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Effects of organic corrosion inhibitors on the performance of repair mortars

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ABSTRACT

Reinforced concrete (RC) structures are severely degraded due to the corrosion of the embedded reinforcing steel, and hence, the upgrading of RC structures is essential. Repairing mortar is widely used to improve durability and strengthen structures; however, further repairing might be required considering the extended life of the structure. The use of inhibitors to protect the reinforcement from corrosion has become of great interest. Therefore, it is vital to study the potential of using corrosion inhibitors in a newly repaired system.

This study investigated the performance of a commercially available polymer-modified mortar with migrating and admixed corrosion inhibitors. The study examined repair mortar's fresh and mechanical properties with corrosion inhibitors using the workability, flexural strength, and compressive strength tests adopting submerged and sealed curing methods. The resistivity of reinforcement against corrosion was measured using the impressed current technique and mass loss test. The results revealed no adverse effect on the workability of repair material from the admixed corrosion inhibitor. The application of migrating corrosion inhibitor improved corrosion resistance by 29% with reduced mass loss; however, increasing the inhibitor dosage did not result in substantial changes under submerged and sealed curing conditions. On the other hand, the admixed corrosion inhibitor enhanced corrosion resistance by 15%, 28%, and 47% when the inhibitor dosage was at 0.5%, 1%, and 2%, respectively. This study proves that incorporating a corrosion inhibitor to the repair mortar in a repairing process can further delay the potential reinforcement corrosion.

1. INTRODUCTION

Exposure of reinforced concrete (RC) structures to chloride environments can lead to cracks and affect the durability of the structure. The corrosion of the embedded reinforcing steel is one of the reasons to degrade the durability of RC structures; hence a considerable amount of time and money is spent to repair these structures (Ke, 2013). A repair should be undertaken as soon as possible to prevent the whole structure from failure and longer use. Therefore, repairing damaged RC structures has turned out to be a critical factor, and the repairing technologies shall meet the demands of different structures.

The mortars are the primary material to repair damaged structures with no aggregates compared to the general concrete. Corrosion inhibitors are one of the admixtures for the concrete or mortar, preventing or delaying rebar corrosion. Generally, the inhibitors are classified into organic and inorganic corrosion inhibitors where both types can enhance the corrosion resistance of the rebar. Although inorganic inhibitors are comparatively cheap, the toxic nature and the side effects on the environment and human body have become a significant disadvantage. On the other hand, organic inhibitors are low-toxic; they can be obtained from nature and have negligible impacts on humans and the environment (Palanisamy, 2019). Hence, organic corrosion inhibitors have become a current trend in the construction-built environment. The use of organic corrosion inhibitors to protect the rebar from corrosion can be vital in improving the durability of a structure and can be an effective repairing system.

There are only a few studies that investigated the impact of corrosion inhibitors on the properties of repairing mortar. It has been found that inhibitors would decrease the concrete's mechanical strength while some other studies say that the inhibitor has no significant impact on the mechanical strength. The effects of the inhibitor on the mechanical properties of concrete mainly depend on the constituents of the inhibitor. Inorganic inhibitors have been used in the construction industry for a long period. Studies have found that the nitrite-based inhibitor can decrease the compressive and flexural strength of concrete (De Schutter and Luo, 2004, Das, 2013, Ahmed, Abdel-Latif and Abdelzaher Ali, 2020). However, according to some studies, the compressive and flexural strengths increase by a proper dosage of the nitrite-based inhibitor (Reddy, Prashanth, Raju V and Prashanth, 2020).

The past test results have proved that organic inhibitors, such as amino and ester-based inhibitors, can decrease the compressive strength by 10-20% (Ahmed, Abdel-Latif, and Abdelzaher Ali, 2020). The variation of strength depends on many factors, such as constituents of the inhibitor, the dosage, materials, and curing methods.

