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Investigation on the mechanical properties and durability of high performance concrete reinforced with waste tires fibers

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Abstract
This paper aims to evaluate the mechanical behavior and durability of high-performance concrete reinforced with steel fibers recycled from waste car tires at 1% and 2% volume fractions and 2 cm and 3 cm lengths. Compressive and flexural strength tests were conducted on confined cubic and prismatic specimens at 28 days of age, with ultrasonic testing performed to confirm concrete properties non-destructively. Additionally, immersing specimens in 5% HCl and MgSO4 solutions to study their resistance in aggressive environments assessed the durability of the concrete. The findings indicated that the incorporation of steel tire fibers had a positive impact on the flexural and compressive strength of the material. Furthermore, a distinct correlation was evident between the ultrasonic pulse velocity and both the compressive and flexural strength. Additionally, the high-performance concrete exhibited resistance to chemical reactions in aggressive environments.
Keywords: Waste steel fibers, High-performance concrete, Mechanical properties, Chemical resistance, Durability.

1. Introduction

In modern times, high-performance concrete has become a widely used material for investigating and achieving good performance and durability in construction projects. This type of concrete is specifically designed to have superior strength, and resistance to various types of deterioration, such as chemical attack, freeze-thaw cycles, and abrasion. But is a material with brittle behavior, which is why the addition of randomly distributed fibers is often used to improve its mechanical performances and ductility (Makani and Vidal, 2018). Improving the performance of concrete can be achieved through various methods, including the addition of natural fibers and fiber-reinforced polymer confinement (Smarzewski, 2018; and Zhang *et al.*, 2018). Short fibers can also be added to cementitious composites to create high-performance construction materials. The addition of fibers to concrete can help to improve its mechanical properties, particularly its resistance to cracking and toughness. However, the effect of fiber content on the compressive strength and elastic modulus of the concrete is relatively weak. This is because the primary role of fibers in concrete is to provide additional reinforcement to the material, which helps to distribute stresses more evenly and reduce the risk of cracking (Kim *et al.*, 2010) These improvements are especially important for structures that are subject to dynamic loadings, such as bridges, pavements, and earthquake-resistant buildings.

The quality of concrete depends on the choice of materials and the mixing process. For SF concretes, the compressive strength is highly dependent on the ratio of the water-to-cementitious material, which is the ratio of water to cementitious materials (such as silica fume, fly ash, crashed dune sand and slag), used in the mixture (Kadri *et al*., 2012; and Agha *et al*., 2023) . A decrease in this ratio can significantly increase the compressive strength of the concrete. In addition, the addition of silica fume can improve the strength of the concrete by filling the gaps between cement particles and contributing to the formation of additional cementitious compounds.

For studying the behavior of high performance fiber reinforced concrete many factors were investigated, including mechanical behavior, and durability test. Ultra High Performance Concrete (UHPC) is a type of concrete that is designed to have exceptional strength, durability, and toughness. It is typically characterized by a minimum specified compressive strength of 150 MPa as well as specified requirements for toughness properties, tensile ductility, and durability(Naaman & Shah, 2022). These properties are achieved through the use of specialized materials and mix designs, which may include fibers, high-strength aggregates, and/or supplementary cementitious materials. The compressive strength of fiber-reinforced concrete can be influenced by a variety of factors, including the aspect ratio and size of the test specimen (Riedel & Leutbecher, 2021). In general, larger specimens tend to yield higher compressive strength values than smaller specimens, while the aspect ratio (the ratio of the height to the diameter or width of the specimen) can also have an impact on the results.

Nevertheless, it is crucial to differentiate these consequences from other factors that might influence the efficacy of fiber-reinforced concrete. The mechanical efficiency of High-Performance Fiber-Reinforced Cementitious Composites (HPFRCCs) is substantially affected by the interfacial transition zone (ITZ) that exists between the fibers and the cementitious matrix. The ITZ plays a crucial role in determining the bond strength between the fibers and the matrix, which can significantly influence the overall mechanical properties of the material. Therefore, when devising and selecting fibers for HPFRCCs, it is essential to consider the nature of the ITZ and its potential impact on the performance of the material.

