



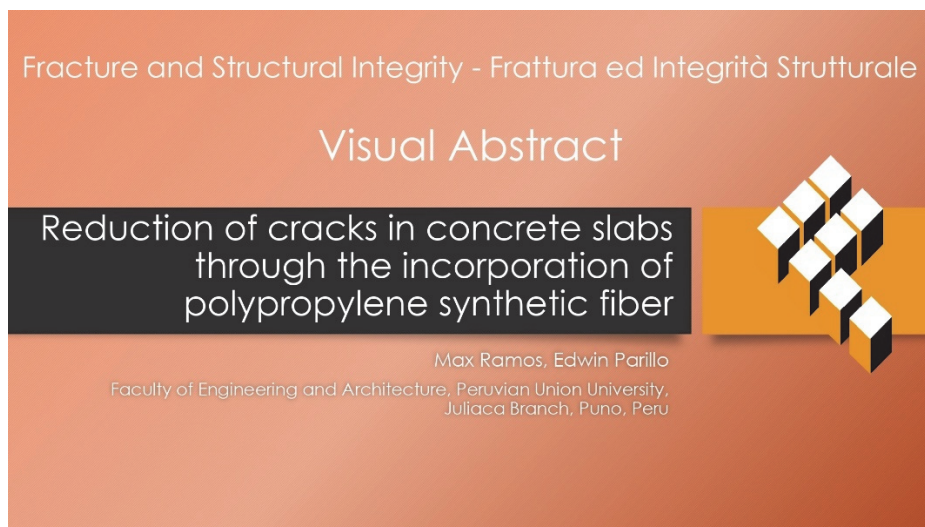
Reduction of cracks in concrete slabs through the incorporation of polypropylene synthetic fiber

Max Ramos, Edwin Parillo

Peruvian Union University, Peru

max.ramos@upeu.edu.pe, <https://orcid.org/0009-0009-4993-983X>

edwin.parillo@upeu.edu.pe, <https://orcid.org/0000-0003-1175-0512>



Citation: Ramos, M., Parillo, E., Reduction of cracks in concrete slabs by incorporating synthetic polypropylene fiber to improve integrity, *Fracture and Structural Integrity*, 75 (2026) 399-434.

Received: 03.10.2025

Accepted: 03.12.2025

Published: 11.12.2025

Problem: 01.2026

Copyright: © 2026 This is an open access article under the terms of the CC-BY 4.0 license, which permits unrestricted use, distribution and reproduction in any medium, provided that the original author and source are cited.

KEYWORDS. Fiber, Concrete, Width, Length, Crack, Polypropylene.

INTRODUCTION

In the construction sector, concrete cracking is a very common problem, as it significantly reduces the lifespan and integrity of structures [1]. For this reason, research on this topic has increased in several countries, seeking quick and simple solutions.

In Colombia, research conducted by Dias, Calmon, and Vieira [2] focused on the plastic shrinkage of concrete, demonstrating that conventional concrete is very weak and practically lacks resistance to cracking. This problem significantly affects the appearance and structural strength of buildings, requiring additional processes, such as crack sealing, in 90% of cases for its resolution, resulting in relatively high additional costs.

Given this situation, the use of alternative materials that reduce or prevent the appearance of cracks is presented as a more sustainable and accessible strategy. Among them, synthetic polypropylene fiber has proven to be a promising option, improving the internal cohesion of concrete and controlling crack formation during the initial stages of setting and curing [3].

In Peru, research on concrete slab cracking has been very limited in the construction sector, or, where it exists, it has not generated sufficient general interest to warrant further study. This lack of scientific evidence stems from the widespread belief that concrete cracking is not a short-term problem and is therefore often ignored. However, when analyzed over the long term, it presents significant issues that require thorough investigation.

Numerous local, national, and international studies have promoted the use of unconventional natural and synthetic fibers to reduce concrete cracking. For example:



Chaisa and Maccarcco [4] they determined that the incorporation of 0.5 kg of fibers reduced settling by 69.95%, considering that a higher fiber content would further reduce settling.

Prakash et al. [5] concluded that adding 0.5% polypropylene fibers to a concrete mix increased tensile strength by up to 24%, suggesting that polypropylene fibers can be used to optimize the mechanical properties of concrete.

Similarly, Ghali et al. [6] found that compressive strength increased by 38.6% with the addition of polypropylene fiber.

Qasim and Jassam [7] they determined that adding 40% polypropylene fiber increased compressive strength by 46.40% after 14 days.

Shan et al. [8] demonstrated that the incorporation of 1 kg/m³ of polypropylene fiber improved compressive strength by 42.2% at 28 days, highlighting the importance of using polypropylene fibers in concrete mixtures.

Najaf and Abbasi [9] they reported that the addition of polypropylene macrostructural fibers increased compressive strength by 32% and flexural strength by 85%, representing a significant improvement.

Maafi et al. [10] concluded that synthetic polypropylene fiber improved compressive strength by 23% and tensile strength by 21%, emphasizing that the ideal amount of fiber is crucial for a significant improvement.

Zhao et al. [1] discovered that the addition of polypropylene and steel fibers resulted in increases of 29.1% in compressive strength and 53.4% in tensile strength, demonstrating the benefits of using both plastic and metallic fibers.

Callamamani et al. [11] demonstrated that shorter synthetic fibers disperse more effectively compared to longer fibers, which tend to concentrate in one area of the concrete.

Christopher et al. [12] demonstrated that hybrid polyester and steel fibers improved compressive strength by 26%, suggesting and recommending the combined use of different fibers in concrete.

Akbulut et al. [13] concluded that the use of synthetic fibers improves ductility, helps mitigate micro-cracks due to shrinkage, and improves performance under dynamic loads.

Laskhmi et al. [14] demonstrated that as the polypropylene fiber content increases, shrinkage initially decreases but then tends to stabilize or even increase if the dosage is too high. The optimum percentage is around 1.0–1.5 kg/m³. Dosages above 1.5 kg/m³ reduce the cohesion of the mixture and increase porosity, inducing cracking .

In contrast, Kistan et al. [15] obtained different results from previous studies, indicating that the incorporation of plastic fibers as a substitute for fine aggregate led to a 16.9% reduction in compressive strength and a 17.6% reduction in flexural strength.

Similarly, Mohammed and Kasim [16] they concluded that the increase in waste polyethylene fibers reduced compressive strength by 15.74%, negatively affecting workability and performance.

In Peru, the use of concrete is highly standardized in all types of construction, as it is an efficient building material. Therefore, ignoring the problem of cracking represents negligence on the part of researchers that must be addressed as soon as possible [17].

At the national level, there is no standardized test that directly assesses the presence of cracks in slabs.

This situation highlights a research gap: the lack of standardized tests to evaluate concrete's behavior in response to cracking and the absence of technical criteria to optimize the dosage of synthetic fibers according to local material and climatic conditions. In this regard, ASTM C1579 is a valuable reference, providing an experimental method for analyzing plastic shrinkage cracking in physical models that simulate concrete slabs. Although it is a US standard, its adaptation to the Peruvian context allows for obtaining representative results without compromising the test's technical validity.

Therefore, this research aims to analyze the effect of incorporating polypropylene synthetic fiber on reducing the number, width, and length of cracks in physical models of concrete slabs with $f_c = 210 \text{ kg/cm}^2$. Tests were conducted with different dosages of polypropylene fiber in the mix: MP (0 g/m³), DM-01 (500 g/m³), DM-02 (1000 g/m³), and DM-03 (2000 g/m³). These were evaluated at 7, 14, 21, 28, and 35 days to determine the impact of the fiber on crack formation.

The aim of this research is to identify the optimal dosage of polypropylene synthetic fiber that provides the greatest benefits to concrete in terms of cracking and formation. By discovering its ability to reduce cracking, not only can the lifespan of structures be increased, but long-term maintenance and repair costs can also be reduced—topics of interest for future scientific studies.

MATERIALS AND METHODS

Methodology

Based on Tang's approach [18], this research was classified as applied, as it seeks to improve the plasticity of conventional concrete by incorporating polypropylene synthetic fiber at dosages of 500, 1000, and 2000 g/m³, with fiber lengths of 2 to 2.5 cm, to determine the optimum dosage. The approach is quantitative, as it uses concrete design parameters established by the ACI-318 standard, incorporates an unconventional additive—polypropylene synthetic fiber—and obtains data through the ASTM C1579 standard formula .

This research aims to analyze the behavior and progression of the number, width, and length of cracks appearing in physical models of slabs, as determined and proposed by ASTM C1579, which simulates crack formation in concrete. To this end, four mix designs were developed: MP (0 g/m³), DM-01 (500 g/m³), DM-02 (1000 g/m³), and DM-03 (2000 g/m³). Three of these mix designs incorporated polypropylene synthetic fiber to compare them with the control concrete (MP) and determine the optimal mix design that provides the greatest structural benefits.

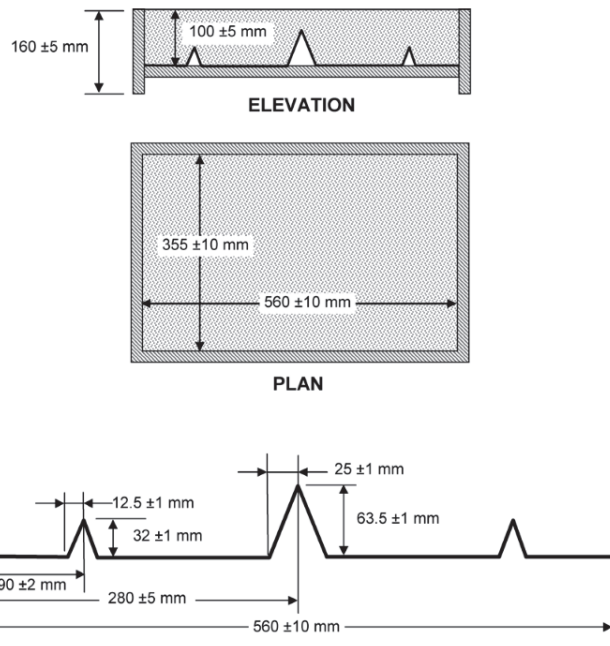


Figure 1: Dimensioning of the formwork for the samples.

These physical models will be manufactured with a material that prevents water absorption.

To determine the optimal dosage, a formula proposed in ASTM C1579, known as the "Crack Reduction Index," will be used. This index is directly proportional to the fiber-reinforced concrete and inversely proportional to the control concrete. Comparative graphs of the Crack Reduction Index versus Fiber Dosage were developed for each aspect of the cracks (number, length, and width), showing the dosage that yielded the greatest possible benefit for the concrete.

$$CRR = 1 - \frac{\text{Crack length in concrete mix incorporating fiber}}{\text{Crack length in concrete without fiber incorporation}} * 100 \quad (1)$$

Number of samples and materials

According to Navidi [19] a sample is a subgroup of the population, since it is rarely possible to accurately measure the entire population. Therefore, this subset seeks to faithfully represent the total population under study. For this research, 20 specimens were prepared to represent the population of concrete slabs.

The sample size for the physical models was calculated using formula (2), adopting a 90% confidence level ($Z=1.645$), a probability of success $p=0.95$, considering 12 favorable precedents out of 13 consulted studies, and a margin of error $e=0.08$ (8%). Substituting the values into the formula yields $n \approx 20.08$. However, given the experimental conditions and the minimal practical difference, a sample size of $n = 20$ is also considered acceptable, which implies an effective margin of error of $\approx 8.02\%$. It should be noted that the reviewed precedents mostly correspond to compression and tensile strength tests, etc., and not to specific cracking tests. Therefore, the choice of $p=0.95$ is based on previous evidence on general material improvements and is recognized as a conservative approach in the absence of specific local experimental studies on cracking.

$$n = \frac{Z^2 * p * (1 - p)}{e^2} \quad (2)$$

The properties of polypropylene synthetic fiber were characterized to better understand its behavior in concrete. This characterization allows for the identification of its physical and mechanical properties, such as tensile strength, density, melting point, water absorption, and coefficient of friction, which influence the material's ability to control the appearance and propagation of cracks.

Object of Study	Independent Variable (% of Fiber)	# of physical slab models	Dependent Variable (% of Cracking)
Concrete slabs exposed to cracking	0 gr/m ³	5	M1
	500 gr/m ³	5	M2
	1000 gr/m ³	5	M3
	2000 gr/m ³	5	M4
	Total =	20	

Table 1: Breakdown of the number of samples for each dosage of polypropylene synthetic fiber proposed in the research.

PROPERTIES	WORTH
Density	0.902 g/cm ³
Tensile strength	161.64 kg/cm ²
Melting point	160 °C
Water absorption (24 hours)	<0.01%
Coefficient of friction	0.26

Table 2: Characterization of the properties of the synthetic polypropylene fiber.

The materials used in this research were selected based on the researcher's needs, with the aim of optimizing the study's execution. The purpose of this research was to replicate and utilize materials commonly available in the local market for construction in this sector.

The physical molds were manufactured using phenolic wood boards, following the specifications detailed in Figure 1. This material was selected for its ability to prevent water absorption, which is essential to ensure the quality of the formwork in the slab molds.

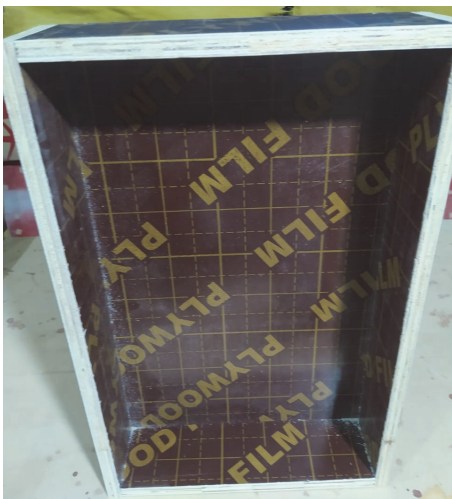


Figure 2: Fabrication of the physical model of the slab.

