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Research Article / Araştırma Makalesi

Examination of The Mechanical Properties of Carbon Fiber Reinforced Concrete Under Impact Loads

Karbon Lifli Betonların Mekanik Özelliklerinin Darbe Yükleri Altında İncelenmesi

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Abstract

This study examined the impact response of carbon fiber-reinforced concrete under low-velocity impacts. The tests were executed utilizing the instrumented drop-weight test setup, which is also proposed in ACI 544.2R. The study focused on two specific lengths of fiber: one measuring 3 mm, and another measuring 12 mm. The fiber content of the mixtures was 5 kg/m^3, 10 kg/m^3, and 15 kg/m^3, based on the concrete volume. The impact behavior was analyzed using force and energy graphs derived from the time history data. Research showed that 3 mm short fibers outperformed 12 mm long fibers. All fiber-reinforced samples, except for the 12_15 mixture, improved energy dissipation compared to the control concrete. The 3_15 mixture exhibited the highest energy dissipation at 162.1%, relative to control sample, followed by 12_10 at 137.4%. The damage patterns indicated that the control samples and the 12_15 mixture were the most damaged, while the 3_15 mixture showed the least damage.

Anahtar Kelimeler: *Karbon lifli beton, Darbe davranışı, Aletli ağırlık düşürme, Enerji emilimi*

Öz

Bu çalışma, karbon fiber takviyeli betonun düşük hızlı darbe altındaki tepkisini incelemiştir. Testler, ACI 544.2R'de de önerilen, aletli ağırlık düşürme test düzeneği kullanılarak gerçekleştirilmiştir. Çalışma, 3 mm ve 12 mm olmak üzere iki farklı fiber uzunluğuna odaklanmıştır. Karışımların fiber içeriği, beton hacmine bağlı olarak 5 kg/m^3, 10 kg/m^3 ve 15 kg/m^3 olarak belirlenmiştir. Darbe davranışı, zaman tanım alanında elde edilen kuvvet ve enerji grafikleri kullanılarak analiz edilmiştir. Araştırma, 3 mm kısa fiberlerin 12 mm uzun fiberlerden daha iyi performans gösterdiğini ortaya koymuştur. 12_15 karışımı hariç tüm fiber takviyeli numuneler, kontrol betonuna kıyasla enerji emilimini iyileştirmiştir. 3_15 karışımı %162,1 ile en yüksek enerji dağılımını gösterirken, bunu %137,4 ile 12_10 karışımı izlemiştir. Hasar durumları, en fazla hasarı kontrol örneklerinin ve 12_15 karışımının aldığını, en az hasarı ise 3_15 karışımının aldığını göstermektedir.

Keywords: *Carbon fiber reinforced concrete, Impact behavior, Instrumented drop-weight, Energy dissipation*

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1. Introduction

Concrete is recognized as a brittle material, largely due to its low tensile strength in comparison to its high compressive strength, which results in sudden fractures [1]. While the tensile strength of concrete is often overlooked, enhancing it and managing crack development has become increasingly vital in modern engineering challenges. Fiber reinforcement presents a practical solution for a wide range of applications, influencing both everyday scenarios and specialized fields such as nuclear power plants and military structures. For example, in industrial facilities, fiber reinforcements can effectively control crack development in concrete floors that are frequently subjected to vibrations from dynamic loads. Research has shown that the fibers significantly enhance the seismic performance of reinforced concrete elements when exposed to earthquake conditions, serving both design and strengthening objectives [2]. Fiber-reinforced concrete is made using various types of fibers, including stainless steel, carbon steel, polypropylene (PP), glass fibers (GFRC), polyvinyl alcohol (PVA), and carbon fibers. These fibers can vary in fineness, strength, and elasticity. The use of fiber-reinforced concrete offers multiple benefits, such as reducing microcracks and shrinkage cracks, enhancing fracture toughness, minimizing brittle behavior, and improving resistance to both low- and high-velocity impacts [3]. Additionally, fibers increase energy dissipation during dynamic loads, enhance freeze-thaw resistance, improve abrasion resistance, and help maintain concrete integrity in diverse conditions [4,5,6].

Carbon fibers provide several advantages, including high abrasion resistance, UV protection, a high modulus of elasticity relative to their weight, excellent creep resistance, and strong resistance to chemicals and environmental factors. These qualities make them ideal for seismic strengthening, historical structures, modern bridges, high-speed railways, and airport runways. However, drawbacks include high cost, fire sensitivity, and recycling challenges [7]. Fiber-reinforced concrete is a popular research topic, with numerous symposiums held annually [8, 9]. Researchers are focused on developing sustainable and efficient concrete technologies, exploring new material concepts, structural applications, and updating relevant standards [10].

