -based adhesive with a density of 1.08 g/cm^3 and the epoxy-based adhesive with a density of 1.30 g/cm^3 .

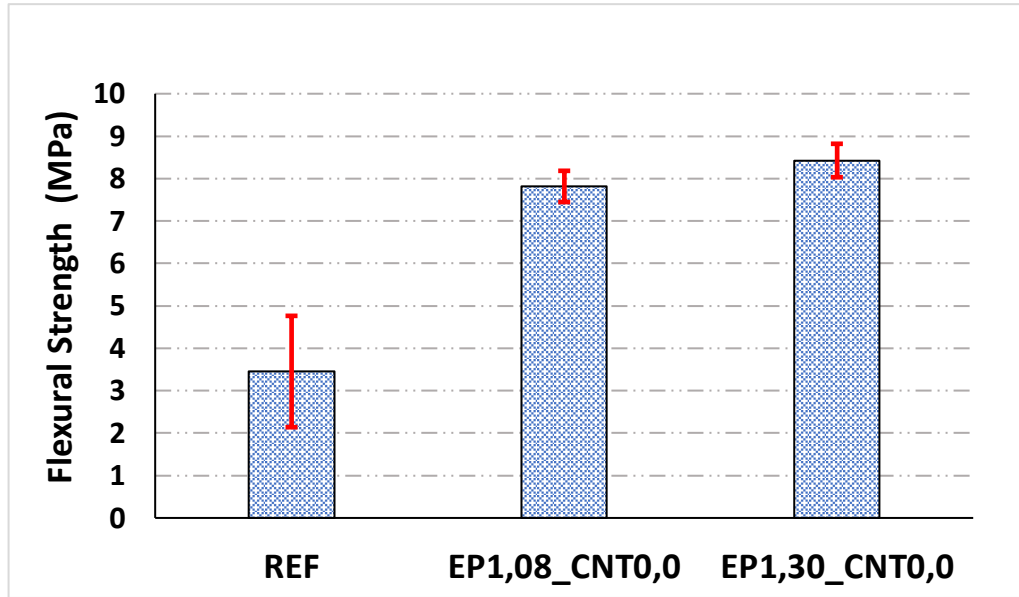


Figure 4.4: Comparison of flexural strength of samples without MWCNT

As seen in **Figure 4.5**, in epoxy samples with a density of 1.08 g/cm³, the highest flexural strength result was obtained in the mixture without MWCNTs, and a slight decrease in flexural strength was observed as the MWCNT addition amount increased. This shows that the epoxy product became brittle with the addition of MWCNTs.

As shown in **Figure 4.6**, the change in the flexural strength of epoxies with a density of 1.30 g/cm³ with the addition of MWCNT is given. In epoxy samples with a density of 1.30 g/cm³, the highest result was obtained in the mixture without MWCNT, similar to the 1.08 g/cm³ samples. When the standard deviation values are taken into consideration, it can be said that there is no significant difference between the different rates of MWCNT additions.

