EFFECTS OF CORROSION OF STEEL BARS ON THE BOND STRENGTH OF CONCRETE

by

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CERTIFICATION OF APPROVAL

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Approved by,

(Assoc. Prof. Dr. Nasir Shafiq)

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CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

(Norliza Binti Salihin)

ABSTRACT

In reinforced concrete structures, the bond between concrete and reinforcement can be deteriorated by corrosion of the reinforcing steel. Corrosion of reinforcing steel bar is one of the main durability problems of concrete structures. The corrosion product, rust, resides at the interface between reinforcing steel bar and concrete, degrading the bond between them and thus reducing the service life of the structure. The objectives of this study are to determine the bond strength of different types of concrete by pull-out test using different diameter of bars and to study the effects of corrosion environment on bond strength and compare with the bond strength as obtained in a control environment.

For the study of the effects of corrosion in steel bars on the bond strength of concrete, 10mm, 12mm and 16mm bars to be embedded in concrete cylinders. After normal curing, the cylinders were exposed to chloride environment, which created by mixing 3% of Sodium Chloride (NaCl) with water in a container. After 4 weeks and 8 weeks of chloride exposure, the bars were tested for pull-out from cylinders. The trial mix proportion used for the study were 1(cement):2.33(sand):3.5(coarse aggregates) with water cement ratio 0.55. Two concrete types were also were prepared namely Control Mix (100% Cement) and Mix 2 (50% Cement + 50% PFA). Conclusively, based on the results obtained it is figured out that the bond strength of both type of concrete were increased with the increased of steel bar diameters. However, the bond strength of steel bars in Mix 2 was higher than Control Mix due to presence of Pulverized Fuel Ash (PFA) with corrosion up to a certain amount.

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CHAPTER 1
INTRODUCTION

1.1 Background of Study

Steel reinforced concrete has been extensively used for over a century because it is normally a versatile, economical, and durable construction material. The embedment of reinforcing steel bars (rebar) in concrete both provides a structure with adequate mechanical and bond strength[1] and furnishes the rebar with a protective environment. Steel in concrete is protected against corrosion by passivation. This passivation is due to the presence of Calcium Hydroxide $Ca(OH)_2$ in the pores of the cement matrix, the pH has an average value of 12.4 [1].

Under these circumstances, a thin oxide layer is formed around the reinforcement helping them to remain uncorroded. Reinforcement corrodes only if the protective layer deteriorates. Corrosion of steel in concrete has received increasing attention for the past three decades due to its widespread occurrence and the high cost of repairs. The corrosion of steel reinforcement has been widely observed in marine structures, chemical manufacturing plants, bridge and underground pipes.

1.2 Problem Statement

Corrosion of embedded reinforcing steel is a major cause of deterioration in concrete. Corrosion of reinforcement leads to a volume increase, causing splitting stresses in the Concrete, therefore there is a close interaction between corrosion and bond where failure of bond between steel and concrete will occur. This loss of bonding reduces the unified effect of reinforced concrete to resist tensile and compressive forces [2]. Basically, the perfect bond between the reinforcing bar and concrete is an essential requirement of the composite action of reinforced concrete. Bond arises primarily from friction and adhesion between concrete and steel and from mechanical interlocking in the case of deformed bars. One of the assumption in reinforced concrete design is the perfect bond must exist between the steel rebar and concrete.

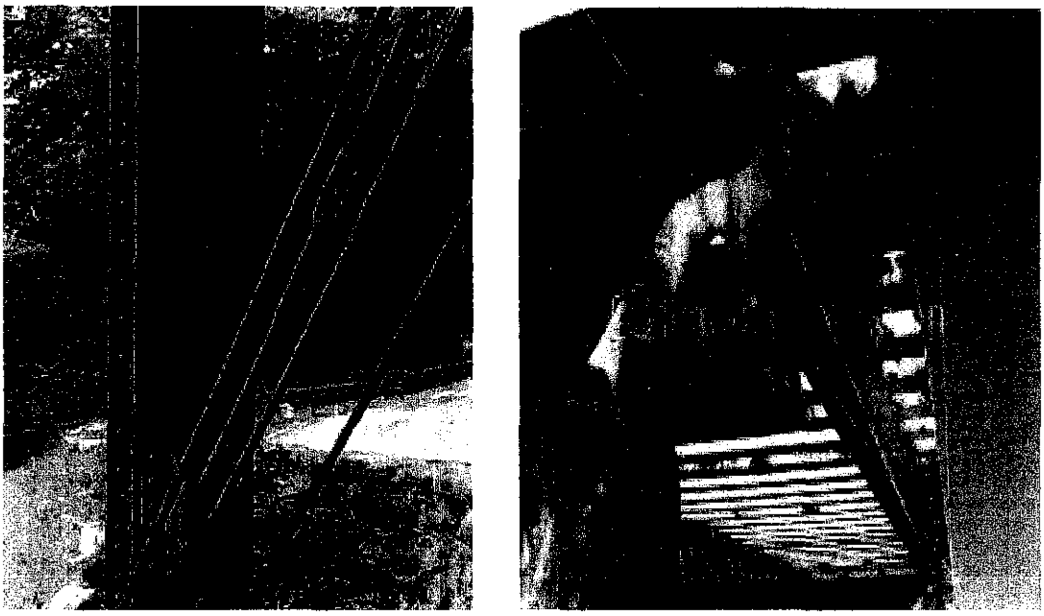


Figure 1.1: Corrosion was observed at the bridges, indicated by the yellowish colour due to the corrosion product, rust.

1.3 Objectives

Following are the main objectives of the study:

1. To determine the bond strength of different types of concrete by pull-out test using different diameters of bars
2. To study the effects of corrosion environment on bond strength and compare with the bond strength as obtained in a control environment

CHAPTER 2

LITERATURE REVIEW AND THEORY

2.1 Common types of corrosion

Corrosion is degradation of a material due to reaction with its environment. All corrosion processes include electrochemical reactions. Galvanic corrosion, pitting corrosion, crevice corrosion, and general corrosion are purely electrochemical [3]. The type of corrosion and cause should be identified to assure that a meaningful evaluation is performed.

- General atmospheric corrosion is defined as corrosive attack that results in uniform thinning spread over a wide area. It is expected to occur in the ambient environment of hydraulic steel structures but is not likely to cause significant structural degradation.
- Localized corrosion is the type of corrosion most likely to affect hydraulic steel structures. Five types of localized corrosion are possible:

(a) Crevice corrosion occurs in narrow openings between two contact surfaces, such as between adjoining plates or angles in a connection. It can also occur between a steel component and a nonmetal one.

(b) Pitting corrosion occurs on bare metal surfaces. It is characterized by small cavities penetrating into the surface over a much localized area.

(c) Galvanic corrosion can occur in gate structures where steels with different electrochemical potential (dissimilar metals) are in contact. The corrosion typically causes blistering or discoloration of the paint and failure of the paint system adjacent to the contact area of the two steels and decreases as the distance from the metal junction increases.

2.2 Consequences of Corrosion

The consequences of corrosion of steel reinforcement do not involve only the serviceability or the external conditions of the structure, but may also affect its structural performance and therefore its safety [4]. Corrosion is often indicated by rust spots that appear on the external surface of the concrete or by damage to the concrete cover produced by the expansion of the corrosion products.

These products in fact occupy a much greater volume than the original steel bar. The volume of the corrosion products can be from two to six times greater than that of iron they are derived from depending on their composition and degree of hydration [4]. These corrosion products generate sufficient stress to disrupt the concrete cover by cracking or spalling [5].

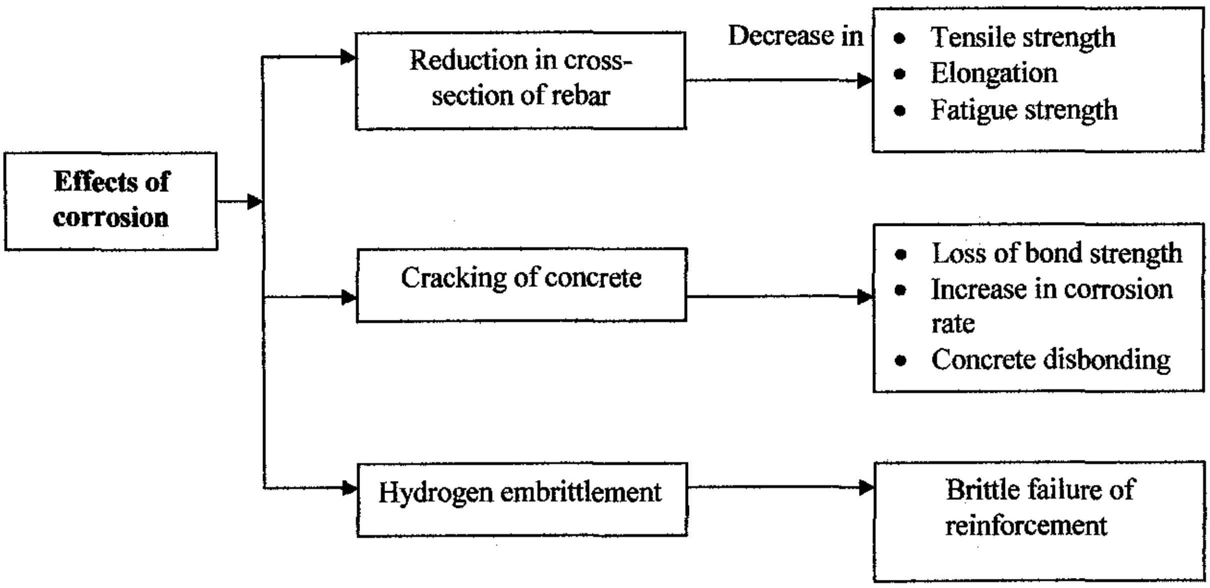


Figure 2.1: Structural consequences of corrosion in reinforced concrete structures

2.3 Significance of Bond in Concrete

Bond between concrete and reinforcement has principal significance on structural behavior of reinforced concrete which is independent of the type of the reinforcement or the application of prestressing [6]. Without the presence of bond (or a special anchoring device) the constituent elements of the composite material such as concrete and reinforcement would not be able to carry loads together. Bond performance has an effect on the flexural, shear and torsion load bearing capacity of reinforced concrete members and particularly on serviceability behavior [6]. Tension stiffening and crack widths can be evaluated directly from an analysis based on bond and force transfer. In addition, development lengths splice lengths and transfer lengths of reinforcing and prestressing bars could not be determined without bond analysis. Bond action can also influence the ductility of a structural member [6]· Figure 2.2 summarizes the most important phenomena that are attributed to bond action.

