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تسليح الخرسانة بالألياف الفولاذية والتسليح التقليدي

Reinforcement of concrete with steel fibers and traditional reinforcement

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الملخص:

تشتهر الخرسانة بمتانتها عند الضغط وضعفها عند الشد. ولمعالجة هذا القيد، تتضمن الطرق التقليدية دمج قضبان التسليح الفولاذية لحمل قوى الشد بعد تشقق الخرسانة، أو الإجهاد المسبق للحفاظ على غالبية الخرسانة تحت الضغط. في السنوات الأخيرة، كان هناك اهتمام متزايد في صناعة البناء فيما يتعلق بمزايا التسليح بالألياف في الخرسانة. من بين خيارات الألياف المختلفة المتاحة (مثل الفولاذ والألياف الصناعية والزجاجية والطبيعية)، تمت دراسة ألياف الفولاذ على نطاق واسع وهي شائعة الاستخدام. يُستخدم التسليح بالألياف بشكل أساسي في تطبيقات مثل الأرضيات الصناعية والطبقات والخرسانة المرشوشة، على الرغم من وجود مجالات استخدام محتملة أخرى. يوفر إدراج الألياف في الخرسانة فوائد مثل تحسين التحكم في الشقوق وإمكانية تصميم هياكل أكثر نحافة. ومع ذلك، تعتمد فعالية التحكم في الشقوق على النوع المحدد وكمية الألياف المضافة. منذ سبعينيات القرن الماضي، شهدت ألياف الفولاذ استخدامًا واسع النطاق في مختلف الهياكل الخرسانية في جميع أنحاء العالم. تتمثل التأثيرات الرئيسية لألياف الفولاذ في الخرسانة في نقل الإجهادات عبر الشقوق بعد حدوثها، وإبطاء نمو وانتشار الشقوق. ونتيجةً لذلك، يُمكن تعزيز قدرة تحمل الخرسانة بعد التشقق ومرونتها (صلابتها) بشكل ملحوظ، وهي هشة بطبيعتها. وبالمقارنة مع طرق التسليح التقليدية، يُقدم التسليح بالألياف مزايا مميزة، كما ورد في الدراسات ذات الصلة. على سبيل المثال، نظرًا للتوزيع العشوائي والمتقطع للألياف داخل مصفوفة الخرسانة، يُمكن تقوية حتى المناطق القريبة من السطح بفعالية، وهو أمر قد يكون صعبًا تحقيقه باستخدام قضبان التسليح التقليدية التي تتطلب حدًا أدنى من التغطية الخرسانية.

الكلمات المفتاحية: تسليح الخرسانة بألياف الفولاذ والتسليح التقليدي

Abstract:

Concrete is known for its strength in compression but weakness in tension. To address this limitation, traditional methods involve incorporating steel reinforcing bars to carry tensile forces after concrete cracking, or pre-stressing to keep the majority of the concrete under compression, In recent years, there has been increasing interest in the construction industry regarding the advantages of fiber reinforcement in concrete. Among the various fiber options available (such as steel, synthetic, glass, and natural fibers), steel fibers have been extensively studied and are commonly used. Fiber reinforcement is primarily employed in applications like industrial floors, overlays, and sprayed concrete, although there are other potential areas of use. The inclusion of fibers in concrete offers benefits such as improved crack control and the potential for designing more slender structures. However, the effectiveness of crack control depends on the specific type and quantity of fibers added, Since the 1970s, steel fibers have seen widespread use in various concrete structures worldwide. The primary effects of steel fibers in concrete are the transfer of stresses across cracks after they occur, and the retardation of crack growth and propagation. As a result, the post-cracking load-bearing capacity and ductility (toughness) of the concrete, which is inherently brittle, can be significantly enhanced. Compared to conventional reinforcement methods, fiber reinforcement offers distinct advantages, as reported in relevant literature. For example, due to the random and discrete distribution of fibers within the concrete matrix, even the surface-near regions can be effectively .strengthened, which may be challenging to achieve with conventional rebars that require a minimum concrete cover

Keywords: Reinforcement of concrete with steel fibers and traditional reinforcement

Introduction

Concrete is a ubiquitous material found in various locations worldwide, such as roads and buildings, playing a crucial role in construction. Throughout history, humans have utilized concrete in their innovative architectural endeavors for thousands of years. Since ancient Egyptian times, people have been combining fundamental components like sand, gravel (aggregate), a cement-like adhesive, and water to create concrete (Miller, 2018).

The utilization of fibers for reinforcement is not a novel concept, as it has been employed since ancient times. Throughout history, various types of fibers were used, such as horsehair in mortar and straw in mud bricks. In the early 1900s, asbestos fibers were incorporated into concrete, but the discovery of health hazards associated with asbestos necessitated the search for alternative materials. In the 1950s, the concept of composite materials emerged, sparking interest in fiber reinforced concrete. This led to the exploration of substitutes for asbestos in concrete and other building materials. By the 1960s, steel, glass (GFRC), and synthetic fibers like polypropylene fibers were introduced as reinforcements in concrete. Ongoing research continues to explore and develop new types of fiber reinforced concretes (Patel, 2020).

