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Investigation and Comparison of Properties of Fresh and Hardened Concrete Containing Industrial and Waste Steel Fibers

Amir Farhang Rahimian[1,*], Hassan Angouraj Taghavi[1]

[1] Department of Civil Engineering, Islamic Azad University, Chalus Branch, Iran; amirrahimaiyan1400@gmail.com.

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Abstract

Concrete is the second most widely used material in the world, and since concrete is inherently brittle and fragile, it has little resistance to impact and intermittent loads. Due to its brittleness, hardened concrete has low tensile strength and low ultimate strain capacity. For this reason, necessary measures must be taken to overcome this limitation. Random dispersion of fibers in concrete has been proposed as an effective and economical solution for reducing fatigue loads and static force transmission by improving the mechanical properties of concrete. Fibers are used to control and prevent the formation of microcracks that occur due to volume changes caused by shrinkage and thermal stresses, and increase the tensile, flexural, and compressive strength, energy absorption capacity, and brittleness of concrete. In this study, the behavior of concrete under the influence of two types of industrial and waste steel fibers was investigated at ages of 7, 14, and 45 days in both dry and wet states, and concrete samples were subjected to compressive, tensile, and water absorption tests. The samples were obtained from a mixing design, in which sample A was used as a control sample without fibers, and samples B1 and B2 were added with 1% by volume of industrial steel fibers, and once with waste steel fibers. As concrete ages, tensile and compressive strengths have increased in both regular and fiber-reinforced concrete. In addition, the results of the test showed that the use of steel fibers in concrete increases tensile and compressive strengths. By examining the increase in tensile and compressive strength in concrete containing industrial and waste steel fibers, it was observed that the use of industrial steel fibers has a greater effect on increasing the tensile and compressive strengths of concrete. By examining and comparing the samples in both dry and wet states, it was observed that, in general, samples containing fibers in the wet state have higher mechanical properties than samples in the dry state. Next, to examine the amount of water absorption, we first dried the samples in an oven and then immersed these samples, which were 7, 14, and 45 days old, in water. By examining the amount of water absorption, it was observed that the samples without fibers had less water absorption than the samples with fibers.

Keywords: Concrete, Compressive strength, Tensile strength, Industrial steel fibers, Waste steel fibers.

1 | Introduction

Due to the expansion of concrete consumption in the construction of various structures and the existence of hazards such as earthquakes, wind, etc., since the beginning of cement and concrete production, humankind has always strived to produce concrete with more desirable properties [1]. These efforts have been in various

Corresponding Author: amirrahimaiyan1400@gmail.com

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fields, ranging from replacing cement with other materials (Such as sulfur concrete) to replacing various materials with parts of cement or aggregate (Such as fiber concrete). However, it can be said that the overall focus of the experiments has been on producing concrete with greater density and cohesion, and of course, economic efficiency [2].

Concrete, which is a structural material, has several properties. These properties include compressive, tensile, torsional, abrasion resistance, etc., which of course are directly dependent on these properties, such as tensile and bending resistance [3]. Usually, a material or method that improves one of the properties of concrete will not affect the other properties of concrete. Still, the effect of some materials on the properties is more significant. Among these materials and methods, the use of fibers in concrete can be mentioned [4]. Fibers in concrete improve tensile and flexural strengths. Types of fibers used in concrete include steel fibers, glass, waste fibers, iron oxide, and nano-silica [5].

Today, concrete is recognized as one of the most important, common, and widely used construction materials in the world. Its economic value, ease of access to components, and relatively high durability have led to increasing attention to it. The consumption of concrete is expanding day by day around the world due to its cheapness and easy access, because the primary materials used in concrete, which are sand and cement, are found in abundance everywhere on Earth. On the other hand, due to the long life of concrete components and its resistance to atmospheric factors, it has attracted the attention of engineers all over the world, and as a result, the use of concrete is increasing day by day, such that the percentage of concrete buildings is rising compared to other buildings [6].

Fibers are generally of special importance due to their wide applications in human life. [7] For centuries, humans have been making and utilizing fibers using resources available in nature. These fibers are actually natural, with the advancement of chemistry and the development of human needs, industries are producing polymers from chemicals and converting them into new fibers with different properties. A new group of fibers emerged, which are called synthetic fibers. One of these advances in recent years that has improved the quality of building materials is fiber concrete. Historical evidence of this technology is the use of straw in buildings. In fact, fiber concrete is an advanced form of this technology, in which new natural and synthetic fibers have replaced straw, and cement has replaced the mud used in straw [8].

