COMPARATIVE INVESTIGATION OF THE COMPRESSIVE STRENGTH OF STEEL FIBER REINFORCED CONCRETE UNDER STATIC AND IMPACT LOADS

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Abstract

This study examines the effect of steel fiber content on compressive behavior of concrete under static and impact loading. The results indicate that increasing fiber dosage reduces workability: the mixture with 0.5% fibers reached the highest flowability (245 mm), while higher contents of (1.0-2.0)% progressively decreased it to 195 mm. This reduction is attributed to greater interparticle friction, the disruption of the granular framework, and fiber orientation resisting flow. Compressive strength under static loading exhibited only slight variation (176.97-179.87) MPa, suggesting limited influence of fibers on quasi-static strength. In contrast, impact loading significantly increased the compressive strength (189.54-194.06) MPa and the strain capacity, with corresponding DIF values of approximately 2.7. A fiber content of 1.5% (MT15) provided the best balance between strength and ductility, whereas 2.0% (MT20) produced the highest toughness but was affected by fiber clustering and stress concentration. Dynamic analysis further confirmed consistent improvements in compressive strength (7-8)% across all dosages, while toughness more than doubled under impact conditions, reaching 1.258 MJ/m³ for MT20. These improvements were governed by crack-bridging and fiber pull-out mechanisms, which delayed crack propagation and enhanced energy absorption. An optimal fiber dosage of 1.5% is recommended to balance workability, strength, and toughness in practical applications.

Keywords: *Compressive strength; static and impact loads; steel fiber; concrete*.

1. Introduction

Concrete is one of the most essential materials in civil engineering, extensively used in structural applications such as buildings, bridges, tunnels, pavements, and protective systems [1], [2]. Its widespread adoption is attributed to its relatively low cost, good durability, and high compressive strength [3]-[5]. In traditional design practice, compressive strength measured under quasi-static conditions is the principal index used to assess the quality and reliability of concrete [6]. However, in real service

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Doi: 10.56651/lqdtu.jst.v8.n2.1073.sce

environments, structures are rarely subjected only to static loads. Instead, they often encounter dynamic actions, including vehicular impacts, seismic excitations, accidental collisions, and even blast or explosion events [6]-[8]. These high-strain-rate loadings can significantly alter the mechanical response of concrete compared with its static behavior, making it crucial to investigate the compressive strength of concrete under both static and impact conditions [4], [6]-[9]. A substantial body of research has shown that the mechanical properties of concrete are highly strain-rate dependent. When subjected to impact or dynamic loading, concrete typically demonstrates increased apparent strength and stiffness relative to static tests, a phenomenon often expressed using the dynamic increase factor (DIF). This increase is generally attributed to inertia effects, delayed crack propagation, and the strain-rate sensitivity of the cementitious matrix. Y. Hao and H. Hao [10] demonstrated through numerical simulations that aggregates play a crucial role in the dynamic compressive strength of concrete, significantly influencing DIF values at high strain rates. Similarly, Cotsovos and Pavlović [11] emphasized that the behavior of concrete under dynamic loading is influenced by multiple parameters, including the geometry and material properties of the investigated structure, as well as the experimental methodology employed. Mustafa *et al.* [12] reported that water saturation induces significant variations in compressive strength and other mechanical properties. Under static loading, saturation was found to reduce compressive strength by approximately 36% and to promote a more ductile response of the cement mortar compared to dry specimens. In contrast, under dynamic loading, water saturation enhanced impact resistance and fracture toughness relative to the dry condition. Moreover, cracks in saturated specimens tended to propagate with shallower depths than those in dry samples. Habel *et al.* [13] conducted drop-weight experiments to investigate the impact bending behavior of ultra high performance concrete (UHPC), reporting that its strength exhibited a positive correlation with increasing strain rate. The experimental findings revealed that UHPC incorporating 1.5% long fibers combined with 0.5% short fibers exhibited the most favorable mechanical performance under both static and dynamic loading conditions.

Although the mechanical behavior of concrete has been extensively studied, important gaps remain. Previous research has often considered static and dynamic loading separately, leading to limited comparative insights, while inconsistencies in experimental methods have produced variable DIF values. Moreover, the combined influence of material parameters such as fiber dosage, aggregate properties, and moisture content has not been sufficiently clarified. To address these gaps, the present study conducts a comparative experimental investigation of the compressive strength of concrete under static and impact loading, with specific objectives to: (i) Effect of fiber dosage on the workability of concrete mixtures, (ii) Comparison of the compressive strength of concrete under static and impact loading conditions, and (iii) Evaluation of strain-rate sensitivity through the calculation of DIF values.

