COMPARISON OF CORROSION BEHAVIOR OF STEEL REINFORCEMENT BARS IN ORDINARY PORTLAND CEMENT AND PORTLAND POZZOLANA CEMENT ENVIRONMENTS

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Degree of Master of Materials Science

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Thesis submitted in partial fulfillment of the requirements for the degree of Master of Materials Science

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DECLARATION

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ABSTRACT

In the Sri Lankan cement market present time blended hydraulic cement which is composited with fly ash or blast furnace slag are given a noticeable marketing share as supplementary cement. It has obtained more popularity for incorporating higher workability and achieving a higher lateral strength in the construction industry. But due to the pozzolanic reactivity of blended cement, there is a possibility of reduction of pH of concrete or cement mortar which may be detrimental to the passivity of reinforced steel.

In this study, the comparison of corrosion effect was researched with 15% fly ash blended cement as the pozzolanic cement (Bag-cement of Blended hydraulic cement) and Ordinary Portland cement. Coarse aggregates were excluded to get a clearer picture of the corrosion effect with the change of cement type. The cement mortar mixtures with 1.0: 3.0: 0.5 of cement: sand: water respectively, from both cement types were prepared. Specimens were cast in moulds with reinforcement bars to prepare the specimens for the pull-out test, Half cell potential test, compression test & loss of mass (due to corrosion). After casting test specimens were salt-conditioned by dipping in 5% NaCl solution for 30 minutes per day for 180 days.

Pull-out and compression test results acknowledge that pozzolanic cement contributes higher lateral strength than ordinary Portland cement. After the compression test, reinforced steel bars were removed from the cubes and it was observed that no corrosion has happened in bars that were fully enclosed with (both types of: PPC and OPC) cement covers. Therefore, it reveals that 15% of fly ash blended hydraulic cement does not disturb the passivity layer of steel reinforcements as a result of consumption of $Ca(OH)_2$. This study can be extended for further research with 25% or higher ratios of fly ash blended hydraulic cement.

Keywords: Ordinary Portland cement; Portland Pozzolanic Cement; corrosion of TMT steel bars; passivity of steel bars

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LIST OF ABBREVIATIONS

Abbreviation	Description
BHC	Blended Hydraulic Cement
C_3A	Tricalcium aluminate, $3CaO.Al_2O_3$
C_3AF	Tetra-calcium alumino ferrite, $4CaO.Al_2O_3.Fe_2O_3$
C_2S	Dicalcium silicate, $2CaO.SiO_2$
C_3S	Tricalcium silicate, $3CaO.SiO_2$
CADR	Corrosion Analysis Detector Reading
CH	Calcium Hydroxide, $Ca(OH)_2$
C-S-H	Calcium silicate hydrate, $3CaO.2SiO2.3H_2O$
CSH_2	$CaSO_4.2H_2O$, Gypsum
H	H_2O
HCV	Half-Cell Voltage
NaCl	Sodium Chloride, Salt
OPC	Ordinary Portland Cement
PPC	Portland Pozzolanic Cement
ppm	parts per million
RHT	Rebound hammer test results
SLSI	Sri Lanka Standards Institution

LIST OF APPENDICES

1. INTRODUCTION

Cement is the most important construction material used to build the smallest building to the largest structures like dams, irrigation works, bridges, industrial complexes and many more. It, as the main ingredient for concreting work, acts as the binding or the matrix material when it is mixed with fine aggregates, coarse aggregates, admixtures and water to form concrete. Concrete is not strong in tension, but strong in compression. Hence concrete is reinforced with steel rebars (ribbed steel bars) to structurally withstand the tensional loads.

Cement for which the "SLS" mark is compulsory, undergoes close monitoring procedure for importing, manufacturing and marketing in Sri Lanka. Sri Lanka Standards Institution (SLSI) awards SLS mark for cement under SLS 107:2015 for Ordinary Portland Cement (OPC), SLS 515: 2015 for Masonry Cement, SLS1247:2008 for BHC and SLS 1253:2008 for PLC. According to the SLSI recommendation, Blended hydraulic cement is strongly recommended for concrete applications subjected to severe exposure conditions also for general-purpose cement [1]. When used for concrete, this type of cement improves properties such as setting time, workability, heat generation (properties of fresh concrete). Also, it improves the properties of hardened concrete such as strength and durability.

PLC is produced with two ways of manufacturing procedures. It can be manufactured by inter-grinding Portland cement clinker together with limestone. Also, PLC can be produced by mixing powdered limestone with OPC. The prime elements of PLC are clinker (80 to 95%), limestone (5 to 20%), and minor additional constituents (0%-5%). BHC (or PPC (old term)) is manufactured by mixing OPC with pozzolanic materials, or by inter-grinding cement clinker, gypsum and pozzolanic materials. According to the latest amendment, the proportion of pozzolanic materials can be varied from 15% to 35 % of clinker. Pozzolanic materials may be siliceous materials such as slag, silica fume or any other siliceous or aluminous material which possesses no cementitious properties, but when combined with lime in the presence of water, it produces cementitious properties. Some examples of natural pozzolanas are burnt clay, pumicite, volcanic ash, paddy husk, while blast furnace slag, fly ash, silica fume are examples of artificial pozzolanas.

BHC can be categorized into two groups considering the main pozzolanic materials used for blending. The main pozzolanic materials of type 1 may be natural pozzolana, silica fume or rice husk ash. Constituent variation can be in the range of 65 to 94% of clinker and 6 to 35% of pozzolanic material are allowed for type 1 of BHC as per the standard of SLS1247:2008. The constituent variation of type 2, as per the standard, ranges from 65% to 94% of clinker, and 6 % to 35% of blast furnace slag as the pozzolanic material.

There are a few local cement manufacturing plants; INSEE Cement (Lanka) Ltd., located at Galle and Puttalam, Tokyo Cement Company (Lanka) PLC, Tokyo Cement Company (Lanka) PLC Colombo and Trincomalee, and also there are hundreds of importers of bag cement of 50kg, and bulk cement importers who do the packing and distribute locally. Almost all imported cement are OPC which falls under SLS 107 and in addition to OPC local manufacturers produce Portland Pozzolanic Cement (PPC) (SLS 1247), Portland limestone cement (SLS 1253).

OPC is manufactured by grinding clinker with 5% gypsum. The main constituents of Portland cement are tri-Calcium Silicate (3CaO.SiO2 (C_3S)), di-Calcium Silicate (2CaO.SiO2 (C_2S)), tri-Calcium Aluminate (3CaO.Al_2O_3 (C_3A)) and tetra-Calcium Aluminate (4CaO.Al_2O_3.Fe_2O_3 (C_4AF)). Minor quantity of impurities may also be available (e.g. Calcium oxide (CaO) and Magnesium oxide (MgO)), in addition to the main constituents mentioned above.

The percentages of the constituents or the composition of cement can be shown below.

C_3S 45%- 60%

C_2S 15%- 30%

C_3A 6%-12%

C_4AF 6%-8%

When water is added to cement, the chemical reaction known as hydration of cement happens. Constituents do not react at the same rate of reaction. Tri-Calcium Aluminate, being the faster-reacting constituent compared to silicates of cement, starts its reaction first and the reaction releases a great amount of heat.

$C_3A + 3(CaSO_4.\ 2H_2O) + 32H_2O \rightarrow C_3A.3(CaSO_4.\ 2H_2O).32H_2O$ (Ettringite)

Later on, Ettringite formed and C_3A hydrate further and transform into Mono-sulfate hydrate.

$C_3A.\ 3(CaSO_4.2H_2O).\ 32H_2O + C_3A + H_2O \rightarrow$ Mono-sulfate hydrate

Tri-Calcium Silicate shows the early age hydration. The strength development of Tri-Calcium Silicate completes within 28 days.

$2C_3S + 6H \rightarrow C_3S_2H_3 + 3CH$

Di-Calcium Silicate reacts slowly and leads to obtaining the ultimate strength of the cement.

$C_2S + 4H \rightarrow C_3S_2H_3 + CH$

As CH (Calcium Hydroxide, $Ca(OH)_2$) is very weak, it decreases the strength of the cement paste. Also, it can easily deteriorate in the presence of acidic and Sulphate water.

Hardened OPC paste composition can be shown as follows;

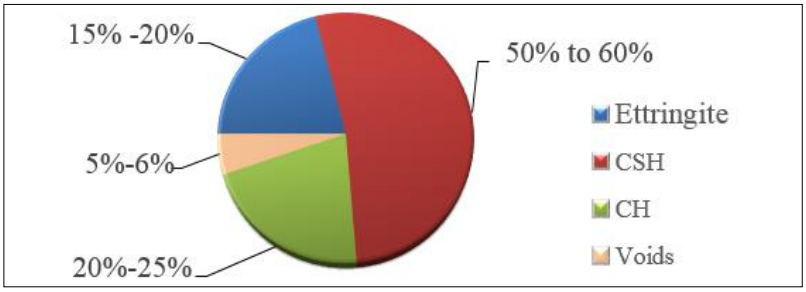

Figure 1.1: Composition of hardened OPC paste

Voids are present as capillary pores, entrapped and entrained air in the hardened cement. The formation of free lime (CH), during the hydration of OPC, introduces a focal point of attack by aggressive media such as Chlorides, Sulphates and it may decrease the durability of cement structures.

It is popular to research and make different types of cement to cater for different requirements such as constructional, environmental and economic. The main attempt of manufacturing PPC is to reduce the cost of production. Strength enhancement of cement is another key reason for partly replacing cement with pozzolanic materials. It also offers other advantages of workability, reduction of permeability, honeycombing, Sulphate attack, shrinkage, creeps, bleeding and many more advantages.

