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EVALUATE THE INFLUENCE OF CONCRETE STRENGTH ON THE LEVEL OF CORROSION OF STEEL REINFORCEMENT IN REINFORCED CONCRETE BEAM STRUCTURES, TAKING INTO ACCOUNT THE APPLIED LOAD

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Abstract: In coastal areas, transportation infrastructure using reinforced concrete beam structures always works in environmental conditions with high corrosive agents, under the effect of load, the level of corrosion of steel reinforcement in the structure is high. The beam condition becomes more severe, which leads to a decrease in the beam's bending resistance. The level of corrosion of steel reinforcement in reinforced concrete beam structures depends on many influencing factors. These factors need to be seriously researched and evaluated to provide early warning results for designer, construction worker, operater for exploit the project safely and effectively. This article presents the results of research evaluating the influence of concrete strength on the level of corrosion of steel reinforcement in reinforced concrete beam structures, often taking into account the effect of load causing beam bending. Reinforced concrete beam samples were made with concrete at different strength levels: C30, C40 and C50 MPa; Then it was loaded with a yoke system with a loading level equivalent to 0.8Pmax of the destructive strength of the concrete sample. After the yokes were loaded, the beam samples were subjected to accelerated corrosion testing in a highly concentrated salt water environment. concentration equivalent to 3.5% NaCl for a period of 30 days, equivalent to an actual exploitation time of about 35 years. The corrosion rate of steel reinforcement is increased by supplying direct current to create an electrolytic corrosion environment, ensuring that the steel bars are corroded equivalent to the estimated calculated time. Beam samples after accelerated corrosion testing were evaluated for damage in terms of reinforcement volume.

Keywords: Concrete strength, reinforced concrete structure, steel corrosion level, applied load

ОЦЕНКА ВЛИЯНИЯ ПРОЧНОСТИ БЕТОНА НА УРОВЕНЬ КОРРОЗИИ СТАЛЬНОЙ АРМАТУРЫ В ЖЕЛЕЗОБЕТОННЫХ БАЛОЧНЫХ КОНСТРУКЦИЯХ С УЧЕТОМ ПРИЛОЖЕННОЙ НАГРУЗКИ

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Аннотация: В прибрежных районах транспортная инфраструктура с применением железобетонных балочных конструкций всегда работает в условиях окружающей среды с повышенным содержанием агрессивных агентов, под действием нагрузки уровень коррозии стальной арматуры в конструкции увеличивается. Состояние балочных элементов становится более тяжелым, что приводит к снижению их сопротивления изгибу. Уровень коррозии стальной арматуры в железобетонных балочных конструкциях зависит от многих влияющих факторов. Эти факторы необходимо серьезно изучать и оценивать с целью раннего предупреждения для строителей, проектировщиков и операторов для обеспечения безопасной и эффективной эксплуатации проекта. В статье представлены результаты исследований по оценке влияния прочности бетона на уровень коррозии стальной арматуры железобетонных балочных конструкций с учетом влияния нагрузки, вызывающей изгиб балочных элементов. Образцы железобетонных балок изготавливались из бетона разной прочности: С30, С40 и С50 МПа; затем его нагружали с использованием системы хомутов с уровнем нагрузки, эквивалентным 0,8Pmax разрушающей прочности образца бетона. После нагружения образцы балочных элементов в течение 30 дней были подвергнуты ускоренным испытаниям на коррозию в водной среде с высокой концентрацией соли, эквивалентной 3,5% NaCl, что соответствует фактическому сроку эксплуатации около 35 лет. Скорость коррозии стальной арматуры увеличивается за счет подачи постоянного тока для создания среды электролитической коррозии, обеспечивающей коррозию стальных стержней в течение расчетного времени. Образцы балок после ускоренных коррозионных испытаний оценивались на предмет повреждений по объему армирования.

Ключевые слова: Прочность бетона, железобетонная конструкция, уровень коррозии стали, приложенная нагрузка.

1. INTRODUCTION

The influence of the level of reinforcement corrosion on the behavior of reinforced concrete structures is an issue of great research interest in the world [1-23]. Because this is the basis for evaluating the load-bearing capacity of corroded reinforced concrete constructions in strongly aggressive environments such as sea areas and polluted areas.

