Chloride Transport and Reinforcement Corrosion in the Vicinity of the Transition Zone between Substrate and Repair Concrete

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Licentiate Thesis

PREFACE

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ABSTRACT

One of the major degradation problems in concrete structures is chloride initiated reinforcement corrosion resulting in cracked, spalled and delaminated concrete. These damages are repaired for large amounts of money and because of high repair costs it is important to perform durable repairs.

This thesis work has included interviews, laboratory and field studies in the area of concrete repairs. The interviews were held mainly with bridge engineers at the Swedish Road Administration and Banverket (the Swedish Railway Administration). The questions asked to these people were about their experience in the field of concrete repairs. The objective with the interview study was to collect knowledge and experience about concrete repair at these two governmental authorities.

The main objective of the laboratory study was to investigate chloride transport in the transition zone between a chloride contaminated substrate concrete and an initially chloride free repair concrete by establishing chloride profiles. The second objective was to detect any reinforcement corrosion in relation to the transition zone. The reinforced laboratory specimens with premixed chlorides (1 or 4 wt % per cement) in the substrate concrete have been exposed during 13 years either outdoors or in a climate chamber with relative humidity of 80 %. The main results show that reinforcement corrosion occurred in and near the transition zone in local active areas with passive areas between, macrocell corrosion, and that the chlorides are transported from the contaminated substrate concrete into the repair concrete.

Three different repaired concrete structures, one road bridge, one pedestrian bridge and one parking structure, were investigated in the field study. All three structures are treated with deicing agents in the winter time. The objective with the field study was to investigate if the same phenomenon can be observed as in the laboratory study. The main conclusions, from the investigation on drilled cores from each structure, are that chlorides in contaminated substrate concrete can be transported into a repair concrete and reinforcement corrosion may occur in the transition zone between the two different materials. The results are in accordance with the results in the laboratory study. It was also seen that a repair concrete with relative low w/c-ratio may reduce the ingress of external chlorides.

Finally, the results in this thesis indicate that there is a risk for reinforcement corrosion in the vicinity of the transition zone between repair concrete and a substrate concrete which must be considered in concrete repair work. For example the chloride content around a repair must not exceed a certain level when a repair is performed. The chloride transport into the repair concrete can be useful to transport chlorides and reduce the content of chlorides in the substrate concrete. The advantages with this are that the amount of removed contaminated substrate concrete can be minimized and the risk for corrosion in the substrate concrete is lower. If the repair concrete is reinforced with conventional black steel there may on the other hand be a risk for corrosion in the repair concrete instead if high levels of chlorides are transported. Also external exposure of chlorides must be considered for the risk of corrosion in the repair material.

Further research is needed about when different corrosion mechanisms and chloride diffusion mechanisms occur in reinforced concrete repairs. The experience from the used analysing

methods in the laboratory investigations are possible to use in coming research projects in the field of concrete repair.

The next step after this thesis work should be in order to increase the understanding of the repaired concrete system including the important compatibility issues, the author believes that the most fruitful way consists of further laboratory investigations, field studies and optimisation of the repair material.

SAMMANFATTNING

Kloridinitierad armeringskorrosion orsakar stora skador på armerade betongkonstruktioner. Kostnaderna för att reparera skador och garantera säkerheten är stora. Därför är det viktigt att man utför reparationen så att en beständig och kompatibel betongreparation erhålls.

Inom ramen för det här licentiatarbetet om betongreparationer har en studie med intervjuer, laboratorieförsök och fältstudier genomförts.

Intervjustudien genomfördes i huvudsak med broingenjörer på Vägverket och Banverket inom området för betongreparationer. Samma förberedda frågor ställdes till samtliga intervjuade. Förutom intervjuerna vid Vägverket och Banverket genomfördes tre referensintervjuer med representanter för byggsektorns olika aktörer, en tillverkare av reparationsmaterial, en entreprenör och en konsult, med kunskaper om betongreparationer. Besök med intervju genomfördes i fem av Vägverkets sju regioner samt i tre av Banverkets fem regioner. Frågorna handlade i huvudsak om deras erfarenheter samt de behov av eventuell ny kunskap som behövs inom regionerna.

Huvudsyftet med laboratorieundersökningen var att undersöka kloridtransport i övergångszonen mellan en substratbetong och en reparationsbetong. Substratbetongen är kontaminerad med ingjutna klorider och reparationsbetongen är initialt fri från klorider. Reparerade och armerade provkroppar med 1 och 4 % ingjutna klorider exponerades och förvarades i 13 års tid utomhus eller i ett klimatrum med konstant relativ fuktighet på 80 %. Laboratoriestudien visar att armeringskorrosion uppkommer i och i direkt anslutning till övergångszonen. Dessutom visar studien att de ingjutna kloriderna transporteras från substratbetongen och in i reparationsbetongen.

I fältstudien ingick tre reparerade betongkonstruktioner, en bro trafikerad med bilar och lastbilar, en trappa till en gång- och cykelbro samt ett parkeringsgarage, som alla vintertid utsätts direkt eller indirekt för tösaltning. Syftet var att jämföra resultaten med avseende på armeringskorrosion och kloridtransport i fält med resultaten från laboratoriestudien. De huvudsakliga resultaten från undersökningen av betongprover från konstruktionerna i fält är att klorider kan vandra ut från en substratbetong samt att kloriderna kan förflyttas från konstruktionsbetongen och in i en reparationsbetong eller en pågjutning samt att det finns risk för att armeringskorrosion uppkommer i övergångszonen mellan två olika betongmaterial.

Resultaten från hela licentiatarbetet indikerar att det finns en stor risk för armeringskorrosion i och i direkt anslutning till en övergångszon mellan substratbetong och reparationsbetong. Denna risk måste beaktas då en betongreparation projekteras. Till exempel bör troligtvis inte klorider över en viss halt kvarlämnas i substratbetongen runt betongen. Kloridtransport skulle kunna utnyttjas för att minimera risken för att armeringskorrosion uppkommer i substratbetongen. Om reparationsbetongen eller pågjutningen armeras med konventionellt kolstål och höga halter klorider diffunderar in kan dock risken för armeringskorrosion förflyttas till det nya materialet. Följaktligen bör även externa kloriders inträngning i reparationsbetong och substratbetong inkluderas i bedömningen av korrosionsrisker.

Framtida forskning är nödvändig för att klargöra när och hur armeringskorrosion och kloridtransport uppkommer i armerade betongreparationer. För att kunna öka denna förståelse och kunskap vilket även inkluderar viktiga kompatibilitetsegenskaper borde den fortsatta

forskningen innehålla laboratorieundersökningar och fältstudier av cementbaserade reparationsmaterial. Dessutom bör stor vikt läggas på optimering av reparationsmaterial med avseende på kvantifiering av kompatibilitet mellan substratbetong och reparationsbetong, ekonomiska aspekter samt livscykelstudier för att minimera påverkan på miljön och naturresursförbrukningen i samband med betongreparationer.

LIST OF PAPERS

Paper I
Skoglund, P. and Trägårdh, J., 'Survey on Swedish Practice for Bonded Overlays and Patch Repair', Proceedings of the International Conference on Concrete Repair, Rehabilitation and Retrofitting (ICCRRR), Cape Town, South Africa, 21-23 November, 2005, pp. 397-398.

Paper II
Skoglund, P., Trägårdh, J. and Kalinowski, M., 'Microstructure, Chloride Migration and Corrosion near the Transition Zone between Substrate and Repair Concrete.' Proceedings of the International Conference on Concrete Repair, Rehabilitation and Retrofitting (ICCRRR), Cape Town, South Africa, 21-23 November, 2005, pp. 401-402.

Paper III
Skoglund, P., Silfwerbrand J., Holmgren J. and Trägårdh, J., 'Chloride Transport and Corrosion near the Transition Zone between Substrate and Repair Concrete – Laboratory Study', Submitted to Materials and Structures in November 2006.

Paper IV
Skoglund, P., Silfwerbrand J., Trägårdh, J. and Holmgren J, 'Chloride Transport and Corrosion near the Transition Zone between Substrate and Repair Concrete – Field Study'. Accepted to International Journal for Restoration of Buildings and Monuments in January 2007.

Pål Skoglund has drawn up the proposals for methodology, performed the main part of observations and analyses, collected the results and written the papers. The co-authors have contributed with their view on methodology, analysis, conclusions and text. Co-author Mariusz Kalinowski, co-author of Paper II, has performed some of the laboratory experiments in Paper II.

CONTENT

Chapter 1

1.   INTRODUCTION

1.1   General

The need of concrete repair becomes more and more obvious in Swedish concrete structures because of the million programmes in the 60's and the 70's when one million apartments, a majority in concrete houses, were constructed in a short time. Now after about 40 years the structures needs durable concrete repairs. Today's research about durability of concrete repairs is rather small compared to this increasing need of concrete repair. There are also a lot of concrete structures between 50 and 100 years and their age becomes critical, for example balconies, back yard floor structures, bridges and parking structures.

Concrete repair is needed when the structure has been damaged and can not meet the demands. The concrete may deteriorate due to several mechanisms, i.e., frost, reinforcement corrosion, acid attack, alkali silica reaction, chemical degradation and leaching. The cause of the damage must be identified before material and method are chosen for the concrete repair.

In Sweden we have a Handbook of Concrete Repair [1]. It describes all the steps in a concrete repair. The Handbook of Concrete Repair is written in 1987 and now there is an ongoing project to try to revise this with the last 20 years of new knowledge and produce an updated electronical version [12]. The Swedish Road Administration, (SRA), has a Handbook for Bridge Inspection [2] that describes and gives advice how inspections of concrete structures should be performed but nothing about how to repair deteriorations. In Bro 2004 [3] there is one chapter about improvement and this can also be used for concrete repairs. SRA also have one publication [4] about quality during construction of bridges but there is no publication about quality control in concrete repairs.

In other countries there are guidelines, textbooks and state of the art reports, e.g. [5], [6], [7], [8], and [9] which give guidance and recommendations about repair materials and repair methods to carry out concrete repairs. Two big European Union projects, Rehabcon [10] and Contecvet [11], have resulted in manuals about degradation and concrete repair. Parts of all these guidelines and textbooks could be useful help in concrete repairs in Sweden.

1.2   Objective

This licentiate thesis is the first part of a PhD project "Chloride Transport and Reinforcement Corrosion in the Vicinity of the Transition Zone between Substrate and Repair Concrete". The initial objective with this licentiate thesis, before it was financed, was to investigate the bond

compatibility, the durability compatibility, the chemical compatibility, the electrochemical compatibility and the permeability compatibility between different materials in a concrete repair. After the financing was decided the whole thesis was divided into three main parts with different objectives.

The objective with the first part in this thesis was to collect knowledge and experience about concrete repair at the Swedish Road Administration and Banverket (the Swedish Rail Administration) and also identify their need of new knowledge in an interview study.

The objective with the second part was to study chloride transport near the transition zone between chloride contaminated substrate concrete and repair concrete in specimens and evaluate the durability of the repair in a laboratory study.

In the third part the objective was to study repaired reinforced concrete structures with chloride contaminated substrate concrete in a field study.

1.3   Limitations

This study has the following limitations.
- The focus is on concrete repairs that are older than five years with chloride contaminated substrate concrete.
- The repair material in the concrete repair is mainly cement based.
- The interview study was performed mainly with staff working with repair and maintenance of concrete structures at the Swedish Road Administration and Banverket. Both these authorities are large managers of concrete structures, especially concrete bridges. Some reference interviews were held with a contractor, a producer of repair material and a consultant.
- The laboratory investigations are limited to chloride analyses and ocular observations of reinforcement corrosion in the substrate concrete and the repair concrete. Also microstructure analysis in the transition zone was performed.
- The field study was allocated to three repaired concrete structures.
- The investigations do not include studies on mechanical characteristics in the concrete materials, e.g. creep and shrinkage.
- Electrochemical studies of the reinforcement as corrosion potential measurements or corrosion intensity measurements were not performed.

1.4   Content of the thesis

This licentiate thesis consists of Chapters 1 to 7 and Papers I to IV which are attached as appendices.

The first Chapter gives a short introduction into the area of concrete repair. The objective and the limitations of the thesis work are also described.

The second Chapter is describing and dealing with concrete repair in general, compatibility between substrate concrete and repair concrete, chloride transport across the transition zone between old and new material, reinforcement corrosion in and near the transition zone and finally microstructure in the transition zone.

In Chapter 3 the different methods used in this work are described.

Chapter 4 includes results from the interview study, the laboratory study and the field study and in Chapter 5 the results are discussed.

In Chapter 6 the conclusions are drawn from the results in Chapter 4.

Chapter 7 includes suggestions about further research and Chapter 8 contains the reference list.

Paper I
Skoglund, P. and Trägårdh, J., 'Survey on Swedish Practice for Bonded Overlays and Patch Repair'. Paper 1 is an investigation based on an interview study with the objective to collect existing knowledge and experience of concrete repairs at Swedish Road Administration and Banverket. Results from these interviews and suggestions about further research were presented in this paper.

Paper II
Skoglund, P., Trägårdh, J. and Kalinowski, M., 'Microstructure, Chloride Migration and Corrosion near the Transition Zone between Substrate and Repair Concrete'. Paper 2 was an initial laboratory study with investigation focused on chloride transport and reinforcement in the transition zone. Another objective with the paper was also to try a method, to analyse chloride profiles across a transition zone with SEM-EDS equipment that could be used in an extended laboratory study.

Paper III
Skoglund, P., Silfwerbrand J., Holmgren J. and Trägårdh, J., 'Chloride Transport and Corrosion near the Transition Zone between Substrate and Repair Concrete – Laboratory Study'., The objective with this third paper was to perform an extended laboratory study on 13 year old reinforced and repaired concrete specimens stored outdoor or in a climate chamber with constant relative humidity of 80 %. The study focused on chloride transport from the substrate concrete into the repair concrete and observations of reinforcement corrosion near the transition zone between the substrate concrete and the repair concrete.

Paper IV
Skoglund, P., Silfwerbrand J., Trägårdh, J. and Holmgren J, 'Chloride Transport and Corrosion near the Transition Zone between Substrate and Repair Concrete – Field Study'. In this paper a field study of repaired concrete structures with assumed chloride contaminated substrate concrete was performed. Three different objects, one bridge for car traffic, one stair to a pedestrian bridge and a parking structure were investigated. All these structures are subjected to deicing salts in one way or another. The objective with this field study was to examine the chloride transport and reinforcement corrosion in the transition zone between chloride contaminated substrate concrete and initially chloride free repair concrete and compare the results with the conclusions from the laboratory investigation.

Chapter 2

2.   CONCRETE REPAIR

2.1   Background

In an interview study [13] the objective was to collect existing knowledge and experience in the area of concrete repairs at the SRA, and Banverket. In order to achieve a more complete picture of the repair strategies currently used in Sweden, interviews with material producers, contractors and repair consultants were also carried out. The conclusions said that there are difficulties and durability problems with patch repairs and because of this they are seldom performed nowadays. The problems are the high costs relative to the area of repair, and difficulties with curing. They are still used in new productions when repairing damages related to mechanical damages, honeycombs and form tie embedment and railing embedment are common. Large concrete repairs with repair concrete with known good quality are often performed and the bridge engineers' experience is that no durability problems occur with these large concrete repairs after the guarantee time of five years for the bridges at SRA and Banverket. Although the experience is good, there are only few investigations that have been analysing the durability of concrete repairs older than five years. Old concrete repairs are not specially investigated and controlled during the regular inspections at Swedish bridges.

In CBI's consulting work it has been observed that local repairs, so called patch repairs or surface repair, are very common when there are local damages in concrete structures for example in parking structures.

2.2   Literature review

2.2.1   Compatibility

One important term that is used in the literature of concrete repairs is compatibility [14]. Emmons et al. [15] write about this term and they suggest "failed repair are the consequence of imperfect choices in the selection of repair materials incompatible with the substrate in a given environment". They further define compatibility as "a balance of physical, chemical and electrochemical properties and dimensions between a repair material and the existing substrate that will ensure that the repair withstand all the stresses induced by volume changes and chemical and electrochemical effects without distress and deterioration over a designed period of time". The selection of a repair material with best compatibility is important to achieve a durable and compatible concrete repair. The compatibility can be divided into six types, [15] and [16]:

1. *Chemical compatibility* is the properties in substrate concrete and repair material including the content of chlorides, alkalis, C_3A, silica, slag, fly ash etc. Chlorides can cause problems with the reinforcement. The alkalis can generate ASR (alkali silica reaction) and the C_3A content has an effect on the chloride binding.
2. *Electrochemical compatibility,* has the repaired system the possibility to inhibit reinforcement corrosion both in the substrate concrete and in the repair concrete? If there is a potential difference (for example different chloride content, permeability and carbonated/uncarbonated) between the repair material and the substrate concrete it may cause galvanic corrosion (macrocell corrosion) with corrosion in a restricted area. Because of the concentrated area the corrosion may be more aggressive, [17], [18] and [19].
3. *Permeability compatibility,* The permeability characteristics for the repair material have to be considered in relation to the substrate concrete. This is important for the transport of chlorides and the ability for a repair to breath.
4. *Dimensional compatibility,* This is probably the type of compatibility that has been most investigated and tested according to the number of papers investigating these characteristics, for example shrinkage, expansion, shape, creep, strain capacity and modulus of elasticity.
5. *Bond compatibility.* The bond between the substrate concrete and the repair material has to be developed to a certain level and then be durable in the environment and structure type where the concrete repair is performed. Bond between overlay concrete for repair and substrate concrete is described in [20].
6. *Structural and mechanical compatibility.* The concrete repair has to carry the load that has been carried by the removed concrete.

Rizzo et al. are writing about selection criteria for concrete repair materials in [21]. In [22] and [23] general material parameters are defined to achieve compatible concrete repairs, see Table 1 for [23].

Table 1. Relationship of characteristics for repair material (R) and substrate concrete (C).

Property	Relationship of repair material (R) and substrate concrete (C).
Shrinkage strain	R < C
Creep coefficient (for repairs in compression)	R < C
Creep coefficient (for repairs in tension)	R > C
Thermal expansion coefficient	R = C
Modulus of elasticity	R = C
Poisson's ratio	R = C
Tensile strength	R > C
Fatigue performance	R > C
Adhesion	R > C
Porosity and resisitivity	R = C
Chemical reactivity	R < C

Vaysburd [24] is writing about key characteristics to achieve a holistic approach to concrete repairs which is important according to his opinion.

In this thesis the focus in the experiments has been to evaluate the permeability compatibility and electrochemical compatibility in concrete repairs.

2.2.2   Chloride transport
Chlorides are transported with different mechanisms in the pores of the concrete. These mechanisms have been described by many researchers such as Bertolini et al. [25] and Tang [26]. The main basic mechanisms are diffusion of ions, migration, capillary suction and permeation.

