Analysis of Reinforced Concrete Durability Against Corrosion Due to Chloride Penetration

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Abstract

Corrosion in reinforced concrete is a serious problem in the construction industry as it can reduce the strength and service life of concrete. Chloride penetration has been identified as one of the main causes of corrosion in reinforced concrete. Therefore, in this study, an analysis of the resistance of reinforced concrete to corrosion due to chloride penetration was conducted. The testing method included varying the concentration of chloride in seawater and testing the compressive strength of reinforced concrete after exposure to chloride for a certain period of time. The results showed that the higher the concentration of chloride, the faster the corrosion occurred and the lower the compressive strength of reinforced concrete. Therefore, prevention efforts are needed by using additives such as corrosion inhibitors or reducing the chloride content in the concrete mix to increase the resistance of reinforced concrete to corrosion due to chloride penetration. From the test results, the use of 5% silica fume by weight of concrete increased the compressive strength of concrete by 13% and reduced the rate of chloride penetration by 30%, as assessed from the chloride ion penetrability value.

Keywords: concrete, durability, structure, chloride, diffusion

Abstrak

Korosi pada beton bertulang adalah masalah serius dalam industri konstruksi karena dapat mengurangi kekuatan struktur dan umur pakai beton. Penetrasi klorida telah diidentifikasi sebagai salah satu penyebab utama korosi pada beton bertulang. Oleh karena itu, dalam penelitian ini, dilakukan analisis ketahanan beton bertulang terhadap korosi akibat penetrasi klorida. Metode pengujian meliputi uji variasi kadar klorida pada air laut dan pengujian kekuatan tekan beton bertulang yang diuji setelah terpapar klorida selama beberapa waktu. Hasil penelitian menunjukkan bahwa semakin tinggi konsentrasi klorida, semakin cepat terjadinya korosi dan semakin menurunnya kekuatan tekan beton bertulang. Oleh karena itu, diperlukan upaya pencegahan dengan cara penggunaan bahan tambahan seperti inhibitor korosi atau pengurangan kadar klorida pada campuran beton untuk meningkatkan ketahanan beton bertulang terhadap korosi akibat penetrasi klorida. Dari hasil pengujian, penggunaan bahan tambah silica fume sebesar 5% dari berat jenis beton meningkatkan kuat tekan beton sebesar 13% dan menurunkan laju penetrasi klorida sebsar 21%, ditinjau dari nilai *chloride ion penetrability*.

Kata kunci: beton, durabilitas, struktur, klorida, difusi

BACKGROUND

The use of reinforced concrete as the main material in building construction, bridges, and other infrastructure has become a popular choice in the construction industry. However, despite its high strength and durability, reinforced concrete can experience damage and corrosion due to harsh environmental conditions. One of the main factors that trigger corrosion in reinforced concrete is chloride penetration, especially in areas near the coast or those exposed to environments that contains rich in chloride. (Ghewa, 2022).

Corrosion in reinforced concrete can cause a decrease in structural strength and shorten the service life of concrete. Therefore, efforts are needed to improve the durability of reinforced concrete against corrosion due to chloride penetration. Common methods used to improve the durability of reinforced concrete include the use of additional materials such as corrosion inhibitors and reducing the chloride content in the concrete mix (Zhang, 2020)

In this study, an analysis of the durability of reinforced concrete against corrosion due to chloride penetration was conducted. Reinforced concrete will be added with 5% of silica fume based on the weight of cement used. The purpose of adding silica fume to concrete is to improve the quality of concrete based on previous studies. Several studies have shown that the use of silica fume in concrete mixtures can increase the compressive strength of concrete, durability against corrosion and chloride penetration, as well as reduce the porosity of concrete (Ghewa, 2022). In addition, the use of silica fume in concrete mixtures can also improve the adhesive ability and fluidity of the concrete mixture, resulting in more homogeneous and higher quality concrete. Another objective of adding silica fume is to reduce the cost of maintenance and repair of concrete in the future by increasing the service life of concrete. In some cases, the addition of silica fume to concrete can also help reduce the environmental impact of the silicon and ferrosilicon industries by utilizing by-products from these industries (Choudhary, 2021)

