KWAME NKRUMAH UNIVERSITY OF SCIENCE AND TECHNOLOGY

COLLEGE OF ART AND BUILT ENVIRORNMENT

DEPARTMENT OF BUILDING TECHNOLOGY

"MODELING THE BOND STRENGTH OF REINFORCED CONCRETE WITH OIL POLLUTED REBARS"

By

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(BSc Building Technology)

A thesis submitted to the Department of Building Technology in partial fulfillment of the Requirements for the award of the Degree of

Master of Philosophy in Building Technology

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DECLARATION

I hereby declare that this submission is my own work towards the attainment of Master of Philosophy in Building Technology, and that, to the best of my knowledge, it contains no material previously published by another person nor material which has been accepted for the award of any other degree of the University, except where due acknowledgement has been made in the text.

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DEDICATION

To my late father Mr. Kofi Boateng

Daddy I love you!!

May your soul Rest In Perfect Peace

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To the ever merciful father, Elohim, the Lion of the tribe of Judah, king of the universe, the allknowing, I bow in reverence of your supremacy. My heart is filled with joy beyond measure for your greatness. How can I repay you for your unflinching love for me? When the world deserted me in the wilderness you were with me. May your kingdom forever reign.

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Posterity will never forgive me if I fail to acknowledge the immense support offered me by Mr. Atongo Luios Sakyimo, the Managing Director of AESL Accra for allowing me to use their Laboratory at Weija, Accra. Daddy God bless you. I also thank the following laboratory technicians: Mr. Jonathan, Mr. Ketu and Engineer Odai who assisted me through the laboratory work.

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ABSTRACT

The serviceability and ultimate strength of reinforced concrete structures is greatly influenced by the strength of the bond mechanism between steel and concrete. The bond ensures that the structure maintains its state of equilibrium under any giving load. This study examined the basic influence of used engine oil on bond strength at the steel–concrete interface and subsequently develops models for predicting it. Ninety (90) concrete specimen of dimension 150 x 150 x 150mm with rebar inserts were used. Three (3) grades of concrete (C15, C20, C25) were designed. The loss adhesion and the decrease in the frictional resistance was evaluated using pullout test specimens with different levels of rebar oil pollution. The results revealed that used engine oil coating has adverse (negative) effect on the bonding action between concrete and steel reinforcement. It forms a layer on the concrete-steel interface which impairs the gripping of the steel bar within the concrete-steel interface and consequently gives rise to a weakened bond. The loss in bond strength was higher for mild steel than for high tensile steel. Finally, using the regression analysis tool pack in Microsoft excel (2010 version) the relationship between the dependent variable (bond strength) and the independent variables (degree of oil pollution and concrete compressive strength) was established for two grades of steel (Mild steel and high
tensile) as follows: $\tau_{Msteel} = 0.2699 f_{cu} - 1.8451\ X_P$ and $\tau_{Hsteel} = 0.3105 f_{cu} - 1.5939\ X_P$.
From the findings it was concluded that the use of oil as formwork releasing agent on construction site should be carefully carried out to ensure that the bars are free from oil. Moreover, designers should factor the effect of oil in the design of the ultimate bond strength of reinforced concrete structures in situation where oil is used on the construction site.

Key words: Bond strength, concrete, used engine oil, compressive strength, mild steel, high tensile steel, steel-concrete interface.

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CHAPTER ONE

GENERAL INTRODUCTION

1.1 Background

In reinforced concrete (R C) structures as in other composite members, there is load transfer between the steel and the concrete. This mechanism ensures that the materials undergo the same stresses and deformations in order to prevent discontinuity, slip or separation of the two materials when subjected to load (Josiah 2010; Hadi 2008; Bhargava *et al*, 2007). Bhargava *et al* (2007) reported that this can only happen if there is adequate bond (anchorage) between the materials. Adukpo *et al* (2011) added that, the strength of the bond mechanism determines the forces to be transferred between the concrete and steel. In cases where an element is loaded beyond its bond strength capacity, high deformation in the form of slip occurs between the rebar and the concrete. Thus, the serviceability and ultimate strength of R C structures is significantly affected by the bond between the concrete and steel (Musa and Haido, 2013;
Bhargava *et al,* 2007; Bamforth, 2004).

According to Darwin (2005) and ACI (2003), forces are transferred from the concrete to the reinforcement in three ways: (a) Chemical adhesion between the concrete and the bar (b) Friction between the bar surface and the concrete (c) Bearing of the ribs against the concrete. It was noted that adhesion and friction provide support initially up to a certain force where the adhesion bond is broken, after which the participation of friction diminishes quickly and the mechanical bearing of the ribs on the concrete takes over carrying the entirety of the load (ACI, 2003). It was further noted that, while load transfer through bearings depends on the geometries of the steel, the magnitude of the friction and the adhesion (bond) between steel and concrete depends on the properties of the concrete, the presence of confinement around the bar, as well as the surface conditions of the bar. Based on the above, it was observed that deformed high tensile steel rebars depend heavily on mechanical interlock for load transfer with the other mechanisms providing nominal support. The bearing of concrete on the steel ribs causes the mechanical interlock. In the case of plain (smooth) reinforcing bars, the absence of ribs means force transfer through mechanical interlock is almost nil; The system therefore depends primary on the chemical adhesion and frictional resistance between the concrete and the steel (ACI, 2003).

1.2. Problem Statement

The condition at the surface of reinforcement bar plays significant role in determining the bond strength between concrete and steel. Reports indicate that the presence of contaminants such as rust, oil, epoxy, concrete splatter etc. at the concrete steel interface reduces the adhesion bond and frictional resistance between concrete and steel rebar (Lee *et al,* 2002; Adukpo *et al,* 2011; Fang *et al,* 2004 and 2006, Bilal *et al,* 2003a; Joseph and Camille, 2012). In response to this most Design Standards and Committees Reports such as ACI 301(1996) for instance stipulates that "In the casting of concrete all the rebars should be free from any material which can negatively affect the bond". ACI Manual of Concrete Inspection also states that, "reinforcement should be clean, and any oil or mortar which has been spilled on it should be cleaned."

Among the various rebar contaminants listed above, oil and corrosion are the key substances which greatly affect bond strength. The effects of corrosion have been widely studied by authors such as: Lee *et al* 2002, Fang et al, 2004 and 2006, Lamya and Alaka 2006, Bhargava *et al,* 2007 and Auyeung et al, 2000 etc. Studies on the effect of oil on the bond strength of R C structures are however limited. Bilal et al (2003a), Adukpo *et al* (2011) and Musa and Haido (2013) are among the few publications. The works by Adukpo *et al* (2011) and Musa and Haido (2013) centered on the influence of unused engine oil coatings on the bond between steel and concrete whilst Bilal *et al* (2003a) extended the scope to include the effect of used engine oil on the structural behavior of reinforced concrete elements. The above studies despite their efforts failed to present any empirical or analytical model which can be used as a guideline in analyzing bond strength. Thus, it is difficult to describe how the bond mechanism is affected by the presence of oil from empirical formulae. Investigation in this direction is therefore considered essential. The objective of the current study was to investigate the effect of used engine oil on concrete bond and consequently develop a model for predicting it (the bond strength) taking into consideration variables such as the degree of oil pollution and concrete strength (i.e. the compressive strength). The inclusion of used engine oil (a waste product from motor oil) is justified by the fact that, it is one of the agents used for releasing formwork from concrete on construction sites. The findings of the current study will help gather enough data on the usage of this material as a formwork release agent and its effect on concrete steel bond.

1.3 Aim and Objectives

1.3.1 Aim

To develop an empirical model for predicting the bond strength of reinforced concrete with oil polluted steel rebars.

1.3.2 Objectives

To address the aim of the study, the following objectives were pursued:

i. To assess the effect of oil at the concrete and steel interface on the bond strength of reinforced concrete (RC); ii. To compare the bond strength for rebar polluted with used engine oil in the transverse direction to that along the longitudinal direction of the bar.

iii. To develop a model to predict the bond strength of R C with oil polluted rebars.

1.4 Research Questions/Hypothesis

From the problem statement, the following questions were posed:

i. To what extent is concrete bond strength affected by the presence of oil at the concrete – steel interface?

ii. How does the bond strength for rebar polluted with used engine oil in the transverse direction compare with that along the longitudinal direction?

iii. What empirical formulae can be used to predict bond strength for R C with oil polluted rebars?

1.5 Scope of the study

The study involved the assessment of the effect of used engine oil from vehicles on the bond between concrete and steel. The work involved standard deformed high tensile steel and deformed mild steel rebars and concrete produced from Ordinary Portland Cement. The oil was used motor engine oil.

1.6 Methodology

The current study seeks to investigate the effect of used engine oil on the bond strength of reinforced concrete. For such cause and effect investigations Creswell (2009) and Fellow and Lui (2008) recommended the use of quantitative research design and experimental research approach since the study has a positivist focus.

In line with the above, the study involved laboratory experiments on 150mm concrete cubes cast with Ordinary Portland Cement. Three grades of concrete (i.e. C15, C20 and C25) were designed. Deformed high tensile steel and deformed mild steel rebars of 16mm diameter were inserted centrally into the cubes. Used engine oil was applied to the rebar surface as coating at varying surface area. The specimen were then mounted into a 500kN capacity electronic tensile test machine and strained until failure in the form of tensile splitting (cracking) of the concrete or pullout of the rebar was recorded. The pullout force was then recorded. In all, there were 30 tests. Each test had three (3) replicate specimens.

Finally, the relationship between the dependent variable (the bond strength) and the independent variables (i.e. degree of oil pollution and concrete strength) was established using the regression data analysis tool pack in Microsoft excel (version 2010). Based on the findings, recommendations were made.

1.7 Significance of the Study

Reinforced concrete structures cannot exist without a good bond between the steel and the concrete which ensures that load is transferred safely between the materials. During construction, the lack of sufficient data on the impact of oil as a contaminant on bond pose a significant challenge to designers. Design codes such as BS 8110 (1997), Euro Code, EN (2004) and ACI 318(2008) which serves as the basis for design by these professionals do not have sufficient data or provisions on how to estimate the magnitude of the effect of oil on bond strength and for that matter the performance of reinforced concrete. Thus, any study on concrete steel bond will help throw more light on the subject by providing sufficient data and basis for design. The current study is meant to help develop an empirical formula that will serve as a guide to designers in estimating the extent of the damage done to concrete steel bond by the presence of oil. Since reinforced concrete is currently the most widely used material for the construction of

Ghana's physical infrastructure, the findings will help developers, planners and designers to appreciate the impact of oil on concrete steel bond; one of the primary mechanisms responsible for the stability and performance of reinforced concrete. Structural failure which may results from inadequate concrete-steel bond will be reduced with adequate knowledge of the public about the effect of oil on bond. To academia, the findings will serve as a source of reference for further studies.

CHAPTER TWO

LITERATURE REVIEW

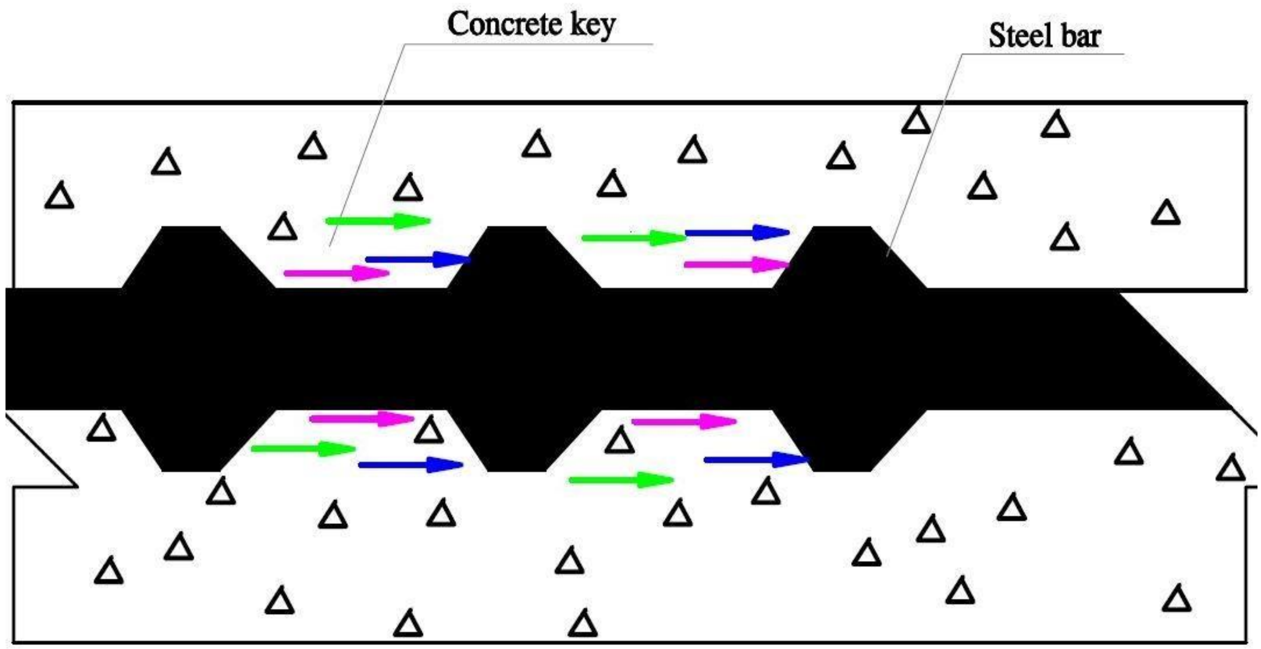
2.1 Introduction

The interaction of reinforcing steel bars with concrete is a quite complex phenomenon that has important effects on the response characteristics of reinforced concrete (R C) elements and structures under static and dynamic loads (Tassios and Yannopoulos, 1981). Generally, R C structures are designed on the premise that concrete and steel jointly take up the stresses induced in the member and that concrete's relatively low tensile strength and ductility are countered by the inclusion of reinforcement having higher tensile strength and ductility. The reinforcement bars also prevent unacceptable cracking at the region of the concrete. In the bid to maintaining the composite action and prevent deformation in the form of slip, direct stresses are transferred between the two materials. This mechanism of force transfer is known as bond and it is viewed as a continuous stress field that develops in the vicinity of the concrete steel interface (Park and Paulay 1975, Bhargava *et al*, 2007). The bond ensures that the structure maintains its state of equilibrium under any giving load. In cases where a structure is moderately loaded, the bond strength capacity will exceed demand resulting in little or no movement between the rebar and the concrete. On the other hand, if the loading is severe, demand may exceed the capacity of the system and consequently results in significant slip between the rebar and the concrete.

This chapter presents a review of various technical reports and documents on concrete-steel bond. The mechanisms of bond, bond response, bond failure and bond strength models by various scholars. The review is extended to look at the effect of oil on concrete-steel bond. The relevance of this chapter is to identify the gaps in current literature and consequently develop methods to address them.