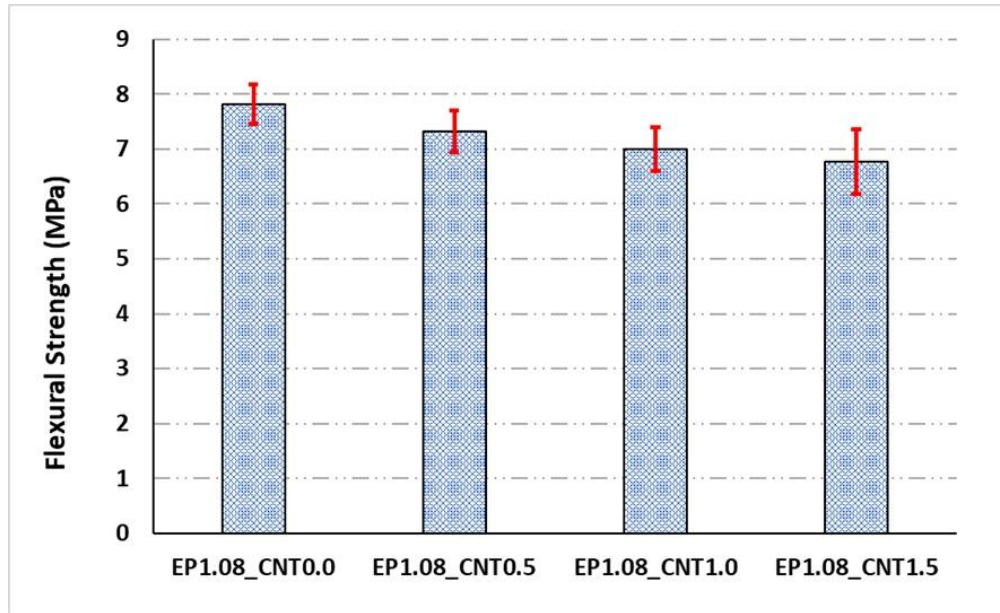


Figure 4.5: Comparison of bending strengths of 1.08 g/cm³ density epoxy samples with 3 different MWCNT ratios.

In addition to the graphs given above, all the results of the epoxy reinforced beam samples with 1.08 and 1.30 gr/cm³ density are shown together in **Figure 4.7**. As mentioned before, the highest strength in both groups was obtained in the samples without CNT. In addition, no significant difference was observed in the mixtures without CNT in both epoxies, and no significant difference occurred with the addition of CNT. This shows that the addition of CNT leads to similar behavior in both epoxies.

