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Experimental Analysis for Corrosion in Reinforced Concrete Structures

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Abstract: ***Corrosion of Structural reinforcement is becoming an issue for constructions that are exposed to environmental conditions. The bond strength between concrete and the reinforcement can be affected by corrosion due to loss of the reinforcement area. This can lead to safety issues in terms of sudden collapse without warning signals. Therefore, it is important to study the effects of corrosion on concrete and the period of bond strength loss in order to take into account safety precautions. The effect of corrosion on bond strength has been studied in several experiments. In this paper, an electrical current with voltage of 24V was used in order to accelerate the corrosion of an embedded rebar within three hours in concrete cubes of 15*15*15. Pull out tests were applied on the specimens after 14 days of casting of the concrete, with compressive strength C30. The specimens have different levels of corrosion (0%, 5% and 10%) and different applied loads pulling the rebar. The applied force on the samples was at 100%, 90% and 80% of the failure load and bond slip relations were compared under different levels of corrosion. This provides a period during the test to monitor the level of cycling before specimen failure. The results showed that a corroded rebar with 5% of corrosion level has higher bond strength and less slip than the other specimens that have different levels of corrosion, which slightly differs from the theories espoused in previous researches. It was remarkable how a slight difference in cycling between corroded and uncorroded rebars indicates that specimens with similar levels of corrosion and the same properties of concrete can affect bond strength under slight impacts. It was also noticed that uncorroded samples cannot be affected by cracks even though the rebar was pulled out by applied force.***

Keywords: Bond Strength, Corrosion, Pull Out test, Bond Slip, Reinforced Concrete

1. Introduction

The corrosion in reinforcement bars in concrete has become one of the most important issues that cause decreasing the performance of the structure which undoubtedly lead to significant effects on the structural safety. It causes loss of bond between the concrete itself and reinforcement. Corrosion has numerous numbers of negative aspects which eventually can lead to collapse of the structure [1]. Structural safety is classified as vital criteria to decide the quality of construction. Not only corrosion of reinforcement causes loss of bond between steel rebar and concrete, but it can also lead to loss of reinforcement area that certainly impacts on the integrity of structure.

It has been documented that, the first concrete building damaged due to steel of corrosion was in 1960s. Since about 1975, the number of cases of deterioration in constructions has increased dramatically. Since then, the maintenance of structure has become a considerable issue to tackle this phenomenon as a matter of urgent priority. Therefore, the number of researches in this area increased significantly [1]. However, some effects of corrosion are still not completely understood, in particular the effect on bond strength.

The major issue that combined with destruction of reinforcement of reinforced concrete resulted in corrosion reduced the properties of mechanical strength of corrosion and therefore, the concrete cracks [2]. As a result of weakening bond, the loss of serviceability will decrease proportionally. The measurement of the level of corrosion can be assessed the loss of serviceability in reinforced concrete. Thus, Pull out test is required to observe different issues related to corrosion and dynamic loading effect on the corroded steel bar in concrete in order to obtain the relationship between the parameters.

2. Description of Experimental Work

The first three cubes should not contain sodium chloride (NaCL 0%) and six of the concrete cubes have different percentages of Nacl: three with 5% of cement weight and the other three with NaCl at 10% of the cement weight. An extra set of three cubes are added to check the compressive strength of concrete after 14 days. The materials that are used are coarse aggregate size 10 mm, sand, cement and water. The properties of material will be shown in table (1).

Table 1: The Mixing Design of Concrete

Material	Quantity
Strength	C30
Approx. Slump	40mm
Aggregate 10 mm	2.82
Sand	2.22
Content Type II (32.5)	1
Water	0.6
A/C ratio	5.04: 1
W/C ratio	0.6:1
7 day strength	25N/mm^2
28 day strength	32N/mm^2

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In order to corrode the rebar, it should be made into an electrical circuit (cathode and anode) to achieve a noticeable result of corrosion within a short period. The next part will discuss thoroughly the acceleration of corrosion.