The pioneering work on fiber strengthening mechanics began with Romualdi et al. in the early 1960s (Nascimento, 2023). They introduced a fracture mechanics approach to determine the cracking strength of mortar reinforced with closely spaced steel fibers. This groundbreaking study provided the first framework for describing the behavior of fiber reinforced composites. In 1974, Swamy et al. proposed a constitutive relationship to estimate the flexural strength of steel fiber reinforced concrete (Huo, 2021). They argued that the interfacial bond stress between the brittle matrix and the fibers followed a largely linear pattern. The proposed relationship showed good agreement with previous experimental data. However, this framework was limited to composites that could sustain additional loads after the formation of the first crack, known as tension hardening behavior.

To address this limitation, Lim et al. in 1987 developed an analytical model that described the tensile behavior of steel fiber reinforced concrete, encompassing both tension hardening and tension softening behavior (Raju, 2020). This model provided a more comprehensive understanding of the material's response. The growing demand for alternative construction methods in the industry led to the widespread adoption of Steel Fiber Reinforced Concrete (SFRC) in various industrial and commercial applications. These include the design and construction of floor slabs supported by piles or the ground, pavements, and tunnel linings. Consequently, there have been significant advancements in SFRC constitutive modeling in recent years, with contributions from researchers such as (Tariq, 2022) (K. Kytinou, 2020)

Fiber reinforced concrete (FRC) is a composite material comprising Portland cement, aggregate, and discrete, discontinuous fibers (Micelli, 2020). Unlike unreinforced concrete, which is brittle and has low tensile strength and strain capacity, FRC incorporates randomly distributed fibers that act as bridges across developing cracks, providing post-cracking "ductility (Kabiri Far, 2021)." When the fibers are strong, well-bonded to the material, and allow the FRC to carry significant stresses over a large strain capacity after cracking, they increase the toughness of the concrete (Khalel, 2021).

While there are alternative and potentially cheaper methods to enhance concrete strength, the primary contribution of fibers is to improve the concrete's toughness, as defined by the area under the load vs. deflection curve, under various loading conditions. Fibers increase the strain at peak load and offer substantial energy absorption in the post-peak portion of the load vs. deflection curve (Shafei, 2021).

When short, discrete fibers are used, they act as rigid inclusions within the concrete matrix, similar in magnitude to aggregate inclusions. Therefore, steel fiber reinforcement cannot directly replace longitudinal reinforcement in reinforced and prestressed structural members (Accornero, 2022). However, the presence of fibers in the concrete body or the provision of a fiber concrete tensile skin can enhance the

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resistance of conventionally reinforced structural members to cracking, deflection, and other serviceability conditions (Voutetaki, 2022) .

Fiber reinforcement can be employed in the form of three-dimensionally randomly distributed fibers throughout the structural member, utilizing the added benefits of improved shear resistance and crack control. Alternatively, fiber concrete can be used as a two-dimensional tensile skin to cover the steel reinforcement, allowing for a more efficient orientation of the fibers (Carvalho, 2020).

Fibers are made from various materials (steel, glass, carbon, or synthetic material) and with different geometrical characteristics (length, diameter, longitudinal shape, cross-sectional shape, and surface roughness). Among the various types of fibers, steel fibers are most widely used in the concrete industry. Steel fibers are short (typically from 0.5 to 2.5 inches) and generally deformed to enhance bond with the concrete (Fig. 1). Available commercial steel fibers have a tensile strength of up to approximately 300 ksi (Abbood, 2021).