Recent research has increasingly focused on the behavior, durability, and mechanical properties of fiber-reinforced concrete under various loading conditions. Common fiber types include basalt, aramid, glass, and carbon. Aduwenye et al. [11] found that carbon fiber-reinforced concrete (CFRC) displays enhanced mechanical properties due to the fibers' ability to seal cracks and strengthen the interface transition zone (ITZ). CFRC performs well in diverse environmental conditions, including freeze-thaw cycles and acidic environments, although the effects on compressive strength remain inconclusive. Dündar et al. [12] investigated fiber-reinforced concrete mixtures with fiber volumes of 0.5%, 1%, 1.5%, and 2%. They noted that basalt fibers were effective at ratios up to 1.5% for compressive strength, while carbon fiber increased strength only at a 2% ratio. Basalt fibers were more effective for compressive strength, but flexural strength was influenced by the fiber ratio. Fiber use also improved abrasion resistance. Akın et al. [13] studied the effects of various lengths of finely chopped corn leaf fibers (fine cut, 0.75, 1.5, 3, and 6 cm) on prismatic concrete specimens. They observed that adding the shortest (fine-cut) fibers to the concrete increased flexural and compressive strengths. However, beyond this length, the strengths decreased as fiber length increased (specifically at lengths of 0.75 cm, 1.5 cm, 3 cm, and 6 cm), with the best performance at the shortest fiber length. Alkayış and Başyiğit [14] reviewed studies on the impact behavior of concrete, finding that a controlled increase in steel fiber quantity enhances impact resistance and mechanical properties. They identified spiral and hook shapes as most effective and noted that longer fiber lengths also improve impact resistance. Demirel and Gönen [15] examined various fiber sizes' effects on concrete capillarity and reported that longer carbon fibers reduced compressive strength. Safiuddin et al. [16] examined the mechanical properties and microstructures of carbon fiber self-compacting concrete. They found that carbon fibers reduced compressive strength in volumes of 0% to 1% but increased splitting tensile strength due to bridging effects. The optimal fiber distribution was 0.25%, which improved flexural strength compared to conventional concrete. However, higher fiber ratios led to agglomeration, as seen in scanning electron microscope images. Şahan and Ünsal [3] studied the effect of steel fiber content on the

bending resistance of 100x100x500 mm concrete beams. Using steel fiber volumes of 0.25% (19.5 kg/m³), 0.50% (39 kg/m³), and 0.75% (58.5 kg/m³), they found that fiber-reinforced concrete showed greater resistance to fractures and reduced crack widths under dynamic loads. An additional study [4] indicated that polypropylene fiber reinforcement further improved performance under impact loads. Tong et al. [5] emphasized the capacity of carbon fibers to retain material stiffness even at high-strain rates. Wang et al. [6] used carbon nanofibers and observed enhanced impact resistance during repeated drop-weight tests. They also confirmed improved abrasion resistance as the fiber dosage increased. A study [17] was conducted to examine the static and dynamic performance of carbon fiber reinforced concrete (CFRC) under varying conditions, specifically temperatures ranging from 200°C to 800°C and impact loading. The results indicated that, although the incorporation of carbon fibers had a limited impact on compressive strength, it significantly mitigated damage to specimens subjected to high temperatures and dynamic loading scenarios. The study emphasized that CFRC possesses the capacity to effectively prevent sudden structural collapse by reducing the likelihood of brittle fractures in structures exposed to abrupt impacts and bursts. Additionally, the material demonstrated exceptional energy dissipation and deformation capabilities before fracture. The experimental outcomes provided both theoretical insights and technical guidance for the development of concrete mix designs that can endure the dual challenges of high temperatures and load pressures.

While the existing literature includes numerous studies on carbon fiber reinforced concretes, research investigating their behavior under low-velocity impact loading is notably scarce. This study explores the performance of carbon fiber-enhanced concrete under static loads and low-velocity impact conditions, with particular attention given to the influence of fiber slenderness on overall performance. In addition to fabricating 100 mm cube specimens, disc specimens with a thickness of 63.5 mm and a diameter of 152 mm were produced for dynamic testing, in accordance with the recommendations outlined in ACI 544.2R [18]. An instrumented drop-weight test setup was employed to evaluate the concrete's performance under low-velocity impact loads. The study utilized two different aspect ratios of carbon fibers, specifically 3 mm and 12 mm in length. Six distinct mixtures were formulated using carbon fibers at ratios of 5 kg/m³, 10 kg/m³, and 15 kg/m³ for each fiber type, relative to the concrete volume. The data from the low-velocity impact tests allowed the generation of time-domain load, displacement, and energy curves. This process enabled a comprehensive interpretation of the influence of carbon fiber reinforcement on the dynamic responses of the concrete.