2.2 Mechanism of Force Transfer in Reinforced Concrete

A number of mechanisms at the interface between steel and concrete are responsible for the force transfer between the two materials in R C structures. However, three primary mechanisms are dominant: (a) Mutual chemical adhesion between the concrete and steel interfaces
(b) Mechanical interlock between the lugs of the rebar and (c) Frictional resistance resulting from the bar surface deformations and the surrounding concrete (Darwin 2005; ACI, 2003). The total effect of these defines the magnitude of the ultimate bond strength. The relative contribution of the above three mechanisms to the overall bond strength depends on the strength of the concrete, the steel rebar type and the presence of contaminants such as oil, rust, epoxy etc. at the bar surface. It has been found that (ACI, 2003), deformed high tensile steel rebars relies heavily on the mechanical interlock, with the bearing resistance offered by concrete against the reinforcing steel bar ribs and friction between concrete keys and surrounding concrete both helping to a lesser extent. Plain (smooth) reinforcing bar on the other hand relies primarily on the chemical adhesion and frictional resistance between the two materials; the mechanical interlock is almost non-existent (Mo and Chan, 1996).



Adhesion and friction ( ) Bearing stress against the rib ( )

Friction b/w concrete key and surrounding concrete ( )

Fig 2.1: Force transfer mechanism for deformed bars (Ahmed et al 2007; ACI, 2003)

2.2.1 Characterization of the Bond Zone

Past studies suggest that the surrounding area between concrete and steel interface is subjected to complex stresses, strains, and deformations which are functions of several system parameters (Goto 1971, Josiah, 2010, El-Hacha *et al*, 2006). When force is applied, Bond and Radial stresses are developed (Fig 2.2). These stresses result primarily from the shear interlock between the reinforcing bar and the surrounding concrete. The bond stresses act parallel to the longitudinal axis of the rebar whereas the radial stresses are developed in a direction orthogonal to the bond stresses (ACI, 1992). The direct stresses are transferred from the concrete to the bar interface so as to change the tensile stress in the reinforcing bar along its length. For members subjected to flexure beyond the cracking state of the concrete in tension, the steel reinforcement gets tensile stresses.

Cracks also begin to form on the concrete surface. As soon as the interface cohesive cracks and radial cracks form and propagate, the bond strength diminishes rapidly and the rebar slips (i.e. lateral displacement between steel and concrete which occurs in a direction parallel to the longitudinal axis of the rebar). Radial deformations also occur in the form of displacement that is orthogonal to the longitudinal axis of the rebar (See Fig 2.3).

Mathey and Watstein (1961) observed that at rebar slip of 0.254 mm, bond stress reaches critical bond strength levels. At this stage, the interface between the reinforcing bars and concrete do not reach failure but the adhesion mechanism fail and no cracks are formed. The systems can still resist external forces until the ultimate bond stress, called nominal bond strength is reached.

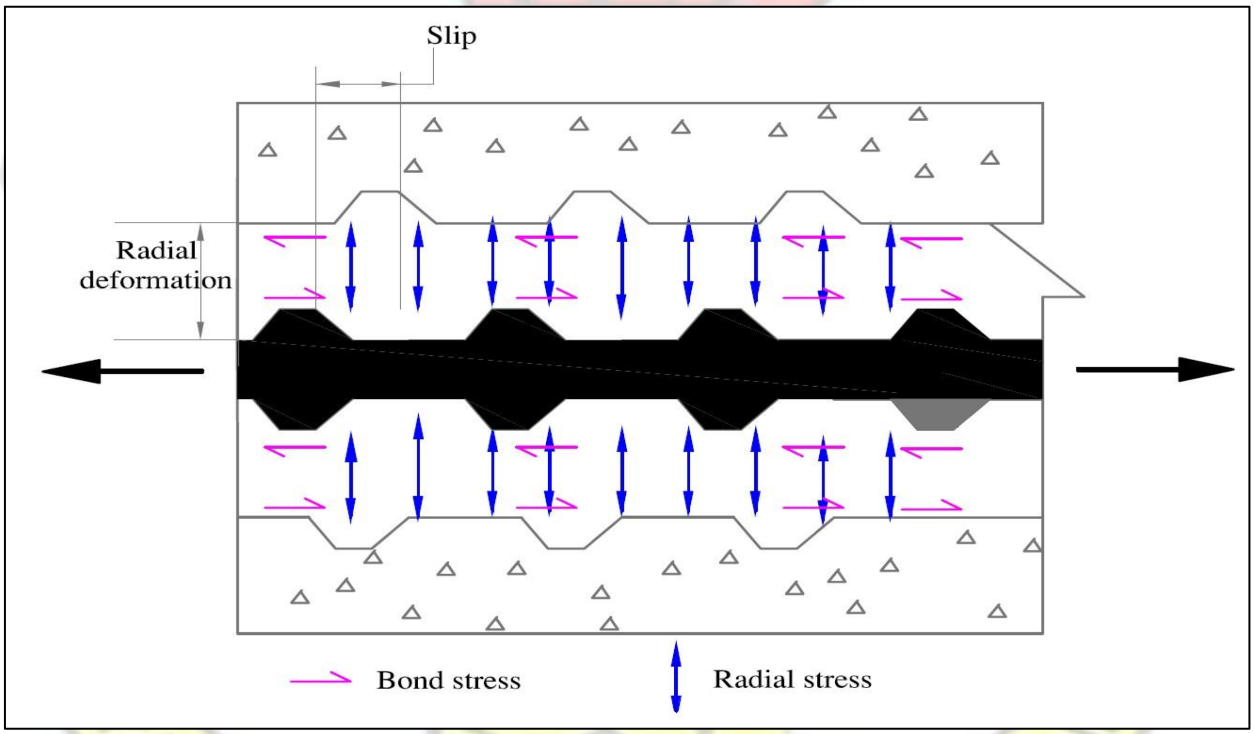


Fig 2.2: The idealized bond zone (Ahmed et al, 2007)

2.3 Bond Strength

The bond strength of R C is taken as the average bond stress calculated over the embedment length. It is calculated as follows:

$f_b = F_s/\pi\varphi_e l$ .... (Eqn. 48 of BS 8110-1:1997)

Where, f_b is the bond stress which is assumed to be uniform; F_s = the force acting on the rebar, l = the embedment length; φ_e = the diameter of the bar

The ACI (2013) defines anchorage bond stress as the bar force divided by the product of the bar perimeter or perimeters and the embedment length.

2.4 Parameters Defining Bond Response

As explained earlier in this chapter, the bond resistance of reinforced concrete is attributed to (a) the mutual chemical adhesion between the concrete and steel interfaces (b) Mechanical interlock between the lugs of the rebar and (c) Frictional resistance resulting from the bar surface deformations and the surrounding concrete. Based on the above, bond strength is said to be influenced by factors related to the concrete properties, the reinforcing bar profile and the type of contaminant/coating at the concrete steel interface. From literature (Behfarnia *et al* 2005; Johnson 2010; ACI 2003; Eligehausen et al, 1983) bond response is defined by the variables below:

(i) Concrete Properties related factors

- ✓ Concrete strength
- ✓ Curing Time

(ii) Bar Profile

- ✓ Relative rib area, Rib angle face
- ✓ Embedment length
- ✓ Size/Diameter and spacing

(iii) Presence of confinement/Cover

(iv) Rust/corrosion

(v) Surface coating

- ✓ Oil and Epoxy

2.4.1 Concrete Related Factors

(i) Concrete Strength and Composition

The deterioration of concrete at the vicinity of the steel-concrete interface, determines bond strength. Thus bond strength is defined as a function of concrete strength (Eligehausen *et al*, 1983). The tensile and compressive strengths of concrete play significant role in the bond response of reinforced concrete structures. Force transfer through bearings induces compressive stresses in the concrete key. These internal stresses are then resisted by the compressive strength of the concrete (Orangun *et al*, 1977). The development of micro cracks and the ultimate splitting of concrete are also controlled by the tensile resistance of concrete. Moreover, pullout type of bond failure is described by the crushing of the concrete in front of the ribs of the rebar. This makes the shear strength of concrete an integral factor in the ultimate bond strength.

The relative importance of compressive strength in the characterization of bond response has led to various studies proposing relationships between the two variables. Eligehausen *et al* (1983) defines the bond strength of concrete in terms of its compressive strength as

$$\tau_{bond} \propto (f_c)^{\beta} \quad \text{Where } \frac{1}{3} \leq \beta \leq \frac{1}{2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2\text{-}1)$$

In the above equation Tepfer (1979) and ACI Committee 318 (1979) simply suggest $\beta = \frac{1}{2}$.

The test results of Alavi-Fard (1999) indicated that for high strength concrete (i.e. from 70N/mm² to 90N/mm²) a beta value of one − third ($\beta = \frac{1}{3}$) gives more accurate results. Zuo and Darwin (2000) also noted that $\beta = \frac{1}{2}$ significantly under-estimates bond strength for specimen with transverse reinforcement.

The British Standard (BS 8110-1:1997) equation 49 also calculates the design ultimate anchorage bond stress, f_{bu} as

$$f_{bu} = \beta \sqrt{fcu} \qquad \ldots\ldots\ldots\ldots\ldots\ldots (2\text{-}2)$$

Where, β is a constant which depends on the type of rebar used

Besides the above, the composition of the concrete matrix also influences the bond strength characteristics. A study by Pradahan and Bhattacharjee (2009) revealed that concrete with fly ash shows better resistance to corrosion damage than open concrete. This is because the former has high electrical resistivity property. Al-sulaimani *et al* (1990) noticed that the introduction of 0.2% polypropylene fibers into concrete enhances the bond strength of concrete, particularly at the post cracking stages of corrosion. Finally, the bond strength of lightweight aggregate concrete is also reported to be higher than those of normal weight concrete because of the higher mortar strength (How-Ji et al, n.d).

(ii) Curing Time

Behfarnia et al (2005) studied the effect of initial curing on bond strength. Samples prepared with Ordinary Portland Cement were cured in curing tank for 1, 3, and 7 days. When the specimen were tested on the 28th day, the result revealed that samples with longer period of initial curing gain higher bond strength; Based on the results, the bond strength of the samples with 3 and 7 days initial curing increased by 11.8% and 12.2% respectively compared to those with samples having 1 day curing period. Moreover, it was observed that an increase in curing beyond 3 days did not considerably increase bond.

2.4.2 Bar Profile

(i) Relative Rib Area of bar

The surface characteristics of deformed rebars such as the width and height of the rib, rib spacing, rib face angle etc. significantly affects bond strength and the mode of failure. These properties are represented by a single parameter known as the relative rib area. It is defined as the rib area perpendicular to the longitudinal axis of the rebar standardized by the bar surface area between the ribs.

Studies by Darwin and Graham (993) and Johnson (2010) showed that, an increase in the relative rib area improves bond strength at the initial stages. Moreover, both rebar pullout and tensile splitting of concrete types of bond failures are observed for bars with increasing relative rib area. Further experimental studies also point to the fact that bars with steep rib angle faces greater than 40^o slips only when the concrete in front of the ribs undergo compression. Bars with flat ribs, on the other hand, slip when the rib tends to push the concrete away from the bar (Rehm, 1957; Lutz and Gergly 1966). Hamad (1995) also had similar observation where he noted that specimens with rib face angles ($\propto$) greater than 45^o have higher both strength compared to those with $\propto$ less than 45 degrees. For plain bars, contribution of the lug to bond strength is nonexistent.

(ii) Bar Diameter (size)

The diameter of reinforcing bar affects bond strength and influences the bond failure mechanism. An increase in the bar size results in a decrease in bond strength. The corresponding slips also increases (Ahmed *et al*, 2014; Hadi 2008). In the experimental test results of Ahmed et al (2014), the ultimate tensile bond strength was found to decrease by 10%, 6%, and 5% when the bar diameter increases from 16 to 18 mm for concrete compressive strength of 30, 50, and 90 MPa, respectively. Reinforcement bars of smaller sizes have higher bond strength than specimens with larger bar sizes as a result of an increase in the cover to bar diameter (c/d) ratio.

Increase in concrete cover improves confinement and prevents the formation and propagation of micro cracks (Orangun *et al*, 1977).

(iii) Embedment length

Increase in the embedment length increase bond. In the work by Ahmed *et al* (2014), an increase in the development length from 5 times diameter (5d) to 7.5d and 10d increased bond by 4.3% and 10.0%, respectively. Musa and Haido (2013) conducted a study on reinforced concrete with oil polluted steel bars having 13cm and 15cm embedded lengths. The test results confirmed the report by Ahmed et al (2014) that increase in embedment length increases bond. The specimen with 16mm bar size recorded 6.88% decrease in bond strength when the entire embedded length, 30cm, of the rebar was polluted with the oil. The corresponding value for the specimen with 15cm embedment length was 29%. This clearly shows that, all things being equal, an increase in embedment length increases bond for concrete specimen with oil polluted rebars. In most experimental studies however, short bond length is used. This ensures that the stresses and deformations within the bond zone are uniform. In other words, the short bond length restricts the variations within the bond zone for variables such as stresses, strains, confining pressure, etc. that define bond response.

2.4.3. Confinement

Confinement is one of the key variables which control the value of the ultimate bond stress. This parameter play significant role in the bond strength of concrete structures reinforced with stirrups or subjected to tri-axial stress (Borderie and Pijaudier-Cabot 1992 cited in Ahmed, 2014). According to Al-Sulaimani *et al* (1990) the presence of shear reinforcement (stirrups) increases the bond resistance for specimen with both smooth and deformed bars. The stirrups prevent widening of longitudinal crack through an improvement in the confining capacity of the concrete within the bond zone. For specimen subjected to cyclic loading, confinement reinforcement reduces bond degradation (Fang *et al*, 2005). From the experimental results of Fang *et al* (2005) substantial reduction in bond was recorded for plain bars compared to deformed bars. The maximum bond strength for the deformed bars was 5 to 10 times higher than that of the plain bars after ten (10) cycles of loading. Moreover, it was found that, the nominal bond strength of normal weight concrete and lightweight aggregate concrete could increase approximately 20 % by adding stirrups.

Beside stirrups, concrete cover also provides confinement. Rodriguez *et al*, (1994) noted that, bond strength increases directly proportional to the thickness of concrete cover. The confinement action offer resistance to tensile splitting. In similar studies by Tepfers (1973) and Orangun *et al* (1977) it was revealed that concrete cover and the spacing of transverse reinforcement greatly influence the bond failure mechanism. Small concrete cover usually results in splitting tensile failure whereas pullout failures occur in specimen with larger cover thickness.

2.4.4 Corrosion

Corrosion of reinforcing bar (rust) is so far the most predominant mechanism which causes bonding problems and premature failure of R C structures (Lee *et al,* 2002; Fang *et al,* 2004 and 2006, Fu and Chung 1997, Lamya and Alaka 2006, Bhargava *et al,* 2007 and Auyeung *et al,* 2000 etc.). The corrosion products at the vicinity of the concrete − steel interface enhances the bond strength (Tassios, 1997); however in the extreme cases, the accumulated corrosion products cause volume increase which consequently exerts pressure at the steel–concrete interface. Hoop stresses are developed in the surrounding concrete. In the study by Fang *et al* (2006) on the effect of different degrees of steel corrosion on bond between steel bars and concrete, it was found that up to about 4% degree of corrosion, there is no significant influence of corrosion on bond strength, but substantial decrease in bond occurs when corrosion increase to a higher level

of around 6%. Corrosion levels were measured as a percentage loss in the weight of the steel rebar compared to the weight of the bond length before corrosion. The result of high corrosion is the cracking of the concrete after the hoop tensile stresses exceed the tensile strength of the concrete (Bhargava *et al*, 2007). Loss of concrete cover due to the cracking leads to loss of confinement and a decrease in bond strength at the concrete steel interface (Bhargava et al, 2007). Wang and Liu, (2003) argue that the soft layer created by the corrosion products reduces the friction component of the bond strength. Moreover, the deterioration of the ribs of the deformed bars causes substantial reduction in the force transfer through mechanical interlock between the ribs of the rebars and the concrete keys. Thus the primary mechanism of
force transfer for deformed bars is affected. Auyeung *et al* (2000) also observed a decrease of around 8% in bond strength for unconfined corroded steel rebars with 2% diameter loss.