The workability, another essential fresh property, measured in terms of slump values has shown considerable variations when inhibitors are added to the concrete. The studies show that the workability may be affected by the types of cement, constituents of concrete, and the type of inhibitor. A study has shown that amino and ester-based inhibitors could increase the slump value; nitrite-based inhibitors and phosphate-based inhibitors can decrease the slump value (Ahmed, Abdel-Latif and Abdelzaher Ali, 2020). However, another study (De Schutter and Luo, 2004) showed contrary results where adding calcium nitrite-based inhibitor increased the slump value. The water content and the differences in aggregates can be possible reasons to observe different behaviors. Furthermore, the test results have shown that the amino and ester-based inhibitor has negligible influence on the slump value for the Portland cement concrete. At the same time, a dramatic decrease of the slump is observed for the slag cement-based concrete (De Schutter and Luo, 2004).

Corrosion of rebar in RC structures can lead to the development of cracks, eventually decreasing the strength of the structure. Also, corrosion leads to the loss of the rebar cross-section area where the rebar cannot transfer enough tensile strength to the concrete, influencing the mechanical properties (Goyal et al., 2018). Hence repairing is required considering the extended life of the structure. Inhibitors are constantly added to mortar while repairing to prevent further corrosion. The addition of corrosion inhibitors can affect the mechanical properties of the repairing mortar, and hence simulated experiments need to be performed.

The main objective of this study is to investigate the variation of workability, flexural strength, and compressive strength of mortar due to the addition of organic corrosion inhibitors under submerged and sealed curing conditions. Also, the resistivity of reinforcement against corrosion is analyzed while corrosion inhibitors are incorporated to repair mortars.

2. EXPERIMENTAL SETUP

Materials

A commercially available polymer-modified mortar was used in all the experiments. According to the manufacturer's specification, the chemical base consists of Portland cement, polymer re-dispersable powder, selected aggregates, and additives. The product and mechanical properties of the repair mortar are given in Table 1.

Table 1. Properties of the repair mortar

Item	Value		
Appearance / Colour	Grey powder		
Density (kg/m^3)	~1796		
Maximum Grain Size (mm)	1.5		
Compressive Strength (MPa)	1 day	7 days	28 days
	~11.5	~30	~35
Flexural Strength (MPa)	-	-	~7
Modulus of Elasticity in Compression (GPa)	~ 16.0		
Tensile Adhesion Strength (MPa)	~ 2.0		
Restrained Shrinkage / Expansion (MPa)	~ 2.5		

Two types of commercially available organic corrosion inhibitors were used. The first one is a migrating corrosion inhibitor (type X), also known as surface applied corrosion inhibitor or penetrating corrosion inhibitor. These types of corrosion inhibitors are applied on the surface of the concrete to penetrate and then diffuse in vapor or liquid form to the reinforcing bars embedded in the concrete. The formation of a protective layer on the reinforcing bar inhibits corrosion caused by the presence of chlorides by suppressing the anodic and cathodic reactions (Lee et al., 2017).

The second type of inhibitor is an admixed corrosion inhibitor (type Y). These are liquid concrete admixtures mixed with the gauging water or added simultaneously into the concrete/mortar mixer. The addition of this type of inhibitor will reduce both the anodic and cathodic reactions of the electrochemical corrosion process by forming a film on the steel surface (Lee et al., 2017). The properties of the corrosion inhibitors are shown in Table 2.

Table 2. Properties of corrosion inhibitors

	X - migrating corrosion inhibitor	**Y - admixed corrosion**
Appearance / Colour	Pale yellow	Liquid green
Chemical base	Amino alcohols and organic inhibiting substances	Nitrogen-containing organic substances
Density (kg/m^3)	1130	1060
pH-Value	11 (±1)	10 ± 1
Viscosity	15 cps	-

Testing

The workability of the repair mortar upon addition of admixed corrosion inhibitor Y was measured using the flow table test conforming to the BS EN 1015-3 (BSI, 2007). The repair mortar was mixed with 0.5%, 1%, and 2% dosages of inhibitor Y (by the mass of the mortar) to obtain flow values. Two flow values were measured perpendicularly for each mix to get the average value as shown in Figure 1. Since inhibitor X is a surface applied inhibitor after curing, X was not used in the workability test.