2.1 Preparation for corroding rebars

As mentioned, corroding the rebar is a part of detecting the range of bond strength due to corrosion of the reinforcement. It will take a long time to achieve a corroded rebar; however, by using an electrical current with voltage 24, it is reasonable to expect corrosion during a limited period. In this paper, the following procedure achieved remarkable results within 3 hours.

An electrical device was used as a source of electrical current in this paper; it was able to provide a voltage of about 24V and it could be controlled by using a gauge to increase or decrease the electrical current as shown in figure (1). Samples corroded from using electricity in under a few hours.

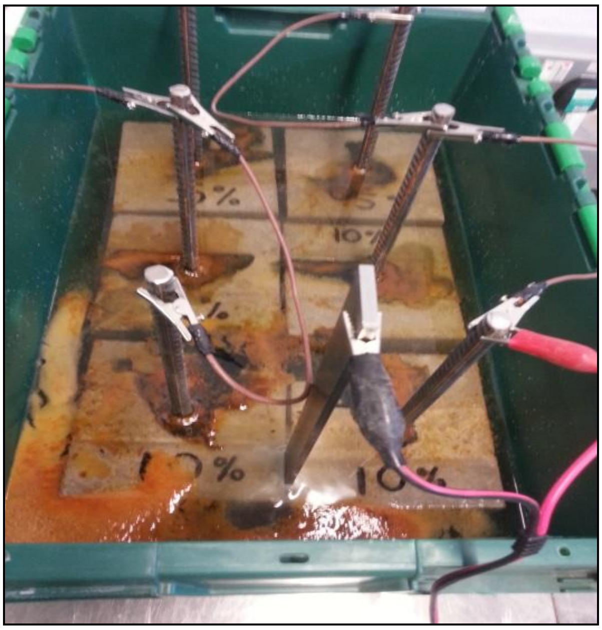

Figure 1: Corroded Samples after Operating Electrical Current

Another point to mention is that during casting of the concrete and corrosion of the steel, to measure the level of corrosion so that it has the required percentages of 5% and 10%, it was necessary to measure the diameter before and after corrosion to detect the changes between the two cases. the measurement of corrosion can be obtain by using a micrometer screw gauge.

2.2 Pull Out Test

The pull out test is the most important method that can be used to measure the bond strength between concrete and steel rebar. The required force to pull the inserted rebar from the concrete as needed is explained in figure(2).

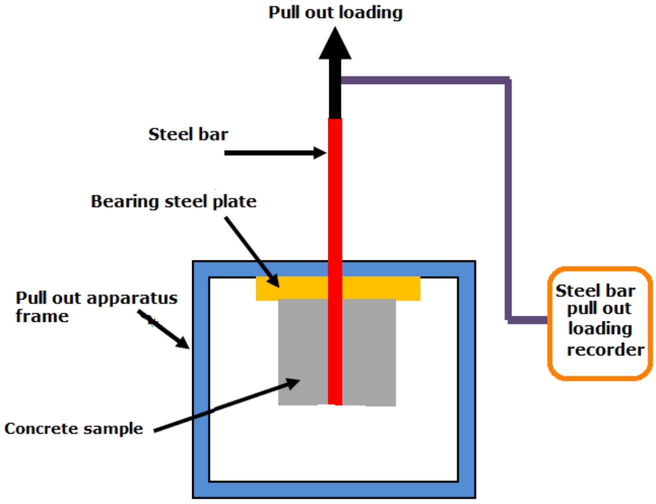

Figure 2: Schematic Layout of Bond Stress Test [3].

The following steps are based on the previous work in terms of preparation of the nine cubes with different levels of corrosion (0%, 5% and 10%). The cubes should be cured well in water for three days at least and the inserted rebar should be vertical as mentioned above. The strength of concrete should be C30 after 14 days to make sure the bond between reinforcement and concrete is reasonable and it is ready for testing.

These points should be taken into account before the test.