2.4.5 Surface Coating –Epoxy Coating

Bond strength is negatively affected by epoxy coating. It reduces the adhesion and friction at the concrete steel interface (Joseph and Camille, 2012). The loss in bond strength ranges from 15% to 50% depending on the thickness of the coating, bar diameter and concrete properties etc. (Choi *et al* 1991; ACI 408R 2003 and Anda *et al* 2006). To address this problem, design codes recommend an increase in the development length of the rebars. Taking ACI 318 for example, a factor of 1.5 is recommended to be applied to the development length for rebars coated with epoxy where the concrete cover is less than 3*d* or the clear spacing between bars is less than 6*d*
(where *d* is the size of the rebar). In the other cases, a factor of 1.2 is to be used (ACI Committee 318, 2008). The AASHTO bridge specification uses the factors 1.5 and 1.15, respectively (AASHTO, 1989).

2.5 Bond Failure

Experimental investigations have revealed two main types of bond failure: shear pullout failure and side splitting failure (Ahmed *et al* 2007; Ichinose 2004). These studies describe the characterization and the evaluation process of defining the two failure mechanisms as follows: When a system is subjected to monotonically increasing loads, there is interaction between the steel and concrete interface which results in the formation of stresses. For pullout failure, the concrete directly in front of the lugs of the rebar known as concrete key is first crushed. This occurs when the concrete key is weak and the surrounding concrete is strong. As a result, the concrete key is heavily stressed. According to Ichinose (2004), the stress increases with relatively high rib height $a/d > 0.1$, small rib spacing $^{a}/_{c} > 0.5$ and high rib angle face greater than 70^o (*a, c* and *d* represents the height, width and spacing of the ribs of the rebar respectively). As the design shear stress exceeds the capacity of the concrete, pullout of the rebars occurs. This mode of failure can also occur when the concrete cover is large or the system has moderate shear reinforcement or both.

In the case of bond splitting, small amount of slip initially occurs. The initial slip causes the splitting of the concrete, followed by further slips and an eventual complete failure of the bond. The cracks are formed when the member is subjected to flexure beyond the tensile strength of the concrete. The primary cracks develop near the top of the ribs of the rebar (i.e. for deformed bars) and spread at an angle of around 60^o with respect to the longitudinal axis of the rebar. Several secondary cracks are also formed. The wedging action of the deformed steel rebar being pulled is responsible for the formation of the cracks. As soon as the interface cohesive and radial cracks form and propagate, the bond strength diminishes rapidly and the rebar slips. The development of further cracks results in radial and or longitudinal splitting of the concrete. Typically, specimen embedded with larger reinforcement bars fail by bond splitting whereas those with smaller bars fail through the pullout of the rebar (Orangun *et al*, 1977).

Xiao and Falkner (2005) divide the bond development and deterioration process into five (5) stages: the micro-slip, the internal cracking, the pullout, the descending and the residual stages. The micro-slip stage is where the load is small such that slip is insignificant. At this stage, the load vs. slip curve is linear. At the internal cracking stage, where the load increases towards its critical value, the slip at the free end of the rebar becomes significant. Moreover, the adhesion force between the concrete and the steel becomes almost exhausted. The slip increases and the curve assume a nonlinear shape. As the load reaches its highest value, longitudinal splitting cracks are formed at the weakest area of the concrete cover. This stage is the pullout stage. After this stage, the load declines rapidly and the slip increases until the steel bar is completely pulled out (the descending stage). Finally, the residual stage is reached where the slip of the loading end reaches a certain value. At this point, the load becomes almost constant. The value is less than one half of the peak load (Xiao and Falkner, 2005)

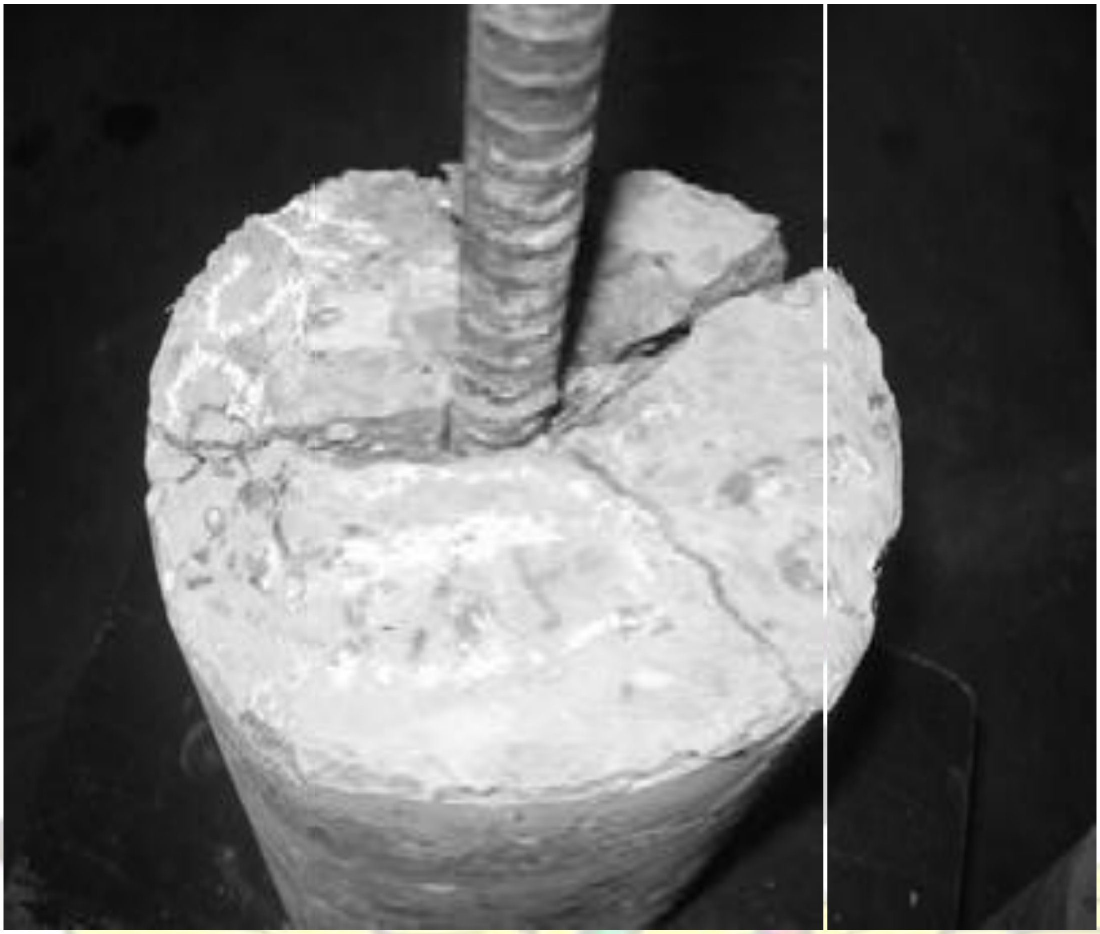


Fig 2.3: Longitudinal splitting failure (Ahmed et al 2007)

2.6 Influence of Oil on Concrete – Steel Bond

Experimental Investigations

2.6.1 Faiyadh (1985)

Faiyadh (1985) was one of the early investigations on the effect of oil on concrete-steel bond. In this work, the bond strength of concrete cured in oil was studied. Concrete specimens embedded with steel rebar were cured in oil at different durations. Afterward, pullout test was carried out to determine the bond strength of the specimen. The results revealed that irrespective of the type of bar, the average bond strength decreases with an increase in the duration of the soaking period. The specimen absorbs more oil as the curing period increases and this negatively affects the bond between the steel and concrete. Compared to the deformed bar, the plain bars recorded a reduction of about 1.8–2.3 times greater in bond strength. Moreover, at the maximum applied load, the local bond stress for the specimen cured in oil was six (6) times greater than those cured in water. From the findings, it can be deduced that, the presence of oil at the bond zone reduces the adhesion and frictional resistance between concrete and steel. Thus, the effect of oil on bond is similar to that of epoxy. Moreover, oil affects the bond strength of concrete structures reinforced with plain bars more than those with deformed bars.

2.6.2 Bilal *et al*, (2003a and 2003b)

These two studies were designed as a two phase research program to investigate into the effect of oil on concrete. The oil was used engine oil. In the Bilal *et al*, (2003b), the effect of oil on the properties of concrete at the fresh and hardened states were studied. At the fresh state, the slump and air content were studied. The compressive strength, flexural strength, the splitting tensile strength and the modulus of elasticity were the properties of the concrete studied at the hardened state. Twenty (20) concrete mixes with different dosage of oil were prepared. The water to cement ratio for the mixes was varied between 0.62 and 0.59. The test results revealed the following:

(i) The effects of engine oil whether new or used on the properties of concrete are similar.

(ii) An average loss of 21% and 17% in flexural strength and splitting tensile strength respectively was recorded for the mixes prepared with used engine oil.

The report above suggests that, the presence of oil at the bond zone affects the strength properties of the concrete.

The second study (Bilal *et al*, 2003a), on the other hand was aimed at evaluating the effect of the oil on the bond, shear and flexural strength of concrete elements. Two beam specimens were tested in bond. One had the entire embedded surface area of the rebar coated with oil whereas the other one did not have the oil. After testing the beams in positive bending, it was observed that the effect of the used engine oil on the load-deflection behavior of beams is insignificant.

2.6.3 Adukpo et al (2011)

This study was also designed with the aim of determining the effect of engine oil on concrete steel bond. Six (6) standard concrete cubes of size 150mm were used for the experiment. A piece of deformed mild steel reinforcement bars of 12mm diameter was centrally embedded in each of the cubes. The rebars of 3 of the specimen had their entire bond length (i.e. 150mm) coated with engine oil. The remaining 3 set had no oil. After 28days of curing, pullout test was carried out. The results of the experiment revealed that engine oil reduces the bond strength of concrete. As previously noted by Faiyadh (1985) the oil acts as a film between the concrete and steel interface and weakens the gripping of the concrete to the steel rebars. Thus force transfer through adhesion is reduced.

In the flexure strength test 150 x 150 x1600mm concrete beams were used. As in the first experiment, one set of the beams were embedded with 12mm deformed mild steel bars coated with engine oil. The beams were reinforced with 12mm and 10mm diameter bars at the bottom and top respectively. The stirrups were 6mm mild steel bars. The beams were cured for 28 days after which they were subjected to third-point loading. The deflections at the mid-span of the beams were recorded. The results revealed that for all other things being equal, the oil-coated steel reinforced concrete beams recorded higher magnitude of displacement (deflection) compared to the un-coated steel reinforced concrete beams.

2.6.4 Musa and Haido (2013)

In this work, the bond strength of reinforced concrete with the steel rebars polluted with oil was studied. Standard 150mm diameter x 300mm long cylindrical concrete specimens were used. The compressive strength of the concrete was 24 N/mm^2. The bond length of the steel rebars was varied between 30 cm and 15 cm. Four different bar diameters namely 10, 12, 16 and 20 mm were considered. Thus, one of the objectives of their study was to look at the effect of bar diameter and embedment length on bond. Tensile pullout test was carried out. The results of the experiment revealed that pollution of steel bars with oil negatively affects bond strength as the bar diameter increases and the embedded length decreases. In other words, the effect of oil on the bond strength of specimen with smaller bar sizes or long embedment length is insignificant.

Moreover, given the same embedded length, specimen with small bar sizes had greater bond strength than those with large bar sizes. Most of the test specimen failed by tensile splitting of the concrete.

2.6.5 Influence of Direction of application of oil on Bond

One a construction site, oil can pollute the surface of steel rebar in two possible patterns or direction as illustrated in Fig 2.4 and Fig 2.5. In the first case, part of the surface of the steel within the bond zone is polluted with the oil in a direction parallel to the longitudinal axis of the bar. The pullout force (F) is also applied in in that direction (Fig 2.4). In the other case the oil is applied in the transverse direction of the bar (Fig.5). In the work by Musa and Haido (2013), the specimen had the oil applied to the rebar in the longitudinal direction. The results showed that, the section of the bond zone which is coated with the oil had a weak bond. Compared with the specimen without oil, there was about 19% reduction in bond when 50% of the embedded surface area of the bar was polluted with the oil in the longitudinal direction.

With respect to pollution of oil in the transverse direction, none of the experimental investigations looked at that. The current study hopes to contribute to knowledge by finding out if the bond strength for steel rebar polluted with oil in the longitudinal direction significantly vary from that in the transverse direction. It is hypothesized that, there will be difference in the two results. However, as to whether the difference will be significant will be decided by the test results.