The addition of fibers to concrete can also enhance its ability to resist other forms of deterioration. For instance, the occurrence of corrosion due to stray current in rail infrastructure can be minimized or eliminated by incorporating dispersed and non-interconnected fibers, as opposed to using continuous steel bar reinforcement structures. This is because the fibers function as a shield against the flow of stray current, lowering the probability of corrosion.

In addition, polymeric fibers in Fiber-Reinforced Concrete (FRC) can reduce or prevent explosive spalling in situations of fire. This is because the fibers melt when exposed to high temperatures, creating voids that allow for the release of steam and gas, and reducing the build-up of pressure that can cause spalling. (Paul Suvash Chandra, 2020) and (Öksüzer et al., 2022)

Various types of testing, including compressive strength, flexural strength, and durability testing, may be required to comprehensively assess the characteristics of concrete. In addition to these methods, ultrasonic pulse velocity testing is a valuable tool for examining specific properties of concrete, such as its elastic stiffness and mechanical strength. The ultrasonic pulse velocity technique operates by measuring the velocity at which an ultrasonic pulse travels through the concrete. This velocity is affected by the material's elastic stiffness and mechanical strength, as previously mentioned. (IAEA., 2002)

Measurements are compared with reference material to assess the condition of in-situ material and degradation is judged by the ratio of those measurements. Piezoelectric transducers are commonly used for ultrasonic inspection, with an embedded technique showing promise and good conformance with classical ultrasonic tests using external transducers (Harshit Jain & Patankar, 2021)

Studies have discovered an exponential link between compressive strength and ultrasonic velocities in concrete, implying that as the strength of the concrete grows, so does the ultrasonic velocity. As a result, ultrasonic pulse velocity testing may be used to assess the strength and quality of concrete in construction.

Furthermore, hardened concrete test results reveal a high connection between compressive strength, rebound number test, and ultrasonic test. The rebound number is a measure of surface hardness that is frequently used to predict compressive strength in concrete. The fact that these three qualities are correlated implies that they may be used together to measure the strength and quality of concrete in a specific construction (Boudjedra & Benouis, 2020; and Belouadah *et al*., 2021).

Many experiments have been conducted to assess the endurance of high-performance concrete in harsh conditions such as acids and carbohydrates. In terms of observed behaviors, the physical, durability, and mechanical qualities of concretes cured in a damp chamber and an atmospheric marine environment varied depending on the parameter investigated. However, the RA (recycled aggregate) impact is proportionate in both cases.

The acid attack on SCC (self-consolidating concrete) samples were assessed by curing them in an HCl solution for 60 days(Thomas *et a*l., 2012; Vaidevi *et al*., 2020; and Ahmed Soufiane, 2011). The results indicate minimal weight loss during chemical curing and less weight loss in higher-age concrete. In terms of strength, replacing marble aggregate in SCC affects the structure of the concrete, with the best results achieved at 25% marble aggregate replacement compared to conventional SCC. The sulfate attack test showed less weight loss in all various percentage replacements during both curing periods. However, increasing the amount of marble waste in SCC reduces the strength of the concrete. For 56 day curing age, SCC concrete is less affected by sulfate curing than at 28 days. Reducing the penetration of SO_4 sulfate ions in composites can decrease the degradation factor of various concrete structures, making it of practical importance.

A microscopic study of concrete samples exposed to sulfate attack was performed. The pore structure of the concrete generates an environment and channels for sulfate attack in the early phases of corrosion. Ettringite and gypsum are generated as the corrosion process progresses, and they occupy the interior pores. Corrosion creates significant quantities of ettringite, which causes structural damage and cracking development.(Chen, 2022)

These characteristics are consciously adjusted to improve the durability of concrete by reducing the penetration of aggressive agents. However, the low roughness of concrete structures is also unfavorable for the physical attachment of organisms. Durability depends primarily on porosity, cracking, and compressive strength. Moreover, the difference in alkalinity between the interstitial solution and the exterior environment can influence durability. Previous studies have demonstrated that adding fibers can limit crack development and improve durability. (Bouchard, 2018; and Fedaoui-Akmoussi *et al*., 2015).