Diffusion of ions
The ions can be transported in the pore solution of the concrete due to a gradient of concentration and the ions move from a concrete volume with high relative concentration to a concrete volume with low relative concentration. The diffusion may be stationary or non-stationary. Stationary diffusion is described with Fick's first law, Equation 1.

$$F = -D\frac{dC}{dx}$$
(Equation 1)

F is the chloride flux (kg/m^2*s), D is the diffusion coefficient (m^2/s), C is the concentration of chlorides and x is the distance (m) from surface with external chlorides.
The non-stationary diffusion follows Fick's second law, Equation 2.

$$\frac{dC}{dt} = D\frac{d^2C}{dx^2}$$
(Equation 2)

Bertolini et al. [25] say that the chloride binding is one factor that must be considered in non-steady state chloride diffusion in concrete.

Migration
Charged ions can be moved in an aqueous solution under an electrical field. In the solution the ion mobility is related to the diffusion coefficient, the Einstein relation, see Equation 3

$$D_i = \frac{RTu_i}{z_iF}$$
(Equation 3)

R is the relative gas constant (J/K,mol), T is the temperature (K), F is the Faradays constant (96490 C/mole), u_i is the ion mobility (m^2/s*V) and z is the valence of the ion. The ion movement in a concrete appears in the water-filled pore system. Chlorides and other negative ions move in the opposite direction as the current in the field. Positive ions move in the same direction as the current. This principle is used in electrochemical techniques as chloride removal and realkalization. It is also the principle behind macrocell corrosion in reinforced concrete.

Diffusion and migration occurs mostly at the same time and the total flux is the sum of them both.

Capillary suction
Water is absorbed by the pores in the concrete due to a subpressure caused by capillary action. When the pore diameter decrease the capillary action is stronger. On the other hand the friction increases because of larger wall areas when the pores become smaller.

Other ion transport mechanisms are;
- *Permeation*, when a pressure difference pushes a liquid into a saturated concrete according to Darcy's law.

- *Wick action,* where there is a chloride solution on one side of a concrete and air on the other side. The chloride solution will be absorbed and migrate. The water will evaporate into the air and the chlorides will precipitate.
- *Moisture flow* due to a vapour pressure.

Combinations of several of these mechanisms are often possible and it is complex to calculate the influence of each one in a certain case.

In this thesis the chloride transport from a chloride contaminated concrete into a chloride free concrete is studied. Because of the concentration gradient it is probable that diffusion is one of the most important transport mechanisms in this case. We also have different w/c-ratios in the repair concrete and the substrate concrete and different carbonation depths or cement composition. All these factors may give rise to a potential difference and then the transport mechanism of migration can take place. The difference in w/c-ratios also means that we have different pore structures and pore diameters. The smaller pores in the concrete with lower w/c-ratio can give rise to a process like the capillary suction.

Chloride transport from contaminated concrete into repair concrete has not been widely investigated. Fagerlund [27] discusses the phenomenon when an overlay repair concrete is cast on a chloride-contaminated concrete. He suggests two possible cases;

1. The chloride level at the reinforcement is lower than the threshold value for corrosion.
A cast repair concrete on the surface of a substrate concrete can absorb the chlorides from the substrate concrete, reduce the concentration at the reinforcement and at the same time delay the start of the corrosion. Fagerlund [27] hypothesises that cement with high chloride adsorbing capacity should be used.

2. The chloride level has initiated the corrosion and a repair concrete could (should be tested) reduce the oxygen flow and eventually stop the reinforcement corrosion. In this case it is only possible to reduce corrosion rate by casting a concrete overlay. This overlay makes it more difficult for oxygen and water to reach the reinforcement which delays the re-start of the reinforcement corrosion.

Janz [28] performed an accelerated laboratory pilot investigation on chloride transport from a substrate concrete into a concrete overlay. The result from this study showed that there was significant chloride diffusion from the chloride contaminated concrete into the concrete overlay. Differences in chloride diffusion into the concrete overlay were not significant with different cements.

Paulsson-Tralla [29] has analysed the chloride profile in eight Swedish bridges with concrete overlays and he has also predicted the service-life of these repaired concrete bridge decks regarding the chloride profile. He has used a method based on the moving boundary theory to calculate how fast chlorides move into concrete and to estimate service life of a concrete structure. This method has earlier been used to calculate carbonation and there are several conditions that must be fulfilled when calculating ingress. The advantages of this method are that it calculates a chosen threshold value accurately for a certain life time, it requires no guessing about values, it is an easy and cheap method and it avoids the need to quantify the surrounding environment if it is not altered.

Yu et al. [30] has analysed the transport from an OPC-paste with w/c-ratio of 0.5 contaminated with 2 wt % chloride ions per cement across a transition zone and into a chloride free similar paste. Yu et al. concluded "By assuming a Langmuir-type relationship between the free and bound chloride, the effect of chloride binding on diffusion was incorporated into diffusion equations derived from Fick's First Law and mass conservation. This also yielded a good characterization of the free chloride profile".

In a report [31] from the Danish Road Administration, Vejdiktoratet, chloride transport from a contaminated substrate concrete into a repair concrete was analysed in 11 bridge pillars. Chloride transport from the contaminated substrate concrete across the transition zone into the repair concrete is clearly seen. The report is comprehensive and shows also that the repair material is cracking due to shrinkage which may give external chlorides a possibility to penetrate into the dense repair concrete.

2.2.3   Reinforcement corrosion

The pore solution in a concrete during hydration has a pH between 13 and 14. Steel reinforcement in this environment has a passive state. The passivity is caused by the formation of a thin oxide layer. The formation of this layer which is formed at pH > 13 is also a corrosion product with low permeability and as long as this layer is undamaged no detrimental reinforcement corrosion can start. Mechanical deformation, lowering of the pH in the pore solution (due to carbonation or an acid reaction) or chloride content higher than a certain amount, threshold value, can depassivate the reinforcement by making holes into the protective oxide layer on the surface of the steel reinforcement. After this depassivation the corrosion may occur and propagate. General and specific information about reinforcement corrosion has been written by many researchers, e.g. Bertolini et al. [25] and Tuutti [32].

The focus in this thesis is repaired systems with chloride induced reinforcement corrosion. The time it takes for the chlorides to penetrate the concrete and depassivate the reinforcement by destroying the thin layer of protective oxides is called the initiation time. A certain concentration of chlorides, threshold value, is needed at the surface of the reinforcement before the corrosion can start. This level is mainly depending on the relative humidity and the oxygen concentration. Pettersson [33] lists several investigations that have tried to evaluate the threshold value in reinforced concrete. These values differ between 0.06 and 2.02 percent chlorides per cement weight. In Raupach et al. [34] it is indicated that the critical value for chloride content in concrete repairs varies between 0.5 and 1.0 wt % for ordinary Portland cement and between 0.5 and 2.0 wt % blast furnace slag cement and fly ash cement depending on permeability, cover of concrete and cement type.

After the initiation time has been reached the corrosion takes place and that phase is called the propagation time. When the corrosion has gone to a certain level the life time for the construction part is achieved. Tuutti [32] has made a schematic figure over this corrosion model, see Figure 1.

The initiation time is dependent on
-   the thickness of the concrete cover
-   the binding capacity in the concrete
-   the threshold value
-   concentration difference
-   permeability of the concrete

When the passive layer is destroyed corrosion can start according to Equation 4.

$$Fe + H_2O + 1/2O_2 \rightarrow Fe(OH)_2$$ (Equation 4)

The corrosion rate during the propagation time is dependent on the relative humidity in the pore system, the concentration of oxygen, the temperature, the porosity etc.
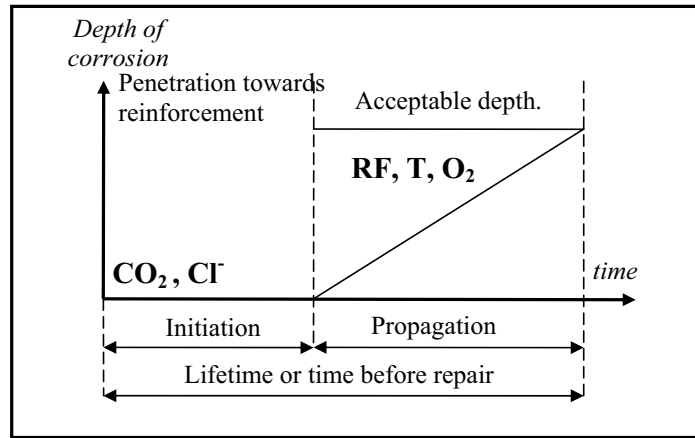

Figure 1. Schematic figure for the model of reinforcement corrosion, Tuutti [32].

Possible ways for chlorides, e.g. NaCl, $CaCl_2$ or $MgCl_2$, to come into the concrete is from deicing salts or sea water. Another possible way is premixed chlorides, as $CaCl_2$, that was used as an accelerator in concrete casting before the early 80's in Sweden and many other countries.

The breakdown of the passive layer leads to small local holes and the corrosion can attack even if the pH is around 13-14. This small active zone is called the anode zone. The reaction at the anode is;

$$Fe + 2Cl^- \rightarrow FeCl_2 + 2e^- \rightarrow Fe^{2+} + 2Cl^- + 2e^-$$ (Equation 5)
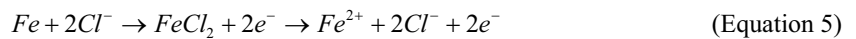
according to Scott [35] in Pettersson [33]. The surface with passive reinforcement is then the cathode where;

$$O_2 + 2H_2O + 4e^- \rightarrow 4(OH)^-$$ (Equation 6)

This kind of corrosion with a small anode and a larger cathode intrinsically mixed is called microcell corrosion. The area of the anode is dependent of the concentration of chlorides at the reinforcement surface and the higher concentration the larger is the anode. In the bottom of this anode an acid environment, pH even lower than 3, is created and because of this the corrosion accelerates and finally there is a local hole in the steel reinforcement. Some times the anode and cathode are clearly separated in different areas; the corrosion mechanism is then called macrocell corrosion. This kind of corrosion may appear when the active and passive areas are connected to each other and an electrical current is created due to the difference in potential. This potential difference can be created for reinforced structures in

atmosphere environment or when parts of the reinforcement have been depassivated by carbonation or chloride penetration and these parts of the reinforcement are connected to internal passive reinforcement. This kind of corrosion process is also possible when the reinforced concrete is buried in soil immersed into sea water.

Several researchers have investigated concrete repair with chloride contaminated concrete around the repair concrete and observed these phenomena in laboratory investigations, e.g.

Kobayashi et al. [36] have performed a laboratory study in which they observed that different chloride densities in two concrete materials adjacent to each other often give corrosion in the concrete with the higher chloride concentration. They also observed when using a denser repair concrete, e.g. SCC, that the corrosion was delayed in the repair concrete but the macrocell corrosion was much more severe in the substrate concrete near the transition zone to the repair material. From this they concluded that it is important to remove all chloride-contaminated surfaces when repairing with denser repair concrete than substrate concrete because of the extended risk for macrocell corrosion. In other words it is important to take the electrochemical compatibility into account.

Nagataki et al. [37] have also performed a laboratory investigation and concluded that the macrocell corrosion in material with high chloride content increased if there was a big difference in chloride concentration in two different jointed materials. They also found a maximum for the corrosion rate at an optimal relative humidity and that the macrocell corrosion needed a certain value, 2.0 kg/m^3, for the chloride content.

Courard et al. [38] have observed that reinforcement corrosion generally begins in the transition zone if non-porous materials are used as repair material. They say "this corrosion is essentially due to a loss of alkalinity at the interface and may propagate if the adhesion is not sufficient".

Raupach et al. [34] discussed the practical consequences of their results in chloride induced macrocell corrosion of steel in concrete near a patch repair. They mean that all concrete around a spalling with chloride content exceeding a critical value have to be removed to avoid macrocell corrosion. The critical value is dependent on the permeability of the concrete (affected by the curing and w/c-ratio), cover of concrete and kind and amount of cement, [39].

Barkey [40] has used similar specimens to those in our project with simulated mortar and concrete repairs adjacent to a chloride contaminated concrete and investigated them with electrical methods. The inhomogenity of chloride content and concrete in the repair zone drives the macrocell corrosion. Barkey also claims that the compatibility must be considered when a repair material is selected.

Gu et al. [41] have observed that reinforcement corrosion appears in material with the lower w/c-ratio when two reinforced concretes are adjacent and explains this with that the oxygen diffuses slowly to the surface of the reinforcement in the denser material and therefore appears the anodic reaction in the denser material and the cathodic reaction appears in the material with high porosity. These conclusions are based on impedance spectroscopy measurements but they are not verified with ocular observations of the reinforcement in this paper.

Zhang et al. [42] have done a review about corrosion of concrete reinforcement in concrete patch repair. They say that corrosion in and near a patch repair is a complex problem and the knowledge is quite limited about the possible mechanisms. It is known that a ring-anode effect of corrosion around a repair often appears in the substrate concrete or in the transition zone due to macrocell corrosion. This is possible even if the repair is done with a repair material with low permeability and good bonding and the cause is the electrochemical incompatibility. The review discusses the three possible corrosion locations (in the substrate, in the repair or in the transition zone) around a concrete repair and which factors governing the corrosion. They finally conclude that both microcell corrosion and macrocell corrosion may appear in a concrete repair and even at the same time and this must be considered when a repair strategy is chosen. They also conclude that different material properties give different electrochemical environments in the patch and the substrate and this affects the location of the active corrosion. At last they suggest further research about which of the two corrosion mechanisms, microcell corrosion and macrocell corrosion, that controls the corrosion rate and where the anode is placed in macrocell corrosion.

Chapter 3

3. METHODS

3.1 Interview study

The interviews have been held with bridge engineers in five different regions at the Swedish Road Administration (SRA) and three different regions at Banverket in the period November 2003– February 2004. The SRA has in all seven regions and Banverket has five regions in all. Beside these interviews at the SRA and Banverket reference interviews were also held with experts at one material producer, one contractor and one repair consultant. All interviews were held at the interviewed person's office with prepared questions. The same questions were asked to all interviewed persons at the SRA and Banverket.

3.2 Specimens for laboratory study

3.2.1 Casting of specimens

In 1992, the Swedish Cement and Concrete Research Institute (CBI) started a research project of investigating reinforcement corrosion in patch repaired concrete specimens. The investigation was, however not completed. The authors – not involved in the original project – have 13 years later used some of the specimens for the current test series enabling a long-term performance study.

In 1992 several reinforced concrete specimens, see Figure 2, were cast simulating concrete repair systems. The w/c-ratio in the substrate concrete was 0.50 and 0.70 when the specimens were cast according to reports. The concrete was mixed in a 25 liters concrete mixer and thus it may have been difficult to achieve the required homogeneous w/c-ratio or homogeneous chloride distribution. The w/c-ratio of the repair concrete at the casting time is not known but oral communication reports a w/c-ratio of 0.40 or 0.45. Based on practice of making concrete repairs in 1992, a probable w/c-ratio between 0.4 and 0.5 may be assumed. Each specimen was cast with a major substrate concrete part and some weeks after with one minor part with repair concrete. Specimens were cast with 1 and 4 % chlorides per cement weight. The specimens were then exposed to different environments (outdoors and indoors in 80 % RH, 85-90 % RH and 95 % RH). Unrepaired reinforced specimens were also cast as a reference to the repaired specimens in all environments.

Figure 2. One repaired and reinforced concrete specimen in this investigation. The rectangle to the right is the repair concrete and the rest is the substrate concrete.

3.2.2   The specimens used in this laboratory study

In the present investigation two sets of reinforced concrete specimens selected from the specimens cast in 1992 were examined, (33R, 43R, 53R and 63R, see Table 2). One of the sets has been exposed to outdoor environment for 13 years at CBI in Stockholm without external chlorides and no shelter for rain or snow. The other set of specimens has been stored for 13 years in a climate chamber with 80 % RH. The concrete cover was 16 mm in the specimens. Originally 1.0 % chlorides of cement weight were mixed into the substrate concrete in samples 33R and 43R and 4.0 % chlorides of cement weight were mixed into the substrate concrete in samples 53R and 63R, see Table 2. The specimens had no surface treatment.

Table 2. Water/cement ratios and initial chloride concentrations in the investigated specimens.

Specimen and storing environment	W/C (Substrate concrete) Initial	W/C (Substrate concrete) Investigation time	W/C (Repair concrete) Initial	W/C (Repair concrete) Investigation time	Initial chloride concentration in substrate concrete (wt % per cement)	Initial chloride concentration in repair concrete (wt % per cement)
33R field	0.70	0.60	0.40-0.45	0.55	1.0	0
43R field	0.50	0.40	0.40-0.45	0.45	1.0	0
53R field	0.70	0.50	0.40-0.45	0.60	4.0	0
63R field	0.50	0.40	0.40-0.45	0.55	4.0	0
33R 80RH	0.70	0.70	0.40-0.45	0.55	1.0	0
43R 80RH	0.50	0.55	0.40-0.45	0.45	1.0	0
53R 80RH	0.70	0.70	0.40-0.45	0.60	4.0	0
63R 80RH	0.50	0.45	0.40-0.45	0.50	4.0	0

3.3   Concrete structures used in the field study

Three different repaired concrete structures were investigated in the field study in this licentiate thesis work. All these three objects are located in central part of Stockholm.

Pålsund bridge is an arch bridge in one span (total length 62 m and span 52.5 m), see Figure 3, in the centre of Stockholm. It was built in 1947 across a narrow part of the lake *Mälaren* between *Söder Mälarstrand* and the island *Långholmen*. The bridge is narrow and highly

trafficed by cars and trucks. In winter time the bridge is treated with deicing agents. In 1992 the asphalt overlay was removed and the concrete bridge deck was blasted with water jet and about 20-30 mm concrete was removed [43]. A 50 mm thick fibre reinforced overlay concrete was cast on the top of the substrate concrete according to documents, see Figure 4. Totally 60 kg steel fibre was intermixed per m^3 concrete. In 1994, the whole concrete part of the bridge was hydrophobed by applying some kind of impregnation, probably some kind of silane/siloxane, to reduce the ingress of chlorides, water and moisture. The function of the concrete layer is a wearing surface**.**
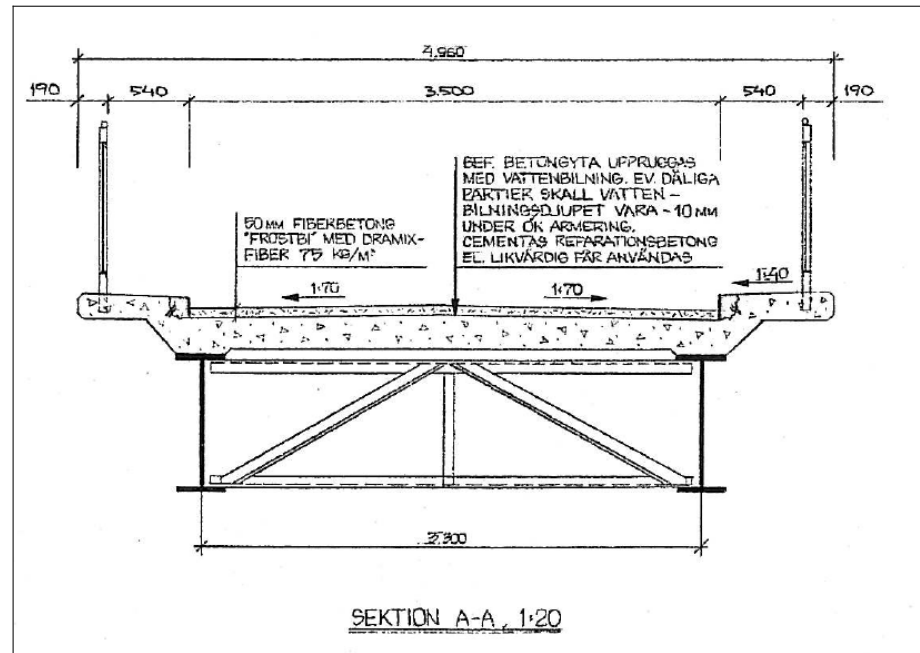

Figure 3. *Pålsund bridge*

Figure 4. Principal sketch for the repair of the overlay of the bridge

The second object was a pedestrian concrete bridge with stairs built in 1974 across *Valhallavägen* in the centre of Stockholm, see Figure 5. Damages on the stairs were observed already in the early 90's, see Figure 6, probably caused by salt-frost actions and reinforcement corrosion. The stairs have been treated with deicing agents in the winter time.