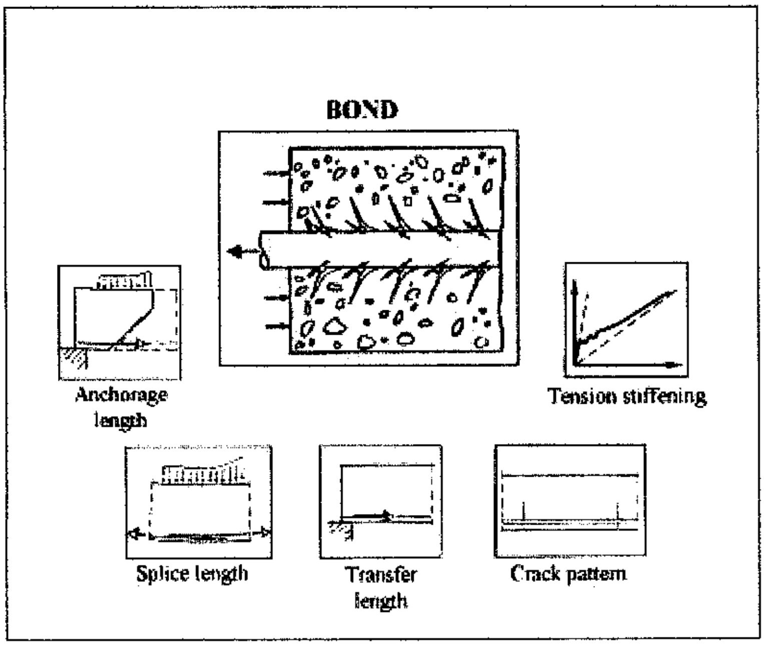


Figure 2.2: Bond and structural behavior

2.4 Bond in General

Bond stresses are the result of the change of forces between reinforcement and concrete. Slip is generated due to the different deformation capacities of the concrete and that of the reinforcement. By definition, slip is the absolute difference (in mm) between those concrete and reinforcement sections that were in coincidence before loading. Slip is the integral of the difference between the accumulated strains of reinforcement and concrete over bond length. Bond stress can be calculated as the change of the internal force of steel or concrete related to the interface surface: The bond strength (t_{bu}) is the maximum value of the bond stresses. Figure 2.3 gives a schematic representation of bond stress vs. slip (t_b-s) responses of deformed and smooth steel reinforcing bars.

Under relatively small loads bond stresses are represented mainly by *adhesion* and slip is zero. Adhesion results from several actions: shrinkage of concrete during setting, chemical bond between concrete and reinforcement and Van der Waals type molecular forces are the most important reasons of adhesion. Adhesion represents less than 20 percent of bond stresses. Slip starts to accumulate under loads higher than the adhesion resistance. Slip does not mean that the load bearing capacity of the system is reached. *Mechanical interlock* forces are formed around the reinforcement ribs due to the accumulated slips. Bond force is increased by the longitudinal component of the mechanical interlock forces. On the other hand, the perpendicular component of the mechanical interlock forces induces hoop tensile stresses around the reinforcing bar. Hoop tensile stresses induce micro-cracking in the surrounding concrete. The number of micro-cracks as well as their length and width increases with the increase of loads.

Concrete is in a multi-axial stress state in the vicinity of a reinforcing bar according to the confining effect of concrete. Stresses in the concrete can reach much higher values than the uni-axial strength of the concrete. Deformed reinforcing bars can develop considerably higher bond stresses than smooth bars due to the mechanical interlock. Further increase in the load results in shearing-off of the concrete lugs between reinforcement ribs. Bond force is provided by only *friction.*

However, bond resistance is not equal to zero (residual bond strength), but the slips can be increased without limit. Bond action is represented in Figure 2.3. Bond failure of steel reinforced concrete can be caused by:

- Concrete lugs failure in shear around the reinforcement (pull-out failure),
- The case of insufficient concrete cover wherein the micro-cracks can spread to the concrete surface resulting in complete disintegration of the structure (splitting failure).

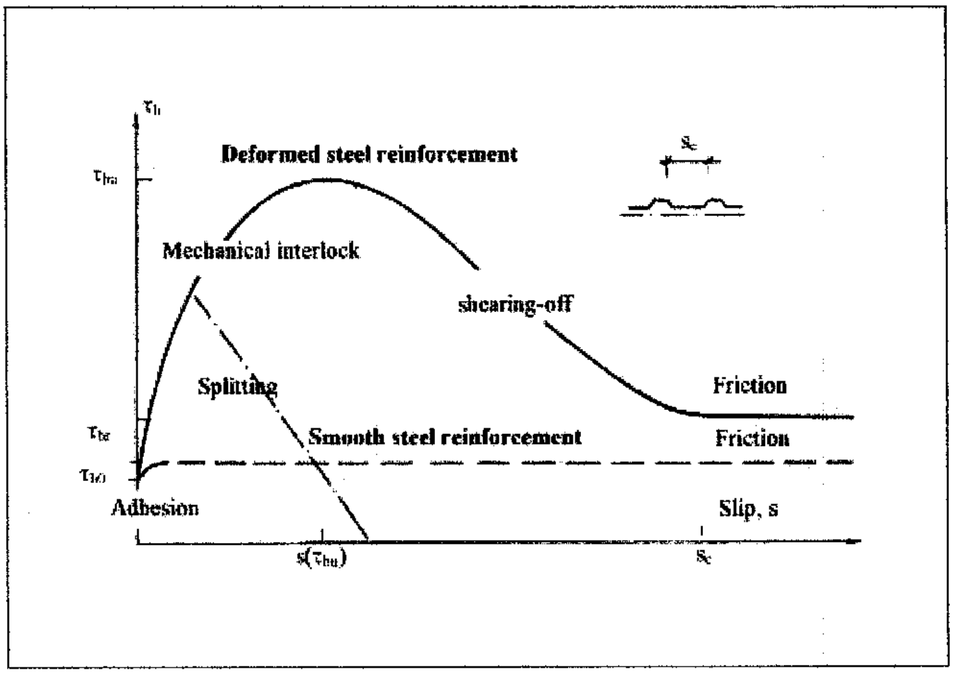


Figure 2.3: Typical bond stress vs. slip (t_b-s) responses of steel reinforcing bars

It can be concluded that in case of steel reinforced concrete the failure of bond is attributed to the failure of concrete locally. In case of deformed reinforcing bars the bond strength is generally reached at more than 1.0 mm slip [6].

2.5 Anchorage Bond

The reinforcing bar subject to direct tension must be firmly anchored if it is not to be pulled out of the concrete. The anchorage depends on the bond between the bar and the concrete, and the area of contact [7]. Let

L = minimum anchorage length to prevent pull out

ϕ =bar size or nominal diameter

f_{bu} = ultimate anchorage bond stress

f_s = the direct tensile or compressive stress in the bar

Considering the forces on the bar

- Tensile pull-out force = bar's cross sectional area x direct stress

$$= \frac{\pi\phi^2}{4} f_s$$

- Anchorage forces = contact area x anchorage bond stress

$$= (L\pi\phi) f_{bu}$$

Therefore,

$$(L\pi\phi) f_{bu} = \frac{\pi\phi^2}{4} f_s$$

Hence,

$$L = \frac{f_s}{4 f_{bu}} \phi$$

When $f_s = 0.95f_y$, the ultimate tensile or compressive stress, the anchorage length is

$$L = \frac{0.95 f_y}{4 f_{bu}} \quad \text{Where } f_{bu} = \beta\sqrt{f_{cu}}$$

The coefficient β depend on the bar type and whether the bar is in tension or compression. Values of β are given in Table 2.1.

Table 2.1: Bond coefficient β (BS 8110: Clause 3.12.8.4) [8]

Bar type	β	
	Bars in tension	**Bars in compression**
Plain bars	0.28	0.35
Type 1: deformed bars	0.40	0.50
Type 2: deformed bars	0.50	0.63
Fabric	0.65	0.81

2.6 Effect of Chloride Ions

Damage of concrete effected by chloride ions occurs both by destroying the concrete and corrosion of the rebar. Firstly, the chloride ions decrease the bonding of concrete compositions by the following reactions:

$$Ca^{2+} + 2Cl^- + 3CaO.Al_2O_3 + 10H_2O \longrightarrow 3CaO.Al_2O_3.CaCl_2.10H_2O$$

Or:

$$MgCl_2 + Ca(OH)_2 \longrightarrow CaCl_2 + Mg(OH)_2$$

Secondly, chloride ions increase the corrosion of rebar in concrete by the following actions:

- Decreasing the electric resistance of electrolyte in concrete
- Speeding up the initiation of corrosion process, and
- Destroying the passive layer on the rebar in concrete.

The reactions involved are:

$$Fe + 3Cl^- \longrightarrow FECl_3 + 3e$$

$$FeCl_3 + 3OH^- \longrightarrow Fe(OH)_3 + 3CL^-$$

Together, this leads to damaging of the concrete cover, decreasing the alkalinity of electrolyte in concrete, freeing the aggressive ions and finally resulting in the increase of corrosion of the rebar in the concrete.