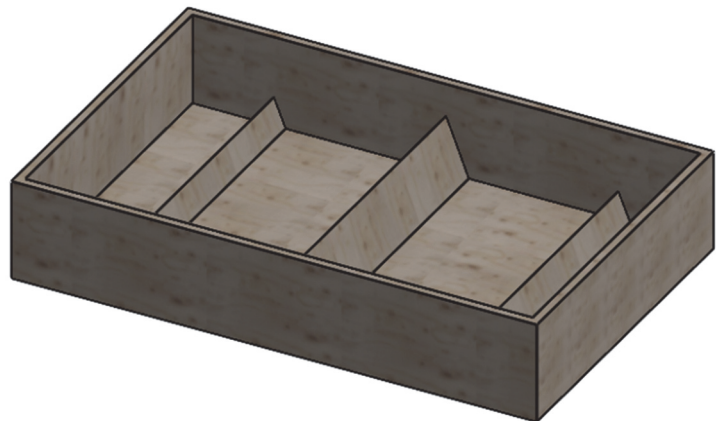


Figure 3: Digitized physical model of the slab.



Figure 4: Synthetic polypropylene fiber used in the research.



For the preparation of the concrete, coarse and fine aggregates from the Yocará quarry were used, which were processed and selected. This type of material is one of the most commonly used in housing construction in the city of Juliaca, where the research was conducted.

The key material in this study is polypropylene synthetic fiber, a necessary component due to its accessibility to the population and its viability in the building construction process. This fiber was acquired from local plastic supply stores in Juliaca, providing the raw material for its unconventional application in the concrete used in this research.

Mix design used

The dosage used in this study was 210 kg/cm², developed by the researchers themselves, who were also responsible for the article. This ensured the integrity and reliability of the results obtained during its execution. The design and testing were supported by the Laboratory of the Peruvian Union University, which guaranteed the results of all the tests necessary for the proper execution of this research.

The materials required for the mix design were crushed stone and coarse sand, for which laboratory tests were conducted to determine the physical properties necessary for the concrete mix design. The tests performed on both the coarse and fine aggregates, in accordance with ASTM standards for mix design, were: particle size analysis (ASTM C-136), moisture content (ASTM D-2216), specific gravity and absorption (ASTM C-128), and unit weight (ASTM C-29). The results of these tests are presented in the following data table:

Property	Fine aggregate	Coarse aggregate
Specific gravity (g/cm ³)	1.091	2.228
Loose unit weight (g/cm ³)	1.313	1.257
Compacted unit weight (g/cm ³)	1,659	1.436
Absorption (%)	2.47%	2.89%
Moisture content (%)	3.20%	2.50%
Fineness modulus	2.98	6.52
Maximum nominal size	---	1/2"

Table 3: Physical properties of the aggregates needed for the design of 210 kg/cm².

The cement used in the mix was RUMI Type IP, one of the most common cements used in residential slab construction due to its low cost and good performance in cold climates. It has a density of 2.8 g/cm³, according to the supplier's technical data sheet.

The mix design of 210 kg/cm² was developed following the guidelines of the American standard ACI 211.1, which explicitly outlines the steps for proper concrete mix design. The resulting mix design required for this research was as follows:

Mix design	Cement	Fine aggregate	Coarse aggregate	Water (l/bag)
210 kg/cm ²	1.00	0.81	2.03	23.89

Table 4: Mix proportions for the design of 210 kg/cm² concrete according to ACI 211.1, showing the proportions of materials for cement, aggregate and water.

During the preparation of the concrete, the slump test was performed in accordance with ASTM C143 to verify the workability of the designed concrete.

Samples	Proposed in mix design	Obtained
MP	3"-4"	4.00
MP	3"-4"	3.92
DM-01	3"-4"	3.47
DM-01	3"-4"	3.53
DM-02	3"-4"	3.41
DM-02	3"-4"	3.48
DM-03	3"-4"	3.65
DM-03	3"-4"	3.81

Table 5: Results of the concrete slump test according to ASTM C143 to verify the workability of the designed concrete.



Using the developed mix design, a total of 8 specimens were prepared to evaluate the compressive strength of the hardened concrete. These specimens were cured at 7 and 28 days, submerged in water tanks. Under identical environmental conditions for each specimen evaluated, as part of the tests necessary for quality control of the construction materials used. The following table shows the results obtained from the tests carried out in the Concrete Laboratory of the Peruvian Union University:

Witness	Dimensions (cm)		Emptying date	Test date	Age (days)	Gross area (cm ²)	Applied load (kgf)	Compressive strength (kg/cm ²)
	Diameter	High						
T-01	15.10	30.17	10.02	17.02	7	179.08	34360.00	191.87
T-02	14.90	29.71	10.02	17.02	7	174.37	35502.30	203.61
T-03	14.90	29.78	20.01	17.02	28.00	174.37	45921.40	263.36
T-04	15.15	30.44	20.01	17.02	28.00	180.27	45536.50	252.61
T-05	15.10	29.85	20.01	17.02	28.00	179.08	42369.10	236.59
T-06	15.10	30.25	20.01	17.02	28.00	179.08	41735.30	233.06
T-07	15.15	29.78	20.01	17.02	28.00	180.27	42434.50	235.40
T-08	15.15	30.00	20.01	17.02	28.00	180.27	43588.40	241.80

Table 6: Results of compression strength tests according to ASTM C39 standard.

Based on the concrete mix design, this was established as the Control Concrete (CP), which served as the basis of the research, to which synthetic polypropylene fiber was incorporated to obtain the following dosages:

- Control sample (MP) (0 g/m³)
- Sample design 01 (DM-01) (500 gr/m³)
- Sample design 02 (DM-02) (1000 gr/m³)
- Sample design 03 (DM-03) (2000 gr/m³)

Dosage (g/m ³)	Sample	Volume (m ³)	Necessary raffia (g)
0	M-01	0.0274	0.00
	M-02	0.0274	0.00
	M-03	0.0274	0.00
	M-04	0.0274	0.00
	M-05	0.0274	0.00
500	M-06	0.0274	13.68
	M-07	0.0274	13.68
	M-08	0.0274	13.68
	M-09	0.0274	13.68
	M-10	0.0274	13.68
1000	M-11	0.0274	27.36
	M-12	0.0274	27.36
	M-13	0.0274	27.36
	M-14	0.0274	27.36
	M-15	0.0274	27.36
2000	M-16	0.0274	54.71
	M-17	0.0274	54.71
	M-18	0.0274	54.71
	M-19	0.0274	54.71
	M-20	0.0274	54.71

Table 6: Incorporated weight of polypropylene synthetic fiber in the control concrete.

RESULTS AND ANALYSIS

In Peru, there is no specific standard or guideline that details or explains the measurement of drying shrinkage cracks in concrete. Standards NTP 399.022, NTP 399.013, NTP 399.011, and NTP 399.015 provide general guidelines for evaluating cracks in concrete, without specifying a direct and simple method.

For this reason, the present research is based on the American standard ASTM C1579. This standard was used with the objective of proposing the use of physical models (see figure 1), which seek to accurately represent real slabs for applied research purposes.

Simultaneously with the verification of a suitable mix design, 20 samples of the physical slab models were molded: 5 control concrete slabs (MP), 5 MP-01 slabs, 5 DM-02 slabs and 5 DM-03 slabs.



Figure 5: Emptying of the 20 samples of the physical slab models.

After molding, the samples underwent a continuous curing process under identical environmental conditions, as the objective was to simulate the actual curing of concrete slabs in construction. Therefore, simply immersing them in water was not representative of the real-world conditions anticipated in the research. Consequently, it was determined that the best way to cure the physical slab models was to water their surfaces daily, supplemented by a cover that would help retain moisture for an extended period, thus ensuring that the samples remained in constant contact with moisture for proper concrete curing.

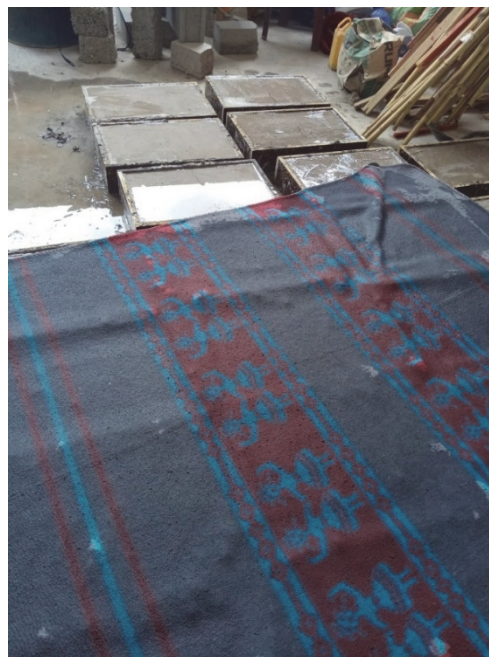


Figure 6: Curing of the physical slab model samples.

Data on the number, width, and length of cracks were collected as the curing process progressed. Days 7, 14, 21, 28, and 35 after pouring were determined to be the most suitable for obtaining sample data, allowing for organized record-keeping with assessments every 7 days after pouring on these five designated dates.

During January and February 2025, the city of Juliaca (Puno) experienced typical rainy season weather conditions. During the curing and testing of the concrete samples, the average temperature hovered around 11.5°C. ° C, with minimum values of 4 ° C and maximums of 18 ° C, while the average relative humidity remained at 72 %, with a range of 65 80% %, which were obtained using external climate measurement equipment.

The application of ASTM C1579 is based on the design of the physical slab forms, which induce cracking in the concrete due to the presence of three raised sections in their structure, creating areas of reduced width where cracks tend to form. Although the original test established by the standard is performed over a short period of 3 to 4 hours—corresponding to the setting time—in this study, the procedure was adapted for an extended evaluation of 35 days, encompassing the complete curing and post-curing process. These modifications do not affect the comparative validity of the results, since at the time of measurement the cracks are fully developed and stabilized within the concrete's structural system, allowing for reliable visual evaluation.

Sample results

During each week following sample molding, data were collected to support the results of this research, evaluating the frequency, width, and/or length of cracks that appeared in the samples during the curing period. Considering the behavior and nature of the cracks, a random pattern was observed in their appearance, with no predictable trend in their number or location.

A handheld crack gauge was used to accurately, practically, and efficiently measure the width and length of the cracks.

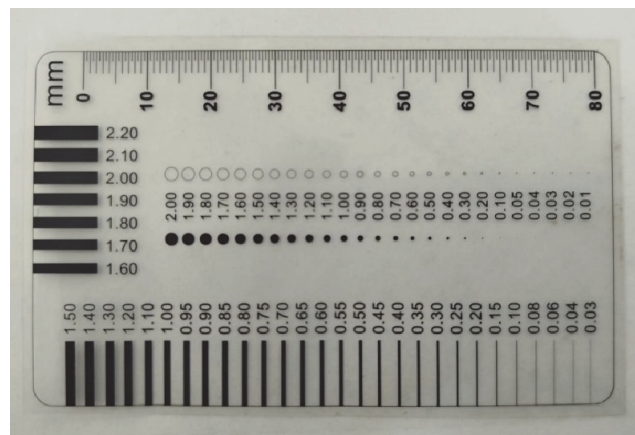


Figure 7: Manual crack gauge used for measuring the width and length of cracks.

Crack measurement in concrete slabs was performed using a manual crack gauge. The surface of the physical slab models was cleaned beforehand. Each visible crack was identified and marked, and its width was determined by placing the crack gauge's millimeter scale over the crack and recording the value. This measurement was repeated at different points to obtain an average. The length of each crack was measured with the same instrument, adding together sections in the case of irregular cracks. The total number of cracks was counted within the measurement area of the various molds created for each mix design.

Many of the cracks initially analyzed appeared insignificant, but over time they developed considerably, becoming detrimental to the concrete slabs. Many of the cracks assessed at the final date were due to the merging of smaller cracks that connected linearly to form a crack of considerable size for the slabs. While some cracks maintained their width and length throughout the assessment period, others developed further, increasing in size and becoming visible without the need for a crack gauge.

The following tables present the results of the visual evaluation, which numerically show the process of appearance and growth of cracks, divided according to the doses used in the research and described previously.