2. Methodology

2.1. Materials

The mix composition adopted in this study is detailed in Table 1. Four sets of specimens were prepared with steel fiber contents of 0.5%, 1.0%, 1.5%, and 2.0%, designated as MT05, MT10, MT15, and MT20, respectively, to facilitate subsequent reference, comparison, and analysis throughout this study. The fiber has a diameter of 0.3 mm, a length of 30 mm, and a specific mass of 7.90 g/cm³ [14]. It possesses a tensile strength of 2580 MPa and an elastic modulus of 200 GPa, indicating high strength and stiffness suitable for reinforcing concrete [14]. Specimens were initially cured under plastic sheets at (20 ± 2)°C for 48 h, then demolded and subjected to hot-water curing at (90 ± 2)°C for 3 days with controlled heating and cooling cycles. All tests were performed after 28 days of dry curing. The specimens were cylindrical with a diameter of 75 mm and a length of 75 mm, as shown in Fig. 1. Strain gauges were affixed to the concrete specimens to measure longitudinal strain during the dynamic compression test (Fig. 1). The measured mass of the specimen was approximately 830.9 g.

Tab. 1. Mix proportions of the mixtures by weight for 1 m³ of concrete

Matrix	Steel fiber (kg)	Cement (kg)	Sand (kg)	Silica fume (kg)	Silica powder (kg)	Superplasticizer (kg)	Water (kg)
MT05	39.27	853.24	938.57	213.31	255.97	59.73	179.18
MT10	78.55	853.24	938.57	213.31	255.97	59.73	179.18
MT15	117.82	853.24	938.57	213.31	255.97	59.73	179.18
MT20	157.09	853.24	938.57	213.31	255.97	59.73	179.18

Fig. 1. Compressive specimen.

2.2. Experimental methods

The flowability of all mixtures was evaluated in accordance with ASTM C1437. Each mixture was cast into a small conical mold placed on an automated jolting table. The mold was then removed vertically, after which the specimen was subjected to 25 jolts. Finally, the mean value of two perpendicular diameters of the spread sample was determined.

Static compressive strength was measured using a universal testing machine (UTM), as shown in Fig. 2, whereas impact compressive strength of ultra-high-performance fiber reinforced concrete (UHPFRC) was evaluated with a split Hopkinson pressure bar (SHPB), as illustrated in Fig. 3. A constant static loading rate of 1.0 mm/min was maintained, while a compressive impact velocity of 14.1 m/s was applied. Compressive strength was determined from three specimens for each matrix.

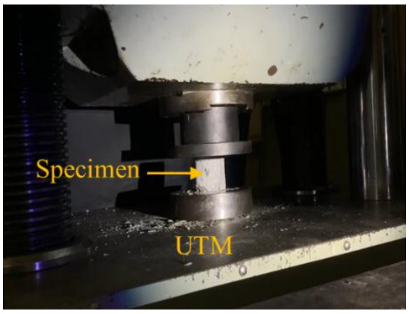


Fig. 2. Static compression testing procedure.

In the SHPB tests, strain gauges on the incident and transmitted bars recorded the strain waves. The dynamic stress-strain response of the specimens was then derived from the one-dimensional stress wave theory, as shown in Eqs. (1)-(4) [15], [16].

$$\sigma_{front,s} = \frac{A_b}{A_s}(\sigma_i + \sigma_r) \tag{1}$$

$$\sigma_{back,s} = \frac{A_b}{A_s}\sigma_t \tag{2}$$

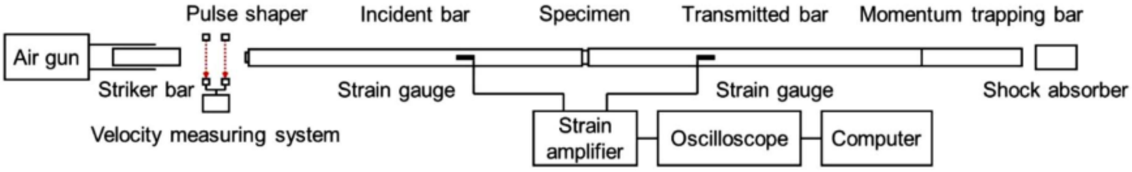
$$\sigma_s = \frac{1}{2}(\sigma_{front,s} + \sigma_{back,s}) \tag{3}$$