CHAPTER 3
METHODOLOGY

3.1 Flow Chart Diagram defining the methodology of this study

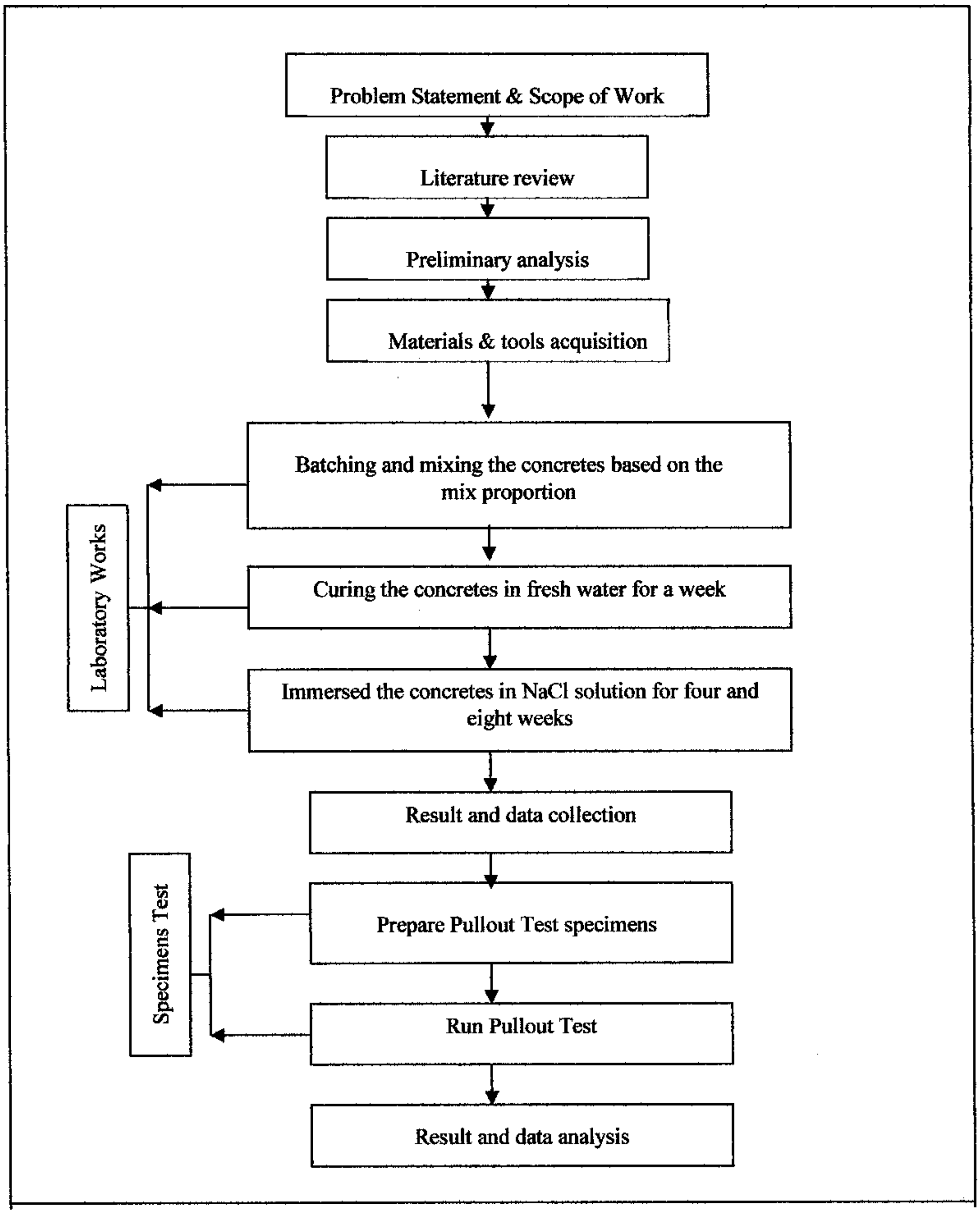


Figure 3.1: Flow Chart of the project

3.2 Summary of Steps in Methodology of the Project

3.2.1 Problem Statement & Scope of Work

This was the first step need to be taken in every research and project. In problem statement, there were three elements to be taken into considerations namely:

- A statement of the design problem proper
- Limitations placed upon the solution such as the constraints. The constraints of the study should consist of time, cost and availability of materials.
- The criterion of excellence to be worked to, such as performance, durability and safety.

The three elements correspond to the goals, constraints and criteria of the study brief.

3.2.2 Literature Review

Literature review was done in order to gain fundamentals understanding on the topic itself. Most of the sources of information were obtained from Internet, engineering journals as well as reference books.

3.2.3 Preliminary Analysis

In this stage of work, analysis on trial mix calculation as attached at the Appendices, was performed based on concrete formulas and some assumptions. Basically, there are 24 specimens of specimens to be completed within the time frame of the Final Year Project

3.2.3.1 Types of Mixtures

There were two types of mixtures used in the study namely:

- Mix 1(Control Mix) : 100% Cement
- Mix 2: 50% Cement + 50% PFA

3.2.3.2 Corrosion Environment

Specimens were partially immersed in 3% of Sodium Chloride (NaCl) solution for four and eight weeks after the normal curing process. Chloride ions were introduced by diluting 3% of NaCl with water. 3% of NaCl represent the average salt content of sea water.

3.2.4 Materials and Tools Acquisition

- <u>Materials</u>

3.2.4.1 Reinforcing Bars

Three different deformed bars were used throughout the study. There were 10, 12 and 16 mm diameter deformed bars.

3.2.4.2 Cement

Ordinary Portland Cement (OPC) was excellent general cement. Therefore, the cement was most widely used in the industry. OPC with high fines was selected during trial mix. OPC was selected based on the assumptions that concrete does not expose to sulphate and chloride attack.

3.2.4.3 Aggregate

Coarse aggregate that was used in the mix were limestone and fine aggregate. The fine aggregate used was unwashed sand.

3.2.4.4 Pulverized Fuel Ash (PFA)

PFA was a mineral admixture to produce high performance concrete. PFA particles was spherical and generally of greater fineness than the cement particles. Generally, PFA composed of oxides of silicon, aluminium and iron that combined to form complex amorphous and crystalline compounds.

- <u>Tools</u>

3.2.4.5 Concrete Specimens

Cylindrical moulds were used throughout the project as it was the requirement moulds for pull tests to be conducted. There were cylindrical concrete specimens (200mm by 100mm) incorporated the various steel rebars. The concrete was designed with mix proportions of 1: (cement):2.33(sand):3.5(coarse aggregates) proportion with water cement ratio of 0.55. Each of specimens will have 20mm cover. Refer to *Appendix 1: Trial Mix Calculation* for more details.

3.2.4.6 Concrete mixer

Concrete mixers must not only achieve the uniformity of the mix, just referred to, but they must also discharge the mix without disturbing that uniformity.

3.2.4.7 Pullout Machine

Pull out machine was used in order to conduct pull out test. In this test, concrete cylinder containing steel bar, mounted on a stiff plate and a jack was used to pull the bar out of the cylinder. The results of the pullout test described the bond development in hardening concrete. The bond between steel and concrete caused an inner restraint in the construction. Stresses caused by this restraint also lead to cracks. The pull-out test assumes that no concrete splitting will occur and is a measure of the bond strength in confined conditions [9].

It is important to note that with reinforced concrete members, both the concrete and the steel bars were simultaneously placed in tension in positive moment regions. However, in the pull out test mechanisms, the pulled-out steel bar was subjected to tension, while the surrounding concrete was in compression [10]. The confining compressive stresses around the steel bar were therefore reduced by positioning the bonded region of the bar away from the loaded end of the specimen.

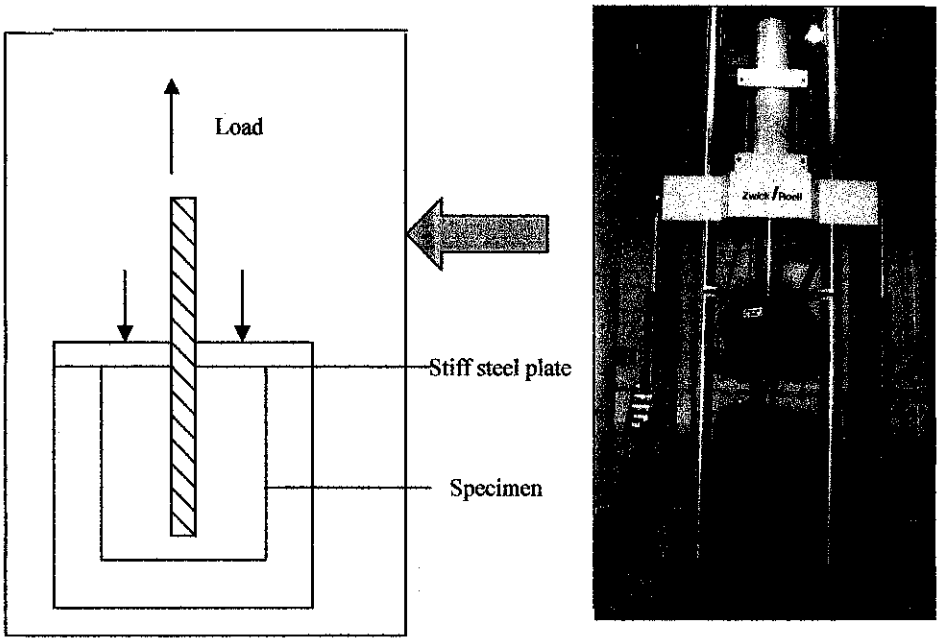


Figure 3.2: Pull out mechanism

3.2.5 Laboratory Works

3.2.5.1 Concrete Batching and Mixing

Mixing process was very important to produce uniform fresh concrete. The mixing operation consisted essential of rotation and stirring in order to coat the surface of all aggregate particles with cement paste and to blend all the ingredients of concrete into uniform mass. The uniformity of the concrete should not be disturbed by the process of discharging from the mixer. The concrete mixer should be wet before feed in the aggregate.

During concrete mixing, small amount of water was fed into the mixer after coarse aggregates fed into the mixer uniformly and simultaneous. After that fine aggregate and cement will be fed into mixer. After all aggregate and cement fed into mixer, remainder of water was fed into the mixer. The mixing time of the concrete mix was not more than 2 minutes.

3.2.5.2 Curing

In order to obtain good quality concrete, the specimens were placed in the curing tank in order to prevent water loss through evaporation during development of strength concrete. The curing in the fresh water for all specimens was a week instead of 28 days. After a week, the specimens were immersed in the NaCl solution for 28 days.

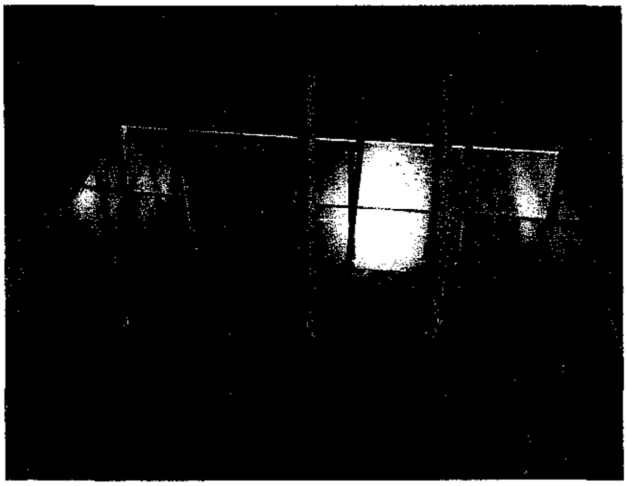


Figure 3.3: Curing in fresh water

3.2.5.3 Immersed in Sodium Chloride (NaCl) solution

All the specimens were immersed in the Sodium Chloride (NaCl) solution for four and eight weeks. The objective of the stage was to introduce ion chloride for corrosion purposes.

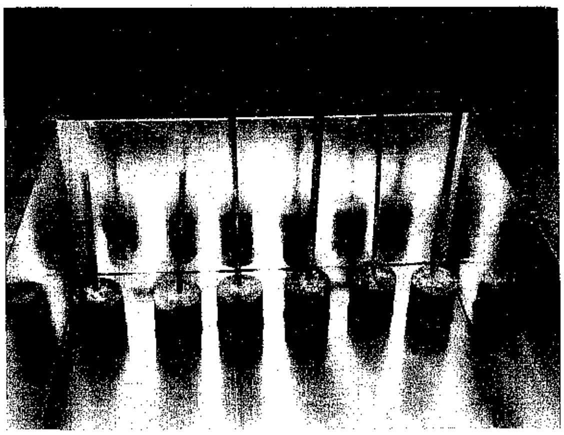


Figure 3.4: Immersed in Sodium Chloride (NaCl) solution

3.2.6 Specimens Test

3.2.6.1 Prepare and Run Pull Out Test

Specimens that already completed the immersed process in NaCl solution were prepared for Pullout Test. The Pull out Test was performed by the machine and all the results in form of graphs were obtained.