CRACKS	M-01		M-02		M-03		M-04		M-05		
	W(mm)	L (mm)	W (mm)	L (mm)	W (mm)	L (mm)	W (mm)	L (mm)	W (mm)	L (mm)	
7 DAYS	F-01	3.00	288.00	1.00	156.00	1.00	21.00	1.00	91.00	1.00	103.00
	F-02	---	---	1.00	24.00	2.00	95.00	2.00	59.00	2.00	62.00
	F-03	1.00	236.00	---	---	---	---	1.00	61.00	---	---
	F-04	2.00	256.00	---	---	---	---	---	---	---	---
	F-05	---	---	---	---	---	---	2.00	50.00	---	---
14 DAYS	F-01	3.00	303.00	1.00	169.00	3.00	55.00	2.00	106.00	3.00	128.00
	F-02	1.00	6.00	2.00	91.00	2.00	106.00	3.00	65.00	2.00	80.00
	F-03	1.00	302.00	1.00	21.00	1.00	4.00	2.00	87.00	1.00	24.00
	F-04	2.00	292.00	---	---	---	---	2.00	11.00	---	---
	F-05	1.00	11.00	1.00	19.00	---	---	3.00	66.00	1.00	18.00
	F-06	---	---	1.00	21.00	1.00	12.00	---	---	---	---
	F-07	---	---	1.00	20.00	---	---	---	---	---	---
21 DAYS	F-01	4.00	326.00	1.00	194.00	3.00	56.00	2.00	111.00	3.00	151.00
	F-02	3.00	11.00	2.00	98.00	2.00	135.00	4.00	89.00	3.00	91.00
	F-03	2.00	405.00	1.00	46.00	1.00	15.00	3.00	94.00	2.00	39.00
	F-04	2.00	320.00	1.00	22.00	1.00	15.00	2.00	22.00	1.00	8.00
	F-05	2.00	33.00	1.00	34.00	1.00	11.00	3.00	78.00	1.00	31.00
	F-06	---	---	1.00	39.00	1.00	31.00	1.00	29.00	3.00	21.00
	F-07	---	---	2.00	41.00	1.00	15.00	1.00	6.00	---	---
	F-08	---	---	1.00	8.00	---	---	---	---	---	---
	F-09	---	---	---	---	---	---	---	---	---	---
	F-10	---	---	1.00	40.00	---	---	---	---	---	---
28 DAYS	F-01	4.00	380.00	2.00	225.00	3.00	70.00	2.00	121.00	3.00	160.00
	F-02	3.00	19.00	2.00	118.00	3.00	151.00	4.00	110.00	3.00	109.00
	F-03	2.00	443.00	2.00	66.00	2.00	20.00	3.00	111.00	2.00	50.00
	F-04	2.00	341.00	2.00	36.00	2.00	29.00	2.00	38.00	2.00	14.00
	F-05	3.00	45.00	1.00	51.00	1.00	22.00	3.00	91.00	2.00	44.00
	F-06	1.00	15.00	1.00	62.00	1.00	49.00	2.00	37.00	3.00	38.00
	F-07	---	---	2.00	53.00	1.00	22.00	1.00	19.00	2.00	11.00
	F-08	---	---	1.00	13.00	---	---	---	---	---	---
	F-09	---	---	1.00	9.00	---	---	---	---	---	---
	F-10	---	---	2.00	61.00	---	---	---	---	---	---
35 DAYS	F-01	4.00	385.00	2.00	230.00	3.00	75.00	2.00	125.00	3.00	162.00
	F-02	3.00	25.00	2.00	120.00	3.00	153.00	4.00	111.00	3.00	111.00
	F-03	2.00	450.00	2.00	70.00	2.00	23.00	3.00	115.00	2.00	50.00
	F-04	2.00	350.00	2.00	36.00	2.00	35.00	2.00	40.00	2.00	15.00
	F-05	3.00	55.00	1.00	52.00	1.00	25.00	3.00	95.00	2.00	45.00
	F-06	1.00	18.00	1.00	68.00	1.00	50.00	2.00	40.00	3.00	40.00
	F-07	---	---	2.00	60.00	1.00	22.00	1.00	19.00	2.00	15.00
	F-08	---	---	1.00	15.00	---	---	---	---	---	---
	F-09	---	---	1.00	10.00	---	---	---	---	---	---
	F-10	---	---	2.00	65.00	---	---	---	---	---	---

Table 7: Collection of crack data in the control sample (MP), at 7, 14, 21, 28 and 35 days of concrete curing.



CRACKS	M-06		M-07		M-08		M-09		M-10		
	W(mm)	L (mm)	W (mm)	L (mm)	W (mm)	L (mm)	W (mm)	L (mm)	W (mm)	L (mm)	
7 DAYS	F-01	3.00	325.00	---	---	1.00	72.00	1.00	151.00	---	---
	F-02	2.00	35.00	1.00	41.00	1.00	92.00	---	---	---	---
	F-03	---	---	1.00	199.00	1.00	119.00	1.00	159.00	2.00	130.00
	F-04	---	---	---	---	---	---	---	---	1.00	70.00
	F-05	---	---	---	---	---	---	---	---	---	---
	F-06	1.00	60.00	---	---	---	---	---	---	---	---
14 DAYS	F-01	3.00	339.00	1.00	65.00	2.00	80.00	2.00	161.00	1.00	46.00
	F-02	3.00	42.00	1.00	49.00	1.00	100.00	1.00	25.00	2.00	35.00
	F-03	1.00	11.00	1.00	209.00	1.00	127.00	1.00	165.00	2.00	138.00
	F-04	---	---	---	---	---	---	1.00	11.00	1.00	79.00
	F-05	---	---	---	---	---	---	---	---	---	---
	F-06	1.00	68.00	---	---	---	---	---	---	---	---
	F-07	1.00	10.00	---	---	---	---	---	---	---	---
	F-08	1.00	28.00	---	---	---	---	---	---	---	---
21 DAYS	F-01	4.00	352.00	1.00	73.00	2.00	87.00	2.00	166.00	2.00	54.00
	F-02	3.00	49.00	1.00	60.00	2.00	108.00	2.00	33.00	2.00	41.00
	F-03	1.00	18.00	2.00	218.00	1.00	133.00	2.00	172.00	3.00	143.00
	F-04	1.00	10.00	1.00	62.00	---	---	1.00	19.00	1.00	87.00
	F-05	1.00	19.00	---	---	---	---	---	---	---	---
	F-06	1.00	77.00	---	---	---	---	---	---	---	---
	F-07	1.00	18.00	---	---	---	---	---	---	---	---
	F-08	1.00	35.00	---	---	---	---	---	---	---	---
28 DAYS	F-01	4.00	366.00	1.00	80.00	2.00	99.00	3.00	174.00	2.00	61.00
	F-02	3.00	62.00	1.00	86.00	2.00	115.00	2.00	41.00	2.00	50.00
	F-03	2.00	24.00	2.00	227.00	2.00	141.00	2.00	180.00	3.00	152.00
	F-04	1.00	15.00	1.00	71.00	---	---	2.00	24.00	1.00	94.00
	F-05	1.00	25.00	---	---	---	---	---	---	---	---
	F-06	2.00	86.00	---	---	---	---	---	---	---	---
	F-07	1.00	27.00	---	---	---	---	---	---	---	---
	F-08	1.00	43.00	---	---	---	---	---	---	---	---
35 DAYS	F-01	4.00	370.00	1.00	82.00	2.00	101.00	3.00	180.00	2.00	62.00
	F-02	3.00	60.00	1.00	89.00	2.00	117.00	2.00	42.00	2.00	52.00
	F-03	2.00	25.00	2.00	230.00	2.00	144.00	3.00	182.00	3.00	155.00
	F-04	1.00	20.00	1.00	74.00	---	---	2.00	25.00	1.00	95.00
	F-05	1.00	28.00	---	---	---	---	---	---	---	---
	F-06	2.00	90.00	---	---	---	---	---	---	---	---
	F-07	1.00	30.00	---	---	---	---	---	---	---	---
	F-08	1.00	45.00	---	---	---	---	---	---	---	---

Table 8: Collection of crack data in the samples of sample design 01 (DM-01), at 7, 14, 21, 28 and 35 days of concrete curing.



CRACKS	M-11		M-12		M-13		M-14		M-15		
	W(mm)	L (mm)	W (mm)	L (mm)	W (mm)	L (mm)	W (mm)	L (mm)	W (mm)	L (mm)	
7 DAYS	F-01	1.00	79.00	---	---	---	---	1.00	80.00	1.00	51.00
	F-02	---	---	---	---	---	---	1.00	165.00	1.00	57.00
	F-03	---	---	2.00	138.00	---	---	---	---	---	---
	F-04	1.00	118.00	1.00	119.00	0.00	---	---	---	1.00	58.00
	F-05	---	---	---	---	---	---	---	---	---	---
	F-06	---	---	---	---	1.00	119.00	---	---	---	---
14 DAYS	F-01	1.00	85.00	1.00	29.00	---	---	1.00	87.00	1.00	59.00
	F-02	1.00	35.00	2.00	55.00	1.00	28.00	2.00	171.00	2.00	64.00
	F-03	1.00	44.00	2.00	143.00	2.00	75.00	---	---	1.00	48.00
	F-04	2.00	125.00	2.00	128.00	---	---	---	---	1.00	65.00
	F-05	1.00	27.00	---	---	1.00	49.00	---	---	---	---
	F-06	1.00	43.00	---	---	1.00	124.00	---	---	1.00	48.00
21 DAYS	F-01	2.00	94.00	1.00	36.00	1.00	12.00	2.00	95.00	2.00	67.00
	F-02	1.00	43.00	2.00	64.00	2.00	35.00	2.00	179.00	2.00	71.00
	F-03	1.00	50.00	3.00	152.00	3.00	81.00	1.00	17.00	1.00	53.00
	F-04	2.00	132.00	3.00	135.00	1.00	8.00	---	---	1.00	73.00
	F-05	1.00	33.00	---	---	2.00	58.00	---	---	1.00	19.00
	F-06	1.00	51.00	---	---	2.00	131.00	---	---	1.00	55.00
28 DAYS	F-01	2.00	103.00	1.00	44.00	1.00	22.00	2.00	101.00	2.00	74.00
	F-02	1.00	51.00	2.00	72.00	2.00	46.00	2.00	188.00	2.00	68.00
	F-03	1.00	59.00	3.00	161.00	3.00	90.00	1.00	25.00	2.00	61.00
	F-04	2.00	140.00	3.00	148.00	1.00	14.00	---	---	1.00	80.00
	F-05	1.00	41.00	---	---	2.00	67.00	---	---	2.00	27.00
	F-06	1.00	60.00	---	---	2.00	140.00	---	---	1.00	64.00
35 DAYS	F-01	2.00	105.00	1.00	45.00	1.00	24.00	2.00	103.00	2.00	75.00
	F-02	1.00	52.00	2.00	74.00	2.00	48.00	2.00	190.00	2.00	70.00
	F-03	1.00	61.00	3.00	164.00	3.00	93.00	1.00	26.00	2.00	63.00
	F-04	2.00	143.00	3.00	150.00	1.00	15.00	---	---	1.00	81.00
	F-05	1.00	42.00	---	---	2.00	69.00	---	---	2.00	30.00
	F-06	1.00	65.00	---	---	2.00	141.00	---	---	1.00	68.00

Table 9: Collection of crack data in the samples of sample design 02 (DM-02), at 7, 14, 21, 28 and 35 days of concrete curing.



CRACKS	M-16		M-17		M-18		M-19		M-20		
	W(mm)	L (mm)	W (mm)	L (mm)	W (mm)	L (mm)	W (mm)	L (mm)	W (mm)	L (mm)	
7 DAYS	F-01	---	---	---	---	---	2.00	138.00	2.00	145.00	
	F-02	---	---	---	---	---	3.00	158.00	---	---	
	F-03	---	---	1.00	76.00	---	---	---	---	---	
	F-04	3.00	58.00	1.00	199.00	---	---	---	---	1.00	84.00
	F-05	3.00	169.00	---	---	---	---	---	---	---	---
	F-06	---	---	---	---	1.00	82.00	---	---	---	---
14 DAYS	F-01	---	---	---	1.00	47.00	3.00	146.00	2.00	151.00	
	F-02	2.00	75.00	1.00	30.00	---	---	3.00	165.00	1.00	40.00
	F-03	3.00	36.00	1.00	85.00	2.00	46.00	---	---	2.00	37.00
	F-04	3.00	64.00	2.00	208.00	2.00	41.00	---	---	1.00	91.00
	F-05	3.00	175.00	---	---	2.00	67.00	---	---	---	---
	F-06	---	---	---	---	2.00	90.00	---	---	---	---
21 DAYS	F-01	1.00	7.00	1.00	10.00	2.00	54.00	3.00	160.00	3.00	158.00
	F-02	3.00	82.00	1.00	36.00	1.00	17.00	4.00	180.00	2.00	47.00
	F-03	3.00	43.00	2.00	91.00	2.00	55.00	---	---	2.00	42.00
	F-04	4.00	71.00	2.00	211.00	3.00	49.00	---	---	2.00	97.00
	F-05	4.00	182.00	---	---	2.00	75.00	---	---	---	---
	F-06	---	---	---	---	3.00	98.00	---	---	---	---
28 DAYS	F-01	2.00	15.00	1.00	21.00	2.00	60.00	4.00	160.00	3.00	167.00
	F-02	3.00	91.00	1.00	42.00	1.00	25.00	4.00	180.00	3.00	53.00
	F-03	4.00	50.00	2.00	100.00	3.00	63.00	---	---	3.00	49.00
	F-04	4.00	80.00	2.00	220.00	3.00	57.00	---	---	2.00	104.00
	F-05	4.00	190.00	---	---	3.00	82.00	---	---	---	---
	F-06	---	---	---	---	3.00	109.00	---	---	---	---
35 DAYS	F-01	2.00	16.00	1.00	25.00	2.00	61.00	4.00	162.00	3.00	169.00
	F-02	3.00	95.00	1.00	45.00	1.00	28.00	4.00	181.00	3.00	55.00
	F-03	4.00	52.00	2.00	103.00	3.00	65.00	---	---	3.00	53.00
	F-04	4.00	81.00	2.00	222.00	3.00	60.00	---	---	2.00	109.00
	F-05	4.00	193.00	---	---	3.00	84.00	---	---	---	---
	F-06	---	---	---	---	3.00	110.00	---	---	---	---

Table 10: Collection of crack data in the samples of sample design 03 (DM-03), at 7, 14, 21, 28 and 35 days of concrete curing.

Twenty physical molds were prepared and experimentally evaluated by visual inspection and manual measurements using a crack width gauge, with the aim of recording and analyzing the crack formation and development process.



Figure 8: Physical Model M-01.



Figure 9: Physical Model M-02.



Figure 10: Physical Model M-03.



Figure 11: Physical Model M-04.



Figure 12: Physical Model M-05.



Figure 13: Physical Model M-06.



Figure 14: Physical Model M-07.



Figure 15: Physical Model M-08.



Figure 16: Physical Model M-09.



Figure 17: Physical Model M-10.



Figure 18: Physical Model M-11.



Figure 19: Physical Model M-12.



Figure 20: Physical Model M-13.



Figure 21: Physical Model M-14.



Figure 22: Physical Model M-15.



Figure 23: Physical Model M-16.



Figure 24: Physical Model M-17.



Figure 25: Physical Model M-18.