The main objective of this research work is to evaluate the mechanical behavior and durability of high-performance concrete reinforced with steel fibers recycled from waste car tires at 1% and 2% volume fractions and 2 cm and 3 cm lengths.

2. Experimental program and methods

2.1 Materials:

The materials used in this study for concrete construction include Portland cement, type I 42.5 MPa, a sulfate-resistant cement made from low calcium aluminate and low gypsum, its chemical composition is reported in Table 1studied according to NF EN196-2:2013 code. Clean water is required for mixing, with limited dissolved salts. A SikaViscoCrete superplasticizer with 29% dry extract and 1.085 density is used. Local aggregates from Bechar region include crushed sand class limestone with 0.3 cm seizing and 3/8 inch crushed gravel; the characteristics of aggregate used are illustrated in Table 2 investigated according code NF EN 12620+A1:2008. Two types of fibers used were recycled from car tires and building waste with a length of 2 and 3 cm and 1 mm diameter. The characteristics of each type of fiber are displayed in Table 3, and their properties are kept controlled in the university lab with EN 14889-1: 2006 code.

Table 1- Chemical composition of cement

Al_2O_3	SO_3	SiO_2	CaO	MgO	Fe_2O_3	K_2O	LOI
6.40	1.8 - 3	20.05	61.23	1.2 - 3	3.45	0.01 – 0.05	0.5 - 3

Table 2- Aggregate properties

Aggregate Type	Apparent density (kg/m³)	Absolute density (kg/m³)	Fineness Modulus
Gravel	2.60	1.25	-
Sand	2.54	1.53	2.78

Table 3- Waste steel fibers properties

Type	Length (mm)	Diameter (mm)	ratio	Density (Kg/m3)
Tiers steel fibers	20 - 30	1	20-30	7,84

Figure 1 - Waste steel tiers fibers recycled from tiers

3. Mix proposition and testing

In this part, we will first present the compositions of HPFC, five compositions are formulated according to the method of Faury, after optimization of the granular skeleton and dosage in super plasticizer experimentally because there is no special formulation method for HPFC.

Table 4 shows the five formulations that were selected after optimizing the granular skeleton and superplasticizer assay. These formulations were created from sand and crushed gravel, reinforced or not with steel fibers from car tires waste.

To obtain high-performance concrete, it is important to mix it well. Throughout the study, all initial test mixes were made in a small 20-liter vertical-axis planetary mixer to ensure homogenization of the components and fluidity of the mixture. The mixer has three rotation speeds: low, medium, and high. The medium speed was applied to all test mixes as it best corresponded to the speed of larger mixers used later in the study.

These tests were mainly carried out to obtain mechanical properties such as compressive strength, flexural strength, and ultrasonic pulse velocity at 28 days, and to observe the durability of the mixture in the aggressive environment to study the effect of aggressive solutions on high-performance concrete with and without fibers of different volumes and dimensions. When using this small mixer, the fiber content was 1% and 2%, with a 2 and 3cm length.

In order to evaluate the endurance of the concrete in specific circumstances, various samples were exposed to extended periods in different environments. The samples were submerged in water, HCl, and $MgSO_4$ solutions for a period of 90 days. The purpose of this immersion was to imitate the performance of the concrete in harsh and corrosive settings. After the exposure time, the weight loss of the samples was measured and compared to their performance prior to exposure. Moreover, the concrete's capacity to withstand wet/dry cycles was assessed by immersing the samples alternately in water and the aggressive environment solution, with a volume ratio of 5%. The resulting measurements offered valuable information regarding the durability of the concrete and its ability to withstand severe circumstances.

This study employed code NF EN 12390-4:2000 to examine compressive strength, code EN 12504-4:2005 to analyze ultrasonic pulse velocity, and code ASTM C267-97 to assess the chemical resistance of concrete in aggressive solutions.