1) Three cubes of each level of corrosion (0%, 5% and 10%) are readied for testing (nine cubes).
2) Setting up the machine (actuator) for testing requires special criteria, such as specific tools and putting the samples in the right place. This is to fix the samples and prevent the specimens from movement.
3) This actuator is connected to software, which can detect the value of the applied force and the displacement by connecting the rebar with the LVDT, as illustrated in figure (3). The LVDT can determine whether the slip is up or down.

Figure 3: LVDT Device Located on the Base.

The first step is putting the sample into the specific position by passing the rebar through the small hole; it should not touch the sides of the hole in order to avoid affecting the measurements. Then, start applying force with a constant rate

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0.25KN/sec until the force which causes failure for the specimen is detected, for each level of corrosion of the specimens (0%, 5% and 10%).

The next samples with levels of corrosion at 0%, 5% and 10% are tested with an application of 90% of the previous force that caused failure; this means that the force would not reach the failure point at the first loading. It will take three cycles before reaching the failure force, which is exactly what is required in this project. The last three samples would take four cycles before reaching the failure load. The method of loading would be gradual as mentioned. Therefore, the same force is applied (90% in the second case) several times and the specimen loaded and unloaded by pulling out the rebar until failure point can be achieved. The 90% loading force is applied to three samples with 0%, 5% and 10% levels of corrosion.

The final step involves applying the same procedure to the last three samples which have different levels of corrosion. However, the applied force would be minimized to 80% of total force, which can take more cycles in order to reach the failure point. In this case, the number of cycles would be four before the maximum failure load is applied.

The results are collected for each case of loading and each level of corrosion using software connected to the machine as shown in figure(4).

Figure 4: Software to Collect Data from Actuator.

A comparison between all cases can be done to reflect upon the impacts of corrosion on the bond strength and reinforcement. The next chapter will present the results of this test, illustrated by figures with critical discussions of each case of loading.

3. Results and Discussion

3.1 Introduction

This part will present the results of the pull out test under different levels of corrosion (0%, 5% and 10%). The applied loads were 100%, 90% and 80% of the total load failure. The purpose of this chapter is to detect the load which causes the failure of the specimen and its displacement due to force applied during the test. It is also to calculate the bond strength and to study cases of cracking. The pull out force rate was constant in the entire test (0.25 KN/sec).

3.2 Cases of Pull Out Test with 100% Failure Force

3.2.1 Case of 0% level of corrosion

As shown in figure (5), it can be clearly seen that the pull out force increased sharply to reach a peak load of 31 KN, with slip around 0.7mm. At this point the pull out force decreased dramatically to 13 KN with displacement 1.1mm. It should be noted that with 1.8mm of slip the load started decreasing gradually over the rest of the period. A final point to mention from this graph: the displacement rose steadily during the whole period of testing the specimen and the maximum slip has been observed around 9.5mm.

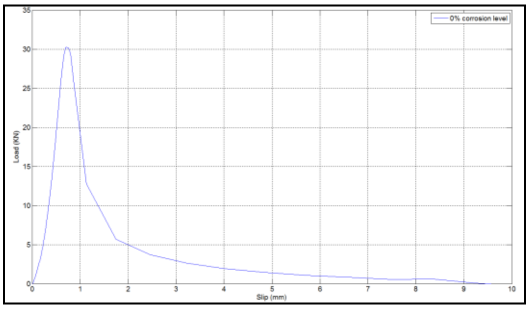

Figure 5: Applied Pull Out Force and Slip Movement of 0% Corrosion Level

This behaviour can be explained by the bond strength between reinforcement and concrete, which can carry loads of 31KN before failure, with no cracks during the test. The rebar has been pulled and no cracks appear on the surface of the samples. This reflects the extent of the quality of concrete and high yielding stress of steel, especially with 0% level of corrosion.

3.2.2 Bond stress calculation

The bond stress can be calculated by the average maximum pull out force divided by the area surrounding the embedded rebar along its length. This equation can be used to obtain the maximum bond stress:

$$S = \frac{P}{\pi * L * d} \quad (1)$$

Where:
S: maximum bond stress KN/mm2
P: maximum pull out test
L: Length of embedded bar
d: Diameter of rebar

Based on the equation above, the bond stress can easily be calculated.