2. Material and Methods

A total of seven concrete mixtures were formulated for the study. This included three distinct concrete mixtures with 3 mm fiber, three distinct concrete mixtures with 12 mm fiber, and a control mixture without fiber reinforcement. For instance, the designation 3_15 for a mixture refers to 15 kg of carbon fiber per cubic meter, with a length of 3 mm. Disc samples with a diameter of 152 mm and a thickness of 63.5 mm were prepared for the impact events following the recommendations outlined in ACI 544.2R [18]. Cement, water, and aggregate ratios remain consistent across all mixtures, as specified per cubic meter in Table 1. The specified water-to-cement ratio is 0.48.

Table 1. Concrete mix (per cubic meter)

Material	Amount (kg)
Cement	446
Water	214
Fine Aggregate	589
Medium Aggregate	553
Coarse Aggregate	518

Carbon fibers of two distinct lengths, 3 mm and 12 mm, were employed for analysis. The mechanical properties and corresponding image are detailed in Table 2 and Figure 1, respectively, as provided by the supplier, DostKimya [19].

Table 2. Properties of carbon fiber

Properties	Value
Tensile strength	3800 (MPa)
Modulus of elasticity	228 (MPa)
Specific gravity	1.81 (g/cc)
Fiber diameter	7.2 mikron
Fiber length	3 mm – 12 mm
Carbon Content	%95

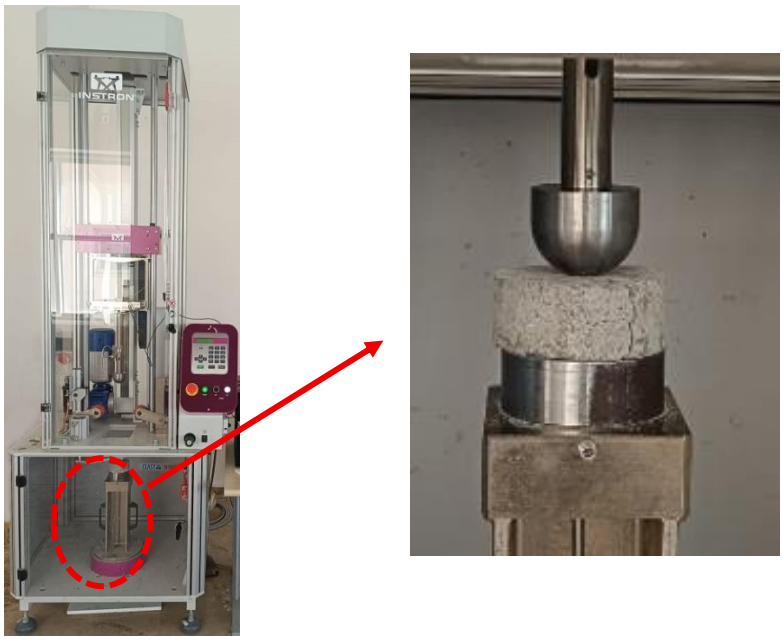


a) b)

Fig.1. Illustration of carbon fiber a) 3 mm b) 12 mm [19]

The fiber incorporation into the mixtures was 5 kg/m³, 10 kg/m³, and 15 kg/m³, based on the concrete volume. Disc samples with a diameter of 152 mm and a thickness of 63.5 mm were prepared for the impact events following the recommendations outlined in ACI 544.2R [18]. To assess the quasi-static compressive strength and splitting tensile strength, which are essential characteristics of concrete, cube samples measuring 100 mm were fabricated from each mixture, in accordance with TS EN 12390-1 [20], TS EN 12390-3 [21], and TS EN 12390-6 [22]. A total of 63 samples were prepared for the purpose of conducting static compression, splitting tensile, and impact tests. This included three representative samples from each of the seven distinct mixtures.