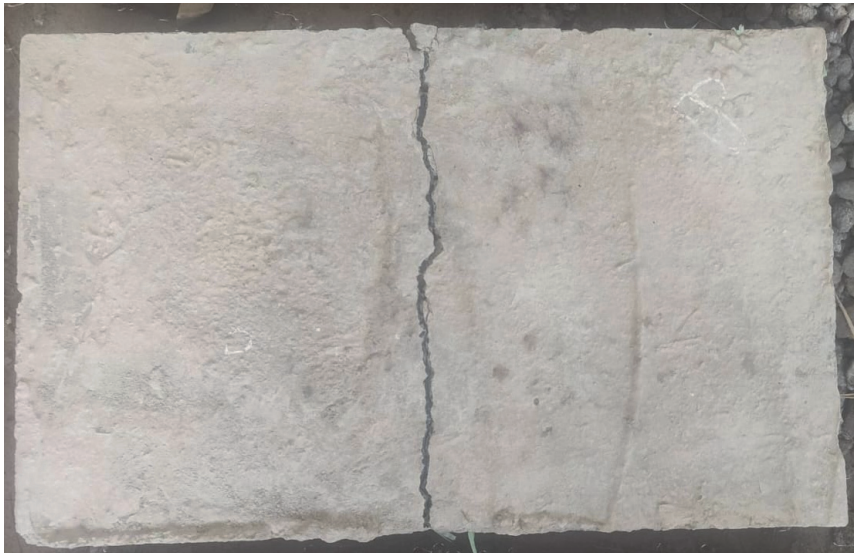


Figure 26: Physical Model M-19.



Figure 27: Physical Model M-20.

Through data collection, a consistent pattern was identified in the width of cracks in concrete slabs. Therefore, based on the researchers' assessment, it was deemed appropriate to establish a method for classifying the severity of cracks present in the slabs. Using the observed crack width as a reference, the following classification table was developed to provide a theoretical and visual understanding of the risk range and significance of cracks in concrete slabs.

Width (mm)	Risk Classification	Interpretation
1	Low	Width almost visually imperceptible, can be ignored at this stage, but should be addressed in the future to prevent serious damage.
2	Medium-Low	Width barely noticeable visually, should not be ignored; it should be addressed in the medium term to prevent serious damage.
3	Medium-High	Width clearly noticeable visually, cannot be ignored; it should be resolved in the short term to avoid posing a risk to structural integrity.
4	High	Width very clearly noticeable visually, must never be ignored; it should be addressed immediately as it poses a risk to structural integrity at the time of evaluation.

Table 11: Classification of crack severity in physical models of concrete slabs (for this research).



The data for this research were collected on five different dates after the pour to observe the growth, width, and length of the cracks. Therefore, the data from each date will be analyzed independently to identify when the greatest benefits for the concrete slabs were observed.

Statistical analysis

In this research, four statistical tests were used to analyze and express the relationships and significance of the data collected from the samples. These statistical tests help to understand the levels of significance in each sample analyzed, facilitating a consistent technical analysis.

The SPSS software version 30.0.0 (Statistical Package for the Social Sciences) was used to perform all statistical tests on the quantitative data obtained during the research.

The statistical tests used were the following:

DESCRIPTIVE STATISTICS

Descriptive statistical analysis of data allows us to determine the number of data points, the maximum, the minimum, the mean, and the standard deviation, which are necessary to understand the nature of the quantitative data collected on different dates.

Date	Sample	N	Minimum	Maximum	Mean	Standard Deviation	
7 days	MP	Width	13	1.00	3.00	1.5385	0.66023
		Length	13	21.00	288.00	123.2308	104.39281
	DM-01	Width	12	1.00	3.00	1.3333	0.65134
		Length	12	35.00	325.00	121.0833	81.73623
	DM-02	Width	10	1.00	2.00	1.1000	0.31623
		Length	10	51.00	165.00	98.4000	38.79347
DM-03	Width	9	1.00	3.00	1.88	0.92796	
	Length	9	58.00	199.00	123.2222	49.32235	
14 days	MP	Width	24	1.00	3.00	1.6667	0.81650
		Length	24	4.00	303.00	84.0417	93.95164
	DM-01	Width	20	1.00	3.00	1.4000	0.68056
		Length	20	10.00	339.00	89.4000	82.02079
	DM-02	Width	21	1.00	2.00	1.3333	0.48305
		Length	21	27.00	171.00	72.9524	41.79172
DM-03	Width	18	1.00	3.00	2.0000	0.76696	
	Length	18	30.00	208.00	88.5556	55.86772	
21 days	MP	Width	34	1.00	4.00	1.8529	0.95766
		Length	34	6.00	405.00	78.3824	97.63786
	DM-01	Width	23	1.00	4.00	1.6522	0.83168
		Length	23	10.00	352.00	88.4348	80.65517
	DM-02	Width	25	1.00	3.00	1.6400	0.70000
		Length	25	8.00	179.00	69.7600	45.77416
DM-03	Width	21	1.00	4.00	2.3810	0.97346	
	Length	21	7.00	211.00	84.0476	60.35187	
28 days	MP	Width	37	1.00	4.00	2.1081	0.84274
		Length	37	9.00	443.00	87.9189	103.20863
	DM-01	Width	23	1.00	4.00	1.8696	0.81488
		Length	23	15.00	366.00	96.6522	81.92824
	DM-02	Width	25	1.00	3.00	1.7200	0.67823
		Length	25	14.00	188.00	78.2400	46.16120
DM-03	Width	21	1.00	4.00	2.7143	1.00712	
	Length	21	16.00	222.00	93.7619	59.36658	
35 days	MP	Width	37	1.00	4.00	2.1081	0.84274
		Length	37	10.00	450.00	91.2162	104.29822
	DM-01	Width	23	1.00	4.00	1.9130	0.84816
		Length	23	20.00	370.00	99.9130	82.26670
	DM-02	Width	25	1.00	3.00	1.7200	0.67823
		Length	25	15.00	190.00	79.8800	46.37916
DM-03	Width	21	1.00	4.00	2.7143	1.00712	
	Length	21	16.00	222.00	93.7619	59.36658	

Table 12: Main width and length characteristics of sample designs at different ages of concrete.



This analysis is fundamental to obtaining an overall perspective of the data and establishing a solid foundation that facilitates the exploration of the relationships between the sample designs proposed for this research [20].

Descriptive statistical analysis allowed for the identification of the maximum and minimum crack width and lengths. The minimum width recorded in the samples was 1 mm, while the maximum reached 4 mm, values present in all analyzed samples. Similarly, the minimum crack length was 4 mm and the maximum reached 450 mm, considering the five measurement dates.

This behavior indicates that the cracks have grown irregularly over time, without a predictable pattern.

Furthermore, taking the control concrete (MP) as an example, it was observed that the average width of the cracks evolved as follows:

- Day 7: 1.54 mm
- Day 14: 1.67 mm
- Day 21: 1.85 mm
- Day 28: 2.11 mm
- Day 35: 2.11 mm

These values suggest a progressive increase in crack width over time.

On the other hand, the average length of the cracks in the control concrete (MP) showed the following variation:

- Day 7: 123.23 mm
- Day 14: 84.04 mm
- Day 21: 78.38 mm
- Day 28: 87.92 mm
- Day 35: 91.22 mm

Initially, relatively large cracks were recorded, reflected in high average length values. However, over time, smaller cracks began to appear, altering the average lengths. This behavior suggests that while cracks continue to appear, their distribution changes over time.

This example indicates, as in the other sample designs, that the average widths and lengths do not follow a progressive growth pattern, but rather adapt to the appearance of new cracks present in the samples throughout the measurement period.

Normality Test (Shapiro-Wilk)

The Shapiro-Wilk statistical test allows you to evaluate a data set by interpreting: “ $p_value > 0.05$ ”, which accepts the null hypothesis and indicates a normal distribution of the data, and “ $p_value < 0.05$ ”, which rejects the null hypothesis and indicates that the data does not follow a normal distribution [20].

The following are the results of the Shapiro-Wilk statistical test for the sample designs analyzed on the different measurement dates, analyzing each date independently of the others.

Date	Sample	Statistic	gl	Shapiro - Wilk		
				Sig.	Condition	
7 days	Width	MP	0.750	13	0.002	Not Normally Distributed
		DM-01	0.592	12	<0.001	Not Normally Distributed
		DM-02	0.366	10	<0.001	Not Normally Distributed
	Length	DM-03	0.780	9	0.012	Not Normally Distributed
		MP	0.829	13	0.015	Not Normally Distributed
		DM-01	0.875	12	0.076	Normally Distributed
14 days	Width	DM-02	0.919	10	0.348	Normally Distributed
		DM-03	0.923	9	0.417	Normally Distributed
		MP	0.736	24	<0.001	Not Normally Distributed
	Length	DM-01	0.631	20	<0.001	Not Normally Distributed
		DM-02	0.599	21	<0.001	Not Normally Distributed
		DM-03	0.818	18	0.003	Not Normally Distributed
21 days	Width	MP	0.764	24	<0.001	Not Normally Distributed
		DM-01	0.840	20	0.004	Not Normally Distributed
		DM-02	0.880	21	0.015	Not Normally Distributed
	Length	DM-03	0.864	18	0.014	Not Normally Distributed
		MP	0.802	34	<0.001	Not Normally Distributed
		DM-01	0.757	23	<0.001	Not Normally Distributed
	Width	DM-02	0.767	25	<0.001	Not Normally Distributed
		DM-03	0.886	21	0.019	Not Normally Distributed



	Length	MP	0.697	34	<0.001	Not Normally Distributed
		DM-01	0.821	23	<0.001	Not Normally Distributed
		DM-02	0.926	25	0.072	Normally Distributed
		DM-03	0.902	21	0.038	Not Normally Distributed
28 days	Width	MP	0.860	37	<0.001	Not Normally Distributed
		DM-01	0.823	23	<0.001	Not Normally Distributed
		DM-02	0.785	25	<0.001	Not Normally Distributed
		DM-03	0.877	21	0.013	Not Normally Distributed
	Length	MP	0.697	37	<0.001	Not Normally Distributed
		DM-01	0.824	23	<0.001	Not Normally Distributed
		DM-02	0.925	25	0.068	Normally Distributed
		DM-03	0.911	21	0.058	Normally Distributed
35 days	Width	MP	0.860	37	<0.001	Not Normally Distributed
		DM-01	0.840	23	0.002	Not Normally Distributed
		DM-02	0.785	25	<0.001	Not Normally Distributed
		DM-03	0.877	21	0.013	Not Normally Distributed
	Length	MP	0.698	37	<0.001	Not Normally Distributed
		DM-01	0.825	23	0.001	Not Normally Distributed
		DM-02	0.922	25	0.057	Normally Distributed
		DM-03	0.911	21	0.058	Normally Distributed

Table 13: Normal distribution test (Shapiro-Wilk) at different ages of concrete.

Applying the Shapiro-Wilk statistical test, it was identified that the crack width and length variables in the different sample designs (MP, DM-01, DM-02, and DM-03) and at different concrete ages (7, 14, 21, 28, and 35 days) mostly showed a p-value < 0.05, indicating that they did not follow a normal distribution. However, the crack length did follow a normal distribution in DM-01 (p-value = 0.076), DM-02 (p-value = 0.348), and DM-03 (p-value = 0.417) at 7 days; in DM-02 (p-value = 0.072) at 21 days; and in DM-02 (p-value = 0.068) and DM-03 (p-value = 0.058) at 28 days. In DM-02 (p = 0.057) and DM-03 (p = 0.058) at 35 days, a significant decrease was observed. Since parametric tests, such as ANOVA, require this assumption to be met, and most of the data did not satisfy it, nonparametric tests were used. To compare the four sample designs at each concrete age, the Kruskal-Wallis test was applied, and in cases where significant differences were found, the Mann-Whitney U test was used for pairwise comparisons. This approach ensures appropriate and reliable statistical analysis for interpreting the effect of polypropylene synthetic fiber on concrete cracking.

Kruskal-Wallis Statistical Test

Since the normality test indicated that not all the data followed a normal distribution, analysis of variance (ANOVA) was not appropriate for this research. Instead, the Kruskal-Wallis test was chosen, as it is more flexible and suitable when the assumption of normality is not met in at least one of the analyzed groups.

Date	Samples		Kruskal-Wallis		
			Kruskal-Wallis H	gl	Sig.
7 days	MP, DM-01, DM-02 Y DM-03	Width	6.121	3	0.102
		Length	1.384	3	0.709
14 days	MP, DM-01, DM-02 Y DM-03	Width	9.537	3	0.023
		Length	1.945	3	0.584
21 days	MP, DM-01, DM-02 Y DM-03	Width	8.872	3	0.031
		Length	3.313	3	0.346
28 days	MP, DM-01, DM-02 Y DM-03	Width	14.172	3	0.003
		Length	3.800	3	0.284
35 days	MP, DM-01, DM-02 Y DM-03	Width	13.590	3	0.004
		Length	3.066	3	0.382

Table 14: Kruskal-Wallis statistical test at different ages of concrete.

The Kruskal-Wallis test results showed that at 7 days there were no significant differences in crack width or length among the different sample designs. However, over time, differences in crack width began to appear, becoming significant at 14 days (p = 0.023), 21 days (p = 0.031), 28 days (p = 0.003), and 35 days (p = 0.004). This suggests that



the effect of sample design on crack width becomes more pronounced over time, differentiating one sample design from another.

On the other hand, although the crack lengths did not show significant differences according to the Kruskal-Wallis test, the Mann-Whitney U test was applied to verify whether there was at least a small difference between each sample design (DM-01, DM-02, and DM-03) and the control concrete (MP). To identify this difference, the significance value (p-value) of the test was analyzed, where a p-value < 0.05 indicates a statistically significant difference between the compared groups, while values close to 0.05 could suggest trends or small differences that might be relevant to the research.

Mann-Whitney U Statistical Test

After determining, using the Kruskal-Wallis statistical test, that there was a significant difference between at least two of the sample designs, the Mann-Whitney U test was applied. This is a non-parametric test used to compare each sample design (DM-01, DM-02, and DM-03) with the standard sample (SP). The objective is to identify which sample design shows significant differences compared to the standard sample.