Figure 5. Pedestrian bridge across *Valhallavägen at Fältöversten.*

Figure 6. Damaged stairs at Fältöversten, 1998.

In the year of 2000 the top of the concrete stairs was repaired. The existing granulite concrete and the damaged structural concrete were removed. At the edges of the stair steps the removing of concrete was done with a handheld equipment to avoid too big losses of concrete and the rest of the stairs was blasted with water jet. New concrete was cast with 80 mm cover to the reinforcement according to the documents. After the casting granite steps were placed on the top in a mortar. Finally the concrete stairs were impregnated. The stairs can be seen in profile in Figure 7.

Figure 7. Stairs to the pedestrian bridge across *Valhallavägen at Fältöversten*

In the middle of the 60's the parking structure called *Plankan* was built in the southern part of Stockholm centre, see Figure 8. The parking structure consists of two parking levels and a total area of about 5000 m^2. The floor structure is totally 300 mm thick. The top of the floor structure has no concrete overlay or water protecting membrane. The cars are driving directly on the structural concrete. Traffic during the years has brought deicing salts into the parking structure. CBI has carried out an assessment of the parking structure in 2006 and during that investigation [49] it was found that premixed chlorides have probably been used as an accelerator during the casting in the 60's. Damages caused by chloride initiated reinforcement corrosion on the top of the concrete floor have been patch repaired between years 1994 and 1998. After 1998 several new damaged areas have raised and even some of the patch repairs are damaged.

Figure 8. The entrance to the carpark *Plankan*.

In all these three structures concrete cores, Ø 50-100 mm, were drilled out across and along the transition zone between repair concretes and substrate concretes. The cores and reinforcement, if any, were ocularly examined and after that material was sawn out at different distances from the transition zone. The sawn material was analysed regarding the chloride content (weight-% per cement weight) with an ion selective electrode. The chloride contents were then arranged to chloride profiles across the transition zone to investigate if any chlorides had been moving from the substrate concrete and into the repair concrete.

3.4   Chloride analysis

In the laboratory study and the field study in this thesis two different methods were used to determine the chloride content in the cement paste in hardened concrete. The main method in the laboratory study was based on analysis with a Scanning Electron Microscope, SEM. The other method, which was the main method in the field study, was a wet-chemical method with an ion-selective electrode. The second method is a common used method for analysing chloride content in concrete because the advantage that the cement content is analysed. The great advantage with the SEM method is that you can do analysis with very small distance between. About 0.5 mm distance is used in this thesis, even shorter distance between the analyses is possible.

3.4.1   SEM-EDS analyses

From the specimens, 10 mm thick slices, see Figure 9, were cut with a precision saw. To prevent the chlorides to be washed out during the sawing process no cooling water was used. The cuts were directed so the transition zone between the substrate and repair concrete was located in the middle of the slices and 25 mm of concrete on both sides of the transition zone was included.
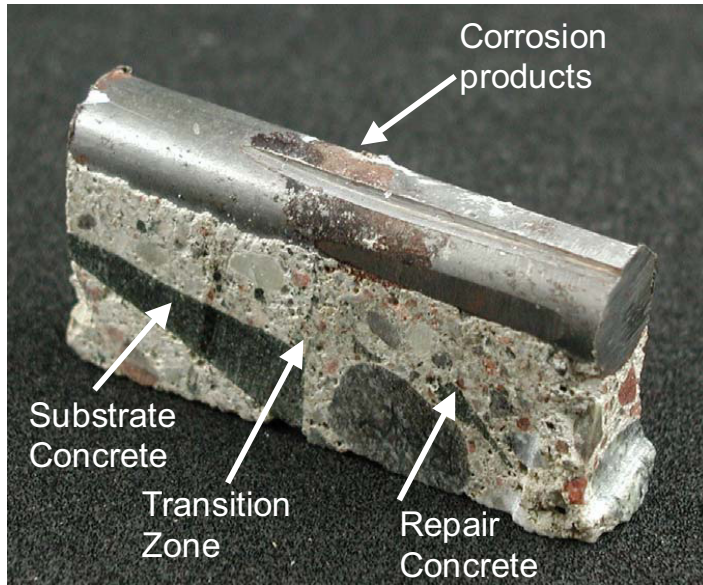

Figure 9. Specimen slice with rebar attached to the concrete.

Subsequently, the slices were fractured perpendicularly to the transition zone. This preparation technique is believed to produce the least altered surfaces for the purpose of chemical analysis. The amounts of chloride in the samples for all specimens were analysed using a Scanning Electron Microscope (SEM) equipped with Energy Dispersive Spectrometer (EDS). The EDS detector detects most of the X-ray spectrum generated from the probe surface when the accelerated electrons from the microscope hit the analysed surface [44]. The SEM-EDS-analyses were carried out on fractured surfaces and the analytical results are presented as wt % of chloride per cement weight. The EDS instrument detects the total chloride content in the cement paste, the sum of the free chlorides and the bound chlorides. All the SEM-EDS-analyses were carried out in the cement paste and the beam was focused to point analyses. As the chlorides are not uniformly distributed in the cement paste on the micro scale, at least five SEM-EDS-analyses were done at every distance from the transition zone. Pictures were taken at different distances, see example in Figure 10, and the analysed points were marked and the distance from the transition zone was measured. Mean values at each distance were calculated and chloride profiles were made, see example in Figure 11. In the profile the transition zone is defining the origo, the distance into the substrate concrete is negative and the distance is positive into the repair concrete. Distances are given in millimetres (mm). In some of the specimens it was not possible to make chloride SEM-EDS-analysis all the 25 mm in each material because of aggregate interference. A similar method has been used by [45] to determine the chloride profile and the diffusion coefficient.
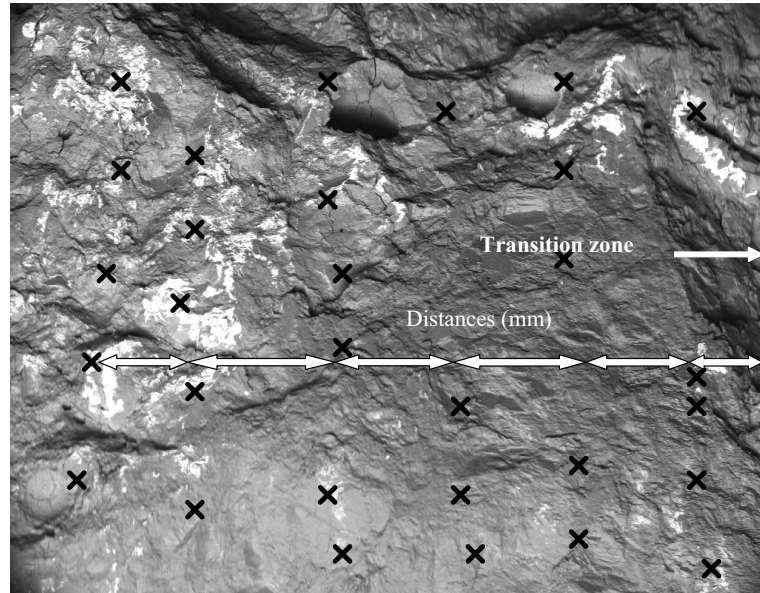
Figure 10. SEM-image over an analysed area. Total length of the sample in this image is 6.5 mm.

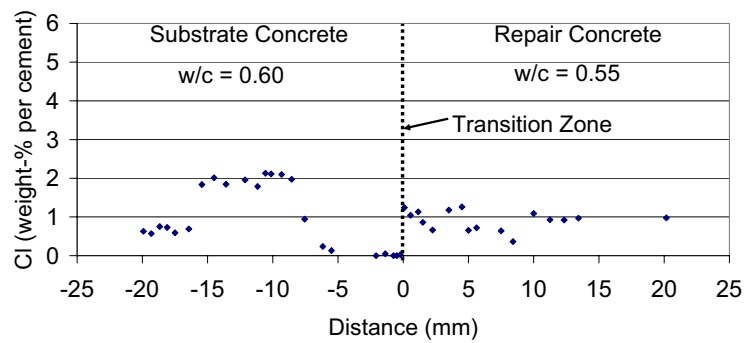Figure 11. Chloride profile from a SEM-EDS analysis in a sample.

3.4.2   Ion selective electrode

The method is developed at CBI [46] and is useful for quantitative determination of the total chloride content per cement weight in hardened concrete. The concrete to be analysed is cut with a diamond-saw. Then 1-1.5 g of the cement paste, aggregates are avoided, is weighed into a boiling tube. Nitric acid and water is added and the chlorides are dissolved from the cement paste during heating. After cooling and sedimentation the clear liquid phase is

analysed. With a chloride selective electrode the potential, mV, is measured and with a calibration curve the chloride content, mg, is determined. The Ca^{2+} is determined, mg/dm^3, in the clear liquid phase by an EDTA-titration. The chloride content in the probe is then calculated to chlorides per cement (weight %). The accuracy of this measurement at 1.0 wt % chlorides is 0.1 wt % chlorides. The chloride contents were then arranged to chloride profiles across the transition zone to investigate if any chlorides have been moving from the substrate concrete and into the repair concrete. In this thesis the chloride selective electrode method is used to check if the SEM method is valid in the laboratory specimens. Totally about 200 analyses have been done in this thesis to make chloride profiles in the repaired specimens stored in the field station at CBI, to check the chloride content in their unrepaired reference specimens and to produce the chloride profiles in the repaired field structures. All analysis was done at CBI

3.5   Thin section analysis

Thin-sections of concrete for light microscopy were prepared with an epoxy resin containing a fluorescent dye according to NT Build 361 [47] to be able to estimate the w/c-ratio. The concrete was grinded to a thickness of 0.025 mm before the analysis could take place in a polarizing light microscope. The equivalent w/c-ratio was estimated for both substrate and repair concrete in all specimens in the laboratory and in the field study by comparing the contrast in the cement paste for the investigated thin-sections and the reference thin-sections with known equivalent w/c-ratio (0.35, 0.40, 0.45, 0.50, 0.60 and 0.70). Ten spots in each thin-section were estimated and finally a mean value was calculated. The w/c-ratio is a non-dimensional number with two decimals where the second decimal is rounded to 0 or 5.

If the concrete is homogeneous the variation of w/c-ratio is < 0.10 but if the concrete is very inhomogeneous the variation may be > 0.20 for the ten spots. The w/c-ratio may also differ from the initial because of cement hydration over the years leading to a lower w/c-ratio in the concrete. Some divergence from the initial recipe during the mixing may also give a changed w/c-ratio.

The thin-section enabled also microscope study of the density of the cement paste from the substrate concrete towards the transition zone and into the repair concrete as well as calcite formation due to carbonation. Thin-sections were prepared perpendicularly to the transition zone between substrate concrete and repair concrete for two of the specimens in the laboratory study. Totally 31 thin sections were produced in the whole thesis work.

3.6   Corrosion

The specimens in the laboratory investigation were ocularly observed. Cracks in the concrete especially along the reinforcement were noted. Thereafter the concrete was removed from the reinforcement and then the reinforcement near and in the transition zone in the laboratory study were ocularly observed and photographed. The position and colour of eventual corrosion on the surface of the reinforcement was noted. In the field study concrete cores were taken out from the structures and where reinforcement was found in or near the transition zone the steel surface was observed and photographed in the same way as in the laboratory investigations.

3.7   Carbonation

The carbonation in the different samples was determined according to SS 13 72 42 [48]. The specimen was fractured to receive a surface that has not been exposed to the atmosphere. The surface was wetted with phenolphthalein solution, a pH – indicator. If the cement paste has a pH < 9.2 the concrete looks wet and if the pH > 9.2 the cement paste in the concrete becomes purple. Thereafter the depth was measured with a sliding calliper with an accuracy of ± 0.2 mm. A mean value was calculated from several measurements.

Chapter 4

4.   RESULTS

4.1   Experience from people working in the area of concrete repairs.

The complete interview study and all the results are presented in a CBI-commission report [13] and summarised in Paper I. Based on the interviews with bridge engineers at SRA and Banverket and with one consulting company, one producer of repair material and one contractor for concrete repairs, the main results concerning this thesis can be summarised as follows;

1) Concrete patch repairs in old bridges are seldom performed because of earlier bad experience with the durability, high installation costs and difficulties with the curing.

2) Recommendations and requirements [3] are often prescribed by the bridge engineers in the different regions for SRA and Banverket. Despite this, prescribed test methods are not used in some regions, for example the pull-off test to determine bond between new and old concrete.

3) The expected remaining service life of the bridge is taken into account when choosing the extent of the repair but is not considered in the phase of choosing repair material. The bridge engineers often recommend a concrete with higher quality than prescribed. This means a higher quality of repair material than substrate.

4) Conventional concrete with w/c ≤ 0.45 is often used in large concrete repairs. In some regions shotcrete is used in concrete repairs, but in other regions the use of shotcrete is prohibited because of durability problems.

5) Generally, new repair materials such as polymer modified cement grouts are rarely used.

6) Two methods are normally used to remove concrete, water jet and mechanical abrasion techniques. In some regions, where water jetting is used, water flushing on horizontal surfaces is the only prescribed method to clean the substrate surface. Bro 2002, [3], always prescribes cleaning of water jetted surfaces, e.g. by water with high pressure, water flushing with high flows, compressed air and vacuum cleaning.

7) Pre-wetting of the substrate surface is always prescribed in concrete repairs on SRA's and Banverket's bridges. The bridge engineers think that the pre-wetting is difficult especially when the repaired areas are small and the weather is extreme.

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8) Durability problems exist with patch repairs in new productions when repairing damages related to mechanical damages, honeycombs and form tie embedment and railing embedment are common.

9) The bridge engineers experience that no durability problems occur with large concrete repairs after the guarantee time of 5 years.

10) Though the experience is good, there are no known investigations at SRA or Banverket that have been analysing the durability of concrete repairs older than 5 years. In most regions there are several reference bridges available for an investigation of this kind.

11) Old concrete repairs are not specially investigated and controlled during the inspections after the guarantee time.

12) Sometimes during the guarantee time problems like cracks occur in the repair material and sometimes there is poor adhesion between the repair material and the old concrete. In some regions, it is then necessary to repair once more. In other regions, alternative methods like impregnation, injection or economical deduction are used.

13) The common strategy is to leave the quality control of concrete repairs to the self control by the contractor, except major concrete repairs which are controlled by final inspections and guarantee inspections.

Out from these results, especially items 1, 4, 8, 10 and 12 above, the investigations in Paper II, Paper III and Paper IV were planned. Because that concrete is used in the majority of all concrete repairs the further studies in this thesis were focused on concrete repairs with normal concrete as a repair material. Different sizes of the repairs were chosen to identify if there are more durability problems with smaller repairs than larger repairs.

4.2 Chloride transport, reinforcement corrosion and carbonation near the transition zone between substrate concrete and repair concrete

The main results from analyses of chloride transport, reinforcement corrosion, carbonation and microstructure from the laboratory study and the field study are presented in Paper II, Paper III and Paper IV. All profiles and figures from the laboratory study and the field study are attached in Appendices 1 and 2.

In this Chapter typical results are presented in text and exemplified by diagrams and figures.

4.2.1 Chloride transport and carbonation

The chloride contents across the transition zone between substrate concrete and repair concrete were determined with the SEM-EDS analysis and with a method based on chloride selective electrode. Chloride profiles were then arranged. Totally eight chloride profiles in the laboratory specimens were established with the SEM-EDS analysis and eleven chloride profiles in the field structures were made with the ion selective method.

In the laboratory specimens it was seen that the premixed chlorides have been transported into the repair concrete during the 13 years of exposure. In Figure 12 an established chloride profile is shown for a specimen with initially 1 wt % chlorides in the substrate concrete exposed outdoors. The chlorides have moved more than 20 mm into the repair concrete and the concentration at this distance is the same as the initial content in the substrate concrete.
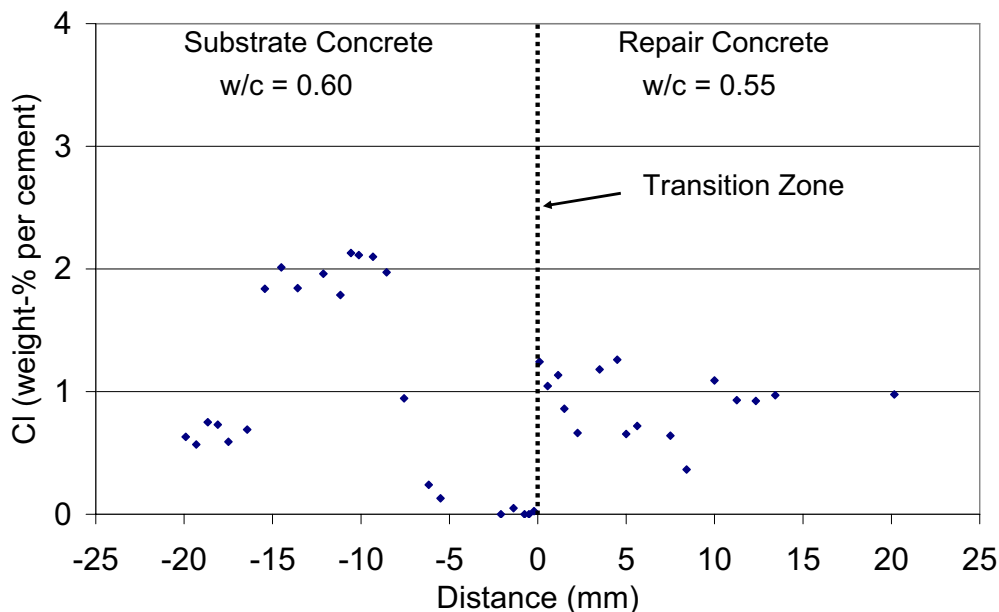

Figure 12. Chloride profile in a specimen with 1 wt % chlorides premixed in the substrate concrete, exposed outdoors.