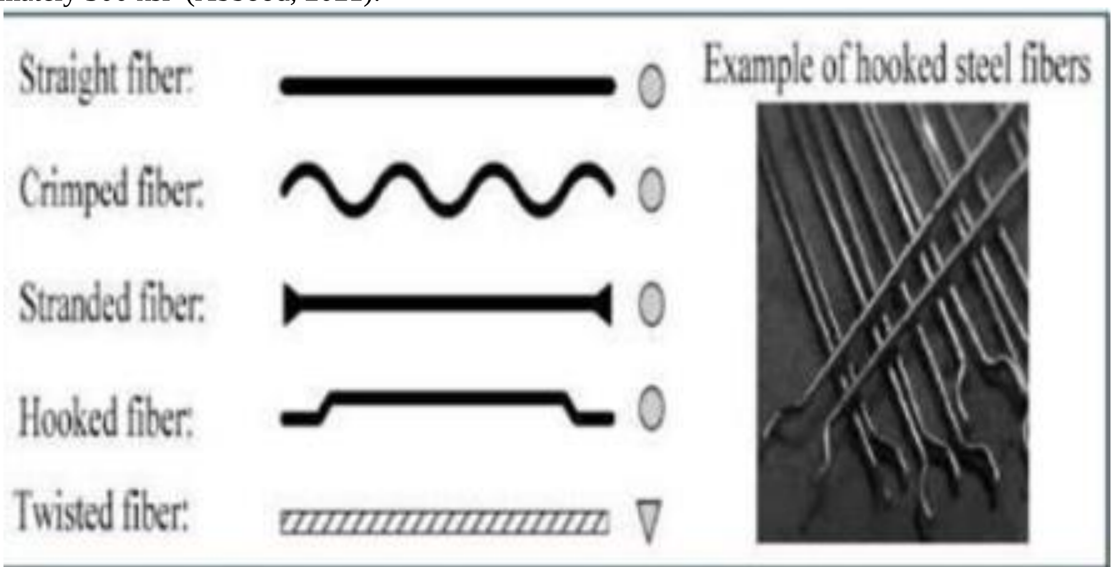

Figure1: Different types of steel fibers

The primary purpose of incorporating fibers into concrete is to improve the properties of concrete that already contains conventional reinforcement. The inclusion of fibers can lead to several enhancements in concrete properties, which include:

a) Resistance to crack propagation caused by plastic and drying shrinkage. b) Resistance to thermal and moisture stresses. c) Increased ductility. d) Enhanced impact and abrasion resistance. e) Improved tensile, flexural, and fatigue strength. f) Reduced permeability. g) Decreased mix-water bleed rate. h) Minimized handling damage during the transportation of dry-cast products to curing areas (Ali, 2020).

The general types of fiber reinforcement materials used in concrete include: (Begich, 2020)

Steel Fiber Reinforcement: Steel fibers are widely used and typically have hooks, deformations, or rough surfaces to enhance the bond with the concrete. Carbon or stainless steel is commonly used, and the fibers are typically one to two inches long. The fiber content in concrete mixes generally ranges from 0.5 percent to 2.0 percent by volume. Higher steel fiber contents can result in poor workability and fiber dispersion. The addition of steel fibers increases the concrete's tensile, flexural, and fatigue strength. The extent of strength enhancement depends on various factors, especially the fiber content. For fiber contents of 1.5 percent to 2.0 percent by volume, direct tensile strength can increase by 30 to 40 percent, and flexural strength (at first crack) by 50 to 150 percent.

Glass Fiber-Reinforced Concrete (GFRC): GFRC is primarily used for precast architectural cladding panels, building and site products, and other applications. Early versions of GFRC in the 1940s suffered from degradation due to the alkaline environment of concrete, but later, alkaline-resistant fibers were developed. GFRC gained widespread acceptance in the United States in the 1970s. GFRC offers advantages such as lightweight panels (10 to 25 pounds per square foot), thin sections (minimum 1/2 inch), high early strength, and versatility in shapes and sizes.

Synthetic Fiber Reinforcement: Synthetic fibers, such as polypropylene and nylon fibers, are commonly used in the precast industry. These fibers are relatively short (ranging from 1/8 inch to 2 inches) and interact with the concrete matrix through mechanical bonding. Synthetic fibers do not typically have a chemical impact on the curing process. Polypropylene fibers are the most commonly used and are available in monofilament or fibrillated varieties. Monofilament fibers are continuous and cut to length, while fibrillated fibers are mechanically distressed to create a two-dimensional fiber network. Synthetic fibers can reduce plastic and drying shrinkage cracking and enhance impact resistance in young concrete products. It's important to consider the water absorption of nylon fibers in mix designs with fiber contents greater than 0.2 percent by volume.

As with any other type of concrete, the mix proportions for SFRC depend upon the requirements for a particular job, in terms of strength, workability, and so on. Several procedures for proportioning SFRC mixes are available, which emphasize the workability of the resulting mix. However, there are some considerations that are particular to SFRC. In general, SFRC mixes contain higher cement contents and higher ratios of fine to coarse aggregate than do ordinary concretes, and so the mix design procedures the apply to conventional concrete may not be entirely applicable to SFRC. Commonly, to reduce the quantity of cement, up to 35% of the cement may be replaced with fly ash. In addition, to improve the workability of higher fiber volume mixes, water reducing admixtures and, in particular, superlasticizers are often used, in conjunction with air entrainment. The range of proportions for normal weight SFRC is shown in table 1 (Blazy, 2021).

For steel fiber reinforced shot Crete, different considerations apply, with most mix designs being arrived at empirically. Typical mix designs for steel fiber shot Crete are given in table 2. A particular fiber type, orientation and percentage of fibers, the workability of the mix decreased as the size and quantity of aggregate particles greater than 5 mm increased; the presence of aggregate particles less than 5 mm in size had little effect on the compacting characteristics of the mix (Zhou, 2020).