$$\varepsilon_s^{'} = c_{1,b}\left(\frac{\varepsilon_i - \varepsilon_r - \varepsilon_t}{l_s}\right) \tag{4}$$

$$E_d = \lim_{\Delta\varepsilon \to 0}\left(\frac{\Delta\sigma}{\Delta\varepsilon}\right) \tag{5}$$

where $\sigma_{front,s}$ and $\sigma_{back,s}$ denote the stresses at the interfaces of the specimen with the incident and transmitted bars, respectively. The average dynamic stress and strain rate of the specimen are represented by σ_s and $\varepsilon_s^{'}$. A_b and A_s refer to the cross-sectional areas of the bars and specimen, while σ_i, σ_r, and σ_t denote the incident, reflected, and transmitted stress waves, with their corresponding strains expressed as ε_i, ε_r, and ε_t. The elastic wave velocity in the bars is given by $c_{1,b}$, and the specimen length by l_s. The dynamic elastic modulus (E_d) was evaluated by Eq. (5), where Δσ represents increment of stress, and Δε denotes the increment of strain.

a) SHPB *b) Test specimen configuration*



c) SHPB test setup [16].

Fig. 3. Impact compression testing procedure.

3. Results and discussion

3.1. Role of fiber content in governing concrete flowability

Figure 4 illustrates the influence of steel fiber content on the flowability of the concrete mixtures. The mixture with 0.5% steel fiber (MT05) achieved the highest flowability of 245 mm. As the fiber content increased from 1.0% (MT10) to 1.5% (MT15) and 2.0% (MT20), the flowability gradually decreased to 230 mm, 205 mm, and 195 mm, respectively. This trend clearly demonstrates that higher fiber dosages reduce the workability of fresh mixtures. The reduction in flowability can be attributed to several factors: (1) the elongated shape and larger surface area of steel fibers compared to aggregates, which increase interparticle friction and cohesion within the mix; (2) the disruption of the granular framework by the fibers hindering the free movement of cement paste; and (3) the tendency of fibers to orient perpendicular to the flow direction during mixing and spreading, thereby generating resistance forces that restrict paste mobility [17]. It can be seen that increasing the steel fiber content reduces the flowability of the mixtures. While a small amount of fiber reinforcement (0.5%) only slightly restricts the fresh mixture flow, higher dosages (≥1.5%) significantly decrease workability, which should be carefully considered in practical applications requiring both high mechanical performance and adequate workability. This observation is consistent with previous findings reported in [18].

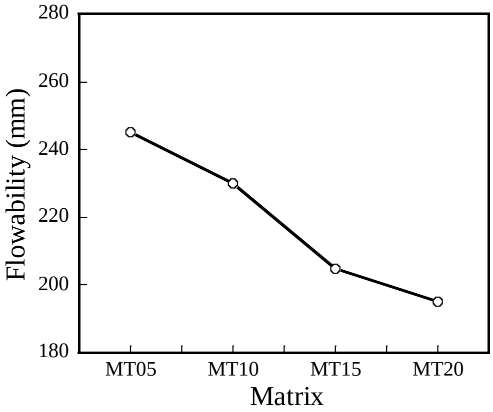
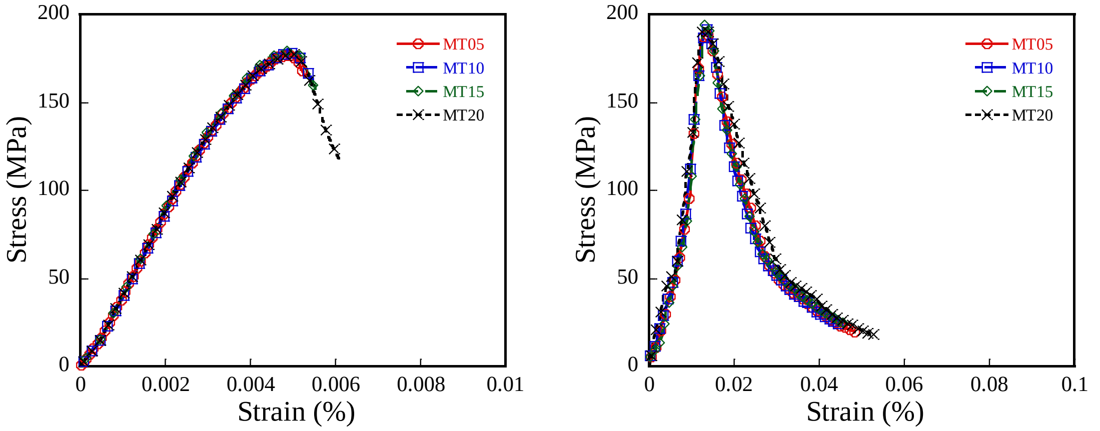


Fig. 4. Variation of concrete flowability with fiber content.