Steel bars in the form of ribbed steel, round bars that are used for reinforcing concrete to withstand higher tensile forces on concrete structures happen to be one of the main reasons with regards to failures of concrete structures. The corrosion product (rust) engages a higher volume, after steel get corroded by reacting with oxygen, moisture or with chloride ions. When the steel is embedded in concrete, it creates a volumetric expansion and may introduce stresses within the concrete structure. The resultant may be delamination, cracking or spalling.

The silicates of the fly ash material of PPC combines with the free lime ($Ca(OH)_2$) which is released during the process of hydration. The content of the secondary cementitious products from the pozzolanic reaction may increase with time which therefore results in higher strength and increased durability. Though steel naturally tends to corrode in normal circumstances, steel gets protection against corrosion through the alkalinity nature (pH: 12 to 13) of general cement/concrete

The passive layer on the reinforced steel is formed due to CH. In the high pH environment, a thin oxide layer forms on the steel and prevents metal atoms from dissolving. Therefore there might be a risk of disturbing the passive layer by the pozzolanic reaction. There is a need to establish how blended cement would behave in chloride-rich environments for the durability purposes of reinforcing steel. Due to the pozzolanic reactivity of blended cement, there is a possibility of reduction of pH of concrete or cement mortar which may be detrimental to the passivity of reinforced steel.

This research study was performed using a commercial Ordinary Portland cement complying with SLS 107: 2015 and a Pozzolanic cement complying with SLS 1047: 2015. Bag cement of Blended hydraulic cement (SLS 1247:2015) which is 15% fly ash was selected as the Pozzolanic cement for this study. A local cement manufacturing plant that manufactures both OPC and PPC and who is having the highest cement market share was selected to collect both cement samples.

The objectives of the research study are to compare the corrosion effect of reinforcement bar with OPC, PPC in Chloride rich environment and a normal environment and to investigate the effect of the ingress chloride ions on the compressive strength development of OPC and PPC.

Though, there are a lot of previous studies on corrosion of reinforcements in various scopes, research on the comparative study of effects of corrosion on reinforcement steel bars with commercially available OPC and PPC is not available.

Constructors hesitate to use PPC due to its lower initial and standard strengths compared to OPC, even though PPC is offering higher workability and lower heat of hydration compared to OPC. Also, there may be a risk of destroying the passivity of steel reinforcement bars due to pozzolanic reaction and affect detrimentally to structures.

This comparative study of OPC and PPC will clear out the suspicions related to corrosion, strength build-up with hardening further on, and bond strength to the reinforcements.

2. LITERATURE SURVEY

The process of manufacture of cement consists of grinding the raw materials, mixing them intimately in certain proportions, and burning in a large rotary kiln at a temperature of up to about 1450 °C. At the high temperature, the material sinters and partially fuses into balls known as clinker. The clinker is cooled and ground into a fine powder, with some gypsum added, and the resulting product is the commercial Portland cement so widely used throughout the world.

For structural concrete, concrete has to be reinforced to obtain tensile properties as concrete has higher compressive load-bearing capabilities but is lower in tensile strength. With engaging steel as a composite material to the concrete structure, it contributes to adding tensile properties to the structure.

Corrosion of reinforcement in concrete is examined widely by several previous studies. For example, several previous studies [2–4] addressed the structural effects of corrosion. Various studies investigated that addressed the effects of corrosion on bond behaviour [5–6], change in mechanical properties [7–9], and other corrosion-related phenomena [10–12].

Steel in concrete is usually in a non-corroding, passive condition. However, steel-reinforced concrete is often used in severe environments where seawater or deicing salts are present. When chloride moves into the concrete, it disrupts the passive layer protecting the steel, causing it to rust and pit. The carbonation of concrete is another cause of steel corrosion. When concrete carbonates to the level of the steel rebar the normally alkaline environment, which protects reinforcement steel from corrosion, is replaced by a more neutral environment. Under these conditions, the steel is not passive and rapid corrosion begins. The rate of corrosion due to carbonated concrete cover is slower than chloride-induced corrosion [13].

2.1 Mechanism of Corrosion of steel in concrete

The corrosion mechanism of steel is a collection of electrochemical reactions that convert refined steel into a chemical stable oxide. Concrete is a porous structure composed of aggregates, hydrated cement paste, and voids. C-S-H grains, capillary pores, gel pores, and interlayer porosity all together form a hydrated cement structure. The pore solution or gel pores of concrete is very alkaline. This pore solution is formed by saturated in $Ca(OH)_2$ of which pH values range between 12.6-14. As a

result of this pH range or high alkalinity, a passivity effect is resultant on steel surrounded with cement hydration and is naturally protected by this and by the barrier effect of the cover itself. De-passivation can happen due to chloride ingress and carbonation. (Figure 2.1.1). Carbonation usually induces generalized corrosion while chloride will lead to pitting or localized attack. The corrosion can be easily recognized by the rust presence on the rebar and by the appearance of cracks running parallel to the reinforcement bar. In fig. 2.1.1 is also identified another particular type of corrosion, the stress corrosion cracking, that develops in pre-stressed wires subjected to special aggressive conditions.

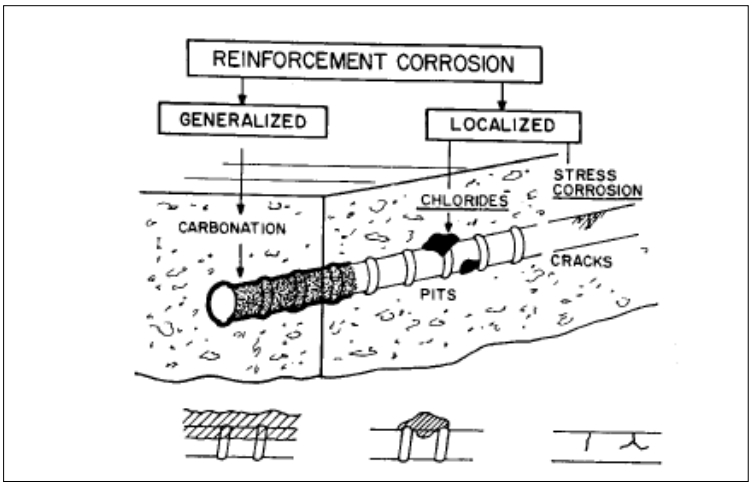

Figure 2.1.1: Types and morphology of the corrosion in concrete [2]

Corrosion is an electrochemical process that involves the flow of electrons and ions. It involves a half-cell oxidation reaction, or the anodic reaction and the reduction reaction or cathode reaction. At the anode which happens to be active sites of steel bar, iron atoms lose electrons and move into the surrounding concrete as ferrous ions. It can be represented as follows.

$$2Fe \rightarrow 2Fe^{2+} + 4e^{-}$$

The electrons flow to sites cathode sites and react with water and oxygen in the concrete. A reduction reaction can be written as

$$2H_2O + O_2 + 4e^{-} \rightarrow 4OH^{-}.$$

The ferrous ions migrate through the concrete pore water to these cathode sites where they combine to form iron hydroxides or rust:

$2Fe^{2+} + 4OH^- \rightarrow 2Fe(OH)_2$

This initially precipitated hydroxide react further with oxygen and form higher oxides which increase rust volume gradually. The increment in volume as the reaction products react further with dissolved oxygen leads to internal stress within the concrete that may be sufficient to cause cracking and spalling of the concrete cover.

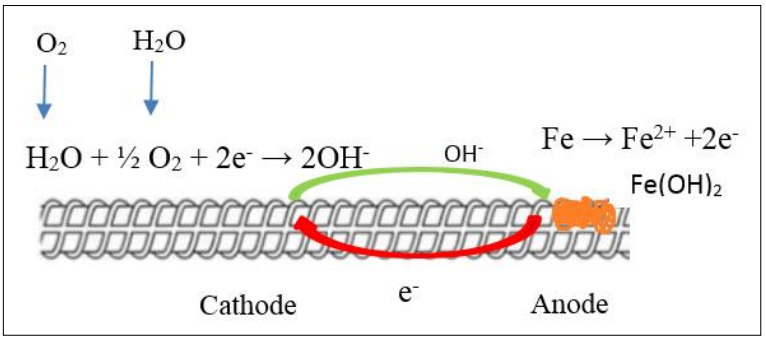

Figure 2.1.2: Schematic diagram for steel reinforcement corrosion

Corrosion of embedded metals in concrete can be reduced by placing crack-free concrete with low permeability and sufficient concrete cover. Low-permeability concrete can be attained by decreasing the water to cementitious materials ratio of the concrete and the use of pozzolanic materials.

2.2 Concrete and the Passive Layer

Although steel's natural tendency is to undergo corrosion reactions, the alkaline environment of concrete (pH of 12 to 13) provides the steel with corrosion protection. At the high pH, a thin oxide layer forms on the steel and prevents metal atoms from dissolving. This passive film does not actually stop corrosion; it reduces the corrosion rate to an insignificant level. For steel in concrete, the passive corrosion rate is typically 0.1 µm per year [14].

The presence of sodium hydroxide, (NaOH), potassium hydroxide, (KOH) and saturated calcium hydroxide solution, $Ca(OH_2)$ results in high alkalinity of the cement matrix (pH> 12.5). The high alkalinity of the cement matrix usually causes steel embedded in concrete to exist in a non-corroding, passive condition [15]. This is because the high pH suppresses steel corrosion due to the formation of a very thin (1-

10nm thick) passive gamma ferric oxides (γ-Fe2O3), iron oxide hydroxide (FeO(OH)) and magnetite (Fe_3O_4) on the steel surface [16].

