DIVISION BUILT ENVIRONMENT

Continuous Preventive Bridge Maintenance

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Content

1 Sammanfattning

I Sverige, som i många andra länder, anses förebyggande underhåll av konstruktioner och broar vara viktigt. Det har flera fördelar som att förlänga livslängden eller bruksskedet, minska behovet av reparationer och förhoppningsvis minska kostnader och miljöpåverkan.

En stor del av Sveriges brobestånd börjar bli relativt gammalt. Det gör att förebyggande underhåll får mer uppmärksamhet och ges större vikt. Idén att mindre åtgärder kan förbättra och /eller förlänga standarden på bron och förskjuta behovet av reparationer eller förebygga skador med en minskning i livscykelkostnader är generellt i ägarens intresse. En typ av förebyggande underhåll är den årliga tvättningen av broar. Tydliga positiva effekter kan ses på fogar, dränering samt brons visuella intryck men en viktig fråga är hur tvättningen påverkar kloridinträngning från huvudsakligen tösalter i armerad betong. Hypotesen är att högtryckstvätt tar bort föroreningar på ytan, vilket på lång sikt minskar kloridmängden i betongen. Den praktiska erfarenheten ska ha varit positiv i Sverige, men ingen forskning har utförts på vilken effekt högtryckstvättning har på kloridinträngningen i en bro av betong.

En studie om det förebyggande brounderhållet hos Trafikverket och kommuner har utförts med hjälpa av Trafikverkets och föregångarna Vägverkets dokument, annan litteratur, en enkät till kommuner samt medverkan och observationer av det praktiska genom deltagande vid utförandeentreprenader årliga utförande av underhållet. Fält- och laboratorieprover för undersökning av tvättningens effekt på kloridinträngningen har utförts. En fältstation på en kantbalk på en bro har installerats och följts under tre års exponering, med vinterklimat, vinterunderhåll samt årlig tvättning i juni. En accelererad provmetod har utvecklats för att simulera den årliga exponeringen och undersöka effekterna av högtryckstvättning i en långtidssimulering på bara några veckor.

Ur praktisk synvinkel verkar brounderhåll vara ganska likt i Sverige och andra länder. Dock verkar beskrivningar och tillgängliga ekonomiska medel för underhåll och reparation visa större skillnader, vilket kan ha en stor påverkan på broarnas skadestatus. För fältstationen, är resultatet efter ett års exponering inte speciellt tydligt förutom den förväntade skillnaden mellan de två undersökta betongtyperna (en äldre och en modern, mer beständig kvalitet). För år två syns en mindre skillnad mellan tvättad och otvättade prover. Skillnaden kan inte observeras i resultaten för år tre. Orsaken till detta måste undersökas vidare. Detta görs genom de kontinuerliga provningarna.

Laboratorieexperimentmetoden har utvecklats och kontinuerligt förbättrats. Formen och nivån på kloridinträngningen kan anses rimliga och jämförbara (på formen) med fältprover. Dock finns det ett behov att undersöka påverkan av naturligt regn vilket kanske har samma eller större effekt på att späda ut kloridmängden som att högtryckstvätta ytorna en gång per år. Andra aspekter behöver också undersökas, till exempel när och hur ofta underhållet ska utföras. Ett första steg att mögligöra det har avslutats med utvecklingen av den accelererade provningsmetoden.

2 Summary

In Sweden, as in many other countries, preventive maintenance of structures and bridges are considered important. It gives several benefits such as prolonged life span or service life, less need for repair and hopefully reduced costs and less environmental impact.

A large part of Sweden's bridge stock is getting quite old. As preventive maintenance is getting more attention and is given more importance, the idea that small actions can improve and/or prolong the status of the bridge and postpone repair needs or prevent damages with a reduction in life cycle cost is generally in the owner's interest. One such preventive maintenance measure is the yearly washing of bridges. While clear positive effects on the expansion joints, drainage system and the bridge's visual appearance have been stated, an important question is how the washing effects the chloride ingress from mainly de-icing salts in reinforced concrete bridge members. The hypothesis is that the high-pressure washing cleans away the contaminants on the surface and in the long run reduces the chloride content. While the practical experience has been positive in Sweden, no research has previously been done concerning the effect of the high-pressure washing on the chloride ingress in a concrete bridge.

A study on the preventive bridge maintenance practice of the Swedish Transport Administration (STA) and Swedish municipalities by means of documentation, literature studies, survey with municipalities and practical participation with contractors during the yearly maintenance has been conducted. Field and laboratory tests on the washing effect on chloride ingress in two types of concrete have been caried out. A field station on an edge beam of a bridge has been installed and has been followed during three-year exposure with winter seasons, winter maintenance and yearly washing in June. An accelerated test method has been developed to simulate the yearly exposure and test the effect of high- pressure washing on a long-term simulation in just a few weeks.

The practical aspects of the bridge maintenance seem to be quite similar in Sweden and in other countries. However, descriptions and available means for maintenance and repairs seem to show larger differences. For the field station, the results after one year's exposure does not show anything more than the anticipated difference between the two investigated concrete types. For year two, a slight difference indicated that washed samples had a reduced chloride content. For year three, however, there was no distinct difference between washed and unwashed samples. The reason for this needs to be further investigated and examined. This will be done in the continuous tests.

The laboratory experiment method has been developed and successively improved. The shape and levels of chloride ingress are considerably reasonable and comparable (in shape) with field samples. However, there is a need to examine the effect of natural rain exposure that might have the same or larger effect on diluting the chloride content as washing the surface once a year. Other aspects also need to be considered, such as when and how often the maintenance is performed. A first step to be able to examine this has been completed through the developed accelerated test method.

3 Introduction

Sweden has over 30 000 bridges, where more than 60% of today's bridge stock was built before 1980's, and most, 85%, is made out of concrete. There is an interest of the Swedish Transport Administration (STA) and municipalities to increase the preventive maintenance and make it more effective to decrease the need for repair and prolong the lifespan of the bridges.

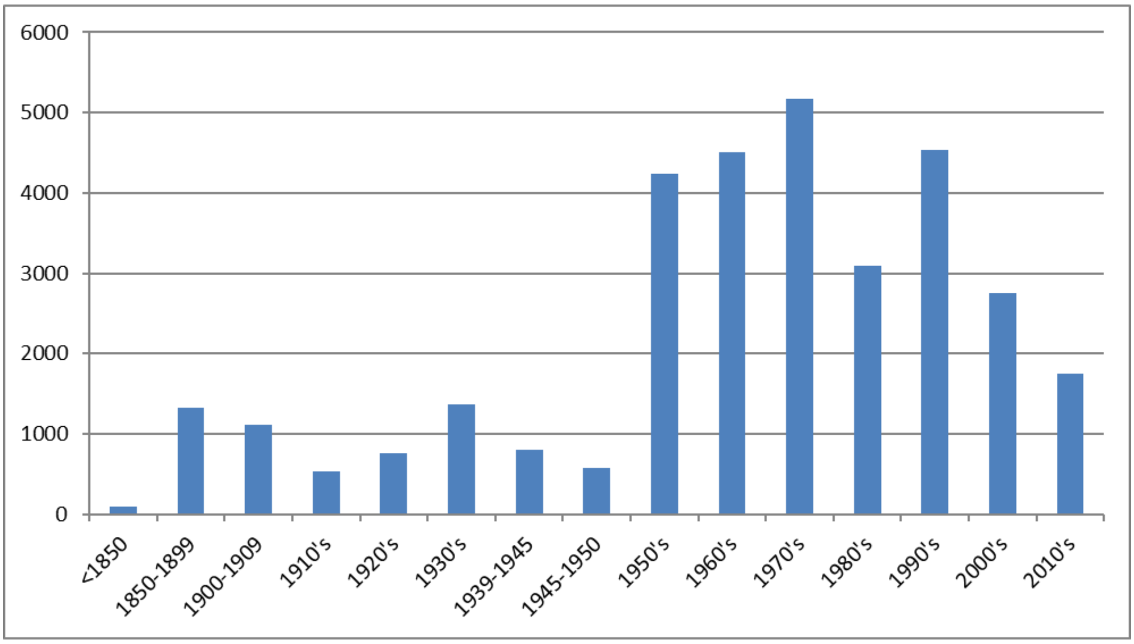

Figure 3-1 Year of construction for Sweden's bridges (BaTMan, 2018). Note: In the bridge database, there are large spikes for the years 1900 and 1950, this is due to bridges where the years is unknown and given a rough estimation. Small peaks are also seen 1960 and 1970.

3.1 Problem and purpose

One part of the preventive maintenance is the washing of bridges. While a clear positive effect of this can be seen for the drainage and the expansion joints the effect on chloride ingress in reinforced concrete members is mostly theoretical. To be able to increase the effectiveness of the washing, there is an initial need to understand how it effects the chloride ingress in the concrete. As this is a procedure done for the last 40 years, the long-term effect is what is most interesting as the hypothesis is that the washing reduces the level of chlorides on the surface, which in the long run reduces the chloride content in the concrete.

The problem to answer for the project is as follows:

- Does the yearly washing effect the chloride ingress?
- Can an accelerated method be developed?
- Is the timing of washing of importance?
- Is the number of washings of importance?
- How can the yearly continuous bridge maintenance effectiveness be increased?
- Effectiveness of washing in comparison to rain?

The first two questions are to be examined in the first part of the project, by field and development of lab experiments, and when an accelerated method is fully developed, further examinations can be carried out regarding the later problems stated above.

3.2 Hypothesis

The main hypothesis to be tested is the following:

High-pressure washing increases the lifespan of concrete by reducing the chloride ingress

3.3 Limitations/restrictions

Limitations in the project have been done. The project has been limited to examine the high-pressure washing of concrete, focusing on its effect on chloride ingress in concrete. Examination of other types of preventive maintenance and other parts of the yearly maintenance have been limited to literature studies. The effect of the high-pressure washing on other construction materials than concrete has not been examined except for literature and minor tests. In this part the effect of dirt and other deterioration mechanisms are not examined in detail as the effects can be seen in other research. Initially there was a wish to also include the washing in tunnels but as the issue with finding a possible field station fitting with set requirements and following safety requirements has been an issue, the focus is therefore on the field station on a bridge. The effect of washing on chloride ingress in concrete has been studied both in the field and in the laboratory. The concrete qualities are limited to two types, one representing concrete from the 1960's and one from today. Fields test observations are limited to three years.