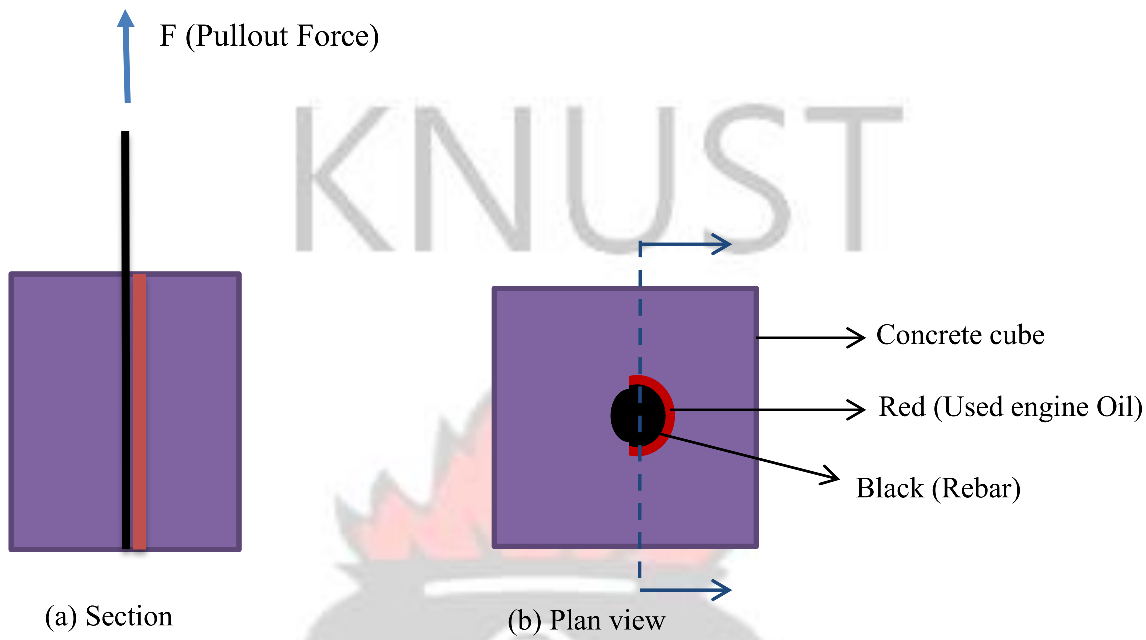


Fig 2.4: 50% of embedded surface area of rebar pollution with oil in the longitudinal

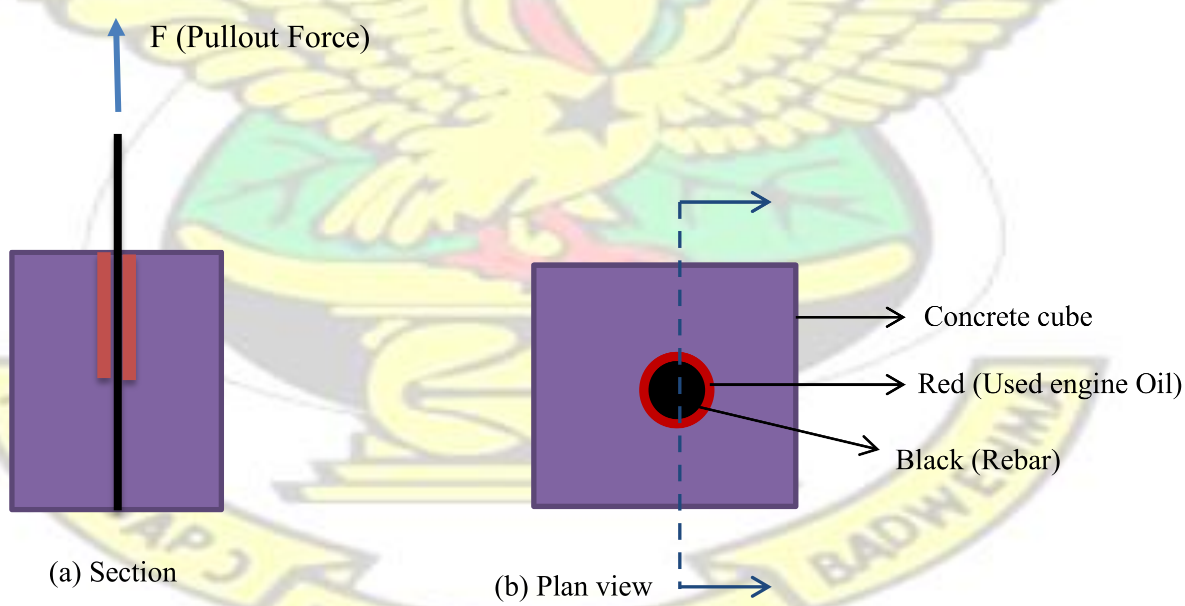


Fig 2.5: 50% of embedded surface area of rebar pollution with oil in the transverse

2.6.6 Comments and Summary of Gaps in literature

The above studies basically either evaluated the effect of oil on concrete strength or its effect on the adhesion and frictional resistance at the concrete steel interface. Whereas Faiyadh (1985) just used the oil (i.e. diesel oil) as curing medium, Bilal *et al* (2003a) used the oil (engine oil) in the preparation of the specimen. Thus Bilal *et al's* specimen ideally represents an oil-concrete composite. Moreover, despite looking at the compressive and split tensile strength of the concrete, other variables such as the shear strength was not looked at. That notwithstanding, their works facilitate some aspects of the current study by providing us with some basic information on the oil concrete composite. Furthermore, it was revealed that engine oil whether new or used performs the same.

The works by Adukpo et al (2011) and Musa and Haido (2013) on the other hand centered on how oil coating on steel affects the adhesion and frictional resistance at the concrete - steel interface. They failed to look at the damage done to other strength properties of concrete such as shear, compressive strength etc. by the presence of the oil at the bond zone. Moreover, in the work by Adukpo et al (2011) the sample size of just 3 specimens was too small hence making a general statement from such small sample size might be misleading. A larger number of sample size would have been ideal. Despite this, their results provide some basis for further work to be carried out. Musa and Haido (2013) reported that "*the presence of oil does not affect bond strength when the embedded length of the rebars is increased and the diameter decreased*". From this report, it was not clear the extent to which the embedded length should be increased and the diameter decreased so as to prevent the oil from having adverse effect on bond. An empirical formula to describe the relationship will have been considered ideal. It was observed from the mode of failure of their specimen that, tensile splitting of the concrete was predominant.

It presupposes that, the oil in some way affected the tensile strength of the concrete at the bond zone. However, the author's work was silent on that. As a general observation, none of the studies looked at the bond versus slip relationship for the tested specimen. The influence of oil on bond strength is based on the test results of the various studies. No general empirical formulae exist. It is therefore difficult to determine how the bond mechanism is affected by the presence of oil at the vicinity of the concrete steel interface from empirical formulae. Finally, they did not look at how the directions of application of the oil on the rebar affects bond. That is when the oil is applied parallel to the longitudinal axis of the bar or in the transverse direction, how the bond strength in the two cases compares. The above gaps in literature triggered the current study. Thus the aim of this study is to develop an empirical formulae for predicting the bond strength of reinforced concrete with the steel rebars contaminated with oil.

2.7 Development of the Oil Influence – Bond Strength Model (O-Bmodel)

Experimental investigations so far indicate that various factors control bond response and that bond strength is determined by the deterioration of concrete within the vicinity of the concrete-steel interface. This suggests that bond strength of concrete can be defined in terms of its strength. Moreover, since bond failures occur by the crushing or splitting of concrete, it is rational to define bond strength in terms of the split tensile, shear and compressive strengths of concrete (Noriyuki *et al,* 2007). Thus, any attempt to develop a formula (model) for the effect of oil on bond should involve (1) An assessment of the impact on the strength properties of the concrete and (2) Evaluation of the effect on the adhesion and frictional resistance at the concrete steel interface. However, in the former case, the quantity of oil at the bond zone on a normal construction site is so insignificant that its effect on concrete strength is negligible. Hence the current model will focus on the adhesion and frictional effect of oil on bond. The oil is hypothesized to affect bond through the formation of protective barrier between the concrete − steel interface. Consequently, force transfer through adhesion and friction is affected. This aspect is critical for smooth bars since the greatest contribution to bond is offered by adhesion and friction mechanisms as noted by the following studies: Darwin (2005), Mo and Chan (1996) and ACI (2003).

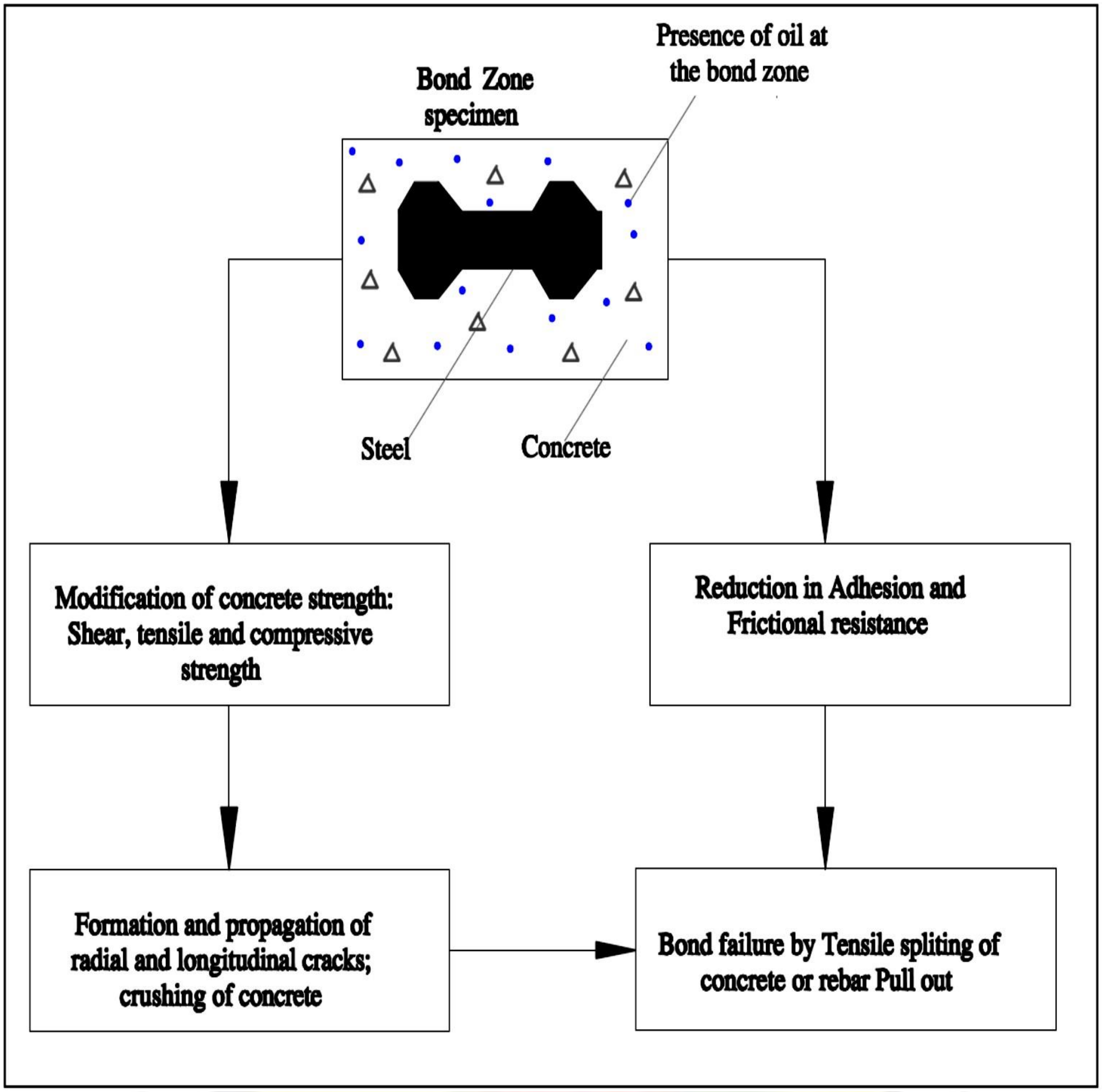


Fig 2.6: Theoretical framework on the effect of oil on bond (Source: Author's own construct)

2.8 Existing Bond Strength Models

Several attempts have been made so far to develop formulae for the bond strength between steel rebars and concrete in terms of various parameters. The equations below are few of them:

Orangun *et al*, (1977) defines bond as:

$$\tau_u = 0.08305\sqrt{f_c'}\ [1.2 + 3(\frac{c}{d_b}) + 50\ (\frac{d_b}{L_d})] \quad \ldots\ldots (2\text{-}3)$$

Where f_c' is the cylinder compressive strength of the concrete expressed in N/mm²; c is the minimum concrete cover in millimeters; d_b is the size of the bar and L_d is the development length

Eligehausen et al (1983) also expresses bond strength of concrete in terms of its compressive strength as:

$\tau_{bond} \propto (f_c)^{\beta}$ Where $\frac{1}{3} \leq \beta \leq \frac{1}{2}$ ……………………………………………(2-1)

In the above equation Tepfer (1979) and ACI Committee 318 (1979) simply suggest $\beta = \frac{1}{2}$

The British Standard, BS 8110 ((1997) part 1 also calculates the design ultimate anchorage bond stress, f_{bu} as

$f_{bu} = \beta\sqrt{f_{cu}}$ …………………………………………… (2-2)

Where, β is a factor that depends on the type of the rebar and f_{cu} is the compressive cube strength

The Euro Code 2, EN (2004) proposes the design ultimate anchorage bond stress as

$f_{bu} = 2.25\eta_1\,\eta_2\,f_{ctd}$ ……………………………………………..(2-4)

Where η_1 is a coefficient related to the quality of the bond condition and the position, η_2 is related to the bar equals to 1.0 for bar diameter ≤ 32 mm and f_{ctd} is the design value of concrete tensile strength calculated using Equations (2-5) and 2-6) according to EN (1992).

$f_{ctd} = (0.21 f_{cu}^{\frac{2}{3}})/\gamma_c$ for $f_{cu} \leq 60$ MPa …….. ……………… (2-5)

$f_{ctd} = 1.484\ln(1 + (f_{cu} + 8)/10)/\gamma_c$ for $f_{cu} > 60$ MPa.................................... (2-6)

Where $\gamma_c = 1.5$

In the current study, the new model will be developed taking into account concrete compressive strength and the degree of oil pollution at the concrete steel- interface.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Introduction

This chapter explains the processes employed in carrying out the research. It addresses the design of the research, the study variables, preparation of the test specimen, data collection instrument (test procedure), and analysis techniques among others. It provides detail explanation to each of the methods employed and how the methods adopted were used to address the aim and objectives of the study.

3.2 Research Design

The current study aimed at investigating into the effect of oil on concrete-steel bond. For such cause and effect investigations Creswell (2009), and Fellow and Lui (2008) recommend the use of quantitative research design and experimental research approach since the study has a positivist focus. Thus, the current study involved series of pullout test (bond test) to determine how the presence of oil affects the adhesion and frictional resistance at the concrete − steel interface.

3.3 Types of Data and Data Sources

The study collected both primary and secondary data to facilitate the discussion of the results.

3.3.1 Secondary Data

This data was gathered from existing studies published in Journals, Institutional reports, Newspapers, magazines, Books etc. The findings from these sources helped to identify the gaps in literature and also define an appropriate methodology for undertaking the current study. It was also meant to facilitate the discussion of the results obtained from the primary data.

3.3.2 Primary Data

This was the data gathered through the laboratory experiments. The processes involved in the collection of this data are the main focus of this chapter.

3.4 Bond Test

Various methods exist for determining bond strength of reinforced concrete. They include Pullout test, cantilever bond test, Bond beam test, and the University of Texas beam test (Musa and Haido 2013, Ferguson 1988 cited in Bhargava 2007; Bilal *et al* 2003a, Almulsallam *et al*, 1996). The pullout test requires the use of standard concrete specimen (cubic or cylindrical in shape) with reinforcement bar centrally embedded in them. The specimen is then mounted in test machine to pull the metal insert (i.e. the reinforcement bar) from the concrete. The force required to pull the rebar is then measured as the bond force. This method is preferred to the other methods due to the ease in the test set up program. For this reason, the current study adopted the tension pullout test technique.

3.5 Study Variables

A variable is defined as anything that has a quantity or quality that varies. The literature review revealed that several variables are responsible for bond strength characterization. However, in the development of the current model, three key variables which relate to concrete strength, rebar surface characteristics and the type of contaminant at the concrete-steel interface were used. The independent variables were (i) the degree of oil pollution (measured as a percentage of the embedded surface area of the rebar which is polluted with the oil). Consequently, 0%, 25%, 50% 75% and 100% degrees of oil pollution were considered. The oil was applied to the bars in the transverse direction (see Fig 3.12). (ii) Bar type –Deformed high tensile steel and deformed mild steel bars of 16mm diameter were used. (iii) Compressive strength of concrete. Three grades of concrete were designed (C15, C20, C25). The controlled variables were the embedment length and bars size. The embedment length was taken as 150mm (i.e. 9.375 times the bar diameter).

The short bond length was chosen to ensure that the stress is uniform along the bond length.

Moreover, the bar size that was chosen helped to prevent the failure of the steel bar when loaded.