The maximum applied force as shown in figure (5) was roughly 31KN and the length of embedded rebar as mentioned in the methodology was 13cm with a diameter of approximately 12mm.

Therefore, the maximum bond stress is:
S= 31/(3.14*0.13*0.12)=6328 KN/mm^2

3.2.3 Case of 5% level of corrosion

It is remarkable that the maximum pull out force with 5% corrosion level obtained around 41KN as illustrated in figure(6). The applied load force grew markedly to reach a maximum load with a constant rate of 0.25KN/sec. That had

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a displacement of 0.8mm before falling down to 2KN with slip 11mm. This point of loading started decreasing slightly. Meanwhile, the displacement continued to increase to reach a maximum of 3.5mm.

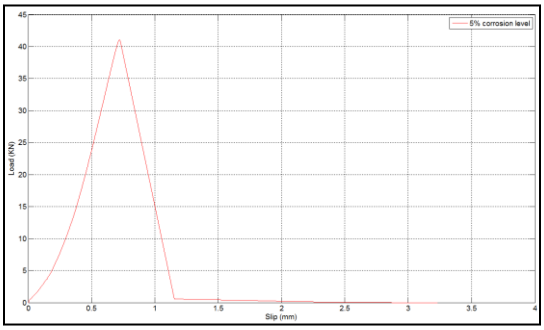

Figure 6: Applied Pull Out Force and Slip Movement of 5% Corrosion Level.

To sum up this case, corrosion can increase the bond strength in the early stages before cracking appeared. At the point when cracks started the load decreased significantly with increase of displacement. Cracks as shown in figure (7) caused early failure even with a high bond strength during the early stages of applying the load.

Figure 7: Concrete Specimens after Pull Out Test of 5% corrosion level

It is remarkable from the figure above that cracks occurred at the centre of samples due to distribution of loads. The bond strength can be calculated by using the previous equation:
$S=41/(3.14*0.13*0.012)=8730 \text{ KN/mm}^2$

3.2.4 Case of 10% level of corrosion

It can be seen from figure (8) that the pull out force increases markedly with a peak loading of approximately 28KN. However, it should be noted that the displacement has rocketed after reaching a peak load to obtain a maximum slip of roughly 2.8mm.

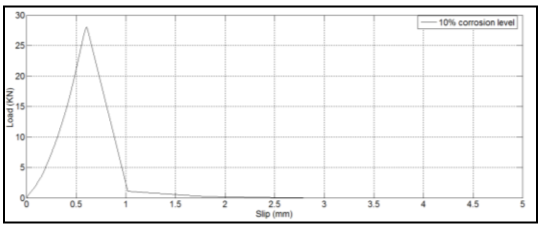

Figure 8: Applied Pull Out Force and Slip Movement of 10% Corrosion Level.

In this case, the bond strength has been calculated as $S=28/(3.14*0.13*.012)=5716 \text{ KN/m}^2$.

There are visual cracks in the corroded samples in three directions. This reflects how the corrosion not only causes the loss of bond strength in later stages, but can also cause cracks in the concrete.

To conclude, the maximum force that can pull the rebar as seen in figure (9) is 41KN (percentage of corrosion level 5%) and the maximum slip was 9.5mm (with 0% corrosion). It is a noticeable that 5% of corrosion can withstand a higher force than the cases of 0% and 10%. This can be explained by how the effect of corrosion on bond strength can increase within the first stages; it then decreases dramatically, which indicates the impacts of corrosion levels on bond strength. It is also remarkable that cracks occur only on samples which have corrosion levels 5% and 10%, with no cracks on those specimens that have 0% of corrosion. Therefore, as the level of corrosion increases the cracks would also increase proportionally.