3.4 Structure of thesis

The structure of the thesis is as follows:

- *Introduction* is about the basic fact about Sweden's bridge stock, with the studied problems, and the hypothesis as well as the limitations and restrictions of the project.
- *Background* about preventive maintenance. Shortly describing different types of preventive maintenance measures and then describing the continuous preventive maintenance.
- *Methods* consist of literature study, field visits, survey with municipalities, a field station and development of an accelerated laboratory method.
- *Results* from the field observations, survey, field and laboratory samples.
- *Discussion* of results from the survey, fields station and laboratory accelerated experiments.
- *Conclusions* of the results and discussion and *further research.*

4 Background

4.1 Preventive maintenance of concrete structures

Here a distinction is made between preventive maintenance and continuous preventive maintenance. The preventive maintenance deals with single measures that are performed on an irregular basis whereas continuous preventive maintenance is measures conducted every year, i.e., continuously.

4.2 Different types of preventive maintenance

In practice preventive maintenance can mean many different things. It can be small and faster repairs and removal of deteriorating causes as fast as possible. It can be impregnation and painting/coating. It can be installing sensors, corrosion protection etc during construction or repairs. All have the same purpose, to maintain the structure's conditions for a prolonged period of time. Here just a few of the most common or known measures that are considered as preventive maintenance are summarized.

4.2.1 Impregnation

Impregnation generally refers to hydrophobic impregnation to reduce the moisture ingress and the deterioration mechanism where water is needed in the reaction. The principle of impregnation and its influence on the contact angle is shown in Figure 4-1. One major factor is the chloride ingress, which with impregnation can be delayed and reduce the risk of reinforcement corrosion. It is commonly prescribed for vulnerable structural parts made of concrete in road environment such as edge breams. The experience has been good if a proper impregnation depth and effect can be achieved [1]. While its long-lasting effect is still being studied positive effects have been seen even after 10 years [2] in some studies. Most owners stipulate re-applying hydrophobic impregnation usually every 5-10 years. Without destructive testing there is no way to know if the application has worked and/or the required impregnation depth has been reached. In field applications, the impregnation efficiency might also be uneven for a large application area. The re-application every few years is considered to be more timewise and economically a better option.

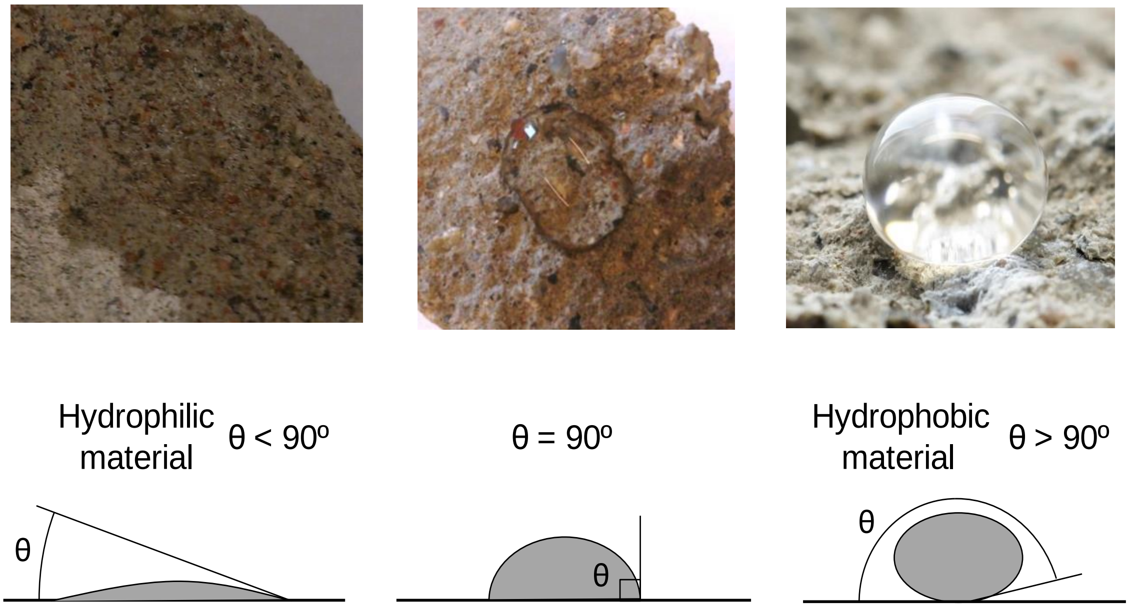

Figure 4-1 Schematic description of hydrophobic impregnation (Selander et al 2014 [3])

4.2.2 Cathodic protection

Cathodic protection is a preventive action to protect the reinforcement from corrosion and/or reduce its progress and effect. The two types are sacrificial anodes and impressed current[4]. The first one is mainly used in new construction or larger repairs to prevent corrosion to occur by the electric current between the electrodes (anodes) placed in the concrete and the rebars (making it cathodic). Since the anode is active and takes the risk of corrosion, the rebars stay intact. The second type is generally used on existing structures where the electrodes are placed on the outside of the structure and with a continuous supply of current making the chloride move to the electrodes (anode) making the reinforcement thereby cathodic and reduce the risk of corrosion.

4.2.3 Crack repair

Another preventive maintenance is the sealing of cracks. This is to reduce the deterioration processes that accelerate when cracks are open, such as ingress of moisture, chlorides or other harmful substances causing frost damages and reinforcement corrosion[5]. Cracks in need of repair are usually found during inspection and planned for the next following years as part of the integrated maintenance, see 4.3.2.

4.2.4 Patch repair

Patch repair is a part of the pre-determined maintenance suitable for minor issues. Local areas of damaged concrete are removed and replaced by new concrete, usually special repair products are used.

4.3 The continuous preventive maintenance

The continuous preventive maintenance is in this project defined as the maintenance performed each year with the purpose to remove and/or reduce the deteriorating mechanisms and substances that can result in damages to the structure in the long term.

Examples are debris, de-icing salts and vegetation, that if not removed can deteriorate the structure and its materials. Washing of bridges are performed with high-pressure wash. The literature on the effect of high-pressure washing is severely lacking, most is based on practical experience. In Sweden there have been documentation that are based more on practical experience than research. These experiences however, span several decades. The experience shall have been positive for the effect of the maintenance in comparison to doing nothing. The exact types of positive experiences or in what degree is, however, unclear.

4.3.1 Documents of the STA and its predecessors

The Swedish Transport Administration, STA, owns the majority of Sweden's bridges[6] and is the lead influencer and recommendation developer regarding bridge maintenance in Sweden. Other owners include municipalities and other private or state owners. All have a keen interest in reducing the need for repair and extending the life span of their bridge, preferably with reduced cost and environmental impact.

4.3.1.1 Old versions of predecessors

STA's predecessors have since at least 1969 published various documents on preventive maintenance where the cleaning of structures is described. The fundamental idea, that structures should be clean from vegetation and contaminations that have a deteriorating effect, has existed for a long time. In the state's requirement documents, the procedure of cleaning concerns its own bridges but these documents are also leading in the maintenance of other bridges in Sweden. Other owners use or are inspired by the requirement document, current or older versions.

In 1969, [7] the official document stipulating the maintenance of structures as follows: ”*all surfaces of structures are to be kept free of vegetation and contaminants, including gravel on the bridge pavement as well as on edge beams, bearing pallets, the upper pillar surface and steel structures”*. The idea with this type of maintenance came to be quite constant even until today. The formulations and descriptions have varied but the idea of keeping the structures free from vegetation and contaminants has been there for a long time.

In 1979 [8] there was the ad-on that the washing should be performed after the de-icing period had finished. The cleaning of drainage regularly came in 1988 version [9]. The importance of removing fine materials and moss on the horizontal surfaces because of their ability to contain moisture was pointed out here but can not be seen in later versions. A prompt of using surface treatment to protect against salt ingress came also in the 1988 version, with treatment every 5 years. Cathodic protection was also included for the first time.

In 1994 [10], the maintenance is divided into preventive maintenance and repairs. The preventive maintenance is then further divided into measures suitable for concrete and steel structures. Measures for the concrete include surface treatment for chloride ingress and carbonation, and that if there is cathodic protection it should be maintained and continuously measured. For steel structures, there is only protective painting as a preventive measure. For the substructure, vegetation is to be removed if it is considered to have an effect. The document is more detailed in reimbursement/compensation and supervision than in the description preventive measures.

In 1998's "Preventive maintenance" [11], the demand about cleanliness is reintroduced. The document is a complement to the one from 1994. The technical demands are divided for each structural part, but not complete since some had no demands. The parts that had no demands were the substructure and the insulation. It is in this document that the demand of "*95% clean of visible contaminants*" first appears, and that surfaces should be completely free of vegetation or only have a certain height. Concerning the cleanliness for contaminants, the demand should only be valid if it is in the technical description. For the edge beam as a separate structural part, the demands were only in regard to railing attachment. For the drainage system the demand was of a flow-through area of > 80%. For the 95% cleanliness, the demand should be valid from two months after the end of winter maintenance stopped until the start of the winter maintenance. The demand of the time could be changed in the technical description. Here, there was also a definition of preventive maintenance: "*preventive maintenance is the measures taken to maintain the structure's function and/or capital value*".

Bridge maintenance 2002 [12] has many more sub-sections for structural parts. The demands are either measures or characteristic properties. This document replaced the versions of 1994 and 1998. The demand should have been verified at least once a year. Here, it is stated explicitly on several places that "*concrete surfaces in road environment should be impregnated*". "*Protection against carbonation occurs by replacement or completion of concrete cover*", was another occurring phrase. The regulations regarding vegetation in substructure were increased. The replacements Bridge Maintenance 2006 [13] and 2009 [14] are pretty much the same as 2002's version for this type of maintenance. The last of Vägverket's (Swedish Road Administration: predecessor to STA) publications, version 2010 [15] is comparably thin. The structure of the text has changed. The maintenance is divided in two sections, remedial and preventive maintenance. Here, the terms contractor and owner choices are mentioned. The demands themselves are the same.

Silfwerbrand [16, 17] has done several reviews about the shortcomings of these requirements. Including openness to interpretation of the quantification of requirement and the validation of performed maintenance, as well as the time when requirement should be fulfilled. The different of requirement and description for different members seems to be more based on accessibility than need or risk of the member.