Table 1: Range of proportions for normal weight fiber reinforce Concrete

Property	Mortar	9.5mm Maximum aggregate size	19 mm Maximum aggregate size
Cement (kg/m^3)	415-710	355-590	300-535
w/c ratio	0.3-0.45	0.35-0.45	0.4-0.5
Fine/coarse aggregate(%)	100	45-60	45-55
Entrained air (%)	7-10	4-7	4-6
Fibre content (%) by volume			
smooth steel	1-2	0.9-1.8	0.8-1.6
deformed steel	0.5-1.0	0.4-0.9	0.3-0.8

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Table 2: Typical steel fiber reinforce shot Crete mixes

Property	Fine aggregate mixture (Kg/m^3)	9.5mm Aggregate mixture (Kg/m^3)
Cement	446-559	445
Blended sand (<6.35mm)[a]	1438-1679	697-880
9.5mm aggregate		700-875
Steel fibres[b, c]	35-157	39-150
Accelerator	Varies	Varies
w/c ratio	0.40-0.45	0.40-0.45

- [a] the sand contained about 5% moisture
- [b] 1% steel fibers by volume = 78.6kg/m3 –

[c] since fiber rebound is generally greater than aggregate rebound, there is usually a smaller percentage of fibers in the shot Crete in place

In recent decades, steel fiber-reinforced concrete (SFRC) has gained widespread use worldwide as a substitute for conventional reinforcing bars in various applications, including flat slabs, sewer pipes, industrial floors, and tunnel structures (such as shot Crete and precast tunnel lining segments). The primary advantage of incorporating steel fibers is the improvement in the load-bearing capacity of concrete beyond the peak load, resulting in increased ductility and toughness of the material, which is inherently brittle. This enhancement is achieved by the fibers bridging cracks and transferring stresses, thereby impeding crack growth and propagation. Initially, SFRC was primarily used for crack control in non-structural applications. However, with the advancement of fiber types and modern concrete technologies, high-performance SFRC has increasingly been employed for fully replacing conventional reinforcement in structural applications (Ahmad, 2020).

Methodology

Materials

Sand: The sand gradation varies from fine to moderate in size (Figure 1).

Gravel: Gravel is obtained by crushing the limestone rock, the gravel has two fractions 3/8 and 8/15. While some physical, morphological and mechanical properties are found in Table (1, 3).

Cement: The cement utilized was CPJ 45 (Portland cement), which has a density of 3.1 and a specific surface area of 3600 cm2/g according to Blaine's measurement. Table 4 presents the results of the quantitative analysis performed via x-ray fluorescence, while Table 5 provides the mineralogical composition of the cement based on Bogue's equations, indicating the percentage of the main compounds present.

Admixture: The admixture product employed was a super-plasticizer. This super-plasticizer possesses a density of 1.2, a dry matter content of 36.16%, and a pH level around 7. As for the fibers, steel fibers were utilized, which have a diameter of 1.2 mm and a length ranging from 30 to 50 mm. Table 6 provides detailed information regarding the physical and mechanical properties of these steel fibers.

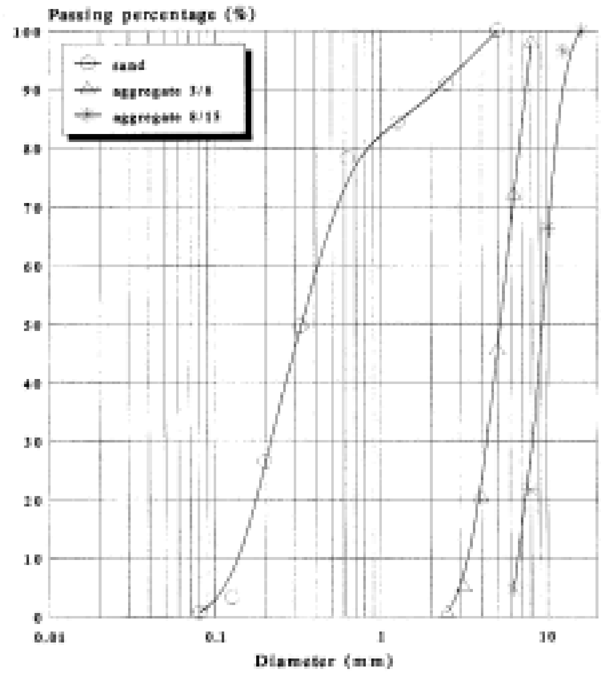

Figure 1. Grain size distribution of the sand and the aggregates used.

TABLE 1. Some Characteristics of the Sand and Gravel Used in the Tests.

Materials	Density	Porous/dense	Compactness	Porosity	Sand equivalent
Sand	2.56	1.64/1.83	36.42/70.76	36.58/29.24	75.4/77.2
Gravel 3/8	2.68	1.28	47.46	52.24	----
Gravel 8/15	2.68	1.32	49.25	50.75	----

TABLE 2. Chemical Composition (%, by weight) of the Sand of Dune Used.

Constituent, %	SiO2	Al2O3	Fe2O3	a O	Mg O	CaO free	O3	.F	Insoluble
Sand of dune	86.04	1.35	0.86	.63	0.08	----	--	.00	---

TABLE 3. Some Physical and Mechanical and Morphological Properties of the Gravel Used.