Low-velocity impact tests were performed using the Instron Ceast 9350 test setup, in accordance with the specifications outlined in ACI 544.2R [18]. The impact energy level was calibrated to 200 joules by adjusting the weight to 26.235 kg, allowing it to free fall from a height of 777 mm. A hemispherical striking tip with a diameter of 63.5 mm was employed to contact the samples. The configuration of the instrumented drop-weight impact test setup is depicted in Fig. 2 [1]. This instrumented approach facilitates a time history analysis of load, displacement, and energy during an impact event [23-25].



a) b)

Fig. 2. The instrumented drop-weight test machine a) Instron Ceast 9350 b) Hemispherical striking tip

3. Results And Discussion

3.1. Quasi-static test results

Figure 3 presents the 28-day compressive and splitting tensile strength values. The displayed error bars represent the variation of plus or minus one standard deviation. The inclusion of 3 mm carbon fibers at a dosage of 5 kg/m³ resulted in a 23.1% increase in compressive strength compared to the control samples. At a fiber content of 10 kg/m³, the compressive strength remained consistent with the control samples; however, a content of 15 kg/m³ led to an 18.9% reduction in strength. For the 12 mm carbon fibers, the optimal results were observed with a fiber content of 10 kg/m³, yielding a 27.7% enhancement in compressive strength. Conversely, fiber amounts of 5 kg/m³ and 15 kg/m³ resulted in decreases in compressive strength of 38.3% and 35.4%, respectively. Existing literature suggests that increasing the length of carbon fibers generally diminishes the compressive strength of concrete [15]. This trend also appears in the other 12 mm mixtures, except for the 12_10 sample. Furthermore, a separate study that utilized natural fibers indicated that the compressive strength of concrete declined as fiber content increased [13]. A similar effect is observable in the data for the 3 mm mixtures. Nonetheless, some studies argue that the influence of carbon fibers on compressive strength is limited [17], while others assert that they can enhance compressive strength when utilized in appropriate proportions [12, 16].

The addition of 5 kg/m³ of 3 mm carbon fibers resulted in a 16.3% increase in tensile strength compared to the control samples. At a fiber content of 10 kg/m³, the increase was measured at 7.5%. However, with 15 kg/m³ of fiber content, the tensile strength values were comparable to those of the control samples. For the 12 mm carbon fibers, the most pronounced results were found with a mixture of 10 kg/m³, yielding a 19.1% increase in tensile strength. In contrast, fiber contents of 5 kg/m³ and 15 kg/m³ led to decreases of 13.8% and 12.4% in tensile strength, respectively. The most significant enhancements in both compressive and tensile strengths were observed at 5 kg/m³ for the 3 mm fibers and 10 kg/m³ for the 12 mm fibers.

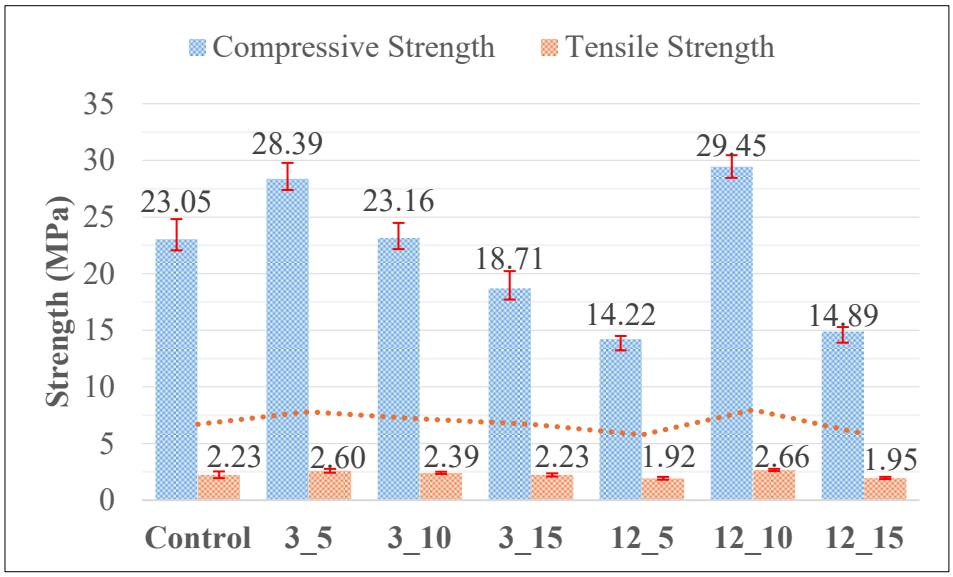


Fig. 3 28-day compressive and splitting tensile strength results

3.2. Dynamic drop-weight test results

The average force-displacement curves for each mixture are presented in Figure 4. The curves represent the average values obtained from three samples corresponding to each mixture. In general, there was a tendency for the maximum force to decline when comparing control samples to fiber-reinforced samples. Remarkably, the 3_15 mixture demonstrated a unique characteristic, increasing the maximum force by 1.7%. A comparative analysis of the energy-displacement curves is illustrated in Figure 5, which presents the mean value for three samples per mixture.