The testing methods include testing the chloride ion penetrability obtained by measuring the rate of electric current flowing through the concrete body, and testing the compressive strength of reinforced concrete after being exposed to chloride for a certain period of time. The results of this study are expected to provide useful information for the construction industry in strengthening reinforced concrete structures and extending their service life. Furthermore, this study is also expected to improve understanding of the factors influencing the durability of reinforced concrete against corrosion due to chloride penetration, and can serve as a basis for further research in this field. The problem that occurred is the pier structure experiencing severe spalling, until the reinforcement is exposed.

THEORITICAL BASIS

1. Reinforced Concrete

Reinforced concrete is a construction material consisting of a mixture of cement, water, and coarse aggregate reinforced with steel reinforcement. The steel reinforcement serves to increase the strength and stiffness of the concrete structure, allowing it to withstand the load it is subjected to. However, steel reinforcement can experience corrosion due to exposure to a harsh environment, especially in areas near the sea (Susanto, 2019).

Corrosion on reinforcing steel can accelerate the deterioration process of reinforced concrete, which ultimately reduces the strength of the structure and shortens its service life. Aggressive corrosion environments such as coastal areas or areas exposed to chloride-rich environments can accelerate the corrosion process on the reinforcing steel of concrete. This occurs because the chloride present in the environment can damage the protective layer on the reinforcing steel, making it vulnerable to corrosion. To address the problem of corrosion on reinforcing steel in concrete, many methods can be used, such as using corrosion inhibitors and reducing the chloride content in the concrete mix. One commonly used method is to add supplementary materials such as silica fume to the concrete mix. Silica fume can increase the compressive strength of concrete, resistance to corrosion and chloride penetration (Zhao, 2014).

2. Corrosion in Reinforced Concrete

Corrosion in reinforced concrete occurs when the reinforcing steel oxidizes due to a chemical reaction between the metal, oxygen, and water. This occurs in environments where the concrete contains high levels of chloride, especially in areas near the sea. Corrosion of the reinforcing steel can cause a reduction in the strength of the concrete structure and shorten its service life. Corrosion can occur under certain environmental conditions, where the reinforcing steel is exposed to a sufficiently humid environment and high levels of chloride. Chloride is one of the chemical substances that can cause corrosion in reinforced steel concrete (Gupta, 2021).

Chloride can come from various sources such as seawater, groundwater, additives in concrete mixtures, and so on. The chloride content in the concrete environment must be controlled to prevent it from being too high, thus reducing the risk of corrosion on the reinforcing steel. If it is not controlled, chloride penetration into reinforced concrete will accelerate the corrosion of the reinforcing steel and shorten the service life of the concrete (Gupta, 2021).

The corrosion reaction on the reinforcing steel can cause a decrease in the strength of the concrete structure and shorten its service life. The decrease in strength of the concrete structure can have a negative impact on the safety of the building's users. Therefore, good maintenance and supervision of reinforced concrete are crucial to maintaining the safety and durability of the building structure.

Several ideas can be taken to prevent the occurrence of corrosion in reinforced concrete, such as selecting high-quality additives, reducing chloride levels in the concrete environment, and regularly maintaining reinforced concrete. In addition, the use of more advanced technologies, such as reinforced concrete with protective layers on steel reinforcement, can help reduce the risk of corrosion on steel reinforcement and extend the life of concrete. Furthermore, good planning in the design of reinforced concrete structures, including the selection of suitable locations and surrounding environmental conditions, is necessary to avoid the risk of corrosion on steel reinforcement. All of these efforts must be carried out regularly and systematically to maintain the safety and durability of reinforced concrete building structures (Ghoddousi, 2022).