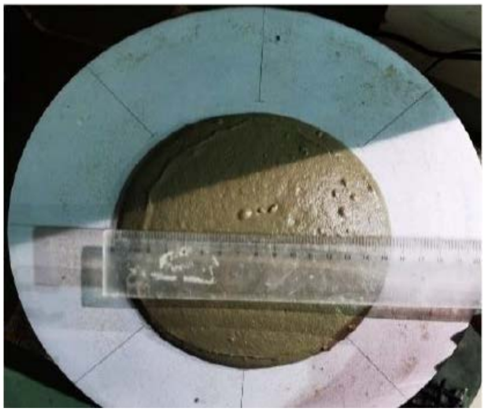

Figure 1. The measurement of flow value

Figure 2. Submerged curing

Figure 3. Sealed curing

Two different curing methods were adopted during the experiments; submerged curing and sealed curing, as shown in Figures 2 and 3, respectively. In submerged curing, the specimens were placed in a container with water, and calcium hydroxide was added to neutralize the carbonates to minimize impacts on the development of strength. The specimens were placed inside plastic bags in sealed curing, and water was sprayed to keep the moisture constant within the bag during the curing period.

Mortar prisms with the dimensions of 160 mm X 40 mm X 40 mm were subjected to the three-point bending test according to BS EN 1015-11 (BSI, 2006) to obtain the flexural strength under submerged and sealed curing at 7 and 28 days. The far edge of both residual pieces (40 mm X 40 mm) from the flexural strength test was used to check the compressive strength of the mortar. Similar to flexure, 7 and 28-day compressive strengths for each mix were obtained as per BS EN 1015-11 (BSI, 2006). The testing scheme of the flexural and compressive tests is shown in Table 3.

Table 3. Test specimens for flexural and compressive tests

Y (%)	Curing method	Curing period
0.00	Submerged	7 days
0.50	Submerged	
1.00	Submerged	
2.00	Submerged	
0.00	Sealed	
0.50	Sealed	
1.00	Sealed	
2.00	Sealed	
0.00	Submerged	28 days
0.50	Submerged	
1.00	Submerged	
2.00	Submerged	
0.00	Sealed	
0.50	Sealed	
1.00	Sealed	
2.00	Sealed	

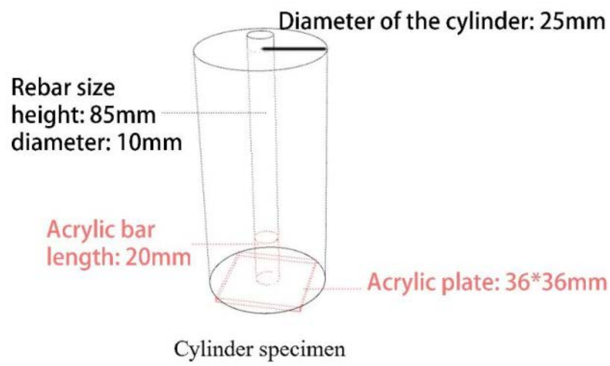

Figure 4. The cylinder specimen for accelerated corrosion test

The corrosion inhibiting efficiency of repair mortar modified with corrosion inhibitors was measured using the impressed current technique and mass loss test. The test specimen was developed in the form of a cylinder with rebar embedded at the center, as shown in Figure 4.