With steel reinforcement used in reinforced concrete structures, the level of corrosion of the steel reinforcement is greatly influenced by the behavioral state and material structure of the protective concrete layer. When the reinforcement is still surrounded by solid protective layers of concrete, the alkaline environment in the concrete is high enough to create a protective film for the reinforcement. If this protective film is destroyed, the steel reinforcement will corrode [6,7,8,11,12,22,23]. One of the important reasons why the passive membrane is destroyed is the penetration of chloride ions from the outside environment into the position of the reinforcement. Micro cracks that appear in the protective concrete layer will facilitate chloride ions to penetrate faster, putting the structure at risk of corrosion sooner than expected [10,11,14,16]. Different types of reinforced concrete structures are also studied, in order to find differences in the design of reinforced concrete structures. In 2016, a group of authors from Cairo University, Egypt published research results on the difference between the corrosion process of steel reinforcement on prestressed reinforced concrete beams and this process on reinforced concrete. Traditional steel, Behavior of corroded bonded fully prestressed and conventional concrete beams; Research results have shown that the effect of corrosion due to aggressive environments has a strong effect and quickly reduces the bending resistance of conventional reinforced concrete beam structures. This has less impact on prestressed reinforced concrete beam structures under the same experimental environmental conditions. The team also pointed out that the reason why prestressed reinforced concrete is less affected is because cracks in the concrete develop less. In addition, high-strength steel is surrounded and protected by concrete mortar and pipe, so it is difficult for corrosive agents to come into contact to promote the corrosion of steel reinforcement [15]. Applying technology in building models to decode the behavior of reinforced concrete structures when the reinforcement is corroded has also been widely deployed in recent times: In 2018, an announcement by a research team from Chalmers University of Technology by using the finite element (FE) model to evaluate the behavior of reinforced concrete beams subject to steel bar corrosion. The research results concluded that the corrosion process changes the load-bearing cross section of the beam. reinforcement, reducing the bond force between concrete and reinforcement, thereby affecting the load-bearing capacity of reinforced concrete beams [17]. In 2020, a research team from the University of Technical Education. Ho Chi Minh City for proposing an algorithm and developing an independent calculation program to evaluate corrosion behavior affecting the bending capacity of reinforced concrete structures [18]. As stated, the material structure is a factor that directly affects the level of corrosion of steel reinforcement in reinforced concrete structures, so the strength of the concrete used to make beams - plays the role of a protective concrete layer. Protection that prevents corrosive agents from coming into contact with the reinforcement is a parameter that needs to be evaluated and analyzed in detail.

This study will clarify the influence of concrete strength on the corrosion level of steel reinforcement in reinforced concrete structures. Reinforced concrete beam samples will be tested for accelerated corrosion with different loading levels before being immersed in a corrosive environment. The corroded beam samples were then evaluated for damage to the steel reinforcement due to corrosion.

The results of this research will contribute to the corrosion analysis of reinforced concrete structures in practice, taking into account the effects of load and environment; is the basis for predicting the lifespan and operating capacity of these structures.

2. EXPERIMENTAL PROGRAM

An experimental procedure was established to collect data to serve the assessment and analysis of the influence of concrete strength for making reinforced concrete beams on the level of corrosion of steel reinforcement in reinforced concrete beam components considering to the effect of load.