3.2. Effect of fiber volume fraction on the compressive strength of concrete

Figure 5 illustrates the compressive stress-strain behavior of the matrices under static and impact loading, whereas Table 2 summarizes the comparative outcomes of static and dynamic compression tests on matrices. The results confirm that steel fiber incorporation markedly improves the dynamic response of high-strength concrete. While compressive strength exhibited only slight increases, the most significant enhancements were observed in strain capacity and toughness, especially under impact loading. Among the tested mixtures, MT15 (1.5% fiber content) provided the best balance between compressive strength and toughness under dynamic conditions, whereas MT20 (2.0%) exhibited the highest toughness but a slightly lower compressive strength compared to MT15.

Under static loading, the compressive strength of the specimens ranged from 176.97 MPa to 179.87 MPa, with only marginal variation among different fiber contents. The highest value was obtained for MT15 (179.87 MPa), followed closely by MT10 and MT20. Under impact loading, however, all mixtures exhibited enhanced compressive strength, with values between 189.54 MPa and 194.06 MPa. The strain at peak stress also exhibited a marked increase under impact loading. Static strain values remained nearly constant (4.908×10^{-3} to 4.944×10^{-3}) regardless of fiber content, indicating that steel fibers had minimal influence on deformation capacity under quasi-static conditions. Conversely, under impact loading, the strain increased significantly, ranging from 1.318×10^{-2} to 1.361×10^{-2}, with DIF values around 2.7. This result implies that fiber-reinforced mixtures developed greater ductility when subjected to high strain rates. The slight increase in strain with higher fiber content (from MT05 to MT20) suggests that fibers enhanced the ability of concrete to absorb deformation energy prior to failure. These findings are in agreement with the conclusions of K. Sun *et al.* [19], indicating that steel fibers contribute significantly to the enhancement of strain capacity and toughness under dynamic loading scenarios.



a) Static *b) Impact*

Fig. 5. Compressive stress-strain responses of matrices.

Tab. 2. Comparative results of static and dynamic compression for the matrices

Matrix	**Load**	**Compressive strength**		**Strain at peak stress**		**Peak toughness**		**Dynamic elastic modulus**
		MPa	DIF	-	DIF	MJ/m^3	DIF	GPa
MT05	Static	176.97	-	4.908×10^{-3}	-	0.495	-	-
	Impact	189.54	1.071	1.318×10^{-2}	2.685	0.997	2.012	68.57
MT10	Static	178.07	-	4.913×10^{-3}	-	0.509	-	-
	Impact	191.81	1.077	1.332×10^{-2}	2.711	1.052	2.069	69.91
MT15	Static	179.87	-	4.932×10^{-3}	-	0.510	-	-
	Impact	194.06	1.079	1.348×10^{-2}	2.733	1.102	2.161	70.39
MT20	Static	177.14	-	4.944×10^{-3}	-	0.637	-	-
	Impact	190.17	1.074	1.361×10^{-2}	2.753	1.258	1.976	68.64

3.3. Rate-sensitive compressive strength of concrete

The DIF values ranged from 1.071 to 1.079, indicating a consistent improvement of approximately (7-8)% across all fiber dosages. Notably, MT15 achieved the highest impact strength (194.06 MPa), suggesting that an optimal fiber dosage of 1.5% provided the most effective reinforcement under dynamic conditions. The inclusion of steel fibers in concrete improved its impact resistance by bridging cracks and slowing the propagation of failure [18].

The most pronounced effect of steel fiber addition was observed in peak toughness. Under static conditions, values ranged from 0.495 MJ/m³ (MT05) to 0.637 MJ/m³ (MT20), indicating a gradual improvement with increasing fiber content. Under impact conditions, peak toughness more than doubled, reaching 1.258 MJ/m³ for MT20. The corresponding DIF values (1.976-2.161) highlight the superior energy absorption capacity of fiber-reinforced specimens under dynamic loading. This trend is consistent with the crack-bridging and pull-out mechanisms of steel fibers, which dissipate more energy under high loading rates [4], [20].

a) MT05 *b) MT10*

c) MT15 *d) MT20*

Fig. 6. Failure characteristics of the cylindrical specimens after impact testing.