Darrell S. Leek addresses the electrochemical basis for the passivity of iron in aqueous solution and the anodic and cathodic reactions which occur are detailed in relation to pH-potential (Pourbaix) and current-potential (Evans) diagrams. The breakdown of the passive film has been discussed in relation to the commonly observed causes of deterioration of reinforced concrete i.e. carbonation of concrete, the presence of chloride ions at the steel surface and sulphate attack [17]. Corrosion can occur when the passive layer is destroyed. The destruction of the passive layer occurs when the alkalinity of the concrete is reduced or when the chloride concentration in concrete is increased to a certain level.

Exposure of reinforced concrete to chloride ions is the primary cause of premature corrosion of steel reinforcement and will lead to deleterious effects on rebar [15]. The intrusion of chloride ions, present in deicing salts and seawater, into reinforced concrete can cause steel corrosion if oxygen and moisture are also available to sustain the reaction. Chlorides dissolved in water can permeate through sound concrete or reach the steel through cracks. Chloride-containing admixtures can also cause corrosion.

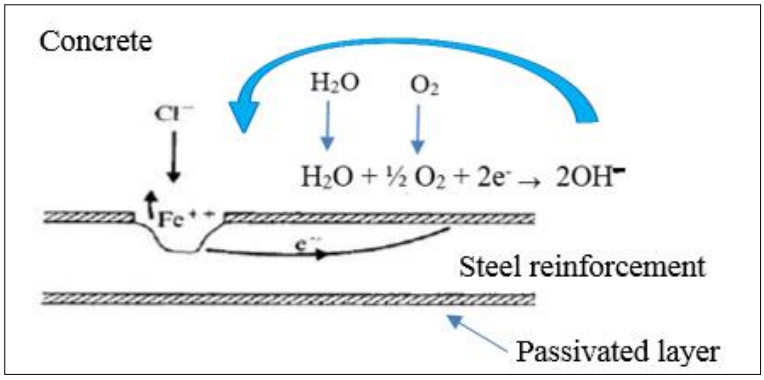

Figure 2.2.1: Schematic diagram for destruction of passivity layer by Cl^-

Chlorides are made available into the concrete through contact water that has chlorides, for example, brackish water, seawater and industrial effluents [18]. The risk of corrosion increases as the chloride content of concrete increases. When the chloride content at the surface of the steel exceeds a certain limit, called the threshold value, corrosion will occur if water and oxygen are also available. Although chlorides are

directly responsible for the initiation of corrosion, they appear to play only an indirect role in the rate of corrosion after initiation. The primary rate-controlling factors are the availability of oxygen, the electrical resistivity and relative humidity of the concrete, and the pH and temperature. This results in the formation of rust which has two to four times the volume of the original steel and none of its good mechanical properties [19]. Chloride induced corrosion produces pits or holes in the surface of reinforcing steel, reducing strength as a result of the reduced cross-sectional area [20]. The ingress of chloride ions, among other factors, depends on the permeability of the concrete or mortar [21].

Various types of corrosion inhibitors have been developed and marketed to mitigate corrosion in concrete structures. Studies have been done with testing of two commercially available Corrosion inhibitors to determine the effectiveness and their influence on the durability of Concrete (with OPC and PPC) using the Rapid Chloride Permeability Test. The rapid chloride permeability tests revealed that the resistance of concrete for the ingress of chloride ions is improved by the addition of corrosion inhibitors [22].

2.3 Carbonation

Carbonation occurs when carbon dioxide from the air penetrates the concrete and reacts with hydroxides, such as calcium hydroxide, to form carbonates. In the reaction with calcium hydroxide, calcium carbonate forms:

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$$

This reaction reduces the pH of the pore solution to as low as 8.5, at which level the passive film on the steel is not stable. Carbonation is generally a slow process. In high-quality concrete, it has been estimated that carbonation will proceed at a rate up to 0.04 inches per year. The amount of carbonation is significantly increased in concrete with a high water-to-cement ratio, low cement content, short curing period, low strength, and highly permeable or porous paste.

The carbonation of concrete also lowers the number of chloride ions needed to promote corrosion. For newly build concrete, according to the previous research studies, 7,000 to 8,000 ppm of chloride ions are required to start corrosion of embedded steel. But if the pH gets lowered to a range of 10 to 11, the chloride

threshold for corrosion is significantly lower as at or below 100 parts per million. Like chloride ions, however, carbonation destroys the passive film of the reinforcement but does not influence the rate of corrosion [23].

2.4 Ionic transport mechanisms

The mechanisms by which aggressive ions may penetrate concrete could be due to one or a combination of the following ionic transport mechanisms: pressure-induced water flow, water absorption, water vapour diffusion, wick action, ion diffusion, gas diffusion and pressure-induced gas flow. For chloride ions transport, the predominant mechanism is to be ionic diffusion. Hence, the performance-based methods for estimating corrosion initiation are developed based on calculating chloride ions diffusion causing corrosion initiation. The chloride ions diffusion is governed by Fick's second law as follows:

$$\frac{\partial C(x,t)}{\partial t} = D\frac{\partial^2 C(x,t)}{\partial x^2} \qquad \text{--------- (1)}$$

x, t, c(x,t) and D represents depth of chloride penetration, time, concentration of chloride ion at depth *x* and time *t*, and chloride ion diffusion coefficient of concrete, respectively. The boundary conditions for solving Equation (1) is:

$$C(x,t) \begin{cases} Cs \text{ if } x=0 \\ C_o \text{ if } x=\infty \end{cases} \qquad \text{--------(2)}$$

C_o and C*s* is an initial concentration of chloride ion in the body of concrete and concentration of chloride ion at the concrete surface, respectively. Assuming homogenous diffusion of concrete property, solution of Equation (1) with boundary condition as in Equation (2) gives:

$$\frac{C_S - C(x,t)}{C_S - C_o} = erf\left(\frac{x}{2\sqrt{Dt}}\right) \qquad \text{---------(3)}$$

Equation (3) may be used to estimate the corrosion initiation by substituting *x* with the depth of embedded reinforcement and *c(x,t)* with the critical chloride concentration (Cl_{cr}) [24].

Pozzolana is defined as a siliceous and/or siliceous aluminous material, which in itself possesses little or no cementitious value, but will, in finely divided form and presence of moisture, chemically reacts with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties [25]. The primary pozzolanic reaction during the early curing is with alkali hydroxides, followed by the main and long-term reaction with CH [26]. The behaviour of the delay in pozzolanic reaction results in more permeable concrete at an early age and gradually become denser than plain concrete with time [27].

This behaviour is due to two reasons, firstly as mentioned before, pozzolana particles become the precipitation sites for the early hydration CSH and CH. This hinders pozzolanic reaction. Secondly, the strong dependency of the breaking down of the glass phase on the alkalinity of the pore water could only attain the high pH after some days of hydration [28].

One of the main strategies to reduce the environmental impact of the concrete industry is the reuse of waste materials. The first approach consisted of replacing variable amounts of cement with industrial by-products with pozzolanic activity. Under this strategy, several supplementary cementing materials were tested and developed, such as silica fume, fly ash, ground granulated blast furnace slag, etc. The success of these by-products was absolute, and nowadays it is very usual to use them. Nevertheless, other pozzolans have been successfully implemented in cement products, although their use has not been so extended or many times they have never been applied to real construction. As examples of these minor pozzolans, the following can be listed: rice husk ash [29], sewage sludge ash [30], metakaolin [31], other metal industry slags [32], red sludge ash [33], spent catalytic cracking catalyst [34], calcined clays [35], etc. The light usage of these minor pozzolans on the concrete manufacture can be related to the small quantity of them that are produced with respect to the total cement demand, the heterogeneity of these materials composition and/or the need for laborious pre-treatments in some cases.

CSH contributes most to the strength of mortar or concrete. Hydration of C_3S and C_2S characterize strength development of mortar or concrete. C_3S contributes mainly to early strength and C_2S contributes mainly to long-term strength [36].

Natural steel corrosion of reinforced concrete structures is a slow process that researchers find necessary to accelerate in laboratory tests to obtain needed damage in a short time. Regrettably, there is no standard procedure for accelerating steel corrosion in reinforced concrete specimens. Researchers, therefore, continue to use various techniques to accelerate it. Unfortunately, structural damage and the rate of steel corrosion are dependent on the accelerated corrosion technique used [37].

Both the relative apparent yield and ultimate strengths of the corroded reinforcing steel bars decreased with an increase in average cross-section loss of the reinforcing steel bar. However, the relative apparent ultimate strength had a better correlation with the average cross-section loss of the reinforcing steel bar than did the relative apparent yield strength. The elongation ratio decreases with increased corrosion for those corroded in concrete [38].

An investigation has been carried out to study "Mechanical strength and corrosion detection of pozzolanic cement". Various pozzolanic cement pastes based on ordinary Portland cement (OPC), granulated blast furnace slag and metakaolin have been studied in comparison to their corresponding ordinary Portland cement, to evaluate the probability of steel corrosion. The results showed that mix containing 70% OPC, 15% metakaolin and 15% granulated blast furnace slag has higher compressive strength and corrosion resistance than the neat cement paste. The results of thermal analysis have indicated that the presence of 30% granulated blast furnace slag and metakaolin consumed the CH formed as a result of the hydration of OPC (pozzolanic reaction). The compressive strength values of the hardened blended cement pastes increase with a hydration time. This is due to the increase in the amount of hydration products (CSH) which is responsible for binding. As the hydration proceeds, more hydration products (CSH) are formed and accumulated within the pore system of the hardened paste. Therefore, the porosity of the cement pastes decreases and then the compressive strength increases. For all cement blends, increasing metakaolin–slag contents in the range used in this investigation decreases the chemically combined water content and increases the compressive strength values. The specimens with higher slag–metakaolin contents were found to have higher corrosion resistance; this means that the mineral admixture (slag–metakaolin) can reduce the probability of steel corrosion in concrete structures [39].