3. Silica Fume

Silica fume or also known as microsilica, is a byproduct of the silicon and ferrosilicon industry. Microsilica is a highly reactive material and has very fine particles, about 100 times smaller than cement particles. Microsilica is produced from the high-temperature reduction process of raw materials such as silicon oxide and carbon, and consists of particles mainly composed of amorphous silica that is very fine and porous. Microsilica is often used as an additive in concrete mixtures because of its unique properties, such as the ability to increase strength and resistance to corrosion and chloride penetration. In addition, the use of microsilica in concrete mixtures can also improve the bonding strength and fluidity of the concrete mixture, resulting in stronger and more durable concrete. However, the use of microsilica also has some limitations, such as higher costs and difficulties in adjusting the mixing time. Therefore, the use of microsilica in concrete mixtures should be carefully considered depending on the specific conditions and needs of the construction project (Sasanipour, 2021)

4. Chloride Penetration in Concrete

Chloride penetration in reinforced concrete is the process of chloride ions entering the pores of concrete and reaching the reinforcing steel within it. Chlorides can originate from seawater, soil, or additives in concrete mixtures. Chloride penetration in reinforced concrete will accelerate corrosion of the reinforcing steel and shorten the service life of the concrete. The process of chloride penetration in reinforced concrete is very dangerous because it can cause corrosion of the reinforcing steel inside the concrete. Corrosion of the reinforcing steel can cause concrete to lose its strength, even to the point where it can no longer be used. This is very dangerous, especially if reinforced concrete is used for structures that have heavy loads or are long-lasting (Gupta, 2021)

Corrosion in reinforced concrete can occur due to the presence of chloride dissolved in the water within the concrete pores. These dissolved chlorides can inhibit the formation of an oxide layer that protects the reinforcement steel from corrosion. As a result, the reinforcement steel will corrode, and the concrete will lose its strength.

Commonly, the level of chloride penetration in reinforced concrete depends on various factors, such as the properties of the concrete, the amount of chloride contained in the additives or the environment, and other environmental factors such as humidity, temperature, and so on. Therefore, to prevent corrosion of the reinforcing steel inside the concrete, various preventive measures need to be taken, such as the use of high-quality additives, the selection of the appropriate type of concrete, and regular maintenance of the structure. If no preventive measures are taken, chloride penetration into reinforced concrete will accelerate corrosion of the reinforcing steel and shorten the service life of the concrete. Therefore, routine maintenance and strict supervision of reinforced concrete are necessary to ensure the structure can withstand long-term use safely (Ghewa, 2022).

METHOD

The research methodology used in this study is based on ASTM Rapid Chloride Penetration Test 1202-12 and concrete compressive strength based on ASTM C-39. The mix design used can be seen in table 1. The use of silica fume in concrete is done gradually to obtain results with a standard deviation that is not too large between one composition and another. The increment used for the addition of silica fume is 1% by weight of cement, with a maximum value of 5% of the weight of cement. The use of silica fume in concrete is not directly in large quantities but little by little because silica fume has a significant thickening effect on the concrete mixture. If the amount of silica fume added is too much in one mixing, the concrete mixture can become too thick and difficult to mix. In addition, silica fume also has very high reactivity, so if added in large quantities directly, it can cause excessive reactions in the concrete mixture. This can result in damage to the concrete structure because concrete that hardens too quickly will have less desirable properties. By adding silica fume little by little in several mixing stages, the thickening effect can be avoided and the reactivity of silica fume can be effectively utilized. In this case, silica fume can work optimally in improving the strength and durability of concrete. Therefore, the addition of silica fume to concrete should be done gradually and in accordance with the recommendations of the manufacturer or experienced technical consultants to ensure that the amount added is appropriate and safe to use.