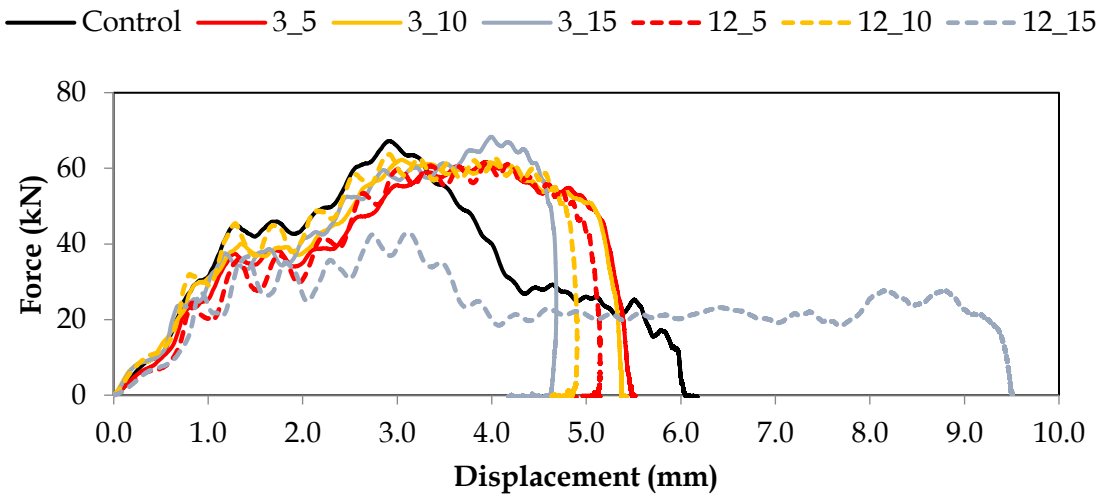


Fig. 4 Force – displacement relation under impact event

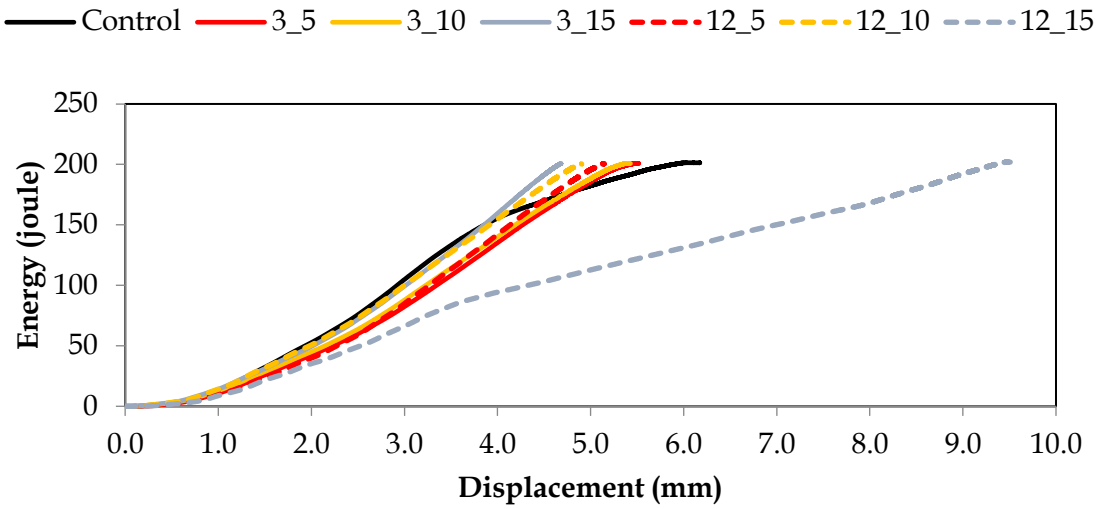


Fig. 5 Energy – displacement relation under impact event

Figures 6 and 7 were prepared to visualize the maximum force and peak energy values. The 12_10 mixtures, which stood out for static strength in the 12 mm fiber group, showed a 5.2% decrease in maximum force under impact load compared to the control mixtures. Similarly, in the 3_5 mixture, which stood out for static strength in the 3 mm fiber group, the maximum force decreased by 8.2%. An increase in energy was observed across all fiber-reinforced mixtures, except the 12_15 samples. Notably, the 3_15 samples exhibited the highest increase, reaching 62.1%. Generally, it can be concluded that mixtures utilizing 3 mm fibers demonstrated superior performance compared to those incorporating 12 mm fibers.