Mortar cylinders prepared with different dosages of the two inhibitors were subjected to impressed current scheme to analyze the degree of resistance to corrosion. The details of the test specimens are given in Table 4. Corrosion of reinforcement under natural conditions is a long-term process. Therefore, most of the experimental studies related to corrosion use the impressed current technique to accelerate corrosion in the laboratory. In this method, corrosion on the steel reinforcement is induced by applying an electrochemical potential between the steel bar (anode) and a stainless steel plate/bar (cathode) (Soltani, Safiey and Brennan, 2019, El Maaddawy and Soudki, 2003). According to Faraday's law, the required degree of corrosion can be achieved by varying the current intensity and time of application (El Maaddawy and Soudki, 2003, Kashi, Ramezanianpour and Moodi, 2017).

Table 4. Test specimens subjected to impressed current scheme

Inhibitor	Dosage	Curing Method
X	0 g	Submerged
	5 g	Submerged
	8 g	Submerged
	11 g	Submerged
	0 g	Sealed
	5 g	Sealed
	8 g	Sealed
	11 g	Sealed
Y	0.00%	Submerged
	0.50%	Submerged
	1.00%	Submerged
	2.00%	Submerged
	0.00%	Sealed
	0.50%	Sealed
	1.00%	Sealed
	2.00%	Sealed

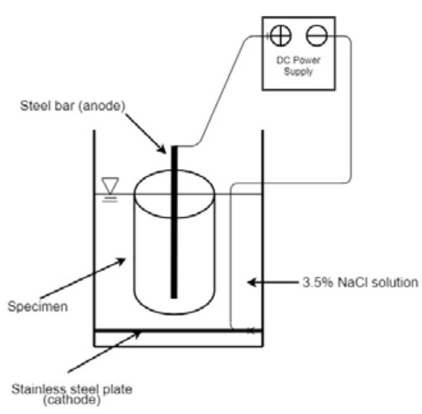

Figure 5. Schematic view of impressed current setup

The inhibitor X was applied on the specimen surface three days before the test as the inhibitor would take some time to reach the rebar surface. All the cylinder specimens were subjected to impressed current using a DC supply, as shown in Figure 5.

The current was controlled throughout the process. As per the past studies, the current density shall not exceed 200 μA/cm^2. The reason behind this is that the current density above this threshold may increase the concrete strain response (Zhang, Chen and Luo, 2019, Hong et al., 2020). Hence the current density was limited to 200 μA/cm^2.

A constant current of 18±1 mA was applied, and the change in voltage was recorded within the considered period. According to Ohm's law, the voltage drop is proportional to specific electrical resistance (Caré and Raharinaivo, 2007). The resistance (R) can be calculated by R = V/I, where V is the recorded voltage value, and I is the constant current applied. Therefore, by plotting the variation of voltage with time, the efficiency of the corrosion inhibitive effect can be judged on every combination.

At the end of the impressed current corrosion scheme, the steel bar was extracted out to clean the corrosion products using a metal brush. The mass of the cleaned bar was obtained to calculate its mass loss by comparing it with the initial mass before subjecting it to the impressed current.

3. RESULTS AND DISCUSSION

Workability

The admixed corrosion inhibitor Y was added to the repair mortar in the quantities of 0.5%, 1%, and 2% by the mass of mortar to observe the flow values. A control test with no inhibitor was also conducted as a reference.

Table 5. Variation of flow values

Dosage of Y (%)	Direction 01 (cm)	Direction 02 (cm)	Mean Flow value (cm)
0%	15.5	15.8	15.65
0.5%	16	16.5	16.25
1%	17.5	18	17.75
2%	15.8	16	15.9

Even though the amount of water was reduced corresponding to the quantity of inhibitor added, the flow values have been slightly increased as per the results shown in Table 5. Hence it can be observed that the workability of repair mortar can be affected by the addition of corrosion inhibitors. The increments in the flow values for the inhibitor dosages of 0.5%, 1%, and 2% were 3.83%, 13.42%, and 1.6%, respectively, compared to the reference group. These results are in line with those of previous studies that analyzed the workability of concrete upon the addition of corrosion inhibitors. However, the variation of workability of polymer-modified mortar has not been widely investigated. Overall, these results indicate that there is only a minor effect on the workability of repair material from the admixed corrosion inhibitor.