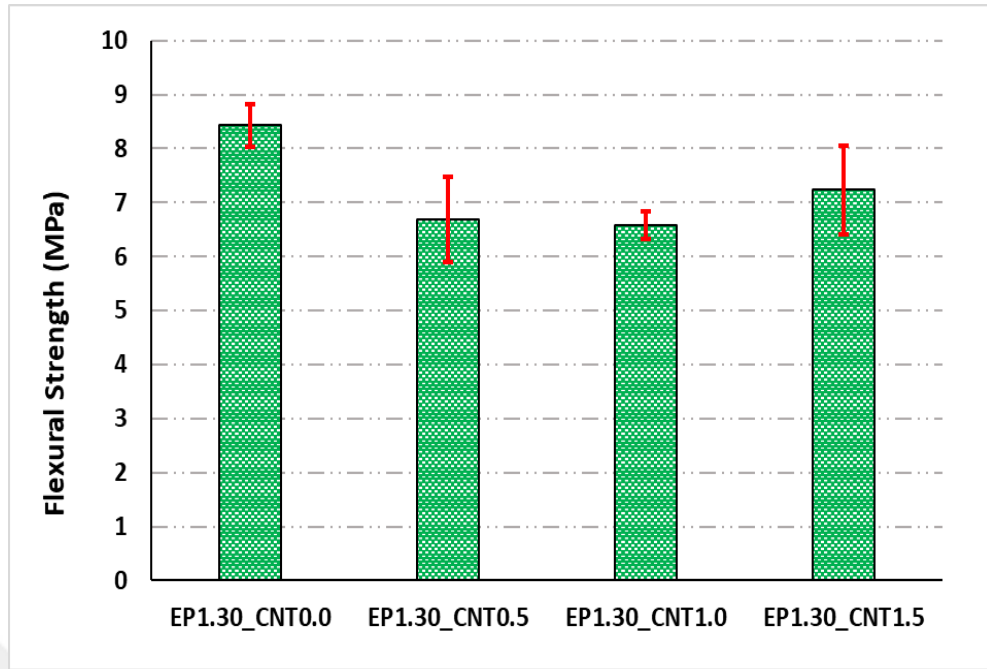


Figure 4.6: Comparison of bending strengths of 1.30 g/cm³ density epoxy samples

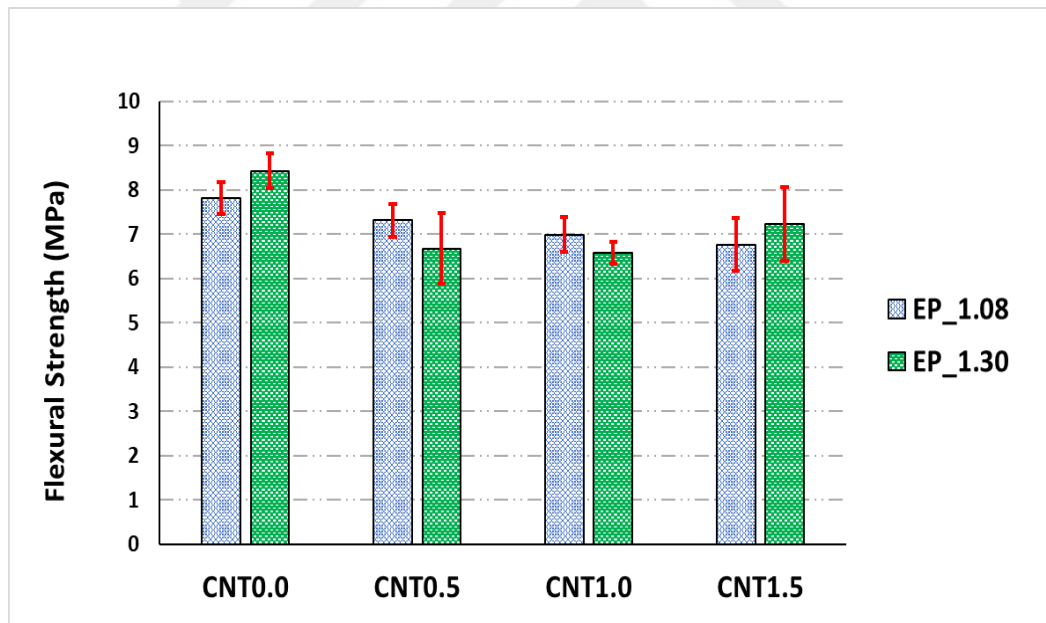


Figure 4.7: Comparison of flexural strengths of both density epoxy samples with different MWCNT ratio

Load-displacement relationships of epoxy reinforced beams with a density of 1.08 g/cm³, for which maximum displacement and load results are given in **Table 4.6** and **Table 4.7**, are given in **Figure 4.8**. When the graph is examined, the load decreased

with the addition of MWCNT, but an increase in the displacement value was observed. In addition, while the highest displacement value was obtained in the mixture containing 0.5% MWCNT, when the MWCNT addition was increased to 1 or 1.5%, a similar result was obtained to the mixture without MWCNT.