The energy dissipation of the 12_15 mixture was only 55% of that observed in the control mixture, whereas the 12_5 and 12_10 mixtures exhibited a high level of energy dissipation. Optimal fiber content levels are crucial for fiber-reinforced concrete. When fiber content exceeds this optimal range, the fiber within the concrete matrix undergoes a cycle of "dispersion - saturation - agglomeration." Excessive fiber content can lead to significant agglomeration, resulting in increased porosity, decreased material density, heightened heterogeneity, and diminished specimen strength [26]. The observed decline in performance can be attributed to this issue. This finding underscores that excessive fiber use can adversely affect concrete's overall performance.

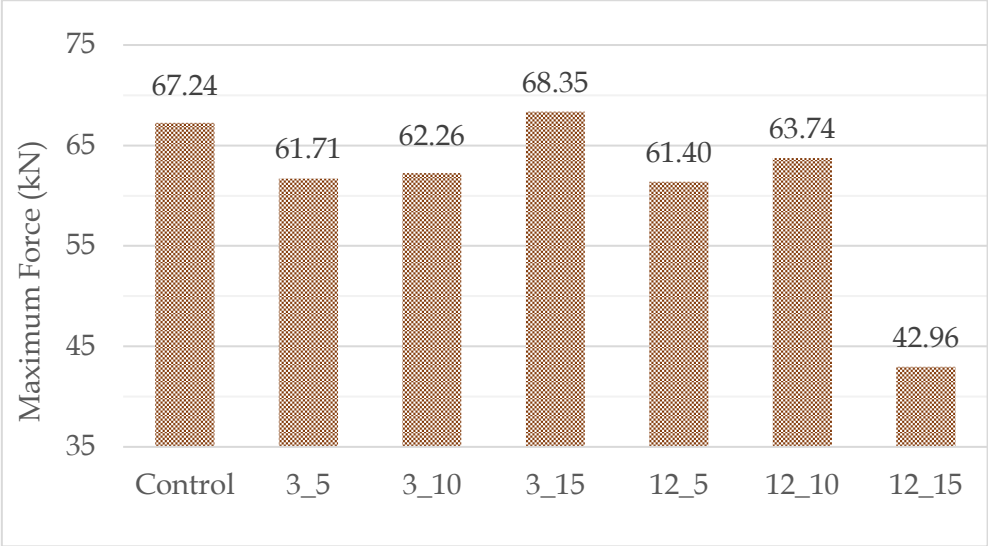


Fig. 6 Average maximum force under impact event

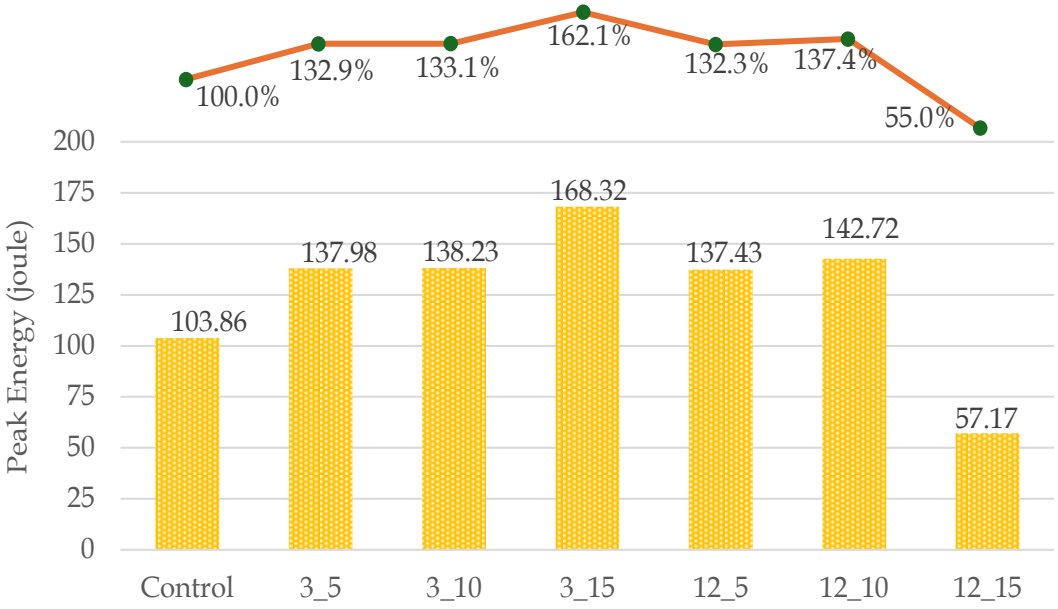


Fig. 7 Average energy dissipation under impact event

The numerical values for the maximum force and energy in Figures 6 and 7 are provided in Table 3.