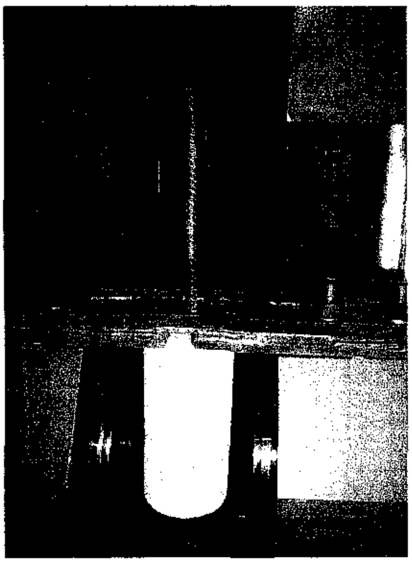


Figure 3.5: Specimen and setup of pull out test

3.2.7 Result and Data Analysis

All the results that obtained from observation and Pull out Test were analyzed. Complete calculation will be developed from the overall analysis.

CHAPTER 4
RESULTS AND DISCUSSION

4.1 Analysis on the level of corrosion of steel bars

Chloride ions were introduced into the reinforced concrete specimens through a natural migration process by immersed the specimens in a solution of 3% sodium. From the experiment that have been conducted for both mixes and phases, local corrosion mainly concentrate at the area over which reinforcement yields instead of along the embedded rebar in the concrete as it was effectively reduced the ductility of the reinforcement. Based on the analysis, it have found that the local corrosion occurred was pitting corrosion.

Pitting corrosion was characterized by the fact that the depth of penetration is much greater than the diameter of the area affected. Pitting was one of the most destructive forms of corrosion. Pitting will attack at the weak point and ruptures the passivation of the film. This will result in reduction of cross sectional area and brittle fractures. It can be seen that small cavities penetrating into the surface over a localized area. In terms of pitting corrosion, control mix showed a greater corrosion effect than Mix 2 (50% cement + 50% PFA). In addition to that, larger diameter rebar will experienced greater corrosion effects too. Mix 2 experienced less severe corrosion due to the presence of PFA. Replacing a percentage of the cement with Pulverized Fuel Ash (PFA) produced a significantly less permeable concrete with improved resistance to aggressive conditions.

Used of fly ash increases the absolute volume of cementitious materials (cement plus fly ash) compared to non-fly-ash concrete; therefore, the paste volume was increased, leading to a reduction in aggregate particle interference and enhancement in concrete workability. The spherical particle shape of fly ash also participates in improving workability of fly ash concrete because of the so-called "ball bearing" effect [11]. Refer to *Appendix 2: Sample of Level of Corrosion for Control Mix and Mix 2.*

The cover thickness was an important item to be checked whether it was within the value specified by the specification or not. Too thin cover thickness may result in bar corrosion. In this experiment, 20mm cover was used throughout the project which seemed sufficient to protect the rebar in the concrete. The nominal cover for all steel, and allows for maximum fixing tolerance such that the actual cover does not fall below 5mm less than that specified [7]. The basic requirements are given in *Appendix 3: nominal covers and mixes requirements for normal weight 20mm maximum size aggregate concrete (BS 8110).*

Although the surface concrete was affected, the reinforcing steels were remained protected by alkaline concrete. Once this covers breaks down, water and possibly sodium chloride ions can reach the steel, rusting and consequent expansion lead rapidly to cracking and spalling of the cover concrete and severe damage.

However, measurements of loss cross sectional area for overall specimens were not as significant as there were minors corrosion effects detected. Corrosion cannot be so severe within two months as basically, corrosion needs about 10 years or more to create such serious effects to the structural. Longer duration is required to initiate greater corrosion effects. A loss of cross section in a member causes a reduction in strength and stiffness that leads to increased stress levels and deformation without any change in the imposed loading. Flexure, shear, and buckling strength may all be affected.

4.2 Results from the pullout test

4.2.1 Theoretical bond, F_{tb}

- **Control Mix**

Table 4.1: Theoretical bond force

Steel Bar Diameter, ϕ	Length embedded (mm)	Theoretical bond, F_{tb} (kN)
10	180	14.08
12	180	16.90
16	180	22.53

- **Mix 2**

Table 4.2: Theoretical bond force

Steel Bar Diameter, ϕ	Length embedded (mm)	Theoretical bond, F_{tb} (kN)
10	180	10.12
12	180	12.15
16	180	16.20

4.2.2 Control Mix

- **Corrosion for four weeks**

Table 4.3: Experimental bond force of control mix for 4 weeks

Steel Bar Diameter, ϕ	Length embedded (mm)	Experimental force bond, F_{be} (kN)
10	180	29.5
12	180	39.5
16	180	41.5

- **Corrosion for eight weeks**

Table 4.4: Experimental bond force of control mix for 8 weeks

Steel Bar Diameter,ϕ	Length embedded (mm)	Experimental force bond, F_{be} (kN)
10	180	40.0
12	180	49.0
16	180	51.5

4.2.2 Mix 2 (50% Cement + 50% PFA)

- **Corrosion for four weeks**

Table 4.5: Experimental bond force of Mix 2 for 4 weeks

Steel Bar Diameter,ϕ	Length embedded (mm)	Experimental force bond, F_{be} (kN)
10	180	33.75
12	180	37.50
16	180	59.50

- **Corrosion for eight weeks**

Table 4.6: Experimental bond force of Mix 2 for 8 weeks

Steel Bar Diameter,ϕ	Length embedded (mm)	Experimental force bond, F_{be} (kN)
10	180	49.0
12	180	34.0
16	180	61.0

Refer to *Appendix 4: Calculations on Bond Forces*

4.3 Summary of the pullout test result

4.3.1 Control Mix

Steel Bar Diameter, ϕ(mm)	Reasons for machine halting Corrosion for:		Bond Strength kN	
	4 weeks	8 weeks	4 weeks	8 weeks
10	Rebar snapped		29.5	40
12	Rebar slipped from the concrete	Concrete crushed	39.5	49
16	Concrete crushed		41.5	51.5

4.3.2 Mix 2 (50% Cement + 50% PFA)

Steel Bar Diameter, ϕ(mm)	Reasons for machine halting Corrosion for:		Bond Strength, kN	
	4 weeks	8 weeks	4 weeks	8 weeks
10	Rebar slipped from the concrete	Concrete crushed	33.75	49
12			37.5	34
16			59.5	61

Refer to *Appendix 5: Typical graph of pullout test*

4.4 Discussion on the Pull out test result

The results of the pullout test described the bond development in hardening concrete. The bond between steel and concrete caused an inner restraint in the construction. Stresses caused by this restraint also lead to cracks. The pullout test was a measure of the bond strength in confined conditions.

4.4.1 Control Mix

- **Y10 reinforcement bar**

In the test specimen of reinforcement bar Y10 of control mix, which well confined in the center of the specimen, pullout failure was obtained. Theoretically, the bond failure occurred after breaking of the initial bond which of adhesion and interlocking of the cementitious matrix with the steel surface, force transfer mainly governed by bearing ribs against the concrete. However, in this case, the reinforcement bars Y10 broken before bond failure occurs. This might due to the Y10 rebar that was too small to resist the forces induced. To overcome the problem, larger steel rebar diameter need to be used.

- **Y12 and Y16 reinforcement bar**
  - **<u>Corrosion 4 weeks</u>**

    For Y12 of control mix, the rebar came out from the concrete with some cracking seen along the concrete. In other words, the rebar have achieved sufficiently forces that the rebar was able to come out from concrete after the bond failure occurs.

  - **<u>Corrosion 8 weeks</u>**

    The specimens were crushed two but the bond forces of Y16 can be higher than expected since it was restraint by major corrosion along the rebar. The crushed of concrete showed that the steel bar diameter of Y16 is stronger that the concrete. Thus, the concrete were not able to sustain the greater tension forces induced by the pullout machine resulting in concrete crashed. The corrosion that initiated along the rebar at the intermediate point of the concrete also contributed to the action.

Refer to *Appendix 6: Corrosion 4 weeks of Control mix* and *Appendix 7: Corrosion 8 weeks Control mix.*

4.4.2 Mix 2 (50% Cement + 50% PFA)

- **Y10, Y12 and Y16 reinforcement bar**
  - **Corrosion 4 weeks**

    For all specimens, the rebar came out from the concrete with cracking detected along the concrete but no concrete crushed or split detected. The greater the size of the rebar, the greater the cracking is. However, these specimens have achieved the sufficient forces required to pullout the rebar from the concrete.

  - **Corrosion 8 weeks**

    The specimens' concretes were crashed as it had achieved the maximum forces that were induced by the machine. The physical property of the PFA has played a very important role to improve compressive strength of the concrete. As mention earlier, PFA is greater fineness than cement particles and thus improve the microstructure of the hydrated cement paste.

    This effect has contributed a better packing and reduction in volume of entrapped air in the concrete which eventually increase the compressive strength of concrete. In addition this packing effect has provided a strong adhesion and interlocking of the cementitious matrix with the steel surface. So higher force needed to break the effective bond that exists on the interface between steel bar and concrete.

Refer to *Appendix 8: Corrosion for 4 weeks of Mix 2* and *Appendix 9: Corrosion of 8 weeks of Mix 2*

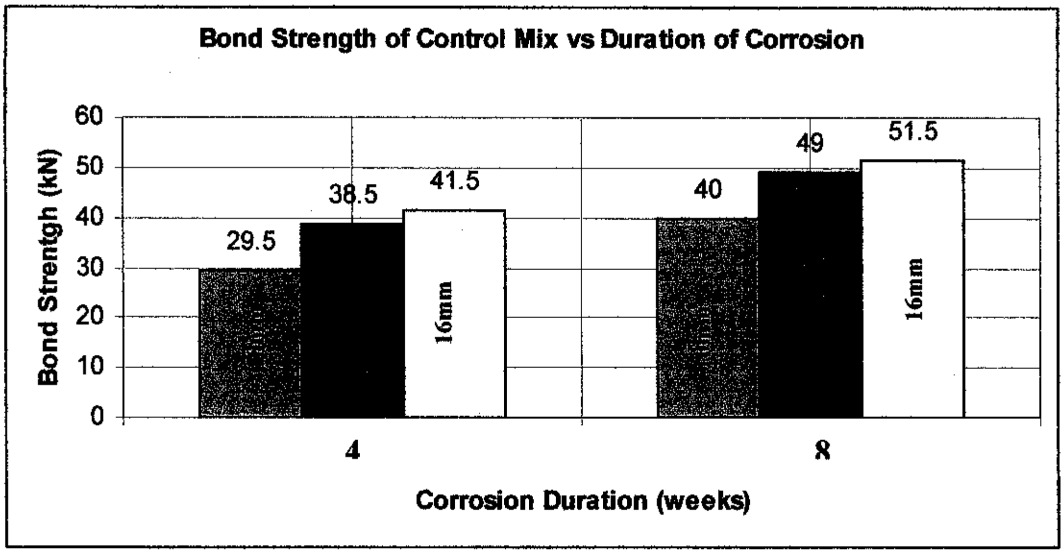
4.5 Bond Strength

The bond strength of deformed bars and concrete increased with corrosion up to a certain amount. The concrete cover seemed to have no effect on the bond strength. Based on the graph 4.1 and 4.2, it is shown that the bond strength of each particular steel bar diameter is increasing with the increasing of steel bar diameter and corrosion duration. The longer the specimens were immersed in the NaCl solution, the higher the bond strength of the concrete was, since the corrosion initiation is small. Furthermore, the concretes became even stronger as time goes by, which result in contributing of good bond between concrete and steel bar diameter. If the specimens were immersed in longer duration such as up to 8 years as well as increased the concentration of NaCl solution, the results would need further discussion since the corrosion initiation would be greater.