Table 4 - HPFC composition

Composition	*RC*	*CT1L2*	*CT1L3*	*CT2L2*	*CT2L3*
Cement (kg/m^3)	**400**	**400**	**400**	**400**	**400**
Sand (kg/m^3)	**665**	**665**	**665**	**665**	**665**
Gravel (kg/m^3)	**1111**	**1093**	**1093**	**1075**	**1075**
Water (kg/m^3)	**148**	**148**	**148**	**148**	**148**
Superplasticizer (%)	**1.75**	**1.75**	**1.75**	**1.75**	**1.75**
Fiber Volume (%)	**-**	**1**	**1**	**2**	**2**
Fiber length (mm)	**-**	**20**	**30**	**20**	**30**
W/C ratio			**0.37**		

RC: reference concrete
CT: waste car tires fibers

4. Discussion and results

4.1 Mechanical strength:

The mechanical behavior of high-performance concrete is an important consideration. Evaluating its performance can take several forms, including studying its resistance to pressure, tensile strength, and shear. By understanding these properties, we can better assess the overall durability and reliability of the concrete in various applications.

Figure 2 shows the compressive strength of high-performance concrete, both with and without reinforcement using waste tire steel fibers. The addition of fibers to the concrete led to an improvement in compressive strength compared to the reference concrete without fibers. The best performance was observed in specimens containing 1% fiber, especially in concrete with a fiber length of 2 cm. In general, shorter fibers tend to have a more positive effect on the compressive strength of concrete compared to longer fibers. This can be attributed to the fact that the high compressive strength performance of concrete is closely related to its compactness. Longer fibers can decrease the homogeneity of the composite material and lead to lower compactness, which can in turn result in decreased compressive strength. Therefore, the use of shorter fibers can help to maintain the homogeneity and compactness of the concrete, resulting in higher compressive strength.

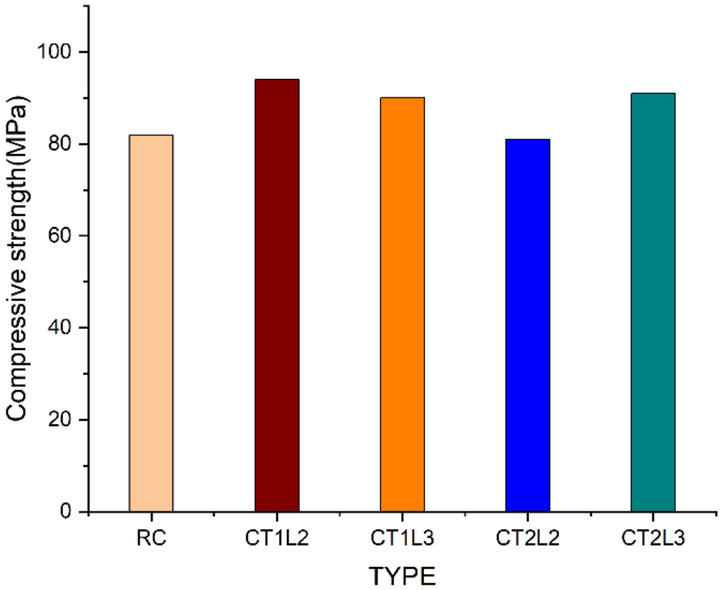

Figure 2 - Compressive strength of HPFC

In addition to studying the compressive strength of concrete reinforced with waste tire steel fibers, we also evaluated its performance using an ultrasonic test. Figure 3 shows the change in pulse velocity of ultrasonic waves based on the variation in fiber geometry and volume. CT1L2, CT1L3, and CT2L3 were found to have good sound speeds and were classified as having excellent performance based on the average ultrasonic test results. The best performance was observed in concrete with a 2 cm fiber length and 1% fiber volume, indicating that this concrete had a low number of cracks that could have disrupted the electromagnetic wave.

Based on the results shown in Figure 4, a clear relationship can be observed between compressive resistance and ultrasonic pulse velocity testing for concrete. In the case of CT1L2, the compressive strength was greater than the velocity, while the opposite was true for CT1L3. However, there was a great convergence observed in CT2L3, indicating a strong correlation between compressive strength and ultrasonic pulse velocity in this case.

There are several factors that could explain the differences in compressive strength and velocity between CT1L2 and CT1L3, including the geometry and volume of the waste tire steel fibers used in the concrete mix, as well as the quality and uniformity of the mixing process.