The profiles for the specimens stored in 80 % relative humidity during the 13 years have the same appearance, for example see Figure 13.
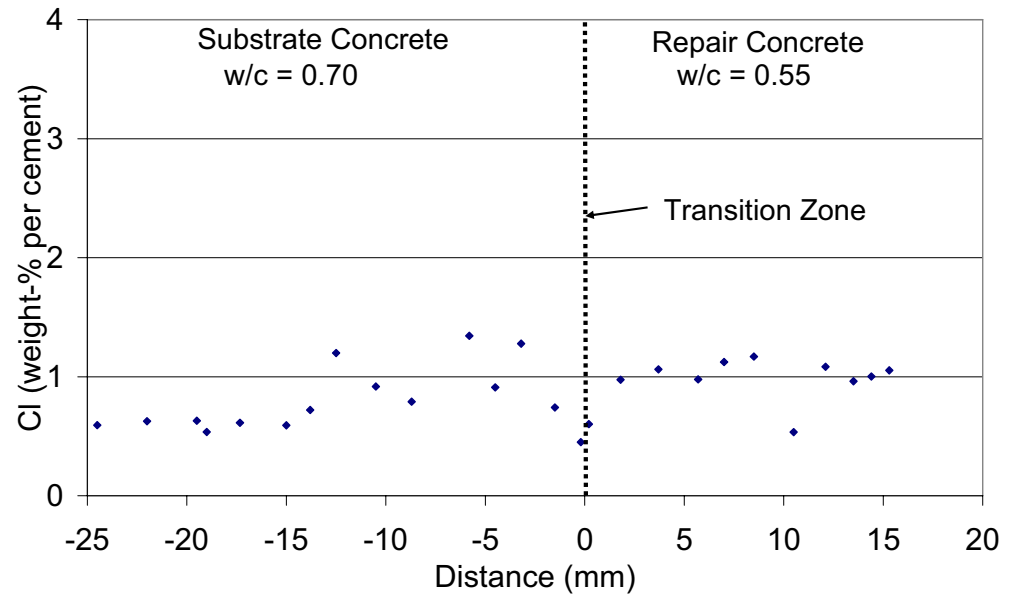

Figure 13. Chloride profile in a specimen with 1 wt % chlorides premixed in the substrate concrete, stored 13 years in relative humidity of 80 %.

This chloride transport has occurred in all the laboratory specimens with two exceptions. These two had an equivalent w/c-ratio 0.45, see example in Figure 14, but the equivalent w/c-ratio in the substrate concrete differed between these two specimens from 0.40 to 0.55. The other six specimens had an equivalent w/c-ratio $\geq$ 0.50 in their repair concretes.
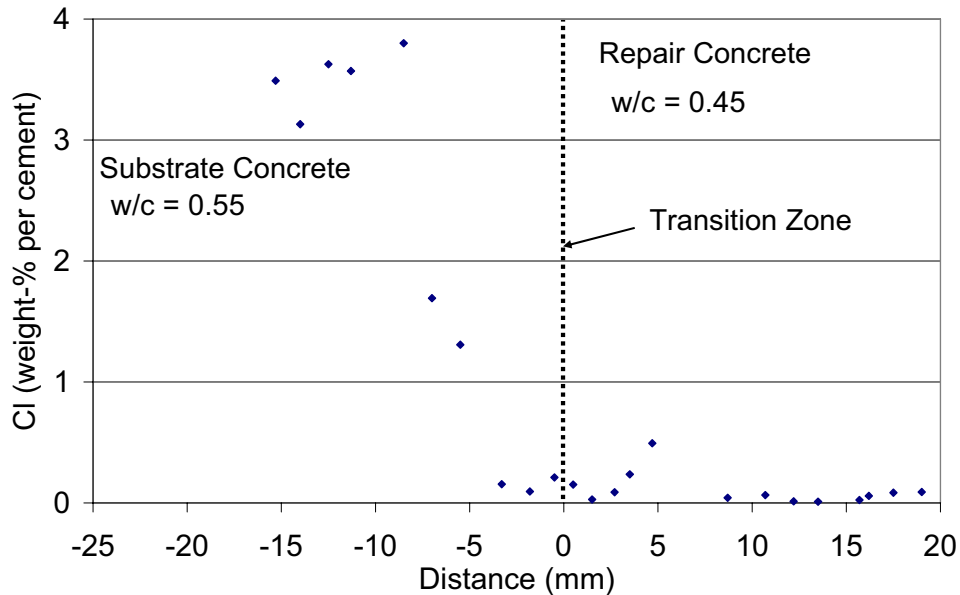
Figure 14. Low chloride transport across the transition zone when the equivalent w/c-ratio is 0.45 in the repair concrete.

In the field study chloride transport was observed across the transition when the substrate concrete was contaminated with chlorides, see Figure 16. In field samples it was also observed that some chlorides have penetrated the top of the concrete overlay but it was clear that a dense concrete overlay reduces the chloride ingress. This is discussed further in Paper IV.

Carbonation was observed in the transition for the specimens in the laboratory specimens. A principal sketch can be seen in Figure 15.
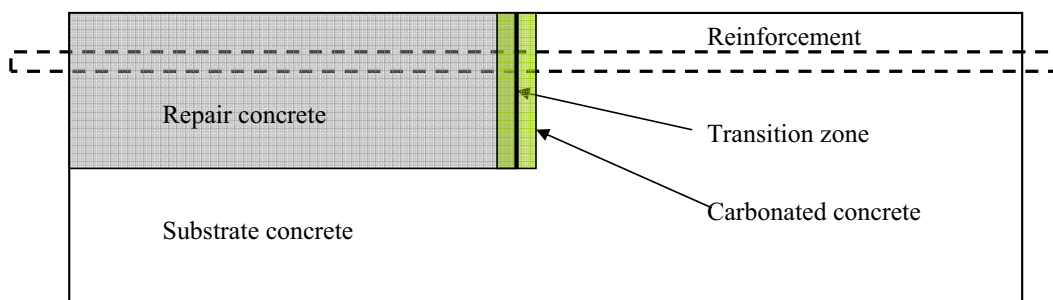

Figure 15. Schematic figure for specimen with carbonation in the transition zone.

Table 3. Carbonation depths in the transition zone.

Specimen	Substrate concrete Carbonation (mm)	Repair concrete Carbonation (mm)
33R field	2.3	0.1-0.2
43R field	1.6	0-0.2
53R field	2	0.1
63R field	1	0.1
33R 80RH	20	Entire depth
43R 80RH	5-10	2
53R 80RH	15-20	15-20
63R 80RH	5	2

In Figure 13 another general observation can be seen. The chloride concentration in the first millimetres of the substrate concrete just near the transition zone was very low. For the specimens stored in the field this zone is comparable with the depth of carbonated concrete. It seems that the carbonation front has forced the chlorides into the substrate concrete and behind the carbonated concrete there are accumulated chlorides, the carbonation depths can be seen in Appendix 1, Table 1. Behind this zone the chloride level went down to a background value in most of the profiles. It would have been interesting to extend these analyses up to 50 mm distance from the transition zone. This was not possible because of the sizes of the samples were too small. If the chloride transport into the repair concrete occurred before the carbonation or if the chlorides still can move through the carbonated zone is not investigated and fully understood. The same phenomenon with carbonation front and chloride content has been seen and explained earlier by Tuutii [32]. This is further discussed in Section 5.4.2 and Paper III. In the specimens stored in 80 % relative humidity the carbonation depths are larger, see Table 3, and it is not the same clear relation to the chloride profiles. The higher carbonation is due to a environment in the chamber compared to outdoors and the carbonation rate is higher in a concrete with 80 % relative humidity. The maximum for the carbonation rate occurs at 65-70 % relative humidity [25].
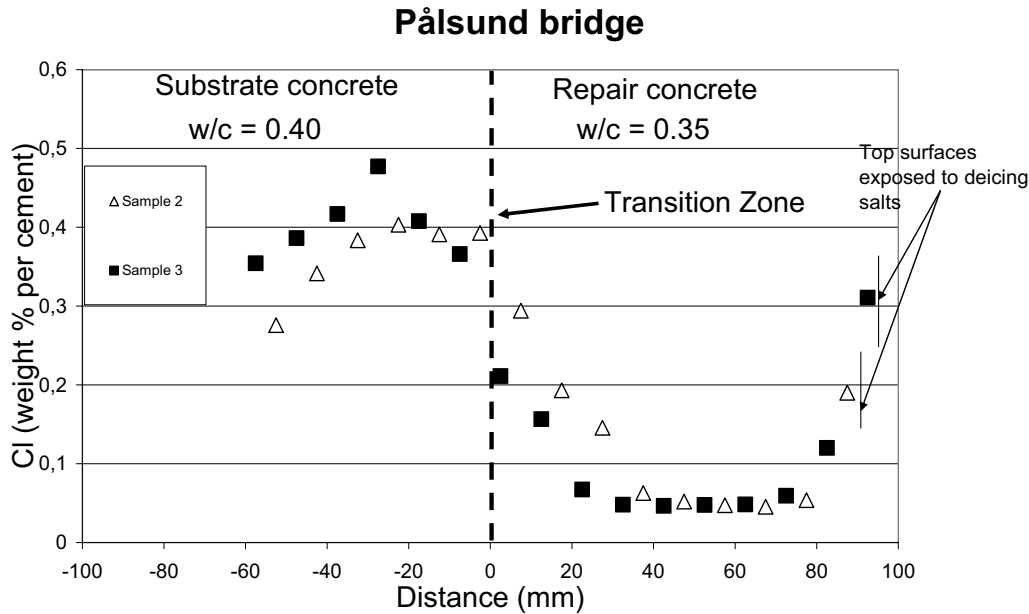
Figure 16. Chloride profile across transition zone in two field samples from a concrete repair.

4.2.2 Reinforcement corrosion

All eight specimens in the laboratory study had more or less corroded reinforcement. In three of the field specimens and four of the specimens exposed to 80 % RH rebars were corroded in the transition zone, see example in Figure 17. All the specimens were corroded in the substrate concrete
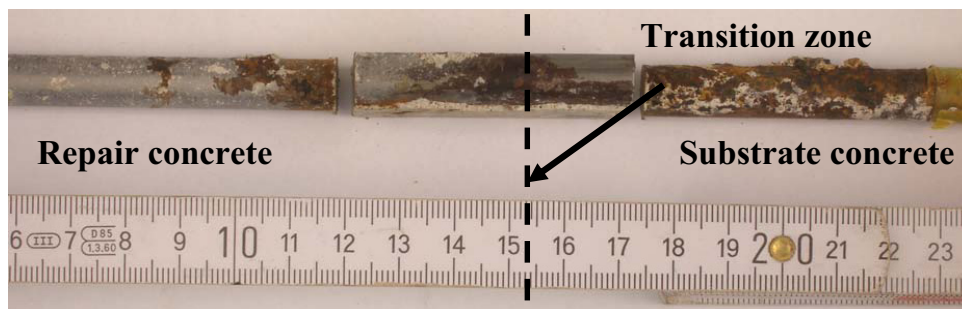

Figure 17. Reinforcement corrosion in separated large areas. Corrosion appears in this specimen in both the materials and in the transition zone.

In two of the investigated field structures reinforcement corrosion was found in the transition zone. In the parking structure, see Figure 18, all the concrete cores were broken during the drilling process and in several of them corroded reinforcement was found in the transition zone.

Figure 18. Concrete samples from patch repairs in parking structure *Plankan* with corroded reinforcement in the transition zone.

The expansive corrosion products in the repairs in the parking structure are caused by the high levels of chlorides near the transition zone, between 0.7 and 2.0 weight % chlorides per cement weight.

Reinforcement corrosion was also found in the transition zone between the substrate concrete and the repair concrete in the pedestrian bridge, see Figure 19.
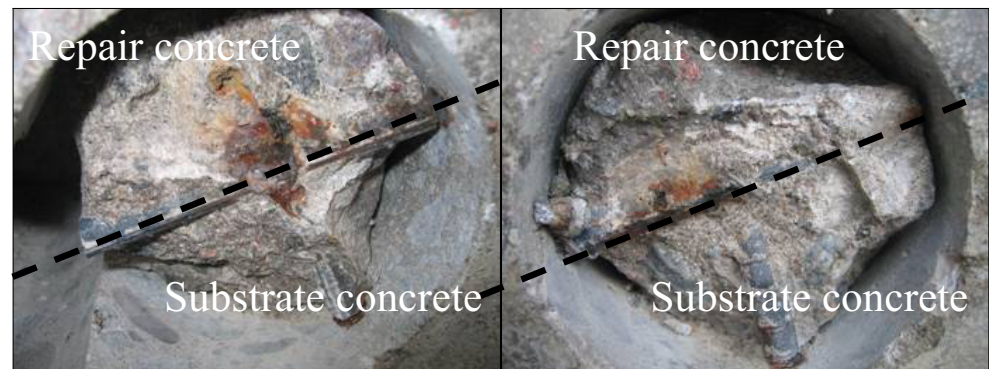

Figure 19. Reinforcement corrosion in the transition zone in the pedestrian stairs. The dotted lines indicate the location of the theoretical transition zone

The only difference between the substrate concrete and the repair concrete is to be found in the mix design. It is obvious that some kind of electrochemical phenomenon has occurred. In this case it seems that reinforcement corrosion can occur in the transition zone between two different concretes without chlorides present or carbonation in any of the two materials. In this study just a few samples and observations are carried out. Further analyses regarding chloride content and concrete composition etc. would be valuable. Another possible explanation could be galvanic corrosion if the reinforcement is connected to a more noble

metal for example in the railing of the stairs. This has not been checked. A third theory is that chloride contaminated concrete has been removed around the reinforcement but the corrosion products, maybe including some chlorides, were not removed completely during the cleaning before the repair.

Chapter 5

5.   DISCUSSION

5.1   The relevance of the thesis

The relevance of the laboratory experiments seems to be good. Several laboratory investigations, see Section 2.2.1 Literature review, have earlier observed that there is a risk for reinforcement corrosion in and near the transition zone between a chloride contaminated substrate concrete and a repair concrete. None of these observations has reported about the chloride transport across the transition zone. Certain levels of chlorides may initiate reinforcement corrosion. Therefore the investigations and studies on the chloride profiles in the transition zone are very important. The used specimen design is also relevant regarding the premixed chloride content and reinforcement across the transition zone. The analyses of the chloride profiles compared to the corrosion of the reinforcement may clarify which characteristics are optimal in a concrete repair. It is also urgent to do a field study to verify if the picture of corrosion and chloride transport is the same in the reality as in the laboratory study. The performed field investigations in this thesis are rather small and limited but at least an effort to make an initial study of the reality.

The bias of the interview study can be discussed. A majority of the interviewed people is bridge engineers at governmental authorities and maybe they are not fully representative for the entire bridge society. It may be a risk that the bridge engineers will suppress the durability problems when they have written the documents how to repair. However three reference interviews were performed with persons at private companies and those interviews indicated to give the same answers on the prepared questions. All the interviewed people are working, in one way or another, with concrete repair projects. Because of this the interviews seem to be rather objective and unbiased.

5.2   Discussion of results

5.2.1   Durability of concrete repairs

From the interview study it is clarified that conventional concrete with w/c ≤ 0.45 or shotcrete with high quality are often used in large concrete repairs on concrete bridges. The bridge engineers' experience is that no durability problems occur with large concrete repairs after the guarantee time of five years. Although the experience is good no investigations that have been analysing the durability of concrete repairs older than five years are known for the bridge engineers. Concrete patch repairs in old bridges are seldom performed because of earlier bad experience with the durability, high installation costs and difficulties with the curing. Old

concrete repairs are not specially investigated and controlled during the inspections after the guarantee time is ended. A follow-up study of documented concrete repairs older than the guarantee time is needed.

From the laboratory study and the field study in this thesis it can be seen that the large repairs at the *Pålsund bridge* and at the pedestrian stairs at *Valhallavägen* seem to perform well after more than five years. The smaller repairs in the laboratory study and the allocated patch repairs in the parking structure *Plankan* have more obvious durability problems. This indicates that the bridge engineers' experience seems to correspond to the results in this thesis.

5.2.2   Performance of concrete repairs

The Swedish Road Administration and Banverket have no handbook that includes assessment, concrete analysis methods, repair techniques etc. There is one handbook for bridge inspection [2] but it is written more than 10 years ago and is not complete in all areas. The bridge engineers often use the Concrete Handbook of Repair, [1], written 1987 and their own experience to choose repair methods and techniques to fulfil the demands in Bro 2002, [3]. Recommendations and requirements are often prescribed by the Swedish bridge engineers in the different regions when a concrete repair will be performed. Despite this, prescribed test methods are not used in some regions, for example the pull-off test to determine bond between new and old concrete. Most of the interviewed bridge engineers think that the Concrete Handbook of Repair [1] needs to be revised and completed. Now three years after this interview study a project has started to produce a Swedish electronic handbook for concrete repairs [12] as a revised version of [1].

The expected remaining service life of the bridge is taken into account when Swedish bridge engineers are choosing the extent of the repair but is not considered in the phase of choosing repair material. The bridge engineers often recommend a concrete with higher quality than prescribed. This means often a higher quality of the repair concrete than in the substrate concrete. Which quality should be used to achieve an optimal concrete repair with optimal service life? When and how should we repair to achieve profitable concrete repairs? A compilation of all the facts from bridge inspections can give a hint of existing and future need of concrete repair. It is also important to determine the economical difference of the repair at an early stage and in a later phase. When and how should we repair to achieve profitable concrete repairs?

5.2.3   Chloride transport in concrete repairs

From the laboratory study it seems that the chloride transport into a repair concrete is low when the w/c-ratio in the repair concrete is 0.45 or less. It also seems that a low w/c-ratio (0.40) in the substrate concrete gives lower chloride transport into a repair material. Janz (2005) has observed significant chloride diffusion when the w/b-ratio in the repair concrete was 0.4 and in the substrate concrete the w/b-ratio was 0.7. In this thesis' there are just two laboratory specimens with this low w/c-ratio in the repair concrete. In the investigations from the *Pålsund bridge* it is obvious that the chlorides in the substrate concrete are transported into the denser (w/c-ratio 0.35) repair concrete. It seems from the chloride profiles in this thesis that diffusion, or a combination of diffusion and migration is the predominant transport mechanisms in the specimens. The transport of chlorides from a substrate concrete into a repair concrete may reduce the risk for reinforcement corrosion in the substrate concrete when lowering the chloride content under a critical level. This phenomenon may be desirable when it is expensive or hard to remove the contaminated concrete. Even when the w/c-ratio is lower

in the repair concrete than in the substrate concrete the chloride transport across the transition zone may occur. It would be interesting to identify when the chlorides will move into the concrete. Is it mainly immediately after the casting or are they still moving 10 or 15 years after the repair was performed?