4.3.1.2 Present versions

In 2010, the administrations for roads (Vägverket) and railroads (Banverket) were combined and created one institution, STA (Trafikverket). Until now there have been four different versions of the STA documents. First version 2013, 2nd 2015, 3rd 2017 and 4th 2019. Today there are two separate documents: demands [18-21] and advices [22-25]. In the documents, the two types of maintenance have changed name to condition based and pre-determined maintenance. Washing and cleaning are in the pre-determined maintenance. Several other factors have been included, for example administration and paragraphs concerning the contractors. The structures have also been divided in different groups depending on complexity.

In the present document, and its predecessors, the demand for "*95% clean*" has been replaced by "*to be cleaned from contaminants*" and "*the cleaning is performed by high-pressure washing with water at a working pressure of 160-200 Bar*". The distance to the structural part is also specified to 15-25 cm. It should have been used in practice before the demand was written down, by the suggestion from the contractor. Control is described as either measurements or by visual inspection. Drainage systems shall now have the flow-through area of 100%. The cleaning is to be performed at the same time as the other washing.

The difference between the first and second version is that the first version specified the water temperature and the second the distance between nozzle and surface. There are very small differences between the second, third and fourth versions, only an ad-on about cleaning the road surface close to the edge beam, and substructure. It is worth noting that previously the maintenance was primary performed by the in-house personnel. Today it is done by contractors, with few exceptions after outsourcing begun in the 1990's. That has motivated the change to so called performance-based requirements in the documents.

The demands are used as base for contract with the version valid at the time of writing/signing. Since the contracts are valid for a few years it is interesting to study earlier versions. For municipalities, they might use or base their demands on even older versions of the demands for their own contracts and/or requirements.

A tender document [26] for the region of Jönköping has been studied as an example on how the technical demands for the pre-determined maintenance could look like. The tender document is based on version 1. Overall, it doesn't add any demands but the demands are more descriptive concerning how and when the maintenance should be performed and checked, as well as what is paid for by whom. Some factors concern all the bridges, like checklist for verification, washing is not to occur when there is risk of freezing etc. The deviation from version 1 is that the water is allowed to be cold, if nothing else is stated. In version 2 this is directly in the demand document. Depending on which classification a bridge is placed in, the measures shall be performed in different time spans. Overall, the measures shall occur from late spring until sometime during the summer or early autumn. Structures with higher classification/traffic shall generally be treated earlier than those with lower classification.

4.3.2 Integrated bridge maintenance

The STA uses something called "integrated bridge maintenance" [26, 27]. It is simplified a way to improve the efficiency of bridge maintenance by having contractors working in pre-determined geographical areas as to conduct maintenance for bridges in geographical closeness to one-another to increase time efficiency and reduce costs. The integrated bridge maintenance contract also includes minor repairs on selected bridges during the contract period. This is done for both types of maintenance, conditioned and pre-determined. The purpose is to make maintenance more effective and the experience has been positive from both sides.

4.3.3 Other countries

The US's *The Bridge Preservation Guide* [28]put washing under Preventive Maintenance & Cyclical Maintenance Activities and states the following: "*Bridge cleaning and/or washing; Cleaning of decks, joints, drains, superstructure, and substructure elements slows the deterioration of concrete and steel elements that would* *otherwise be accelerated by debris, bird droppings and contaminants*". It is suggested to wash every 1-2 years.

For states starting with the maintenance they suggest the following: "*Start a bridge cleaning program using basic tools that most agencies have readily available such as brooms and shovels, to remove accumulated debris and road grit. Afterward, hoses and pressure washed can dilute deicing chemicals from concrete and remove any remaining debris and road grit not removed from sweeping*".

The actual bridge maintenance seems to differ depending on the state, as each state has a separate Department of Transportation running independently. A survey by the Minnesota Department of Transportation [29]with its examination of 18 stated shows some of it. Less than ¾ of the correspondents used washing on their bridges. The states seemed to have different levels of means to perform the maintenance also. The consensus is that the preventive actions have positive effects. While none can say direct effects, the need for repair seems to diminish. Furthermore, less reported issues during inspections can be seen as an indirect effect. A technical report on bridge joints by the Massachusetts Department of Transportation [30], hinted/drew the same conclusion that regular maintenance reduced problems/damages and decreased the need for repairs and/or prolonged the need for replacement of expansion joints. Some of the states in the surveys talk about the great effect the financial restraints are having on the maintenance and thereby the standard and condition of the bridges.

A simple examination of the STA's equivalence in Finland, Liikennevirasto (LV), showed that the performance for this type of maintenance is similar to Sweden's [31, 32] They also use contractors and a similar structure of integrated maintenance, with geographically divided areas where the maintenance is contracted for about 5 years.

Comparing with the STA, LV is responsible for fewer bridges. In Finland's bridge registry, there is less than 21 000 bridges, but since it is voluntary to use the register for the municipalities and private owners, exact numbers are unknown. The most common issue in Finland is concrete weathering on the edge beam and problems with waterproofing layers. Also, the drainage and joints shall be a recurring problem.

The focus on the demands are on the road slabs, edge beams, transition structures and drainage systems, where the cleaning is thoroughly described while others are briefly mentioned, excluding bearings. Once a year the joints and drainage pipes shall be cleaned by high-pressure washing. Finland uses lower pressure of 5-8 MPa (50-80 Bar) with demands of flow rate of at least 70 l/min. the washing is to be finished by 1st of June, but sometimes 15th of June. No vegetation should grow on the bridge except for "green bridges". Their document is partly demands with a combination of performance and description. Cleaning of bearings is not allowed with water. The document includes items that are in the contracts in Sweden or informed verbally to the contractors. The Finnish document uses pictures, both to show examples of problems but also how it shouldn't look like. The contractor is also in charge of the yearly inspection. Revision each year has resulted in improved work performance.

Norway has similar but less descriptive documentation concerning washing. In the Norwegian road administration's (Statens Vegvesen) Standard for operation and maintenance of National Roads [33] it is shortly stated that bridge elements exposed to de-icing salts should be cleaned once a year during summer (or otherwise specified) by high-pressure washing with water at 100-150 Bar. There are much more stipulated about removal of vegetation and drainage system. In a theme booklet [34] for the handbook of standard of operation and maintenance [35] is stated that the reason for performing the maintenance include preventing chloride ingress among other reasons. The washing is limited to easy access structural parts. It's advised to do the maintenance as fast as possible.

Overall, it seems like that the practical part is very similar for the studied countries, but the exact demands and descriptions differ. All have similar issues, work structure and need for continuous revision.

5 Method

5.1 Literature study

The literature on the effect on high-pressure washing on concrete is scarce. The literature review was therefore focused on the regulations and recommendations from the STA and from the City of Stockholm, both current and previous. The chloride ingress and corrosion literature was also a focus. As a minor part of the study, other types of preventative measures and maintenance were studied as well as other durability issues as one problem seldom is alone and may influence and accelerate others. The problems with malfunctioning expansion joints and insufficient drainage in bridges have also been briefly examined.

The literature studied has been various documents, books and articles. The types of information in the Swedish bridge and tunnel database, BaTMan, have also been studied, mostly to get background information on what data are available and how they are used in consideration to maintenance and repair. Other related bridge documents have also been studied. The maintenance of other countries with winter maintenance was of interest to study. The focus has been on other Nordic countries and North America which have the most similar conditions. The focus has been on finding official documents on the state levels describing similar maintenance and reports and recommendations on the issue.

5.2 Field visits

To gather information about the actual bridge maintenance procedure in Sweden and its effects, the study of the practical side is of great importance. The author has therefore participated during a few sessions of cleaning of bridges, a few times with the City of Stockholm's contractor and one time with a contractor of STA. Some of it can be read in more detail in the report: "*The continuous preventive maintenance of bridges- a pre-study*" (In Swedish) [36].

The purpose of the field visits was twofold:

i. To examine the practical performance of the maintenance as well as
ii. To examine important aspects that can affect the impact and effectiveness, both directly and indirectly.

There have been visits with contractors working for the City of Stockholm to seven different bridges, both large and small and a few movable bridges. One half day has been spent with a contractor of the STA, that was mostly small bridges on the countryside. The aim was to observe differences and similarities. There have also been visits to two tunnels during periodic maintenance shutdowns. These observations took place during 2017 and 2018.

The results came from observations of the author during the visits and some answers from the contractors and workers that participated during the visits. Different documentations and protocols were also observed as well as other tools studied.

It has not been possible to do one-sided blind observations without the contractor knowing of the presence, due to practical aspects such as locations and safety. This might have had an influence on the performance. The work might be conducted more thoroughly than it would have been without supervision. At the first and second visits there were also other representatives from the contractor and the City. This might have had an mental impact on the workers, resulting in more thorough work or different than it would have been without supervision. This is hard to be sure of without some version of blind test where the workers would not be aware that they were observed, put would be difficult in practice due to safety regulations.

5.3 Survey

A survey inquiry was sent out to some of Sweden's municipalities concerning different questions about their bridge maintenance during 2017. The purpose of the survey was to examine the differences and similarities between the municipalities and with the STA.

In total 100 out of 290 municipalities of Sweden were contacted about participation in the survey. It was decided to reduce the number of contacted municipalities in regards to populations, geography, closeness to other large municipalities and availability for contacts. For small municipalities it was indicated that it was common for the STA to take over the management & maintenance and/or several municipalities coming together to share the responsibility. In total 17 answered the survey, in different fullness. A few more gave indication, as above, as why they couldn't participate. Other reasons were new at the job, or quitting or not comfortable to answer, or that the municipality didn't have any bridges. It was generally difficult to find the right person or in some cases, any. The few that answered seem to have found it quite interesting.

The survey consisted of 31 questions, of which 16 had answer options. The questions concerned:

- General questions: bridge stock, types, economy, contractors etc
- Inspections: how often, when, who etc
- Maintenance: de-icing salts, washing
- Demands: documents, instructions, problems, actions etc
- Control: who, how, in case of problems
- Other: definition of maintenance.

Quite a lot of additional information could be obtained in general corresponding with people from the municipalities that might have an effect on the maintenance and its quality.

The survey can be read in full in [37].

5.4 Choice of concrete types and casting of samples

The existing bridges in Sweden are from late 19th century to today, a few are even older. About 40% of existing bridges were built during the 1950-70's. The importance of preserving these structures is of interest and some bridges have exceeded their designed life-span. As the properties and standards for concrete and bridges have changed over the decades it may influence the effect the washing has on the chloride ingress. It was thereby of interest to have concretes that could be somewhat representative for an old bridge and a new bridge. The old type is based on Swedish standards and requirement from the 1960's and the new one is based on a simplified version of a concrete used today. The main requirements have dealt with water/cement-ratio, cement type, aggregate types and air content. The determined properties can be seen in Table 5-1.