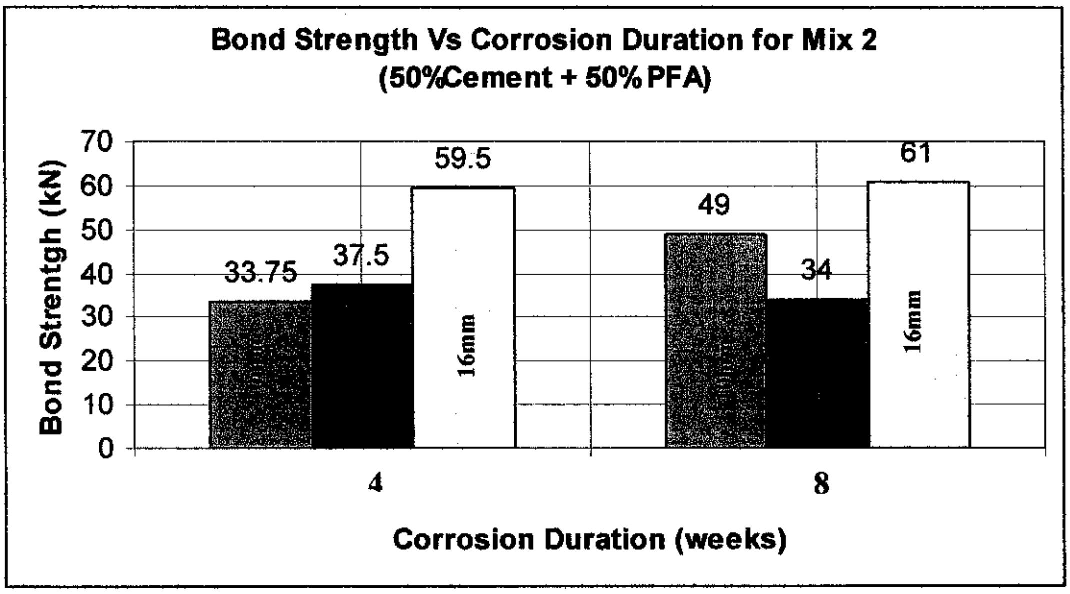
The bond strength gained by Mix 2 was higher than the control mix. This was due to application of PFA in the mixtures. The PFA contribute strength to the concrete has been attributed to few distinct factors which are by reducing the mix water demand, increasing the effective volume of the paste in the mix and pozzolanic reaction. These characteristics improve the workability, denser matrix structure and homogeneity of the concrete mix which eventually increase strength of concrete. Moreover, the pozzolanic reaction of the PFA with Portland cement hydration goes on gradually to develop higher strength values compared to normal concrete [11].

However in graph 4.2, for Y12 reinforcement bar, the bond strength for corrosion 8 weeks (34kN) was smaller than corrosion 4 weeks (37.5 kN). It has been observed that the corrosion is quite greater at the intermediate point of concrete and steel bar of Y12 Mix 2 compared to Y12 control mix. Further study need to be done in order to figure out the reason of the results contradiction.

- **Control Mix**



Graph 4.1: Bond Strength of Control Mix vs. Duration of Corrosion

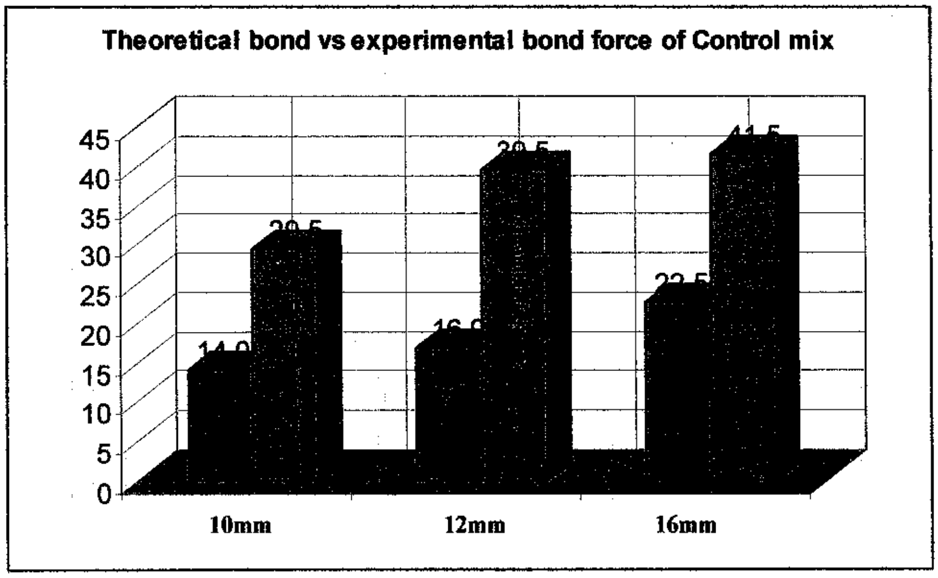


Graph 4.2: Bond Strength of Control Mix vs. Duration of Corrosion

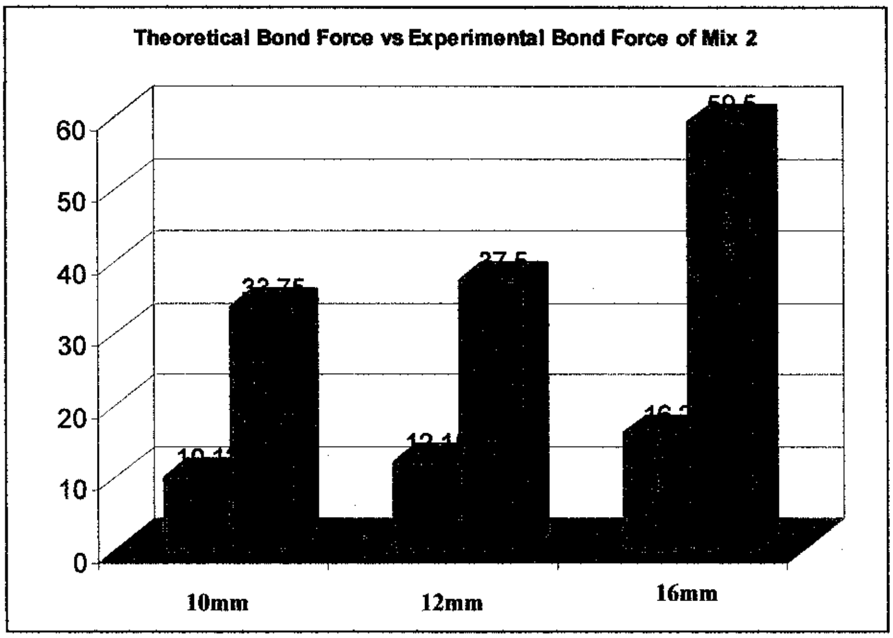
4.6 Theoretical Bond Force

Based on the graph below, it was shown that the theoretical bond forces for Control mix and Mix 2 were smaller compared to the experimental value obtained. The theoretical bond forces were obtained from equation of $(L\pi\phi)f_{bu}$. This deviation shows that the anchorage bond equation need to be modified so that it can reflects bond forces accurately. The equation should consider overall aspects that contribute to the performance of the concrete. Refer to 4.2.1 for more details. By taking sample value for corrosion for 4 weeks for both mixes, the comparison was as below:

- *Corrosion 4 weeks*



Graph 4.3: Theoretical bond force vs. Experimental bond force of Control mix



Graph 4.4: Theoretical bond force vs. Experimental bond force of Mix 2

CHAPTER 5: CONCLUSION AND RECOMMENDATION

5.1 Conclusion

- Pitting corrosion was detected at the bottom of the rebar as well as at the intermediate between the rebar and the concrete on the surface. Based on the result, it is observed that the bigger the steel diameter, the severe corrosion initiated.
- The bond strength gained by PFA was higher than the control mix. This was due to application of PFA in the mixtures. Furthermore, the bond strength of each of types of concrete was increased with the increased of the steel bar diameter size due to the good grip between the steel bar diameter and the concrete.
- The theoretical bond forces for Control mix and PFA were smaller compared to the experimental value obtained. The theoretical bond forces were obtained from equation of $(L\pi\phi)f_{bu}$.
- The effects of corrosion of steel rebar of the bond strength for 4 and 8 weeks result in minor corrosion. However, the bond strength of the concrete is increasing with the increasing of steel bar diameter. From overall results, it can be concluded that the main objective of the study (1) To determine the bond strength of different types of concrete by pull-out test using different diameters of bars and (2) To study the effects of corrosion environment on bond strength and compare with the bond strength as obtained in a control environment have been achieved.

5.2 Recommendation

- Reduction in cross section area of the rebar were difficult to determined since the corrosion occurred was so small due to exposing to the NaCl solution for 28 days. If longer exposing period to the NaCl solution implemented, the corrosion occur will result in severe reduction of cross sectional area. Thus, reduction in cross sectional area can be calculated and determined.
- The experiment should be conducted based on acceleration techniques instead of static approach. By this way, it will help to get more accurate and reliable result. More findings can be obtained based on the acceleration approach.
- The theoretical bond forces were smaller than the experimental bond forces for both mixes. This deviation shows that the anchorage bond equation need to be modified so that it could reflects bond forces accurately. The equation should consider overall aspects that contribute to the performance of the concrete.

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APPENDIX 1: TRIAL MIX CALCULATION

- **TRIAL MIX CALCULATION**

The trial mix proportion design was based on 1 (cement): 2.33 (fine aggregate): 3.5 (coarse aggregate) and the water/ cement ratio used was 0.55.