Flexural strength

The test specimens prepared with admixed inhibitor subjected to flexural test after curing for 7 and 28 days under submerged conditions indicated decrements of strengths compared to the reference group, as shown in Figure 6.

The early flexural strength (7 days) decreased by 14.6%, 9.5%, and 15% when inhibitor Y was added at 0.5%, 1%, and 2% by mass, respectively, compared to the reference group. The corresponding decrement of flexural strength at 28 days was 7.3%, 15.9%, and 4%. Hence it can be observed that, although there is a reduction in flexural strength, the decrement is not linear with the increment of inhibitor dosage. Similar observations were made for the specimens tested under sealed curing conditions apart from the sample tested at 7 days with 2% of the inhibitor, where an increment in the strength of 2% was observed. The samples prepared with 0.5% and 1% of inhibitor Y indicated strength decrements of 4.3% and 11.3%, respectively, at 7 days compared to the reference group, as shown in Figure 7. The 28-day strengths decreased in a non-linear manner by 6%, 20.8%, and 19.4% for the inhibitor dosages of 0.5%, 1%, and 2%, respectively. Therefore, in general, it can be observed that the addition of the inhibitor to the repair mortar has reduced its flexural strength considerably in both submerged and sealed curing conditions. The flexural strength reduction can be due to the air entrainment facilitated by amino alcohol available in inhibitor Y, leading to the formation of pores within mortar specimens.

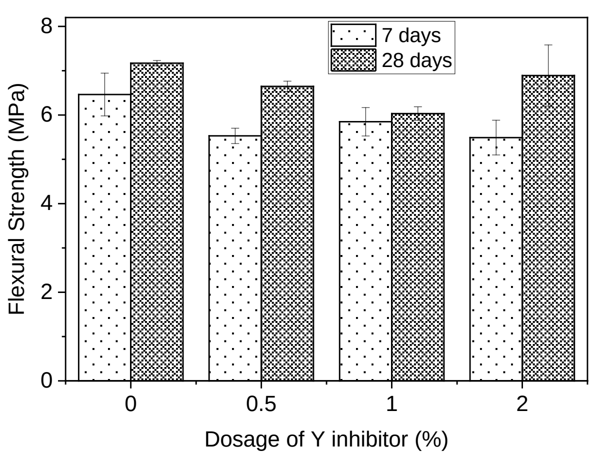

Figure 6. Flexural strength under submerged curing

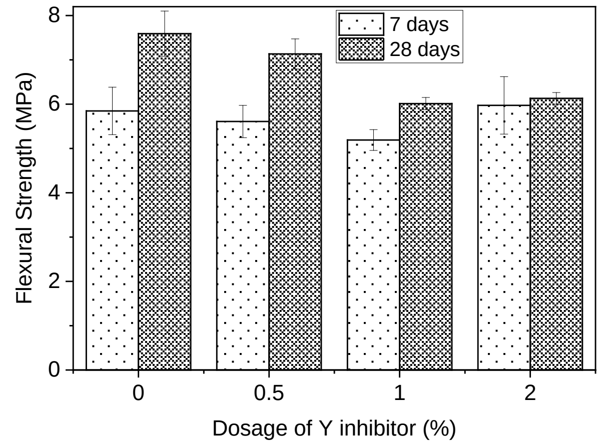

Figure 7. Flexural strength under sealed curing

Compressive strength

The specimens subjected to compression test that adopted submerged curing for 7 days indicated a slight increment of strength with increasing inhibitor Y dosage, as indicated in Figure 8. However, a different trend was observed at 28 days, where strength was decreased by 9.5% and 2.8% for the inhibitor amounts of 0.5% and 2%, respectively. The maximum compressive strength was obtained from the specimen with 1% dosage of inhibitor Y at both 7 and 28 days. The reasons to observe strength increments at the earlier stage can be due to the reactions between the inhibitor and mortar forming a complex to decrease the permeability of the mortar. With time the reaction will be stopped, and the formation of hydration products could cause the individual pores leading to considerable strength losses.