2.5 The Half-Cell Potential Technique

The half-cell potential test is a corrosion monitoring technique standardized by ASTM. It is used to determine the probability of corrosion within the rebar in reinforced concrete structures. The schematic in figure 2.5.1 represents a cell where each side is referred to as a half-cell. Each half-cell is represented by an electrode in a solution (electrolyte) and both half-cells are connected. Since one of the electrodes has a higher tendency to corrode compared to the other, that electrode (anode) will oxidize and in turn will donate electrons.

To keep the system in equilibrium and balance the charges in the electrolytes, there will be an exchange of ions through the salt bridge. The voltmeter will measure the potential difference (voltage) between both electrodes, which indicates the rate of dissolution of the anode. To apply this concept to concrete and to interpret the results of corrosion potential, a reference electrode with a known potential is needed. Typically, for reinforced concrete applications, a copper/copper sulfate electrode (Cu/CuSO4) or silver/silver chloride electrode (Ag/AgCl) is used for the half-cell reference. This reference electrode is connected to the other half-cell represented by the embedded rebar. By connecting that reference electrode to the reinforcing steel and placing the reference electrode on the surface of the concrete, it is possible to measure the potential difference between the two half-cells.

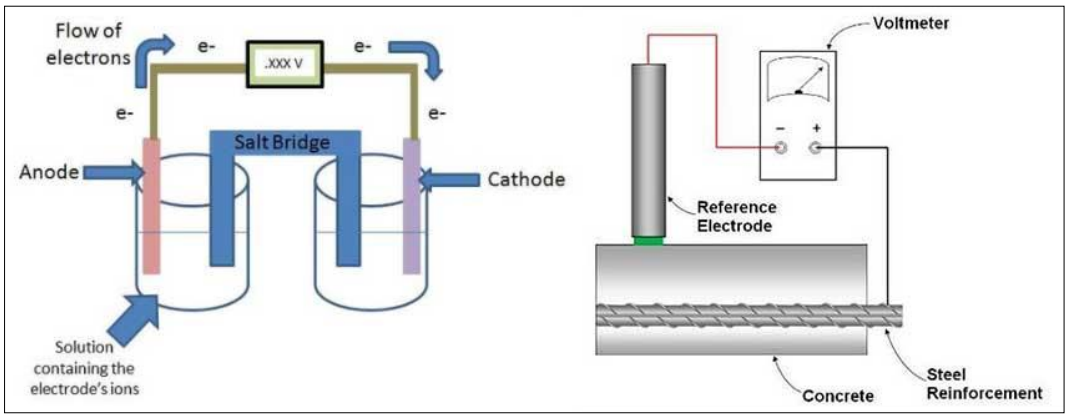

Figure 2.5.1: Half-cell potential measurement technique [40]

Factors that can influence the results by shifting their potential reading towards a more positive or negative value, such as the effect of the concrete condition (dry or wet), presence of chloride, absence of oxygen at the rebar surface (due to saturation), cover thickness, concrete resistivity, and temperature are as shown in table 2.5.

Table 2.5: Typical ranges of half-cell potentials of rebar in concrete

Conditions	Potential values (mV/CSE)
Humid, chloride-free concrete	-200 to +100
Wet, chloride contaminated concrete	-600 to -400
Water saturated concrete without oxygen	-1000 to -900
Humid, carbonated concrete	-400 to +100
Dry, carbonated concrete	0 to +200
Dry concrete	0 to +200

Source: RILEM TC-154, 2003) [40]

Half-cell potential measurement has been recommended as a non-destructive method for assessing the probability of corrosion of reinforcing steel bar before the damage is evident on the surface of the concrete structure. The half-cell potential measurement is currently well-known and is standardized in the ASTM C876. A previous study showed that the half-cell potential decreased (more negative value) with the increase of chloride content and moisture content but increased (less negative value) with the increase of compressive strength. The variation of half-cell potential decreased with the increase of, chloride content and moisture content. The relationship between the level of corrosion and the half-cell potential was found; that is, the level of corrosion increased with the decrease of the half-cell potential [41].

2.6 Rebound hammer testing

The rebound hammer test is a non-destructive convenient test method that gives a rebound number by the testing instrument which is correlated to compressive strength surface hardness and stiffness. It consists of a spring-controlled hammer mass that slides on a plunger within a tubular housing. The hammer is forced against the surface of the concrete, by the spring, and the distance of rebound is measured on a scale.

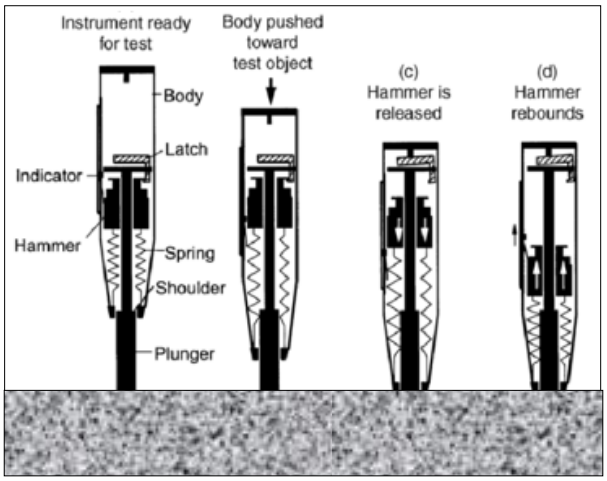

Figure 2.6.1: Schematic diagram of Rebound hammer operating principle

When the body of the instrument is pushed towards the surface of a test object, the spring controlled mass rebounds and the extent of such rebound depends upon the surface hardness of concrete. The surface hardness is taken to be related to the compressive strength of the concrete. The rebound number or rebound index is read with the graduated scale on the instrument body. The rebound index results are influenced by factors such as types of cement and aggregate, surface condition, moisture condition of the concrete, type of cement, aggregate properties, and age of concrete [42].

The rebound hammer test method can be used for assessing the compressive strength of concrete or cement with the correlations between rebound index and compressive strength, assessing the quality of one element of concrete with another.

3. EXPERIMENTAL PROCEDURE

3.1 List of raw materials and apparatus

1. A commercial OPC sample from the selected manufacturer
2. A commercial PPC sample from the selected manufacturer
3. Mahavali river sand
4. Two 5.8m TMT steel bars (same batch) of 12mm diameter
5. Distilled water
6. 100x100x100 mm^3 cubic moulds
7. Electronic balance
8. Mixing scoops
9. Compacting bar
10. Curing tank
11. Corrosion Analysis Detector
12. Salt conditioning baths (5% Sodium Chloride concentration): 4 numbers
13. Rebound Hammer instrument
14. Universal Tensometer (which can perform pull out test)
15. Compression testing machine

3.2 Procedure

The mix proportions of Cement: Sand: Water was 1:3:0.5 as based on SLS ISO 679:2011. TMT bars to be used for the specimens were sampled from a manufacturing plant and were cut into 18 pieces in 400 mm lengths bars and 18 pieces in 100mm lengths. Moulds were cleaned, greased and made ready for casting.

For casting specimens with OPC and blended cement (the compositions of two types of cement was mentioned in Appendix D) mix proportions were measured separately with the electronic balance; Cement 5 400g: Sand 16 200g: water 2 700g. First Cement and fine aggregates were dry mixed and water was added gradually. They were mixed sufficiently and obtained proper consistency. The first set of specimens that were to be tested for pull out tests were moulded with 400mm TMT bars in the

centre position. When filling each mould with mortar, it was strictly cared to fill them in the same manner.

The casting of a specimen was done by filling approximately 1/3 of the mould at a time and ramming each layer with 27 strokes using the tamping bar so the strokes were distributed uniformly. After compacting the topmost layer, using a trowel the surface of the top was smoothed out. 9 specimens from OPC and 9 specimens from pozzolanic cement were moulded with the 400mm TMT bars in the centre position. In the same manner, another set of 9 specimens from OPC and 9 specimens from pozzolanic cement were moulded with 100mm TMT bars at center position. The masses of 100mm TMT bars (initial weights) were measured using the electronic balance.

After casting, each specimen was labeled with an identification number as mentioned below.

Table 3.1: Identification numbers of cement motor specimens

Cement type used	Length of TMT steel bar, mm	Identification numbers
OPC	400	O1, O2, O3, O4, O5, O6, O7, O8, O9
PPC	400	P1, P2, P3, P4, P5, P6, P7, P8, P9
OPC	100	o1, o2, o3, o4, o5, o6, o7, o8, o9
PPC	100	p1, p2, p3, p4, p5, p6, p7, p8, p9

Here, ‘O’ refers to specimen made of OPC with a 400mm reinforcement bar steel while ‘P’ refers to specimen made with PPC with a 400mm reinforcement bar steel and ‘o’ refers to specimen made of OPC with a 100mm reinforcement bar steel while ‘p’ refers to specimen made with PPC with a 100mm reinforcement bar steel. The numerical numbers of 1 to 9 identify each specimen prepared as mentioned above.

After 24 hours of initial hardening, specimens were separated from the moulds, and identification numbers were written on the specimens again.

After labeling with identification numbers, the cement mortar cubes were placed in the freshwater curing chamber. After 28 days of curing time, specimens were taken out from the curing chamber. The state of just after the 28 days of water curing of

cement cubes were considered as the ‘Initial time’ or ‘zero time’ of the timeline of testing.

Figure 3.1.1: OPC and PPC specimens (for pull out test), after casting

Figure 3.1.2:OPC and PPC specimens (for compression test), after casting

Using the “Corrosion Analysis Detector”, half-cell voltage readings were taken. To get the readings, first, specimen surfaces were wetted and three readings were taken from each specimen aligning to the steel bar. Those readings were considered as the initial readings of the Corrosion Analysis Detector. The voltage readings of Corrosion Analysis Detector at the Initial stage of OPC cubes PPC cubes mentioned as ‘I stage_O’ and ‘I stage_P’ respectively. Next, initial Rebound hammer readings were taken on cubic specimens at the surface directly above the reinforcement bar using the Rebound hammer.