Gravel Grading	Superficial tidiness (P)	CaCO3 (%)	Flattening Coef..	Los Angles (LA)	MDE
3/8	1.5	85	18	20	16
8/15	1.28	83	13	23	17

TABLE 4. Chemical Composition (%, by weight) of Cement Portland

Constituent, %	SiO2	Al2O3	Fe2O3	a O	MgO	CaO free	O3	.F	Insoluble
CPJ 45	19.48	5.06	3.72	1.95	0.85	1.63	.1	.44	1.26

TABLE 5. Mineralogical Composition (%) for the Cement Used (according to BOGUE Potential).

Compounds,	C4AF	CSH2	C3A	C3S	BC2S	C (Free)
CPJ 45	11.31	2.37	7.12	55.03	14.64	1.63

TABLE 6. Some Physical and Mechanical Properties of Fibers.

Density	Tensile strength MPa	Elasticity modulus MPa	Dilatation Coef (µ/m)	Fire resistance (°)
7.8	1000 to 3000	2.105	11	1500

Equipment

The workability of fresh mixes was assessed using a specialized LCL workabilimeter (Figure 2). The workabilimeter measures the flow time of the mix, which is an indicator of its workability.

The workabilimeter consists of a prismatic metal mold with smooth and non-deformable surfaces. It is equipped with a vibrator and is divided into two compartments by a removable metal partition. The metal partition is inclined at an angle of 38°C.

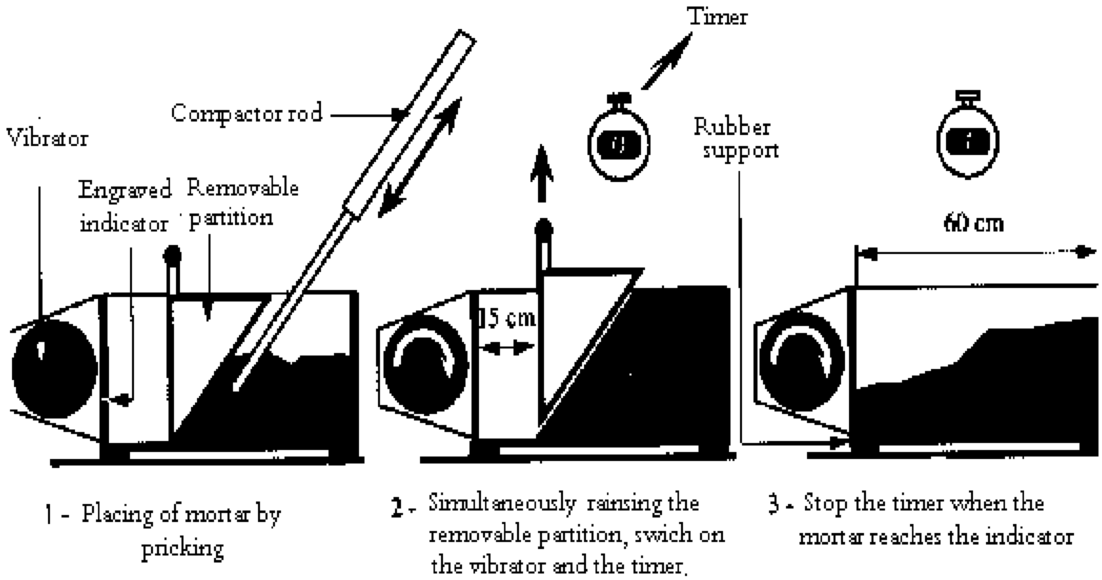

Figure 2. Apparatus for workability measurement

The Baron-Lesage method incorporates two conventional approaches. The first approach, named after Faury and Joisel, is based on the assumption that the required water content is dependent on the volume of voids present between solid grains. The second approach, proposed by Valletta, assumes that the water content is proportional to the surface area of the grains.

According to the Baron-Lesage method, the authors suggest initially determining the optimal ratios between fine and coarse aggregates. This selection is crucial as it directly influences the workability of the mix, which is considered the most significant criterion for assessing the quality of the mixture.

Based on this concept, our method started by selecting the admixture content, the amount of cement and water, keeping $\frac{W}{C}$ constant.

Concrete Mix

The concrete mix proportion used (class 350 daN/ cm^2)

Cement: 350 kg / m^3

Sand: 758 kg / m^3

Gravel: 1073 kg /m^3

Total Water: 215 l /m^3 (This quantity takes into account the degree of aggregates absorption).

Test Samples

For the preparation of all test samples, the total amount of concrete required was prepared at once using a 50-liter concrete mixer. Due to the addition of a liquid superplasticizer, a specific mixing procedure was followed. The procedure involved the following steps:

- Dry mixing of the aggregate in the mixer for approximately 0.5 minutes.
- Dry mixing of the cement and aggregate in the mixer for around 0.5 minutes.
- Addition of water and mixing in the mixer for 3 minutes.
- Addition of the superplasticizer, followed by the addition of fibers.
- Further mixing in the mixer for a duration of 2.5 to 3.5 minutes.