Fiber-reinforced concrete is actually a type of composite that increases its tensile, shear, abrasion, and compressive strength by incorporating reinforcing fibers into the concrete mix. This composite has good integrity and cohesion, allowing the use of concrete as a malleable material to produce highly curved, resistant surfaces. Steel fibers have different shapes and diameters, and their manufacturing methods also differ [9].

Steel fibers currently available in global markets are mainly produced based on four methods:

I. Drawing and cutting steel wires and copper fibers.

II. Rolling and cutting steel sheets (Sheared fibers or strips).

III. Using molten materials (Casting fibers).

IV. Scraping the surface of steel sheets using a scraper (Machine fiber).

The destruction and deterioration of concrete are strongly dependent on the formation of cracks and microcracks due to loading or environmental influences. Thermal and moisture changes in the cement paste cause microcracks to form, and such microcracks are concentrated on the surface of coarse grains. With the increasing impact of loading and other environmental issues, microcracks connect to create cracks and eventually propagate throughout the concrete body [10].

Using various fibers in concrete and making fiber concrete is considered a practical step in preventing the spread of microcracks and compensating for the weak tensile strength of concrete. In fact, reinforcing concrete with short fibers randomly and irregularly stabilizes cracks and increases the tensile strength of concrete [11]. In order to enhance the performance of a structure under loading, the use of fibers has been the subject of many recent research projects. Improvements have included increasing dissipated energy and reducing strain amplitude. The presence of fibers in concrete reduces crack width and increases flexural and tensile strengths, resulting in increased ductility. Knowledge of fiber properties such as tensile strength and the high ratio of fiber modulus of elasticity to concrete modulus of elasticity, which enables stress transfer from concrete to fibers, is of great importance in design [12].

Given the high cost of the construction industry, the necessity and importance of conducting this research is to pay attention to the economic aspect of using waste steel fibers in concrete. By asking questions and conducting experiments in this regard, an attempt is made to answer as much as possible how to produce concrete with better performance while keeping in mind the cost-effectiveness of the project.

2 | Specifications of Consumable Materials

Cement consumption

The cement used in this study is Portland cement type 2. *Table 1* shows the cement specifications and their chemical composition.

Table 1. Chemical compositions of cement used.

Cement Compounds	Sio_2	M_go	Cao	So_3	Fe_2O_3	Al_2O_3	K_2O	Na_2o
%	21/32	3/44	62/02	2/09	2/98	3/83	0/12	0/73

Consumable aggregates

The types of aggregates used in the tested concrete were natural sand, pea sand, and almond sand.

Table 2. Physical characteristics of aggregates used.

Maximum Aggregate Diameter (mm)	Modulus of Elasticity	Density (gr/cm^3)	Water Absorption (%)	Aggregate
19	6.6	2.57	1.74	Sand
10	3.3	2.56	2.3	Sand

Steel fibers used

In this research, steel fibers in wavy and flat shapes with hooked ends produced by Samt Company were used. Steel fibers and scrap can be added to concrete at any time. Usually, when mixing sand, cement, and water in a mixer for 2 minutes, the fibers are gradually added to the concrete in the mixer, and mixing is continued for another 3 minutes. In this regard, metal fibers were used at 1.5% by volume of concrete.

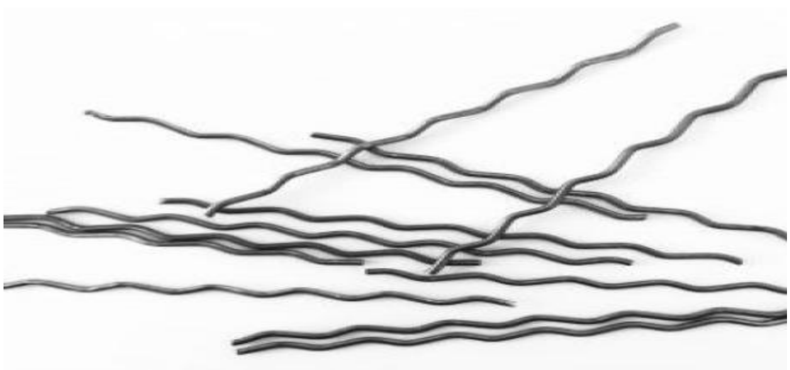

Fig. 1. Corrugated steel fibers.

Fig. 2. Straight steel fibers with hooked ends.

Table 3. Steel fiber specifications.