Table 5-1 Concrete recipe's properties

	Old	New
Water-cement ratio	0,6	0,4
Cement type	CEM I 52,5N (vs)	CEM I 42,5 N-SR3 MH/LA
Cement content [kg/m^3]	324	420
Air content [%]	3,5	5
Aggregate	Natural	Crushed
D_{max} [mm]	16	16

Both concrete mixes use CEM I, which has been standard up until very recently. Previously there were several and sometimes small cement producers in Sweden instead of the large one we have today. The CEM I 52,5N (vs) is the closest to the old cements available, it is produced in Sweden but mainly exported due to the increased requirements over the years. Aggregate size has been restricted to 16 mm due to the size of samples.

5.5 Field experiment

The need to examine the effect of high pressure washing on concrete bridges in real exposure condition is of great importance not only to help evaluating lab experiments but also to see the possible effect on real structures.

In corporation with the City of Stockholm, a field station was installed on a road bridge in the south part of Stockholm. The concrete bridge is located in Älvsjö, Stockholm. Built 1971 for only motor vehicles. The concrete samples were put in a steel cage and then put on the edge beam of the bridge, see Figure 5-1, in January 2018. The location ensures a realistic exposure and at the same time meeting the safety requirements. The bridge is exposed to de-icing salts during the winter and the traffic is moderate to low, depending on the time of day.

Figure 5-1 One of the steel cages with samples at installation. To the right: new (0,4) and to the left: old (0,6) concrete

In each cage there are 30 concrete samples, 15 of each type of concrete, “new”-0,4 and “old”-0,6. One cage is covered and the other one is exposed to the annual high-pressure washing which is performed during spring or early summer. For the three washings the samples have been exposed to at the time of writing (May 2021), all have been in the beginning of June. The bridge in question is among the last to be washed as the cleaning period starts in April/May and continues until June.

Figure 5-2 Washing of field station, during regular maintenance

Samples are collected in October and tested for chloride ingress. The chloride content is then related to the cement content. The purpose of the field experiment is twofold, (i) to be able to compare with lab experiments and (ii) to see the long-time effect of the washing. The field station and the results of one year’s exposure can be seen in [38].

5.6 Collection of environmental data

Environmental data for the field station on weather condition such as temperature, relative humidity and precipitation are collected from the open official database of SMHI, the Swedish Meteorological and Hydrological Institute.

The amount of de-icing salt used during the winter maintenance is gathered from the bridge owner, that get it from their contractor. The timing of the washing is registered as the author participate during the day of yearly maintenance on the bridge to be able to cover samples that should not be washed. This is done in collaboration with the maintenance contractor and the bridge owner.

The author has tried to find the amount of traffic on the particular bridge, but no data on Annual Daily Traffic are available.

5.7 Laboratory experiment

The lab experiment consisted of developing a method to simulate the cyclic exposure of a real edge beam in Sweden in an accelerated condition but still be able to get realistic results and possibilities to see differences between high-pressure washing and non-washed samples.

The aim was to simulate the seasons with corresponding de-icing salt & washing and capillary adsorption and desorption as well as the diffusion that occurs during the seasons and effects the chloride ingress. Its an iterative development of the method, only the current version is presented here.

The same concrete recipes as the field samples are used. The samples were exposed to eight cycles, each cycle taking one week and consisting of four stages representing a season (winter, spring, summer and autumn), the exposure conditions can be seen in Table 5-2. All the samples were sprayed with a 10% NaCl water solution. The high-pressure washing occurred at a distance of about 30 cm with a working pressure of 170 Bar before the samples were exposed to the spring conditions.

Table 5-2 Test setup version 2

	Winter	Spring	Summer	Fall
No of days	1	2	2	2
Temperature [°C]	4	20	40	20
RH [%]	40~100	75	~30	85
Washing		beginning		
Amount of salt [%]	10			
Type of salt	NaCl			

After the eight weeks, the samples were tested in the same way as the field samples, to create a chloride ingress curve.

5.8 Testing of samples

The chloride profiles are created by first milling the centre of the concrete specimens by steps of 1 mm. For deeper depths thin sections every 5 mm is taken out and crushed finely. The fine samples are then acidified and tested for chlorides according to CBI method 5 [39] by an ion-selective-technique, and the amount of calcium, by titration with EDTA, gets the cement rations by backward calculations. The cement content values from the tests compare well with the theoretical values calculated based on the recipes and cement data.

6 Results

6.1 Observations from field visits

During 2017 and 2018, the opportunity to observe the maintenance was realized. At first the observations were carried out with the contractor working for the city of Stockholm, that also has the maintenance of the bridge with the field station. In 2018 it was possible to spend half a day with one of the contractors of the STA, one that does the maintenance in the large area of Region Stockholm. At that time, the observations were conducted on small bridges on a country road. Each time, certain things were the same while some were different.

The time period of the maintenance is mainly performed during late spring, April-June, after the winter maintenance period has ended and the grit has been collected.

6.1.1 The procedure

The washing could be done automatically or manually. The automatic one had different versions where it was possible to remote control the arm holding the water jet, either from the cabin or from the ground outside of the truck (portable).

Figure 6-1 Washing of railings (automatic)

The general working procedure was basically outside-in, alternatively from one side of the bridge to the other one and up to down. The washing started at one side of the bridge and continued along the bridge. When there were two teams they met in the middle. The railings, the slab and edge beam were done first, then the substructure.

Figure 6-2 Collecting water from fire hydrant (brandpost)

The trucks have a limited capacity of water supply. Occasionally there is a need to collect water during the working day from collection points, which could be general water depot stations or use of the fire hydrants (brandpost), see Figure 6-2, if the depots were too far away. However, the fire hydrants were not to be used if water level was too low.

The water pressure decreases with increasing distance between the nozzle and the construction part, even if the area effected increases. This means that a relatively short distance is needed when washing to generate high enough pressure to remove the dirt. The harder the dirt is stuck, the harder it is to remove and more pressure is needed. The distance was stated in the contracts and requirements of the STA, but verification of actual distance used could not be confirmed and the workers themselves were not a hundred percent sure, but the contractors mentioned using a bit longer distance than specified to avoid damages. The contractors used more experience and visual clues.

6.1.1.1 Stockholm City's contractor

The washing occurred in pairs when using hand-hold equipment, one person did the high-pressure washing and the other one kept an eye on the hose, truck and surroundings. Its also a bit of a safety matter, especially when working close to edges with high fall risk, see Figure 6-3. Each pair had at least a truck at their disposal. The exact procedure depends on the scale of the bridge and the type of traffic and intensity. The order of washing of the bridge joints depended on the placement, if it was in the middle/highest position of the bridge it was among the first parts to be washed, but if it was at the end(s) it was done among the last parts before going for the substructure.

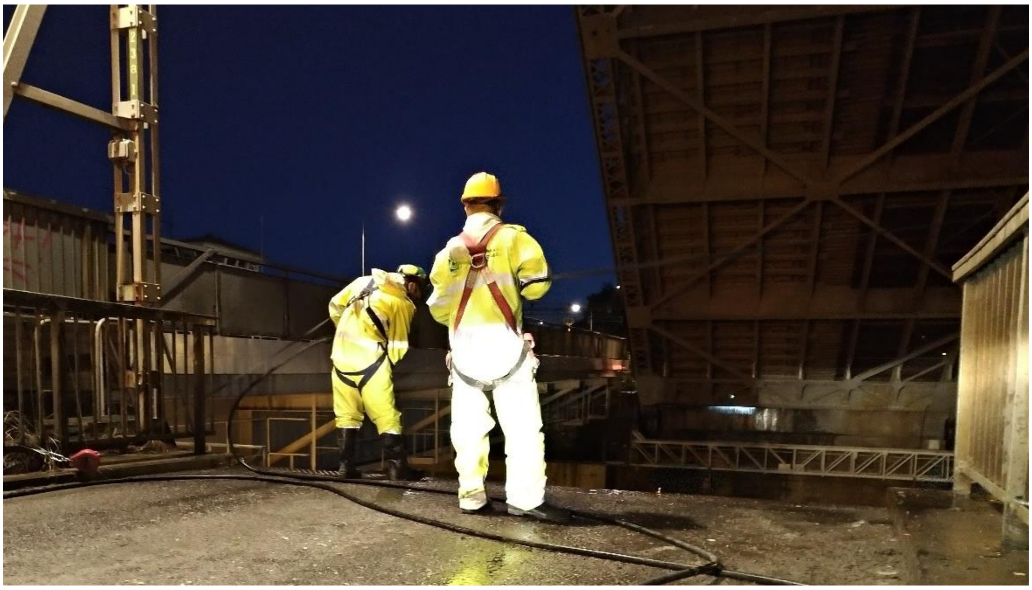

Figure 6-3 Cleaning the edge with fully opened bridge

The drainages were cleaned as they were passed by. When the drainages and joints were cleaned, they are sprayed with a paint at or close by for photographing, which were then sent to the responsible person at the City of Stockholm. This is to prove that the job has been done. The workers were most stressed during the night shifts because of the strict time limit and the frequent interruptions due to release of traffic, especially during certain periods. During the observed night the work was quite on time but the workers said that it could be worse on other nights.

6.1.1.2 STA's contractor

For the STA's contractor there were three people/cars working together at the same time in a row, see Figure 6-4. For traffic safety, one traffic safety vehicle was in the back, in direction of traffic. In front, there was a small vehicle that collected the grit and loose dirt. It was followed by the truck that performed the washing. This truck was designed to be able to do everything from the inside of the truck.

Figure 6-4 Washing of country-side bridge. STA Contractor, June 2018.

6.1.2 Equipment

The contractors use high-pressure water tank trucks. Big and small ones as well as with a crane and/or hand-hold are used. The small water-tanked trucks required more re-filling after some time of use. That generated dead time and resulted in a longer working time with less effectiveness. A large water-tank truck could be used much longer period of time, usually a whole bridge for one tank if the bridges wasn't too large or complicated. The water was always ordinary cold tap water. The shape of the jet is usually circular but can be adjusted to a more oblong shape or line, which is mostly used for joints for better effect and to reach further in.