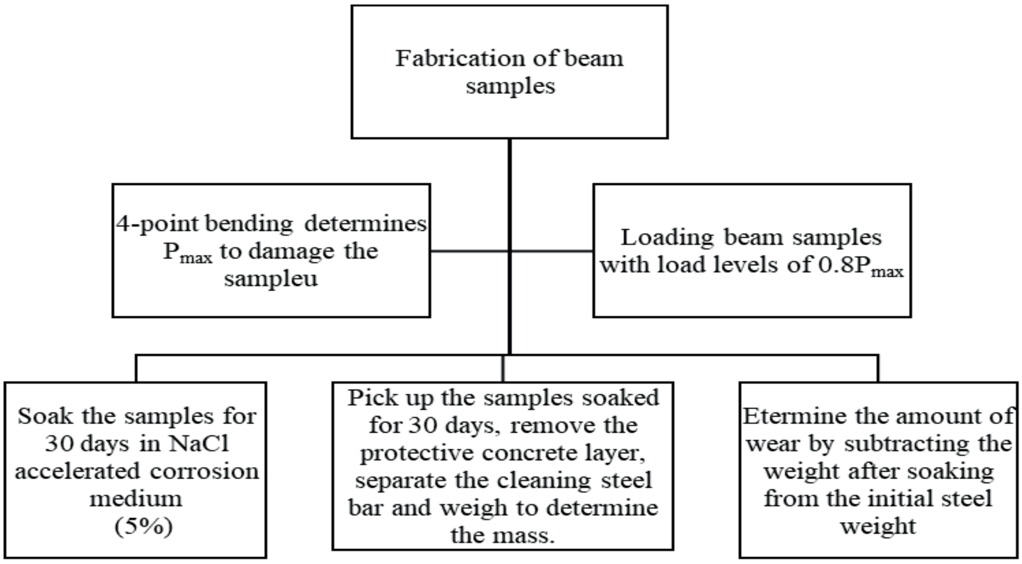

Figure 1. Procedure for performing the experiment

2.1. Materials for making samples

Concrete C30, C40, C50 has an expected compressive strength at 28 days fc' of 30, 40 and 50 MPa, respectively. The mix composition of concrete (mix batch 1m3) is designed according to ACI211.1-91 standard [13].

In there:

fc': Compressive strength of concrete.

C30, 40, 50: Concrete symbols with fc' are: 30, 40, 50 (MPa)

Table 1. Mix composition for 1m3 of concrete

Type of concrete	Material type			
	Stone (Kg)	Sand (Kg)	Cement (Kg)	Water (lit)
C30	1060	848	395	170
C40	1087	625	407	175
C50	1164	773	453,5	195

Average compressive strength of concrete when compressing and testing samples:

Table 2. Average compressive strength of concrete

Type of concrete	P_{max}^{N} (kN)	f'c (MPa)
C30	302,5	38.6
C40	410,6	50,39
C50	525,8	58,32

In there:
f'_c: Compressive strength of the sample
Steel used to make beams: D10, smooth round, f_y = 240 MPa. The steel bars are weighed to determine their weight before making the beam sample.
In there:
D10: Symbol of reinforcement diameter.
f_y: Tensile strength of steel.

2.2. Fabrication of beam samples

The beam samples manufactured for experiments have dimensions of 500x100x100 mm [13, 14, 16]. Quantity of 07 beams. In which: 01 beam determined the bending resistance force P_{max}^{k} of C30, 06 beam samples tested for accelerated corrosion considering the influence of applied load corresponding to 03 concrete levels C30, C40 and C50.

The number of beam samples for each concrete level is made in reserve for the purpose of providing compensation samples when unplanned incidents occur during the testing process.

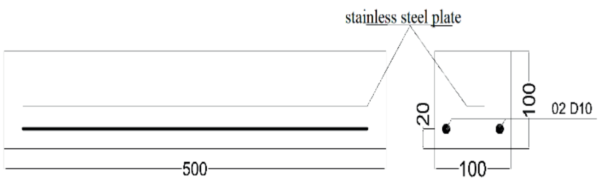

Figure 2. Dimensions and structure of experimental beams

Figure 3. Completed beam sample

2.3. Accelerated corrosion experiment

The corrosive environment is simulated by a concentrated NaCl solution (3,5%) combined with creating an electrode that activates the electrolytic corrosion environment, helping the corrosion process progress faster. The current intensity remains at 0.3A [11, 12, 14]. The corrosion rate of reinforcement is increased by applying electric current, ensuring that the reinforcement is corroded to a maximum of 25% reduction in diameter compared to the original within the expected time.