3.6 Preparation of specimen

3.6.1. Materials

(i) **Concrete:** At the initial stages of the mix design, the coarse and fine aggregates were graded to find out the particle size distribution of the materials. The quantities of the aggregates, cement and water required to achieve the target strength of the concrete were calculated as shown in appendix C. Afterwards trial mixed were prepared, cured and tested on the 7th day to check the possibility of achieving the target strengths. The concrete mix ratios used are shown in Table 3.1. They were designed to provide 28-day compressive strengths of 15, 20, and 25 N/mm². The cement used was Ordinary Portland cement (Grade 32.5). The fine aggregate was medium sand (pit sand) whereas the coarse aggregate was crushed granite with 20mm nominal size. The water/cement ratio was varied between 0.5 – 0.60. The fine aggregate had low silt content of 4%. All the materials were obtained at a site in the Accra Metropolis, Ghana.

(ii) **Oil:** The used engine oil had specific gravity of 0.89. This was applied as a coating on the embedded bar surface at varying coverage area. This type of oil was chosen because it is the normal agent used for demoulding concrete from formwork at construction sites.

(iii)**Steel**: Deformed high tensile steel and deformed mild steel rebars of 16mm diameter having the surface characteristics described in Table 3.4 were used. Three (3) pieces of each type were cut from a full bar. The samples were taken from different sections of the standard bar length as recommended by BS 4449:1998. Each piece of bar which had a length of 0.6m was inserted into an electronic steel tensile test machine and strained until failure occurred. The test was carried out at the laboratory of the Architecture and Engineering Services Limited (AESL) in Accra, Ghana. From the values recorded, the average yield stress was 325N/mm² and 554N/mm² for the Mild and High tensile steels respectively. See Table 3.3 for the mechanical properties of the rebars. The reinforcing bars were free from rust or any other form of contaminant.

Table 3.1: Concrete mix proportion by weight batching

Grade	Cement/Sand/Coarse Aggregate (kg)	W/c ratio
C15	10/21.2/41.1	0.60

C20	10/18.4/35.8	0.55
C25	10/15.6/30.5	0.50

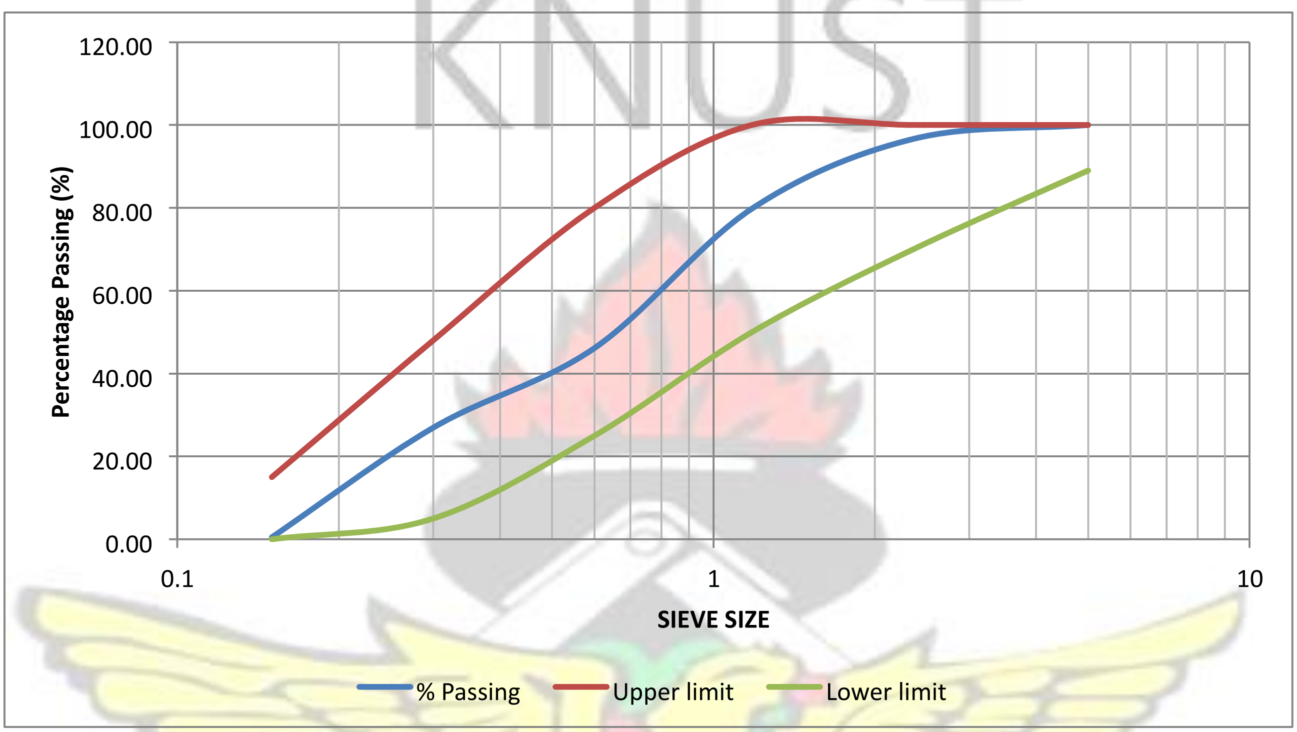


Fig 3.1: Particle size distribution of Fine Aggregate

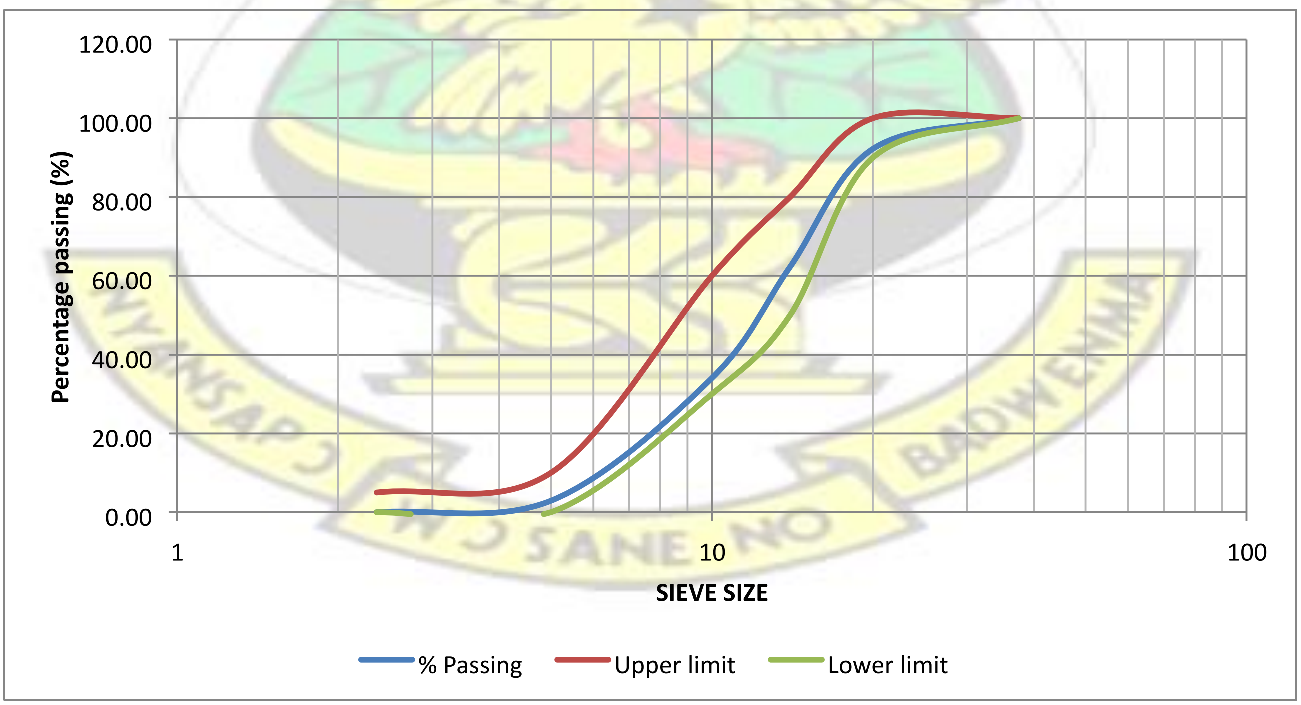


Fig 3.2: Particle size distribution of Coarse Aggregate From Fig 3.1 and Fig 3.2, the distribution of the aggregates falls within the limits set by BS 882:1992.

The compressive strength of the concrete used in the current study were measured. Three cubes (150 x 150 x 150 mm) each (i.e. a total of 9 cubes) were prepared from the various mix proportions and cured until the test day. Each cube was inserted into compression test machine and loaded until failure in the form of crushing of the concrete occurred. See Fig 6. The average of the forces recorded by the three specimen was used to calculate the characteristic compressive strength of the concrete as shown in Table 3.2. The test was carried out at the AESL laboratory in Accra.

Table 3.2: Compressive Strength of Concrete

Grade	ID	Failure load (kN)	Compressive strength (N/mm²)	Mean Compressive strength (N/mm²)	Standard deviation (N/mm²)	Characteristic strength (N/mm²)
C15	1	375	16.667	19.037	2.064	16.973
	2	460	20.444			
	3	450	20.000			
C20	1	485	21.556	22.593	1.263	21.33
	2	540	24.000			
	3	500	22.222			
C25	1	570	25.333	26.563	1.130	25.433
	2	620	27.556			
	3	603	26.800			

From Table 3.2 all the mixes achieved their designed grades since their characteristic strengths were higher than their targeted strengths at the age of 28 days.

Table 3.3: Mechanical properties of the steel

Bar ref	S/n	Measured size (mm)	Yield point Load (kN)	Ultimate Load (kN)	Tensile strength (N/mm^2)	
					Yield point	Ultimate strength

Mild steel	1	15.54	62.78	87.31	324.76	461.55
	2	15.59	62.78	89.27		
	3	15.69	60.82	88.30		
High tensile steel	1	15.68	111.83	140.28	554.31	702.58
	2	15.53	105.95	133.42		
	3	15.95	104.97	135.38		

The test was conducted per BS 4449:1998 specification for carbon steel at the laboratory of AESL in Accra, Ghana. The characteristic Yield Point strength for the bars were above the 250N/mm² and 460N/mm² specifications for mild steel and High tensile steels respectively. This confirms the grade of steel used.

Table 3.4: Surface characteristics of rebars

Type	**High tensile**	**Deformed mild steel**
Rib height	2mm	1.2mm
Rib width	3mm	2mm
Rib spacing	7.5mm	9mm
Rib face angle	55_{o}	50°

3.6.2 Casting of Specimen

150 x 150 x 150 mm steel moulds with the inside coated with oil was placed on flat concrete floor. Pieces of steel reinforcing bars with part of the embedded surface area applied with used engine oil were embedded into the center of the moulds. The oil had been applied 30 minutes before the bars were used. Brush was used to apply the oil so as to get a uniform coverage.

Moreover, the steel reinforcing bars were descaled and cleaned before being used. Fresh concrete was poured into the mould in three equal layers. Tamping rod was used to compact each layer 35 times to remove any entrapped air. Transverse steel bars were designed to hold the bar in position during the casting and compaction. The top of the concrete was leveled with that of the mould using trowel. After hardening sufficiently, each cube was labeled for identification purpose. After 24 hours, the cubes were removed from the mould and cured in a trough full of potable water until the test day (See Figs 3.3 -3.6). In all there were 30 tests with three (3) specimens in each test. Thus, the total specimen was 90. Table 3.5 shows details of the pullout specimen.

Table 3.5: Description of the pullout specimen

Oil pollution	f_{cu}	High tensile steel bars	Mild steel bars	Total
(%)	(N/mm^2)	(Quantity)	(Quantity)	
0	15/20/25	9	9	18
25	15/20/25	9	9	18
50	15/20/25	9	9	18
75	15/20/25	9	9	18
100	15/20/25	9	9	18

Fig 3.3: Casting of concrete cubes

Fig 3.4: Removal of cubes from mould after 24 hours

Fig 3.5: Curing of specimen

3.6.3 Specimen identification

Three characters were used to identify each specimen. The first letter represented the bar type: D–for deformed high tensile steel and M –mild steel. The second number is the concrete grade (either C15, 20 or 25) and the third number represents the degree of oil pollution. Thus, a specimen with identification code D20-25 implies a specimen of concrete grade C20 embedded with high tensile steel bar where 25% of the embedded surface area is coated with used engine oil in the transverse direction as shown in Fig 3.8. Fig 3.6 shows the geometry of the test specimen. The dimensions are in mm.

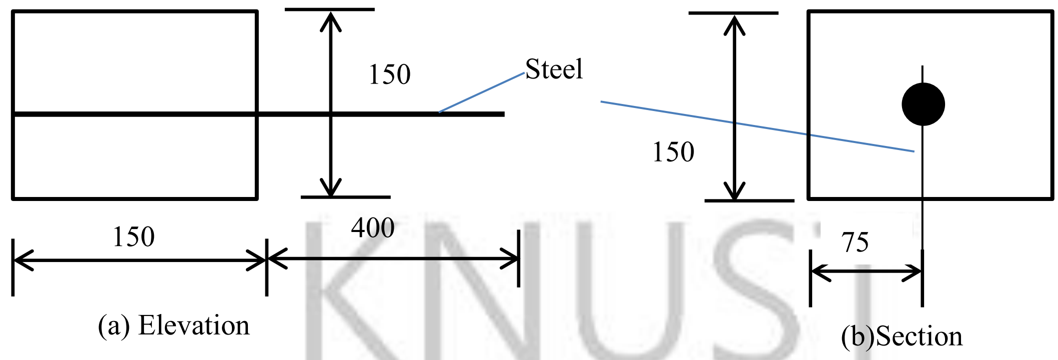


Fig 3.6: Geometry of the test specimens

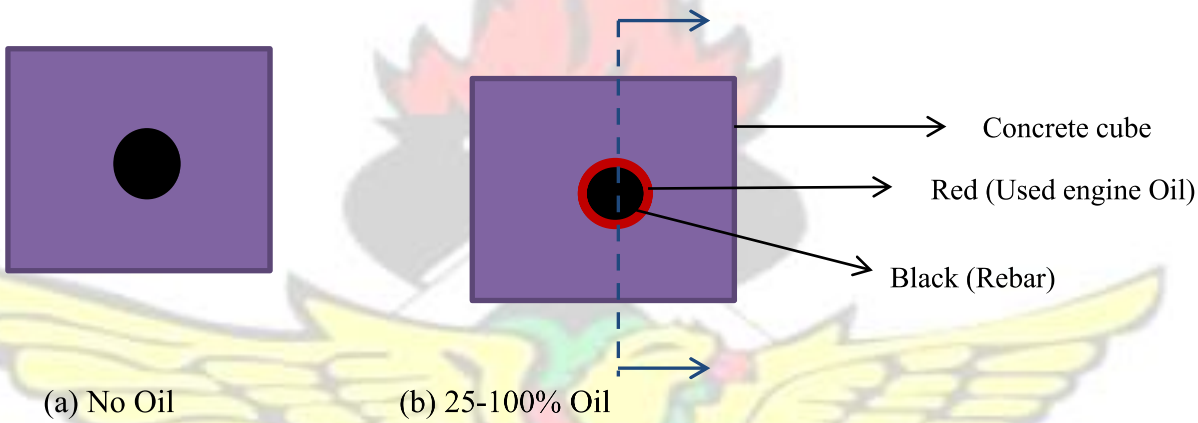


Fig 3.7: Bottom view

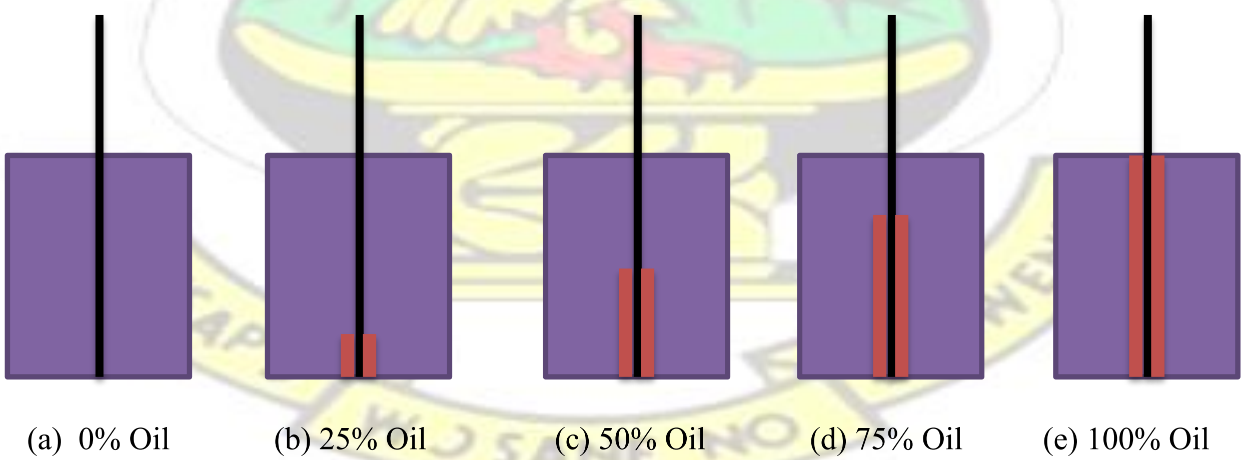


Fig 3.8: Application of oil at different coverage area on the rebar (sectional view)