For example, the difference in compressive strength and velocity between CT1L2 and CT1L3 could be due to variations in the length, diameter, and orientation of the fibers within the concrete. In addition, the volume of fibers used in the mix could also affect the overall strength and velocity of the concrete.

Other factors that could affect the performance of the concrete include the quality and uniformity of the mixing process, the curing conditions, and the age of the concrete at the time of testing. These and other factors may have contributed to the observed differences in compressive strength and velocity between CT1L2 and CT1L3.

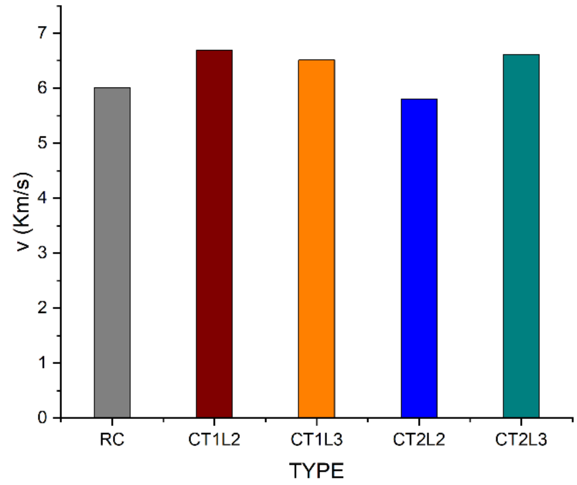

Figure 3 - Ultrasonic pulse velocity

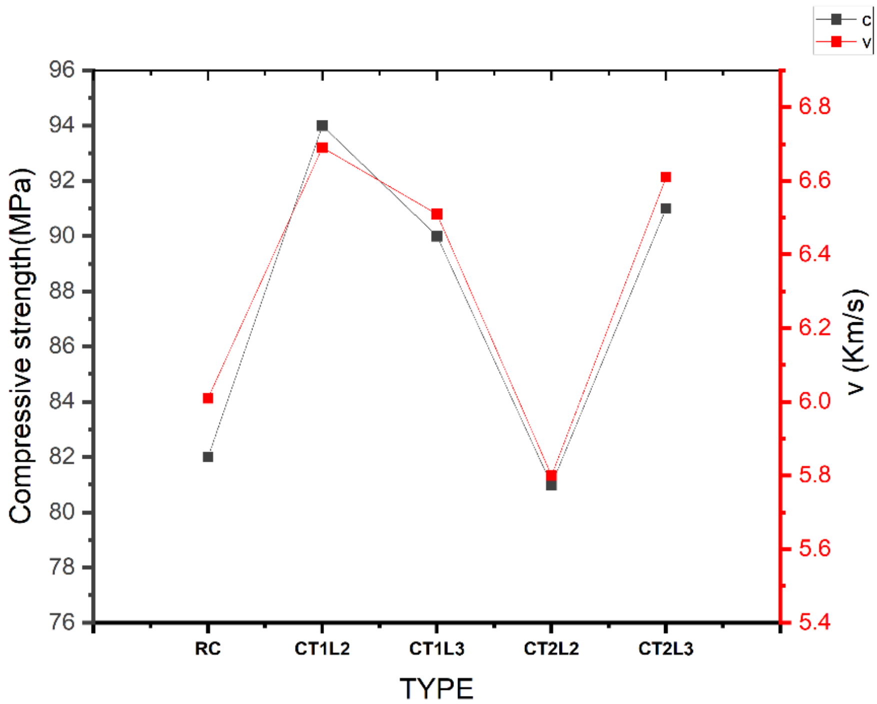

Figure 4 - Comparison with compressive strength and ultrasonic pulse velocity

Figure 5 depicts the flexural strength of high-performance concrete that has been reinforced with waste steel fibers recycled from car tires. The figure clearly illustrates that the addition of fibers to the concrete increases its flexural strength as compared to the reference concrete without fibers. Notably, the highest flexural strength was observed in CT1L2, which was reinforced with 1% of fiber volume and 2 cm of fiber length, indicating the superior performance of this particular configuration.