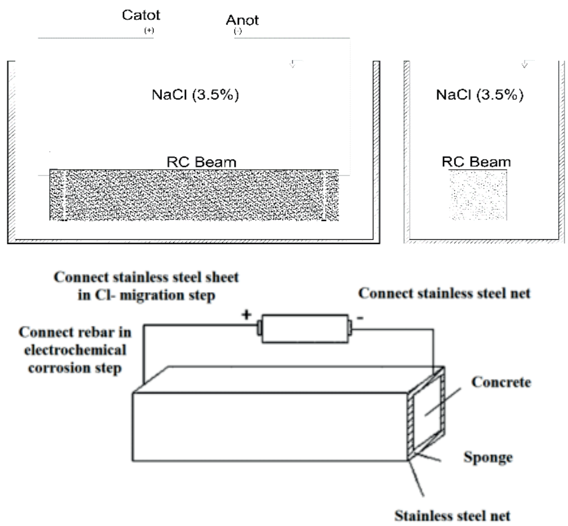

Figure 4. Description of Electrode Corrosion Equipment

After being manufactured for 28 days, beam samples will be loaded in pairs - 2 beams with a load level of $0.8P_{max}$ of sample C30 and immersed in an accelerated corrosive environment.

Figure 4. Loading beams for beam samples

The duration of the accelerated corrosion immersion test is specifically calculated based on the theory of corrosion of steel reinforcement in reinforced concrete structures.

The volume of steel consumed is related to the magnitude of current in electrochemical corrosion cells. Using Faraday's law to describe the mass loss of steel due to corrosion:

$$M_{loss} = \frac{MI_{corr}}{zF} t \qquad (1)$$

In there:

- M_{loss} is the loss of consumed steel volume (g);
- M is the atomic mass of Fe ion, M = 56 g/mol;
- z is the valence of Fe,
- F is Faraday's constant, F = 96,500 C/mol
- t is the corrosion time in seconds (s).

Corrosion current density i_{corr} is defined as the corrosion current per unit steel surface. If the length unit L_0= 1 cm and the diameter unit d is mm, a relationship between I_{corr} (A) and i_{corr} (μA/cm^2) can be obtained as follows:

$$I_{corr} = 1 \times \pi \frac{d}{10} i_{corr} \times 10^{-6} = 10^{-7} \pi d i_{corr} \qquad (2)$$

The percentage loss of reinforcement mass is ρ, we have the mass loss of reinforcement as:

$$M_{loss} = \rho M_s \qquad (3)$$

With ρ_s=7.85g/cm^3 and L_0=1cm we get:

$$M_{loss} = \rho M_s = \rho \frac{\pi}{4}\left(\frac{d}{10}\right)^2 \rho_s = 0.0616 \rho d^2 \qquad (4)$$

Combining equations (1), (4), with z = 2.5 (average value for Fe^{2+} and Fe^{3+}), the corrosion time t in years is related to ρ and icorr (μA/cm^2) as after:

$$t = \frac{zFM_{loss}}{MI_{corr}} = \frac{2.5 \times 96500 \times 0.0616 \rho d^2}{56 \times \pi d i_{corr} \times 10^{-7} \times 3600 \times 24 \times 365} = 26.799 \frac{\rho d}{i_{corr}} \qquad (5)$$

Liu and Weyers (1998) [12] proposed the following corrosion rate:

$$i_{cor} = 0.926 \exp\left[7.98 + 0.7771 \ln\left(1.69 C_t\right) - \frac{3006}{T} - 0.000116 R_c + 2.24 t^{-0.215}\right] \qquad (6)$$

In there:

- i_{cor} is the corrosion rate (μA/cm^2);
- C_t is the total chloride content at the depth of the steel surface (kg/m^3 of concrete);
- T is the ambient temperature (K);
- R_c is the ohmic resistance of the concrete cover layer (Ω);
- t is the time since the start of corrosion (years);

Liu (1996) [11] established the regression relationship between the ohmic resistance of concrete Rc and the total chloride content for field exposed samples as follows:

$$R_c = \exp\left[8.03 - 0.549 \ln\left(1 + 1.69 C_t\right)\right] \qquad (7)$$

Lopez et al [10] studied the relationships between concrete resistance R_c and environmental relative humidity (H) based on experimental results. They give the following relationship:

$$R_c = 90.357 H^{-7.2548} \left[1 + \exp(5 - 50(1 - H)\right] \qquad (8)$$

In equation (6), C_t total chloride content will change over time, C_t is based on Fick's second law of diffusion (considering the initial chloride concentration of concrete to be 0) as follows:

$$C(c,t) = \left\{ C_s \left(1 - erf \frac{c}{2\sqrt{Dt}}\right)\right\} \times \frac{1}{100} \times \gamma_c \qquad (9)$$

In there:

D - chloride diffusion coefficient in concrete;

C_s - chloride concentration on concrete surface;

c - Depth of the concrete layer protecting the steel bar;

t - time ($t = t_l + \Delta t$);
γ_c - the density of concrete.
The results of calculation and processing have determined the time for soaking beam samples in an accelerated corrosive environment with the aim of creating a corrosion process for the reinforcement sample reaching about 25% of the initial reinforcement volume in a specific time. Soak the sample for 30 consecutive days. During the accelerated corrosion immersion period, if an interruption occurs, the sample will be soaked for a corresponding period of time.