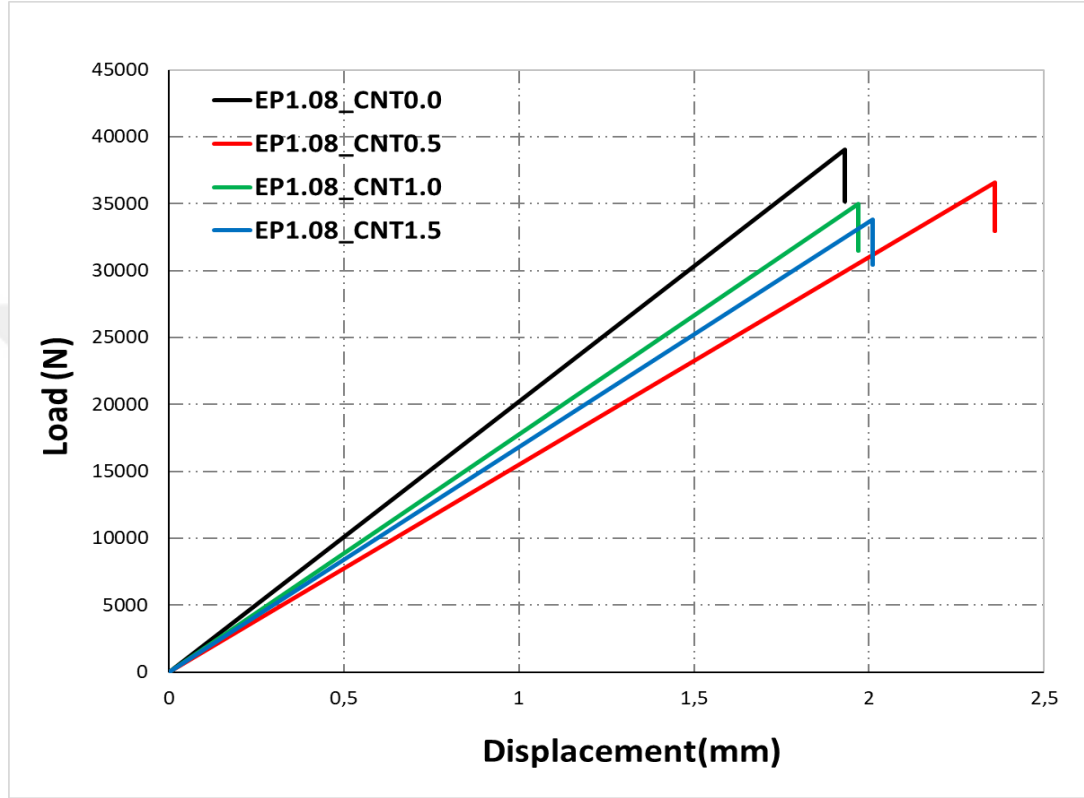


Figure 4.8: Comparison of load-displacement of 1.08 g/cm³ density epoxy samples with different MWCNT ratio

A graph similar to **Figure 4.8** was also drawn for the results of samples strengthened with epoxy having a density of 1.30 and is given in **Figure 4.9**. As in epoxies having a density of 1.08, the displacement value at maximum load increased with the addition of MWCNT. However, this increase was very little for 0.5% and 1.0% MWCNT addition but became much more pronounced when this rate was increased to 1.5%.

The energy absorption capacity of beams strengthened with epoxy having 1.08 and 1.30 gr/cm³ density was calculated by calculating the areas under the graphs in **Figure 4.8** and **Figure 4.9**, and the graph containing the results is given in **Figure 4.9**. Unlike the bending strength results, the addition of 0.5% CNT decreased the bending strength

for beams strengthened with epoxy having 1.08 gr/cm³ density but caused an increase in the energy absorption capacity. In beams strengthened with epoxy having 1.30 gr/cm³ density, although a decrease in the energy absorption capacity was observed with the addition of CNT, almost similar energy value was obtained with the mixture without CNTs with the addition of 1.5% CNT.