The chloride concentration in the bulk of the substrate concrete is lower than the initially reported values and this indicates that we have high mobility of the chlorides at long distances from the transition zone.

5.2.4   Carbonation

The carbonation, in the substrate concrete near the transition zone for the field stored laboratory specimens, seems to force the chlorides into the substrate concrete and behind the carbonated concrete there are accumulated chlorides, (e.g. Appendix 1 figure 2 and Table 1). Behind this zone the chloride level goes down to a background value in most of the profiles. It would have been interesting to extend these analyses up to 50 mm distance from the transition zone. If the chloride transport into the repair concrete occurred before the carbonation or if the chlorides still can move through the carbonated zone is not investigated and fully understood. The same phenomenon with carbonation front and chloride content has been seen and explained earlier by Tuutti [32]. In his investigations he found the following: "Carbonated concrete does not have at all the same capacity for binding chlorides as does non-carbonated concrete. This means that the equilibrium which occurs between the free chloride and bound chloride is displaced so that the free chloride increases in the pore solution. In a concrete which was homogeneous from the beginning, a difference in concentration is gradually built up for the chlorides with the greatest concentration at the surface. The difference in concentration leads to a diffusion process. In popular terms one might say that the carbonation process ploughs the chlorides into the concrete". A chloride level at the reinforcement which was acceptable from the beginning can thus become too high before the carbonation front reaches it. This observation is similar to the results in this present investigation but the chlorides are also transported into the repair concrete. One explanation why the carbonated concrete more or less not bind chlorides is because that the pore system is smaller than in noncarbonated concrete. In noncarbonated concrete the chlorides may be partly bound in $C_3A \cdot CaCl_2 \cdot 10H_2O$ and this formation may be decreased by carbonation [50].

The carbonation depths in the transition zone are larger in the specimens stored in constant relative humidity (80 % RH) than in the specimens stored in the outdoor field exposure site. This result is expected since the carbonation process is faster at 80 % RH compared to when the concrete is wet, Bertolini (2004). The field specimens have not been protected from rain and snow and have probably been wet most of the time.

In the field structures, *Pålsund bridge* and pedestrian stairs, investigated in this thesis the carbonation was very low, < 1 mm, both at the surfaces and in the transition zones. For the surfaces of these concrete structures the finding correlates to Tuutti's [32] observations of low w/c-ratios concrete not sheltered for rain.

5.2.5   Reinforcement corrosion in concrete repairs

Three field specimens and all four specimens exposed to 80 % RH were corroded in the transition zone and this is comparable with the statement in Courard et al. [38]. They observed that reinforcement corrosion generally begins in the transition zone especially if a porous

repair material is used or if the adhesion in the transition zone is weak. All repaired specimens in both environments were corroded in the substrate concrete and four of these were corroded in the repair concrete and in most of the observations the corrosion (the anodes) was allocated in separated large areas. Kobayashi et al. [36] have observed the same between materials with difference in chloride content and explain the mechanism to macrocell corrosion.

Generally the degree of corrosion is lower in the specimens with 1 wt % chlorides intermixed into the concrete than in those specimens with 4 wt % chlorides which was expected because that higher chloride content gives more depassivation of the steel reinforcement. The corrosion seems to be more severe (larger areas are corroded) in the specimens stored in 80 RH (constant climate) than in outdoor climate probably explained by the larger grade of carbonation at the lower RH.

In all the specimens the corrosion products have two colours, black and orange. The colour of the corrosion product may differ because of the oxygen concentration, Nielsen [51]. If there is an excess of oxygen the corrosion products will become brown or yellow, $Fe(OH)_3 \cdot nH_2O$ and in the case when the oxygen is in deficit the colour of the products is black or white, FeO or Fe_3O_4. In he laboratory specimens the two materials near the transition zone have different density and because of that the oxygen transport into the reinforcement may differ and lead to different colours of the corrosion products.

In the field structures both corroded an uncorroded reinforcement was found. In the *Pålsund bridge* an uncorroded reinforcement was found in the substrate concrete about 5 mm from the transition zone where the chloride content was low, < 0.10 wt % per cement weight, and the concrete was non-carbonated. For the pedestrian stairs with non-carbonated concrete and the low chloride contents reinforcement corrosion was found in the transition zone. It is obvious that some kind of electrochemical phenomenon has occurred. Any documented possible mechanism has not been found and the only difference between the substrate concrete and the repair concrete seems to be the mix design when they were cast. The materials have though the same low equivalent w/c-ratio 0.35. Probably different cement compositions were used in the repair concrete, from year 2000, compared to the substrate concrete produced in 1974. In this object it looks like that reinforcement corrosion can occur in the transition zone between two different concretes without chlorides present or carbonation in any of the two materials. In this field observation just a few samples and observations were made. An expanded investigation of this pedestrian bridge to identify the extent of and try to identify the cause of the reinforcement corrosion in the transition zone and further analyses regarding chloride content and concrete composition etc. would be of great interest. Another possible explanation may be galvanic corrosion if the reinforcement is connected to a more noble metal for example in the railing of the stairs. This has not been further investigated.

In the parking structure *Plankan* horizontal cracks were found in the repair material and probably they were caused due to reinforcement corrosion in the repair material. The expansive corrosion products are able to crack and spall the concrete. Another possibility is if the repair concrete was cast in two steps with some time between causing low bond. Cracks and gaps between the repair concrete and the substrate concrete were also observed and are caused by chloride initiated reinforcement corrosion. The levels of chlorides near the transition zone are between 0.7 and 2.0 weight % chlorides per cement weight.

Chapter 6

6.   CONCLUSIONS

The main results from this thesis can be summarised as follows:

Concrete patch repairs are seldom performed on SRA's and Banverket's bridges because of:
   a) Earlier experience with poor durability.
   b) High installation costs.
   c) Difficulties with after treatment.

Concrete patch repairs are performed when:
   a) Damage exists in a load carrying structural part.
   b) Aesthetic reasons.
   c) Construction errors in new production.

Large concrete repairs are performed with pretested conventional cast-in-place concrete, w/c ≤ 0.45, cast in a form or pretested shotcrete with high quality.

The bridge engineers at SRA and Banverket experience that no durability problems occur with large concrete repairs during the guarantee time of five years but there are no known investigations that have analyzed the durability of documented concrete repairs older than five years on SRA's and Banverket´s bridges.

The expected remaining service life of the bridge is taken into account when deciding the extent of the repair but is not considered in the phase of selecting repair material. The bridge engineers often recommend a concrete with higher quality than prescribed.

Chlorides may move from a chloride contaminated substrate concrete into an initially chloride free repair concrete. The chlorides move more easily from the substrate concrete into a repair concrete with higher w/c-ratio than with lower w/c-ratio. This indicates that diffusion or a combination with migration is the predominant transport mechanism.

The carbonation in the substrate concrete seems to force the chlorides deeper into the substrate concrete and behind the carbonated concrete there are accumulated chlorides. This phenomenon is explained by carbonated concrete that does not have at all the same capacity for binding chlorides as non-carbonated concrete. A chloride level at the reinforcement which was acceptable from the beginning can thus become too high before the carbonation front reaches it.

Reinforcement corrosion occurs in the transition zone and near the transition zone in both the substrate concrete and the repair concrete because macrocell corrosion occurs in repaired chloride contaminated concrete. The results indicate that there is a risk for reinforcement corrosion in and near the transition zone between repair concrete and the substrate concrete and it must be considered in concrete repair work in chloride contaminated concrete structures. For example the chloride content around a repair can not exceed a certain level.

Chloride transport into the repair concrete may be useful to reduce the chloride content in a substrate concrete, e.g., to minimize the risk for reinforcement corrosion in the substrate concrete and avoid some removal of contaminated concrete. On the other hand the risk for corrosion may be moved to the repair concrete if it is reinforced with normal black steel. Even external exposure of chlorides must be considered for the risk of corrosion in the repair material.

Chapter 7

7.   FURTHER RESEARCH

The first ideas, when the financial application work started, were to study how to choose a repair material and how to perform a concrete repair. The compatibility was found to be a central term that must be fulfilled between repair concrete and substrate concrete. The focus in the applications was on bond, durability, chemical, electrochemical and permeability compatibility. The investigations were meant to study the performance, the choice of repair material and mix design for pozzolan and polymer modified cement mortars and ordinary Portland cement mortars and concrete. The main objective with the planned study was to create increased understanding of some critical characteristics in the transition zone between repair and substrate material. The second objective was to establish a basis for advices and guidelines for repair and maintenance. This basis may also constitute a platform for developing different test methods to verify the compatibility for a repair system. The third objective in the finance application was that the project should lead to a technical licentiate degree. Economic support was granted for a laboratory study. After a pilot interview study to this laboratory study it was decided that the laboratory investigation would focus on concrete repairs in chloride contaminated substrate concrete with normal repair concrete without polymers or pozzolans. The performed laboratory studies in this thesis have found some answers concerning electrochemical compatibility and permeability compatibility. Further research is needed to answer several more questions for concrete repairs with ordinary repair concrete. Further research should also involve repair materials with different admixtures. The results from this further research together with other research about concrete repairs should answer the questions about how the compatibility can be achieved between different repair materials and substrate concrete and how to achieve durable concrete repairs, both patch repairs and large repairs.

In order to increase the understanding of the repaired concrete system including the important compatibility issues, the author believes that the most fruitful way consists of further laboratory investigations, field studies and optimisation of the repair material.

7.1   Laboratory investigations

Further laboratory investigations ought to be carried out to answer these questions:

- Produce new laboratory specimens with cementitious materials developed for patch repair concrete and study chloride transport and reinforcement corrosion near the transition zone to identify and create understanding for the parameters having an effect

on chloride transport and reinforcement corrosion. One example of cementious materials could be shotcrete with high quality. According to the interview study this material is used in concrete repairs in several regions of SRA and Banverket but not always with a durable repair as a result. The Royal Institute of Technology (KTH) has suggested that a competence centre about shotcrete should be placed at KTH. A shotcrete repair project would create important knowledge about this material and how it should be used and proportioned for different kinds of repairs.

- Carry out corrosion measurements during exposure to verify which corrosion process that is most dominant in and near the transition zone between a repair concrete and a substrate concrete.

- Identify which corrosion process that is predominant in concrete repairs with chloride contaminated substrate concrete and different repair materials, microcell or macrocell corrosion and which is most severe? Is one of the mechanisms more desirable than the other one? If that is the case the selection of repair material can be based on such information.

- Study different types of corrosion products and where they are formed in relation to the transition zone to better understand the different mechanisms like oxygen transport in the materials near the transition zone.

- Which chloride transport mechanism is predominant? When does the chloride transport occur between a chloride contaminated concrete and a repair concrete? Is it immediately after the casting or is the transport across the transition zone going for a longer time? Does the chloride transport across a transition zone make the reinforcement corrosion more severe or does it reduce the risk for corrosion? This is important to know because then it will be possible to optimize conditions and parameters at the casting to achieve to most wanted chloride mobility.

7.2   Further field studies

Field studies are important for providing relevance to the project. Some important topics are the following ones:

- Extended field study of documented concrete repairs older than the guarantee time to investigate the kind of problems occurring and when and why they arise. Which chloride levels can be left in a structure behind a concrete repair?

- Follow concrete repairs of chloride contaminated substrate concretes from the beginning. Observe the reinforcement before the repair concrete is cast, examine the chloride profiles into the substrate concrete. Document the performance of the whole repair and finally follow the durability of the repair over the time. Estimate when the chloride transport across the transition zone occurs and where and when the reinforcement corrosion starts.

- Compare the field study with the results from the extended laboratory study and try to produce advice and guidelines how compatibility should be quantified.

7.3   Optimal repair material

All the optimal parameters found in the laboratory investigations and the field investigation should be used to find out an optimal solution for the whole concrete repair performance together with other aspects for example economical issues and environmental affects. Which characteristics for the repair material and the substrate concrete are most optimal? How can we minimize the risk for reinforcement corrosion near the transition zone, e.g., which chloride level can be left in the substrate concrete around the repair, which water cement ratio in the repair material should be selected regarding the water cement ratio in the substrate concrete? Try to quantify the different parameters to achieve bond compatibility, chemical compatibility, electrochemical compatibility and permeability compatibility in a concrete repair of damaged chloride contaminated concrete. How can we at the same time make the repair most economical including all the moments from start with removing the damaged concrete and all the different steps through the life time of the repair? Which repair method and repair material that are chosen have the best effect if a life-cycle assessment is performed?

Chapter 8

8.   References

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Appendix 1 Laboratory study

In Table 1 all analyses and observations are presented for the specimens, 33R, 43R, 53R and 63R, stored both at CBI's field station and in a climate chamber with relative humidity of 80 %. In the column for specimen the name and exposure for each specimen is written and the equivalent w/c-ratios for the different materials and the intermixed chloride content are presented. The chloride profiles and the observations of carbonation and corrosion are described in the other columns. In Figure 1-25 these results and observations can be seen.

Table 1. Main results from chloride transport, corrosion, carbonation and microstructure in the laboratory investigation.

Specimen	Chloride profile	Carbonation	Corrosion
33R field Substrate w/c = 0.60 Cl = 1.0 wt % Repair w/c = 0.55 Cl	The content of chlorides in the substrate concrete is low, almost 0 wt %, between 0 and 6 mm from the transition zone. Between 6 mm and 16 mm distance from the transition zone, the concentrations of chlorides are about 2 wt %. At larger depths than 16 mm into the substrate concrete the concentration of chloride drops to approximately 0.7 wt %. In the repair concrete the concentration of chloride near the transition zone varies between 0.4 and 1.3 wt % up to a distance of 20 mm from the transition zone. See figure 1.	The substrate concrete was carbonated to 2.3 mm depth from the transition zone. The repair concrete had less than 0.3 mm carbonated cement paste from the transition zone.	Corroded parts in the transition zone both in repair and substrate concrete. In the bulk of the repair concrete there was no corrosion. The whole surface in the substrate concrete was corroded except 20 mm between the corroded part in the transition zone and the main corrosion in the substrate concrete. See figure 9.
43R field Substrate w/c = 0.40 Cl = 1.0 wt % Repair w/c = 0.45	Between 3 mm and 25 mm in the substrate concrete the concentration of chloride lie between 1 and 3 wt %. In the repair concrete the chloride concentration near the transition zone is about 0.5 wt % (0 to 8 mm depth) and almost 0 wt % longer than 8 mm from the transition zone. See figure 2.	The substrate concrete was carbonated to 1.6 mm depth from the transition zone. The repair concrete had less than 0.3 mm carbonated cement paste from the transition zone.	Corroded parts in the transition zone both in repair and substrate concrete. In the bulk of the repair concrete there was just a small spot of corrosion in. In the substrate concrete the corrosion was partial for 43R. See figure 10.
53R field Substrate w/c = 0.50 Cl = 4.0 wt % Repair w/c = 0.60	The chloride concentration between 0 and 1.5 mm into the substrate concrete is less than 1 wt %. At greater depths than 1.5 mm the chloride level is about 2 wt % until 23 mm, which should be compared to 4 wt % intermixed in the concrete when the specimen was cast. In the repair concrete there is a 6 wt % peak in the transition zone between 0 and 4 mm into the repair concrete. Behind this peak the chloride level scatters between 1.0 and 2.5 wt %. 23 mm into the repair concrete the chloride concentration is 2.0 wt % per cement weight. See figure 3.	53R field had carbonated cement paste to about a depth of 1 mm, into the substrate concrete near the transition zone. The repair concrete had less than 0.3 mm carbonated cement paste from the transition zone.	Corrosion on both sides of the transition zone. The corrosion in the substrate concrete was partial in the first 20 mm and thereafter the whole reinforcement surface was corroded across the specimen part. In the repair concrete the embedded reinforcement was partially corroded from the transition zone and to about 30 mm. See figure 11.
63R field Substrate w/c = 0.40 Cl = 4.0 wt % Repair w/c = 0.55	The chloride concentration is relatively low, about 0.5 wt %, for the first 2 mm into the substrate concrete. Behind 2 mm and 20 mm into the substrate concrete chloride levels are between 2 and 3 wt %. The chloride density in the repair concrete is about 0.5 – 1 wt % for the first 7 mm from the transition zone. From 7 to 13 mm the chloride concentration increases	63R field had carbonated cement paste to about a depth of 2 mm, into the substrate concrete near the transition zone.	Near the transition zone of, the steel embedded in the repair material was corroded. The corrosion ended 35 mm into the repair material and sharply at the transition zone. In the substrate concrete there was a corroded area from 35 mm into the substrate concrete and along the whole reinforcement in the substrate