Date	Sample		Mann-Whitney U		
			Mann-Whitney U	Z	Sig.
7 days	MP vs DM-01	Width	63.000	-0.964	0.335
		Length	70.000	-0.435	0.689
	MP vs DM-02	Width	41.000	-1.851	0.148
		Length	63.000	-0.124	0.927
	MP vs DM-03	Width	46.500	-0.875	0.382
		Length	48.000	-0.701	0.483
14 days	MP vs DM-01	Width	198.000	-1.140	0.254
		Length	210.000	-0.707	0.479
	MP vs DM-02	Width	203.000	-1.280	0.201
		Length	214.000	-0.865	0.387
	MP vs DM-03	Width	164.000	-1.416	0.157
		Length	165.500	-1.284	0.199
21 days	MP vs DM-01	Width	350.000	-0.723	0.470
		Length	313.000	-1.269	0.204
	MP vs DM-02	Width	386.500	-0.639	0.523
		Length	347.500	-1.189	0.234
	MP vs DM-03	Width	248.000	-1.981	0.048
		Length	267.000	-1.559	0.119
28 days	MP vs DM-01	Width	356.000	-1.134	0.257
		Length	336.500	-1.353	0.176
	MP vs DM-02	Width	346.500	-1.793	0.073
		Length	379.000	-1.198	0.231
	MP vs DM-03	Width	252.000	-2.315	0.021
		Length	287.500	-1.634	0.102
35 days	MP vs DM-01	Width	369.000	-0.918	0.359
		Length	339.000	-1.308	0.191
	MP vs DM-02	Width	346.500	-1.793	0.073
		Length	387.500	-1.077	0.282
	MP vs DM-03	Width	252.000	-2.315	0.021
		Length	300.500	-1.424	0.154

Table 15: Mann-Whitney U statistical test at different ages of concrete.

The Mann-Whitney U test results show that, overall, there are no statistically significant differences in crack width and length between the standard concrete (MP) and the sample designs (DM-01, DM-02, and DM-03) on most of the days analyzed, as the p-values are greater than 0.05. However, the crack width in DM-02 on days 28 (p-value = 0.073) and 35 (p-value = 0.073) shows a trend toward statistical significance, suggesting a possible reduction in crack width with the addition of fibers. Similarly, in DM-03, the width showed significant differences on days 21 (p-value = 0.048), 28 (p-value = 0.021), and 35 (p-value = 0.021), indicating that the addition of fibers in this design could have a significant effect on reducing crack width. Regarding crack length, no significant differences were found on any of the days evaluated, suggesting that the polypropylene synthetic fiber may have a greater influence on reducing crack width than on crack length. However, although the statistical test did not show a significant difference, this does not imply that

there was no reduction in crack length and width. Therefore, a technical analysis of the data will be performed to corroborate the statistical results and determine an exact percentage reduction, thus complementing the statistical tests for a better understanding of crack reduction in concrete slabs.

Technical analysis

Based on the statistical analysis of data collected during the construction phase, the aim is to determine the optimal dosage of polypropylene synthetic fiber in concrete slabs. To this end, a technical analysis of the information obtained at each curing stage will be performed to understand the cracking process. However, since the Mann-Whitney U test showed a significant difference between the Standard Sample (SS) and the Sample Designs (DM-01, DM-02, and DM-03) at 28 and 35 days, it was decided to identify the optimal dosage using the data corresponding to 28 days. This is because, at this stage, the concrete completes its curing process and reaches its maximum strength, which is more beneficial for the research.

CRACK DEVELOPMENT

Cracks develop during the concrete curing phase, allowing them to be identified through visual observation of their growth. Their appearance is related to the expansion and contraction processes of the material, manifesting primarily in areas where the concrete is thinner. Data collection at the five curing stages allowed for a progressive analysis of crack formation and propagation, as detailed in the following three graphs (Time vs. Width, Length, and Cracks), considering the maximum value for width and length, and the total frequency for the number of cracks.

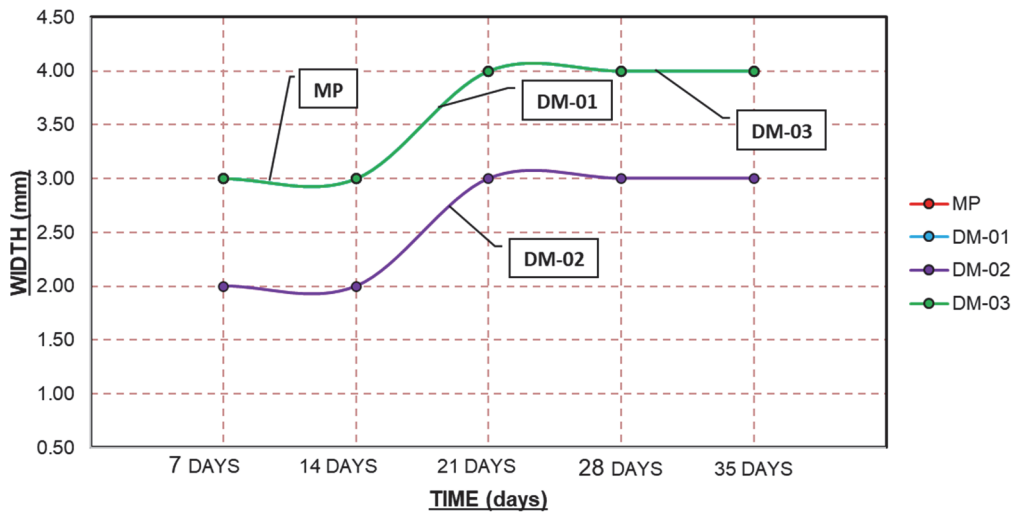


Figure 28: Graph of width versus curing time.

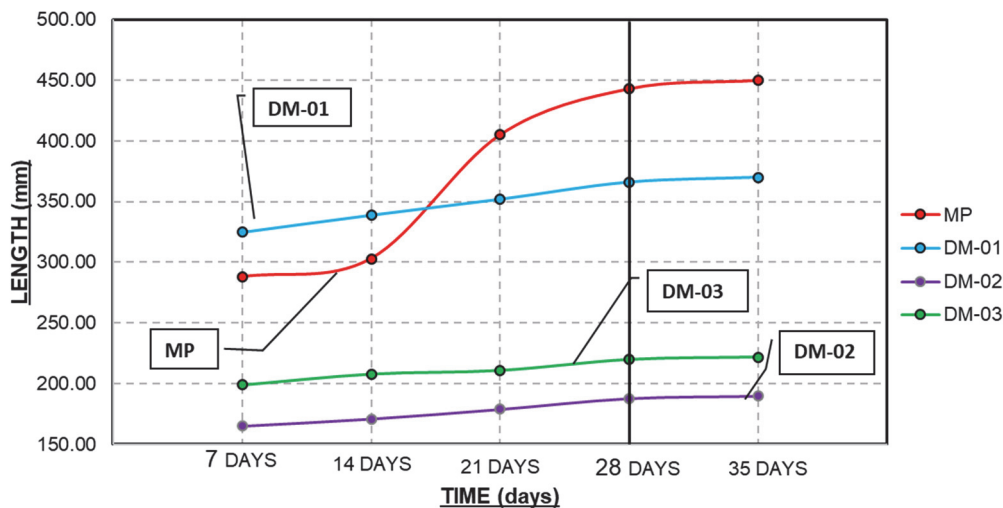


Figure 29: Graph of length versus curing time.

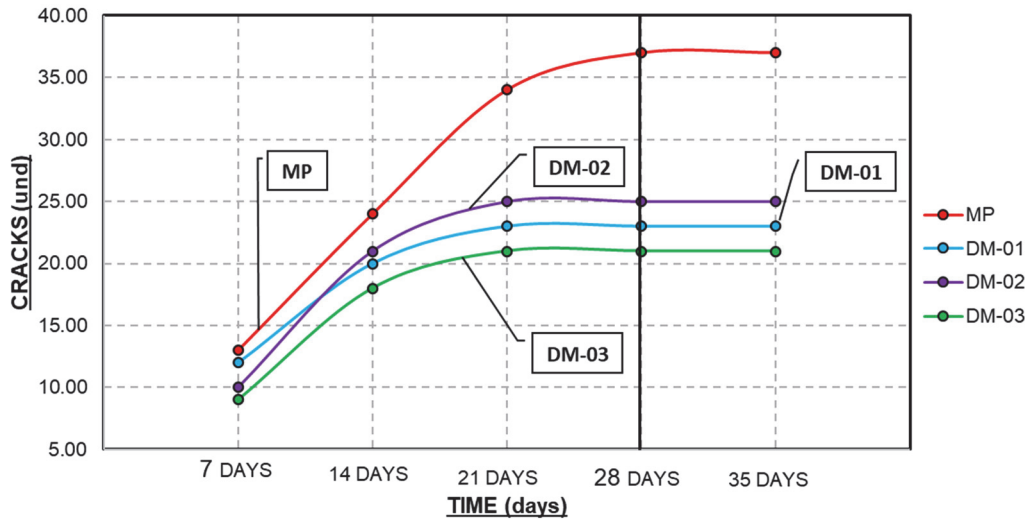


Figure 30: Graph of cracks versus curing time.

The three graphs illustrate the process of crack appearance and propagation during the curing period, allowing for an understanding of crack formation behavior in the simulated concrete slabs. Figures 8 and 9 show the maximum data values corresponding to MP, DM-01, DM-02, and DM-03; therefore, the width and length values shown in the graphs are determined by the maximum crack data and their respective dimensions on the measurement dates. Figure 10, on the other hand, shows the relationship between the number of cracks and the curing time, clearly demonstrating the pattern of crack appearance and evolution in the physical models of the concrete slabs.

The development of these graphs aims to identify the percentage differences in the growth and/or appearance of width, length, and cracks in the physical models of concrete slabs.

Figures 8 and 9 present the graphs showing the relationship between the average width and length of the cracks and the curing time for the different sample designs, considering days 7, 14, 21, 28 and 35. Based on these data, a table was created showing the percentage variations in width and length between each of the measurement dates.

Sample design	Crack	Variation (%)			
		7 days - 14 days	14 days - 21 days	21 days - 28 days	28 days – 35 days
MP	Width	11.04%	8.46%	13.77%	0.00%
	Length	-27.26%	-6.73%	12.17%	3.75%
DM-01	Width	5.00%	18.01%	13.16%	2.33%
	Length	-26.17%	-1.08%	10.28%	2.45%
DM-02	Width	21.21%	23.00%	4.88%	0.00%
	Length	-25.86%	-4.38%	11.58%	2.62%
DM-03	Width	5.88%	19.05%	14.00%	0.00%
	Length	-28.13%	-5.09%	8.67%	2.66%

Table 16: Percentage variation of the average width and length of the crack.

The table indicates that, between days 21 and 28, the physical models show the last significant crack formation in terms of width, with a variation ranging from a minimum of 4.88% in DM-02 to a maximum of 13.77% in MP. In contrast, between days 28 and 35, corresponding to the period after curing, the width variations do not exceed 3%, which does not represent a relevant increase.

When analyzing crack lengths in the physical models, it is observed that between days 7-14 and 14-21, the percentage variations are negative. However, this does not imply that the crack length is decreasing. In fact, it reflects the appearance of new, shorter cracks, which significantly alters the average for each sample. This behavior reveals an erratic and random crack formation pattern that does not follow a defined trend or respond to the implemented control measures.

However, between days 21 and 28, the formation of new cracks begins to cease, focusing solely on the spontaneous growth of existing cracks. During the period from 28 to 35 days, this growth decreases even further, reaching a maximum of only 3.75% in MP, which represents a relatively small increase compared to the samples evaluated.

This analysis helps to directly understand the process of crack formation and propagation in physical models. It also identifies that, around day 28, the cracks stop growing progressively and begin to stabilize, maintaining the same dimensions or, at most, showing a growth rate of less than 4%, which implies a tendency toward stabilization in crack formation and propagation.

Figure 9 presents a histogram showing the number of cracks recorded on each measurement day. The values reflect the number of cracks observed in the physical molds for each sample design, allowing visualization of how crack presence varies over time and identification of the point at which they begin to stabilize or cease altogether.

The objective of this research is to determine the optimal incorporation of polypropylene synthetic fiber. Therefore, the graphs in Figures 7, 8, and 9 initially show, visually, which sample designs meet this research requirement.

Considering that MP is the baseline of the study, represented by the red line in each graph, the following interpretations can be made.

- First, in Figure 7, only DM-01 and DM-02 reach average values below MP for each measurement date, representing the presence of narrower cracks in these sample designs. In contrast, DM-03 shows values above MP, indicating wider cracks in this sample design.
- Secondly, in Figure 8, only DM-02 shows shorter lengths than those found in MP, which represents an advantage for the sample design. Conversely, DM-01 and DM-03 have longer lengths than MP, which is interpreted as a disadvantage for these designs.
- Third, in Figure 9, all data for the sample designs (DM-01, DM-02, and DM-03) are less than MP, meaning that the number of cracks in these designs is much lower and stops appearing 21 days after molding.

Crack Reduction Ratio (CRR)

The American standard ASTM C 1579 presents formula (1), which provides a way to identify crack reduction in partially or totally controlled samples, using as dependent data the width, length and/or average number of cracks of MP and each sample design (DM-01, DM-02 and DM-03) to calculate crack reduction in percentage terms.

By applying formula (1) relating each sample design (DM-01, DM-02 and DM-03) to MP for each measurement date, the corresponding percentages were determined and used to develop the graphs showing the crack reduction.