The first test conducted in this research is the compressive strength test. The compressive strength test is conducted to examine the mechanical properties of concrete. Compressive strength is an indicator of whether concrete has good performance or not. In some empirical approaches, the compressive strength of concrete is often used as a reference to calculate the modulus of elasticity, flexural strength of concrete, and as input for structural calculations. The compressive strength test of concrete is conducted based on the ASTM C-39 guidelines. The method is to test concrete that has aged for 28 days using a concrete compression testing machine. The output of the compressive strength test is the compressive force in Newton units. This compressive force is then divided by the surface area of the concrete, resulting in compressive strength in MPa units. This description can be simplified into equation (1).

$$fc' = P/A \qquad (1)$$

P is the compressive force applied to the surface of the concrete (Newtons) and A is the surface area of the test sample (mm2). After the concrete compressive strength test, the Rapid Chloride Penetration Test is performed. This test aims to evaluate the resistance of reinforced concrete with added material, namely silica fume, to corrosion caused by chloride penetration, using the method from ASTM Rapid Chloride Penetration Test 1202-12.

This testing method is used to measure the resistance of concrete to chloride penetration by measuring the amount of electric current that can flow through the concrete body for 6 hours. Electric current can flow through a medium due to the presence of positive and negative ions.

The use of chloride will increase the concentration of negative ions in the concrete, and NaOH solution will become positive ions in the concrete. The larger the electric current that flows through the concrete body, the greater the indication of chloride penetration. The criteria for evaluating the results of the Rapid Chloride Penetration Test can be seen in Table 2. The value of charge passed is denoted by the symbol Q, which is an indicator to determine whether the chloride penetration in the concrete body is high or low.

TABLE 1.
CRITERIA FOR RAPID CHLORIDE PENETRATION TEST RESULTS

Charge Passed	***Chloride Ion Penetrability***
>4000	*High*
2000-4000	*Moderate*
1000-2000	*Low*
100-1000	*Very Low*
<100	*Negligible*

Source: ASTM C1202

The value of charge passed is expressed in Coulombs (C). The calculation of the value of Q can be seen in equation 2.

$$Q=900(I0+2I30+2I60+\cdots+2I300+2I330+I360) \quad (2)$$

Where I is the current strength at 0 minutes, 30 minutes, 60 minutes, and so on until the current strength at minute 360. The testing scheme can be seen in fig. 1.

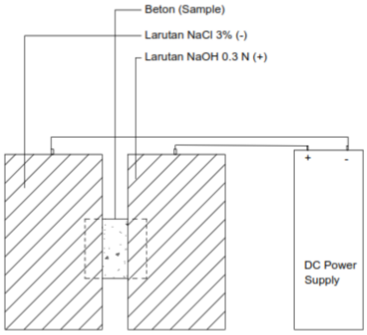

Figure 1. Rapid Chloride Penetrating Test Scheme

This test is conducted by providing a concrete test specimen with an open surface to absorb water, then a constant electric current is applied for 6 hours. The electric current aims to draw chloride ions from the solution into the concrete so that their concentration in the collected water inside the test specimen can be measured.

The results of the RCPT test can be used to evaluate the ability of concrete to protect reinforcing steel from corrosion due to exposure to chloride-containing environments. The NaOH pole will receive a current supply from the positive pole of the power supply, while the NaCl pole will receive a current supply from the negative pole of the power supply. The voltage provided is constant at 60 volts. The specimen used is concrete with a diameter of 95mm ± 5mm, and a specimen thickness of 50mm. The testing scheme can be seen in figure 2.

Figure 2. Rapid Chloride Penetration Testing Procedure

RESULT AND ANALYSIS

In this research, the mix design is varied into 5 variations with different silica fume variations, while the other materials remain in the same proportion (Table 2).