3.7 Test Setup and Procedure

The test was carried out at the laboratory of the Architecture and Engineering Services Limited (AESL) in Accra, Ghana. Fig 3.9 shows the setup of the test. The cubes were each inserted into a 500kN capacity electronic tensile test machine and loaded until failure in the form of tensile splitting (crushing) of the concrete or pullout of the rebar occurred. The failure load was recorded. The load was distributed on steel plate at a rate of 2.5kN/sec. For each group, the average force of the three (3) replicate specimens was used to determine the bond stress. The stress was calculated using the equation below:

$$f_b = \frac{F_s}{\pi \varphi_e l}$$

……………………… (Eqn. 48 of BS 8110-1:1997) Where, f_b is the bond stress which is assumed to be uniform; F_s = the pull out force l = the embedment length (150mm); φ_e = the effective bar size (16mm)

Fig 3.9: Set up for Pull out Test

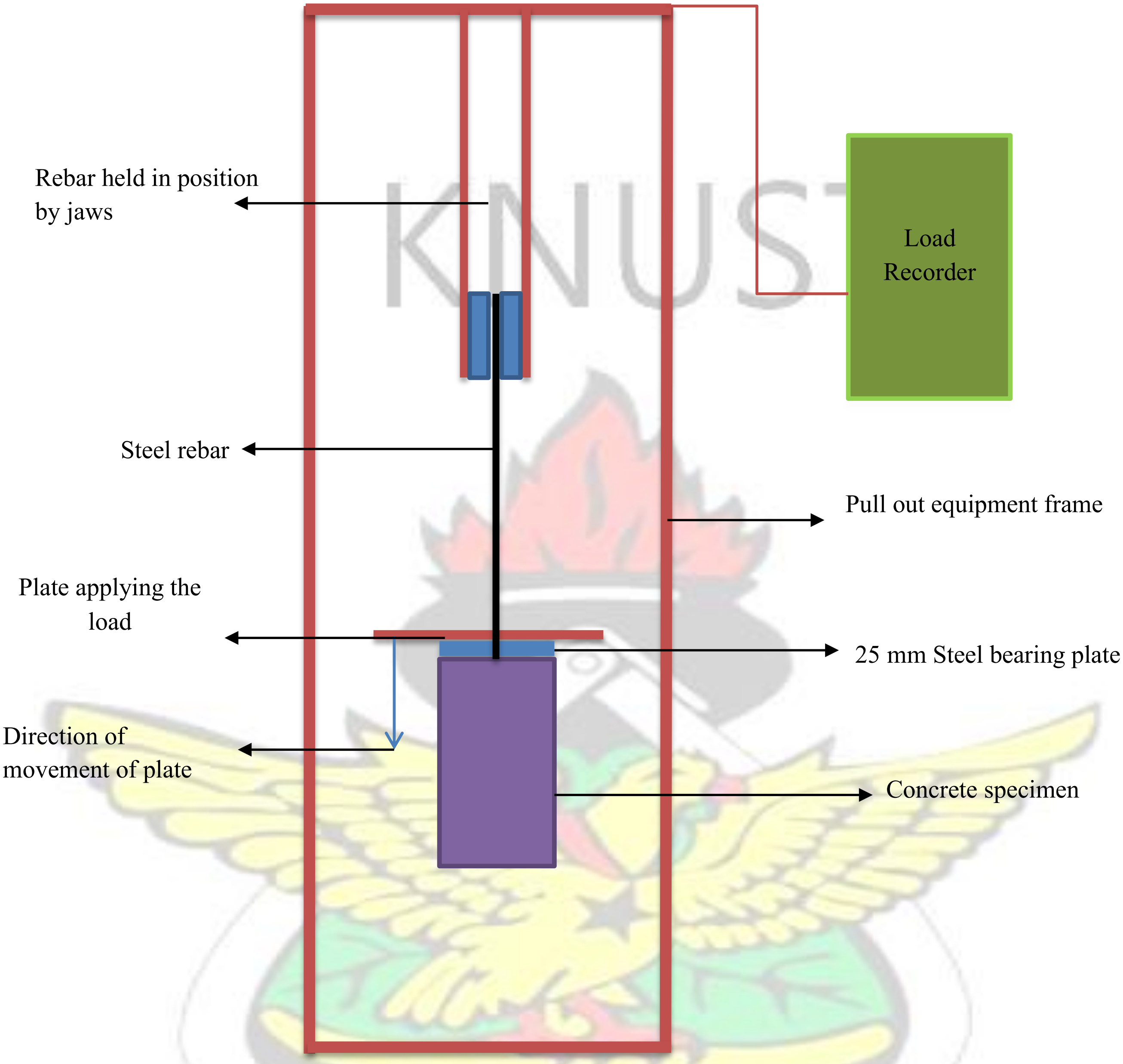


Fig 3.10: Schematic diagram of Pullout test set up.

The study also sought to find out how the direction of application of oil on the steel-concrete interface affects the bond between the two materials. To achieve this, three samples each with the embedded surface area of the rebar coated with oil in the transverse and longitudinal directions as shown in Fig 3.11 and Fig 3.12 were used.

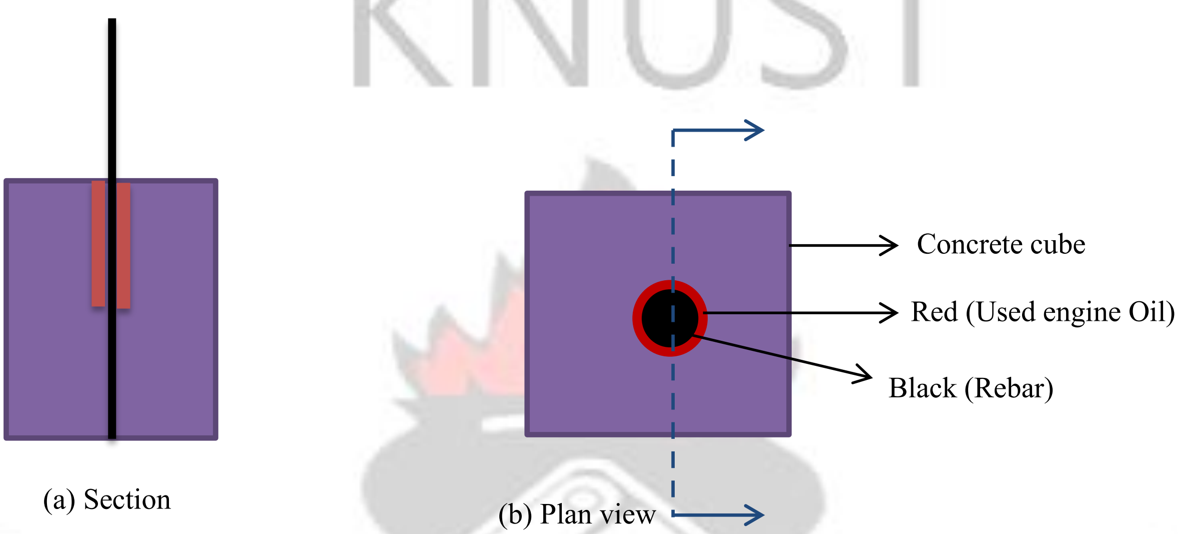


Fig 3.11: 50% of embedded surface area of rebar pollution with oil in the transverse

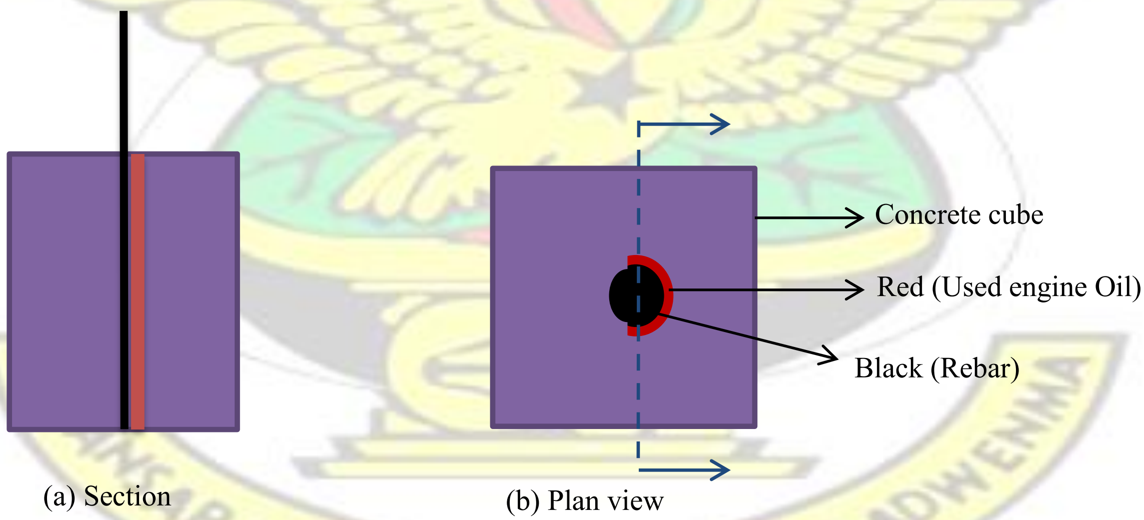


Fig 3.12: 50% of embedded surface area of rebar pollution with oil in the longitudinal

3.8 Data Analysis

The data collected was analyzed using Microsoft Excel regression analysis tool pack to establish the relationship between bond strength (the dependent variable) and the independent variables (the degree of oil pollution and concrete strength). Bond strength was defined in terms of concrete compressive strength (f_{cu}) and degree of oil pollution (X_p) as follows:

$\tau_{bu} = \beta_0 + \beta_1 f_{cu} + \beta_2 X_P$ ………………………………………………….. (3-1)

Where, β_0 , β_1 and β_2 are constants determined from the regression analysis.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents the results of the experiments carried out. The results are analysed to establish the trend in the current study. The findings are compared with previous experimental studies.

4.2 Effect of Oil on Concrete-Steel Bond

As indicated earlier on there were 30 tests, with three replicate specimens per test for a total of 90 specimens. Tables 1− 3 show the pull out forces recorded for each test category (see Appendix A). The forces were converted to bond stresses using equation 48 of BS 8110-1:1997. The results revealed that the bond strength decreases as the percentage of oil at the concrete steel interface increases. Compared with the control specimen (i.e. those with 0% Oil), an average loss of 28%, 38% and 35% bond strength was recorded for concrete grades C15, C20 and C25 respectively when the mild steel rebar was fully (100%) polluted with the used engine oil (Fig 4.1). The corresponding values for the high tensile steel were 24%, 25% and 32% (Fig 4.2). Moreover, the reduction in bond strength is higher for the specimen embedded with mild steel rebars than those with high tensile steel as shown on Fig 4.3. The above observations confirm the earlier report by Adukpo et al (2011) that oil (engine oil) coating has adverse (negative) impact on the concrete and steel bond. The oil coating acts as a layer at the concrete steel interface and impairs the gripping of the steel bar within the bond zone. The adhesion and friction bond mechanisms are weakened. As noted by Darwin (2005) and ACI (2003) the greatest contribution to bond for deformed steel bars comes from the mechanical interlock, with the bearing resistance offered by concrete against the reinforcing steel bar ribs and friction between concrete keys and surrounding concrete both helping to a lesser extent. Consequently it can be inferred from Fig 3.3 that the deformed high tensile steel offered greater resistance to bond than the deformed mild steel since the ribs on the high tensile steel bars were more pronounced (See Table 3.4). Both rebar pull-out and longitudinal splitting failures were also observed. The findings above therefore agree with the following studies: Musa and Haido (2013), Bilal et al (2003a), Darwin (2005) and Faiyadh (1985).