Sodium Chloride (NaCl) solution was prepared by dissolving 500g of NaCl in 10 liters and it was filled into the baths so that level of the salt solution is at the level of the specimens. While keeping a subset of 3 specimens as reference cement motor cubes, other 6 specimens of each sample were dipped up to the top surface level of the

cubes for 30 minutes per day for 180 days. Always care was taken to maintain the same conditions to the two types of cement mortar cubes.

Figure 3.1.4: Test specimens for salt conditioning

Figure 3.1.5: Test specimen in salt baths

While salt conditioning of the test specimens was continued for 30 minutes per day throughout 180 days, Corrosion Analysis Detector half-cell voltage readings were taken after 60 days, 120 days and 180 days respectively. Half-cell voltage readings taken after 60 days time were noted under 60d_O, 60d_P, for specimens made with OPC and PPC respectively. Similarly, voltage readings taken after 120 days-time were noted under 120d_O, 120d_P for specimens made with OPC and PPC respectively and voltage readings taken after 180 days were noted under 180d_O, 180d_P for specimens made with OPC and PPC respectively.

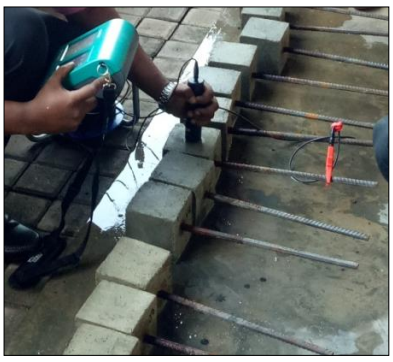

Figure 3.1.6: Half-cell voltage test with Corrosion Analyzer Detector meter

Rebound hammer tests also were conducted after 60 days, 120 days and 180 days respectively on cubic specimens at the surface directly above the reinforcement bar. The plunger of the Rebound hammer were placed firmly at the center of the surface (directly above the reinforcement bar), on each test specimen, perpendicular to the specimen and was pressed toward the test surface till the hammer impact. Rebound number of each specimen was read on the graduated scale and recorded.

Figure 3.1.7: Testing with Rebound Hammer instrument

3.2 Compression testing on Cement cubes

After wiping the platens of the compression testing machine, each specimen was placed in the machine centrally between the platens so that the reinforcement steel bar at horizontal position (top surface of the cube as cast facing sideways). Each cube was placed on the base plate of the machine and the load was applied at the rate of 3kN/s, until the cube fracture. The maximum load at fracture of each cube was recorded.

Figure 3.2.1: Compression testing of cement motor cubes

3.3 Pull out resistance

Each test specimen cast for pull out testing was mounted on the seating of the top of the upper jaws of the Universal tensometer and it was freely placed without tightening the steel bar from the top jaws. Lower jaws were brought to close to the bottom level of upper jaws (25mm distance) and steel bar end was fixed to the lower jaws. From the lower jaw, constant rate of pulling force ($30N/s^{-1}$) was exerted to the steel bar. The maximum loads achieved at failure of the bond anchorage by each sample were recorded.

3.4 Loss of mass at the ends of steel bars

Even though it seemed that no corrosion had been happened on the steel bars which were contact with the cement mortar except the ends which were open to salt environment, the steel specimens were tested for loss of mass due to corrosion as follows [43].

Specimens were brushed with a soft wire brush under running tap water to remove rust. After sufficient cleaning, as rust was still seemed to be on the bar, chemical cleaning was done. 7.0g of Hexamethylenetetramine was dissolved in 1000ml Hydrochloric acid (HCL, ρ=1.19 g/ml) and distilled water was added it until the total solution is 2000ml and stirred well. TMT bars to check for mass loss on corrosion were placed in a vessel and solution was poured in with a funnel to the vessel. After 15 minutes time the solution was drained out and the TMT bars were taken out and scrubbed with the soft wire brush under running tap water until the all the rust on the bars were removed. After final washing with tap water, bars were washed with distilled water. After wiping each bar with an ethanol solution and drying, mass of each bar was recorded.

Figure 3.4.1: Chemical treatment to remove rust

4. TEST RESULTS AND DISCUSSION

At the stage of specimen casting, cement, sand and water were used excluding coarse aggregates as variations of size, shape and distribution patterns of coarse aggregates may affect the real test results. As the objective was to compare the two types of cement, specimens were moulded under the same conditions and only variant to be the type of cement to get a clearer picture of corrosion effect with the change of cement type.

The size of the test cube shall be 100mm or 150 mm in size for testing of concrete specimens [44]. To this research 100mm cube length size was selected as per the SLSI standard [45], as the specific diameter used for this study was 12mm. 12mm nominal diameter size was selected to the study as it is the size which was having highest demand in concrete structural works.

Mahavali river sand with no impurities was used to make the mortar (fine aggregate gradation of the sand used for the cube casting is mentioned in Appendix B).

As there is no standard procedure for accelerating steel corrosion in reinforced concrete/ mortar specimens, researchers, therefore, continue to use various techniques to accelerate it. In this study corrosion acceleration was carried out with 5% Sodium Chloride solution considering the Sodium Chloride concentration used in "Corrosion Tests in Artificial atmospheres–Salt spray tests, SLS ISO 9227: 2015.

4.1 Results of Half-cell voltages

Corrosion Analysis Detector meter reads the half-cell voltage (HCV) against 'the standard half-cell voltage' of the instrument. The test results obtained from the Corrosion Analysis Detector meter are as follows;

Table 4.1.1: Half-cell voltage test results

Cube Number	Voltage, mV							
	I_ stage_O	I stage_P	60d_O	60d_P	120d_O	120d_P	180d_O	180d_P
1	-341	-317	-358	-334	-362	-347	-368	-356
2	-344	-320	-349	-327	-369	-340	-371	-352
3	-346	-326	-354	-336	-372	-349	-375	-355
4	-342	-324	-484	-469	-564	-545	-587	-561
5	-340	-325	-480	-474	-562	-538	-584	-558
6	-347	-329	-485	-467	-565	-534	-588	-554
7	-349	-327	-482	-462	-562	-541	-586	-560
8	-346	-330	-486	-469	-564	-543	-584	-563
9	-347	-320	-481	-473	-562	-535	-582	-559

Above test results was summarized as in Table 4.1.2 considering the average of salt conditioned OPC cubes (SC_O), the average of salt conditioned PPC cubes (SC_P), the average of reference OPC cubes (Ref_O), the average of reference PPC cubes (Ref_P).

Table 4.1.2: Summarized test results of Half-cell voltage

Sample	HCV at , mV			
	0 day	60 day	120 day	180 day
SC_O	-345.17	-483.00	-563.17	-585.17
SC-P	-325.83	-469.00	-539.33	-559.17
Ref_O	-343.67	-353.67	-367.67	-371.33
Ref_P	-321.00	-332.33	-345.33	-354.33

Table 4.1.3: Standard deviations of Half-cell voltage

Sample	Standard deviation of HCV at, mV			
	0 day	60 day	120 day	180 day
SC_O	3.43	2.37	1.33	2.23
SC-P	3.66	4.34	4.41	3.06
Ref_O	2.52	4.51	5.13	3.51
Ref_P	4.58	4.73	4.73	2.08

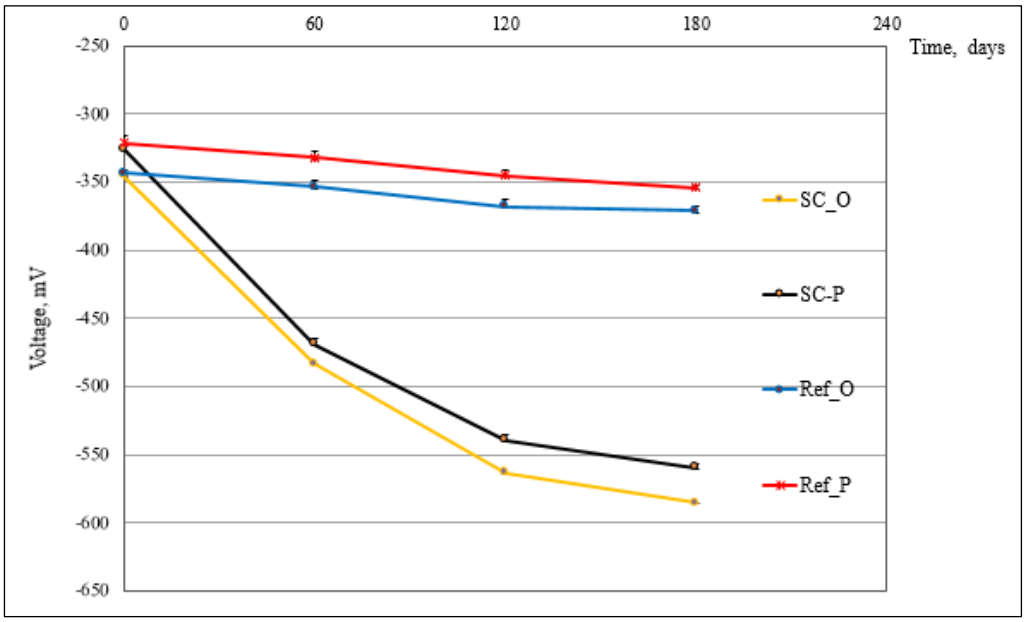

Figure 4.1: Voltage readings of cement cubes vs. Time

HCV of 60 days, 120 days and 180 days of specimens, p1, p2, p3 and o1, o2, o3 which were not undergone salt conditioning (control specimens) were closer to initial stage HCV values compared to HCV of salt conditioned OPC and PPC specimens. But, there were slight incremental minus-voltages with time for both types of cement. It may be a consequence of cement hydration and introducing low resistivity through the pore structures. The specimens which were salt-conditioned were having higher minus HCV of Corrosion Analysis Detector with time. It may be due to the corrosion of steel bars or due to more chloride ions in the pore structure.