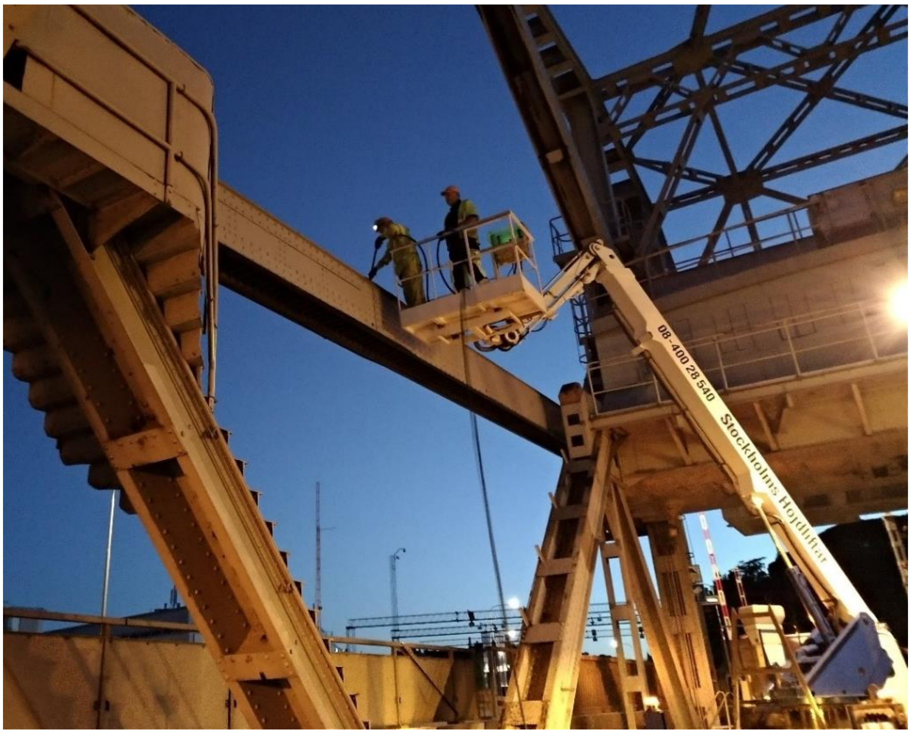

Figure 6-5 Washing at a height.

For most of the structural parts, it was possible to get close enough as required/stated but at a few places it was hard to physically get close enough for the optimal or pre-required distance for cleaning. An alternative is to use sky-lift and/or boat which wasn't always economically motivated.

6.1.3 Documentation and communication

The format depends on the owner. Both paper and/or digital documentation exist. There are documentation of each bridge containing location, overview drawings, detailed drawings and information on what should be done and the location on the bridge, and usually a type of checklist. This is done for every bridge, both small and large ones with different levels of details.

Communication between the owner and contractor is on all levels very important. It was not uncommon that the question of how the cooperation/work with the contractor works, to get the answer: it works well now. Further questioning gave that it was some issues in the beginning, for example that the work wasn't performed according to the owner's wishes. This could be things that the owner considered obvious but not the contractor. There are many details on performance that are general or specific for a bridge that are not stated explicitly in the contracts or in the descriptions (initially).

Previously most of the continuous maintenance was performed by in-house personnel. Both STA and municipalities say that communication when the work is not performed right or satisfactorily was easier when it could be discussed internally. Generally, it still seems to work well with the contractor after an adjustment period. When all the important things are not explicitly put on paper, those things will come to the surface as time goes by. Over time there has been a shift to include more details in the contracts with demands based on the problems or issues that occurred previously.

6.1.4 Movable bridges

Movable bridges can be very complicated, and their maintenance requires more work and knowledge. Both because they need to be cleaned in different positions but also because there is a need to clean more parts, both inside and outside. The movable aspects create more openings and moving of the dirt in more places. The machine room also needs to be cleaned.

Figure 6-6 Washing of a small movable bridge, partly open

Usually, the main work time for the movable bridges is at night to avoid effecting the traffic when opening the bridge. There were at least two large trucks on each side as required in the maintenance instructions. The reason was to be able to wash on both sides during different positions and be more effective. On day work, for both solid and movable bridges, a large or small truck could be used.

6.1.5 Other factors

There were other important factors to consider when washing, as they affect the work and the possibilities of washing. One factor is accessibility. Parts of the bridge structure can be hard to access and thereby clean.

Figure 6-7 Washing the underside with a sky-lift

Access to the underside and substructure of the bridge might also be troublesome, especially when the bridge is crossing water it can be hard to access without the help of sky-lift and/or boat, see Figure 6-7. Inspection walkways, see Figure 6-8, can make the work easier but still restrict access. They may also be more time effective since the moving of a sky lift takes more time. Sky lifts might still be needed to access the inspection walkway or other parts of the structure.

Figure 6-8 Washing the underside using a inspection walkway

The traffic on the bridge is another influencing factor. This is especially important for movable bridges when there is need to open the bridge, resulting in a limited timespan to work by using intervals with cleaning and allowing traffic to pass. It was not always that part could be fully cleaned during just one stop. Clear differences in traffic for different times, which effected the car lines and the length of time the flaps could be open for washings without effecting the traffic and car lines too much. Even for ordinary bridges the work could affect the traffic but to a lesser degree, but it also depends on the bridge and number of lanes. Unfortunately, not all road users understood or respected the traffic stops needed for the cleaning operations.

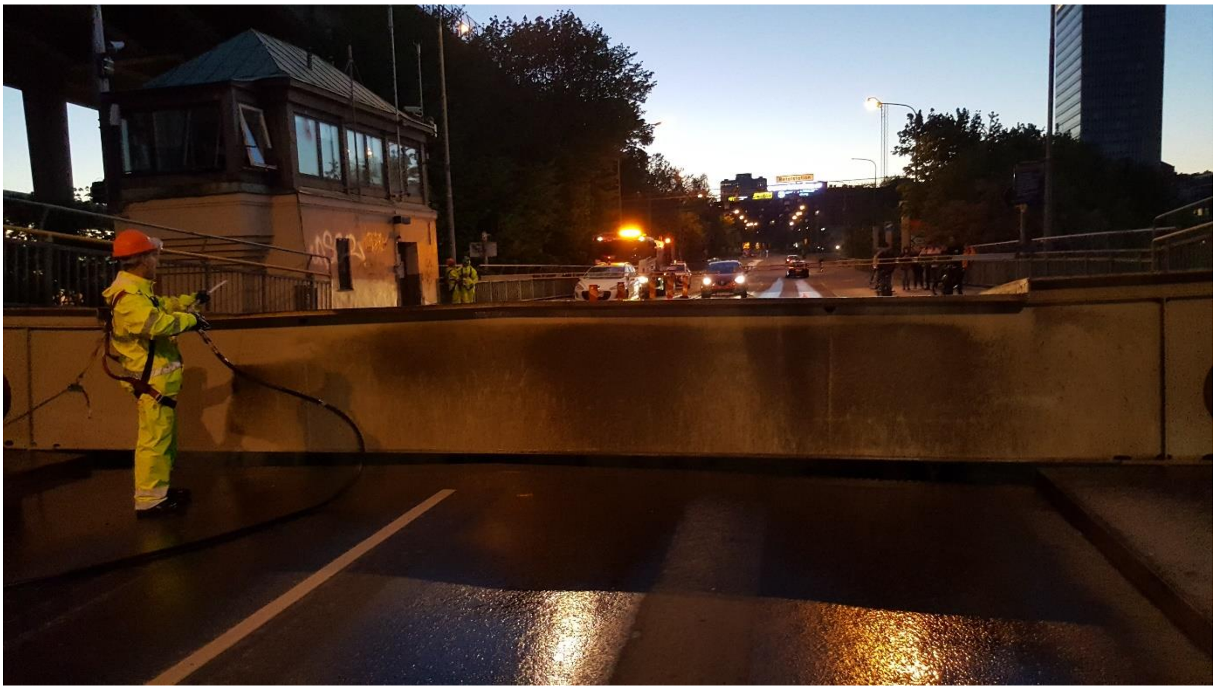

Figure 6-9 Washing of a smaller movable bridge, partly open.

Parked cars, boats in water or on land under the bridge could cause issues when washing since the dirt and water should not end up on them. That could generate extra work to wash also them. The contractors had warned responsible officers for those sections to make sure the underside was clear by barriers and/or information but some ignored this information or were there before the barriers were put up. However, much less than without them.

6.2 Results from the survey with municipalities

Initially there was a wish for diversity and many replies, but the end result was rather few answers but still containing interesting information. The initial goal of the survey was to detect similarities and differences between municipalities and the STA. Some of the municipalities were under change in several aspects, from economical, contracts, investments, personnel, etc. In that case the municipality reported both the current situation and the future one. For future changes, it could mean from weeks to years depending on nature, extension, and degree of the change. The full results of the survey can be found in Paper I.

6.2.1 General facts

There was a good diversity in number of bridges in each municipality, see Figure 6-10. The number of bridges owned by a municipality ranged from 22 to over 200. For the majority of the municipalities the main construction material of their bridges was reinforced concrete or a combination of steel and concrete.