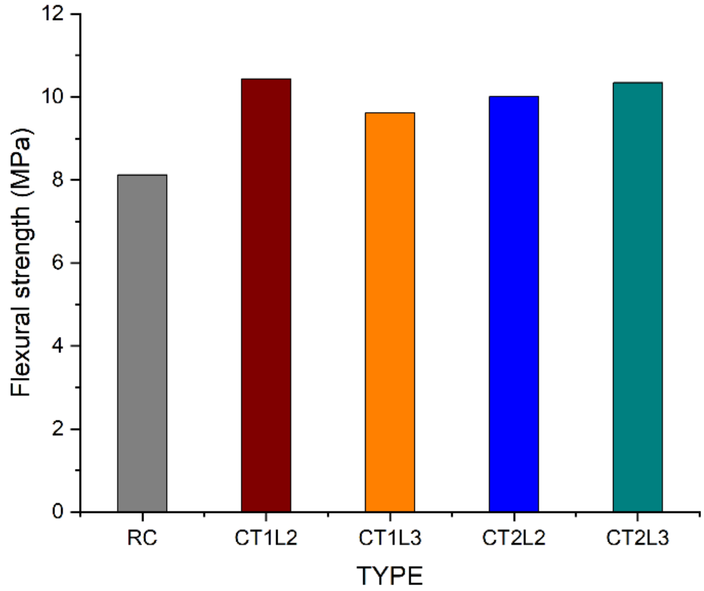

Figure 5 - Flexural strength of HPFC

Figure 6 depicts a distinct relationship between flexural resistance and pulse velocity in high-performance ferrous fiber-reinforced concrete extracted from waste tires of automobiles. The concrete reinforced with 1% volume and 2 cm length of fibers exhibited the best results in both flexural strength and velocity, indicating good density and homogeneity, as seen in CT1L2. Conversely, the concrete reinforced with 2% of volume and 2 cm length of fibers exhibited the lowest flexural strength. Therefore, by analyzing the relationship between flexural resistance and pulse velocity, we can gain insights into the concrete's quality and performance, which are essential for ensuring its long-term durability and reliability.

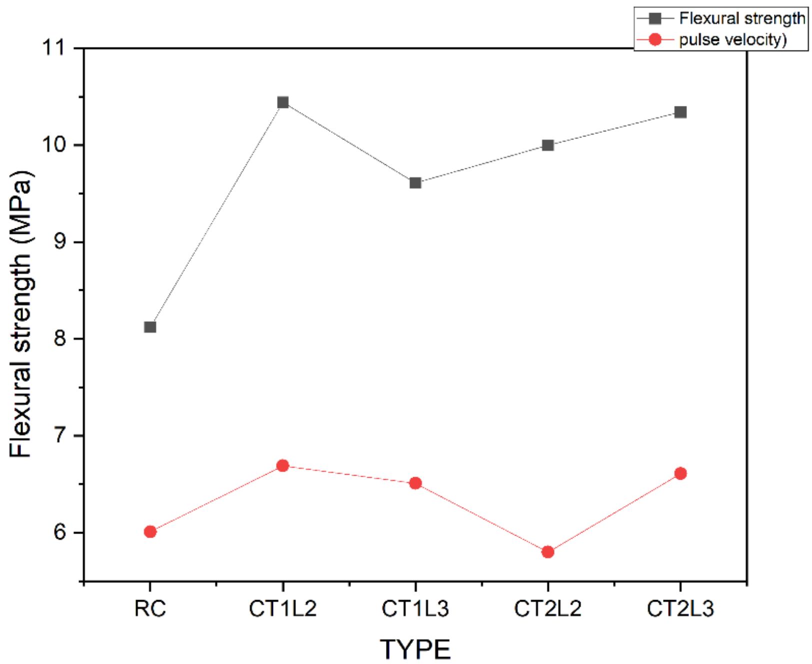

Figure 6 - Comparison with flexural strength and ultrasonic pulse velocity

4.2 Durability:

The submerged concrete study shown in Picture 6 is important because it helps to evaluate the durability of high-performance concrete in different types of aggressive environments. The study involved immersing concrete specimens in three different solutions: HCl, MgSO4, and water.

Picture 7 shows the results of a submerged concrete study in aggressive environments for 90 days. The specimens submerged in chlorine acid HCl experienced more mass loss compared to those immersed in MgSO4 and water. This is due to the decomposition of cement compounds when they interact with these solutions.