- **Control Mix (100% cement)**

Volume of a cylinder = $\pi\left(\frac{0.10^2}{4}\right)0.2 = 0.001571\text{m}^3$

Total volume for 6 specimens = 6 x 0.001571
= 0.009425 m^3

Add 15% loss during trial mix, quantity of specimens required
= 1.15 x 0.009425
= 0.0108 m^3

Assumed concrete density = 2400 kg/ m^3

Cement: $\frac{2400}{(1+2.33+3.5)} \times 0.0108 = 3.52$ kg

Fine aggregate: $2.33 \times 3.52 = 8.20$ kg

Coarse Aggregate: $3.5 \times 3.52 = 12.32$ kg

Water: $0.55 \times 3.52 = 1.94$ kg

- **Mix 2 (50% cement + 50% PFA)**

Cement = $0.5 \times 3.52 = 1.76$ kg

PFA = $0.5 \times 3.52 = 1.76$ kg

Fine aggregate: $2.33 \times 3.52 = 8.20$ kg

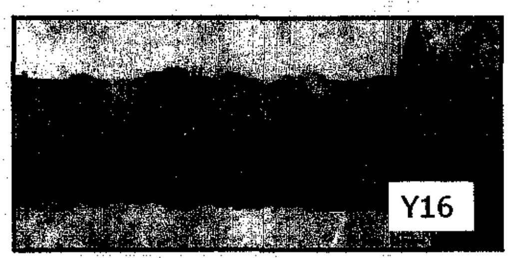
Coarse Aggregate: $3.5 \times 3.52 = 12.32$ kg

Water: $0.55 \times 3.52 = 1.94$ kg

- ***APPENDIX 2: SAMPLE OF LEVEL OF CORROSION FOR CONTROL MIX AND MIX 2***

LEVEL OF CORROSION

- MIX 1 (100% Cement)



- MIX 2 (50% Cement + 50% PFA)

- ***APPENDIX 3: NOMINAL COVERS AND MIXES REQUIREMENTS FOR NORMAL WEIGHT 20MM MAXIMUM SIZE AGGREGATE CONCRETE (BS 8110)***

Environment classification	**Nominal cover to all reinforcement (mm)**				
Mild: for example , protected against weather or aggressive conditions	25	20	20	20	20
Moderate: for example, sheltered from severe rain and freezing while wet; subject to condensation or continuously under water; in contact with non-aggressive soil	-	35	30	25	20
Severe: for example: exposed to severe rain; alternate wetting and drying; occasional freezing or severe condensation	-	-	40	30	25
Very severe: for example exposed to sea water spray, de-icing salts, corrosive fumes or severe wet freezing	-	-	50*	40*	30
Most Severe: for example, frequently exposed to sea water spray, de-icing salts or in tidal zone to 1 m below low water	-	-	-	-	50
Abrasive: exposed to abrasive action(sea water and solids, flowing acids water, machinery or vehicles)	-	-	-	As above + cover loss allowance	
Maximum free water/cement ratio	0.65	0.60	0.55	0.50	0.45
Minimum cement content (kg/m^3)	275	300	325	350	400
Lowest concrete grade	C30	C35	C40	C45	C50

Note: * Entrained air required for wet freezing

• *APPENDIX 4 : CALCULATIONS ON BOND FORCES*

- **Compressive Strength Values**

The compressive value of each mixture was obtained by casting three sample cubes of 150mm x 150mm cubes for each mixture. After curing process for 28 days, compressive test were conducted on each of the cubes. Below were the results:

Table 1: Compressive Test Results

Mix	Compressive Strength of Concrete, f_{cu} (N/mm^2)		
	Cube 1	**Cube 2**	**Cube 3**
Control Mix	38.91	38.17	38.78
Mix 2	20.64	19.82	19.93

- **Calculation on compressive strength of concrete, f_{cu} (N/mm^2)**

f_{cu} of control mix: $\frac{(38.91+38.17+38.78)}{3} = 38.62N/mm^2$

f_{cu} of Mix 2 (50% Cement + 50% PFA) = $\frac{(20.64+19.82+19.93)}{3} = 20.13N/mm^2$

- **Ultimate anchorage bond stress, f_{bu}**

Taking β as Type1: Deformed bars in tension = 0.4

f_{bu} Control mix: $0.40\sqrt{38.62}$ =2.49 N/mm^2

f_{bu} Mix 2: $0.40\sqrt{20.13}$ =1.79N/mm^2

- **Bond Forces**

Sample calculation for steel bar diameter of 10mm for control mix:

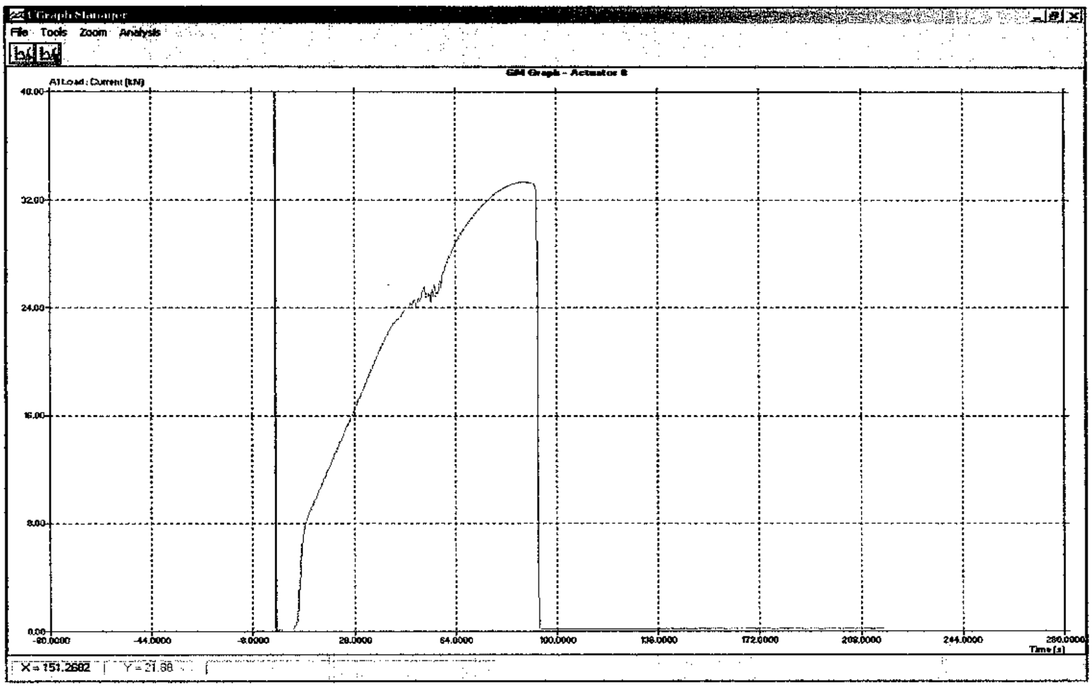
Control Mix: (180x π x 2.49) =14.08kN

Sample calculation for steel bar diameter of 10mm for Mix 2:

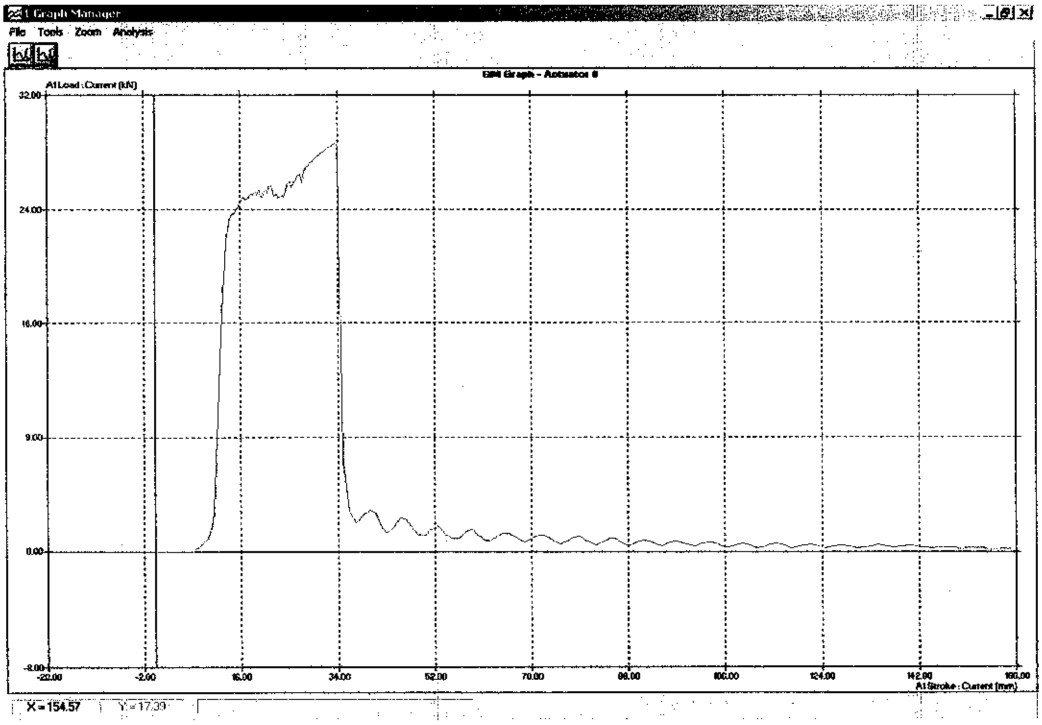
Mix 2: (180x π x 1.79) =10.1kN

- ***APPENDIX 5: TYPICAL GRAPH OF PULLOUT TEST***

- **Typical Graph of pull out test for Y10 reinforcement for Control mix**



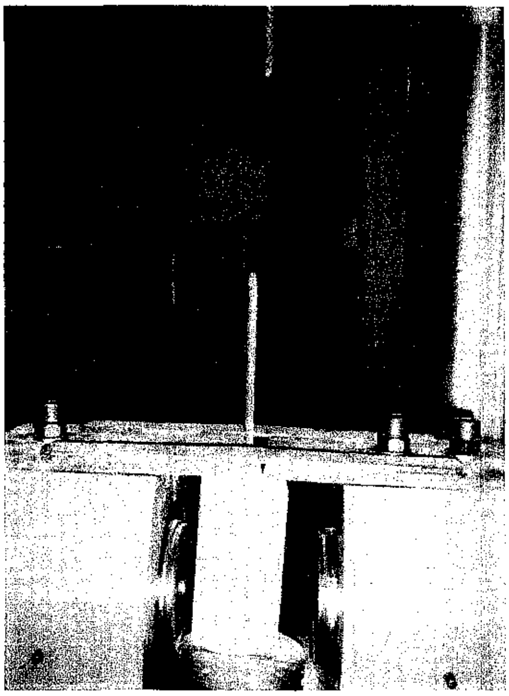
- **Typical Graph of pull out test for Y10 reinforcement for Mix 2**