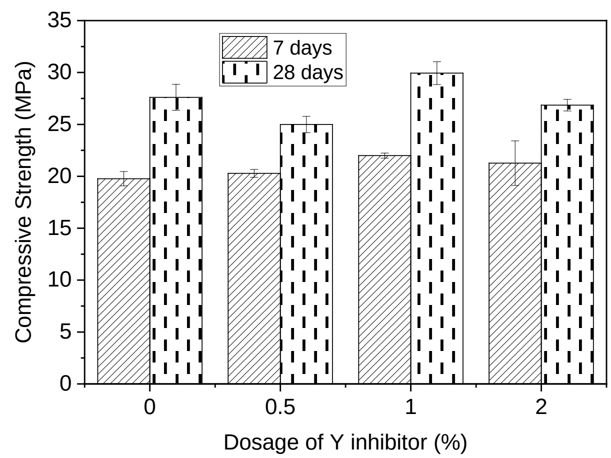

Figure 8. Compressive strength under submerged curing

However, the compressive strength generally tends to decrease at sealed curing conditions, as shown in Figure 9. At 28 days, the compressive strengths of the specimens prepared with inhibitor Y in a dosage of 0.5%, 1%, and 2% indicated strength reductions of 10%, 9%, and 11%, respectively, compared to the reference group. Hence, it concludes that increasing inhibitor dosage does not affect the reduction of compressive strength in sealed curing conditions.

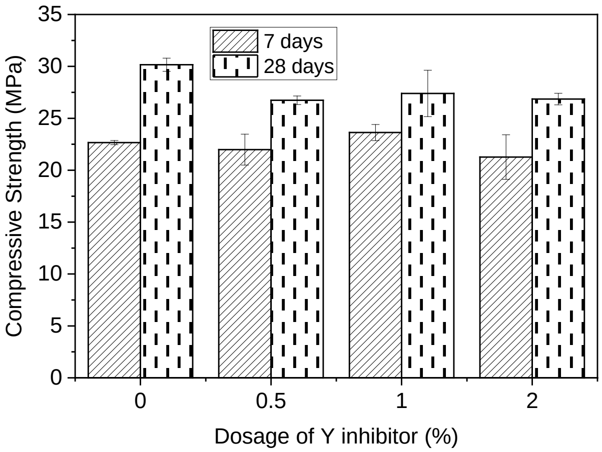

Figure 9. Compressive strength under sealed curing

Corrosion inhibiting efficiency

The impressed current test was adopted on all the cylinders with a constant current of 18±1 mA to monitor the voltage variation. The observed voltage variation against time for the repair mortar cylinders with different dosages of inhibitor X and inhibitor Y are indicated in Figures 10 and 11, respectively.

Since the current was set to a constant value, the voltage reflects the degree of resistance to corrosion. The impressed voltage to the specimens tends to decrease with the progress of the test. This is because the chloride ion penetrates the specimens and hence reducing the resistance to current flow. Hence, it requires less potential to maintain the same current; thus, the DC power supply automatically adjusts the voltage to a low level. The voltage variations of the specimens with applied inhibitor X did not indicate the expected results as the voltages were reduced while the inhibitor dosage was increased, which interprets that the corrosion resistance is decreased with the increasing dosage of the inhibitor. However, this observation can be due to the evaporation of inhibitor X when it is applied and the time to migrate might be insufficient to form the protective layer around the rebar.

The admixed corrosion inhibitor Y indicated the expected results as the required voltage for reaching 18±1 mA tends to increase with the increasing dosage of inhibitor Y. This interprets that the corrosion resistance is enhanced with the increment of the inhibitor dosage. A significant resistivity to corrosion was observed in the mortar specimens prepared with the admixed inhibitor dose of 2%.