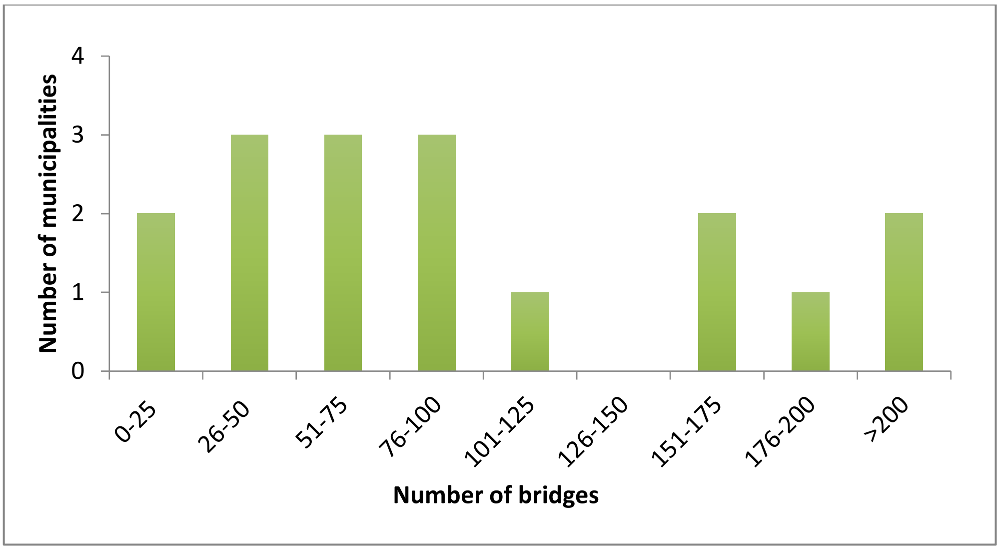

Figure 6-10 Histogram over the number of bridges of the participating municipalities

The municipalities' budgets for bridge maintenance varied, with no clear relation, except maybe incitements from the politicians. Some had very large budgets and others smaller ones. No direct correlation between the budget and the number of bridges or population could be seen. The only factors that had some correlations were unsurprisingly between the population and the number of bridges. Some municipalities had large budgets in order to catch up on required maintenance and repairs. Some were doing repairs after several decades of only acute maintenance and repairs. These investments were both short and long term. Some municipalities were going to start and some were in the middle or end of their catch up repairs. Generally, there seems to be an effect of political decisions to invest in infrastructure. To the frustration of the people working with bridge maintenance there is always a shortage of means in comparison to required maintenance. Thereby there is always a choice on what needs to be prioritized. The STA's experience with the integrated bridge maintenance, see Section 4.3.2, has been positive with better efficiency and reduction in costs. For the participating municipalities, four responded that they use integrated bridge maintenance. Another two responded that they were planning to implement it in the future. Some of the municipalities that didn't use integrated maintenance motivated this by the fact that their geographical area was too small. Most scheduled activities are inspections, washing and cleaning of drainage in correlation with when the gritting sand from the winter season is collected.

6.2.2 Contracts for bridge maintenance

The STA has been using contractors for the practical aspects of the maintenance for the last decades. The assumption that municipalities also did was examined.

All of the municipalities have contracts with consultant firms for the inspection of the bridges, similar to the STA. Few municipalities did this partly, where some small and simple bridges were inspected by their own personnel. The washing of bridges was generally done by contractors. The rest either had contractors doing some of it or the municipalities did everything themselves. For removal of vegetation the municipalities were almost evenly split between using only contractors, partly contractors and or by the municipalities themselves.

Cleaning of drainage systems was either fully or partly done by contractors. A few municipalities didn't use contractors at all.

6.2.3 Maintenance

Due to the winter conditions in Sweden, the use of de-icing salts is common practice. The use of it in the municipalities is therefore an important aspect to consider, especially because de-icing salt contributes to corrosion of steel and of the rebars in concrete. Almost all of the participants used de-icing salts on their bridges to some degree, see Figure 6-11. Some municipalities only use de-icing salts on their road bridges or, as one municipality commented, only on the roads used by public transport. The geographical location of the municipalities didn't indicate any influence. For municipals located next to each other or very close, one municipality usually had a high number and the other one a low number.

The period for using de-icing salts was quite consistent for the municipalities that used de-icing salts. Unsurprisingly, the main period is during the winter months but as all the municipalities commented on, it depends on the weather conditions and prognosis.

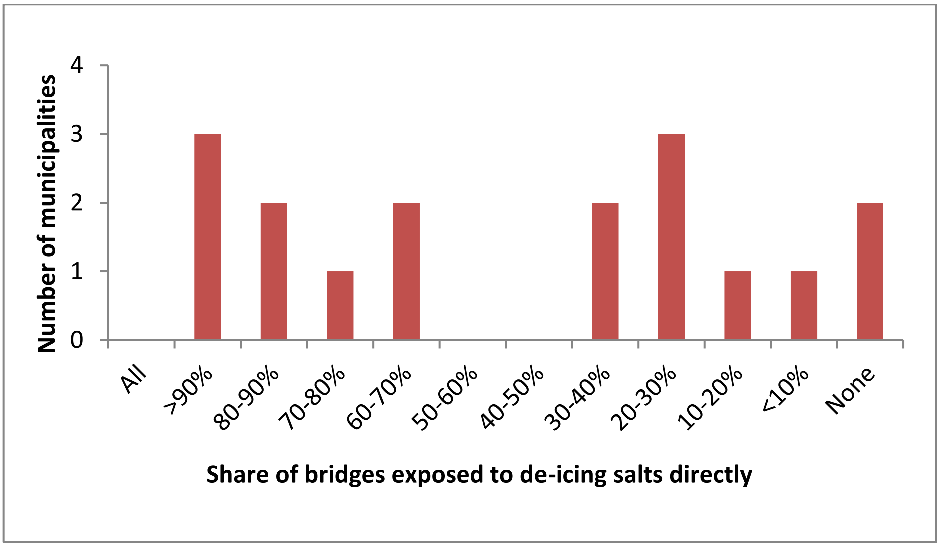

Figure 6-11 Histogram showing what percentage of a bridges within a municipality are directly exposed to de-icing salts.

Washing of bridges occurs when the winter season is over and after the collection of grit sand used for ice prevention during the winter. The main period of washing is late spring and/or early summer, but could also be done later, see Figure 6-12. The municipalities usually have a period or a date when the washing of bridges should be done. Some also have a specified starting date when work can start, which is usually in April or May. The municipals that answered August to November also had washing done in May and/or July, indicating two washing periods.

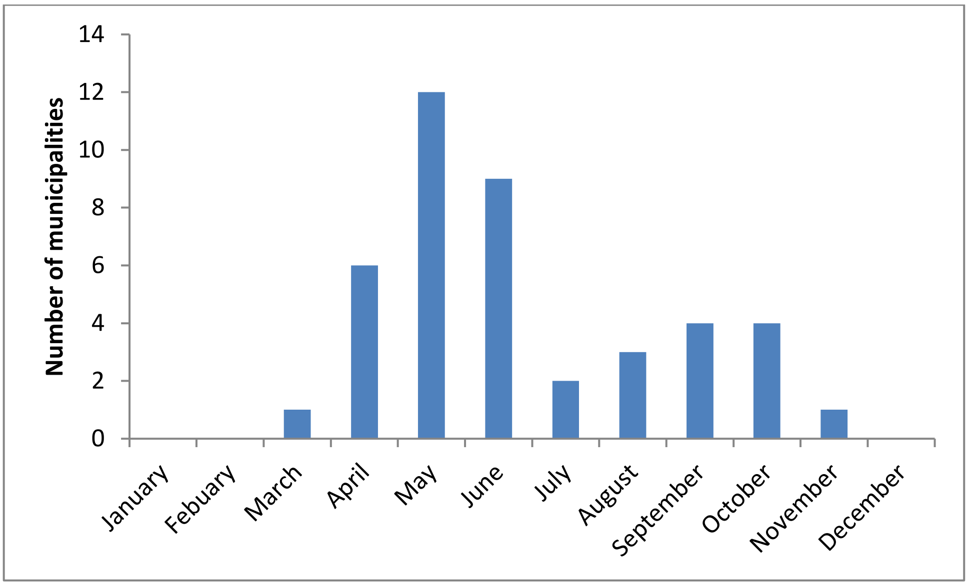

Figure 6-12 The period of a bridge washing in the municipalities

6.2.4 Demands

The majority of the municipalities reported that they used the STA's current demands for bridge maintenance. Of the municipalities only two had additional demands than those based on the STA's. Another two municipalities had occasionally more demands. But the majority didn't have more requirements than those the STA has for bridge maintenance. Some comments from the municipalities indicated, however, the usage of older versions' demands. This can be the result of preferences or lack of knowledge of updates. When asked for their demands on washing, the municipalities either referred to STA's or answered edge beam, bridge bearing & pillars, railings, drainage systems etc. The majority of the municipalities felt that their demands were being fulfilled. There is a consensus amongst the participants that the actions taken on their bridges have had a positive effect on the standard of the bridges.

6.2.5 Influence of budget

A few municipalities had larger faults that needed to be corrected. One municipality that for a long time had to neglect maintenance has in recent years received a larger budget to deal with their problems. The municipalities have noticed an improvement in recent years, which shows that investments in infrastructure have positive effects.

Noteworthy is how much maintenance and repairs that can be done depends heavily on the municipality's budget where they have to prioritize, which for a long time meant doing a few things on the bridges that are in the greatest need and neglect other bridges which in the long run will result in more problems on the other bridges and higher repair costs.

6.3 Field samples

Samples from the field station is taken in every year during regular fall maintenance. Up until now, May 2021, there have been three years. The results from the field show clear differences between "new" and "old" concrete, which is unsurprisingly. Even after less than one year of exposure, but one winter season and one washing, some things can be observed, see Figure 6-13. A clear difference between the "old" 0,6 and "new" 0,4 can be observed. Because of the low water-cement ratio, the "new" samples are denser and have better durability. This can be seen in both lower values of the curve as well as that the maximum point is further towards the surface, indicating a denser concrete. For differences between the washed and unwashed samples, the differences are still too small to say anything concrete.

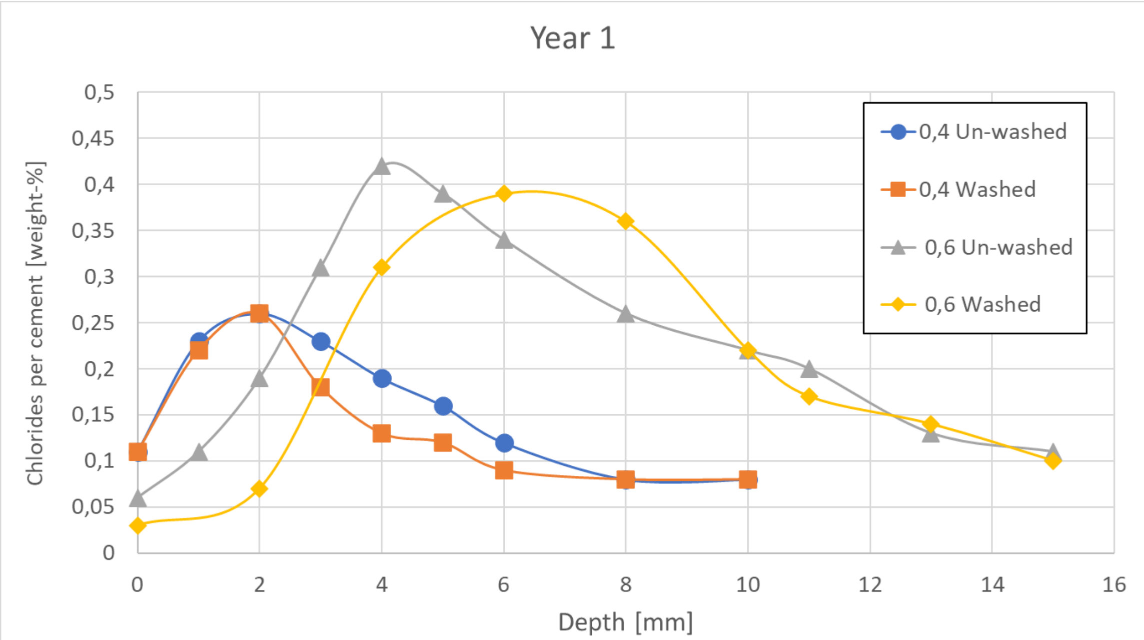

Figure 6-13 Chloride profiles from samples from the field after one year of exposure

For the second year, a clear difference between washed and unwashed could be observed, see Figure 6-14. The reduction of the top of the curve is clear and can give an indication of the reduction of diffusion further in. There is a slight shift where the curve of the washed samples is a bit higher than the un-washed one, but it can still be within the margins of error. Further testing in later years might give clearer results.