Figure 6 illustrates the failure characteristics of cylindrical specimens corresponding to steel fiber contents of 0.5%, 1.0%, 1.5%, and 2.0%. The MT05 specimen exhibited relatively large fractured pieces with limited fragmentation, suggesting that a lower fiber dosage provided only partial crack-bridging capacity under impact loading. For the MT10 specimen, more visible cracks and moderately fragmented pieces were observed, indicating that the increased fiber content enhanced energy absorption but still could not prevent localized brittle failure. In the case of MT15, both large and small fragments were present, with several fiber pull-outs observed along the fracture surfaces, reflecting an improved balance between toughness and brittleness. In contrast, the MT20 specimen produced extensive crushing with numerous small and irregular fragments, signifying that excessive fiber dosage may lead to fiber clustering and stress concentration, thereby reducing the overall impact resistance.

4. Conclusions

This study carried out a comparative experimental investigation on the compressive behavior of fiber-reinforced concrete under static and impact loading. The conclusions drawn from this study are as follows:

- The flowability of concrete mixtures decreased with increasing steel fiber content. While 0.5% fiber addition maintained adequate workability, higher dosages (≥ 1.5%) markedly reduced fresh concrete flow due to increased interparticle friction, disruption of the granular skeleton, and fiber orientation effects.

- Under static loading, compressive strength exhibited only marginal variation among mixtures, whereas impact loading significantly enhanced strength, strain capacity, and toughness. A fiber content of 1.5% (MT15) provided the best balance between compressive strength and ductility, while excessive dosage (2.0%) caused clustering and reduced overall performance.

- The rate sensitivity of fiber-reinforced concrete was confirmed by dynamic increase factors of approximately (7-8)% for compressive strength and nearly double toughness under impact loading. These improvements were mainly attributed to crack-bridging and fiber pull-out mechanisms, highlighting the superior energy absorption capacity of steel fiber-reinforced concrete at high strain rates.

This study is limited by the narrow range of fiber contents (0-2%) and the relatively small number of experimental data points, which hinder the development of a reliable quantitative model describing the effect of fiber content on concrete flowability and other factors. Therefore, further studies are needed to address the gaps identified in this research.

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SO SÁNH CƯỜNG ĐỘ NÉN CỦA BÊ TÔNG CỐT SỢI THÉP DƯỚI TẢI TRỌNG TĨNH VÀ TẢI TRỌNG VA ĐẬP

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Tóm tắt: Nghiên cứu này xem xét ảnh hưởng của hàm lượng sợi thép đến khả năng chịu nén của bê tông dưới điều kiện tải trọng tĩnh và va đập. Kết quả thí nghiệm cho thấy sự gia tăng tỉ lệ sợi làm giảm đáng kể tính công tác của hỗn hợp: mẫu chứa 0,5% sợi đạt độ chảy cao nhất (245 mm), trong khi hàm lượng sợi thép tăng từ (1,0-2,0)% thì độ chảy còn khoảng 195 mm. Đối với cường độ nén tĩnh, giá trị dao động trong khoảng hẹp (176,97-179,87) MPa, phản ánh tác động hạn chế của sợi thép khi bê tông chịu tác dụng của tĩnh tải. Ngược lại, dưới tác động của tải trọng va đập, cường độ nén tăng rõ rệt (189,54-194,06) MPa, đồng thời khả năng biến dạng cũng được cải thiện đáng kể. Khi tốc độ tải trọng chuyển từ tĩnh sang va đập, hệ số tăng cường độ (DIF) được cải thiện từ (7-8)% cho tất cả các hàm lượng sợi, trong khi năng lượng hấp thụ biến dạng tăng khoảng hai lần, đạt 1,258 MJ/m³ ở hỗn hợp chứa 2,0% sợi (MT20). Sự cải thiện các tính chất này chủ yếu bắt nguồn từ cơ chế bắc cầu vết nứt và hiện tượng kéo tuột sợi, qua đó kìm hãm sự phát triển của vết nứt và nâng cao khả năng tiêu tán năng lượng của vật liệu. Trên cơ sở cân nhắc đồng thời tính công tác, cường độ nén và năng lượng hấp thụ biến dạng; hàm lượng sợi thép 1,5% được đề xuất là giá trị phù hợp cho các ứng dụng thực tế.

Từ khóa: *Cường độ nén; tải trọng tĩnh và va đập; sợi thép; bê tông.*

Received: 03/10/2025; Revised: 23/12/2025; Accepted for publication: 26/12/2025

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