The relationship between the level of corrosion, chloride content and the half-cell potential was found in earlier a research study [41] and showed that the half-cell potential decreased (more negative value) with the increase of chloride content, level of corrosion and moisture content.

Therefore the observed results of decrease of the half-cell potential with time may be due to the increment of the level of corrosion or migration of more chloride ions to the pore structures.

Of salt conditioned specimens, PPC specimens were showing a lesser minus HCV than HCV of OPC specimens. The lesser minus HCV may be a result of the denser structure formed as a result of the pozzolanic reaction with time. Chloride ions may migrate more easily into lower resistivity areas or open pore structures.

4.2 Results of Rebound hammer testing

The summarized Rebound hammer test (RHT) results of cubic specimens at the surface directly above the reinforcement bar is shown (in Rebound number) in table 4.2.1.

Table 4.2.1: Rebound hammer test results

Cube Number	Rebound number							
	I stage_O	I stage_P	60d_O	60d_P	120d_O	120d_P	180d_O	180d_P
1	22	18	30	34	38	40	44	54
2	22	18	29	33	38	42	42	52
3	21	19	30	34	36	40	40	50
4	22	18	29	33	38	42	45	49
5	23	16	30	32	36	42	42	50
6	22	18	29	34	36	40	41	53
7	22	18	28	32	34	42	40	54
8	23	17	30	32	36	40	44	50
9	22	18	30	32	36	42	45	49

Above Rebound hammer test results at the surface directly above the reinforcement bar can be summarized as in table 4.2.2.

Table 4.2.2: Summarized Rebound hammer test results

Sample	Rebound number at,			
	0 day	60 day	120 day	180 day
SC_O	22.33	29.33	36.00	42.83
SC-P	17.50	32.50	41.33	50.83
Ref_O	21.67	29.67	37.33	42.00
Ref_P	18.33	33.67	40.67	52.00

Table 4.2.3: Standard deviations of Rebound hammer test

Sample	Standard deviation of RHT at,			
	0 day	60 day	120 day	180 day
SC_O	0.52	0.82	1.26	2.14
SC-P	0.84	0.84	1.03	2.14
Ref_O	0.58	0.58	1.15	2.00
Ref_P	0.58	0.58	1.15	2.00

Above summarized Rebound hammer test results can be graphically shown as below.

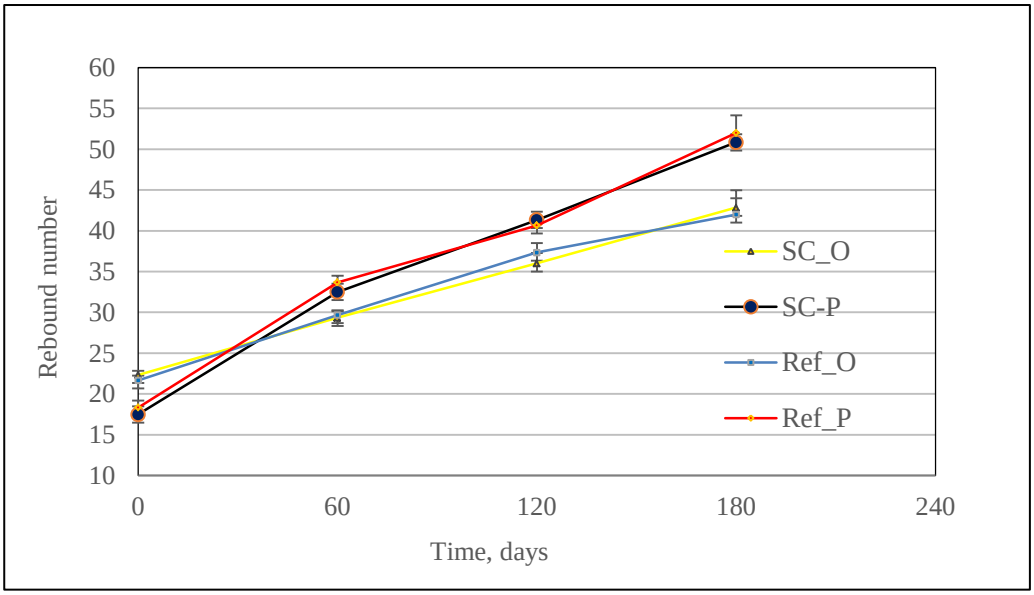

Figure 4.2.1: Rebound hammer test of cement cubes

Rebound hammer test results of` OPC specimens and PPC specimens depicted incremental trend with time. The Rebound hammer test results confirmed that the strengths of all the specimens have increased with the timeline. Though, initially, PPC specimens were having lesser strength than OPC specimens, after the day of 35 and onwards strengths were increasing of both PPC controlled (reference) specimens and PPC salt conditioned specimens. It confirmed that even though standard strength results of PPC were lower than that of OPC, with further hardening PPC's strength factor gradually increase with time. Also, the variations of rebound indexes increased with the timeline. With that, it can be concluded that variations of strengths among the same type of specimens will be higher with time passing over.

4.3 Compressive Test Results

To compare the compressive loads which would withstand without failure by two cement types with a reinforcement steel bar at the centre, compressive test of the specimens were carried out as an additional testing. (Compressive tests as per the SLS ISO 679:2011 for the two types of cement was done at the early stages of the research (please see Appendix A). Also with these test data, it was to get an affirmation for other tests carried out with this research study. In case of reinforcement bars were corroded, the bond between the cement mortar and the reinforcement would be weaker which could be interpreted with the compressive test results.

Table 4.3.1: Compression test results of OPC cement mortar cubes

Specimen	Maximum load, kN	Strength of cube, N/mm^2
o1	527.2	52.7
o2	535.2	53.5
o3	542.2	54.2
o4	528.8	52.9
o5	534.7	53.5
o6	536.2	53.6
o7	537.1	53.7
o8	535.4	53.5
o9	541.4	54.1

Table 4.3.2: Compression test results of PPC cement mortar cubes

Specimen	Maximum load, kN	Strength of cube, N/mm^2
p1	598.9	59.9
p2	594.2	49.4
p3	598.8	49.9
p4	592.6	59.3
p5	594.5	59.5
p6	598.9	59.9
p7	596.6	59.7
p8	597.1	59.7
p9	594.7	59.5

Above compressive strength results of OPC and PPC cement cubes can be graphically shown by figure 4.3.1 .

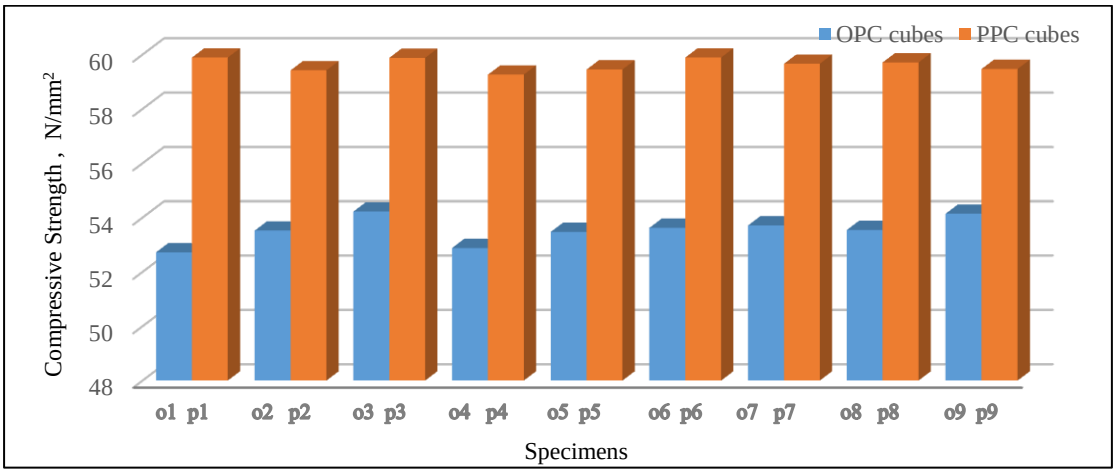

Figure 4.3.1: Compressive strength of OPC and PPC cement cubes

Above table 4.3.1 and table 4.3.2 results were analyzed further by averaging test results of cube specimens as shown in table 4.3.3.