Straight Steel Fibers with Hooked Ends	Corrugated Steel Fibers	Specifications	Row
50	50	Length (mm)	1
0.8	0.8	diameter (mm)	2
62.5	62.5	Length to diameter ratio	3

Fig. 3. Steel fibers used in the experiment.

Fig. 4. Steel fibers used in the experiment.

Waste fibers

The fiber material is made from scraps from the machining of steel parts, and its apparent modulus varies, but can be estimated to be between 31.25 and 100.

Fig. 5. Waste fibers used in the experiment.

Table 4. Waste fiber specifications.

	Specifications	Row
10	Length (mm)	1
0.4	Diameter (mm)	2
40	Length to diameter ratio	3

Superplasticizer additive

The superplasticizer used is Superplasticizer 260, a product of Namikaran Company. This is an effective superplasticizer and water reducer used to produce high-quality concrete and complies with ASTM C494 type and standard 2930 type (G).

Table 5. Superplasticizer specifications.

Specific gravity (gr/cm3)	PH	Color
1.112	7	Brown

Water

The quality of water used in concrete production plays a crucial role in determining the strength and durability of the final product. According to established standards, potable (Drinking) water is generally considered suitable for mixing concrete, as it is free from harmful impurities such as excessive salts, acids, alkalis, and organic materials. Using clean, drinkable water helps ensure proper hydration of cement and prevents adverse chemical reactions that could weaken the concrete structure over time. Therefore, unless specialized testing confirms the suitability of alternative water sources, potable water remains the preferred choice in concrete mix design to achieve optimal performance and longevity.

3 | Manufacturing and Preparation of Samples Containing Industrial Steel Fibers and Waste

Regarding the subject, the aim is to compare concrete containing industrial and waste steel fibers; therefore, in conducting the tests, constant parameters (Including the same mixing design, a continuous amount of volume percentage of industrial and waste steel fibers, and similar ages of concrete samples) were maintained. We will examine and test these two types of fiber concrete. For the intended tests, according to the type of aggregates available and the construction of prototypes to achieve the desired strength (Under prototypes aged 7 days and reaching at least 75% of the final strength), a specific mixing plan is determined as follows.

Table 6. Mixing plan specifications.

Coarse-grained (kg/m3)	Fines (kg/m3)	Cement (kg/m3)	Water (kg/m3)	Design name
565	540	335	175	A

4 | Additive in Concrete: Industrial Steel Fibers

Steel fibers are added to concrete in proportion to volume. To make concrete containing steel fibers, first prepare coarse and fine-grained stone materials and cement in the desired proportions (Based on the mixing plan). And after pouring them into the mixer and while the materials are mixing, we add the desired amount of fibers (Which is given below in the method of calculating their amount) to the mixture of materials while stirring in a step-by-step and spraying manner so that the fibers are spread and dispersed as uniformly as possible.

At this time, water is also added to the mixture, and as a result, concrete mortar is prepared.

Since the mixer has a specific volume and a certain number of samples can be produced in each production run, the amount of material is provided based on the volume required to prepare that number of samples; therefore, the amount of fibers must also be measured and prepared on the same basis. Given that the ratio of adding steel fibers to concrete is a percentage by volume, taking into account the density (ρ) of the steel fibers, the desired weight can be calculated using the following calculations.

For industrial steel fibers: $=7800\ kg/m^3=7.8\ g/cm^3\ \rho$.

Added to concrete: 1/5 Volumetric%.

$$7800/(1.5\%)=117.$$

The amount of industrial steel fibers required to produce one cubic meter of fiber concrete with one and a half percent fiber by volume

For each cubic sample:

$$15*15*15=3375\ cm^3.$$

$$1/5\%\rightarrow 50.625cm^3.$$

Volume of industrial steel fibers consumed in a cubic sample

$$P=m/v\ \rightarrow m=7/8*50.625=394/875\ gr.$$

Weight of industrial steel fibers used for a cubic sample. With these calculations, the weight of the fibers at that stage is determined by multiplying the amount determined for a sample by the number of samples that can be made at each stage of execution. That is, the weight of industrial steel fibers that is poured into the mixer each time to prepare a specific number of samples. In the same way, the amount required for cylindrical samples is also calculated.

5 | Description of Sample Construction

For making cubic and cylindrical samples, since the volume of the mixer used is limited, a certain number of samples can be prepared each time concrete is ready (4 samples each time). Therefore, considering the amount of materials and substances required in one cubic meter of concrete that is included in the mixing plan and the density of the steel fibers, and considering the dimensions of each sample (And therefore the volume of the sample), the required amount of each material and steel fiber is determined in the order explained earlier, so that after combining them, we can reach a particular volume of concrete to prepare the desired number of samples.