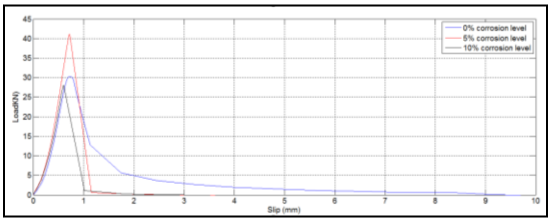

Figure 9: Comparison Case of Concrete Specimens after Pull Out Test for Three Cases.

3.3 General Discussion

The research findings confirm that reinforced concrete is the most widespread material used in the construction industry. The excellent match of the properties of concrete with steel reinforcement to form a composite material (reinforced concrete) has allowed its spectacular dissemination and use over the last century; however, this has also led to certain problems associated with the durability of these structures, which have a great technical, economic and social importance.

Because of this, much effort and money have been devoted to finding, preventing and resolving risks that limit the useful life of a material that began its existence by promoting itself as having unlimited durability and minimal maintenance requirements. The situation is far from satisfactory, even persisting with controversies on key issues. However, it is beyond doubt that the corrosion of the reinforcing steel is by far the main factor limiting the durability of reinforced concrete structures. There is a widespread recognition of the importance of acquired corrosion damage in steel reinforcements; yet the vast majority of inspections are performed on structures where the damage has already become apparent, when it would be desirable to make routine inspections, particularly in highly aggressive environments. The lack of visual access to the reinforcing steel contributes to this state of affairs, because the visible symptoms usually precede the request for inspection and in

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most cases, when it becomes further apparent, is when the damage is already significant.

Clearly, if the products of corrosion do not migrate through the pores, small amounts of corroded metal can generate considerable tensions. The effects of corrosion, in all cases, are manifested in the three fundamental components of reinforced concrete: on steel, on the concrete and on the adhesion/ grip between steel and concrete.

The accumulation of all the effects of corrosion is a major cause of deterioration of reinforced concrete structures, therefore limiting their durability. There is no tolerable upper limit of corrosion, which can vary according to the purpose of the structures, but a numeric index is generally accepted for the calculation of durability, as it is estimated in relation to different parameters: the bond between concrete and reinforcement, the loss of load carrying capacity, lower section of the reinforcement, the time needed for aggressive substances to penetrate to the reinforcement means, or even the visible symptoms of degradation. In any case, whatever the chosen parameter, estimations are always based on the effects of corrosion due to the variation of said parameter. It has been granted that reinforcement corrosion has been an issue, for some time, of greatest importance in the maintenance of existing structures, because it has contributed to structural collapses due to its broad impact.

Because of the low tensile strength of concrete, the durability of the vast majority of projecting structures in reinforced concrete is essentially limited by the corrosion of the reinforcing steel. All of the excellent properties of concrete as a building material would be minimized if it were not for an additional property; its ability to protect the reinforcing steel from corrosion. This ability is conferred by the high pH of concrete, imposed by the $Ca(OH)_2$ formed in the hydration of the major components of cement, tricalcium and dicalcium silicates, which guarantees a passive state of steel reinforcement and thus, a long service life. Reinforced concrete, like many building materials, projects an idea that it would remain stable over time, without losing any of the physical and chemical properties that characterizes it. Because of its constitution, the concrete contains pores, some interconnected, which can be critical in their durability, as the external aggressive agents have ways to penetrate through them, such as by capillarity or diffusion.

The rapid spread of the use of reinforced concrete has contributed significantly to promoting the measurable properties of two materials: steel and concrete together in a composite material, thereby combining the outstanding tensile strength of the first and the good compressive strength of the second. Concrete, also known as cement is a mixture of two components: aggregates and paste. The concrete paste comprises cement, water, additives and may include entrapped air. Aggregates are known as fine (sand) and course (gravel). Reinforcing steel is an iron/carbon alloy, and generally has an embossed surface finish known as corrugated.