Table 4.3.3: Compressive strengths of the two types of cement samples

Sample	Identification	Average Compressive strengths, N/mm^2	Standard deviation
OPC reference specimens of 1, 2, 3	C_o	53.49	0.75
PPC reference specimens of 1, 2, 3	C_p	53.56	0.41
OPC salt treated specimens 4 to 9	S_o	59.73	0.27
PPC salt treated specimens 4 to 9	S_p	59.57	0.22

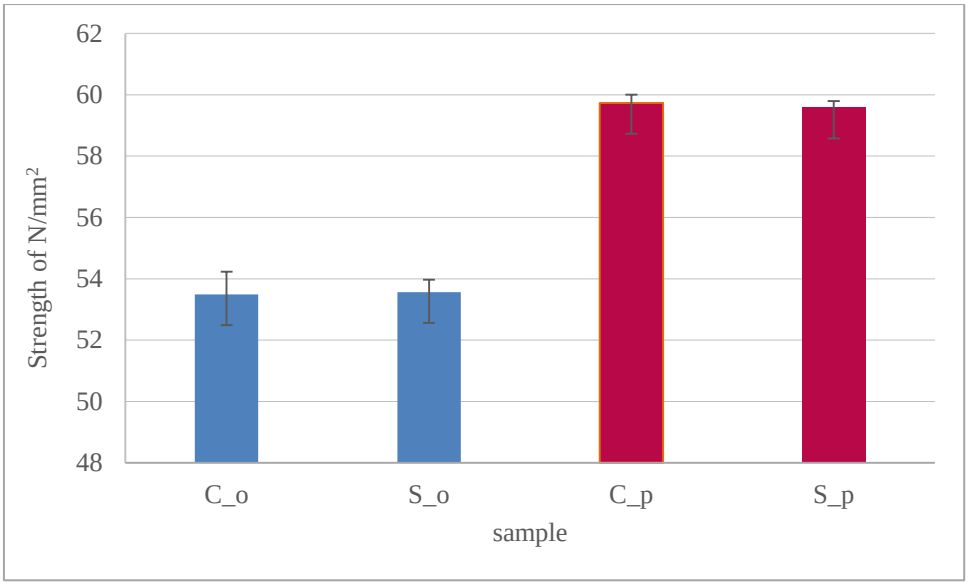

Figure 4.3.2: Average compressive strengths of OPC and PPC cement cubes

Both PPC controlled sample and the salt conditioned sample were able to withstand a crushing strength of nearly 60 N/mm^2, while OPC controlled sample and the salt conditioned sample were able to reach a crushing strength of nearly 54 N/mm^2, after 180 days. Standard deviation of the results of the PPC sample was small compared to that of OPC sample.

This result proves that corrosion of the steel bars (if any corrosion has had happened) has not been affected by the strength results.

With above the crushing strength results and analysis, it again proves that PPC crushing strength is much higher than that of OPC, and PPC can withstand high and reliable ultimate strength.

As per the standard SLS 679:2011, compressive test results of OPC and PPC samples were mentioned in Appendix A. Of the PPC sample, both early strength and standard strength were lower compared to the early and standard strength of the OPC sample.

When the compression test results of two types of cement cubes with the reinforcement bar being at the center of the cube and the horizontal position were considered, PPC cubes depicted higher results than that of OPC specimens.

After the test, the specimens were crushed further to get free the steel bars and it was observed that only the two ends of the steel bars were corroded and other parts were in their original appearance. This was the same for the specimens made with both OPC and PPC.

4.4 Pull out resistance test results

Force got increased to a maximum and suddenly dropped, indicating the breakage of anchorage of steel to cement mortar.

Table 4.4.1: Pull out test results of OPC mortar cubes

Specimen	Maximum load, kN
O1	21.10
O2	22.76
O3	21.80
O4	26.36
O5	23.60
O6	21.80
O7	23.00
O8	24.60
O9	24.96

Table 4.4.2: Pull out test results of PPC mortar cubes

Specimen	Maximum load, kN
P1	26.00
P2	24.78
P3	25.64
P4	28.40
P5	35.28
P6	29.50
P7	24.84
P8	28.60
P9	26.42

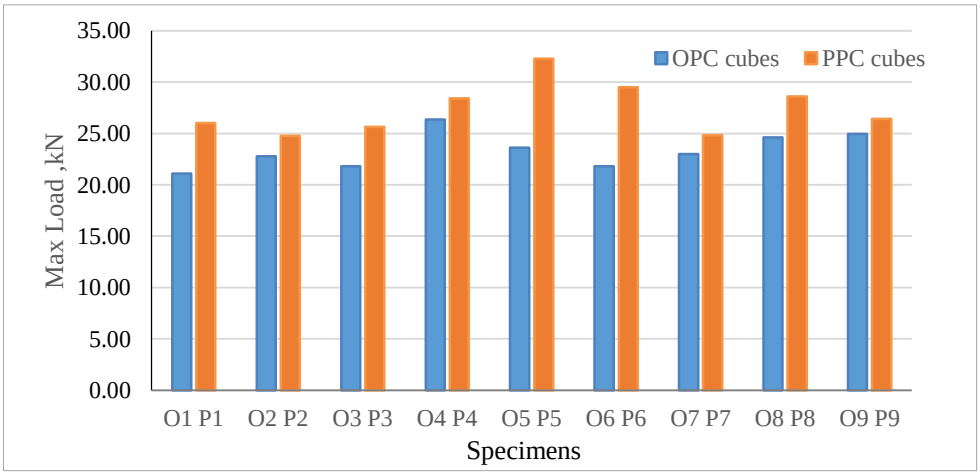

Figure 4.4.1: Pull out test results of OPC and PPC mortar cubes

Figure 4.4.2: TMT steel bars after pull out test

The comparison of figure 4.4.2 shows that the force required to pull out the steel bars, which had been cast into PPC cement mortar cubes, were always higher than that of OPC cement mortar cubes. It explains that PPC cement mortar cubes were having a stronger anchorage to the TMT steel bars.

With the results of the compressive test and pull out test, it is evident that, by removing weaker constituents of the pore structure, pozzolanic reaction introduces C-S-H which is responsible to increase the strength of the cement. The pozzolanic reaction can be written as below.

$$Ca(OH)_2 + SiO_2 + H_2O \rightarrow C\text{-}S\text{-}H$$

The additional calcium silicate hydrate (C-S-H) produced in pozzolanic cement, modifies the pore structure by reducing the permeability as a result of filling up the softer space. It also contributes to strength development slowly and gradually. Hence the pozzolanic reaction tends to impart impermeability, durability, and strength to hardened cement by modification of cement pore structure.

In this test, no significant results variation could be seen with salt-treated specimens and reference (controlled) specimens of two types of cement, OPC and PPC as with the Half-cell potential test and rebound hammer test.

Therefore above figure 4.4.2 results were analyzed further, with table 4.4.3, by averaging pull-out results;

Table 4.4.3: Pull-out results of OPC and PPC samples

Sample	Identification	Average Maximum load, kN	Standard deviation
OPC reference specimens of 1, 2, 3	C_O	21.89	0.83
PPC reference specimens of 1, 2, 3	C_P	24.05	1.60
OPC salt-treated specimens 4 to 9	S_O	25.47	0.63
PPC salt-treated specimens 4 to 9	S_P	28.33	2.56

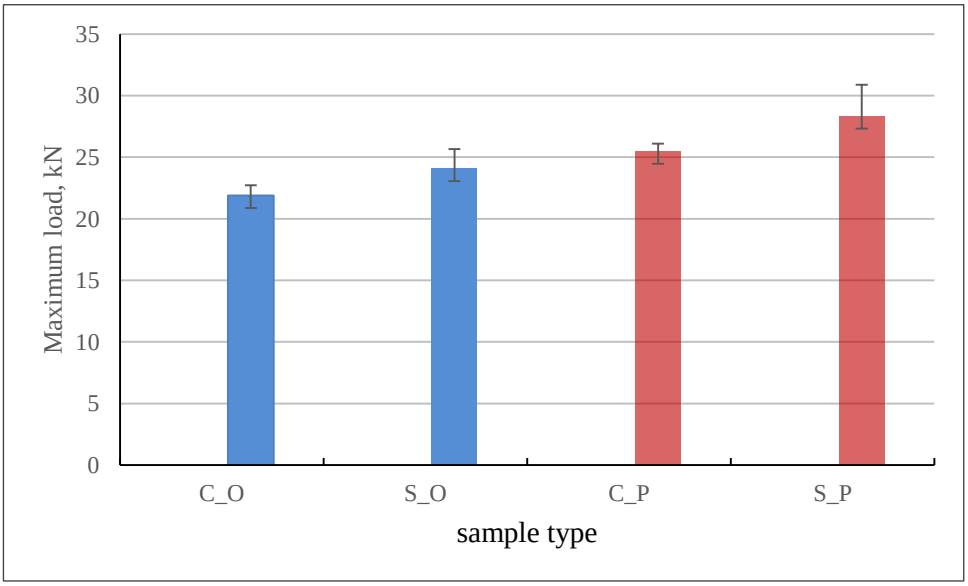

Figure 4.4.3: Pull out test results of OPC and PPC samples

Pull out resistance was higher with the PPC sample than that of the OPC sample, with both salt-treated and control samples. Salt conditioned specimens were having a

higher standard deviation in pull-out resistance test results than controlled specimens (reference specimens). It may be due to the formation of secondary cementitious material and acquiring higher anchorages to the steel bar.

Salt conditioned PPC sample was having a higher pull-out resistance than the salt conditioned OPC sample. But the standard deviation of pull out resistance was higher with PPC salt conditioned sample. It may be happening due to corrosion variations at the outermost ends of the steels from the specimens. With salt and moisture contacted, the outermost ends were with higher corrosion than those of with OPC samples.

4.5 Weight losses at the ends of each steel bars

Table 4.5.1: Weight losses at the ends of each steel bars with OPC mortar cubes

Specimen	Initial weight *, g	After rust removing** , g	Loss of weight, g
1	86.08	85.26	0.82
2	86.26	85.47	0.79
3	91.35	90.55	0.80
4	81.59	80.7	0.89
5	90.08	89.21	0.87
6	83.72	82.86	0.86
7	80.6	79.72	0.88
8	86.5	85.63	0.87
9	84.67	83.81	0.86

Table 4.5.2: Weight losses at the ends of each steel bars with OPC mortar cubes

Specimen	Initial weight *, g	After rust removing** , g	Loss of weight, g
1	88.06	87.26	0.80
2	88.96	88.18	0.78
3	80.99	80.17	0.82
4	87.28	86.4	0.88
5	83.57	82.71	0.86
6	82.70	81.81	0.89
7	83.71	82.84	0.87
8	82.33	81.47	0.86
9	82.23	81.35	0.88

Figure 4.5.2: Ribbed Steel bars after separating from the cubes

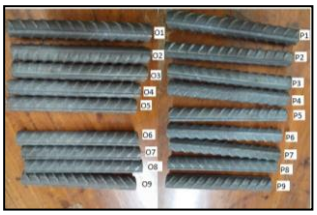

Figure 4.5.3: Steel bars after chemical treatment

According to the Fig. 4.5.2, it was clear that embedded steel parts which were with sufficient cover of cement motor had not been corroded and the two ends of steel bars which were exposed to air and with close contact with the salt solution, moisture had been corroded slightly. The ends of steel bars embedded to reference specimens of both types of cement had been corroded lesser than the cubes treated with the salt solution. This was true again for the steel bars that were in reference specimens used for pull out testing (Figure 4.4.1). Steel ends, which were exposed to moisture and chloride with direct contact, had been corroded.