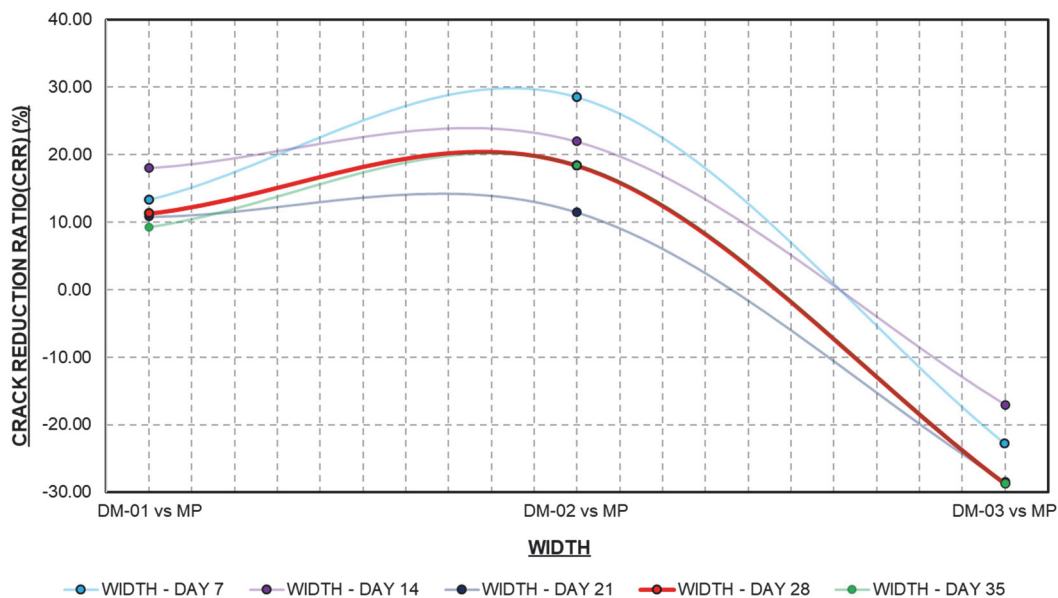


Figure 31: Crack reduction ratio (width).

Figure 31 illustrates a graph showing the crack reduction ratio (CRR) in width versus its respective percentage reduction for each sample design compared to the control sample (DM-01 vs. MP, DM-02 vs. MP, and DM-03 vs. MP). Each line corresponds to a specific post-casting data collection date, which explains why each comparison shows a different behavior. However, all follow a similar reduction trend within their own comparison for each analyzed date.

As mentioned previously, analyzing the data for 28 days (red line) shows that comparisons between DM-01 and MP, and between DM-02 and MP, reveal reductions in crack width of 11.32% and 18.41%, respectively. However, the comparison between DM-03 and MP does not show a decrease, but rather an increase of 28.75% in crack width. This increase represents a clear disadvantage that must be considered when incorporating this mix design into concrete.

Considering only the width variable, it is understood that design DM-03 does not contribute to reducing crack width in concrete, so its incorporation does not provide any significant benefit. In contrast, designs DM-01 and DM-02 do reduce crack width, with DM-02 standing out for achieving the greatest reduction, with a CRR of 18.41%.

Figure 32 shows the crack reduction ratio (CRR) in length and its respective percentage reduction. Evaluating the data obtained at 28 days, it is observed that only design DM-02 achieves a reduction in crack length, with 11.46%, the highest value among the designs analyzed. In contrast, designs DM-01 and DM-03 not only fail to reduce crack length, but

actually cause an increase of 10.92% and 3.88%, respectively, which is an important aspect to consider when applying them to concrete slabs.

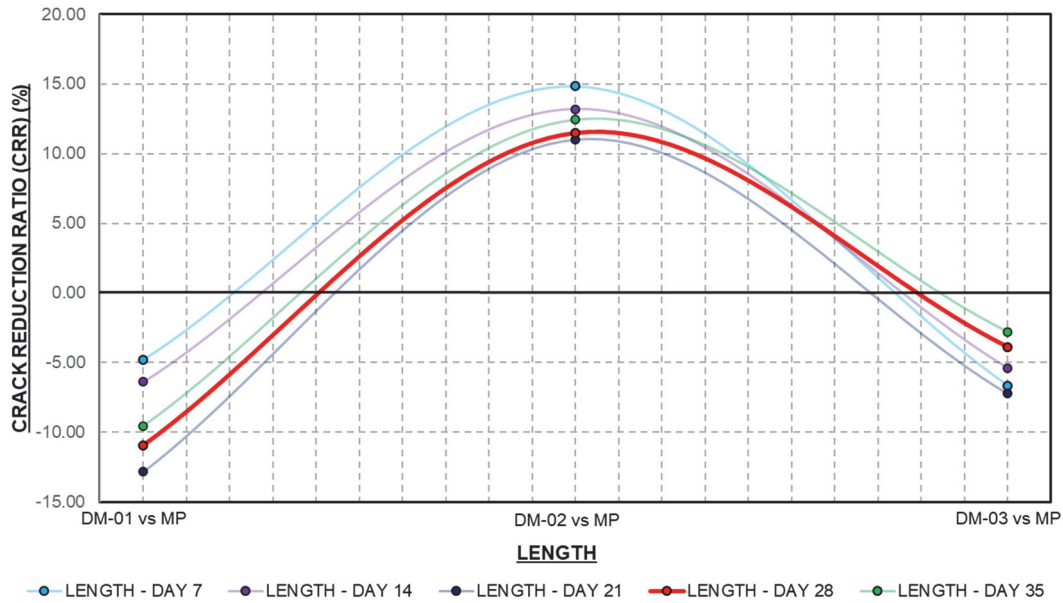


Figure 32: Crack reduction ratio (length).

Focusing solely on crack length, it is concluded that sample designs DM-01 and DM-03 do not contribute to reducing it in the physical models; on the contrary, they cause a considerable increase. In contrast, design DM-02 represents a favorable alternative for incorporating polypropylene synthetic fiber, achieving an 11.46% reduction in crack length.

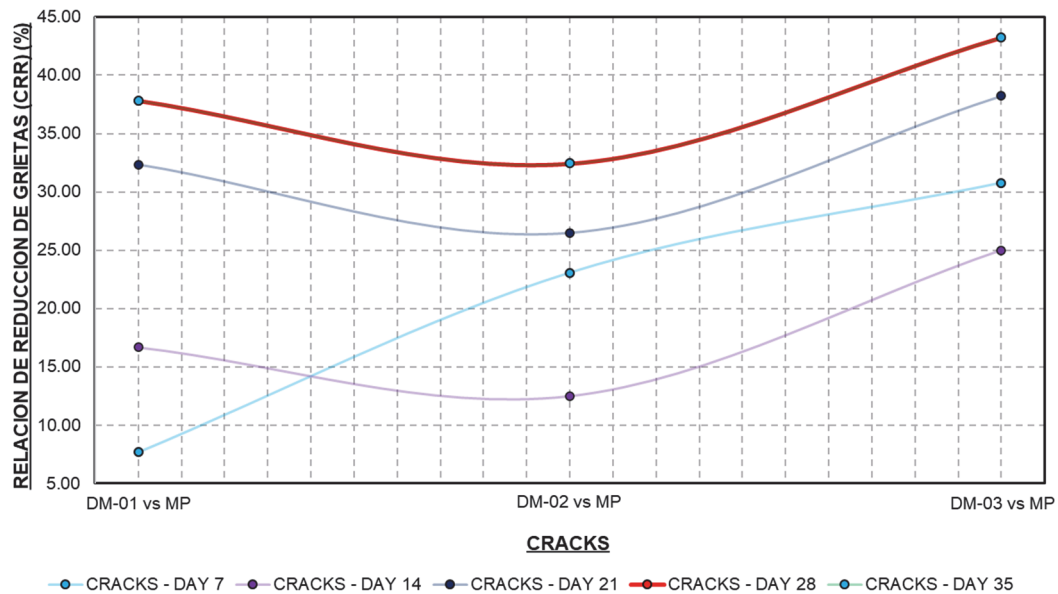


Figure 33: Crack reduction ratio (number of cracks).

Finally, Figure 33 shows the Crack Reduction Ratio (CRR) for the number of cracks and its corresponding percentage reduction. Analysis of the data processed at 28 days shows that all sample designs—DM-01, DM-02, and DM-03—exhibit a reduction in the number of cracks, with respective reduction percentages of 37.84%, 32.43%, and 43.24%. When considering only the number of cracks, it is observed that all dosages (DM-01, DM-02, and DM-03) achieve a reduction in the total number of cracks in the physical models, indicating that any of them is viable for use in concrete. Ordering their effectiveness in crack reduction from highest to lowest, DM-03 shows the greatest reduction, followed by DM-01, and finally DM-02.

The addition of DM-02 (1000 g/m³) of polypropylene synthetic fiber to concrete slabs represents an approximate increase of S/. 40 per cubic meter, equivalent to a 12–16% increase over the base cost of conventional concrete (S/.

250–330/m³) (depending on the urban area where the construction takes place). Despite the initial additional cost, this secondary reinforcement significantly reduces the formation of plastic shrinkage cracks and improves surface durability, decreasing the need for early repairs or maintenance. Therefore, for local construction companies, the implementation of fiber-reinforced concrete can be economically advantageous in the medium term, extending the service life of slabs and pavements and reducing rehabilitation costs associated with cracking.

The graph shows the development of cracks in the concrete after 28 days of evaluation for four sample designs: MP (control concrete without fibers) and DM-01, DM-02, and DM-03, which incorporate different amounts of polypropylene fiber (500, 1000, and 2000 g/m³, respectively). The crack width remains practically constant at around 3–4 mm in all designs. However, both the length and number of cracks decrease significantly with increasing fiber content: the control concrete (MP) exhibits the greatest crack length (443 mm) and the highest number of cracks (37), while DM-02 and DM-03 show notable reductions, reaching 188–220 mm in length and 21–25 cracks, demonstrating that the addition of polypropylene fiber helps limit the appearance and propagation of cracks in the concrete.

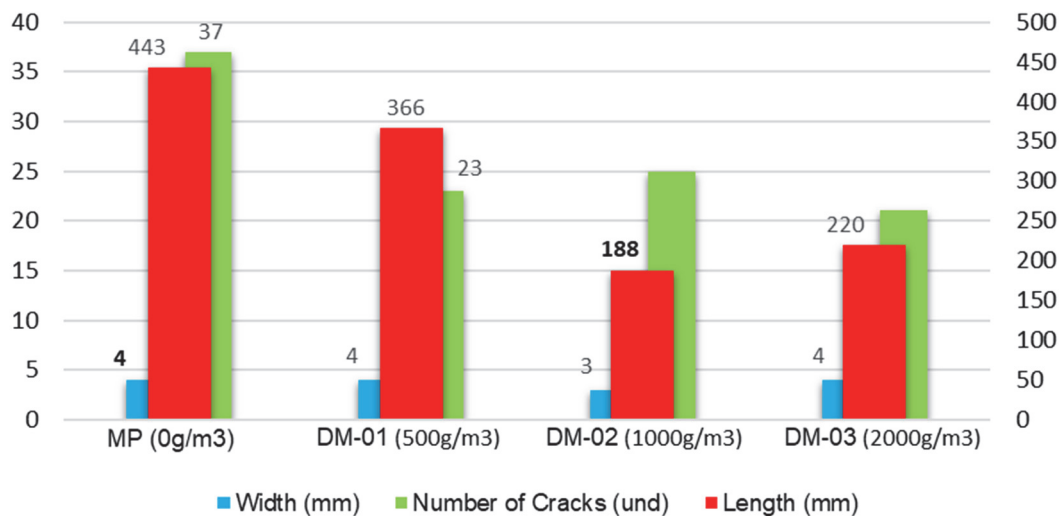


Figure 34: Development of fissures at 28 days of evaluation.

Evaluation of cracks during the first hours of settling

Understanding the behavior of polypropylene synthetic fibers in concrete during the first hours of setting is a practical way to explain the mechanisms of evaporation reduction and, consequently, the risk of shrinkage cracking. Based on previous results, the presence and formation of cracks during the first hours of setting were evaluated in the Control Sample (MS) and in Design Sample 02 (DS-02), since the latter provided the greatest benefits to the concrete at the end of the 28-day curing period.

The evaporation rate test explains the concrete's ability to retain water during setting, evaluating the rate at which moisture is lost from the surface to the environment. This behavior is crucial because, during the first few hours, concrete is in a plastic state and is highly vulnerable to shrinkage and the formation of surface cracks.

The water evaporation rate test establishes a minimum limit for controlling water loss in concrete, which is 1.0 kg/m²·h during the first hour of evaluation, according to ASTM C1579. This reference value allows us to determine if the concrete mix is losing moisture at a rate that could compromise its performance during initial setting. Furthermore, the standard specifies progressive control values: at 2 hours, the rate should exceed 2.0 kg/m²·h; at 3 hours, 3.0 kg/m²·h; and at 4 hours, 4.0 kg/m²·h. Meeting these limits ensures that the concrete retains the minimum amount of water necessary for cement hydration and reduces the risk of shrinkage cracking. Table 18 presents the average results of the two tests for the Control Sample (CS) and Design Sample 02 (DS-02).

The fiber-reinforced mix (DM-02) exhibited an average cumulative evaporation rate of 5.05 kg/m²·h at 4 hours, compared to 6.32 kg/m²·h for the control concrete (MP). This represents a 20.09% reduction in moisture loss for the mixes with polypropylene fibers. This result is consistent with the function of polypropylene fibers in disrupting capillary channels and distributing free water more evenly, thereby reducing its rapid migration to the surface and, consequently, the risk of shrinkage cracking during the initial hours of setting.

Analyzing cracking during the first few hours of setting helps to understand the initial benefits of crack reduction in concrete, since the material is still in a plastic state and highly susceptible to surface water loss. Evaluating the behavior of concrete at this critical stage allows for assessing the effectiveness of control measures, such as the incorporation of synthetic polypropylene fibers, which distribute internal stresses, reduce the evaporation rate, and limit the propagation of microcracks.



The tables show the data collected during the first four hours of curing, a period in which fresh concrete is most susceptible to surface cracking due to rapid water loss through evaporation. This stage is critical because the concrete has not yet developed sufficient internal strength, which favors the appearance and propagation of shrinkage cracks. The information obtained allowed for the creation of comparative graphs that represent the evolution of the concrete's behavior during this interval, facilitating the identification of trends in crack formation and growth over time. Thus, the results not only demonstrate the magnitude of the problem under normal conditions but also highlight the beneficial effect of incorporating polypropylene synthetic fibers as a strategy to control and reduce early cracking.