As mentioned earlier, the mixing method is as follows: first, coarse and fine stone materials and cement (After measuring their weight) are poured into the mixer, and while these materials are being mixed, steel fibers are added to them gradually and in a spray pattern, and water and a lubricant are also added to the mixture at this stage. The resulting mixture is transformed into the desired concrete by the rotary movements of the mixer, which is ready to be poured into cubic and cylindrical samples for testing.

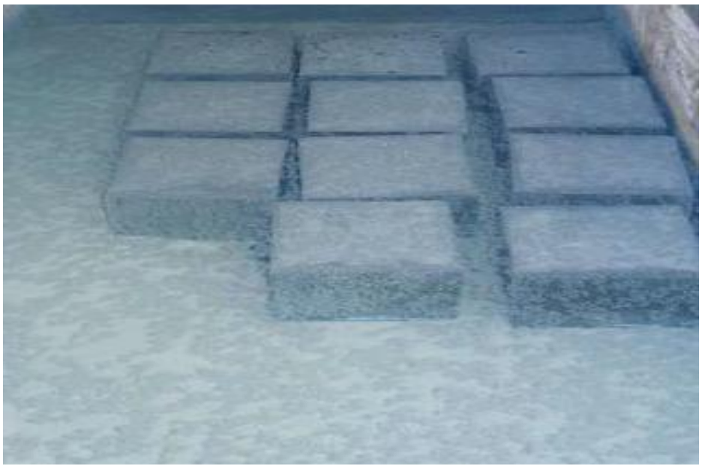

Fig. 6. Concrete pond.

Table 7. Types of samples.

Application	Diameter	Height	Width	Length	
Compressive strength	-	150	150	150	Cubic sample
Tensile strength	150	300	-	-	Cylindrical sample

Making samples with waste fibers

Similar to all other samples for making concrete, the coarse-grained materials were first started and the mixing was completed with the fine-grained materials. During all this time, while these materials were being mixed in the mixer, fibers were also added. The mixing time lasted about 5 to 6 minutes. According to initial trial and error, this mixing method and this time showed the best results in the homogeneity of the samples.

6|Tests Performed

6.1| Compressive strength test

The purpose of the experiment

Since compressive strength is considered one of the essential properties of concrete, knowledge of this parameter plays a vital role in controlling the quality of concrete and improving its preparation methods.

Test method

The ASTM compressive strength test is performed on cylindrical specimens, and the BS test is performed on 150 mm (6-inch) cubic specimens. However, the standard allows for smaller specimens due to the largest aggregate size. According to the ASTM standard, cylindrical specimens are cast in reusable or disposable molds. Type 1 molds are usually made of steel, cast iron, brass, and various plastics. In contrast, type 2 molds may be made of sheet metal, plastic, waterproof paper products, or other materials that provide the desired physical properties, such as impermeability, non-absorption of water, and non-elongation.

In order to prevent the concrete from sticking to the mold walls, the inner walls of the mold should be coated with a thin layer of mineral oil, and then the concrete is poured into the mold in several layers. The compaction of high slump concrete is done in three layers and by giving 25 blows to each layer with a round bar with a diameter of 16 mm. The compaction of low-slump concrete is done in two layers and with internal and external vibrators. The top surface of a concrete cylinder, smoothed by a trowel, is usually not uniform enough for testing, and other measures must be taken on it. The standard allows variations of up to 0.05 mm in the top and bottom surfaces. For this purpose, two methods of abrasion and surface coating are used to create smooth surfaces.

The first method is convenient but expensive. In the second method, a coating is applied to the surface. Three types of materials can be used: hardened cement paste, which is applied to the fresh concrete, a mixture of sulfur and granular materials (Such as fired clay), or a high-strength gypsum coating applied to the hardened concrete. The coating should be thin, 1.5 to 3 mm thick, and have a strength similar to that of the concrete being tested. Probably the best material is a mixture of sulfur and clay, which is suitable for concretes up to 100 MPa.

Fig. 7. Cubic sample.

Fig. 8. Compressive strength test.

6.2| Tensile Strength Test

This test is known as the halving tensile strength of concrete or the Brazilian test. Although concrete is not usually designed to withstand direct tensile stress, understanding the tensile strength of concrete is valuable in estimating the load at which cracks will develop. The absence of cracks is of considerable importance in maintaining the continuity of concrete structures and, in many cases, in preventing corrosion of steel bars. Tensile strength is also of concern in unreinforced concrete structures such as dams under earthquake conditions.