The fresh concrete was poured into standard iron molds and then compacted using a vibration table to ensure proper consolidation. After a period of 24 hours, the specimens were demolded from the

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iron molds. Subsequently, they were stored underwater at a temperature of 22°C for a duration of 27 days. During this storage period, the specimens were allowed to cure and gain strength before conducting the respective tests.

Workability Measurement

The traditional methods used to evaluate the workability of plain concrete are not always suitable for fiber-reinforced concretes. In this case, the workability was assessed using the LCL Workabilimeter. This measurement method involves determining the outflow time of fresh concrete from the moment it is placed in the device until it flows out under the influence of stationary vibration.

The LCL Workabilimeter was developed by Lesage at the Laboratoire Central des Ponts et Chaussées (LCPC) in Paris around 1958. It provides a means to evaluate the castability of concrete. There are two models of the LCL Workabilimeter available: one designed for testing concrete and the other for mortars.

To assess the workability of the concrete using the workabilimeter, the concrete is placed in a vibrating box. The concrete slumps under the vibration until it reaches a reference line, and the time taken for this slump to occur is measured.

Compressive Strength

Compression tests were conducted on cubic specimens measuring 100 × 100 × 100mm at the age of 28 days. These tests were performed using a hydraulic press model. The specimens were placed centrally on the tray of the press, and a continuous load was applied to each specimen. The ultimate compression load for each specimen, both for plain concrete and fiber-reinforced concrete, was recorded during the testing process.

Flexural Strength

Flexural strength tests were conducted on plain concrete and steel fiber reinforced concrete prisms measuring 70 × 70 × 280 mm^3 at the age of 28 days. The same machine that was used for the compressive tests was also used for these flexural strength tests. The loading process was automated and performed at a constant and continuous speed. The flexural strength of the different concrete mixes was evaluated using the classic formula commonly employed for such assessments.

RESULTS

Initially, a concrete mix was selected based on the method of absolute volumes, targeting a total volume of one cubic meter. However, to facilitate readings on the workabilimeter, an equivalent volume of 10 liters of concrete was prepared.

For the experiments, different percentages of fibers were chosen: 0%, 0.5%, 1%, 1.5%, and 2%. These percentages were matched with corresponding percentages of admixture values: 0%, 0.5%, 1%, 1.25%, 1.5%, 1.75%, and 2%. In total, five different fiber concentrations were considered, each paired with seven different admixture values.

The test program consisted of 35 different concrete mixes. For each mixture, the flow time was measured using the workabilimeter. The obtained results allowed for the creation of seven distinct curves, as shown in Figure 3.

To determine the acceptable range of workability using the LCL method, it is desired for the flow time to fall within the limits of 10 and 15 seconds. To represent these limits, two straight parallel lines, denoted as Δ1 and Δ2, were drawn. Δ1 corresponds to a flow time of 10 seconds, while Δ2 corresponds to a flow time of 15 seconds. These two lines intersect each of the seven curves presented in Figure 3, resulting in five points of intersection on each line.

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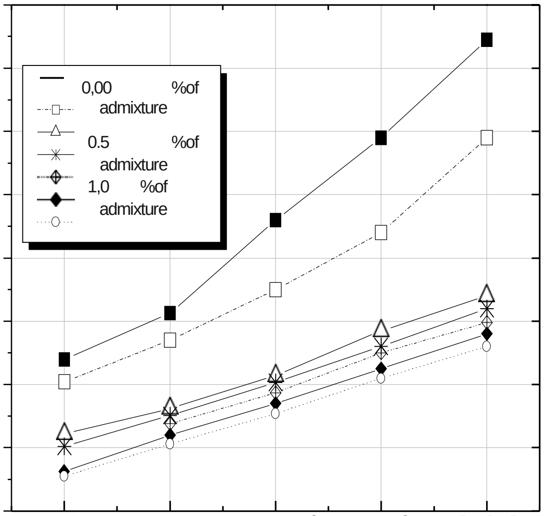

Figure 3. Variation of time of workability as a function of fiber percentage.

To ensure the reliability of the determined range, concrete test specimens were prepared using quantities of fibers and admixture that fell within the limits of the range. Intermediate points between Δ1 and Δ2, which represent the average values of the lower and upper limits, were selected for this purpose. The selected percentages of fibers are denoted as f1, f2, f3, f4, and f5.

For each chosen percentage of fibers, three cubic test specimens measuring 100 × 100 × 100 mm were cast. These specimens were subsequently tested for compression strength. Additionally, three prismatic test specimens measuring 7 × 7 × 28 cm were cast for flexural strength tests. Both the compression and flexural tests were conducted on specimens that had reached an age of twenty-eight days.

It was noted that the obtained range only covers the lower percentages of the fibers that are less than 1%. To resolve this problem, it was decided to repeat this second stage of the study, which consists of the investigation of volume increase influence (W and C), keeping the ratio $\frac{W}{C}$ constant in the translation range limits.