Table 3 Maximum force and corresponding energy dissipation values

Sample	Fiber Amount (kg/m³)	Maximum Force (kN)		Energy Dissipation (Joule)	
		Mean Strength	Standard Deviation	Mean Strength	Standard Deviation
Control	-	67.24	4.77	103.87	9.10
3_5	5	61.71	2.91	137.98	34.38
3_10	10	62.26	2.01	138.23	44.98
3_15	15	68.35	5.58	168.32	6.37
12_5	5	61.39	2.00	137.43	12.60
12_10	10	63.74	1.54	142.72	32.82
12_15	15	42.96	7.79	57.17	32.51

Figure 8 presents an analysis of the fracture modes of the samples subjected to impact energy. Radial cracks were found to be more prominent on the non-impact surface in comparison to the contact surface. The control samples predominantly fractured into three or four pieces upon the application of 200 joules of impact energy. Conversely, the fiber-reinforced samples generally exhibited a remarkable capacity to maintain their structural integrity. The fibers improved the damage mechanism of the samples with a bridging effect. The least damage was recorded in groups 3-15, while the most was observed in the 12-15 mixtures. The damage situation in the 12-15 mixtures again points to the need for an optimal fiber ratio. Furthermore, it is known that impact tests inherently exhibit high variations for failure mode and crack pattern [27]. Here, the failure modes and crack patterns show considerable similarity within each mixture,

indicating that the variation is not high. Figure 9 presents a thorough overview of all samples collected upon the completion of the test.