Figure 5. Girder specimen in corrosive environment

After soaking the beam samples for 30 days, they will be salvaged, the protective concrete layer will be removed, the steel bars will be removed and the surrounding steel rust and concrete adhering to the bars will be cleaned and then weighed to determine mass.

Figure 6. Sample after immersion in accelerated corrosive environment

Figure 7. Steel reinforcement is corroded after removing the concrete layer

Figure 8. Weigh the reinforcement sample to determine the level of corrosion

3. RESULTS AND DISCUSSION

The mass of steel consumed by corrosion in the accelerated corrosion test is calculated by the difference in mass between the steel types before and after the accelerated corrosion test. In fact, the corroded steel reinforcement is not balanced between sections. In this experiment, iron ore can be pre-formed by loading, so the mid-span position is considered as a representative disclosure in the steel corrosion price war. These data are set up in tables to conduct analysis and evaluation.

Table 3. Weight of corroded steel reinforcement

Sample symbol	Initial volume of reinforcement M_s (g)	Amount of corroded steel reinforcement M_{loss}(g)	Corrosion level of steel reinforcement ρ (%)
C30	560	141.5	25.2
C40	572	134,4	23,5
C50	568	130,07	22,9

A relationship chart between the strength of concrete for making reinforced concrete beams and the level of corrosion of steel reinforcement due to the influence of an environment containing chloride ions is built on experimental results of corroded beams in a corrosive environment move fast.

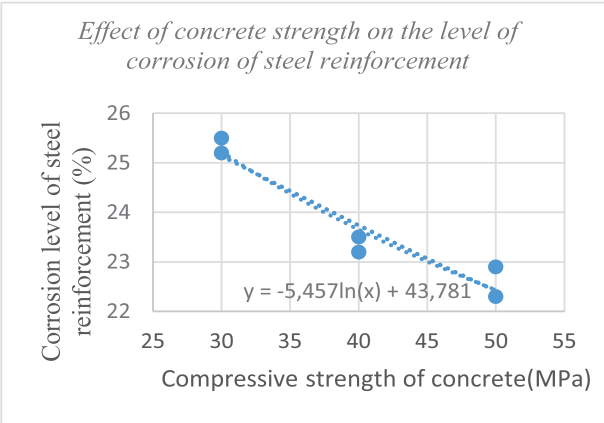

Figure 9. Effect of concrete strength on the level of corrosion of steel reinforcement after 35 years

Through the results of accelerated corrosion testing (same soaking time) of reinforced concrete beam samples with different strengths, loaded with the same load level of $0.8P_{max}$ of sample C30, we see: Corrosion level Reinforcement in reinforced concrete bridge beam components is inversely proportional to the strength of concrete used to make the beam. When concrete strength increases, the level of corrosion of reinforcement decreases specifically at 25% for C30 concrete and approximately 23.5% for C40 concrete and 23% for C50 concrete (same working conditions).
The slow decrease in the level of corrosion of reinforcement in beam samples with increasing strength is because the tensile strength of concrete increases slowly with the grade of concrete, so increasing the tensile capacity of concrete protects the position. The grain under the beam at the mid-span shear eye is insignificant, thereby having little impact on the ability of concrete to prevent crack development at the tensile grain of the beam.

4. CONCLUDE

The influence of concrete strength is significant on the level of corrosion of steel reinforcement in bending reinforced concrete beam structures, especially when reinforced concrete beams work in environments containing chloride ion corrosive agents;
The level of corrosion of steel reinforcement in reinforced concrete beam structures, taking into account the effect of load, is affected by many factors: thickness of protective concrete layer, temperature, humidity, ..., so it is necessary to present detailed evaluation studies with full parameters affecting the above process.

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