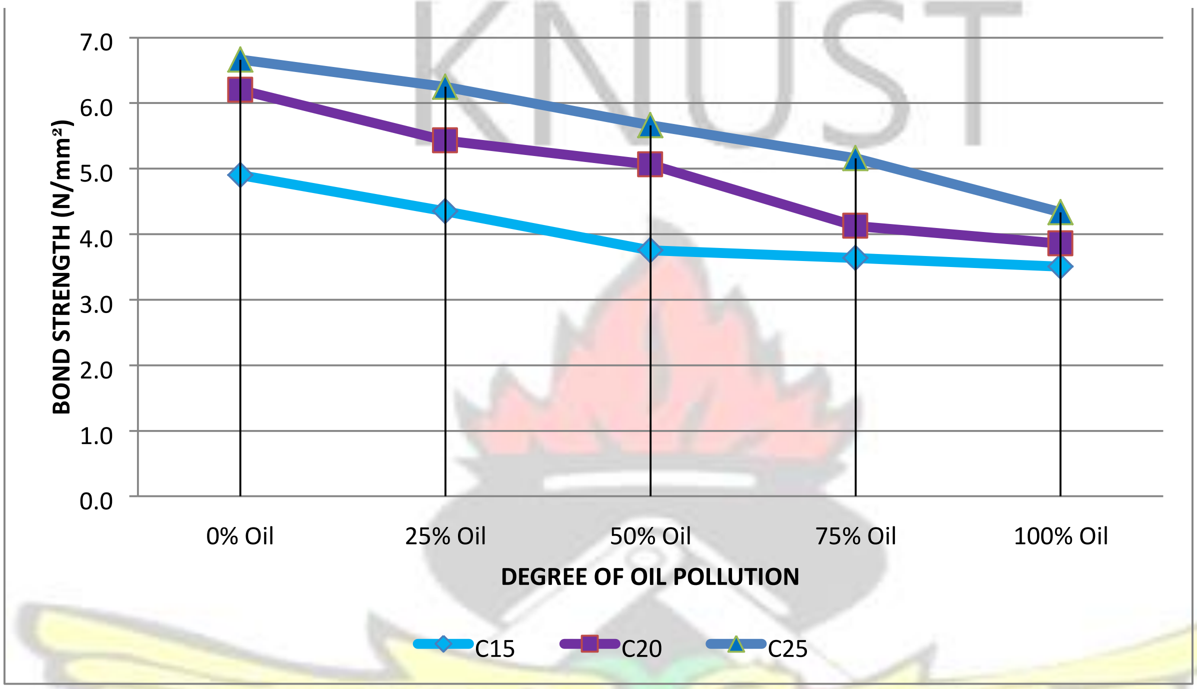


Fig 4.1: Effect of Oil on Bond for specimen embedded with Mild steel rebars

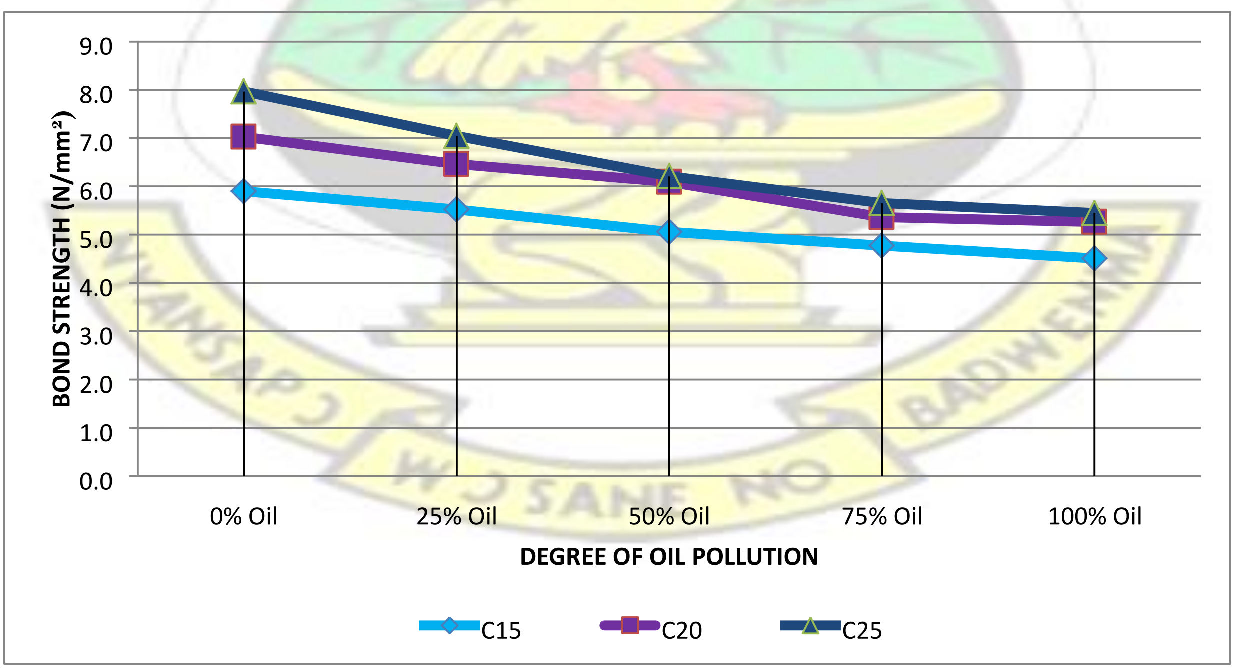


Fig 4.2: Effect of Oil on Bond for specimen embedded with High Tensile steel rebars

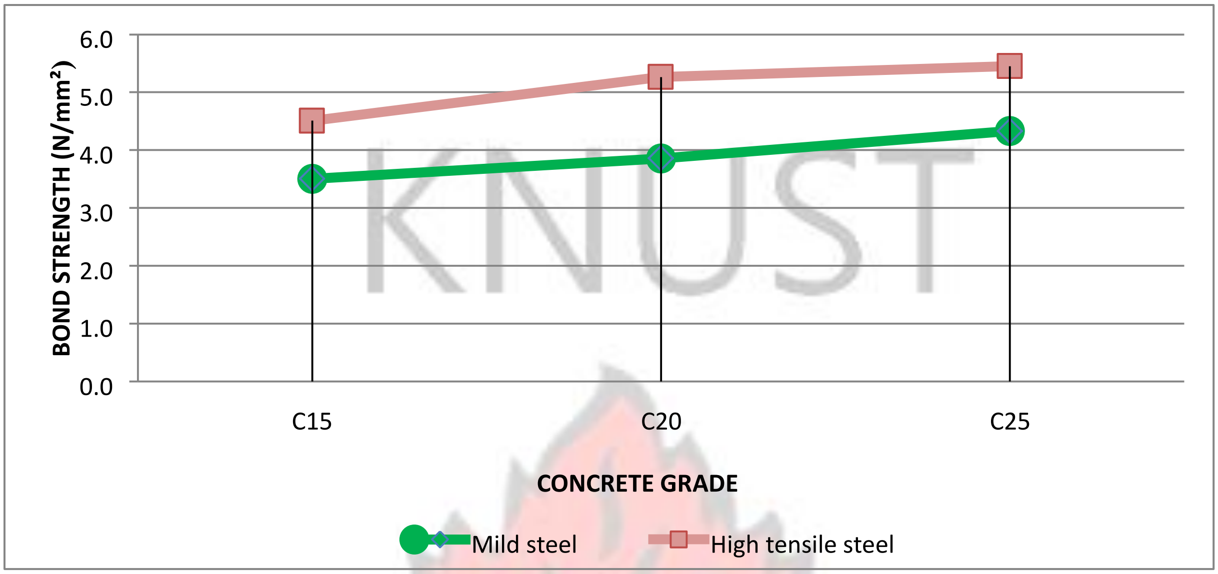


Fig 4.3: Comparison of the Bond strength for specimen embedded with High tensile steel to those with Mild steel rebars for 100% rebar pollution

4.3 Effect of Compressive Strength on Bond

Another variable which was included in the current study is the effect of concrete's compressive strength on bond. It was revealed from the experimental results that bond strength is directly proportional to concrete's compressive strength. That is, as the compressive strength increases, bond strength also increases (see Fig 4.1 and 4.2). This result corroborates with the study by Eligehausen et al, (1983).

4.4 Bond Strength for rebars polluted with Used engine oil in the Transverse direction compared to that along the Longitudinal direction of the rebar

The study looked at two possible cases of rebar pollution on site: where part of the bonded surface of the rebar is polluted with the oil (i) along the longitudinal axis of the bar (Fig 3.11) and (ii) in the transverse direction (Fig 3.12). Three samples each of specimens with 50% of the rebar surface coated with oil in the transverse and longitudinal directions was used to test hypothesis to find out if there exist significant difference in the two results. Given a small sample size less than thirty (30) and hypothesis testing involving two independent samples (i.e. differences in the pattern of oil pollution), two-sample t-test was used as recommended by

Creswell (2009) and Fellows and Lui, (2008).

The null hypothesis, H_o of equal mean bond strength for the 2 patterns of oil pollution (i.e. transverse and longitudinal) was tested. The result is shown in Table 4.1. At 5% significance level, the null hypothesis is accepted since the two tail p-value (0.59) is greater than 0.05. In other words, the computed t Stat < t Critical (-0.578 < 2.776) and hence the assumption that bond strength for rebars polluted with oil in the transverse direction does not vary significantly from that along the longitudinal direction is correct.

Table 4.1: t-Test: Two-Sample Assuming Equal Variances (p = 5%)

	Transverse direction	***Longitudinal direction***
Mean bond stress	5.661	5.959
Variance	0.2867	0.5131
Observations	3	3
Pooled Variance	0.3999	
Hypothesized Mean Difference	0	
df	4	
t Stat	-0.577968828	
P(T < = t) one-tail	0.297131229	
t Critical one-tail	2.131846786	
P(T<=t) two-tail	0.594262459	
t Critical two-tail	2.776445105	

4.5 Empirical Bond Strength Model

Multivariate regression analysis was carried out using the data in Tables 6 and 7 (see appendix A) to establish the correlation between bond strength (the dependent variable) and the independent variables (i.e. degree of oil pollution and concrete compressive strength). In the current study, bond strength of concrete is defined in terms of its compressive strength (f_{cu}) and the degree of oil pollution (X_p) as follows:

$\tau_{bu} = \beta_0 + \beta_1 f_{cu} + \beta_2 X_P$ ……………………………… (3-1)

Where, β_0, β_1 and β_2 are constants determined in the regression analysis

From the coefficients obtained (Table 13 and 14 at the appendix) the following relationships have been proposed for bond strength of reinforced concrete with oil polluted rebars.

$\tau_{Msteel} = 0.2699 f_{cu} - 1.8451\ X_P$ ……………………….Mild steel (4-1)

$\tau_{Hsteel} = 0.3105 f_{cu} - 1.5939\ X_P$ ……………………….High tensile (4-2)

From both models it can be observed that the presence of oil negatively affect bond while concrete compressive strength increases bond. For mild steel there is a reduction of 1.8451N/mm² when the entire embedded surface area of the rebar is fully polluted with oil. The corresponding value for high tensile steel is 1.5 N/mm². Thus, oil has much adverse effect on bond for mild steel than high tensile steel. The ribs on deformed high tensile steel help to reduce the effect of oil on bond. In addition to the above, a unit increase in f_{cu} results in 0.2699N/mm² and 0.3105N/mm² increase in bond for mild steel and high tensile steel respectively.

The above models reasonably give accurate prediction of bond strength for the two independent variables. As revealed by the Adjusted R Square values (Table 10), 91.73% of the variations in bond strength for reinforced concrete embedded with mild steel rebars is accounted for by this model (τ_{Msteel}). The corresponding value for high tensile steel rebars is 91.19% (Table 11).

The reliability of the relationships above was further assessed on the basis of the Integral Absolute Error (IAE, %) used by Nihal *et al*, (2006). This index is used to determine the goodness of fit of a proposed model. It is calculated as follows:

$$\text{IAE} = \sum \frac{\sqrt{[(O_i - P_i)^2]}}{\sum O_i} \times 100 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(4-3)}$$

Where O_i are the observed values and P_i are the predicted values obtained from the regression model. The IAE measures the absolute deviations of data from the regression model. If the value is zero, the estimated values are equal to the observed values. In practice a range of values from 0 to 10% is regarded as an acceptable value for regression equation (Nihal et al, 2006). From Table 8 and 9, AIE values of 6.31% and 8.96 % were recorded for the mild steel and high tensile steel models respectively. These values are within the acceptable limits. Moreover, from the Anova Tables (Table 12 and 13) the F values are statistically significant.

4.6 Comparison of Model results with existing experimental results

The results from the current study are compared with that of existing empirical studies as follows:

Adukpo et al (2011)

This study was conducted on 150mm concrete cubes with 12mm mild steel rebar inserts.

The results revealed that the average bond strength for the specimen with oil polluted rebars was 5.63 N/mm² whereas the value for those without oil was 8.26 N/mm². The f_{cu} = 29.29 N/mm². Using the model for mild steel to predict the results we have

$\tau_{Msteel} = 0.2699 f_{cu} - 1.8451\ X_P$

= 0.2699 (29.29) – 1.8451 (0)

= **8.0N/mm²** as compared to **8.26N/mm²**……… (Uncoated bar)

$\tau_{Msteel} = 0.2699 f_{cu} - 1.8451\ X_P$

= 0.2699 (29.29) – 1.8451 (1)

= **6.01N/mm²** as compared to **5.63 N/mm²** ………. (Fully coated bar) The model values compares very well with the lab results.

4.7 Summary

The effects of oil at concrete-steel interface on bond strength have been discussed. Empirical models have been developed to help predict bond strength for R C with mild steel and high tensile steel rebars. The models values were compared with that of existing experimental studies. The results revealed that, the models give accurately reasonable prediction of bond strength.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Summary of findings

The current study was designed to investigate into the effect of used engine oil on the bond strength of reinforced concrete and consequently develop empirical models for its prediction. Based on the tests and analysis carried out, the following are the main findings:

Objective 1: Effect of Used engine oil on bond

(i) Used engine oil coating has adverse (negative) effect on the bond between concrete and steel rebars. It forms a film on the bar surface which weakens the adhesion and frictional resistance between the concrete and the steel within the bond zone.

(ii) The mild steel recorded an average reduction of 28%, 38% and 35% in bond strength for concrete grades C15, C20 and C25 respectively when the rebars were fully polluted with the oil. The corresponding values for the high tensile steel were 24%, 25% 32%.

(iii) Loss in the bond strength was higher for the mild steel than the high tensile steel due to the breakdown in the adhesion and friction mechanisms (the primary mechanisms responsible for force transfer in plain bars)

Objective 2: To compare the bond strength for rebar polluted with used engine oil in the transverse direction to that along the longitudinal direction of the rebar

(i) The pattern of pollution of oil at the concrete-steel (whether transverse or longitudinal directions) interface do not significantly vary the results.

(ii) However, pollution in the transverse direction reduces the bond more than pollution along the longitudinal direction.

Objective 3: Develop empirical model for bond strength

(i) Bond strength of concrete is defined as a function of its compressive strength (f_{cu}) and the degree of oil pollution (X_p) as follows

$\tau_{bu} = 0.2699 f_{cu} - 1.8451\ X_P$ ………………………Mild steel

$\tau_{bu} = 0.3105 f_{cu} - 1.5939\ X_P$ ………………………High tensile

(ii) Used engine oil negatively affect bond while concrete compressive strength increases bond. For mild steel there is a reduction of 1.8451N/mm² when the entire embedded surface area of the rebar is fully polluted with oil. The corresponding value for high tensile steel is 1.5 N/mm².

(iii) A unit increase in f_{cu} results in 0.2699N/mm² and 0.3105N/mm² increase in bond for mild steel and high tensile steel bars respectively.

5.2 Conclusion

The presence of used engine oil at concrete – steel interface negatively affects bond and consequently the force transfer between the two materials. The adhesion and frictional resistance mechanism is broken down by the presence of oil and this has the tendency of affecting the ultimate strength of reinforced concrete structures.

5.3 Recommendations

Based on the findings of the current study recommendations are made in the following directions:

(i) The use of engine oil as form oil on construction sites should be carefully carried out to ensure that the rebar surface is free from oil.

(ii) Where the rebar is accidently soil with the oil, steps should be taken to thoroughly clean the oil or the rebar should not be used especially when the anticipated effect on bond is found to be very high

5.4 Further Studies

The main purpose of the current study was to develop an empirical model for predicting bond strength. It was revealed that the models perform very well for the selected range of concrete strengths and bar size used for the study. Studies that focus on high strength concrete and the effect of bar size are encouraged.