|			
	up to about 2 %. Deeper than 13 mm into the repair concrete a large aggregate particle interfered and it was not possible to continue the profile. See figure 4.	The repair concrete had less than 0.3 mm carbonated cement paste from the transition zone.	concrete. See figure 12.
33R 80RH Substrate w/c = 0.70 Cl = 1.0 wt % Repair w/c= 0.55	In the first 2 mm into the substrate concrete the chloride content is about 0.5 wt %. Between 3 and 12 mm the content of chlorides rises to 1 wt % and deeper than 12 mm into the substrate concrete the chloride content reaches a background value near 0.5 wt %. In the repair concrete the chloride level is 1 wt % from the transition zone and into 15 mm distance. See figure 5.	The substrate concrete was carbonated 20 mm. The entire repair concrete was carbonated.	Partly corrosion in the whole substrate concrete. From the TZ and 25 mm into the repair concrete the whole reinforcement was corroded. From 25 mm to 35 mm into the repair concrete there was no corrosion at all. Between 35 mm and 60 mm there was another area with corroded steel. See figure 13
43R 80RH Substrate w/c = 0.55 Cl = 1.0 wt % Repair w/c= 0.45	The chloride concentration in the transition zone is 0.1 wt % 1 mm into both the substrate and the repair concrete. The chloride content increases up to 3.5 – 4 wt % at 10- 17 mm distance into the substrate concrete. In the repair concrete the level of chlorides between the transition zone and 15 mm distance is between 0 and 0.5 wt %. See figure 6.	5-10 mm distance from the transition zone was carbonated in the substrate concrete. 2 mm into the repair concrete was carbonated	Corrosion on both sides of the transition zone. In the repair concrete the corrosion ends 10 mm into the material. In the substrate concrete there was partial corrosion about 60 mm into the concrete. See figure 14.
53R 80RH Substrate w/c =0.70 Cl = 4.0 wt % Repair w/c= 0.60	In the substrate concrete between 0 and 5 mm distance from the transition zone the chloride concentration is from 0.5 to about 1 wt %. Behind 5 mm the profile rise all the way to 25 mm where the chloride concentration is almost 8 wt %. In the repair concrete the chloride content scatters between 3 and 6 wt %. See figure 7.	The substrate concrete and the repair concrete was carbonated 15-20 mm distance from the transition zone.	Massive corrosion along the whole reinforcement both in the substrate concrete and repair concrete. See figure 15.
63R 80RH Substrate w/c = 0.45 Cl = 4.0 wt % Repair w/c= 0.50	63R 80RH has chloride content lower than 1 wt % in the first 3 mm into the substrate concrete. In the repair concrete the highest concentrat are found near the transition zone, 5.5 wt %. Deeper into the repair concrete the chloride contents decrease to 3.5 wt % at 25 mm. See figure 8.	5-10 mm distance from the transition zone was carbonated. 2 mm from the transition zone was carbonated into the repair concrete.	Corrosion in the transition zone and the main part of this corroded zone was 10 mm into the repair concrete. No further corrosion was observed in the repair concrete. In the substrate concrete there was an uncorroded area between 10 and 20 mm distance from the transition zone. The reinforcement is totally corroded from 20 mm distance from the transition zone and all through the substrate concrete. See figure 16.
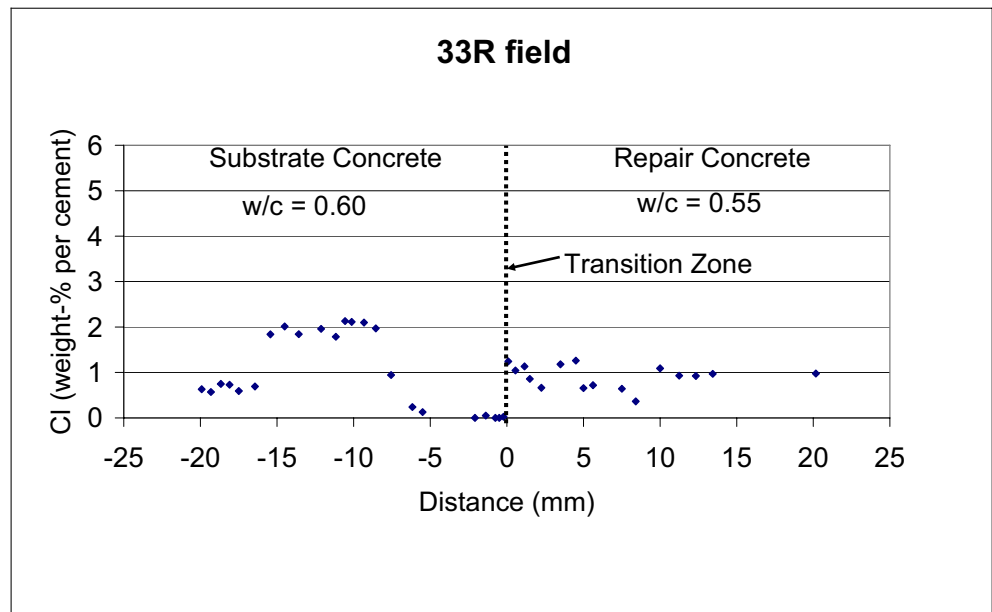
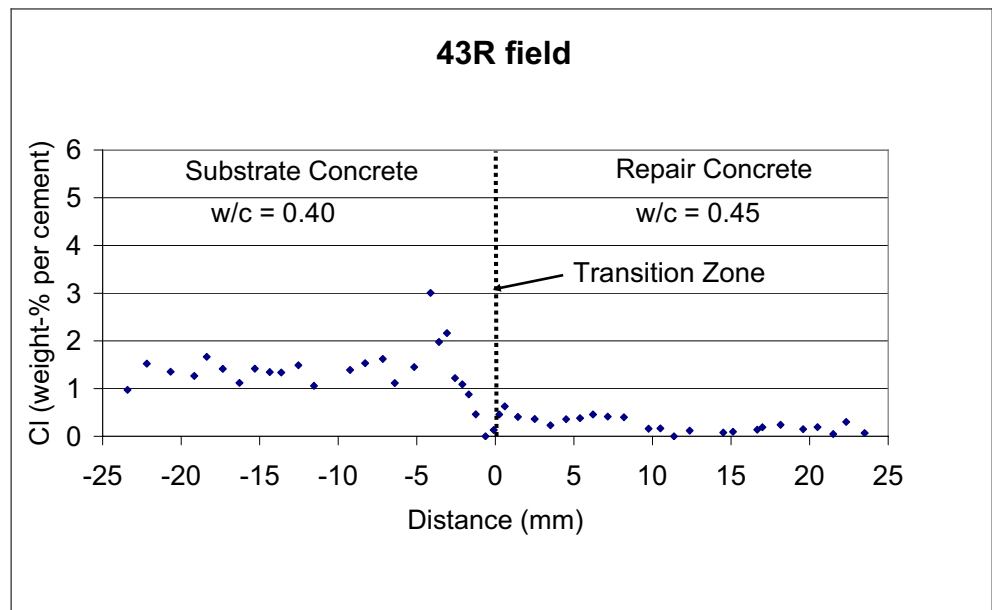Figure 1. Chloride profile across the transition zone in 33R field, SEM-EDS-analysis.

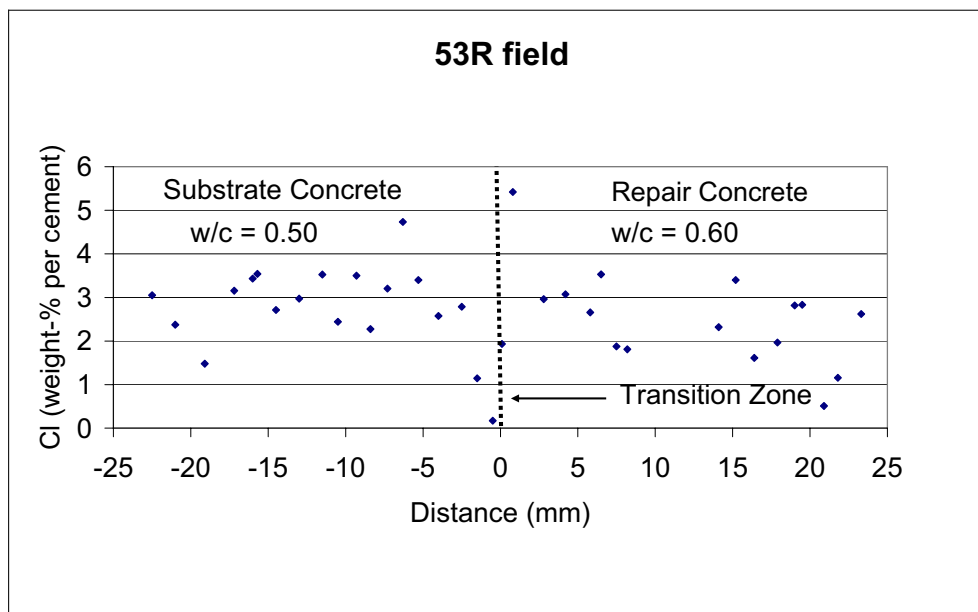Figure 2. Chloride profile across the transition zone in 43R field, SEM-EDS-analysis.

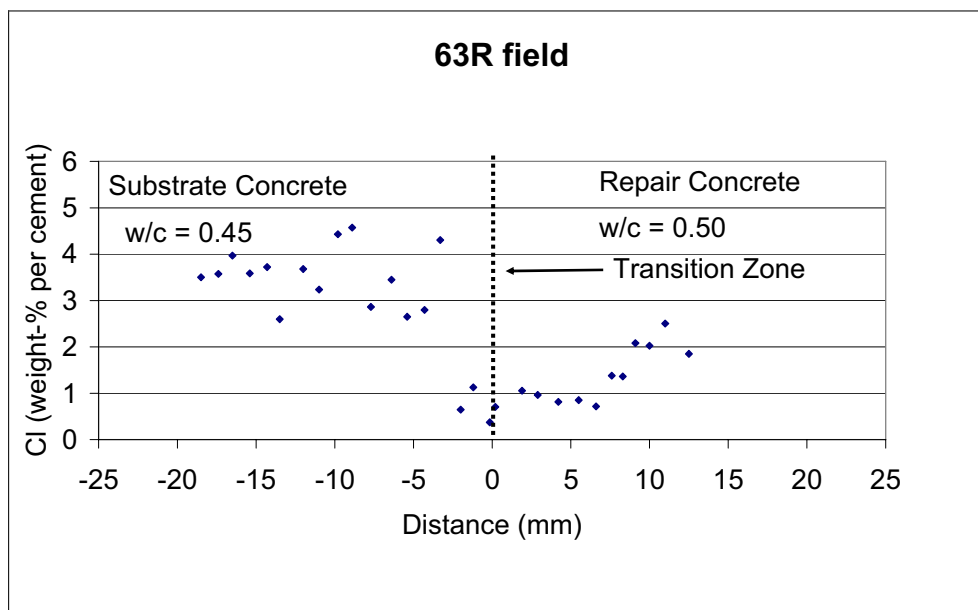Figure 3. Chloride profile across the transition zone in 53R field, SEM-EDS-analysis.

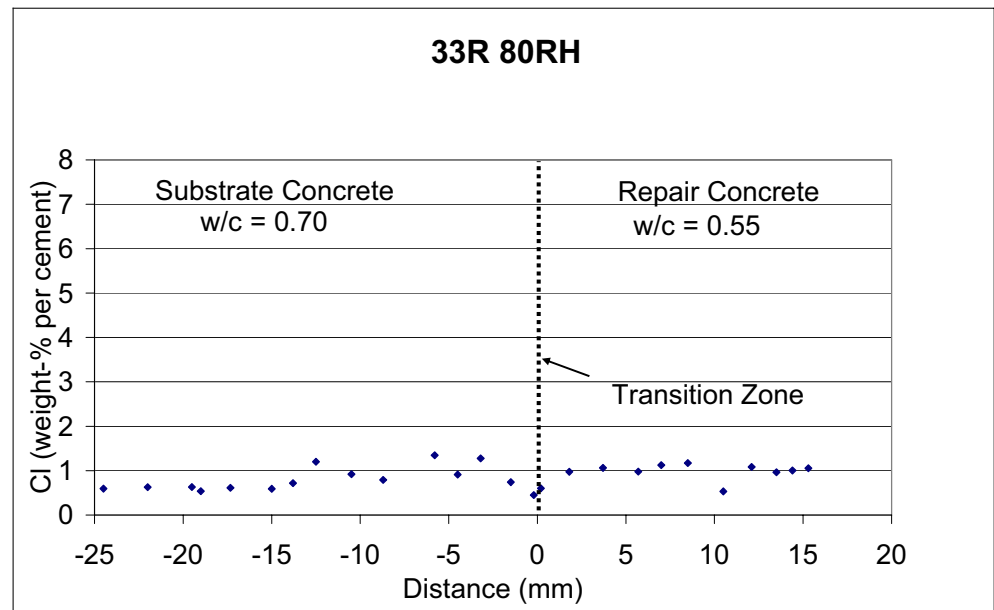Figure 4. Chloride profile across the transition zone in 63R field, SEM-EDS-analysis.

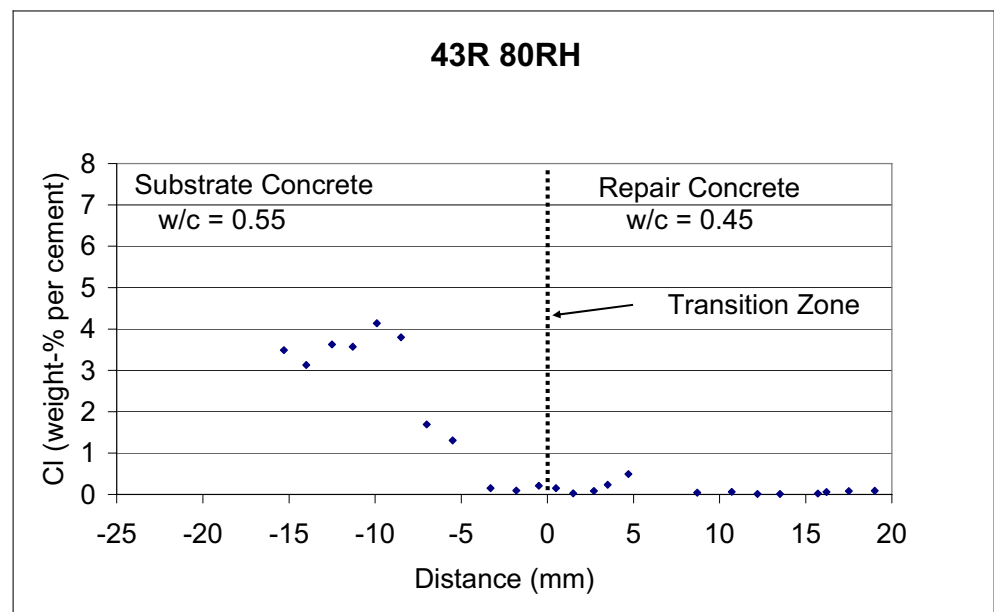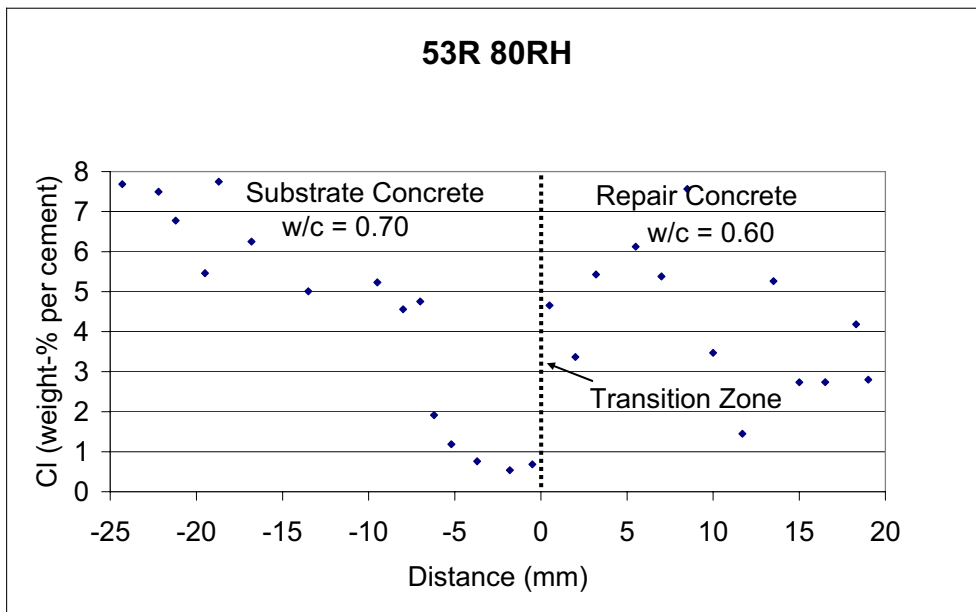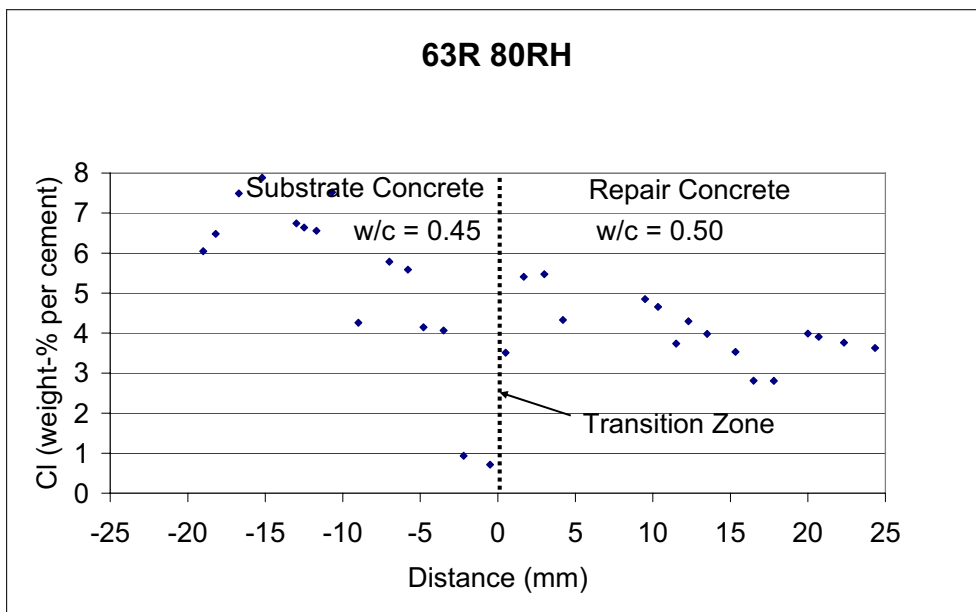Figure 5. Chloride profile across the transition zone in 33R 80 % RH, SEM-EDS-analysis.

Figure 6. Chloride profile across the transition zone in 43R 80 % RH, EDS-analysis.

Figure 7. Chloride profile across the transition zone in 53R 80 % RH, EDS-analysis.

Figure 8. Chloride profile across the transition zone in 63R 80 % RH, EDS-analysis.

Table 2. Carbonation depths in the transition zone.

Specimen	Substrate concrete Carbonation (mm)	Repair concrete Carbonation (mm)
33R field	2.3	0.1-0.2
43R field	1.6	0-0.2
53R field	2	0.1
63R field	1	0.1
33R 80RH	20	Entire depth
43R 80RH	5-10	2
53R 80RH	15-20	15-20
63R 80RH	5	2

Substrate Concrete   **TZ**   **Repair Concrete**

Figure 9. Steel in 33R field

Substrate Concrete   **TZ**   **Repair Concrete**
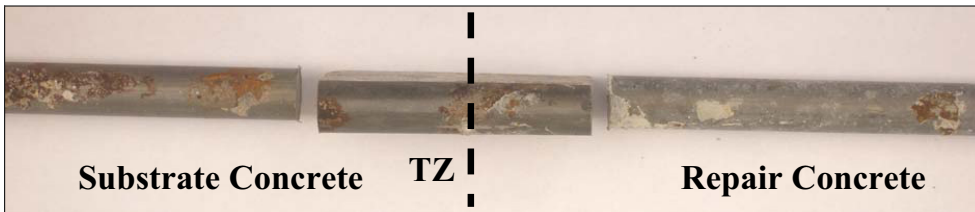
Figure 10. Steel in 43R field.

Substrate Concrete   **TZ**   **Repair Concrete**
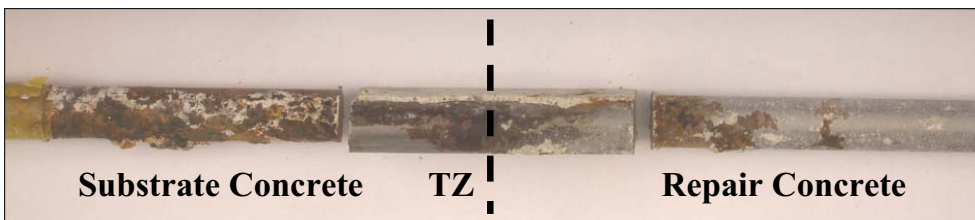
Figure 11. Steel in 53R field.