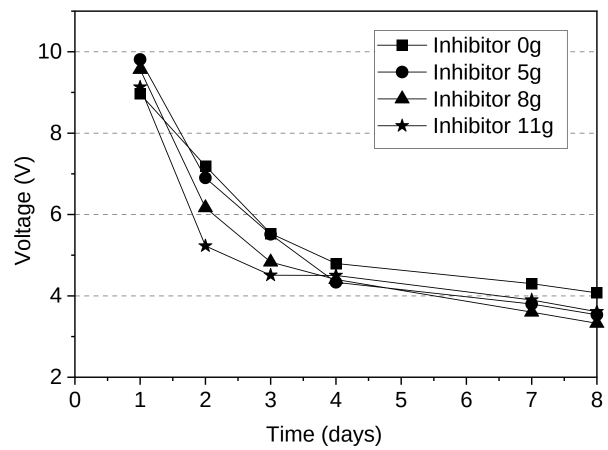

Figure 10. Voltage with applied inhibitor X (submerged curing)

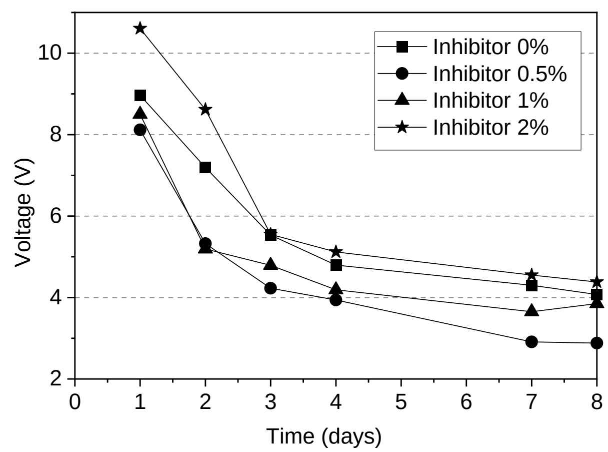

Figure 11. Voltage with admixed inhibitor Y (submerged curing)

To further investigate the effect of corrosion inhibitors, the mass loss of rebar caused by the impressed current was calculated. As the impressed current was continuously applied for 7 days (168 hours), according to Faraday's law, the theoretical mass loss should be 3.151g when the impressed current is 18 mA. However, the actual mass loss of the rebars was in the range of 3g to 8g. The possible reasons include the form of the rebar, which influences the corrosion as the rebar contains several non-ironic elements. External factors such as DC value fluctuations during the experiment can also result in deviations in theoretical and actual results. Besides, cracks were observed on the specimen surfaces due to the expansion of corrosion products. The crack propagation for all the specimens was initiated after 3 days from the application of the impressed current. Once the specimens are cracked, the corrosion product would leak out of the samples, resulting in non-uniform localized corrosion.

The mortar specimens treated with 5g, 8g, and 11g of inhibitor X under submerged curing conditions indicated percentage mass losses of 8.39%, 8.84%, and 6.67%, respectively, as shown in Figure 12. The corresponding mass loss percentage for sealed curing conditions was 8.54%, 8.76%, and 6.81%. Hence it is evident that increasing the inhibitor dosage did not result in substantial changes under submerged and sealed curing conditions. Also, the curing methods seem to have negligible influence on the inhibiting efficiency when inhibitor X is used.

The mortar specimens prepared with doses of 0.5%, 1%, and 2% of inhibitor Y indicated excellent inhibiting efficiency under submerged and sealed curing conditions, as shown in Figure 13. A percentage mass loss of 10.19%, 8.65%, and 6.37% under submerged conditions, and 10.12%, 9.05%, and 7.74% were observed when the doses of inhibitor Y is 0.5%, 1%, and 2%, respectively. Similar to inhibitor X, the curing method has negligible influence on the inhibiting efficiency when the admixed corrosion inhibitor Y is used. Overall, the admixed corrosion inhibitor Y had enhanced corrosion resistance by 15%, 28%, and 47% when the inhibitor dosage was at 0.5%, 1%, and 2%, respectively.