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APPENDIX A LABORATORY RESULTS

Table 1: Pull out forces (C15; d=16mm; Embedment length: 9.375d)

Steel type	ID	0% Oil	25% Oil	50% Oil	75% Oil	100% oil
High tensile	1	56.898	38.354	39.468	35.43	35.221
	2	39.297	47.316	38.487	38.449	34.335
	3	37.278	39.297	36.487	34.183	32.487
	Average	44.491	41.656	38.1473	36.021	34.014
Mild steel	4	39.24	28.449	25.506	30.434	28.335
	5	42.183	35.449	27.055	26.126	26.487
	6	29.43	34.468	32.373	25.772	24.525
	Average	36.951	32.789	28.311	27.444	26.449

Table 2:Pull out forces (C20; d=16mm; Embedment length: 9.375d)

Steel type	ID	0% Oil	25% Oil	50% Oil	75% Oil	100% oil
High Tensile	1	53.955	50.525	46.667	41.392	39.316
	2	46.107	47.506	47.278	40.601	41.563
	3	58.86	48.221	43.955	39.43	38.259
	Average	52.974	48.751	45.967	40.474	39.713
Mild steel	4	49.05	38.259	32.373	31.468	36.297
	5	47.088	41.392	41.993	33.449	28.449
	6	44.145	43.164	40.145	28.449	22.563
	Average	46.761	40.938	38.170	31.122	29.103

Table 3: Pull out forces (C25; d=16mm; Embedment length: 9.375d)

Steel type	ID	0% Oil	25% Oil	50% Oil	75% Oil	100% oil

High tensile	1	60.221	51.278	47.43	40.259	33.354
	2	61.183	53.955	45.449	42.335	45.43
	3	58.86	54.24	47.62	45.316	44.567
	Average	60.088	53.158	46.833	42.637	41.117
Mild steel	4	41.202	49.43	43.164	40.221	26.487
	5	58.56	51.012	46.487	43.164	34.35
	6	51.012	41	38.449	33.354	37.225
	Average	50.258	47.147	42.700	38.913	32.687

Table 4: Summary of Pull out forces (kN) for specimen embedded with Mild steel rebars

		Degree of oil pollution				
		No oil	25% oil	50% oil	75% oil	Full oil
Concrete grade	C15	36.951	32.789	28.311	27.444	26.449
	C20	46.761	40.938	38.17	31.122	29.103
	C25	50.258	47.147	42.700	38.913	32.687

Table 5: Summary of Pull out forces (kN) for specimen embedded with High tensile steel

		Degree of oil pollution				
		No oil	25% oil	50% oil	75% oil	Full oil
Concrete Grade	C15	44.491	41.656	38.147	36.021	34.014
	C20	52.974	48.751	45.967	40.474	39.713
	C25	60.088	53.158	46.833	42.637	41.117

Table 6: Bond stresses (N/mm²) for Specimen embedded with Mild steel

		Degree of Oil pollution				
		0% Oil	25% Oil	50% Oil	75% Oil	100% Oil

Concrete Grade	C15	4.899	4.347	3.753	3.638	3.506
	C20	6.199	5.427	5.060	4.126	3.858
	C25	6.663	6.251	5.661	5.159	4.334

Table 7: Bond stresses (N/mm²) for Specimen embedded with High tensile

		Degree of Oil pollution				
		No oil	25% Oil	50% Oil	75% Oil	100% Oil
Concrete Grade	C15	5.898	4.948	4.615	4.201	3.891
	C20	7.023	6.331	6.094	4.924	4.249
	C25	7.966	6.650	6.209	4.857	4.567

Table 8: The Integral Absolute Error (IAE) for eqn 4.1 (Mild Steel)

Observation	**Residual(O-P)**	**(O-P)²**	**√{(O-P)²}**	**[√{(O-P)²}] /∑Oi**
1	0.3170	0.1005	0.3170	0.0043
2	0.2265	0.0513	0.2265	0.0031
3	0.0941	0.0089	0.0941	0.0013

4	0.4404	0.1940	0.4404	0.0060
5	0.7698	0.5926	0.7698	0.0106
6	0.4414	0.1949	0.4414	0.0061
7	0.1307	0.0171	0.1307	0.0018
8	0.2250	0.0506	0.2250	0.0031
9	-0.2481	0.0616	0.2481	0.0034
10	-0.0545	0.0030	0.0545	0.0007
11	-0.2026	0.0410	0.2026	0.0028
12	-0.1537	0.0236	0.1537	0.0021
13	-0.2820	0.0795	0.2820	0.0039
14	-0.3228	0.1042	0.3228	0.0044
15	-0.6869	0.4718	0.6869	0.0094
$\sum O_i$ =72.833 IAE = 6.31%				

Table 9: The Integral Absolute Error (IAE) for eqn 4.2 (High Tensile Steel)

Observation	**Residual(O-P)**	**$(O-P)^2$**	**$\sqrt{(O-P)^2}$**	**$[\sqrt{(O-P)^2}] / \sum O_i$**
1	0.62828	0.394737	0.628281	0.0071
2	0.65087	0.423629	0.650868	0.0074
3	0.58423	0.341326	0.584231	0.0066
4	0.70077	0.491078	0.70077	0.0079

5	0.83326	0.694325	0.833262	0.0094
6	0.40006	0.160052	0.400065	0.0045
7	0.23864	0.056947	0.238636	0.0027
8	0.26803	0.071839	0.268029	0.0030
9	-0.06164	0.003799	0.061638	0.0007
10	0.23587	0.055633	0.235866	0.0027
11	0.06922	0.004791	0.06922	0.0008
12	-0.45109	0.203483	0.451091	0.0051
13	-0.89111	0.794069	0.891105	0.0101
14	-1.04895	1.100305	1.048954	0.0119
15	-0.85194	0.725805	0.851942	0.0096
$\sum O_i$ = 88.301 IAE = 8.96%				

Table 10: Summary Output (Mild steel)

Regression Statistics	
Multiple R	0.9973
R Square	0.9946
Adjusted R Square	0.9173
Standard Error	0.3917
Observations	15

Table 11: Summary Output (High tensile steel)

Regression Statistics	
Multiple R	0.9948
R Square	0.9896
Adjusted R Square	0.9119
Standard Error	0.6517
Observations	15

Table 12: ANOVA (Mild steel)

ANOVA					
	df	***SS***	***MS***	***F***	***Significance F***
Regression	2	366.835	183.4177	1195.499	1.551E-14
Residual	13	1.9945	0.1534		
Total	15	368.8299			

Table 13: ANOVA output (High Tensile steel)

ANOVA					
	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	526.5758	263.2879	619.8577	7.76E-13
Residual	13	5.52182	0.424755		
Total	15	532.0976			

Table 14: Coefficients (Mild steel)

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0	N/A	N/A	N/A	N/A	N/A
Compressive Strength	0.2699	0.0079	34.0136	4.33E-14	0.2528	0.2871
Oil pollution	-1.8451	0.2790	-6.6143	1.68E-05	-2.4478	-1.2425

Table 15: Regression Coefficients (High tensile steel)

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0	N/A	N/A	N/A	N/A	N/A
Compressive strength	0.3105	0.0132	23.5134	4.89E-12	0.28197	0.3390
Oil pollution	-1.5939	0.4642	-3.4341	0.00444	-2.5967	-0.5912

APPENDIX B PROJECT PICTURES

Fig 1: Specimen ready for testing

Fig 2: Inserting specimen into Pullout test apparatus

Fig 3: Longitudinal splitting of concrete

Fig 4: Pull out of rebar

Fig 5: Steel reinforcement bars used in the current study

Fig 6: Compressive Strength Test

APPENDIX C DETAILS OF CONCRETE MIX DESIGN

DESIGN OF CONCRETE GRADE C25

Step 1: Design Data

Cement: Ordinary Portland cement Grade 32.5; Specific gravity = 3.05

Fine aggregate: Medium sand; Fineness Modulus: 2.5 (Zone II) Specific gravity = 2.65

Coarse aggregate*:* 20mm graded crushed granite stone aggregate; Specific gravity = 2.80

Workability: compacting factor = 0.7; Degree of quality control: Very Good

Step 2: Target Mean Strength (TMS)

TMS = Characteristic strength + k δ

Where k = Himsworth Statistical coefficient (taken to be 1.65 for 5 % probability of failure);

δ = Standard deviation which is based on the degree of control. The value was taken to be 4.3N/mm^2 for very good control

$\therefore$ TMS = 25 + 1.65 x 4.3 = 32.1N/mm^2

Step 3: Selection of Water to Cement (W/C) Ratio

Given cement grade 32.5, cement curve A is selected (see IS 10262-1982 page 15 for details). Based on cement curve A and TMS of 32.1 1N/mm^{2,} a w/c ratio of 0.38 is selected (refer to Fig 2 of IS 10262-1982).

Step 4: Determination of Cement Content

Using IS method, water demand = 186 kg/m^3 for compaction factor = 0.8 and maximum aggregate size of 20 mm. Decrease water demand 3% for compaction factor of 0.7.

∴ Net water demand = 186 – 3% x 186 = 180.42 kg/m^3

Weight of cement = $\frac{Weight\ of\ water}{W/C\ \ ratio} = \frac{180.42}{0.38} = 474.79$ kg/m^3

Step 5: Fine and Coarse Aggregate content

Using IS method, the weight of sand as a percentage of total aggregate weight is 35% (i.e. given that w/c = 0.6, 20mm aggregate). The value is to be adjusted by 1% for every 0.05 increase in w/c ratio. Total adjustment for w/c of 0.38 is 4.6%. Thus net sand content = 35 – 4.44 = 30.6%

Weight of coarse aggregate is given by the formula

$$1000 \text{ x } V = W + \frac{C}{S_c} + \frac{1}{1-p} \text{ x } \frac{C_a}{S_{ca}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where V = Absolute volume of fresh concrete

V = Gross volume – volume of entrapped air

V = 1 – 0.02 = 0.98 (NB: entrapped air assumed as 2 %)

W = water demand = 180.42kg/ m^3

C = cement content = 474.79kg/m^3; p = ratio of fine aggregate to total aggregate = 0.306

S_c = specific gravity of cement = 3.05; C_a = weight of coarse aggregate

S_{ca} = Combined specific gravity of coarse aggregates = 2.8. Substituting the values into eqn. 1 above we have

$$1000 \text{ x } 0.98 = 180.42 + \frac{474.79}{3.05} + \frac{1}{1-0.306} \text{ x } \frac{C_a}{2.8} \qquad \therefore\ C_a = 1251.2 \text{ kg/m}^3$$

For the fine aggregate, it is calculated from the formulae

$1000 \text{ x } V = W + \frac{C}{S_c} + \frac{1}{p} \text{ x } \frac{f_a}{S_{fa}}$ ………………………. (2) 644.33

Where S_{fa} = the specific gravity of the fine aggregate = 2.65

$1000 \text{ x } 0.98 = 180.42 + \frac{474.79}{3.05} + \frac{1}{0.306} \text{ x } \frac{f_a}{2.65}$ $\therefore$ f_a = 522.49 kg/m^3 The final mix proportion for C25 is

Water	Cement	Fine Agg.	Course Agg
180.42	474.79	522.49	1251.20
0.38	1	1.10	2.63

DESIGN OF CONCRETE GRADE C20

Step 1: Design Data

The same as used for C25

Step 2: Target Mean Strength (TMS)

TMS = Characteristic strength + k δ

δ = 3.6N/mm^2

$\therefore$ TMS = 20 + 1.65 x 3.6 = 25.94N/mm^2

Step 3: Selection of Water to Cement (W/C) Ratio

For cement curve A and TMS of 25.94N/mm^{2,} a w/c ratio of 0.43 is selected

Step 4: Determination of Cement Content

$\therefore$ Net water demand for compaction factor of 0.7 = 186 – 3% x 186 = 180.42 kg/m^3

Weight of cement = $\frac{Weight\ of\ water}{W/C\ \ ratio} = \frac{180.42}{0.43}$ = 419.58 kg/m^3

Step 5: Fine and Coarse Aggregate content

The weight of sand as a percentage of total aggregate weight is 35% (i.e. given that w/c = 0.6, 20mm aggregate). Adjusting the value for w/c ratio of 0.43 we have sand content = 35 – 3.4 = 31.6%

Weight of coarse aggregate is given by the formula

$1000 \text{ x } V = W + \frac{C}{S_c} + \frac{1}{1-p} \text{ x } \frac{C_a}{S_{ca}}$ …………………. (1)

Where V = Absolute volume of fresh concrete = 0.9

W = water demand = 180.42kg/ m^3

C = cement content = 419.58kg/m^3; p = ratio of fine aggregate to total aggregate = 0.316 S_{ca} = Combined specific gravity of coarse aggregates = 2.8. Substituting the values into eqn. 1 above we have

$1000 \text{ x } 0.98 = 180.42 + \frac{419.58}{3.05} + \frac{1}{1-0.316} \text{ x } \frac{C_a}{2.8}$ $\therefore$ C_a = 1267.88 kg/m^3

For the fine aggregate, we have

$1000 \text{ x } 0.98 = 180.42 + \frac{419.58}{3.05} + \frac{1}{0.316} \text{ x } \frac{f_a}{2.65}$ $\therefore$ f_a = 554.37kg/m^3 The final mix proportion for C20 is

Water	Cement	Fine Agg.	Course Agg
180.42	419.58	554.37	1267.88
0.43	1	1.321	3.02

DESIGN OF CONCRETE GRADE C15

Step 1: Design Data

The same as used for C25

Step 2: Target Mean Strength (TMS)

TMS = Characteristic strength + k δ

δ = 2.5 N/mm^2 $\therefore$ TMS = 15+ 1.65 x 2.5 = 19.125N/mm^2

Step 3: Selection of Water to Cement (W/C) Ratio

For cement curve A and TMS of 19.125 N/mm^{2,} a w/c ratio of 0.55 is selected

Step 4: Determination of Cement Content

$\therefore$ Net water demand for compaction factor of 0.7 = 186 – 3% x 186 = 180.42 kg/m^3

Weight of cement = $\frac{Weight\ of\ water}{W/C\ \ ratio} = \frac{180.42}{0.55}$ = 328.04kg/m^3

Step 5: Fine and Coarse Aggregate content

The weight of sand as a percentage of total aggregate weight is 35% (i.e. given that w/c = 0.6, 20mm aggregate). Adjusting the value for w/c ratio of 0.55 we have sand content = 35 – 1 = 34%

Weight of coarse aggregate is given by the formula

1000 x V = W + $\frac{C}{S_c} + \frac{1}{1-p}$ x $\frac{C_a}{S_{ca}}$ ………………… (1)

Where V = Absolute volume of fresh concrete = 0.98

W = water demand = 180.42kg/ m^3

C = cement content = 328.04kg/m^3; p = ratio of fine aggregate to total aggregate = 0.34

S_{ca} = Combined specific gravity of coarse aggregates = 2.8. Substituting the values into eqn. 1 above we have

1000 x 0.98 = 180.42 + $\frac{328.04}{3.05} + \frac{1}{1-0.34}$ x $\frac{C_a}{2.8}$ $\therefore$ C_a = 1278.85 kg/m^3

For the fine aggregate, we have

1000 x 0.98 = 180.42 + $\frac{328.04}{3.05} + \frac{1}{0.34}$ x $\frac{f_a}{2.65}$ $\therefore$ f_a = 623.51kg/m^3 The final mix proportion for C15 is

Water	Cement	Fine Agg.	Course Agg
180.42	328.04	623.51	1278.85
0.55	1	1.90	3.898