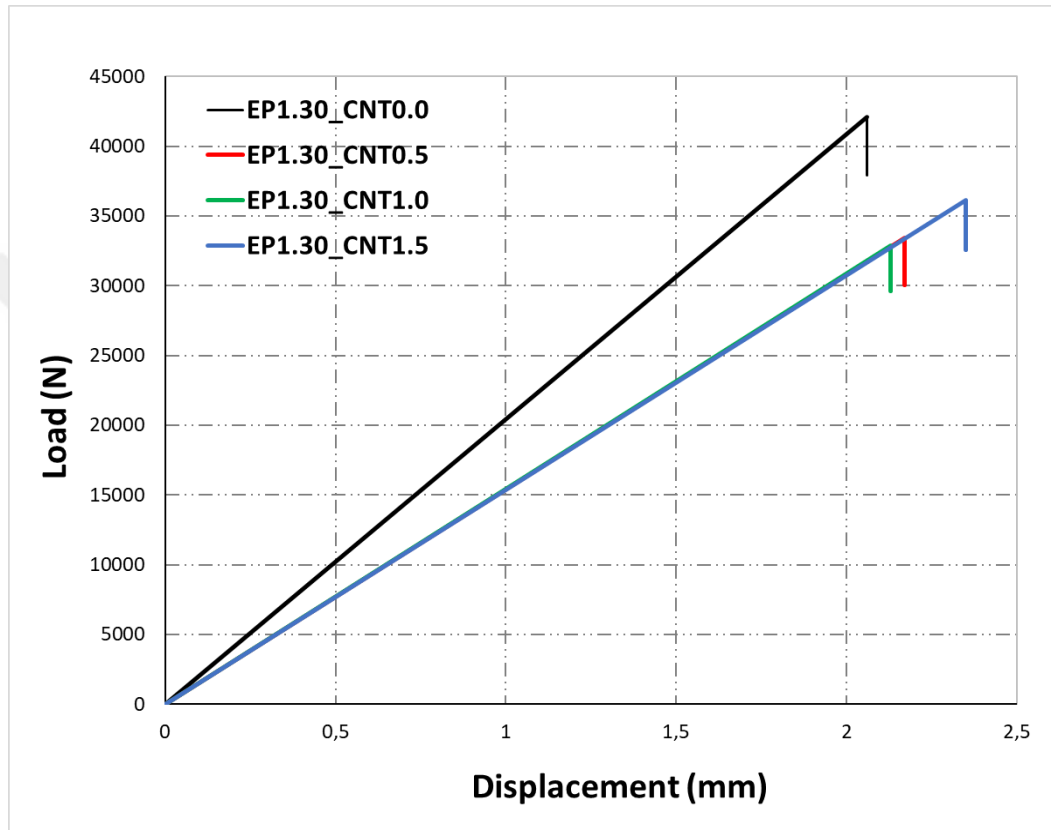


Figure 4.9: Comparison of load-displacement of 1.30 g/cm³ density epoxy samples with different MWCNT ratio

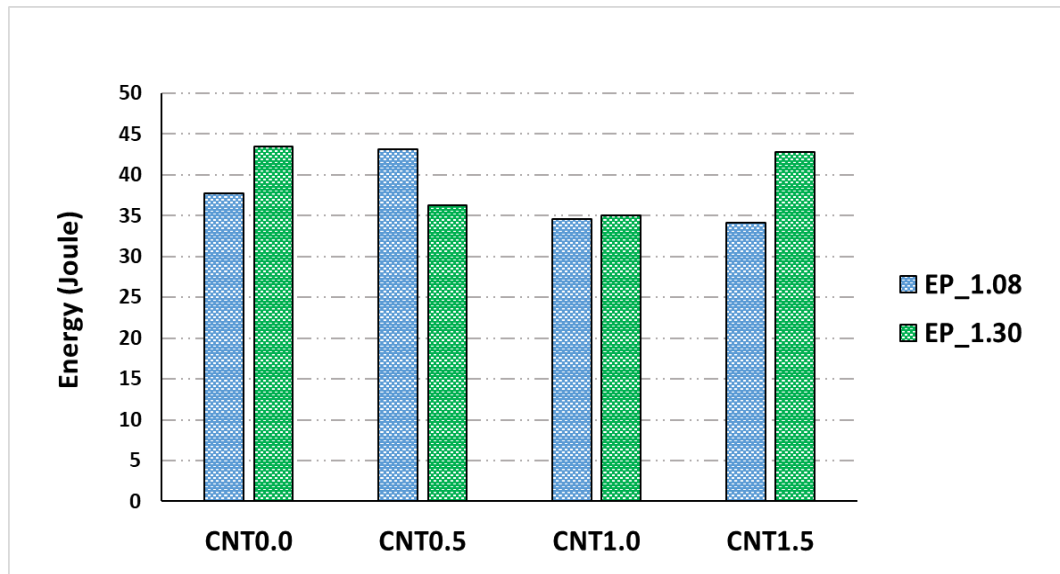


Figure 4.10: Comparison of energy absorption capacity both density epoxy samples with different MWCNT ratio

The strengthened beams split under flexural-shear loads and broke as a result of the separation of the CFRP sheet. Images of the broken specimens are shown in **Figure 4.11**, **Figure 4.12** and **Figure 4.13**.