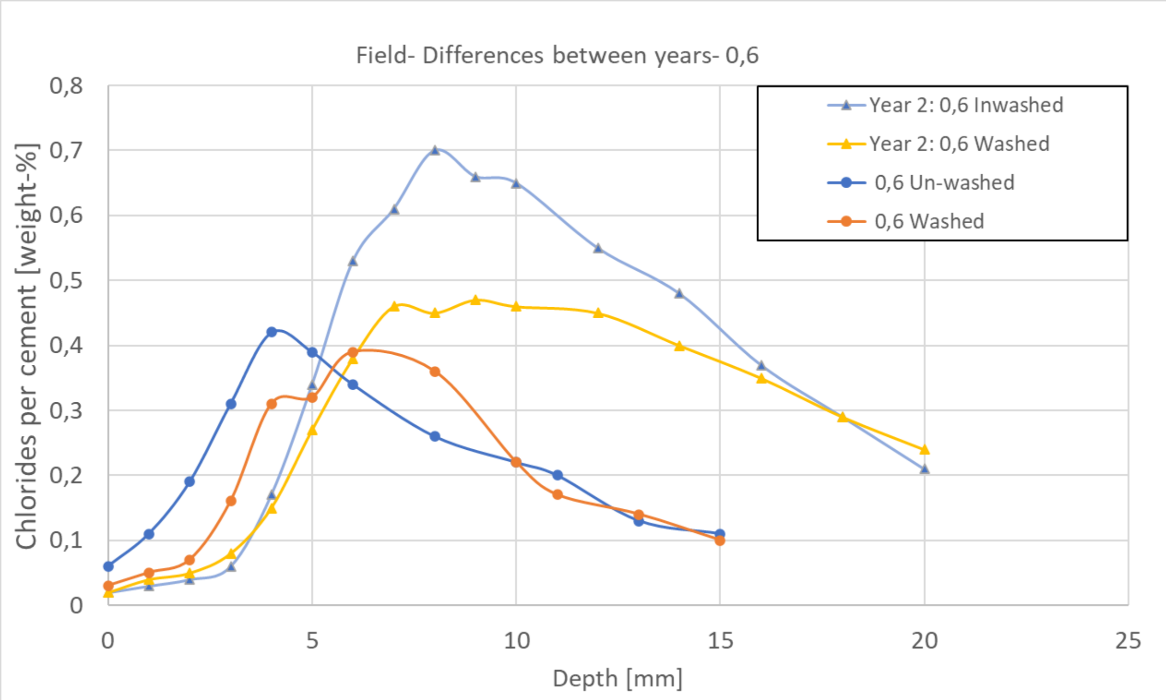

Figure 6-14 Comparison of field results for "old" 0,6 after one and two years.

Measurements from year 3, seen, in Figure 6-15 give results that are harder to interpretate and differ from year 2, resulting in raising more questions than answers. There is uncertainly in spread between samples as only on is tested each year. The effect of continuous rain is also a factor to consider. The results after a few more years could give better answers or at least an indication.

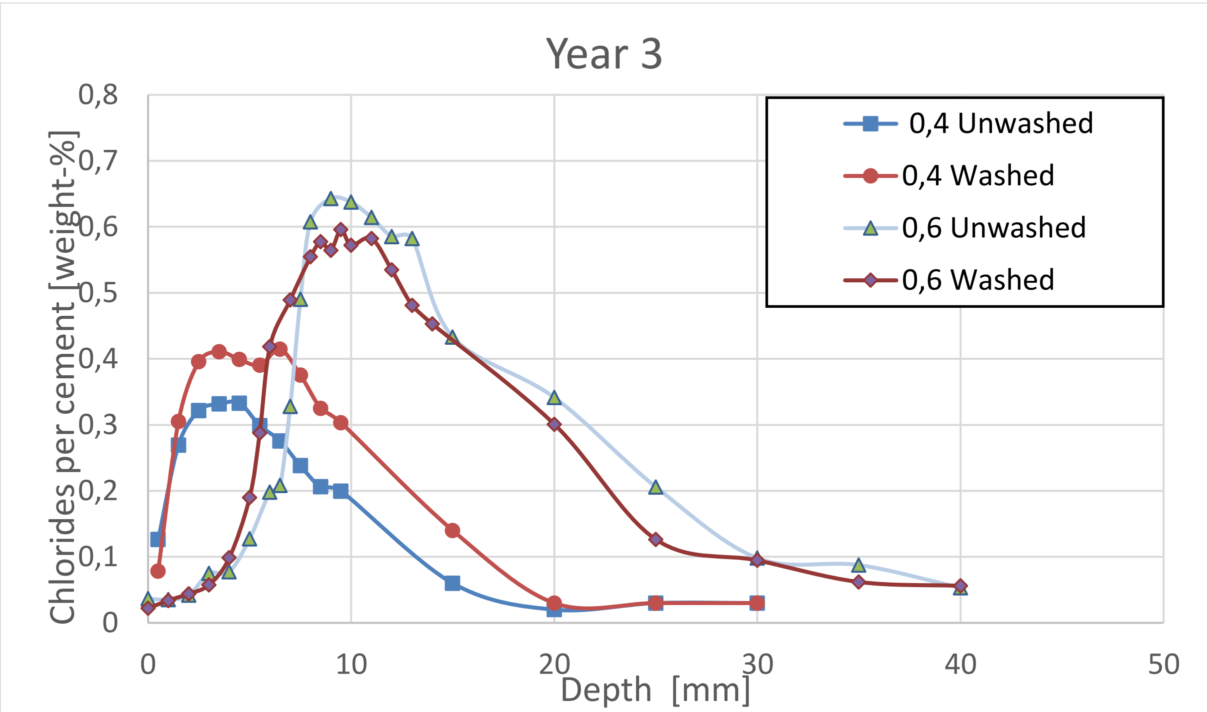

Figure 6-15 Field results for Year 3

6.4 Environmental data at the field station

Temperature, relative humidity average and precipitation per month for 2018-2020 can be seen in Figures 6-16 and 6-17. The data are collected from SMHI. For the winter period 2017-2018 the de-icing salts were used 67 times in the area and for 2019-2020 it was 31 times. No data for 2018-2019 could be collected. This can be compared to the amount of days with average temperature being less than 0°C which were: 86, 51 and 21 times for each period. There figure show that the first and second year were colder during winter buth the third one had more persipation

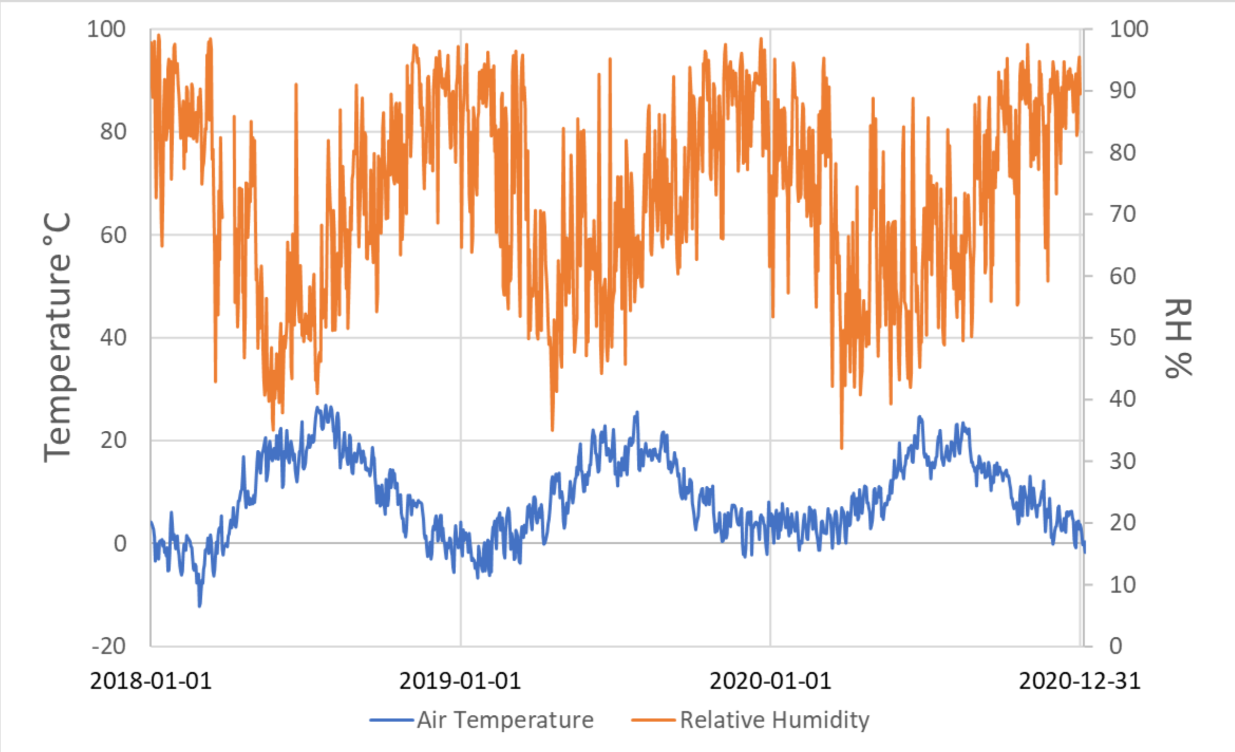

Figure 6-16 Graph of temperature and RH in Stockholm (Data from:SMHI)