Other structures, such as roads and airports, are designed based on flexural strength, which includes tensile strength. Tensile strength testing is usually performed on a cylindrical (Rarely cubic) specimen. The specimen is placed between the plates of the machine so that its axis is horizontal. Then the load is increased until a fracture occurs in the form of a halving in the plane containing the vertical diameter of the specimen. This test method is recommended in BS 1881-8371 and ASTM C496-71.

Under these conditions, a significant horizontal compressive strength is created at the top and bottom of the cylinder, but because this stress is accompanied by a vertical compressive stress of the same size, a state of uniaxial stress is created, so that rupture does not occur at these points. Instead, rupture occurs due to horizontal and uniform tensile stress in the rest of the cylinder sections.

If wooden strips are not used, the recorded tensile strength of the cylinder will be about 8% lower.

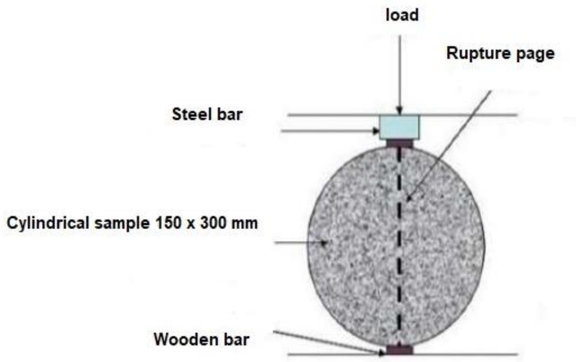

Fig. 9. Schematic of tensile testing in concrete.

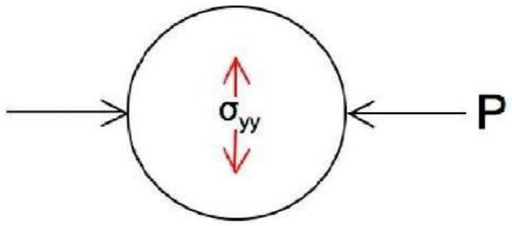

Fig. 10. Schematic of stresses in tensile strength testing.

Fig. 11. Cylindrical samples.

Fig. 12. Tensile strength testing device.

6.3 | Water Penetration Test

This test attempts to determine the amount of water absorbed by a horizontal surface of a concrete specimen or part of a precast concrete structure when the water height is limited to 200 mm and there is not much pressure to apply. In this test, the amount of water absorbed is reported in grams or milliliters per unit area (m2) at different time intervals. The permeability of concrete and the rate of material transfer through it depend on the structure of the concrete. To determine the permeability of a structure's concrete, the concrete permeability coefficient must be determined, which is the rate of liquid or gas flow (Usually in liters).

Per unit time through unit cross-sectional area, under a unit hydraulic gradient (Ratio of head, one meter of water, to the passage, unit concrete thickness in meters) which is usually quantitatively characterized by the permeability of concrete with the liquid (Fluid) permeability coefficient, which is determined and calculated with the gas or water permeability factors by a conventional index.

Concrete permeability is one of the essential properties of concrete in terms of its durability. This property provides facilities for water or other fluids to flow through the concrete and carry harmful and damaging substances with them into the concrete.

To perform the water absorption test, the samples are first placed in a high-temperature environment until the moisture is completely absorbed and the sample is dried. Then, we immerse the cube-shaped samples in a container of water and, by accurately recording the time according to the time values, we give the samples the opportunity to absorb water.

7 | Conclusion

By adding industrial and waste steel fibers, the tensile and compressive strengths of concrete have increased, and by examining the samples in dry and wet states, it has been concluded that wet samples have greater mechanical properties than dry samples. Among the critical things that should be considered when using steel fibers are the following: observing which will help us achieve more desirable results.

I. One of the fundamental problems in achieving a uniform distribution of fibers is the tendency of fibers to clump, which can have various reasons.

II. Steel fibers may have clumped and pelletized before being used in the concrete mix, and the mixing process may not be able to remove this clumping.

III. Fiber may be added to the mixer at too high a rate, not allowing it to disperse properly in the mixture.

IV. Defects in the mixer and its inefficiency in mixing the fibers with the concrete mix

V. Adding fibers to the mixer before other components are added to the concrete also causes clumping and reduces the workability of the concrete.

Author Contributions

Amir Farhang Rahimian designed the study and supervised the experiments. Hassan Angouraj Taghavi conducted the tests and performed the data analysis. Both authors contributed to writing and approved the final manuscript.

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Data Availability

The data generated and analyzed during this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflict of interest related to this publication.

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