Figure 4.11: Fracture shape of beam sample and debonding of EP1.08-CNT0.5



Figure 4.12: Fracture shape of beam sample and debonding of EP1.08-CNT0.5



Figure 4.13: Fracture shape of beam samples with code EP-1.30

5. CONCLUSIONS

This paper investigated the effect of MWCNT ratio on increasing the strength efficiency of reinforced concrete beams reinforced with MWCNT reinforced epoxy composites and CFRP plate by using epoxy adhesives of different densities. A total of twenty-seven beams were cast, reinforced with CFRP plate and tested under three-point loading. The integration of MWCNTs was achieved by mixing them with sonicator aid in epoxy-based resins. The effect of epoxy modification with MWCNT's was investigated by subjecting to three-point bending test and the following conclusions were reached.

1. All strengthened samples exhibited approximately three times higher flexural strength compared to the reference samples. Furthermore, no significant difference in strength was observed between both types of epoxy.
2. In epoxy samples with a density of 1.08 g/cm^3 , the highest flexural strength was obtained in the mixture without MWCNT; there was a slight decrease in strength as the MWCNT ratio increased. This shows that the brittleness of the epoxy matrix increased with the nanotube addition.
3. Similarly, in epoxy samples with a density of 1.30 g/cm^3 , the highest flexural strength was observed in the mixture without MWCNT. It was observed that there was no significant difference between different additive ratios.
4. When the results of both epoxy groups were examined together, the mixtures without CNTs provided the highest strength, while the addition of CNTs showed similar trends in both 1.08 and 1.30 g/cm^3 density resins.
5. When the load-displacement relationships were examined, the addition of MWCNT in epoxy reinforced beams with a density of 1.08 g/cm^3 decreased the load capacity while increasing the displacement amount. The highest displacement was obtained in the sample containing 0.5% MWCNT, and this increase decreased at 1% and 1.5%.
6. A similar trend was observed in epoxies with a density of 1.30 g/cm^3 ; while a limited increase was achieved with low-rate additives, 1.5% MWCNT additive created a significant increase in displacement.

7. When evaluated in terms of energy absorption capacity, the addition of 0.5% CNT in epoxies with a density of 1.08 g/cm^3 decreased the flexural strength but increased the energy absorption capacity. On the other hand, although the energy absorption capacity decreased with the addition of CNT in samples with a density of 1.30 g/cm^3 , it approached the levels of the mixture without CNT with 1.5% addition.
8. When evaluated in terms of debonding, all beams strengthened with 30 mm wide plates experienced fracture in shear in bending, while no fracture occurred in the CFRP plates. Post-fracture debonding between the CFRP plates and the beams occurred at the adhesive interface. The same type of failure and debonding was observed in all samples. There was no clear difference in the debonding pattern between the epoxy density and MWCNT dosage.

These results generally reveal that CNT addition can have significant effects not only on strength but also on mechanical properties such as ductility and energy absorption, but this effect varies depending on the resin density and addition ratio.

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BIOGRAPHY

After completing my high school education at Sinop Science High School in 2010, I joined the Civil Engineering Department of Istanbul Technical University the same year. I graduated from Istanbul Technical University, Civil Engineering Department in 2016. In May 2016, I started working as the Underground Structures Regional Sales Representative in the Construction Chemicals Department of BASF Türk Kimya. As of January 2022, I continued as the Underground Structures Regional Sales Manager at Master Builders Solutions Construction Chemicals. For approximately 8 years, I carried out the sales and technical support processes of construction materials in highway, railway, dam and metro tunnels and mining projects. In addition to these duties, I took part in the preparation of monthly, annual, 3-year and 5-year plans and budgets in the last 2 years. In addition, I managed the creation and implementation of marketing activities in the last 2 years. I left the company as of October 2023 and started my business life as the founding partner of The Roc Construction Technologies Industry and Trade Inc. in January 2024. I am currently carrying out the sales activities of the products in the portfolio of underground construction chemicals and the applications of reinforcement, injection, repair, maintenance and insulation items in infrastructure projects. I am married and have one child.

PUBLICATIONS AND PRESENTATIONS FROM THE THESIS

Cisdik, C.M., Acar, V., Cakir, F. (2025). "CFRP takviyeli beton kirişlerde kompozit-beton arayüz mekaniğinin incelenmesi" in Bursa 4th International Conference on Mathematics and Engineering, Bursa, Turkey.