The integrity of a reinforced concrete structure depends on both the quality of these components as well as their quantities to achieve the best properties that ensure a prolonged service life. The barrier between the concrete and the steel rod is reinforced by the alkaline pH value reached after cement hydration reactions, and passivates the metal element, thus protecting it chemically. However, interaction with the environment means that environmental protection is diminished, with main aggressive agents being chlorides in marine regions and carbonation in rural and industrial areas. The combination of such aggressive agents has a synergistic effect, accelerating the degradation process of reinforced concrete structures.

4. Conclusions and Recommendation for Future Works

4.1 Conclusions

The purpose of the paper is to detect the extent of endurance of structures under corrosion impacts due to environmental issues. This can lead to corrosion reinforcement with effects on the bond strength. The samples were exposed to different levels of corrosion with different applied forces in order to count the time taken for keeping the structure safe and stable. A series of tests were performed to determine the relationship between applied force with different levels of corrosion and time cycling to detect the failure point of specimens for integrity purposes. They also determined the slip range under applied forces, especially for applied forces which are less than the critical load.

Based on the test results, some vital points can be extracted as follows:

1) It can be seen that the rebar with 5% of corrosion has a higher bond strength than the other cases, which have different levels of corrosion. This investigation does not seem to conform to theories that corrosion undoubtedly has a negative impact on the bond strength between concrete and reinforcement. This can be explained by the increase in rust due to corrosion causing pressure in the surrounding area, which could probably increase the bond strength. However, after increasing the level of corrosion to 10%, the bond decreased, which could be due to high pressure on the surrounding area causing cracks to appear, resulting in loss of bond strength.
2) As the level of corrosion increased, the failure load would decrease. Otherwise, the period of cycling below percentages of 90% and 80% of failure load will decrease compared with the uncorroded cases.
3) During the pull out test, the specimens which have high levels of corrosion had cracks of greater width than cases with 0% and 5% corrosion, even though the concrete in the specimens have the same properties, such as water cement ratio.
4) Compressive strength can be affected slightly for concrete when NaCl is added as a percentage of the cement weight at 0%, 5% and 10%.
5) Acceleration of corrosion as shown in the methodology section can be achieved within three hours by using an electrical current of 3A and voltage 24V.

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6) The case of slippage of the uncorroded rebar was in the middle range of the other specimens, which had varied levels of corrosion compared with the same applied load and time cycling.

To sum up these results, this paper can be useful for general structures whether with corroded or uncorroded reinforcement under the influence of dynamic loading, which in reality would represent earthquakes. This reflects the vibration of loads employed in this experiment to study the structural integrity and the period of the construction's resistance until collapse. As this work is based on a pull out test, it may not reflect real behaviour and vibration in reality is variable, while in the investigation it was constant with the same rate for all specimens.

4.2 Recommendations for Future Work

While this research investigated the effects of corrosion, some points are needed to be studied deeper in future in order to improve the quality of structures. One of the main points recommended for study is the effects of corrosion on smooth rebars and those with different diameters to simulate the main issues in structural reality. This study focused on a deformed rebar with diameter 12mm. Another suggestion is the need to carry out the pull out test under different applied forces, which means the loads are variable; this did not happen in our case in this paper, as the loads were constant. The final recommendation for future work is to use an oil to protect the reinforcement when examining loss of bond.

However, it is acknowledged that there are gaps and limitations in this study that need to be mentioned:

1) Each piece of work studied only one rebar located at the centre of one concrete cube, while in practice rebars have different diameters and locations within the concrete, which can affect bond stress depending on the different positions in concrete.
2) Acceleration of corrosion took just about three hours through using salts, while on site this period may last several years. This can lead to different bond strengths in reality, compared with what has been done in the experiment.
3) The compressive strength of concrete was taken within 14 days due to the limited period of this work. It is more accurate to take it in 28 days to represent the standard conditions for evaluating bond strength parameters.

Overall, this paper has investigated properly the hypothesis and the outcomes achieved the expectations, with some points needing to be taken into account for future work. This test examined nine samples and two of them failed during the test. Therefore, it is more accurate to use for each case at least three samples and then the average can be taken, which may better reflect the accuracy of the results.

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