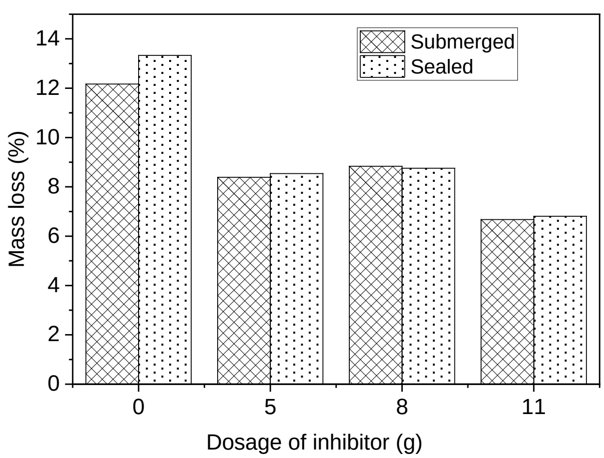

Figure 12. The percentage mass loss of rebar with inhibitor X

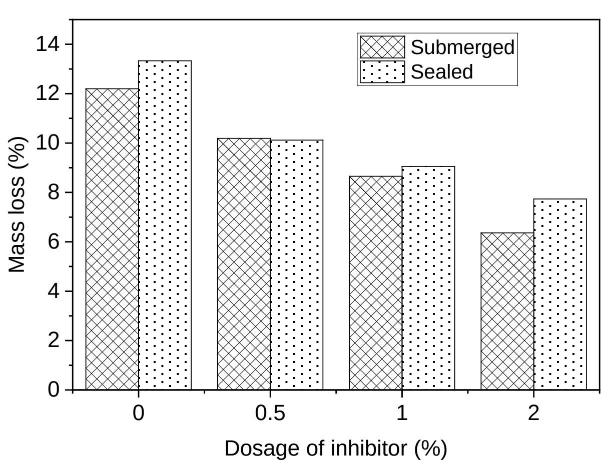

Figure 13. The percentage mass loss of rebar with inhibitor Y

4. CONCLUSIONS

The primary objectives of this study were to investigate the variation of workability, flexural strength, and compressive strength of mortar due to the addition of organic corrosion inhibitors under submerged and sealed curing conditions. Furthermore, the degree of resistance to reinforcement corrosion was examined while corrosion inhibitors were incorporated to repair mortars. Following conclusions are made from this study.

The admixed-type corrosion inhibitors could increase the flow value of repair mortar. However, as the flow value increment is low, there are no adverse effects on the workability of repair material from the corrosion inhibitor.

In general, the flexural strength of the repair mortar kept on decreasing with the content of corrosion inhibitors. The decrement of flexural strength was in the range of 5% to 20% under both submerged and sealed curing conditions. The compressive strengths indicated non-linear behaviors upon introducing the admixed type corrosion inhibitor. Under submerged curing conditions, the early compressive strength at 7 days slightly increased, while a strength loss was observed at the end of 28 days. The decline of compressive strength was in the range of 3% to 10%. A similar late compressive strength reduction was observed under sealed curing conditions ranging from 9% to 11%.

Both migrating and admixed corrosion inhibitors increase the degree of resistance to corrosion. The application of migrating corrosion inhibitor improved corrosion resistance by 29% with reduced mass loss; however, increasing the inhibitor dosage did not result in significant changes under submerged and sealed curing conditions. The increasing dosage of admixed inhibitor enhanced the corrosion resistance by 15%, 28%, and 47% when the inhibitor dosage was at 0.5%, 1%, and 2%, respectively. The curing methods seem to have negligible influence on the inhibiting efficiency for both the corrosion inhibitors.

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