	TIME	SAMPLE WEIGHT (kg)	WATER LOST (kg)	CUMULATIVE WATER LOST (kg)	WATER EVAPORATION RATE (kg/m ² .h)
CONTROL SAMPLE (MP)-01	30 min	22.235	0.05	0.05	0.32
	30 min	22.165	0.12	0.17	1.08
	30 min	22.158	0.13	0.30	1.89
	30 min	22.156	0.13	0.43	2.72
	30 min	22.153	0.13	0.56	3.56
	30 min	22.144	0.14	0.70	4.46
	30 min	22.138	0.15	0.85	5.40
	30 min	22.136	0.15	1.00	6.35
CONTROL SAMPLE (MP)-02	30 min	22.131	0.08	0.08	0.52
	30 min	22.117	0.09	0.18	1.12
	30 min	22.098	0.11	0.29	1.84
	30 min	22.093	0.12	0.41	2.60
	30 min	22.078	0.13	0.54	3.45
	30 min	22.068	0.14	0.69	4.37
	30 min	22.064	0.15	0.83	5.31
	30 min	22.060	0.15	0.99	6.28
SAMPLE DESIGN 02 (DM-02)-01	30 min	22.316	0.07	0.07	0.42
	30 min	22.283	0.10	0.17	1.05
	30 min	22.282	0.10	0.27	1.69
	30 min	22.281	0.10	0.37	2.34
	30 min	22.278	0.11	0.47	3.00
	30 min	22.277	0.11	0.58	3.67
	30 min	22.269	0.11	0.69	4.39
	30 min	22.267	0.12	0.81	5.12
SAMPLE DESIGN 02 (DM-02)-02	30 min	22.162	0.07	0.07	0.45
	30 min	22.143	0.09	0.16	1.01
	30 min	22.133	0.10	0.26	1.64
	30 min	22.132	0.10	0.36	2.28
	30 min	22.129	0.10	0.46	2.93
	30 min	22.128	0.10	0.56	3.60
	30 min	22.126	0.11	0.67	4.27
	30 min	22.120	0.11	0.78	4.98

Table 17: Results of the water evaporation rate test according to ASTM C1579.

SAMPLES	TIME	AVERAGE WATER EVAPORATION RATE (kg/m ² .h)
SAMPLE PATTERN (MP)	1 hour	1.10
	2 hours	2.66
	3 hours	4.42
	4 hours	6.32
SAMPLE DESIGN 02 (DM-02)	1 hour	1.03
	2 hours	2.31
	3 hours	3.64
	4 hours	5.05

Table 18: Results of the water evaporation rate at the evaluated times.



CRACKS		WIDTH (mm)	M-01 LENGTH (mm)	WIDTH (mm)	M-02 LENGTH (mm)
0.5 hours	F-01	---	---	---	---
	F-02	---	---	---	---
	F-03	---	---	---	---
	F-04	---	---	---	---
	F-05	---	---	---	---
1.0 hour	F-01	---	---	---	---
	F-02	---	---	---	---
	F-03	---	---	---	---
	F-04	---	---	---	---
	F-05	---	---	---	---
1.5 hours	F-01	---	---	---	---
	F-02	---	---	---	---
	F-03	---	---	---	---
	F-04	---	---	---	---
	F-05	---	---	---	---
2.0 hours	F-01	---	---	---	---
	F-02	---	---	---	---
	F-03	---	---	---	---
	F-04	---	---	---	---
	F-05	---	---	---	---
2.5 hours	F-01	0.19	5.00	0.07	5.00
	F-02	0.10	7.00	0.13	9.00
	F-03	0.09	8.00	0.13	8.00
	F-04	---	---	---	---
	F-05	---	---	---	---
3.0 hours	F-01	0.23	10.00	0.14	12.00
	F-02	0.22	11.00	0.25	13.00
	F-03	0.14	12.00	0.20	9.00
	F-04	0.25	12.00	0.28	12.00
	F-05	---	---	0.22	13.00
3.5 hours	F-01	0.34	14.00	0.27	14.00
	F-02	0.35	15.00	0.34	15.00
	F-03	0.26	14.00	0.32	12.00
	F-04	0.39	16.00	0.30	17.00
	F-05	0.35	8.00	0.36	18.00
4.0 hours	F-01	0.46	18.00	0.39	16.00
	F-02	0.49	16.00	0.43	18.00
	F-03	0.37	15.00	0.45	15.00
	F-04	0.43	20.00	0.44	19.00
	F-05	0.40	14.00	0.49	20.00

Table 19: Crack data collection for the control sample (MP) during the first 4 hours of setting.



CRACKS	M-03		M-04		
	WIDTH (mm)	LENGTH (mm)	WIDTH (mm)	LENGTH (mm)	
0.5 hours	F-01	---	---	---	
	F-02	---	---	---	
	F-03	---	---	---	
	F-04	---	---	---	
	F-05	---	---	---	
1.0 hour	F-01	---	---	---	
	F-02	---	---	---	
	F-03	---	---	---	
	F-04	---	---	---	
	F-05	---	---	---	
1.5 hours	F-01	---	---	---	
	F-02	---	---	---	
	F-03	---	---	---	
	F-04	---	---	---	
	F-05	---	---	---	
2.0 hours	F-01	---	---	---	
	F-02	---	---	---	
	F-03	---	---	---	
	F-04	---	---	---	
	F-05	---	---	---	
2.5 hours	F-01	0.13	2.00	---	
	F-02	---	---	---	
	F-03	0.09	3.00	0.09	1.00
	F-04	---	---	---	---
	F-05	---	---	---	---
3.0 hours	F-01	0.18	6.00	0.16	7.00
	F-02	0.10	4.00	0.08	8.00
	F-03	0.15	5.00	0.11	3.00
	F-04	---	---	---	---
	F-05	---	---	---	---
3.5 hours	F-01	0.25	11.00	0.22	11.00
	F-02	0.25	9.00	0.19	13.00
	F-03	0.22	10.00	0.21	9.00
	F-04	0.31	8.00	0.25	8.00
	F-05	---	---	---	---
4.0 hours	F-01	0.37	15.00	0.35	16.00
	F-02	0.39	13.00	0.32	15.00
	F-03	0.32	15.00	0.35	14.00
	F-04	0.40	12.00	0.40	13.00
	F-05	0.20	6.00	---	---

Table 20: Crack data collection for sample design 02 (DM-02) during the first 4 hours of setting.

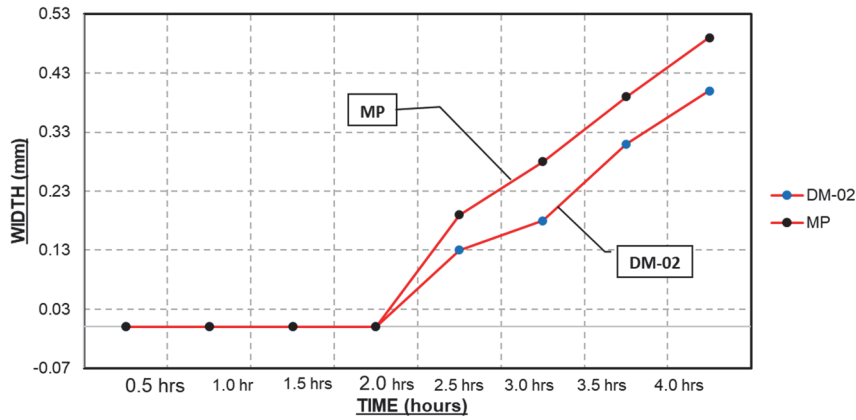


Figure 35: Chart width versus setup time (first 4 hours).

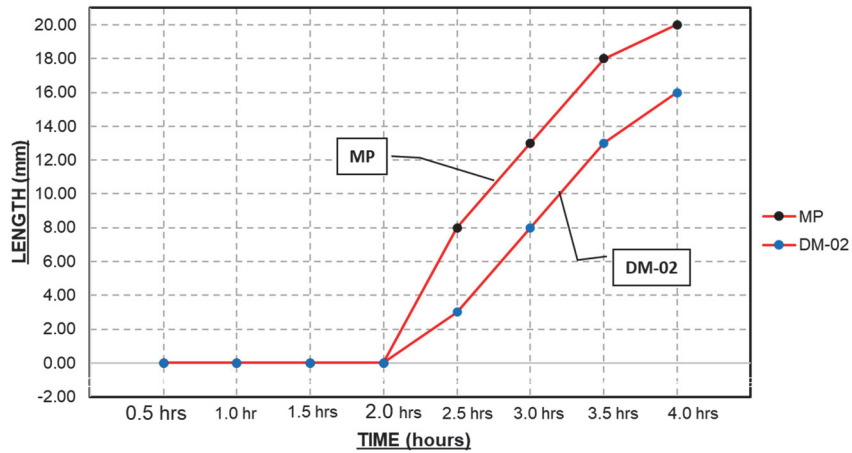


Figure 36: Graph Length vs Fixation Time (First 4 hours).

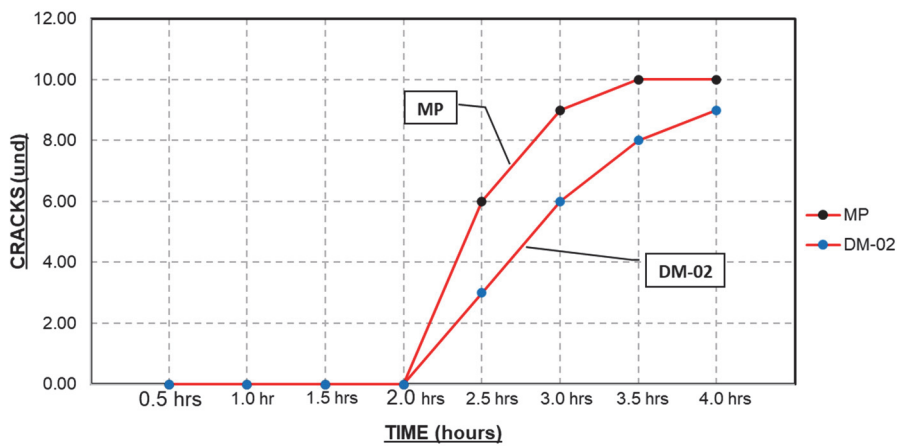


Figure 37: Graph of cracks vs setting time (first 4 hours).

During the first four hours of curing, the results show that the control concrete (MP) exhibited more critical cracking behavior compared to the mixture with polypropylene synthetic fiber (DM-02). MP developed cracks with a maximum width of 0.49 mm, a maximum length of 20 mm, and a total of 10 cracks, while DM-02 registered lower values, with a maximum width of 0.40 mm, a maximum length of 16 mm, and a slightly lower number of cracks (9). These results indicate that, while cracking is not completely eliminated, the addition of polypropylene fiber reduces its severity, limits its propagation, and decreases its frequency, thus confirming its initial benefit as a control mechanism against shrinkage in fresh concrete.



The Crack Reduction Index formula was applied to quantify the percentage decrease in crack width, length, and number, comparing the results obtained in the control concrete (MP) with the sample design containing polypropylene synthetic fiber (DM-02). This procedure allowed for the objective expression of the effect of fiber incorporation on mitigating early cracking of the concrete, facilitating a comparative evaluation of the benefit obtained in each parameter analyzed.

Time (hours)	Width (%)	Length (%)	Number (%)
0.5	0.00	0.00	0.00
1.0	0.00	0.00	0.00
1.5	0.00	0.00	0.00
2.0	0.00	0.00	0.00
2.5	12.68	71.43	50.00
3.0	39.38	52.40	33.33
3.5	27.59	30.94	20.00
4.0	20.82	22.68	10.00

Table 21: Results of the crack reduction ratio during the first 4 hours of setting.

The results of the Crack Reduction Index show that, during the first two hours of setting, there was no difference between the control concrete (MP) and the fiber-reinforced mix (DM-02), as the percentage reductions in width, length, and number of cracks were zero. However, from 2.5 hours onward, a significant change was observed: DM-02 achieved reductions of 12.68% in width, 71.43% in length, and 50% in the number of cracks, indicating an immediate effect of the fiber in mitigating plastic shrinkage cracking. Between 3.0 and 3.5 hours, the percentages continued to show a notable improvement, especially in width and length, with reductions of up to 39.38% and 52.40%, respectively, confirming that the critical setting stage is where the fiber exerts its greatest influence. Finally, at 4.0 hours, the reduction values tend to stabilize, reaching 20.82% in width, 22.68% in length and 10% in the number of cracks, reflecting that the concrete is beginning to gain internal strength and the difference between the two mixtures decreases.

DISCUSSION

Designs DM-01 and DM-02 achieved crack width reductions of 11.32% and 18.41%, respectively, while design DM-03 showed an increase of 28.75%. These results partially agree with the findings of Prakash et al. [5], who observed that the addition of 0.5% polypropylene fiber improves tensile strength by up to 24%, which can reduce crack opening by increasing the internal cohesion of the concrete. Similarly, Ghali et al. [6] concluded that compressive strength increases by 38.6% with the addition of polypropylene fibers, which could also be related to increased cohesion preventing crack width expansion.

However, despite having the highest fiber content, the DM-03 design exhibits an increase in crack width. This phenomenon coincides with the observations of Kistan et al. [15], who highlighted the potential adverse effects of fiber over-dosing, which can alter the workability of the concrete and lead to inefficient fiber distribution. Fiber oversaturation may have interfered with uniform distribution, favoring the formation of thicker cracks.

Regarding crack length, design DM-02 is the only one that achieves a significant reduction of 11.46%, while DM-01 and DM-03 show increases of 10.92% and 3.88%, respectively. This behavior coincides with the findings of Maafi et al. [10], who indicated that the incorporation of polypropylene fibers improves the mechanical properties of concrete, including tensile strength, which could help prevent crack propagation. Similarly, Shan et al. [8] found that the addition of 1 kg/m³ of polypropylene fiber increases compressive strength by 42.2%, which could be related to the observed reduction in crack length in DM-02, an intermediate fiber dosage.

In contrast, the increased crack length in DM-01 and DM-03 could be attributed to a non-uniform fiber distribution. Callamamani et al. [11] demonstrated that longer fibers can concentrate in certain areas of the concrete, resulting in longer cracks. In this respect, DM-02, with an intermediate dosage, appears to have achieved an optimal balance in fiber distribution, thus avoiding these problems.

