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Corrosion Resistance Analysis of Tire Waste Steel Fiber Reinforced Self-Compacting Concrete using Rapid Chloride Penetration Test

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Corrosion of reinforced concrete structures induced by chloride contamination primarily causes structural damage and premature degradation, affecting safety, reliability, economics, and environmental performance. The development of self-compacting concrete (SCC) and Fiber-Reinforced Concrete (FRC) are among the most emerging developments in concrete technologies and significantly improve its strength and durability. SCC has excellent mechanical strength and is denser but has a brittle failure and is susceptible to cracking. In contrast, FRC increases the interfacial bond between constituent materials due to the presence of fiber, which increases its resistance against cracking. Researchers are still questioning whether adding fiber to self-compacting concrete enhances corrosion resistance against chloride penetration. This work develops a tire waste steel fiber reinforced self-compacting concrete (TWSFRSCC) and investigates its influence against corrosion together with other constituent materials such as water and superplasticizer (SP). Sixteen mixtures with different water-cement ratios (0.4 – 0.5), SP content (1 % - 1.8 %), and TWSF amount (0.71 % - 3.29 % or 5 - 15 kg/m^3) and one additional plain SCC were prepared and tested for rheological properties. In addition, the Rapid Chloride Penetration Test (RCPT) was performed on a 100 mm-diameter, 50 mm-thick concrete cylinder. Nine of seventeen mixtures meet EFNARC SCC rheological requirements. The study indicated that water and SP are the main factors affecting the rheological properties of concrete, altering segregation resistance and bleeding. The findings indicate that increased TWSF content leads to higher chloride penetration. This is attributed to the enhanced interconnectivity of the fiber, which forms more pores around the fiber, serving as entry paths for chloride ions. Additionally, the increase in TWSF content also enhances the specimen's electrical conductivity, which increases the charge passed. However, the presence of fiber still produces 11 out of 16 mixtures with moderate chloride penetration, where the TW3 mix attains a maximum decrease of 46.98 % against plain SCC, which attains high chloride penetration. This indicates that TWSF attracts the chloride ion to bond on the fiber first before penetrating the specimen, acting as a sacrificial anode. It was concluded that TWSF can strengthen the SCC and be applied in constructing marine structures.

1. Introduction

Chloride ingress is a major factor contributing to the deterioration of reinforced concrete structures in chloride-contaminated settings, resulting in significant losses in serviceability and safety and causing higher repair and maintenance expenses. When the deposited corrosion product reaches a critical level, the bonding strength between the steel bar (SB) and the surrounding concrete deteriorates significantly, reducing the strength and remaining life of reinforced concrete (RC) buildings (Clemente et al., 2023). The corrosion products might occupy two to six times the original section it was derived from, which pushes the concrete cover, creating a crack. For the past decade, different approaches have been developed with concrete corrosion. Specific techniques were implemented to enhance corrosion resistance, including the incorporation of cementitious materials, nanomaterials (which function as inhibitors) (Ventanilla et al., 2022), the coating of steel rebar (Afshar et al., 2020), and the incorporation of various fibers. The latter becomes the most dominant technique in improving concrete characteristics by controlling cracks and reducing chloride ion entry (Simalti and Singh,

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2021). Due to environmental benefits and lower cost, tire waste steel fiber (TWSF) is a better alternative to manufactured steel fiber (MSF) and is attracting researchers, construction industries, and planners to use in construction. Previous research shows that this fiber has similar mechanical properties to manufactured steel fiber (MSF) in concrete, including bonding to the matrix and tensile strength. Due to environmental benefits, lower cost, high tensile strength, and low carbon emission, TWSF attracts researchers, construction industries, and planners to use in construction (Macmac et al., 2022). Another innovation in concrete is the development of self-compacting concrete (SCC), which has better corrosion control due to its uniform homogeneity. The self-compactibility properties of this concrete produce a more intact bond between constituent materials filling the pores, which is a common issue of regular concrete Macmac et al., 2024. Various study is reported regarding many properties of SCC (such as permeation, bond to steel, mechanical chloride intrusion, and ductility) and confirmed to be improved than conventional concrete (Clemente et al., 2023). However, there is a shortage of information in the literature describing the durability of SCC with TWSF to corrosion (Al-Akhras and Aleghnimat, 2020). To date, only the study of Simalti and Singh (2021) explored the influence of TWSF on the corrosion of SCC and directly compared it with the effect of MSF. Based on the study, introducing both fibers into SCC shows an increase in the chloride ion ingress, but all mixes with fiber lie within the very low category of chloride ion penetration, the same with the control mix. The study explores the chloride ion penetration by a single test through a chloride migration test. Another method for chloride ion penetration and corrosion process was performed in this study to examine the corrosion behavior of SCC with TWSF.

This research explored the use of self-compacting concrete with TWSF for marine structures using rapid chloride penetration. Different mixtures of SCC with varying amounts of water, superplasticizer, and TWSF were tested for rheological properties and 28th day rapid chloride ion penetration. Linear regression analyses determined the effect of material constituents on the RCPT and corrosion of embedded rebar.

2. Materials and experimental design procedure

2.1 Experimental Material

The cementitious materials used to produce self-compacting concrete were Portland cement type 1. The study employed coarse crushed aggregate with a maximum size of 3/8 inches (9.525 mm). The maximum size of the fine aggregates utilized is 4.74 mm. The (EFNARC, 2005) standard served as the basis for the aggregate sizing. Sika Viscocrete 4100 was used as a high-range water reducer superplasticizer to achieve self-compactability requirements with a specific gravity of 1.05 + 0.03 kg/L. Potable water was used to avoid harmful agents such as chloride, sulfate, and acids. Previous research outlined the procedures used in this study to extract tire waste steel fiber (Macmac et al., 2022). It has a density of 13,237.06 kg/m^3 and a tensile strength ranging from 1,800 to 1,960 MPa. The fiber was cut into a length of approximately 30 mm.

2.2 Experimental procedure

Response surface methodology Central Composite Rotatable Design (RSM-CCRD) was used to produce the design mix proportion. This statistical tool is proven to generate combinations that illustrate and provide the influence of varying variables. This was used to generate small quantities of design mixture proportion that can differentiate the behavior of every variable even in the presence of a small number of experimental data, with all parameters varied in the preferred range. This paper is limited to determining the influence of constituent materials (water, SP, and fiber) on the corrosion resistance of SCC with fiber. Table 1 shows the sixteen (16) experimental runs generated by RSM-CCRD and one additional plain SCC. The boundaries were established via experimental mixing trial and error before the 16-mix design was created. The boundary limits dictate the upper and lower amount of the independent variables. The lowest amount of the varying factors arriving with the worst results will serve as the lower limit, and the high amount will be the higher limit. The concrete mixing was performed using the methodology used by Macmac et al. (2022).

2.3 Experimental testing method

2.3.1 Rheological properties

The rheological properties were assessed using EFNARC (2005) criteria. Various tests were used to determine the mixture's rheological properties, such as slump flow using Abram’s cone (550 mm – 850 mm) and T50 (2 s – 5 s) for flowability, L-box (> 0.8) for filling ability, and GTM screen stability (< 20 %) for segregation resistance.

2.3.3 Rapid chloride penetration test (RCPT)

The chloride ion penetration test determines the electrical conductance of the sample concrete. This method can measure the penetration resistance of the concrete in chloride ions. This test was based on the standards and procedure specified on ASTM C1202-19 (2022). All samples used were cast in concrete cylinders with dimensions of 100 mm diameter and 50 mm thickness, following ASTM C192/192M (2015). The voltage is 60 V for 6 h with an interval of 30 min. The total charge passed was computed in Coulombs (C). The chloride penetrations were assessed based on the total coulombs charged passed (C), specified by ASTM Standards. The chloride penetration can be characterized by high (> 4,000 C), moderate (2,000 – 4,000 C), low (1,000 – 2,000 C), very low (100 – 1,000), and Negligible when it is < 100 C.

Table 1: Mix Proportion for Development of TWFRSCC

Label	Pattern	Design Mix Proportion					
		Water (L/m^3)	SP (%)	TW (%)	Cement (kg/m^3)	Gravel (kg/m^3)	Sand (kg/m^3)
SCC		209.25	1.4		465	780	680
TW1	0A0	209.25	1.92	2	465	780	680
TW2	000	209.25	1.4	2	465	780	680
TW3	++-	232.50	1.8	1	465	780	680
TW4	+-+	232.50	1.0	3	465	780	680
TW5	+--	232.50	1.0	1	465	780	680
TW6	00a	209.25	1.4	0.712	465	780	680
TW7	---	186.00	1.0	1	465	780	680
TW8	-++	186.00	1.8	3	465	780	680
TW9	A00	239.18	1.4	2	465	780	680
TW10	00A	209.25	1.4	3.287	465	780	680
TW11	+++	232.50	1.8	3	465	780	680
TW12	-+-	186.00	1.8	1	465	780	680
TW13	000	209.25	1.4	2	465	780	680
TW14	a00	179.32	1.4	2	465	780	680
TW15	--+	186.00	1.0	3	465	780	680
TW16	0a0	209.25	0.885	2	465	780	680

Note: For pattern, the first term refers to water, followed by superplasticizer, and finally, the amount of fiber
The limits (-a) low alpha, (-) low, (0) Mid, (+) High, and (+A) High Alpha

3. Result and discussion

3.1 Rheological Properties

Eleven (11) among the seventeen (17) design mixes pass the rheological properties test and are considered SCC (see Figure 1). Most of those failed mixtures contain either low or high levels of water and SP. Mixture TW8 (-) water but (+) SP and (+) fiber attains the highest flowability, passing ability, and passing segregation resistance, satisfying EFNARC standards. A mixture with the (+ or A) level of water or SP fails due to high segregation, as observed in the TW1 and TW9 mix. However, having (- or a) limit of either water or SP also fails to achieve the desired flowability and passing ability, as seen in mix TW7, TW12, TW14, and TW15. The most significant effect of water was seen in the mixture of TW14, TW2 or TW13, and TW9.
Varying the amount of water from (a to A) level significantly increases flowability by 128.7 %. The result of the L-box test shows no linear trend when varying the amount of water. The mixture fails when the amount of water is (a or -) and simultaneously at (A) limit. The segregation and bleeding increase when the amount of water or SP is at (A) level, resulting in the worst mixture. The effect of SP is evident in mixtures TW16, TW2 or TW13, and TW1, showing an increasing trend in the slump by 34.41 %. This was complimented by the T500 test since as the water content increases, the time becomes faster by 72.09 %. Higher SP content produces a better passing ability; around 28.37 % increases were recorded when (A) limit was included. The increase in fiber inclusion shows an increasing trend in the slump flow of about 15 %. It shows that TWSF increases the flow when the dosage simultaneously increases, as observed in the TW6, TW2, and TW10 mix. This elaborates that improvements in the flowability were observed because of the fiber's stiffness, as mentioned by Macmac et al. (2022). The effect of fiber on the L-Box does not show a linear trend once the fiber increases. The same behavior was observed for mixtures with low or high fiber content. However, for the GTM segregation test, although the following mixture passed the criteria, when the fiber content increases (- to +) or (a to A), there is a gradual decrease of segregation of about 46.15 %. This elaborates that the fiber still influences the rheological properties of SCC when included. However, the effect of fiber is not comparable to the impact of water and SP.

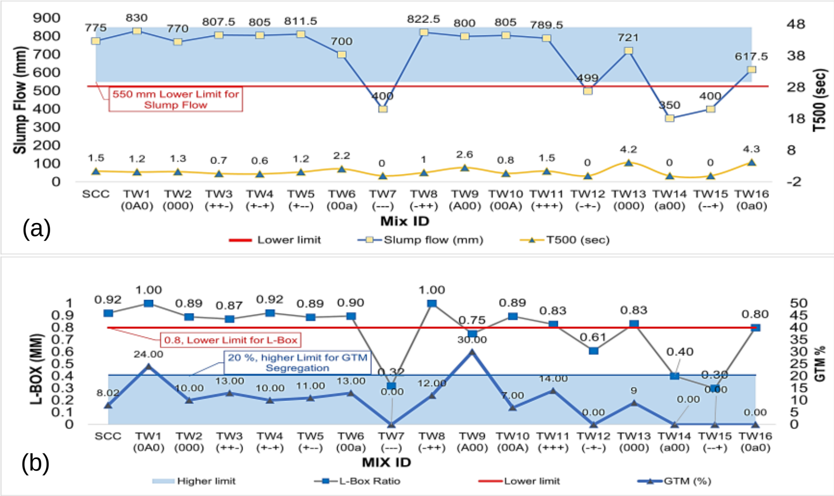

Figure 1: Rheological Properties Test result (a) Slum flow & T50 (b) L-Box & GTM

3.2 Correlation of Rheological Properties and Material Constituents

The influence of each factor was examined using regression analysis measured from its coefficients, P-value, and regression statistics (Table 2). The analysis indicates that the water has the greatest impact on the rheological properties, as this factor only has a p-value of less than 0.05 for filling ability (0.0004), passing ability (0.0158), and segregation resistance (0.0032). The SP has a substantial effect on the SF and GTM, as evidenced by P-values of 0.0466 and 0.033. However, the fiber has less influence on the mixture but is still considered a substantial factor. Analysis shows that fiber has a positive coefficient, which will gradually improve the rheological properties. This justified the claims from previous work (Macmac et al., 2022) that the TWSF has minimal impact on the rheological properties of SCC due to the fiber's stiffness, which does not deform and function the same as the coarse aggregates.

Table 2: Regression analysis of Rheological properties (Coefficient and P-values)

Variables	Slump Flow		T50		L-Box		GTM	
	Coef.	*P-Value*	*Coef.*	*P-Value*	*Coef.*	*P-Value*	*Coef.*	*P-Value*
Intercept	-963.1	0.0084	-2.791	0.5125	-1.028	0.0803	-65.67	0.003
Water (w/c)	2954.4	0.0004	11.219	0.2042	3.0538	0.0158	131.9	0.0032
SP (%)	171.36	0.0466	-0.573	0.5936	0.2515	0.089	10.804	0.033
Fiber (%)	38.366	0.2382	-0.053	0.9007	0.032	0.5676	0.3778	0.8367
Multiple R	0.8423		0.3875		0.7019		0.7858	
R Square	0.7094		0.1501		0.4927		0.6174	
Adj. R Square	0.6368		-0.062		0.3659		0.5218	

3.3 Rapid chloride penetration test (RCPT)

All seventeen (17) mixtures were subjected to RCPT, mixture TW1, TW5, TW8, TW10, TW14, TW15, and the control specimen SCC yielded a high chloride permeability which is > 4000 Coulombs. The results of the actual RCPT vs. the estimated complement each other, proving that the empirical formula for estimating chloride penetration can be applied to this type of concrete (see Figure 2a). Among all mixtures, the mix TW10 (0) water, (0) SP, and (A) fiber yields the highest corrosion level and current flowing for the whole duration of the test. After the specimen was exposed to chloride, corrosion spots and the formation of corroded steel fiber were observed on the exposed surfaces of cylinders in a 3.5 % wt NaCl solution. The mixture with (0) water, (0) SP, and increasing fiber dosage enhances chloride penetration by 84.79 %, as observed on TW6, TW2/TW13, and TW10. Despite large fiber additions increasing chloride penetration, some TWFRSCC mixes are better than plain SCC, which has moderate chloride penetration. Out of sixteen (16) mixtures, eleven (11) combinations containing fiber achieve a moderate level of chloride penetration, with TW3 having the highest drop of 46.98 % when compared to plain SCC. Only 5 of 16 mixes with fiber provide higher chloride penetration, with a maximum increase of 34.82 % observed on the TW10 mix. This emphasizes that the presence of TWSF increases the attraction of the chloride ion to bind on the fiber first, which gradually delays the penetration into the concrete and serves as a sacrificial anode (Clemente et al., 2022). These supplements that fiber is viable for improving chloride penetration, given it has a proper mixture even with a high fiber dosage. The current flow on the samples throughout the RCPT demonstrates that TW10 and TW14 had the consistent highest current flow, resulting in high chloride penetration (see Figure 2b). However, this is not the case for the plain SCC, which is controversial because as time passes, the current does not progressively move upward but downward, and it still achieves higher chloride penetration. This occurred due to the presence of numerous pores on the specimen's surface, which serve as an entry point for chloride ions. In contrast, the increase in chloride ion penetration in concrete containing TWSF was due to the increased porosities around the fibers. Suggesting that the fiber becomes the transport mechanism of the chloride that severely affects the concrete (Hwang et al., 2015). However, it was observed during the test that there was an excessive increase in temperature in the specimen when the dosage of fiber was increased. This suggests that the fiber's electrical conductivity might be the other cause of the increase in the total charge passed, and this phenomenon was also observed by Clemente et al. (2023) when manufactured steel fiber was applied to SCC. This emphasizes that other tests that are less dependent on the electrical conduction of the samples should be performed to determine chloride penetration, which was also suggested by Bede Odorčić and Kravanja (2022).

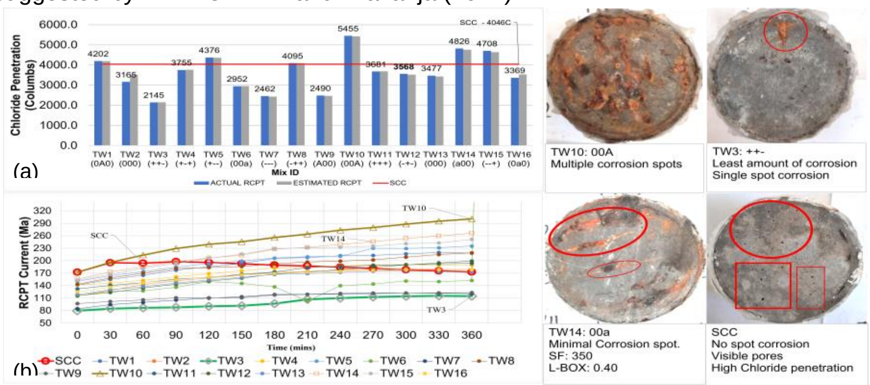

Figure 2: Rapid Chloride Penetration Test result (a) Actual vs. Estimated (b) Current vs. Time

Table 3: ANOVA of RCPT Results Response Surface Model

Source	SS	DF	MS	F-value	p-value	Remarks	Fit Statistics
Model	9.949E+06	9	1.300E+06	11.10	0.0042	Significant	Std.Dev = 342.27
A-Water	2.728E+06	1	2.728E+06	23.29	0.0029		Mean = 3694.44
B-SP	3.469E+05	1	3.469E+05	2.96	0.1361		R^2 = 0.94
C-TWSF	3.133E+06	1	3.133E+06	26.74	0.0021		Adj. R^2 = 0.86
AB	9.786E+05	1	9.786E+05	8.35	0.0277		Pred. R^2 = 0.54
AC	4.315E+05	1	4.315E+05	3.68	0.1034		Adeq.Precision= 9.79
ABC	1.878E+06		1.878E+06	16.03	0.0071		
A^2B	7.090E+05	1	7.090E+05	6.05	0.0491		
A^2C	6.125E+05		6.125E+05	5.23	0.0622		
AB^2	1.492E+06	1	1.492E+06	12.73	0.0118		
Residual	7.029E+05	6	1.171E+05				
Lack of Fit	7.002E+05	5	1.400E+05	52.56	0.1043	Not significant	
Pure Error	2664.50	1	2664.50				
Cor Total	1.241E+07	15					

SS = Sum of Squares, DF = Degree of Freedom, MS = Mean Square

3.4 Correlation of RCPT and material constituents

The total charge passed in coulombs was analyzed using analysis of variance (ANOVA) to assess the impact of each constituent material (water, SP, and TWSF). Table 3 represents the non-linear response surface model showing that terms A (water), C (TWSF), AB, ABC, A^2B, and AB^2 are significant model terms that yield a P value of < 0.05. Despite SP alone not being a significant factor, it still considerably influences rheological properties that might cause highly or non-compact SCC. The P-value of lack of fit (LOF) is> 0.05, indicating that LOF is insignificant, suggesting that the models for all responses are satisfactory.

4. Conclusion

The 17-mix design exhibits different rheological properties when altering water, SP, and fiber dosage. The analysis shows that water and SP significantly influence flowability, filling ability, passing, and segregation resistance. By increasing water content to the (A) limit, flowability rose by 128% and passing ability increased by 34.41 % when SP increased up to the same limit. However, this increase was associated with massive segregation and bleeding, which produced a worse mixture. Including tire waste steel fiber in SCC increased flowability by 15 % without affecting passing ability. However, the segregation test showed a 46.15 % decrease with more fiber, but still within EFNARC standards. This disproves claims that fibers reduce flowability and passing ability while confirming that fiber gradually reduces segregation resistance. This effect was a good sign that TWSF does not hamper SCC's fresh properties. The increase in fiber inclusion raises the chloride penetration due to the interconnectivity of the fiber, which increases the pores around the fiber and the electrical conductivity within the specimen, increasing the charge passed. However, despite the increase, the presence of fiber produces 11 out of 16 mixtures with moderate chloride penetration, where the TW3 mix attains a maximum decrease of 46.98 % against plain SCC. This emphasizes that the presence of TWSF increases the attraction of the chloride ion to bind on the fiber first before penetrating the specimen, completely delaying the chloride penetration and serving as a sacrificial anode. Adding this fiber can improve SCC's corrosion resistance, but the proper mixture is vital. Additional tests, like accelerated corrosion through impressed current, are necessary to consider factors like cracks and electrical conductivity to substantiate claims.

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