It was discovered that a percentage of 7% of fibers could be sufficient to expand and extend the range of workability, covering higher percentages of fibers (as shown in Figure 4). The objective was to compare the mechanical properties of fiber-reinforced concretes prepared using the expanded range with those formulated using the Baron-Lesage method, using the same fiber dosage as in the initial stage (f1, f2, f3, f4, and f5).

In the Baron-Lesage method, a fixed percentage of superplasticizer (1.5% of the cement weight) was initially chosen based on the manufacturer's recommendations. The percentage of fibers (f1, f2, f3, f4, and f5) was then fixed, and the influence of varying the water-to-cement ratio (S/G ratio) on the flow time of fresh concrete was studied.

After conducting multiple operations for each quantity of fibers, the optimal S/G ratio was determined to be 0.7, with an E/C ratio of 0.557. This specific ratio resulted in the highest workability, indicated by the shortest flow time. For each optimal S/G ratio, cubic test specimens measuring 10 × 10 × 10 cm were prepared and subjected to compression tests. Additionally, prismatic test specimens were prepared and evaluated for flexural strength at the age of 28 days.

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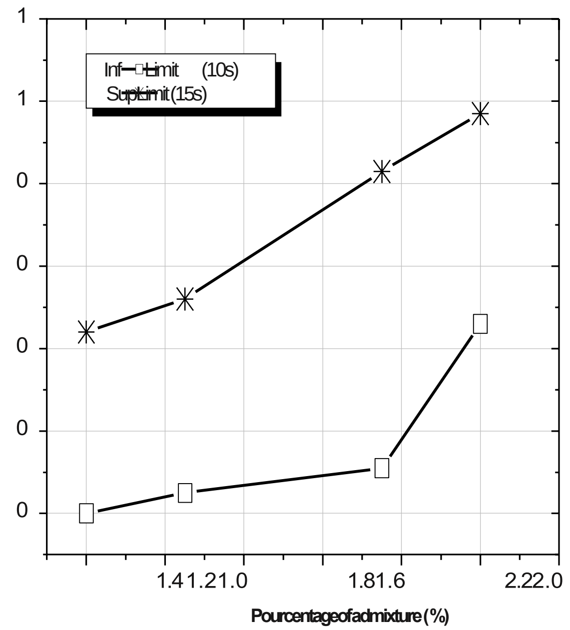

Figure 4. Optimization of mix-composition of fiber concrete

Based on the observation of the curves presented in Figure 3, it can be noted that when the percentage of admixture is below 1%, the workability of the concrete is poor, resulting in a longer flow time. Therefore, it is recommended to avoid using admixture dosages less than 1% when working with fiber-reinforced concrete.

Furthermore, an optimal workability range was established, taking into account the concentration of fibers below 1% and the dosage of admixture. The curves representing the lower and upper limits of this range exhibit a monotonically increasing trend, following a polynomial equation :

Y = a X2 + b X+ c

Y: percentage of fibers, X: percentage of admixture, a, b, c: constants that depend on water quantity increases the porosity of the mixture that has an effect of decreasing the mechanical performances and partially reducing the beneficial effect of fibers in the matrix.

To maintain the ratio of water to cement (w/c) constant, while allowing for slight variations in the quantities of water (W) and cement (C), is a preferred approach. This ensures that the mechanical performance of the concrete matrix remains unaffected. By implementing this consideration, it becomes possible to establish a new range that encompasses slightly higher percentages of fibers (greater than 2%).

The curves representing the lower and higher limits of this new range, as shown in Figure 5, continue to follow the same polynomial law as governed by the previously mentioned equation. This suggests that the relationship between the fibers concentration, admixture dosage, and workability remains consistent, even when considering slightly elevated fiber percentages

The efficiency and reliability of the established range can be assessed by comparing the mechanical strength values obtained using the optimization method with those determined using the Baron-Lesage method.

According to the results shown in Figure 6, it can be observed that the compressive strengths obtained using our optimization method are generally superior to those obtained using the Baron-Lesage method for most percentages of fibers tested. This indicates that our method yields improved mechanical performance in terms of compressive strength. There are two ranges where the compressive strengths obtained using the Baron-Lesage method are superior to those determined by our optimization method. This range falls within the interval of 0.05% to 0.23% of fiber dosage. This finding suggests that the Baron-Lesage method may be more suitable for plain concrete, as it was specifically developed for this type of concrete and may have certain advantages within this fiber dosage range.

However, in the interval of 0.23% to 0.73% of fiber dosage, it is clear that our optimization method is the most efficient. The compressive strengths obtained using our method surpass those obtained using the Baron-Lesage method. This indicates that our optimization approach is particularly effective for achieving enhanced compressive strength in fiber-reinforced concrete within this fiber dosage range.

According to the results presented in Figure 7, the flexural strengths obtained using our optimization method exhibit a similar trend to the compressive strengths. However, there are some differences in the values obtained at the 28-day age.

In general, the flexural strengths (Rt values) determined using our optimization method from the established range are superior to those determined by the Baron-Lesage method, except for the 28-day age. This suggests that our optimization method consistently yields improved flexural strength in the majority of cases.