Consumption of $Ca(OH)_2$ by pozzolanic reaction in the pore solution which may lead to disturb passivity of steel reinforcement had not been affected significantly for 180 days.

6. CONCLUSION

For both types of cement, OPC and PPC, in a chloride rich environment and also in the normal environment, no corrosion was observed in the reinforcement steel bars which were with sufficient cement cover.

With the analysis of Rebound indexes, it shows that the ingress of chloride ions has not adversely affected to the compressive strength development of OPC and PPC.

According to the outcome of the results and analysis of this research study, the followings also can be concluded;

1. Pozzolanic cement specimens reinforced with ribbed steel bars have higher strength than OPC specimens with the reinforcement of ribbed steel bar.
2. Higher anchorage to TMT steel reinforcement bars can be obtained by using PPC cements to structural works with compared that with OPC.
3. PPC which is commercially available under SLS 1247:2015 is much suitable for concrete reinforcing structures with severe exposure conditions due to the non-availability of detrimental effects of passivity disturbances due to consumption of $Ca(OH)_2$ of the pore solution of the hardened cement mortar/ concrete.
4. Pozzolanic types of cement compared to OPC are more suitable for mass concrete structures such as dams, foundations, bridges as the strength strengths get increased continuously after approximately 34^{th} day which may as a result of introducing secondary CSH to the pore solution and making a denser structure, which will protect the steel reinforcements from corrosion and other form forms of chemical attacks.

7. SUGGESTIONS

This research study further can be extended

- with longer time of salt conditioning and/or full-time salt conditioning (continually immersed specimens in a salt solution)
- to research with blended hydraulic cement having a fly ash content of 25% (or higher percentage) and OPC to study if any detrimental effect for the passivity of steel reinforcement.

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Appendix - A

Physical, mechanical and chemical test results of sampled OPC and PPC (Blended hydraulic Cement)

Following test results are of two cement types (OPC and PPC (Blended hydraulic Cement) used for the research study, and the tests were carried out as per the SLS 1247 (second revision):2015, SLS 107: 2015, SLS ISO 679:2011.

Parameter	OPC	PPC
Initial setting time, min	115	227
Soundness - Le-Chatelier's Method , mm	00	01
Chloride content, % by mass	0.04	0.05
Sulphate content (expressed as SO3)	2.5	3.0

Strength tests results of OPC sample

Parameter	Specimen number					
	I	II	III	IV	V	VI
Early strength (02 days) , N/mm^2	28.3	27.9	28.4	28.1	28.1	27.3
Average value N/mm^2	28.0					
SLS 107: 2015 Specification	≥ 20.0 N/mm^2					
Standard strength (28 days) N/mm^2	51.1	52.1	50.8	51.6	51.6	51.3
Average value N/mm^2	51.4					
SLS 107:2015 Specification	≥ 42.5 N/mm^2 And $\leq$ 62.5 N/mm^2					

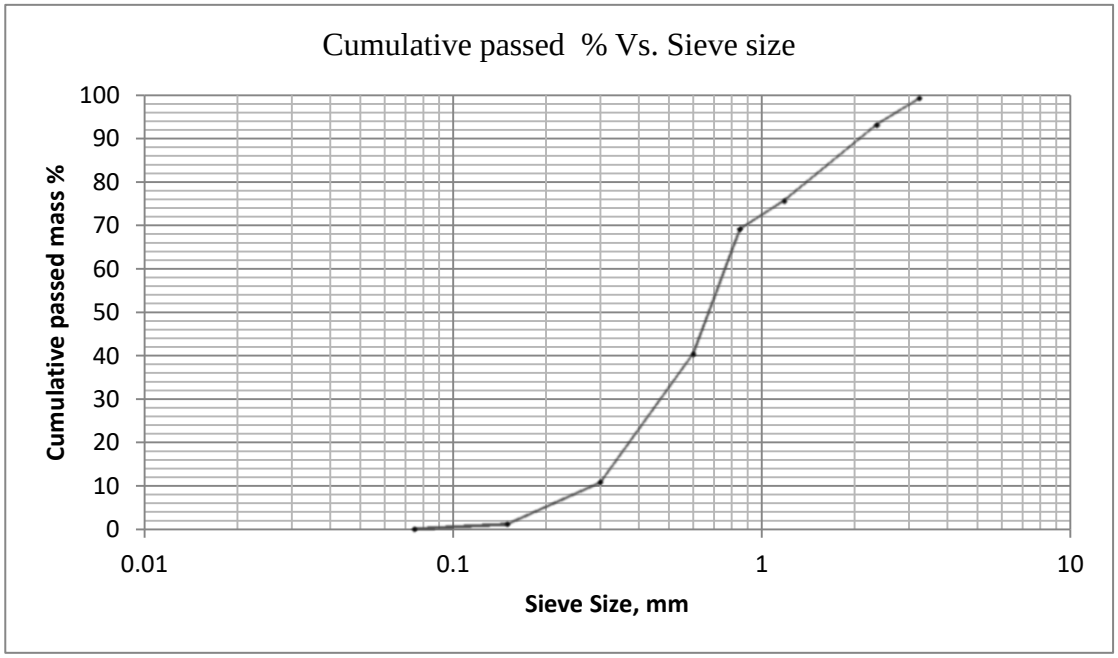
Strength tests results of PPC sample

Parameter	Specimen number					
	I	II	III	IV	V	VI
Early strength (02 days), N/mm^2	23.4	21.9	23.3	23.5	23.3	24.0
Average value N/mm^2	23.2					
SLS 1247:2015 Specification	≥ 10.0 N/mm^2					
Standard strength (28 days) N/mm^2	47.9	47.6	49.3	48.7	48.6	48.1
Average value N/mm^2	48.4					
SLS1247:2015 Specification	≥ 42.5 N/mm^2 And $\leq$ 62.5 N/mm^2					

Appendix - B

The fine aggregate gradation

Sieve Size mm	Retained mass (g)	Retained %	Cumulative retained mass %	Cumulative passed mass %
3.25	3.75	0.75	0.75	99.25
2.36	30.50	6.1	6.85	93.15
1.18	87.50	17.5	24.35	75.65
0.85	32.50	6.5	30.85	69.15
0.6	143.50	28.7	59.55	40.45
0.3	148.00	29.6	89.15	10.85
0.15	48.00	9.6	98.75	1.25
0.075	5.75	1.15	99.9	0.1
Pan	0.25			



Appendix - C

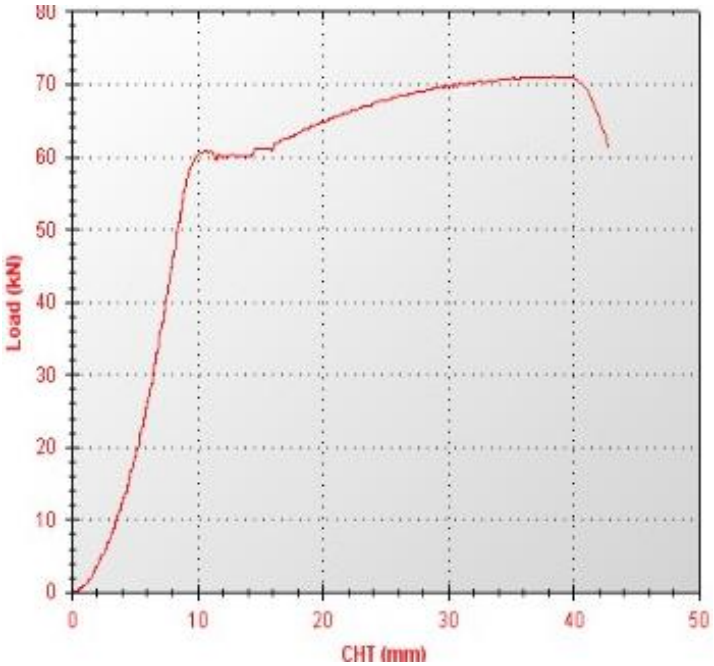
Properties of TMT bars used for the research study

Chemical Analysis results

Element	Percentage
C (%)	0.19
Mn (%)	0.64
P (%)	0.033
S (%)	0.031
Cr (%)	0.11
Ni (%)	0.07
Cu (%)	0.28
V (%)	<0.005
N (%)	0.008
Si (%)	0.24

Element	Percentage
Al (%)	<0.008
Nb (%)	0.018
W (%)	0.154
Co (%)	0.026
B (%)	0.0012
Sn (%)	0.071
As (%)	0.019
Fe (%)	98.09
CE	0.35

Mechanical properties



Load at Yield:	60.48kN
Specimen Cross Sectional Area:	108.47mm^2
Load at Peak:	70.980kN
Elongation at Break:	42.820mm
Yield Stress:	557.586N/mm^2
Elongation %	19.67%

Appendix - D

Composition of OPC and PPC (Blended Hydraulic Cement) samples

Sample data of the composition of OPC and PPC (Blended Hydraulic Cement) samples, used to the research is below.

Product	Composition % , m/m		
	Clinker	Gypsum	Fly Ash
OPC	95	5	-
BHC (PPC)	80	5	15