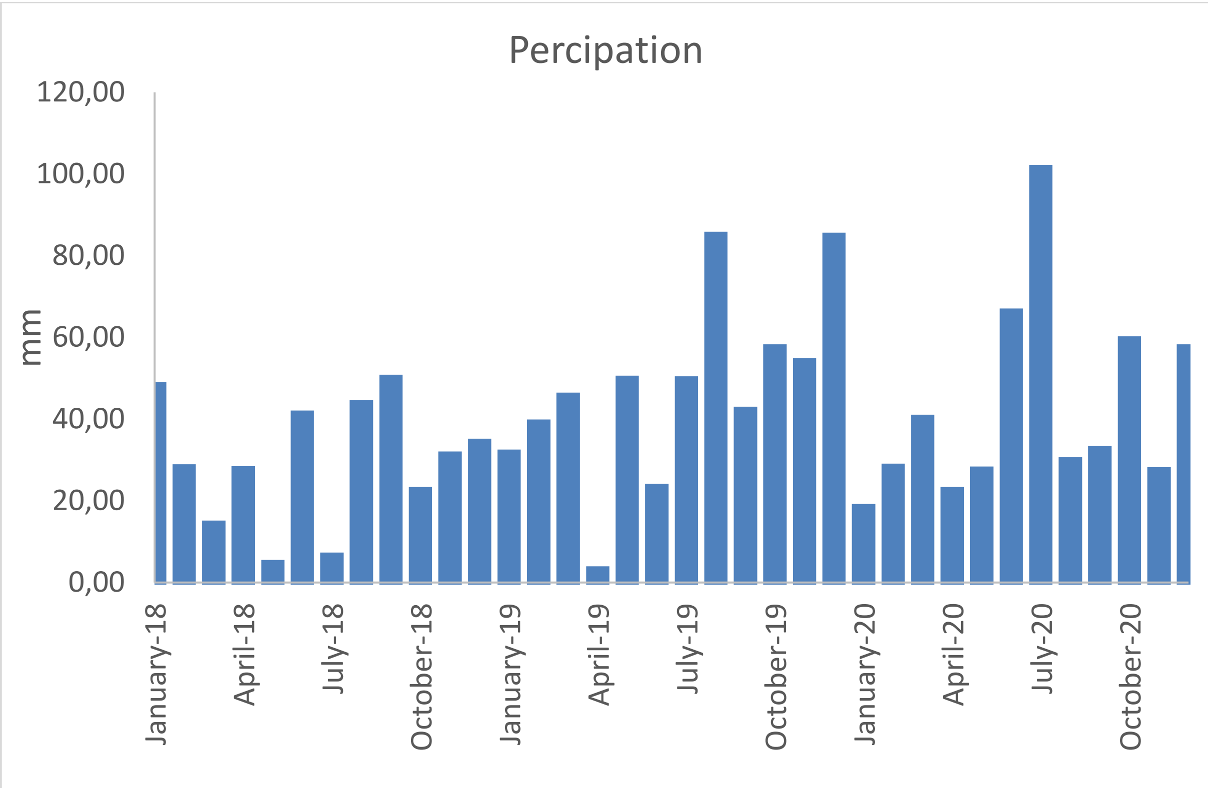

Figure 6-17 Total Precipitation per month in Stockholm 2018-2020 (Data from:SMHI)

6.5 Laboratory/accelerated samples.

To reduce the amount of work when developing the method, only the "old" 0,6 concrete was tested for a chloride profile to analyze the method. The first version had too much of capillary absorption and too much chloride resulting in extreme values. The second version provided more reasonable results. The results from the second version can be seen in Figure 6-18, showing a decrease in chloride content for samples that have been washed in comparison to samples that have not.

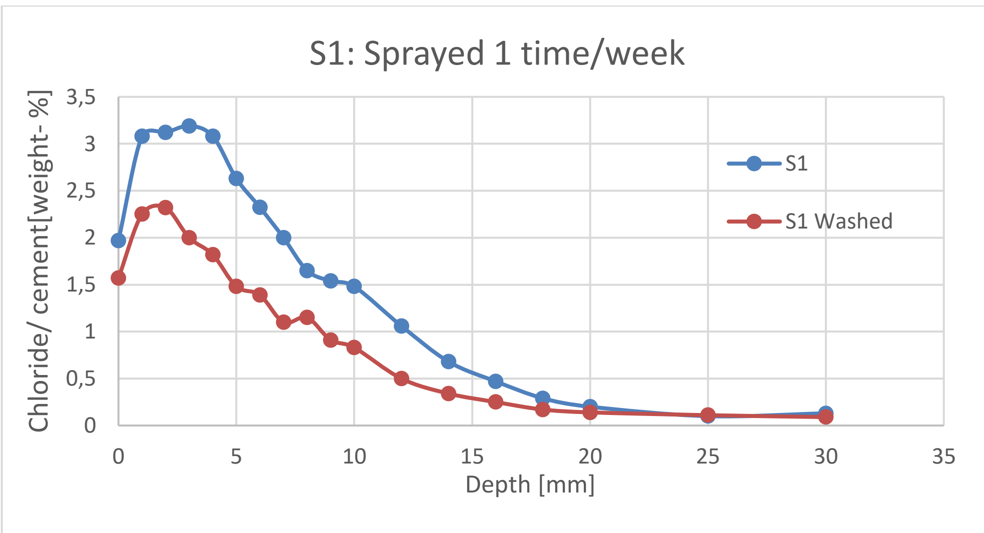

Figure 6-18 Results of "old" 0,6 of accelerated test, method version 2.

7 Discussion

The main aim of the project was to examine if high-pressure washing of bridge concrete had an effect on the chloride ingress due to winter maintenance's use of de-icing salts.

7.1 Survey

The survey showed both differences and similarities between municipalities and STA. The actual maintenance, demands and controls of the bridges are generally the same, but when and by whom it is done differentiate greatly, which could have an effect on the efficiency of the washing. This is probably connected to the way that the municipalities use and adopt the demands and recommendations previously used by the STA as well as their own previous experiences. The survey also showed that each municipality often had a separate issue or solution that was a result of their bridge stock or the budget. An unspoken consensus among the answers seemed to be that having to prioritize and neglect certain maintenance only increases the problems later on. There is always more to be done than can be met with available means.

7.2 Field station

The results from the field station is hard to give definitive answers and will require further testing and analysis. The only concrete thing the results says is regarding the differences between the concrete types, which is already known. Such as that the concrete with w/c= 0,6 has lower resistance and higher porosity and more open pore system, resulting in higher chloride content with a peak further in compared to 0,4. The differences between washed and unwashed is hard to say something about, one way or another. Year 2 indicated a decrease with washing but year 3 showed no real difference that is outside the possible effect of natural scatter and measuring errors. The winters prior to year 3 was colder but with less perception than the winter for year 3. There might be several aspects that can possibly effect and give different conclusions/questions. Further questions are raised and need answers. The only thing that can be concluded is that the washing doesn't make it worse in the short run at least. Clear differences between the years can be seen but can be expected to decrease over the years. The question of effectiveness of rain and frequency of washing, position of samples, yearly differences, etc are being discussed. Is it that simple that the high-pressure washing has little effect on the chloride ingress in comparison to continuous exposure to rain? The long-term effect is still unknown and can do for further exploring of what happens over time. The effects of other contaminants and exposure conditions are also of interest, especially protected from rain, as well as effects on other structural parts, expansion joints etc. The effect of washing versus rain is an important aspect to consider, as well as the effect of earlier or later maintenance in regards to the end of winter maintenance period.

7.3 Lab experiment and development of method

The developed lab method seems to give a good comparison to field samples in regards to shape and levels. Here difference between washed and unwashed can samples be seen. The difference from the field results can have multiple reasons, in regards to chloride level, timing of washing and effect of rain as well as the time component. The method needs to be further developed to be able to examine these parameters. The effect of time also needs to be examined, both in regards to total length of test, maybe shortening down to 4-5 cycles and/or lengthened to 10-20, and examine the effect of increased time of each cycle. For washing, the timing is under examination since in the test the washing occurred right after the winter period but in the field it can occur right before or beginning of summer. The effect of rain is important to examine and should be a priority, as this is one of the major differences between tunnels and bridges and between field and laboratory samples. Vertical versus horizontal position of the surface cleaned also needs to be examined for possible effect.

8 Conclusions and further research

The main aim of the project was to examine if high-pressure washing of bridge concrete had an effect on the chloride ingress due to winter maintenance's use of de-icing salts.

8.1 Conclusions

- The practice for washing as a preventive bridge maintenance measure seems to be similar in Sweden and in other countries with minor differences. This is also the case between the STA and Swedish municipalities.
- The same thought for the maintenance is international, especially with regards to removing contaminants and it is better to do measures as soon as possible after the winter season.
- The whole maintenance is considered healthy for the structure, but individual aspects and measures seem to have different levels of research, with some more than others. Bridge joints and crack repairs for example seems to be better studied.
- Results from field station need more years of exposure before anything definitive can be said. It is too many questions regarding the results in comparison between washed and un-washed concrete samples as well as between the years to say anything at this stage.
- The developed accelerated test method shows promising results and should be further developed to be able to include more testing of different variables.

8.2 Further research

The further testing of samples from the field station is of great interest. Will the difference between washed and un-washed concrete samples increase or decrease and to which degree? This will be a continuous work. At the moment the field station has samples for up to 15 years if one sample is collected each year.

The accelerated test method needs to be further developed to be able to provide answers to the questions stated in Section 3.1, which include the following:

- Is the timing of washing of importance?
- Is the number of washings of importance?
- Effectiveness of washing in comparison to rain?
- Warm vs cold water?
- Effect of stagnated water and longer and shorter exposure rate?
- Cyclic exposure condition within the winter maintenance period?
- Does the washing and rain reduce the surface concentration of chlorides?
- Does the washing affect the chloride concentration a few millimeters in?
- Does the pressure cause a physical push of the chlorides further in?

All of these are needed to answer the final question:

- How can the yearly continuous bridge maintenance effectiveness be increased?

For research outside of this project, the following would be of interest:

- Effect of washing in a tunnel or non-rain exposed structures.
- Effect of washing on chloride ingress in combination with other contaminants.
- The effect of washing on steel and especially the zone between connection the railing and edge beam (concrete), which is a common issue.

Acknowledgements

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