The results showed that the specimens submerged in chlorine acid experienced mass loss, indicating that this solution was the most aggressive in terms of damaging the concrete. This is likely because chlorine acid is a highly corrosive substance that can react with the cement compounds in the concrete, leading to their decomposition and resulting in a loss of mass.

On the other hand, the specimens submerged in MgSO4 have a modest loss of substance, and the most loss was reported in specimens with 1% of volume and 3 cm of length CT2L3, this degradation is due to the reaction between cement composition and MgSO4 solution.

The concrete immersed in water experienced less mass loss, indicating that they were less aggressive to the concrete. This is because water is less likely to react with the cement compounds in the concrete, and therefore does not cause as much damage over time.

When observing mass loss in concrete, regardless of the type of concrete or solution used, it is clear that high-performance concrete demonstrates superior chemical resistance to aggressive solutions. This is evidenced by the low levels of mass loss observed even in cases where the concrete has been subjected to significant damage as an HCl solution, figure 8.

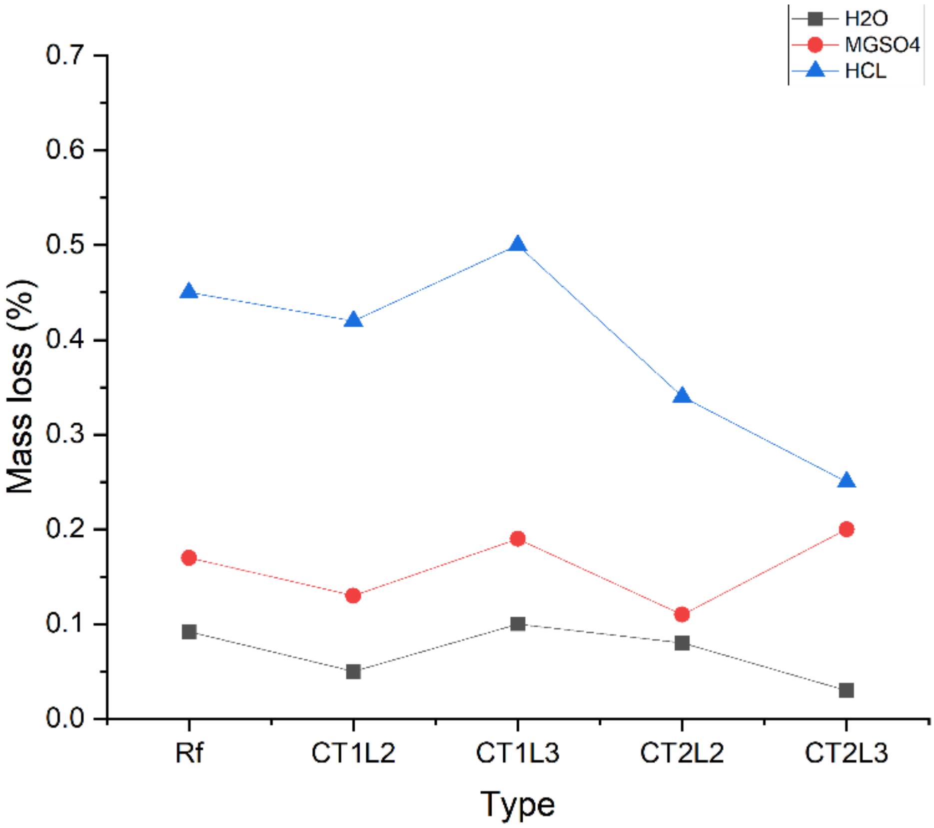

Figure 7- Mass loss of HPFC immerged in water, $MgSO_4$ and HCl

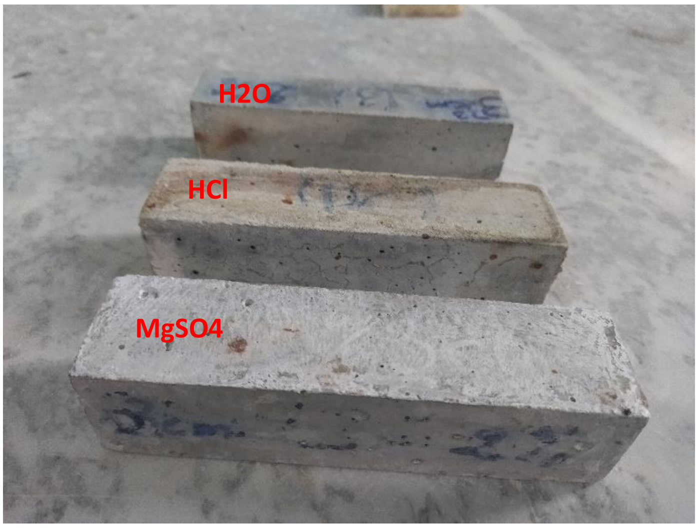

Figure 8- Specimens after immerged in water, MgSO4 and HCl solutions

The effect of HCl is more pronounced on steel than on cement paste, as shown in Figure 9, which reveals brown discoloration on the surface of specimens. To specify the damage, the model was cut into two parts to examine the interior of the concrete. Picture 10 showed no rust damage to the fibers used in high-performance concrete, leading to the conclusion that the brown color formed on the surface is actually an iron protection layer. This layer is formed from the reaction of CaCl with steel fibers.

