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Impregnation as a Method of Active Bridge Maintenance

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Abstract

In Sweden, there are in all 27 000 bridges. The Swedish Road Administration is responsible for 12 000 of these bridges. 50 percent of them are built between 1950 and 1980 and have, thus, obtained an age at which the need of maintenance and repair usually increases. A hypothesis is that the preventive bridge maintenance could be optimised through thorough analyses of properties of the bridge element, actual mechanical stresses, and ambient microclimate. An active maintenance is defined as the optimised preventive maintenance allowing different measures to be selected for different bridge elements. The opposite is passive maintenance, a form of maintenance that is equal to all bridge elements independent of element properties, actual stresses, and ambient microclimate. Impregnation has been regarded as one of the most suitable methods of active bridge maintenance. This paper summarizes a literature survey on active bridge maintenance with focus on impregnation.

1 Introduction

1.1 Bridge statistics

In Sweden, there are in all 27 000 bridges (span length exceeding 2 m, culverts are included) [1]. The Swedish Road Administration is responsible for 12 000 of these bridges. 50 percent of them are built between 1950 and 1980 (Figure 1) and have, thus, obtained an age at which the need of maintenance and repair usually increases. A large percentage (86 %) of these bridges are concrete bridges. Since USA is the country having the largest number of bridges (more than France, Germany and UK together), comparisons with USA are interested. In 1995, USA had 590 000 bridges and culverts (span length exceeding 6 m) [2]. They could be divided into 476 000 bridges and 114 000 culverts. Disregarding the deviating definitions, but regarding the number of citizens, Sweden (9 million citizens) and USA (286 million) have 3000 and 2060 bridges and culverts per million citizens, respectively. We may conclude that the total cost of the Swedish bridge maintenance is comparably high in an international perspective.

The American bridges have also a median age exceeding 40 years (Figure 2). A difference between USA and Sweden is that the US percentage of

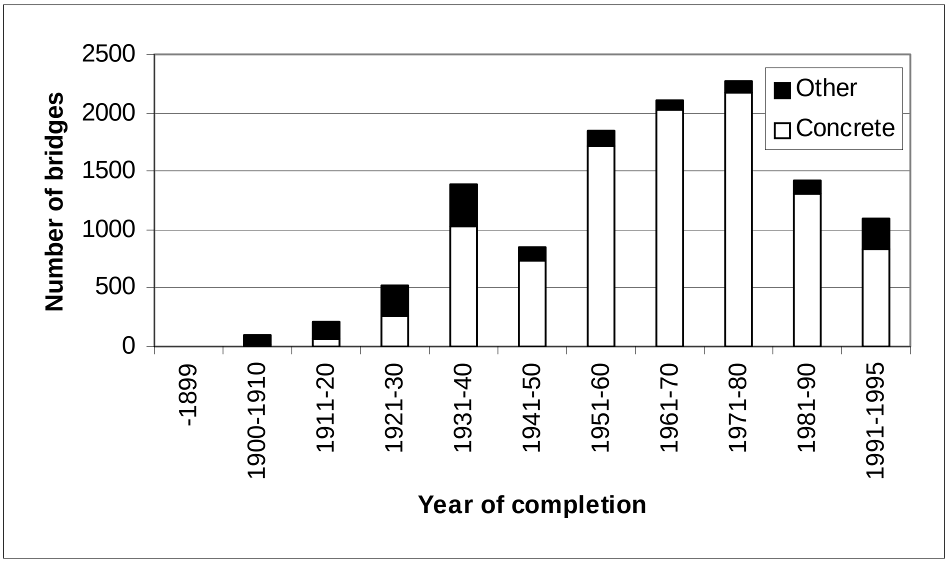

Figure 1: The bridges administered by the Swedish Road Administration subdivided after construction year and construction material [1].