Regarding the number of cracks, all sample designs (DM-01, DM-02, and DM-03) showed significant reductions compared to the control concrete (MP): 37.84% for DM-01, 32.43% for DM-02, and 43.24% for DM-03. These results are consistent with those of Najaf and Abbasi. [9], who stated that the addition of polypropylene macrofibers increases crack resistance and improves the durability of concrete, thereby reducing the number of cracks. Similarly, Zhao et al., [1] reported that the combined use of polypropylene and steel fibers increases both tensile and compressive strength, which can also prevent the formation of new cracks.

Design DM-03, which showed the greatest reduction in the number of cracks, could be due to a higher fiber content acting as reinforcement to prevent crack propagation. However, the increase in crack width suggests that while it reduces their number, its impact on the overall concrete structure may not be entirely beneficial. This issue was also noted by



Qasim and Jassam . [7], who found that increasing fiber content can improve crack resistance, but could compromise other mechanical properties such as durability and structural cohesion.

In general, the consulted bibliography provides valuable context for the interpretation of the results. Chaisa and Maccarcco [4] they found that a higher fiber content reduces settlement, which could be related to the decrease in the number of cracks observed in designs with higher dosage, such as DM-03. However, lower settlement can also be associated with lower workability, which could explain the increased crack width when the fiber content is excessive, as in the case of DM-03.

Christopher et al. [12] highlighted that hybrid fibers (polyester and steel) improve compressive strength, emphasizing the importance of selecting the appropriate fiber type to achieve optimal crack reduction. In this study, although only polypropylene fibers were used, the observed effects underscore the importance of optimizing both fiber dosage and distribution.

As the results show, DM-02 achieved reductions of 18.40% in width, 11.46% in length, and 32.43% in the number of cracks, demonstrating that this material plays a significant role in crack control in concrete slabs. While these results are lower than those reported by Calla and Gómez [21], where a 1.5% dosage achieved a 62.27% reduction in cracking, it is important to note that the scope and approach of the studies differ. Whereas steel fibers showed a more pronounced effect on crack reduction, polypropylene offers practical and economic advantages, such as easy incorporation, minimal impact on workability, and lower cost, making it an efficient and accessible alternative in contexts where steel fibers may not be feasible.

The comparison between the control concrete (CP) and the modified design DM-02 (1000 g/m³ of polypropylene fiber) using the Mann-Whitney U test showed a p-value of 0.073, indicating a trend toward statistical significance. Although the difference was not significant at the conventional level ($p > 0.05$), the technical results demonstrate a relevant positive effect: DM-02 reduced the average crack width by 18.41%, the length by 11.46%, and the number of cracks by 32.43% compared to the control concrete. These results confirm that the moderate dosage of 1000 g/m³ optimizes fiber distribution and anchorage, improving crack control without affecting concrete cohesion. Overall, the findings suggest that, although the effect does not reach strict statistical significance, the magnitude of the improvement is technically and structurally relevant, consolidating DM-02 as the most effective dosage for mitigating shrinkage cracking. According to Delclaux et al., [22] who conducted a climate study of the Altiplano, annual evaporation in the Lake Titicaca basin ranges from 1350 to 1900 mm/year, which is approximately equivalent to 0.15–0.22 kg/m²·h when converted to hourly rates. In contrast, the laboratory results of the water evaporation rate test were significantly higher: the control concrete (MP) reached 6.32 kg/m²·h, while DM-02 registered 5.05 kg/m²·h after 4 hours. This demonstrates that the rates measured in the laboratory exceed the average ambient evaporation in Juliaca by 20 to 35 times. This difference is not due to methodological error, but rather reflects the severe exposure conditions simulated in the test, where water loss is faster due to surface evaporation and the lower water volume. Therefore, the laboratory results represent an extreme scenario for evaluating the actual risk of shrinkage cracking. Under these critical conditions, the incorporation of polypropylene fibers in DM-02 reduced the water evaporation rate by 20.09% compared to the control, confirming its effectiveness as a strategy to mitigate early and long-term cracking in concrete slabs exposed to the Juliaca climate.

CONCLUSIONS

Regarding crack width reduction, designs DM-01 (500 g/m³) and DM-02 (1000 g/m³) proved effective, with reductions of 11.32% and 18.41%, respectively. However, design DM-03 (2000 g/m³) showed a significant increase of 28.75%, suggesting that an overdosage of fibers does not improve concrete properties in terms of crack width, possibly due to ineffective fiber distribution and interference with concrete cohesion. In summary, while polypropylene fibers help reduce crack width in some cases, excessive dosage, as in the case of design DM-03, can be counterproductive. Design DM-02 was the most effective at reducing crack width.

Regarding crack length, DM-02 (1000 g/m³) proved to be the most effective, reducing it by 11.46%, making it a favorable option for limiting crack propagation in concrete slabs. DM-01 and DM-03 not only failed to reduce crack length but actually caused increases of 10.92% and 3.88%, respectively. This highlights the importance of avoiding both insufficient and excessive dosages to ensure a uniform and effective distribution of the fibers.

Regarding the number of cracks, all designs (DM-01, DM-02, and DM-03) showed significant reductions: 37.84%, 32.43%, and 43.24%, respectively. Design DM-03 exhibited the greatest reduction, although it also showed a greater width, suggesting beneficial effects in controlling crack propagation, but also potential drawbacks in terms of width and length. All tested designs confirm that polypropylene fibers, regardless of the dosage, are effective in reducing the number of cracks.

A comprehensive analysis of the three parameters (width, length, and number) suggests that the 1000 g/m³ dose (DM-02) achieved a favorable balance, showing positive reductions in width (18.41%), length (11.46%), and number of cracks



(32.43%). The low (DM-01) and high (DM-03) doses produced mixed results: they were effective in reducing the number of cracks, but less so in reducing their length and width. In particular, the DM-03 dose increased crack width despite being the one that reduced their number the most.

Therefore, a moderate dosage of 1000 g/m³ of polypropylene fibers is the most effective for improving the properties of concrete, reducing both the number and length of cracks without significantly affecting their width. Excessive or insufficient dosages may compromise the effectiveness of the proposed additive.

Similarly, the results of the initial evaluation (first 4 hours) serve as indicators of the concrete's final behavior. The lower evaporation rate (20.09% lower in DM-02 than in MP) and the reduction in cracking during this critical period predicted the behavior at 28 days, where DM-02 again proved most effective, achieving reductions of 18.41% in width, 11.46% in length, and 32.43% in the number of cracks compared to the control. The crack width and length values at 4 hours were higher than those at 28 days, which is explained by the concrete's plastic state, the high moisture loss, and its vulnerability to shrinkage. As setting and curing progress, the concrete acquires internal strength and volumetric stability, causing the cracks to stabilize or evolve less, as reflected in the more controlled values at 28 days. The initial assessment successfully predicted the effectiveness of polypropylene fibers as a mechanism for mitigating initial and long-term cracking in hardened concrete.

The synthetic polypropylene fiber was incorporated manually during the concrete mixing process, given that the volume used in the physical models is much smaller than that of full-scale slabs. These models were used to simulate slab construction and ideally evaluate the effect of the fiber on crack reduction, yielding positive results. No dispersants or auxiliary additives were used, as the small volume of concrete allowed for manual control of the fiber distribution. However, this procedure would not be suitable for larger concrete volumes, where it would be necessary to investigate methods that ensure uniform fiber dispersion.

Furthermore, given its exploratory nature, this study has certain limitations related to sample size, as its primary purpose was to identify an optimal dosage through a preliminary analysis using a small number of specimens. Additionally, the lack of a long-term crack development assessment and the absence of specialized microstructural analyses suggest the need for further studies to gain a deeper understanding of cracking in concrete. Despite its initial focus, this research lays the groundwork for future lines of inquiry, which could include evaluating cracking behavior in full-scale structures and analyzing the effects of non-conventional fibers on various mechanical and durability properties of concrete.

REFERENCES

- [1] Zhao, D., Liu, R., Liu, J. and Yang, L. (2023). Comparative study on the effect of steel and plastic synthetic fibers on the dynamic compression properties and microstructure of ultra-high-performance concrete (UHPC), *Compos Struct*, 324, DOI: <https://doi.org/10.1016/j.compstruct.2023.117570>.
- [2] Dias, D., Calmon, J. and Vieira, G. (2020). Polymeric fiber exposed reinforced concrete to fire, *Journal of the Latin American Association of Quality Control, Pathology and Recovery of Construction*, 10(1), pp. 35-52, DOI: <https://doi.org/10.21041/ra.v10i1.426>
- [3] Meza-de Luna, A., Gurbir, K., Preciado-Martínez, H. and Gutiérrez-Lopez, I. (2023). Flexural Performance of Concrete Reinforced with Recycled Plastic Fibers, *Conciencia Tecnológica*, 10(61), Available at: <https://www.redalyc.org/journal/944/94467989001/94467989001.pdf>.
- [4] Chaisa, E. and Jhonatan, M. (2021). Addition of polypropylene fiber to hydraulic concrete $f'c=175, 210, 280$ kg/cm² to improve its plastic and mechanical properties, César Vallejo University, Available at: <https://repositorio.ucv.edu.pe/handle/20.500.12692/62139>
- [5] Prakash, R., Thenmozhi, R., Raman, SN. and Subramanian, C. (2020). Fibre reinforced concrete containing waste coconut shell aggregate, fly ash and polypropylene fibre, *Facultad de Ingeniería Universidad de Antioquia*, (94), pp. 33-42, DOI: <https://doi.org/10.17533/10.17533/udea.redin.20190403>.
- [6] Ghali, NE., Ezz, EI., Hamad, B., Assaad, J. and Yehya, A. (2023). Comparative study on shear strength and life cycle assessment of reinforced concrete beams containing different types of fibers, *Case Studies in Construction Materials*, 19, DOI: <https://doi.org/10.1016/j.cscm.2023.e02497>.
- [7] Qasim, OA. and Jassam SH. (2022). Experimental Investigation of Plastic Waste Effect on Concrete Mechanical and Durability Properties, *International Review of Civil Engineering*, 13(3), pp. 190-197, DOI: <https://doi.org/10.15866/irece.v13i3.20871>.
- [8] Shan, J., Songs, C., Zhou, S., Duan, T., Zheng, S. and Zhang, B. (2022). Study on Performance of Pervious Concrete Modified by Nano-Silicon + Polypropylene Fiber Composite, *Lecture Notes in Civil Engineering*, 235, pp. 189-198, DOI: https://doi.org/10.1007/978-981-99-1748-8_15.
- [9] Najaf, E. and Abbasi, H. (2023). Impact resistance and mechanical properties of fiber-reinforced concrete using string and fibrillated polypropylene fibers in a hybrid form, *Structural Concrete*, 24 (1), pp. 1282-1295, DOI: <https://doi.org/10.1002/suco.202200019>.



- [10] Maafi, N., Benuadah, A., Benammar, A., Kessal, O., Belkadi, AA. And Beddar, M. (2023). The Effects of Polypropylene Fibers on the Mechanical and Durability Performance of a Roller Compacted Concrete for Pavement, *International Journal of Pavement Research and Technology*, DOI: <https://doi.org/10.1007/s42947-023-00329-4>.
- [11] Callomamani, LAP., Bala, N. and Hashemian, L. (2023). Comparative Analysis of the Impact of Synthetic Fibers on Cracking Resistance of Asphalt Mixes, *International Journal of Pavement Research and Technology*, 16(4), pp. 992-1008, DOI: <https://doi.org/10.1007/s42947-022-00175-w>.
- [12] Christopher, C., Gopal, R., Sadasivam, S., Keerthika, D. and Dinesh, K. (2023). Experimental Toughness and Durability Evaluation of FRC Composite Reinforced with Steel–Polyester Fiber Combination, *Int J Concr Struct Mater*, 17(1), DOI: <https://doi.org/10.1186/s40069-023-00599-z>.
- [13] Akbulut, Z., Tawfik, T., Smarzewski, P. and Guler, S. (2025). Advancing Hybrid Fiber-Reinforced Concrete: Performance, Crack Resistance Mechanism, and Future Innovations, *MDPI AG*, 15(8), pp. 1247-1247.
- [14] Laskhmi, A., Pandit, P., Nayak, G., Bhagwat, Y. and Gundlapalli, P. (2025). Performance evaluation of low volume synthetic fibers in pozzolanic cement concrete, *Materials*, 18(5).
- [15] Kistan, A., Kanchana, V., Parthiban, E., Vadivel, S. and Sridhar, B. (2023). Study on flexural behavior of polypropylene fiber reinforced fly ash concrete beam, *Mater Today Proc*, DOI: <https://doi.org/10.1016/j.matpr.2023.03.172>.
- [16] Mohammed, AA. and Karim, SH. (2023). Impact strength and mechanical properties of high strength concrete containing PET waste fiber, *Journal of Building Engineering*, 68, DOI: <https://doi.org/10.1016/j.job.2023.106195>.
- [17] Vasquez, E. (2020). Compressive and Tensile Behavior of Plain Hydraulic Concrete Reinforced with Polypropylene Fibers for Building Construction, *Universidad Peruana Unión*, Available at: <https://repositorio.upeu.edu.pe/handle/20.500.12840/3404>.
- [18] Tang, H. (2020). *Engineering Research: Design, Methods, and Publication*, 1st ed.
- [19] Navidi, W. (2022). *Statistics for Engineers and Scientists*, 5th ed.
- [20] Machado, C. and Davim, P. (2020). *Research Methodology in Management and Industrial Engineering*, Springer International Publishing.
- [21] Calla, R. and Gomez, J. (2024). Effect of steel fibers on the prevention of plastic shrinkage cracking in concrete, *Juliaca 2023*, Universidad Peruana Unión.
- [22] Delclaux, F., Coudrain, A. and Condom, T. (2007). Evaporation estimation on Lake Titicaca: a synthesis review and modeling, *Hydrol Process*, 21(13), pp. 1664-1667.