TABLE 2.
CONCRETE SAMPLE MIX DESIGN

Sample Code	Cement(kg/m3)	Fine Aggregate (kg/m3)	Coarse Aggregate (kg/m3)	Water (kg/m3)	Silica Fume (kg/m3)	Number of samples
Normal (N)	450	528	865	180	0	5
S1	450	528	865	180	4,5	5
S2	450	528	865	180	9	5
S3	450	528	865	180	13,5	5
S4	450	528	865	180	18	5
S5	450	528	865	180	22,5	5

The study was conducted by making concrete samples, then treated for 28 days. After 28 days, the concrete was then dried in an oven for 48 hours and ready to be tested. The first test carried out was the compressive strength test of concrete. The compressive strength of concrete was tested using cylindrical samples with a diameter of 10cm and a height of 20cm. Each sample code had 5 test objects. The sample without silica fume was coded as N. After the compressive strength test was carried out at the age of 28 days, the results were averaged to obtain the average compressive strength test results for each composition. The average compressive strength test results can be seen in table 3.

TABLE 3.
CONCRETE'S COMPRESSIVE STRENGTH

Sample Code	Average Compressive Strength (Fc')
N	33.13
S1	34.19
S2	35.21
S3	35.33
S4	36.12
S5	37.53

Based on the compressive strength test results, it can be seen that the compressive strength produced by the test samples with codes S2, S3, S4, and S5 meet the researcher's target of 35 MPa, while the compressive strength test results on the sample without silica fume and with the addition of 1% silica fume from the weight of cement have values slightly below the target. This is in line with the theory that silica fume is an additive in concrete mixtures that can increase the strength of concrete. The addition of silica fume can fill the pores in the concrete, thereby reducing gaps and cracks in the concrete. In addition, silica fume can also accelerate the hydration reaction in concrete mixtures if added in the appropriate composition, so that the concrete can harden more quickly [1]. If we look at the chemical reaction, the increase in compressive strength of concrete resulting from the addition of silica fume to reinforced concrete mixtures occurs through two stages of chemical reactions. In the initial stage, silica fume reacts with calcium hydroxide ($Ca(OH)2$) produced from cement hydration ($CaO.SiO2.4H2O$) to form silica gel ($SiO2.nH2O$) and produce calcium silicate hydrate (C-S-H), which is the main product of cement hydration. The formed silica gel will then fill the pores in the concrete and increase the density of the concrete, thereby increasing the compressive strength of the concrete. In the final stage, silica fume will react with calcium hydroxide and C-S-H that did not react in the initial stage to form more silica gel, thus further filling the pores in the concrete and increasing the compressive strength of the concrete. The chemical reaction that occurs in the final stage can be represented as follows: $3Ca(OH)2 + 2SiO2 \rightarrow C3S2H3 + 3H2O$. Therefore, the addition of silica fume to reinforced concrete mixtures can increase the compressive strength of concrete by filling the pores in the concrete with silica gel and producing more C-S-H (Davendra, 2022).

On the other hand, the results of the compressive strength test on the sample without silica fume showed a slightly lower value than the target. This indicates that without the addition of silica fume, reinforced concrete has suboptimal strength and requires improvement in material composition (Das, 2020). When concrete does not use silica fume, the micro pores in the concrete tend to not be filled properly, causing a decrease in concrete density and compressive strength. Moreover, when the pores in the concrete are not filled properly, the ability of concrete to resist chloride penetration will decrease, thereby increasing the risk of corrosion on the reinforcing steel and shortening the service life of the concrete. Therefore, the addition of silica fume in the composition of reinforced concrete can be an alternative to improve the strength of concrete and overall quality of concrete.

The next test is the Rapid Chloride Penetration Test. After conducting the compressive strength test on each concrete composition, the concrete underwent further testing for 6 hours to observe the depth of chloride ion penetration into the concrete. These tests were conducted in a closed room to prevent exposure to sunlight, which could potentially interfere with the accuracy of the results by affecting the chemical reactions or conditions within the samples and apparatus. The results of the test can be seen in table 4.