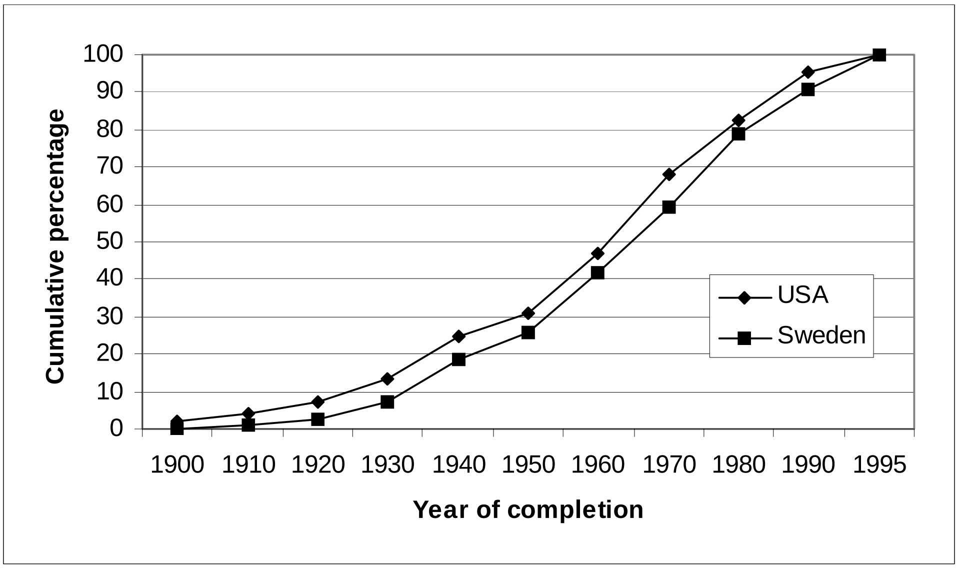

Figure 2: Cumulative distribution of the Swedish and American bridge stock based on figures in [1] and [2]

concrete bridges is limited to 49 %. American investigations conclude that 40 % of the bridges are damaged. The total repair cost has been estimated to somewhat between 51 [3] and 100 [4] billion US$. Corresponding figure for Sweden has been estimated to 2 billion SEK (approximately 300 million US$ according to the exchange rate in December 2004). Expressed as US$ per capita, it means 33 and 180 to 350 for every Swede and US citizen, respectively. An explanation might be that the American authorities did not acknowledge bridge maintenance before 1971 [2].

1.2 Definitions of bridge maintenance

In a pilot study on active bridge maintenance [5], the following terms were defined:

- Active bridge maintenance = effective and optimum preventive bridge maintenance.
- Preventive bridge maintenance = measures taken to maintain the function and capital value of the bridge.
- Corrective bridge maintenance = measures conducted to restore the function of the degraded bridge.

- Routine bridge maintenance = prerequisite maintenance measures when establishing the maintenance plan for obtaining the intended function of the bridge during its intended service life.
- Passive bridge maintenance = measures conducted uniformly on the entire bridge system without a detailed analysis.

The terms preventive bridge maintenance, corrective bridge maintenance, and routine bridge maintenance occur in the international literature. The term active bridge maintenance was introduced in [5]. The hypothesis was that the bridge manager through thorough analyses of properties, mechanical stresses, and environmental loading of bridge elements would be able to optimise the preventive bridge management through selecting suitable maintenance measures or combinations of suitable measures. The word "active" focuses on the role of the bridge engineer in the selection process and alludes to terms like active damping in the design of high-rise buildings and active security in car manufacturing. An Internet search on "active bridge management" in December 2004 gave 5 results on www.google.se and 0 on www.altavista.com. Two of the results were related to [5], one of the others on a painting system.

2 Principles for the optimum selection of maintenance measures

In order to select optimum bridge maintenance, it must be considered that different bridges demand different types of maintenance due to, e.g., bridge type, material, age, traffic, surrounding environment, state, possible detours for the traffic, and intended remaining service life. Furthermore, different bridge elements need different types of maintenance. