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Experimental study on strength reduction due to corrosion in reinforced concrete slabs with and without steel fibers

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Abstract: Corrosion significantly affects deterioration in reinforced concrete structural members, severely compromising their strength and durability, especially in regions with heavy rainfall and exposure in coastal areas. Currently, steel fibers have been increasingly used in the construction industry because of their enhanced durability, crack resistance and overall structural performance and it's been emphasized for more research. Moreover, most previous studies have focused on corrosion damage in reinforced concrete slabs and beams, further research is needed to study the behavior of corrosion in RC slabs with steel fibers and the proneness of steel fibers to corrosion. This study aims to experimentally evaluate the impact of corrosion on the flexural strength and durability of steel fiber-reinforced concrete (SFRC) slabs comparing with conventional reinforced concrete (RC) slabs. An accelerated corrosion process was applied using a 5% sodium chloride electrolyte solution and a 5V output over 240 days. Corrosion levels in the slabs were assessed by using the Cor-Map technique. The results indicated that SFRC slabs exhibited higher corrosion levels than conventional RC slabs, likely due to the increased exposed area from the distributed steel fibers. The results of experimental flexural strength tests showed that the percentage reduction in flexural strength of the SFRC slab was greater than that of the conventional RC slab after corrosion. Although SFRC slabs exhibited faster corrosion due to the presence of steel fibers, fiber corrosion did not contribute to the corrosion of main steel bars and these slabs performed better than conventional RC slabs in terms of flexural strength and crack resistance in both before and after corrosion. According to this experimental research, the behavior of steel fiber corrosion in RC slabs is well known, and it showed that steel fibers could be effectively used in RC slabs and these results provided a valuable reference for assessing the residual capacities of existing steel fibers reinforced concrete slabs affected by corrosion.

Keywords: Accelerated corrosion; Corrosion level; Flexural strength; Strength reduction

1. Introduction

Concrete structures are highly susceptible to the detrimental effects of corrosion, primarily due to the steel reinforcement embedded within them [1]. The integrity, strength, durability, and serviceability of these structures can be significantly compromised as the steel reinforcement corrodes [2]. This process involves the degradation of steel rebar, which can lead to several adverse consequences, including loss of load-carrying capacity, reduced lifespan, and the need for costly repairs or replacement. The corrosion of steel reinforcement is a pervasive problem globally, affecting a wide range of infrastructure such as bridges, buildings, and tunnels. The consequences of corrosion are severe, often leading to structural instability, compromised safety, and reduced functionality of these critical assets [3], [4]. When steels are exposed to oxygen and moisture, an electrochemical process called corrosion takes place, which leads to the growth of corrosion. The corrosion is a significant effect that imposes rise impact on the surrounding concrete when it comes to reinforced concrete [5].

The concrete cover may crack, delaminate, and spall as the corrosion extent develops, ultimately compromising the structural integrity [6]. The load-bearing capability of concrete structures can be greatly impacted by corrosion-induced strength loss and the appearance of visual damage, which is why engineers and researchers alike are highly concerned about this problem [7].

Concrete slabs develop in different varieties, such as flat slabs, one-way slabs, and two-way slabs, each with its own reinforcing combinations and design. Many of variables, including the extent of corrosion, the characteristics of the concrete mix, the thickness of the slab, and the reinforcement design, affect how much the strength of these slabs is reduced as a result of corrosion [8], [9]. Developing efficient mitigation methods requires an understanding of how these factors affect the deterioration process. Steel fibers are being used progressively in construction industries as reinforcement to improve the strength and durability of concrete, especially in high-stress applications including shotcrete, precast concrete, industrial floors, and tunnel linings. By increasing tensile strength, ductility, and crack resistance, these fibers increase a structure's resistance to dynamic loads and overall durability [10], [11]. In order to satisfy the increasing need for durable and sustainable infrastructure, recent developments have concentrated on improving the shapes, sizes, and compositions of fibers for improved distribution and bonding within the concrete matrix and investigating economical manufacturing processes [12].

Corrosion of steel reinforcement in concrete structures is a critical issue that can severely compromise the integrity, strength, durability, and serviceability of the structure. Understanding the corrosion behavior of steel fibers is crucial due to their growing use in the construction industry. The distribution of steel fibers throughout the concrete matrix, in contrast to conventional RC slabs, requiring an understanding of how it impacts the rate of corrosion. So, this research focuses on comparing reinforced concrete slabs with and without steel fibers after corrosion.

Researchers are investigating into alternative reinforcement techniques, such as combing steel fibers with conventional reinforcing bars, to solve this developing problem [13], [14], [15]. Steel fibers have gained interest as an opportunity to increase the durability and strength of concrete structures. Steel fiber reinforced concrete, or SFRC, has become more and more well-known in structural applications, such as shear reinforcement in flat plates and flexural reinforcement in beams [16]. Steel fibers can be added to improve ductility, slow the spread of cracks, and maybe reduce the impact of corrosion on structural performance. In addition to its mechanical advantages, SFRC may be an economical choice that can extend the structural durability of concrete structures. The strength loss upon corrosion in conventional RC beams has been investigated by several researchers [17], [18], [19]. Enhancing their research efforts, the strength loss of conventional reinforced concrete slabs after corrosion as well as the strength loss of reinforced concrete slabs with steel fibers after corrosion is evaluated in this research.

The purpose of this study is to compare the corrosion and flexural strength of concrete slabs with and without steel fibers. The primary objective is to analyze the impact of steel fiber addition on the rate of corrosion and, in turn, the slabs' flexural strength. This research aims to offer significant insights into methods for enhancing the durability of concrete structures by comparing the performance of SFRC slabs versus regular Reinforced Concrete (RC) slabs under conditions of accelerated corrosion. The results are expected to guide the development of sustainable and more resilient infrastructures which might improve the durability and lower maintenance costs of concrete structures subjected to harsh environments. Finally, by addressing a significant issue in the field of civil engineering, our research adds to the ongoing efforts to enhance the durability and performance of reinforced concrete structures.

2. Material and methods

In this study, Double Rhinos brand Type I Ordinary Portland Cement was used due to its consistent and reliable quality. To take into consideration possible variations in local materials, the fine aggregates included seven different kinds of river sand that were collected from different parts of Myanmar, including Yangon (Thanlyin). Because of its longevity, Ayeyawaddy river shingle was chosen for coarse aggregates. To maintain mixture homogeneity, the maximum particle size was kept at 25 mm. To get the required strength and workability, the first preliminary mixes were developed using ACI 211 guidelines. By analyzing two types of reinforced concrete slabs—conventional Reinforced Concrete (RC) slabs and Steel Fiber Reinforced Concrete (SFRC) slabs—the experimental program designed to assess the influence of corrosion on the flexural strength of RC slabs. In the experimental tests, eight identical slabs were selected, each with a length of 1400 mm and a rectangular cross-section of 400 mm x 100 mm. The specimens were designed to achieve a target compressive strength of 28 MPa at 28 days. Both the longitudinal and the transverse bars have a diameter of 9.55 mm and are spaced 175 mm and 150 mm center to center, respectively and cover thickness is 20mm. Four slabs are used for uncorroded strength tests, while the remaining four are used for corroded strength tests. This comparative study provides insight into the performance and possible durability benefits of adding steel fibers to reinforced concrete particularly in corrosive environments. The flow chart of this research is shown Figure 1.

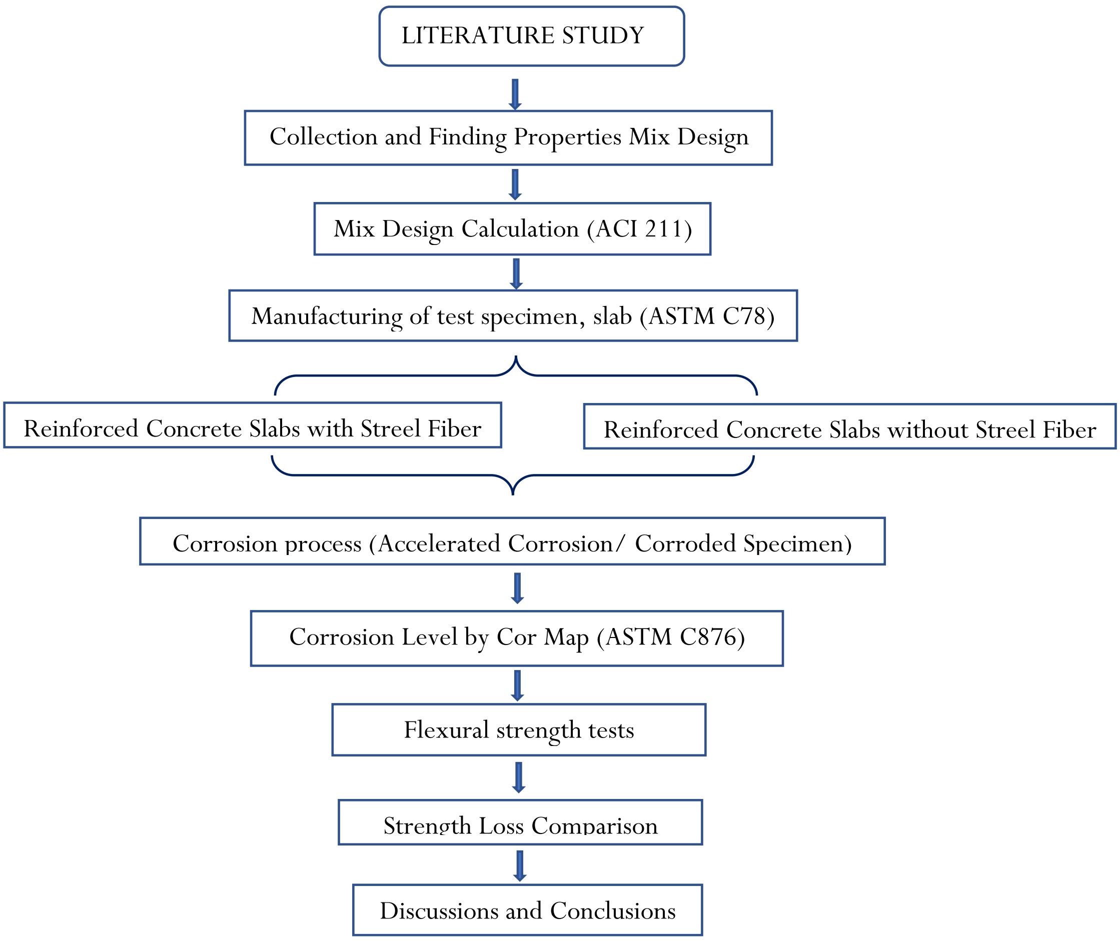


Figure 1. Flow Chart of the study

ISSN 3047-5473
Innovation in Engineering, Vol. 2, No. 1, 2025, pp. 57-72

2.1 Material usage

Table 1 presents the composition of the concrete mixture used to cast the specimen. Based on the American Concrete Institute's (ACI) specification, the specimens target 28-day compressive strength was 28 MPa.

Table 1. Composition of the concrete mixture

Cement (kg/m^3)	Water (kg/m^3)	FA (kg/m3)	CA (kg/m^3)
330	185	715	1089

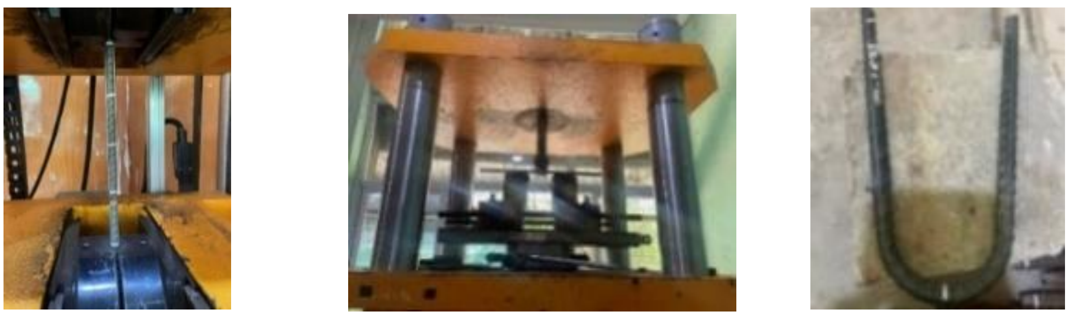
According to literature reviews, the recommended dosage of steel fibers is typically around 1 % by volume, with a range of 0.5 to 2 % commonly used. Therefore, based on the steel fibers types available on the market, hooked-end steel fibers with an aspect ratio of 65 were chosen as shear reinforcements in this research with a volume fraction of 1 %. Details of the steel fibers are shown in Table 2 and Figure 2.

Table 2. Specification of steel fiber

Model	Aspect ratio	Length (mm)	Diameter (mm)	Tensile Strength (MPa)
UF055-3563ZN	65	35	0.55	1050

Figure 2. Steel fiber

The mechanical properties of the reinforcement steel based on steel testing (ASTM E8/E8M for tensile testing and ASTM E290 for bending testing) shown in Figure 3. With a yield strength of 601.59 MPa and an ultimate tensile strength of 708.65 MPa, the steel samples demonstrated strong resistance to deformation under load. The average diameter was 9.55 mm. For reinforced concrete applications requiring both strength and flexibility, the elongation at failure was 15%, indicating sufficient ductility. The material's suitable and reliability for structural usage is demonstrated by these results, which follow ASTM standards.



(a) (b) (c)

Figure 3. Tensile test of steel. (a) tensile test, (b) bending test, and (c) bending behavior after testing

The slab samples were mixed and cast according to the specified composition and procedures, ensuring consistency and uniformity across all specimens shown in Figure 4.

(a) (b) (c) (d)

Figure 4. Mixing and casting concrete samples (a) preparing and arranging molds for concrete casting (b) process of pouring mixed concrete (c) poured concrete in the molds (d) concrete texture and consistency

The early strength development and ultimate durability of the concrete were significantly influenced by the seven-day curing period shown in Fig. 5. The curing process is depicted in (a) Curing of Concrete Samples and (b) Curing of Concrete Cubes for 28 Days Strength.

(a) (b)

Figure 5. Curing process. (a) Curing of concrete samples, and (b) Curing of concrete cubes for 28 days strength

As shown in Figure 6, compressive strength testing shown that the concrete achieved a 28 MPa compressive strength after 28 days. After 28 days, the accelerated corrosion setup was initiated to simulate and study the effects of corrosion on the specimens shown in Figure 7.

(a) (b)

Figure 6. Cube testing. (a) Concrete cube test, and (b) Concrete cubes after compressive failure

2.2 Accelerated corrosion setup

To induce corrosion in the tested slabs, an accelerated corrosion approach applying constant voltage was employed. Initially, the cover block 20mm was placed at the bottom of each slab, then inverted. The corroded area under consideration, the reinforcement bandwidth was surrounded by a dike, as shown in Fig. 7. The dike was filled with an electrolyte solution (5% sodium chloride by weight of water. In order to keep a steady output voltage of 5 V, a regulator power supply has been used to supply a source of direct current.

(a)

(b)

Figure 7. Accelerated corrosion setup of slab specimens. (a) Dike filled with electrolyte solution, and (b) Electrochemical system for applying constant voltage

2.3 Half-cell potential measurements

The uncoated reinforcing bars' corrosion activity is evaluated utilizing the half-cell potential approach, which is standardized by ASTM C876-15. With this technique, the electrochemical potential of reinforcement buried in concrete is measured in relation to a reference put on the concrete's surface. Table 3 displays the occurrence probability of corrosion as indicated by the half-cell potential data.

Table 3. Interpretation of half-cell potential values as per ASTM (C876 2015)

Half-Cell Potential (mV) relative to Cu/CuSO4 reference electrode	Percentage chance of active corrosion
<-350	90
-250 to -350	50
>-200	10

3. Results and discussion

In this experimental study, well-designed concrete mixes were initially used to create Steel Fibers Reinforced Concrete Slab (SFRC), followed by recording corrosion data using Cor Map Figure 8. During the induced corrosion process, measurements of the slab's half-cell potential were taken at intervals of seven days.

3.1 Half-Cell potential

The average half-cell reading is shown against time in Figure 8, the average half-cell reading is shown against corrosion level in Figure 8, and the average half-cell reading is shown against corrosion level in Figure 9. No slab's recorded potential value was less than -150 mV on day 7, indicating that the tested slab would have a less than 10% likelihood of active corrosion. After 20 days, it was found that SFRC slabs and RC slabs had potential values between -400 mV and -300 mV, indicating that, in accordance with ASTM (C876 2015), the percentage chance of active corrosion was approximately 90%. Meanwhile, RC slabs had values between -300 mV and -200 mV, indicating that SFRC slabs may have a 50% chance of active corrosion after 20 days. Therefore, when the concrete strength for SFRC slabs increased it also increased the electrical resistivity of the concrete. As a result of the improved resistance to chloride ion penetration, the rate of corrosion was slowed down, preventing the beginning of corrosion (Ahmad 2003). The potential readings for any location for all tested slabs were found to be higher than -400 mV after 40 days. This indicated that the potential readings at the late testing age of corrosion had very close values compared to another. Therefore, for uncorroded members, this test is just for determining the probability that corrosion may occur. The corrosion levels at 240 days varied among the specimens shown in Table 4.

Figure 8. Corrosion data record

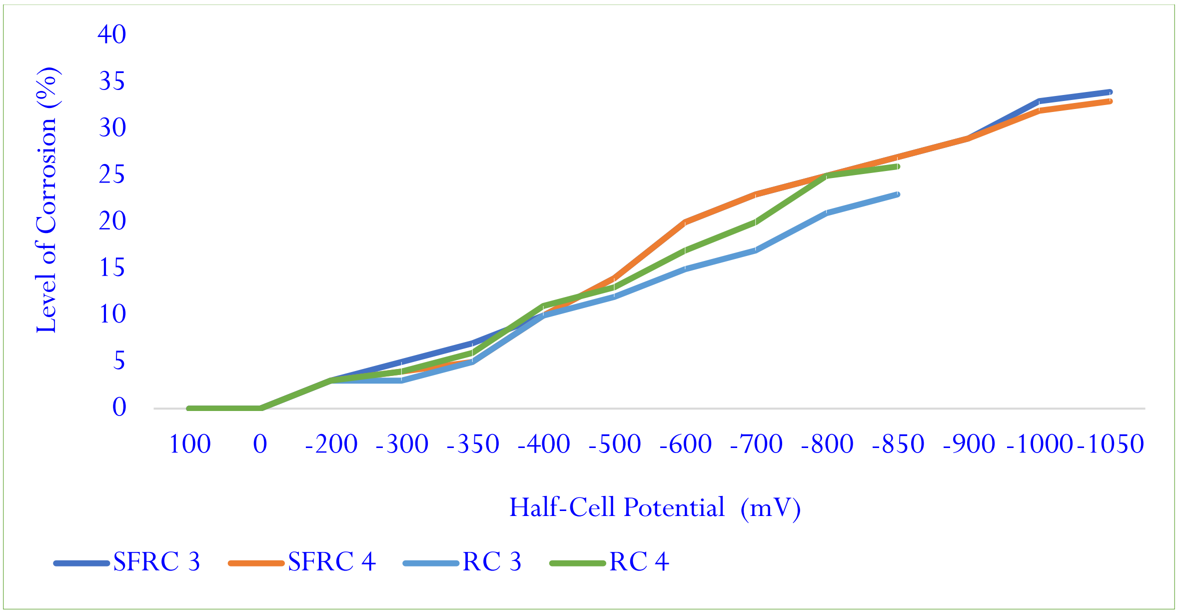


Figure 9. Half-cell potential values vs. Level of corrosion

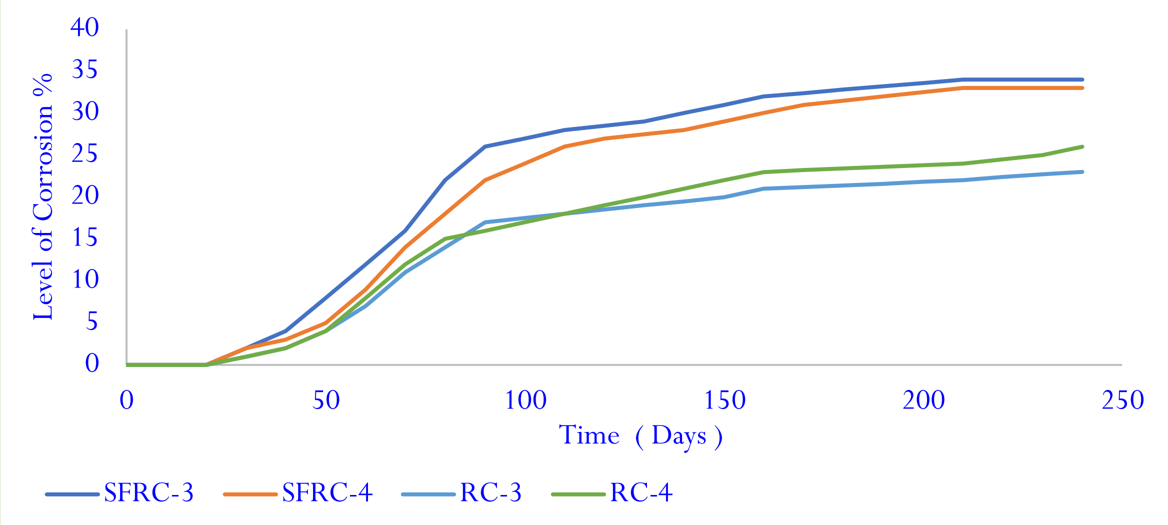


Figure 10. Time vs. Level of corrosion

Table 4. Corrosion level from non-destructive testing (Cor Map)

Specimen	Corrosion Level (%) Time (days)		
	90	180	240
Steel Fiber Reinforced Concrete Slab 3 (SFRC 3)	26	32	34
Steel Fiber Reinforced Concrete Slab4 (SFRC 4)	22	31	33
Reinforced Concrete Slab 3 (RC 3)	17	21	23
Reinforced Concrete Slab 4 (RC 4)	18	23	26

The corrosion behavior of steel fibers-reinforced concrete (SFRC) and conventional reinforced concrete (RC) slabs over 240 days period is illustrated in the graph. All samples show minimal corrosion at first. The corrosion levels increased with time, with RC 3 and RC 4 indicating a slower rate of corrosion than SFRC 3 and SFRC 4. RC samples show significantly improved corrosion resistance by the conclusion of the 240 days period; RC 3 has the lowest corrosion levels, followed by RC 4. From the testing data, it can be seen that SFRC samples show greater rates of corrosion than normal RC slab. It may be because of distributing steel fiber the whole slab area. But it can't be said the corrosion rate is the corrosion rate of reinforcing bars in slab. It can be seen the trend of corrosion rate in SFRC slab is slowly than RC slab after 240 days in Figure 10.

3.2 Flexural strength test at YTU laboratory

Under third-point loading flexural testing ASTM C78, steel fiber reinforced concrete (SFRC) slabs demonstrate smaller crack widths compared to conventional reinforced concrete (RC) slabs, as shown in Figure 11: Flexural Strength Test at YTU Laboratory — (a) Pre-Test Setup of Slab Specimen, (b) Post-Test Setup of Slab Specimen; Figure 12: Flexural Strength Test of SFRC Slab at YTU Laboratory — (a) Post-Test Setup of SFRC Slab Specimen, (b) Crack Patterns Observed During Testing, (c) Crack Patterns Observed After Testing; and Figure 13: Flexural Strength Test of RC Slab at YTU Laboratory — (a) Post-Test Setup of RC Slab Specimen, (b) Crack Patterns Observed During Testing.

ISSN 3047-5473
Innovation in Engineering, Vol. 2, No. 1, 2025, pp. 57-72

(a) (b)

Figure 11. Flexural strength test at YTU Laboratory (a) Pre-test setup of slab specimen, and (b) Post-test setup of slab specimen

(a) (b) (c)

Figure 12. Flexural Strength Test of SFRC Slab at YTU Laboratory (a) Post-test setup of SFRC slab specimen, (b) Cracks pattern observed during testing, and (c) Cracks pattern observed after testing

Flexural strength tests at the YTU Laboratory showed that Steel Fiber Reinforced Concrete (SFRC) slabs had much smaller crack widths and fewer cracks compared to conventional Reinforced Concrete (RC) slabs shown in Figure. 12. By widening microcracks and efficiently distributing tensile stresses throughout the concrete, steel fibers enhanced crack control. As a result, under similar loading conditions, SFRC slabs were better at resisting crack formation and growth. This enhanced crack resistance led to better flexural strength and durability, allowing SFRC slabs to maintain their structural integrity more effectively than conventional RC slabs.

(a) (b)

Figure 13. Flexural strength test of RC slab at YTU Laboratory (a) Post-test setup of RC slab specimen, and (b) Cracks pattern observed during testing

ISSN 3047-5473
Innovation in Engineering, Vol. 2, No. 1, 2025, pp. 57-72

YTU Laboratory's flexural strength test of conventional RC slabs revealed that they had more cracks and deeper cracks than SFRC slabs shown in Figure 13 (a) and (b).

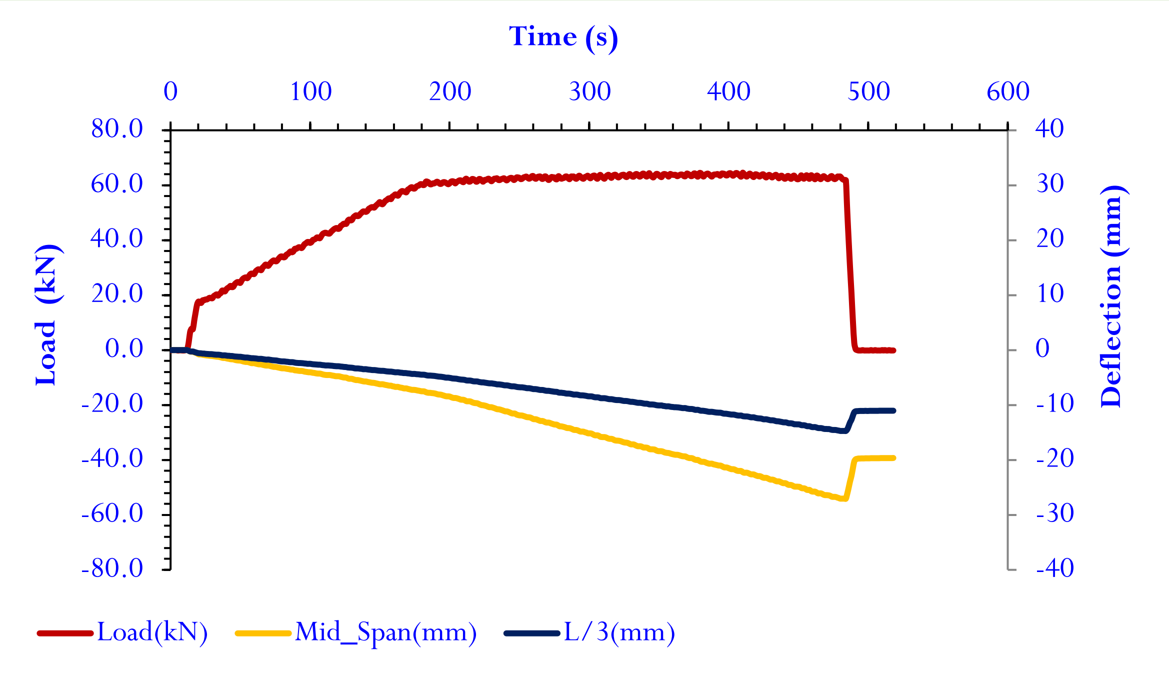


Figure 14. Load vs time vs settlement (SFRC slab - uncorroded sample)

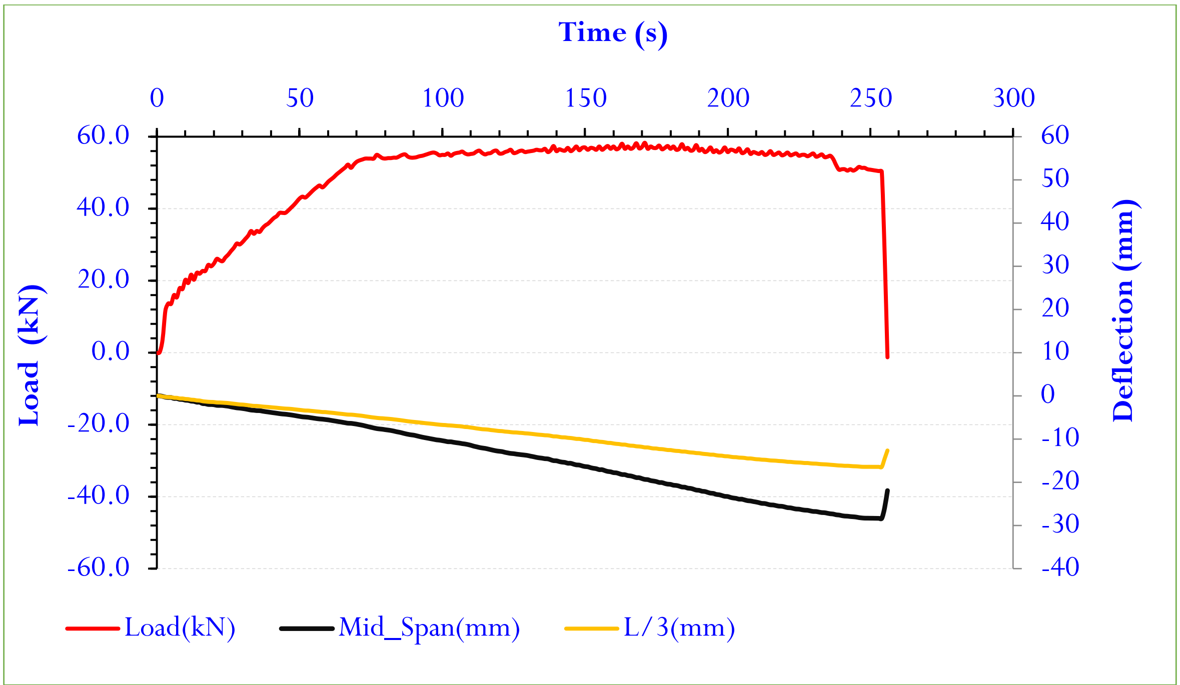


Figure 15. Load vs time vs settlement (SFRC slab - corroded sample)

Corrosion reduces the load-bearing capacity of SFRC slabs by reducing the bond between the concrete and steel fibers. Corroded slabs thus deflect more under the load and settle faster. Furthermore, corroded slabs fracture faster and brittlely than uncorroded ones, which fracture slower and have obvious cracks. This results from the corroded steel fibers decreasing their tensile strength. The

ISSN 3047-5473
Innovation in Engineering, Vol. 2, No. 1, 2025, pp. 57-72

flexural performance of SFRC slabs is affected by corrosion, which reduces them and changes their failure modes. This affects the duration that they continue in corrosive situations, as seen in Figures 14 and 15.

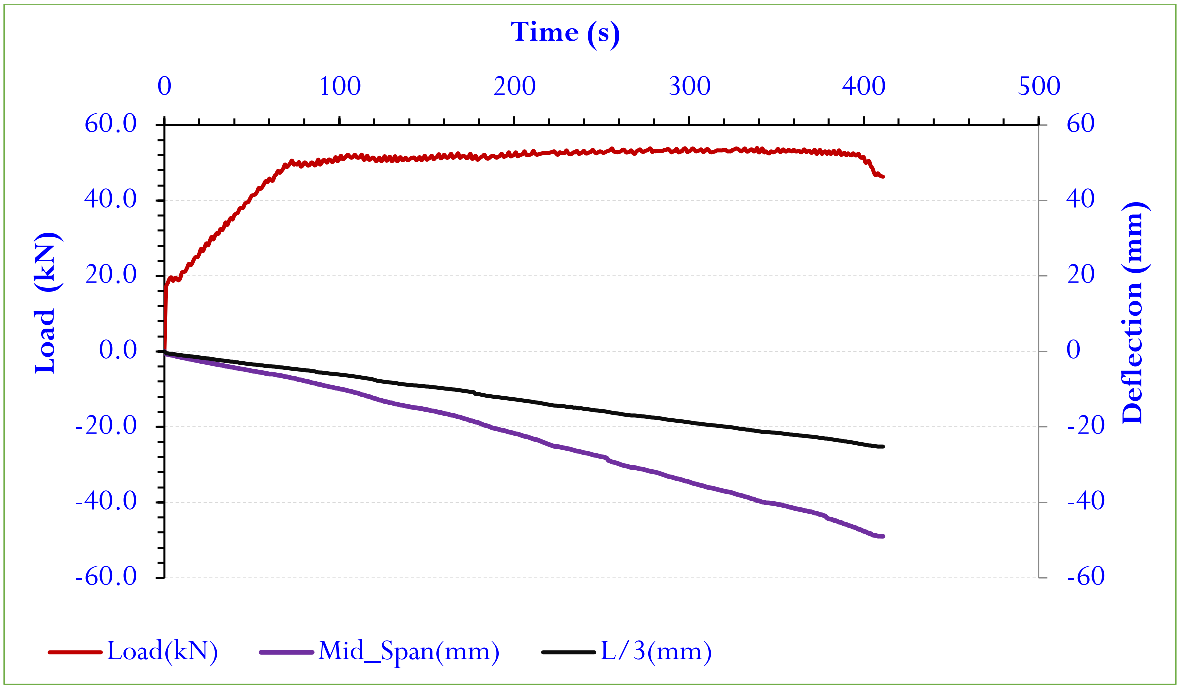


Figure 16. Load vs time vs settlement (RC slab - uncorroded sample)

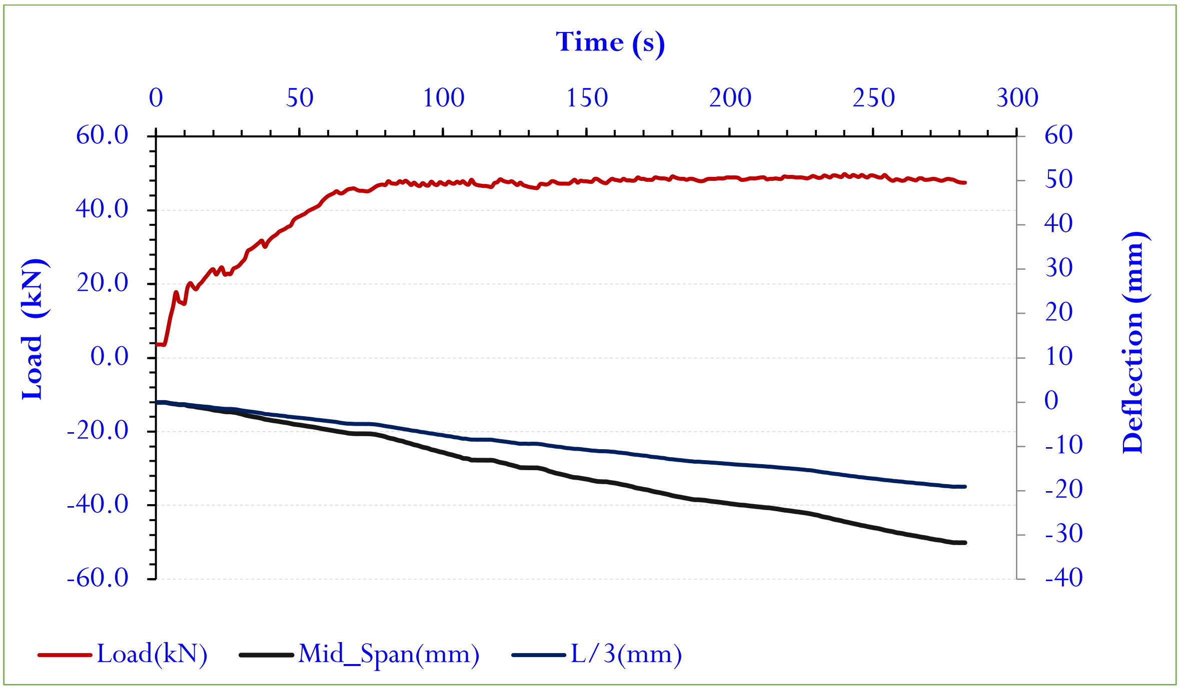


Figure 17. Load vs time vs settlement (RC slab - corroded sample)

According to the crack propagation of the slab under load in the experiment, the corroded RC slabs demonstrates a more brittle failure pattern, an earlier start of settlement, and a smaller load-bearing capacity when compared to the uncorroded slabs. As seen in Figures 16 and 17, the impacts of

ISSN 3047-5473
Innovation in Engineering, Vol. 2, No. 1, 2025, pp. 57-72

corrosion reduce the flexural strength and increase the significance of RC slabs to deformation under applied loads.

Table 5. Comparison of flexural strength in uncorroded vs. Corroded SFRC samples

Samples	**V_u (kN)**		**δ_{max} (mm)**
	Uncorroded	**Corroded**	
SFRC 1	64		20.76
SFRC 2	63		25.22
Mean SFRC (uncorroded)	**63.5**		22.99
SFRC 3		52	22.95
SFRC 4		50	29.73
Mean SFRC (corroded)		**51**	26.34

Table 6. Comparison of flexural strength in uncorroded vs. corroded RC samples

Samples	**V_u (kN)**		**δ_{max} (mm)**
	Uncorroded	**Corroded**	
RC 1	54		35.18
RC 2	54		42.82
Mean RC (uncorroded)	**54**		39.00
RC 3		48	30.5
RC 4		46	25.08
Mean RC (corroded)		**47**	27.79

Based on the analysis, SFRC slabs showed a 20% decrease in flexural strength and a corrosion impact of 33.5% (corr average), suggesting a severe corrosion-related degradation. The presence of steel fibers in SFRC resulted in a comparatively higher sensitivity to corrosion effects, as shown in Tables 5 and 6, Fig.18 and Fig.19, whereas RC slabs demonstrated a 15% reduction in strength with a corrosion impact of 24.5% (corr avg).

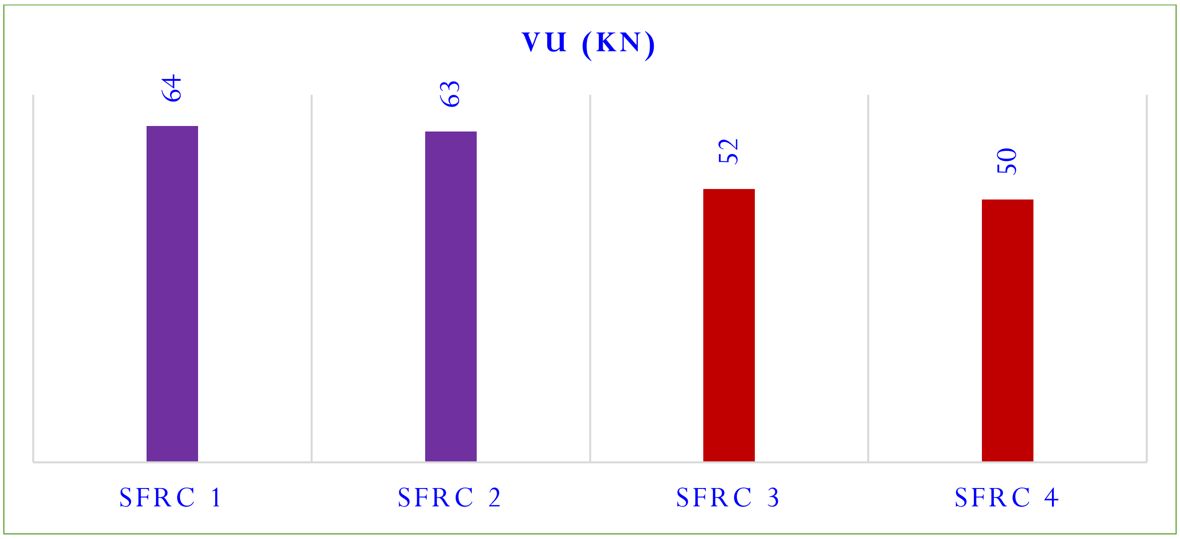


Figure 18. Comparison of flexural strength in uncorroded vs. corroded SFRC samples