TABLE 4.
RAPID CHLORIDE PENETRATION TEST RESULT

	Current Applied					
Testing Time	**S**	**S1**	**S2**	**S3**	**S4**	**S5**
Io	0,05	0,05	0,05	0,05	0,04	0,04
I30	0,06	0,06	0,06	0,06	0,06	0,04
I60	0,07	0,07	0,07	0,07	0,07	0,05
I90	0,08	0,08	0,07	0,07	0,07	0,05
I120	0,09	0,09	0,07	0,08	0,07	0,05
I150	0,09	0,09	0,08	0,08	0,08	0,06
I180	0,1	0,1	0,08	0,08	0,08	0,07
I210	0,1	0,1	0,09	0,09	0,08	0,08
I240	0,11	0,11	0,09	0,09	0,09	0,08
I270	0,12	0,12	0,1	0,1	0,09	0,09
I300	0,13	0,12	0,11	0,1	0,09	0,09
I330	0,14	0,13	0,12	0,1	0,09	0,09
I360	0,14	0,13	0,13	0,1	0,1	0,1
	2133	2088	1854	1791	1692	1476

From the test results, it can be seen that concrete without silica fume has a high indicator of chloride ion penetrability. This is evidenced by the Qs value being more than 2000. Meanwhile, concrete with the addition of 5% silica fume has a lower indicator of chloride ion penetrability than normal concrete, as it has a Qs value less than 2000, and the best option is concrete with the addition of 5% silica fume. The electrical current flowing through the concrete body is influenced by the conductivity produced by the medium in the form of NaOH and NaCl solutions. To produce electrical conductivity, both of these solutions must enter the concrete body and then the electricity will flow through the ions within the concrete (Zhang, 2020). Therefore, the conductivity of this electrical current is greatly influenced by the density and permeability of concrete, which depends on the amount of pores in the concrete. Silica fume or microsilica has been proven to increase the density of concrete and reduce the pores in concrete. The fine particles of microsilica play an important role in improving the mechanical and physical properties of concrete. When microsilica is added to the concrete mix, its particles can fill the gaps between sand grains and aggregates, thereby increasing its density (Nochaiya, 2022). This makes the concrete more compact and sturdy, improving its compressive strength and resistance to corrosion and chloride penetration. In addition, microsilica can also fill the pores in concrete, which are the entry points for water and chemicals, thereby reducing the risk of damage and extending the life of the concrete. In the mixing process, microsilica particles can help regulate the consistency of the concrete mix, making it easier to pour and producing a smoother concrete surface. Therefore, adding microsilica to the concrete mix is an effective solution for increasing density and reducing pores in concrete, resulting in stronger and more durable concrete that can withstand corrosion and chloride penetration (Amin, 2022 ; Baltazar, 2019).

In the Rapid Chloride Penetration Test, concrete with the addition of 5% silica fume has a lower Qs value than normal concrete, indicating that the concrete has better permeability to chloride ions. This shows that adding silica fume can help improve the concrete's resistance to corrosion and extend its lifespan. Therefore, the use of silica fume in reinforced concrete mixes is highly recommended to produce stronger, more durable concrete with better resistance to corrosion and chloride penetration.

Concrete that is exposed to seawater or chemicals containing chlorides tend to undergo corrosion on the reinforcing steel, which can reduce the strength and service life of the concrete. Therefore, based on the previous description, the use of silica fume in concrete mixes can increase the resistance of concrete to corrosion and chloride penetration, thereby extending the service life of concrete and reducing maintenance and repair costs in the future.

CONCLUSION

From the conducted research, it can be concluded that:

1. The addition of 5% silica fume by weight of cement increases the compressive strength of concrete by 13%.
2. The addition of 5% silica fume by weight of cement improves the chloride ion penetrability performance from high to low, or has a 30% better resistance to chloride penetration than concrete without silica fume addition.

Based on these conclusions, a suggestion that the researcher can provide for the future development of this study is to use other additive materials such as High Range Water Reducer to improve the workability of the concrete. High-quality concrete tends to have low workability due to its high density and viscosity. Better workability is also indicated to increase the density of the concrete, as the concrete is considered to be able to fill small gaps on its own without the need for additional tools.

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