Substrate Concrete   **TZ**   **Repair Concrete**
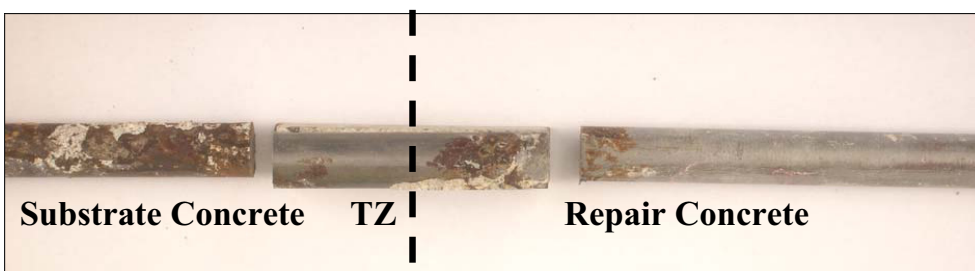
Figure 12. Steel in 63R field.

Figure 13. Steel in 33R 80RH
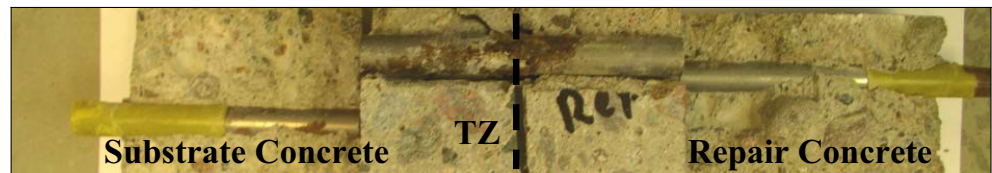
Figure 14. Steel in 43R 80RH.
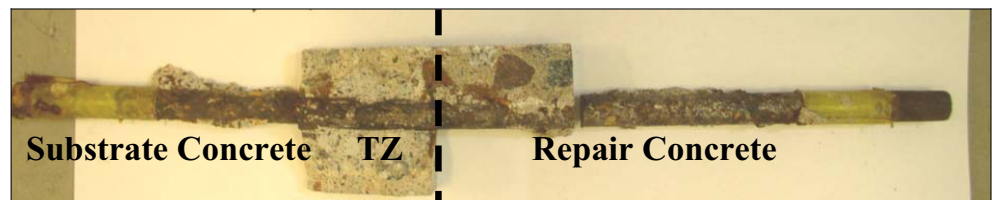
Figure 15. Steel in 53R 80RH.
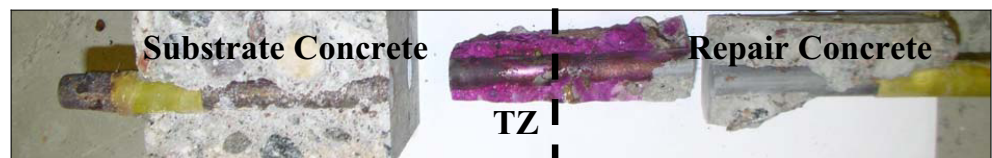
Figure 16. Steel in 63R 80RH.
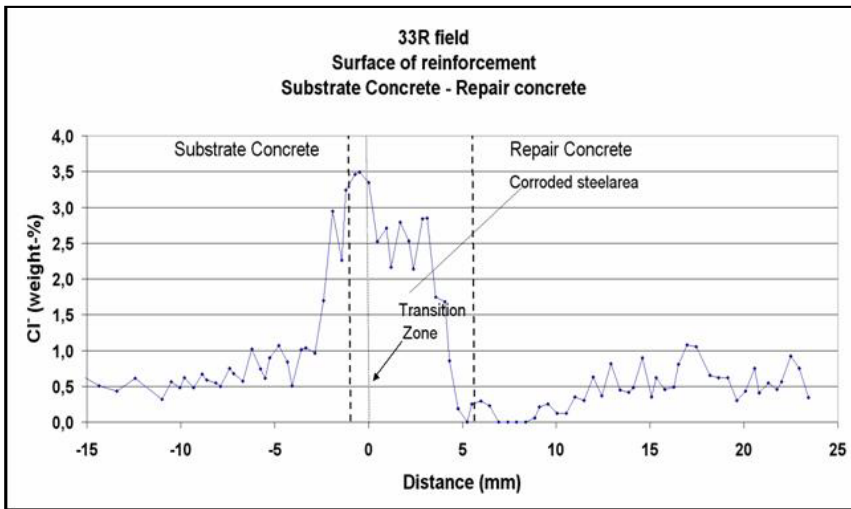
Figure 17. Chloride profile along the surface of reinforcement in 33R field, EDS-analysis.
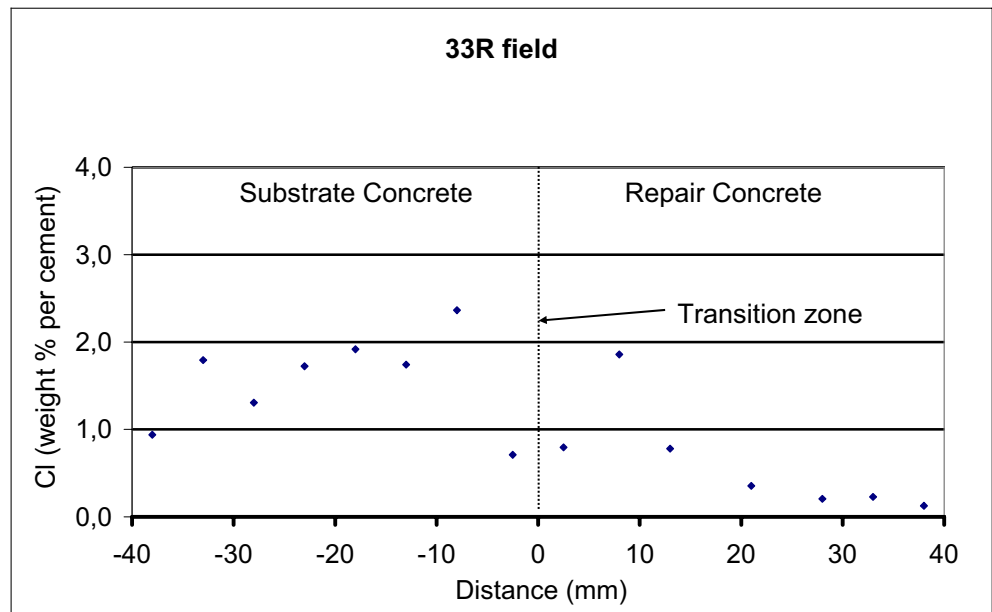
Figure 18. Chloride profile for 33R field analysed with an ion selective electrode method.
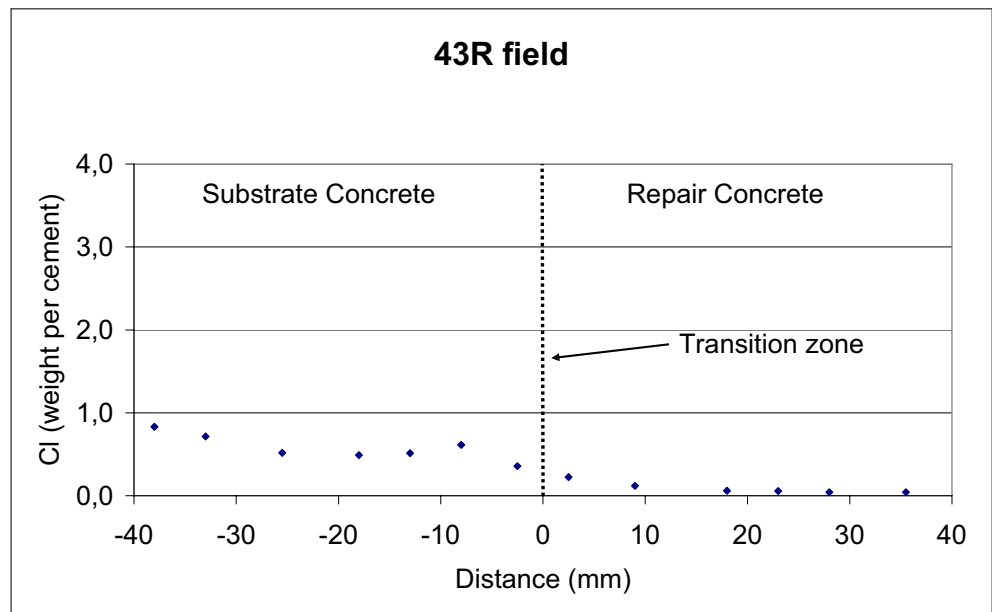
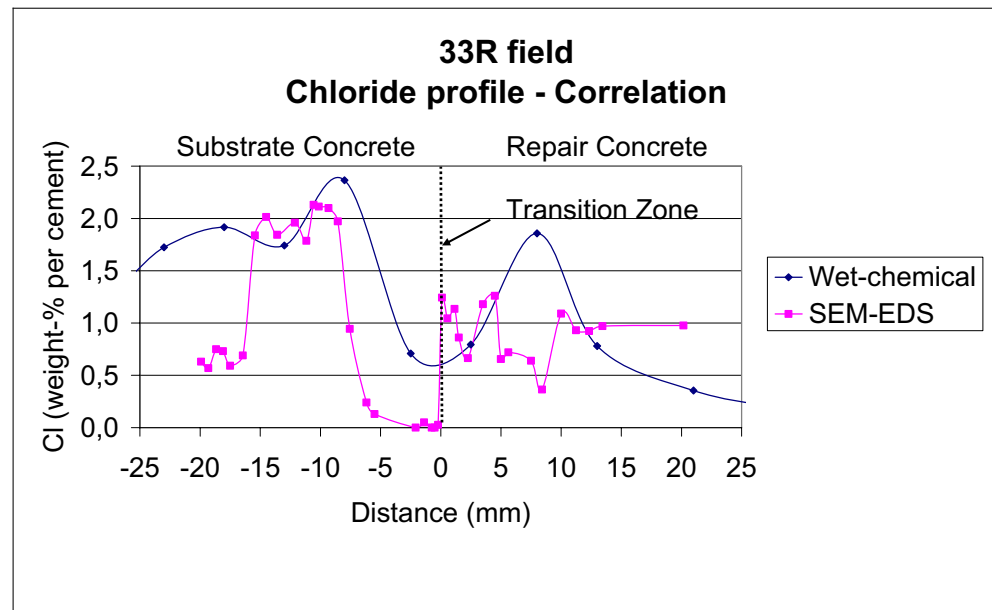Figure 19. Chloride profile for 43R field analysed with an ion selective electrode method.
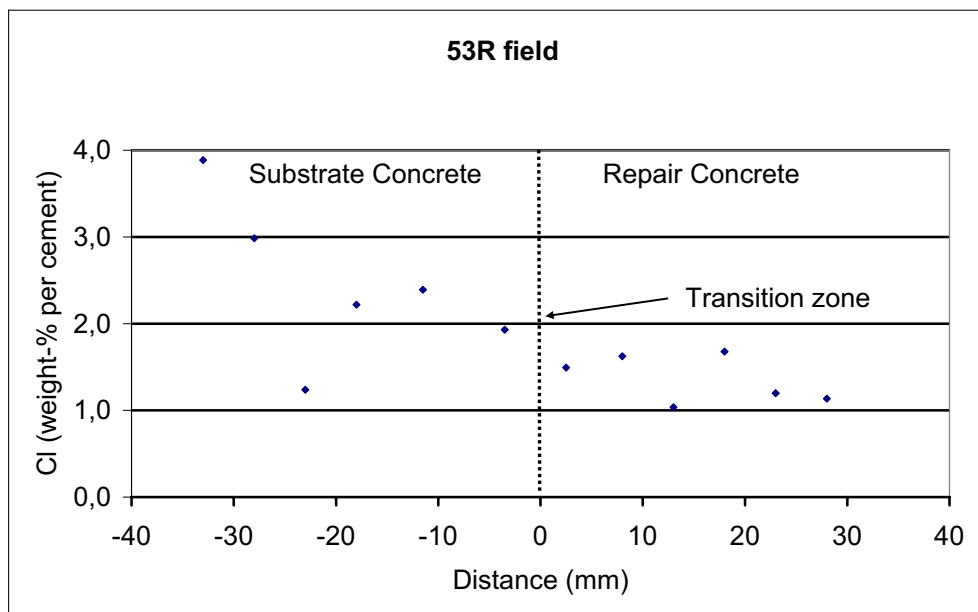
Figure 20. Chloride profile for 53R field analysed with an ion selective electrode method.
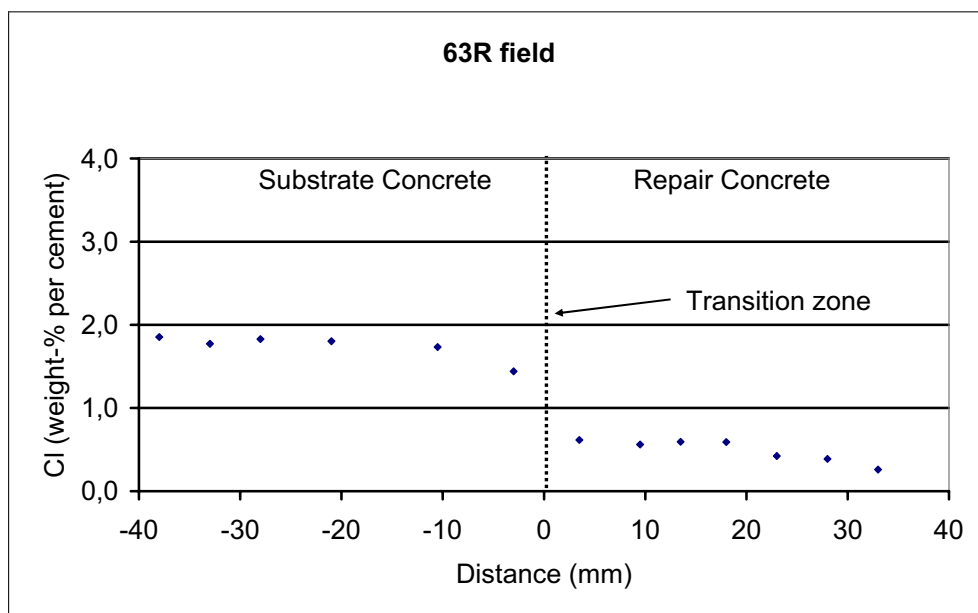
Figure 21. Chloride profile for 63R field analysed with an ion selective electrode method.

Figure 22. Chloride profile in 33R. Correlation between wet-chemical method with ion-selective electrode and SEM-EDS method.
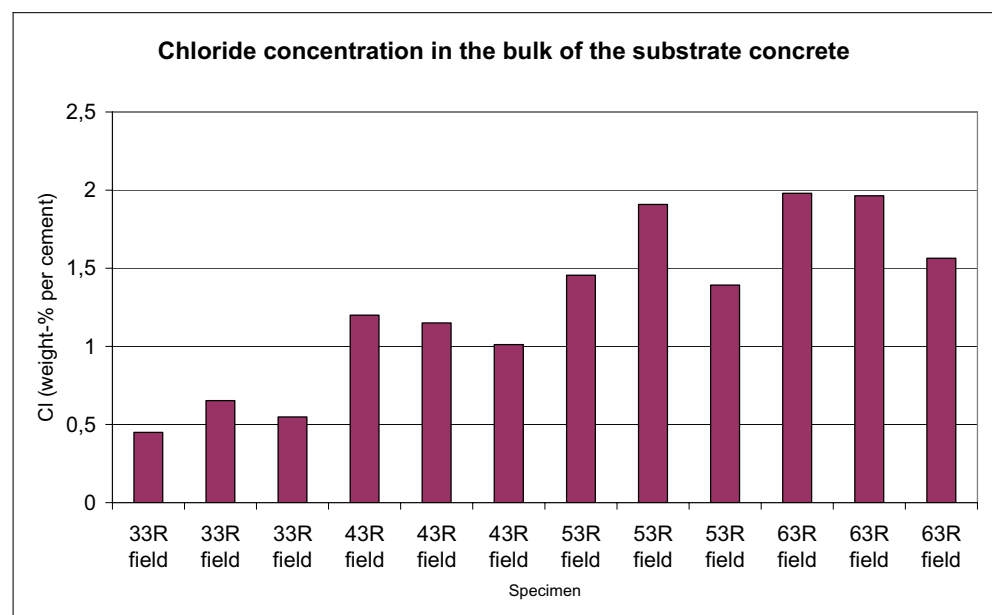
Figure 23. Chloride concentration in the bulk of the substrate concrete for 33R field – 63 R field analysed with ion selective electrode.
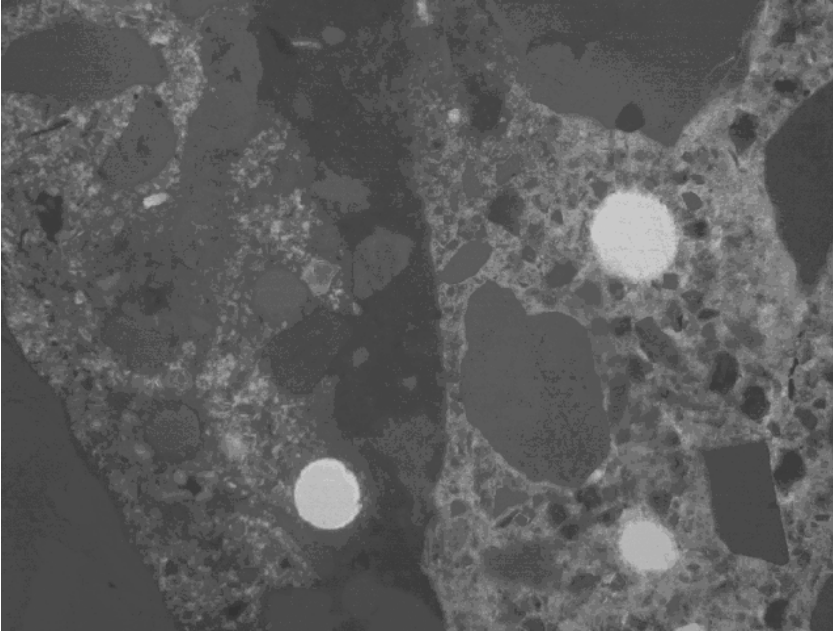
Figure 24. Thin-section of the transition zone between substrate concrete (left) and repair concrete (right). Specimen 33R field. Picture taken in fluorescent light. Total length of the picture is 10mm.
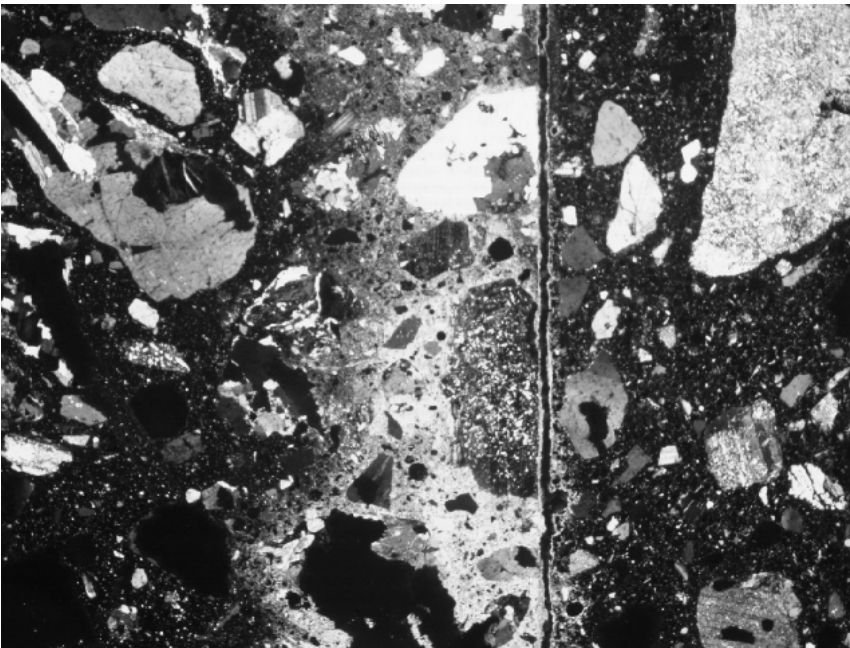

Figure 25. Carbonation from the transition zone and 2-2.5 mm into the substrate concrete (left), the lighter part. The repair concrete to the right is left uncarbonated, dark. Specimen 43R field in polarized light. Total length of the picture is 10mm.