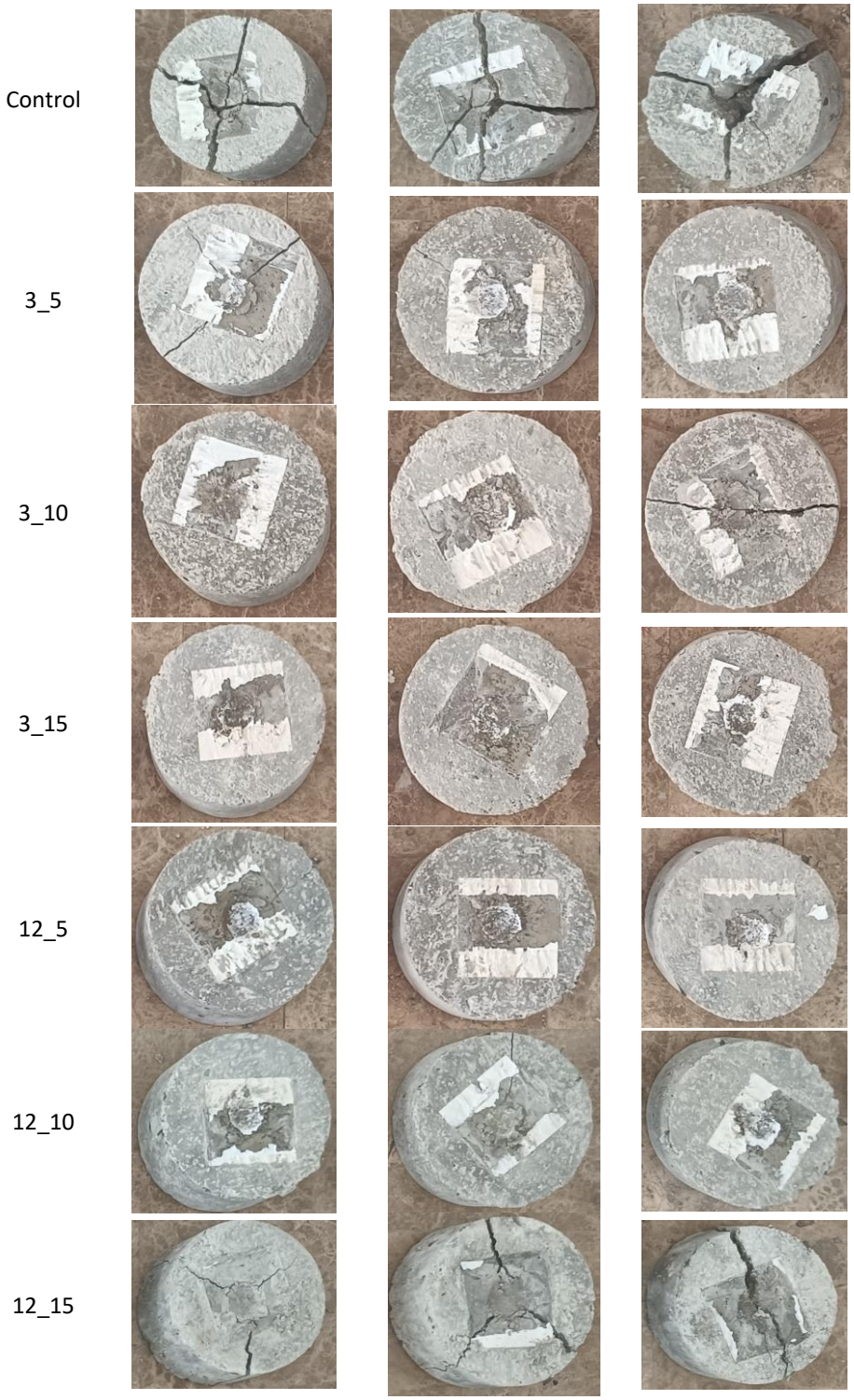


Fig. 8 Failure modes of control and fiber-reinforced samples under 200 joule impact.

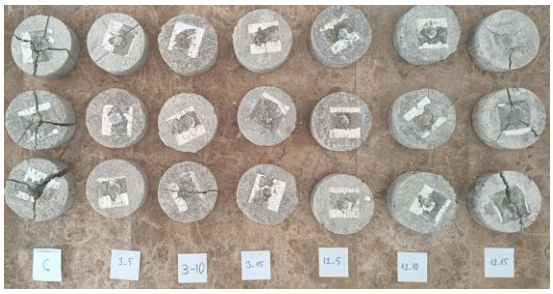


Fig. 9 Thorough overview of all samples following impact

4. Conclusions

This study included both static and dynamic experiments to examine the behavior of carbon fiber-reinforced concrete under impact loads. An instrumental drop-weight test setup on disc specimens was employed. Additionally, concrete compression and splitting tests were conducted on cube specimens. The 3 mm and 12 mm carbon fibers were incorporated at dosages of 5 kg/m³, 10 kg/m³, and 15 kg/m³. The following conclusions were drawn from the data obtained during the experimental studies:

In the 3_5 and 12_10 mixtures, the incorporation of fibers resulted in a significant improvement in both compressive and splitting tensile strengths relative to the control sample. Conversely, the 12_5 and 12_15 mixtures exhibited a marked decrease in these strengths. The 3_10 mixture successfully preserved its strength, whereas the reduction observed in the 3_15 mixture was marginal.

Under dynamic loading conditions, the 3-15 group showed the greatest impact performance, achieving the highest maximum force and energy dissipation. In contrast, all other groups showed a slight decrease in maximum force, with the 12-15 group showing the most significant reduction. Furthermore, the inclusion of fibers improved energy dissipation across all groups, except the 12-15 group, compared with the control concrete. These findings were further corroborated by the damage assessments conducted following the dynamic tests; the control and 12-15 groups sustained the most extensive damage, while the 3-15 group exhibited the least. The control specimens lost structural integrity, fracturing into 2, 3, or 4 pieces. In contrast, the incorporation of fibers in the other groups significantly mitigated damage, enabling these specimens to maintain their integrity.
An analysis of maximum load, energy dissipation, and damage conditions in the samples indicated that incorporating carbon fiber into concrete enhances its impact performance. Nonetheless, this improvement is not universally applicable to all fiber types and ratios. The study identified that 3 mm short fibers exhibited superior impact performance compared to 12 mm long fibers, with an optimal fiber ratio of 15 kg/m³ for the 3 mm fibers. Furthermore, it is noteworthy that the 12-10 mixture, which includes 12 mm fibers at a concentration of 10 kg/m³, achieved the second-highest ranking in dynamic performance. Regarding static compression and splitting tensile strength, this mixture demonstrated marginally better results than those incorporating short fibers.

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Author Credit Statements

İsmail Ünsal: Writing - original draft, Writing - review & editing, Data curation, Conceptualization, Methodology, Investigation, Formal Analysis, Visualization
Mehmet Cihan Korkmaz: Writing - original draft, Investigation, Formal Analysis, Visualization

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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