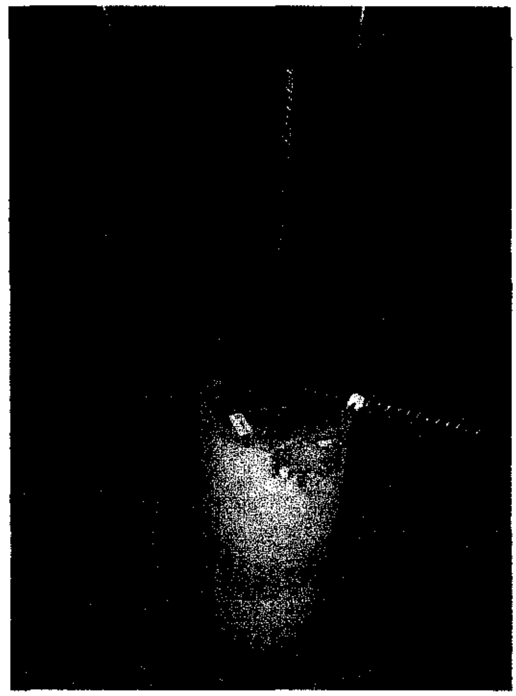


- ***APPENDIX 6: CORROSION 4 WEEKS OF CONTROL MIX***

CONTROL MIX (100% CEMENT)

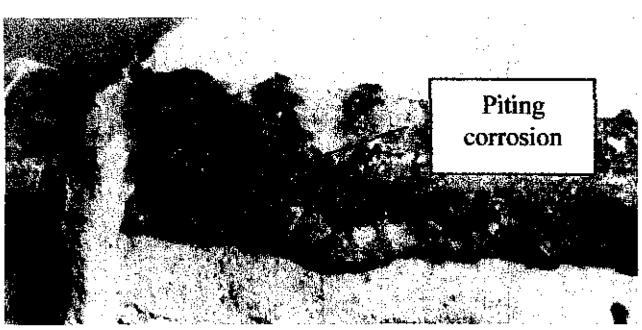
- **Y10 reinforcement bar**

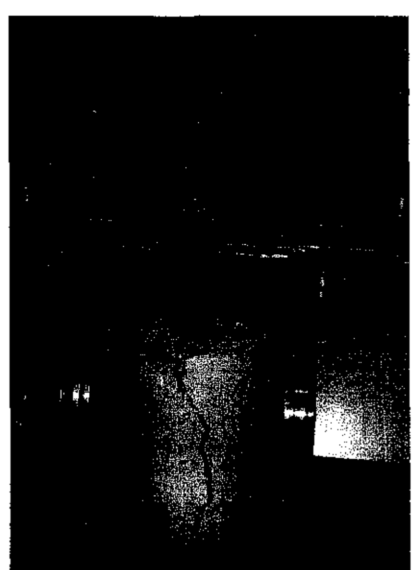




Steels break first before the bond of concrete failed

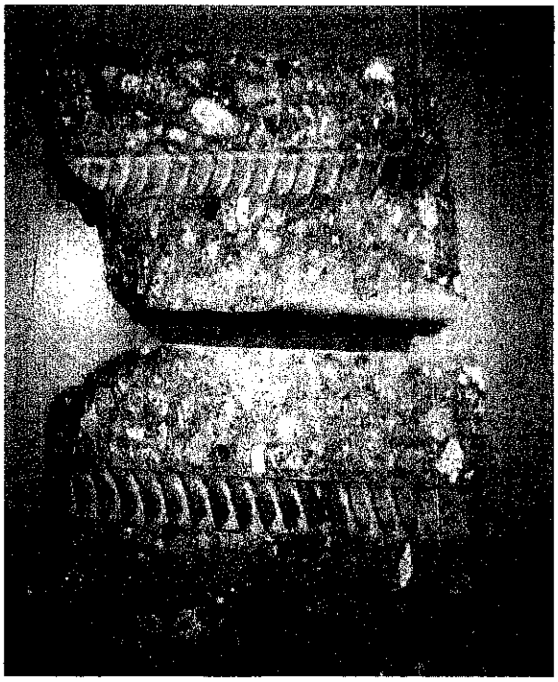
- **Y12 Reinforcement Bar**





Steel rebar slipped from the concrete with cracks

- **Y16 Reinforcement Bar**

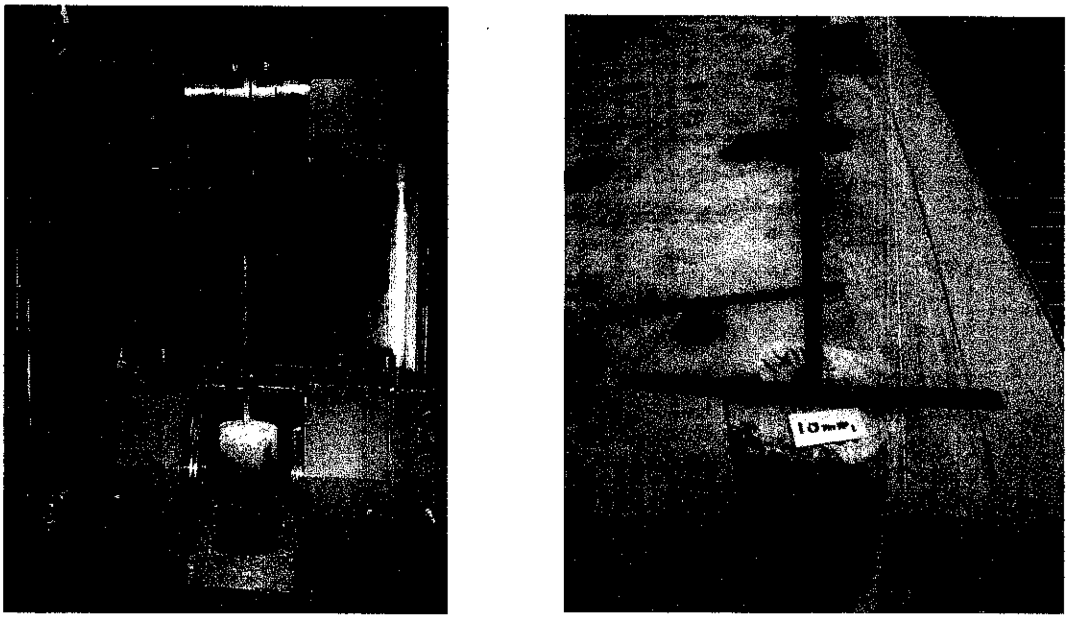


The concrete crushed. Corrosion (as shown by the arrow) was observed at the bottom of the concrete as well as at the intermediate point between steel and concrete.

- ***APPENDIX 7: CORROSION 8 WEEKS OF CONTROL MIX***

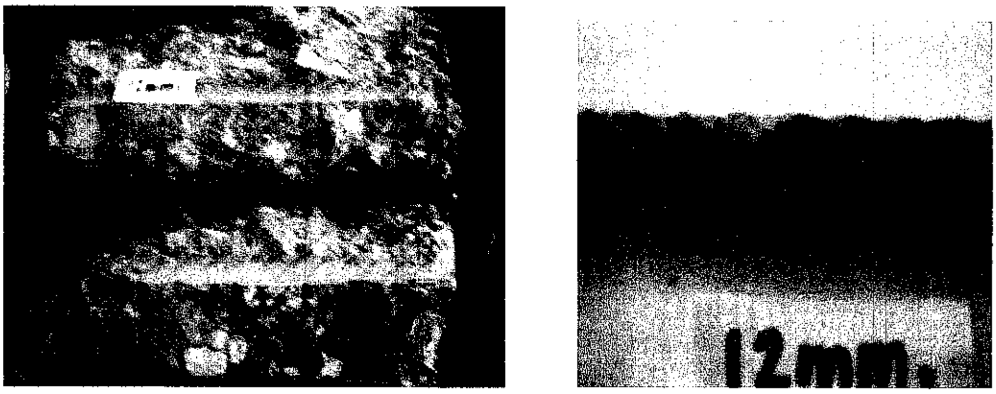
CONTROL MIX (100% CEMENT)

- **Y10 reinforcement bar**



The steel rebar snapped

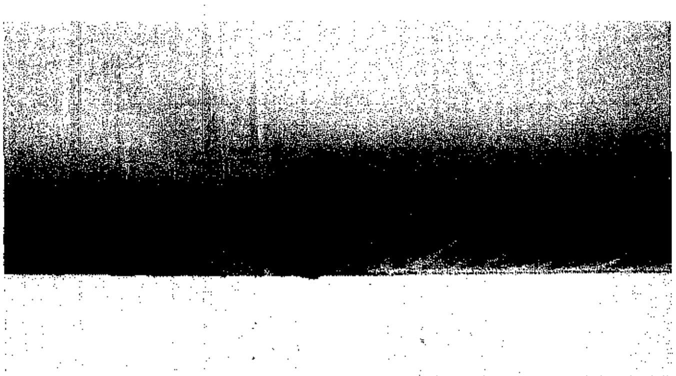
- **Y12 reinforcement bar**



Concrete crushed

- **Y16 reinforcement bar**

Concrete crushed as it was not able to withstand the forces induced by the steel bar diameter

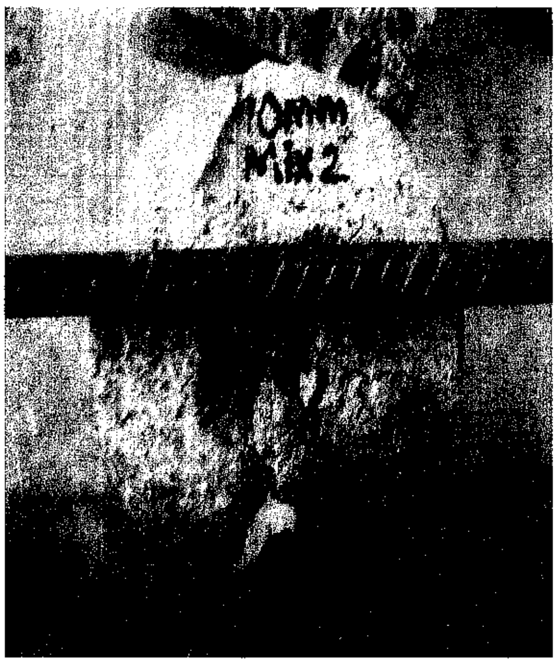


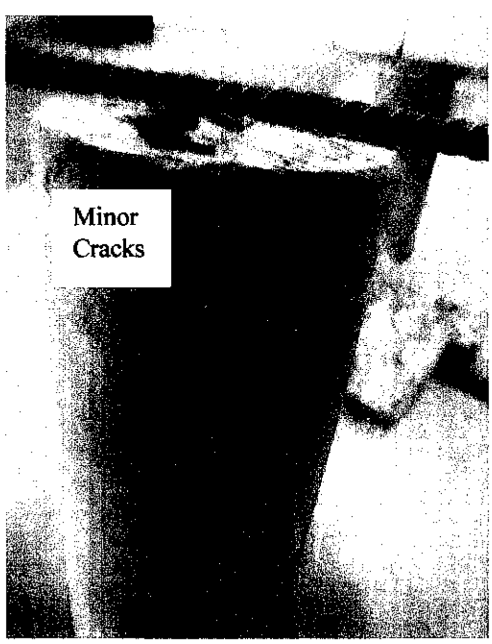
Corrosion was observed along the steel bar diameter