Appendix 2 Field study

This appendix includes pictures for concrete samples and chloride profiles for the three different field structures investigated in the field study.
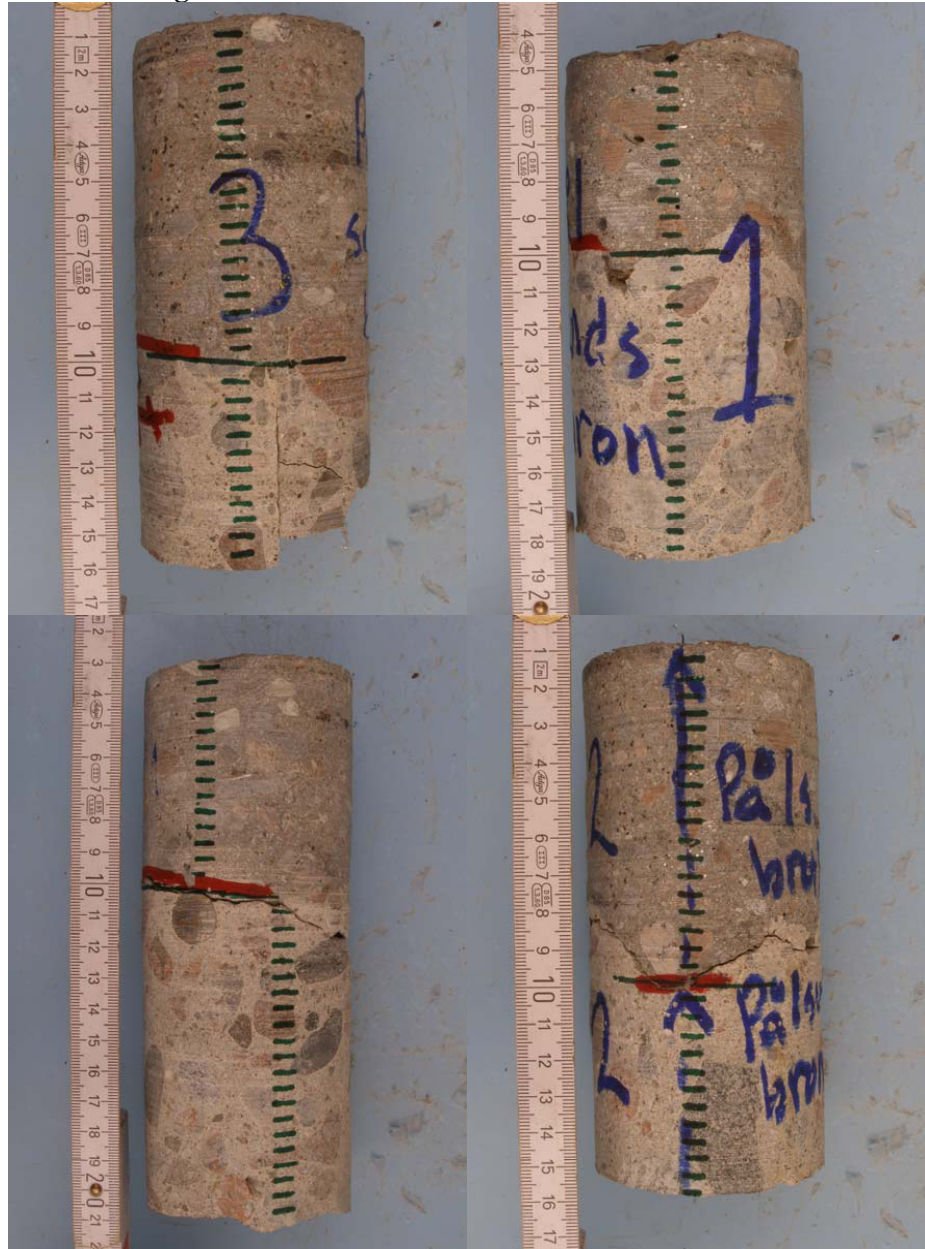
Figure 1. Concrete samples 1, 2, 3, and 4 from the *Pålsund* bridge. The marked levels are the intervals where material was cut out to analyse the chloride content. The darker part of the cores is the repair concrete.
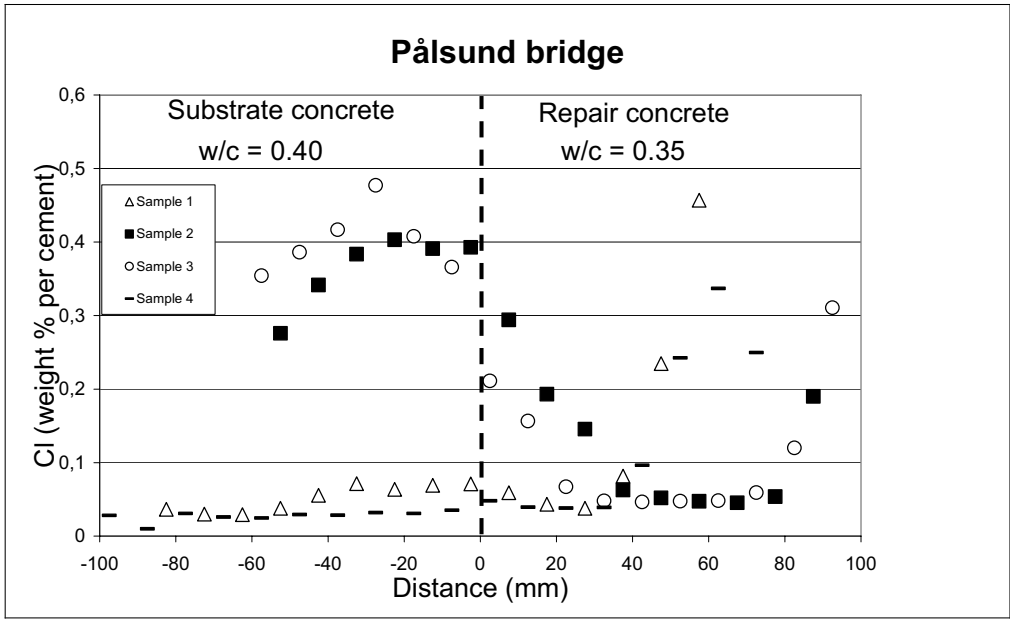
Figure 2. Chloride profile for samples 1-4.

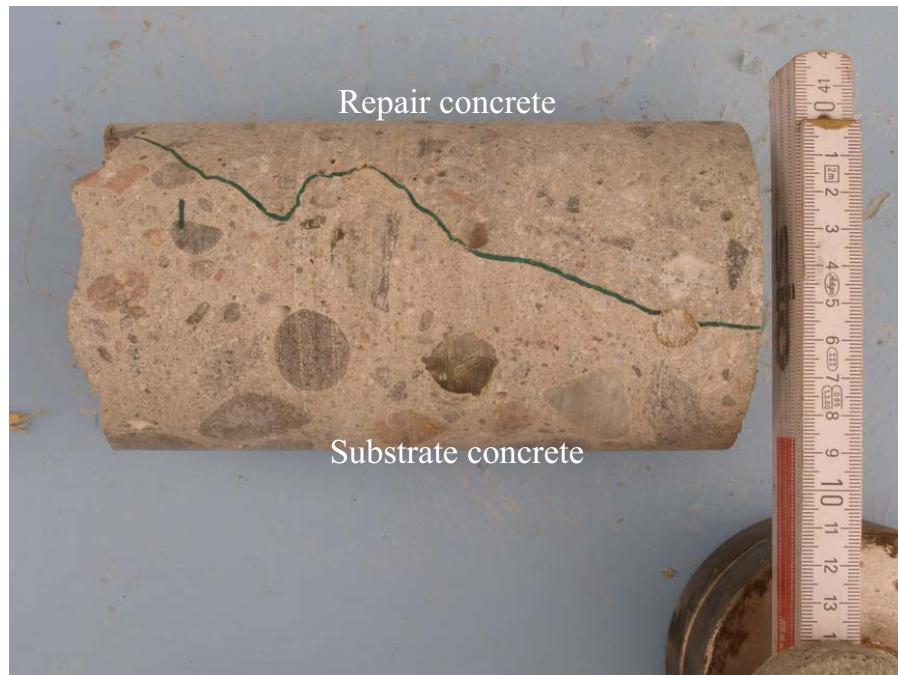**Stairs to pedestrian bridge at *Valhallavägen***

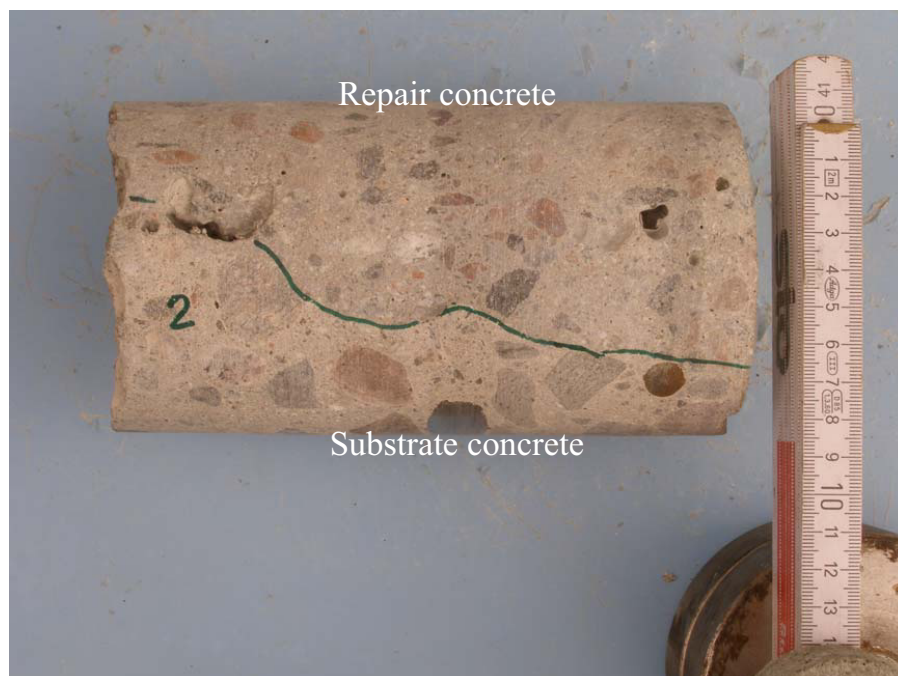Figure 3. Concrete sample 1 from the pedestrian stairs.

Figure 4. Concrete sample2 from the pedestrian stairs.

Figure 5. Repair concrete on the top and substrate concrete beneath.
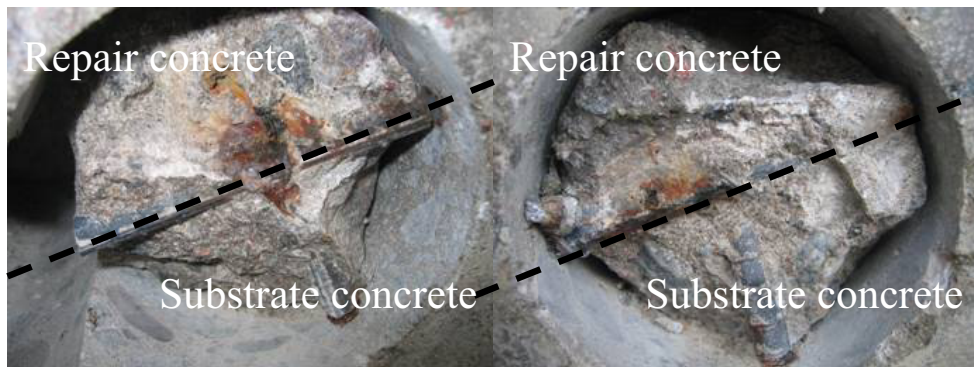Concrete cores 1 and 2 were drilled out.

Figure 6. Reinforcement corrosion in the transition zone in.
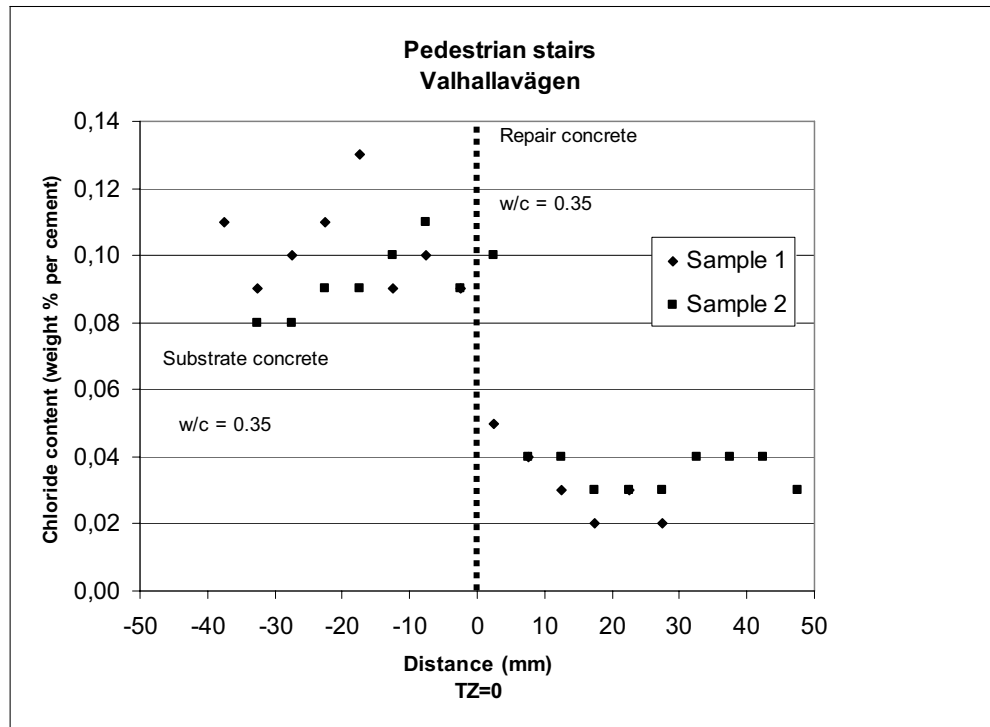
Figure 7. Chloride profile for samples 1-2

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Parking structure, *Plankan*

Cracks in repair concrete and in transition zone

Figure 8. Sample hole in a concrete repair. Note the horizontal cracks.
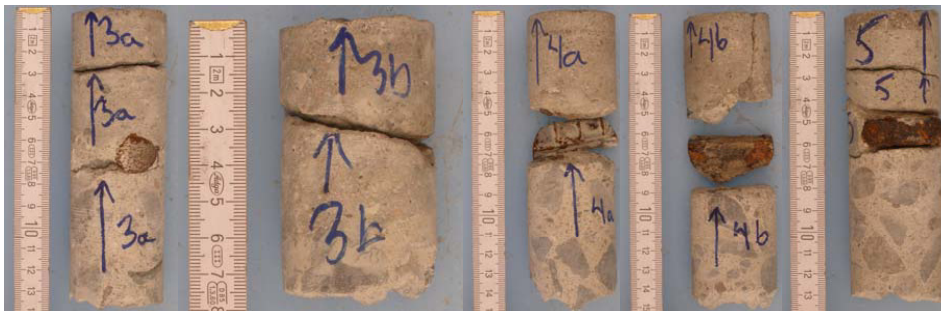

Figure 9. Concrete samples from patch repairs in parking structure *Plankan*. Corroded reinforcement in the transition zone.
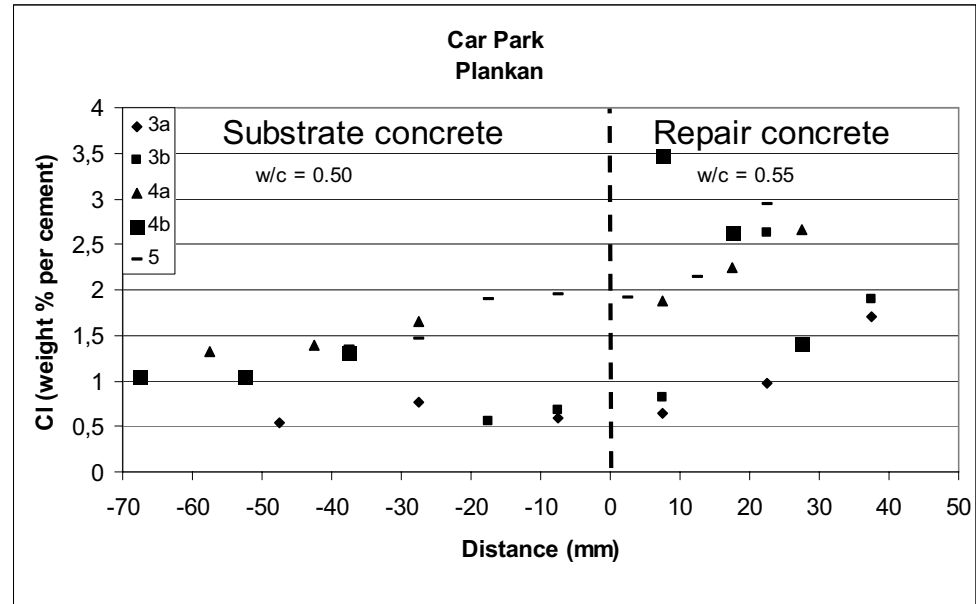
Figure 10. Chloride profile for samples 3a, 3b, 4a, 4b and 5.

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