The reason was that in Baron-Lesage method, the application of admixtures only varies with the flow time. When fibers are added, then the amount of coarse aggregate should be decreased to composite their influence on the flow time accordingly. While in our method, the optimization was based only on the percentage of fibers and strengths.

Pourcentage of fibres (%)

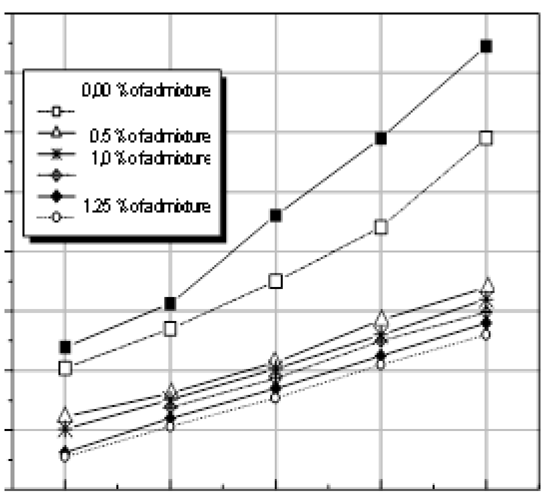

Figure 5. Variation of workability time in function of fiber percentages.

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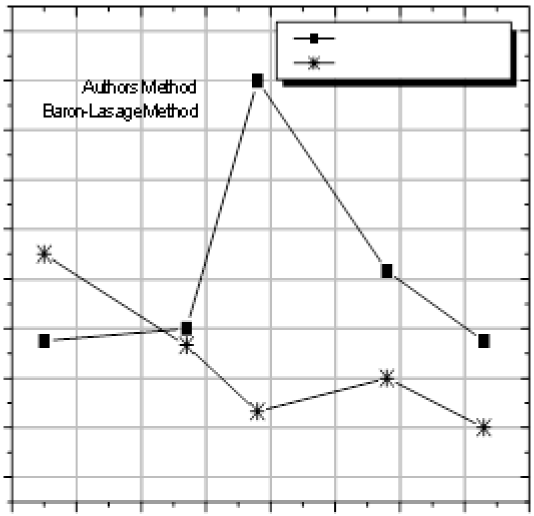
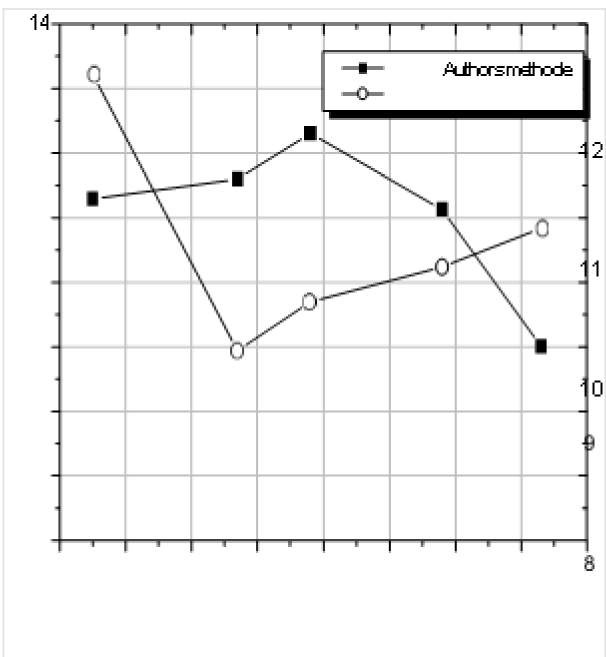


Fiber percentages, (%)
Figure 6. Variation of compressive stress, R_c in function of fiber percentages



Fibrecontent, %
Figure 7. Variation of flexural stress as a function of fibre percentages.

Conclusion

1. It appears that the presented method differs from the Baron-Lesage method in terms of the experimental results obtained for steel fiber-reinforced concrete. While the Baron-Lesage method may yield good results for plain concrete, its effectiveness may not be as significant when applied to steel fiber-reinforced concrete. On the other hand, the results obtained using the presented method for steel fiber-reinforced concrete are more significant, meaning that the method is more effective in improving the mechanical properties of steel fiber-reinforced concrete compared to the results obtained for plain concrete using the Baron-Lesage method
2. Fiber-reinforced concretes exhibit poor workability when the admixture percentages are below 1%.
3. An optimization method of fiber reinforced concrete mix design based only on the variation of the admixture contents and the quantities of W and C keeping, (W/C constant) was proposed.
4. It has been confirmed that it is possible to establish a predefined range of optimization for a specific fiber-reinforced concrete based solely on the characteristics of the fibers (type and dimensions) as well as the quantities of water (W) and cement (C). This range is defined by lower and upper limits, which are determined by a second-degree polynomial equation that governs the relationship between the fiber parameters and the optimization range
5. The mechanical properties of fiber-reinforced concrete obtained through this method demonstrated an advantage over those achieved using the Barron-Lesage method.

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