- ***APPENDIX 8: CORROSION 4 WEEKS OF MIX 2***

MIX 2 (50 %CEMENT + 50% PFA)

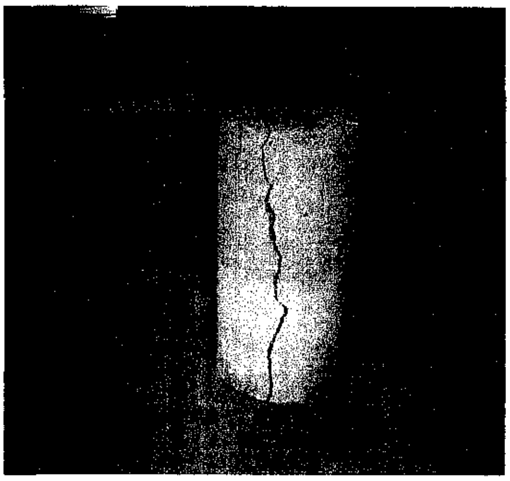
- **Y10 reinforcement bar**





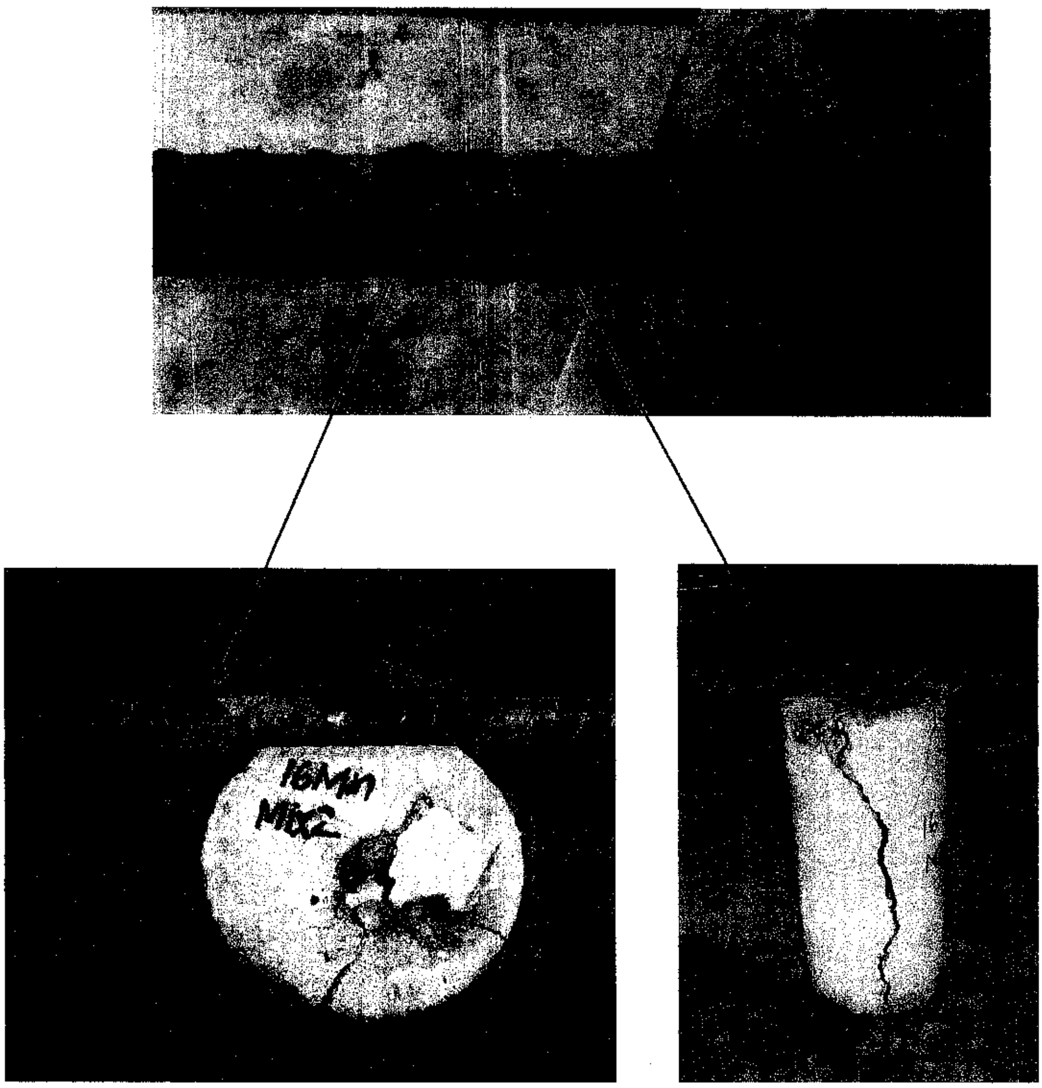
The steel rebar slipped from the concrete after achieved maximum forces induced by the pullout machine

- **Y12 Reinforcement Bar**



The steel rebar slipped from the concrete with corrosion detected at the interface between the concrete and steel rebar

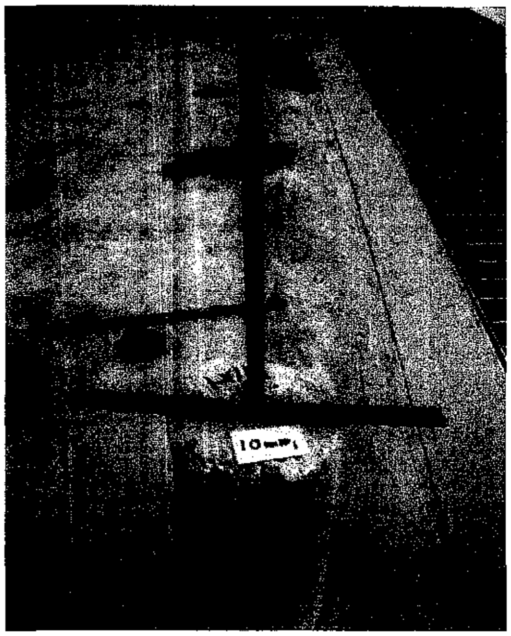
- **Y16 Reinforcement Bar**



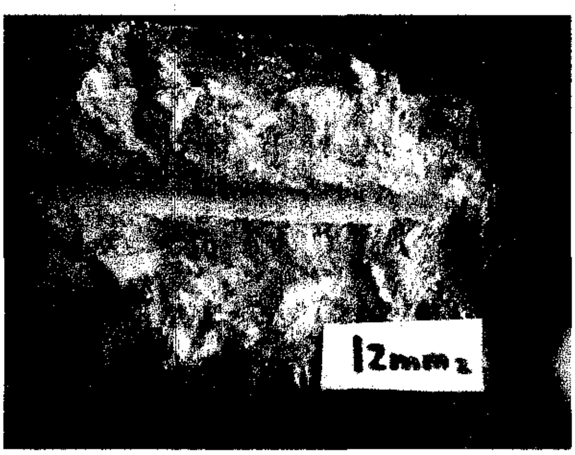
The steel rebar also was slipped from the concrete with greater corrosion detected

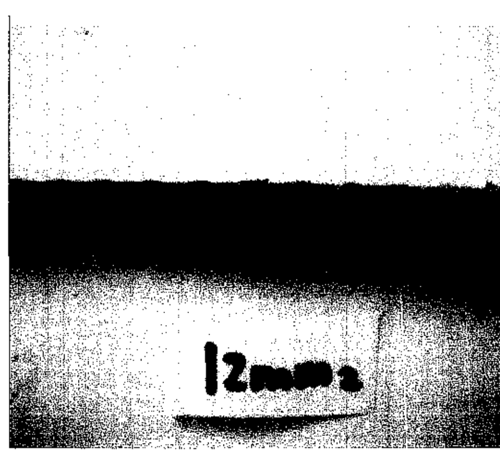
- ***APPENDIX 9: CORROSION 8 WEEKS OF MIX 2***

  - **Y10 Reinforcement Bar**



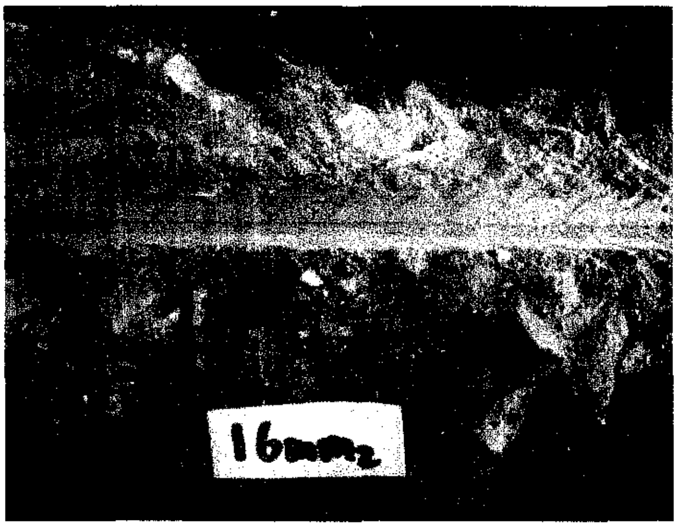
  - **Y12 Reinforcement Bar**



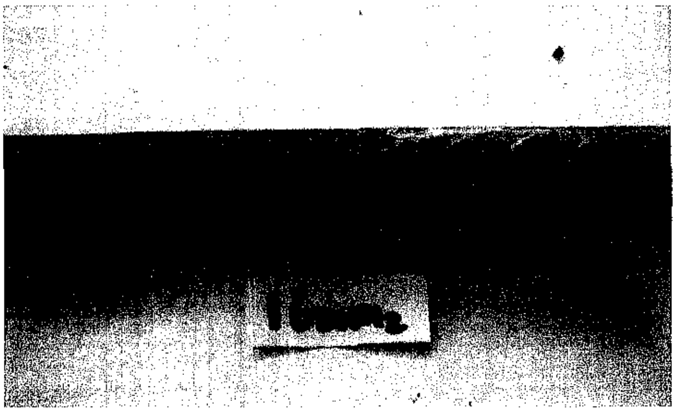


Concrete crushed with corrosion observed along the steel bar diameter

- **Y16 Reinforcement Bar**



Concrete crushed



Minor corrosion was observed along the steel bar diameter