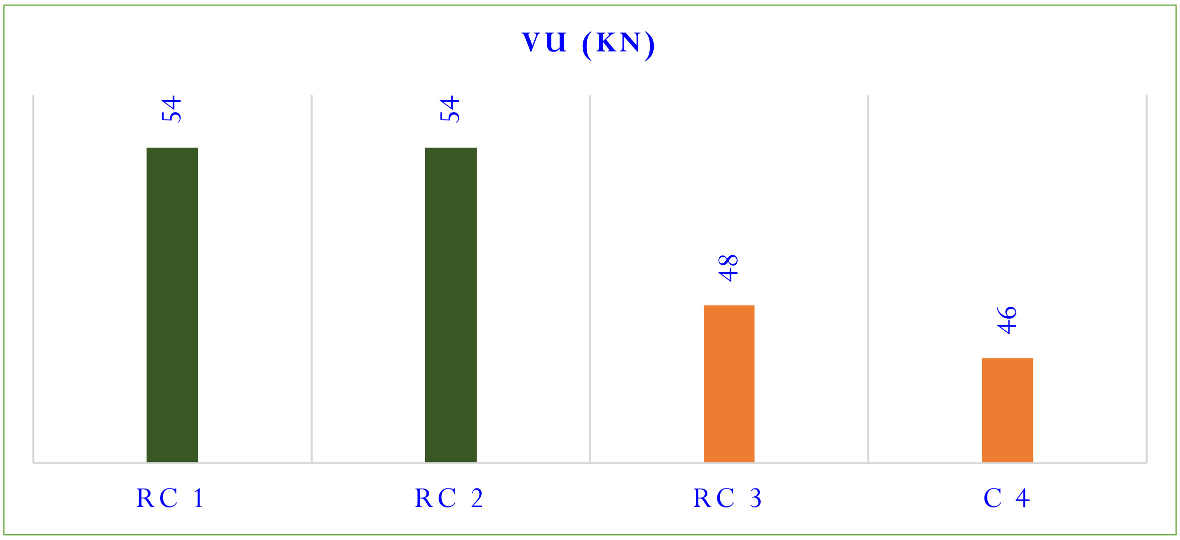


Figure 19 . Comparison of flexural strength in uncorroded vs. corroded RC samples

From Figure10, it can be seen that corrosion levels continued to rise during the testing period, according to the Cor-Map results. Corrosion rates increased rapidly during the first 90 days and climbed steadily in both types of slabs thereafter. The highest corrosion rate was observed in SFRC 3 (34%), followed by SFRC 4 (33%), RC 4 (26%), and RC 3 (23%) at the end of 240 days. The mean corrosion levels varied, with steel fiber-reinforced concrete slabs showing an average of 33.5%, while conventional reinforced concrete slabs showed an average rate of 24.5%. Therefore, conventional RC slabs demonstrated a slower corrosion rate than SFRC slabs before 240 days.

According to the research of [18], adding 1% steel fiber increased the reinforced concrete beam flexural load test by about 11%. In this research, steel fiber-reinforced concrete slabs failed at a mean load of 63.5 kN, demonstrating higher flexural strength than conventional reinforced concrete slabs, which failed at 54 kN, as shown in Tables 5 and 6 for the uncorroded case. From the results of experimental flexural testing, the flexural strength increases by about 15% in the reinforced concrete slab, and it is shown that the effectiveness of steel fiber for flexural strength on the RC slab is more prominent than on the RC beam. The cracks in SFRC slabs also showed numerous cracks with smaller widths than conventional RC slabs. This is due to the expansion of microcracks and the uniform distribution of steel fibers, which enhance crack control and increase the resistance of SFRC slabs.

After accelerated corrosion, the mean failure load of conventional reinforced concrete slabs was 47 kN, and its flexural strength reduction was about 15% due to its corrosion of 24.5%. The result accords with reasonable findings; according to researcher [17], state that when corrosion levels reach 15%, the residual strength of reinforced concrete beams decreases by 10% . The mean failure load of steel fiber-reinforced concrete slabs in flexural testing was reduced to 51 kN after accelerated corrosion. The research revealed that a corrosion rate of 33.5% affects the strength of steel fiber-reinforced concrete slabs reduced by 20%. The studies of [20] showed that severe corrosion can reduce residual strength by 20%. Therefore, the indicated corrosion percentage determined by the the half-cell potential method can effectively estimate the strength reduction of corroded steel fiber-reinforced concrete slab as non-disturbed test.

In comparison of strength reduction in conventional RC slabs and steel fiber-reinforced concrete slabs due to corrosion, strength reduction in steel fiber-reinforced concrete slabs is 20% higher than observed in conventional reinforced concrete slabs, with a 15% reduction. Although the corrosion rate in the SFRC slab was higher due to the steel fibers, which distributed throughout the concrete matrix at a volume of 1%, it showed no obvious impact on the main reinforcement bars. Despite a larger decrease in strength due to corrosion, the SFRC slab exhibited more strength than conventional RC slabs.

4. Conclusion

According to the results of this experimental study, the following facts can be concluded.

(1) Before taking accelerated corrosion, steel fiber-reinforced concrete slabs have higher flexural strength than conventional reinforced concrete slabs. It showed numerous cracks with small widths due to the expansion of microcracks and the uniform distribution of steel fibers.

(2) The corrosion level from Cor-Map data can be effectively used to estimate strength reduction for steel fiber-reinforced concrete slabs like conventional reinforced concrete slabs. The corrosion rate of steel fiber-reinforced concrete slabs is higher than that of conventional reinforced concrete slabs till 240 days of accelerated corrosion tests, and it can occur because the steel fibers are distributed throughout the concrete matrix.

(3) In comparison to the reduction in flexural strength of concrete slabs with and without steel fiber reinforcement under accelerated corrosive effects of 240 days, the reduction of flexural strength in SFRC slabs is greater than that of conventional reinforced concrete slabs. Despite higher corrosion levels of Cor-Map results in SFRC slabs, the main reinforcement bars were not significantly affected, and the residual flexural strength is still higher in SFRC slabs.

The findings from this experimental research provided a valuable reference for assessing the residual capacities of existing reinforced concrete structures affected after corrosion. Future research should additionally consider other factors such as concrete strength and slab thickness. Greater corrosion levels should also be investigated further to understand their impact on flexural strength.

Author's declaration

Author contribution

Hnin Hnin Kyu: Conceptualization, Methodology, Experimentally Investigated, Writing the manuscript reviewing and editing. **Khin Su Su Htwe**: Conceptualization, Methodology, Project management, Supervision, Reviewing.

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Conflict of interest

The authors declare no conflict of interest in this research and publication.

Ethical clearance

This research does not involve human as subjects.

AI statements

This article is my original work and was prepared without using AI tools for writing sentences or creating/editing tables and figures in this manuscript.

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