Figure 9- Corrosion spot

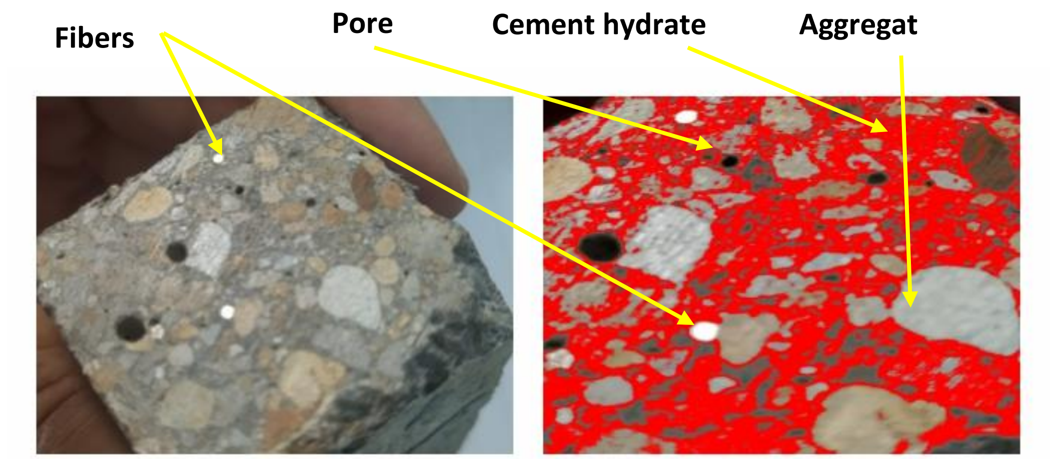

Figure 10- Structure interne of high performance concrete reinforced with waste steel fibers

5. Conclusion

In conclusion, the investigation of using waste steel fibers recycled from car tires has yielded several significant findings: Firstly, the addition of fibers to the concrete resulted in an improvement in compressive strength compared to the reference concrete without fibers. However, longer fibers can negatively impact the homogeneity and compactness of the concrete, resulting in decreased compressive strength. CT1L2, CT1L3, and CT2L3 were found to have excellent performance based on the average ultrasonic test results, indicating the strong correlation between compressive strength and ultrasonic pulse velocity. The addition of waste steel fibers to the high-performance concrete also resulted in an improvement in its flexural strength, as depicted by the results of the flexural strength tests. Additionally, a distinct relationship between flexural resistance and pulse velocity was observed in the high-performance concrete. Furthermore, the specimens exposed to HCl experienced more mass loss compared to those immersed in $MgSO_4$ and water, with the most significant loss reported in specimens with 1% volume and 3 cm length. The concrete immersed in water displayed the least mass loss, indicating its lower aggressiveness to the concrete. The high-performance concrete demonstrated superior chemical resistance to aggressive solutions.

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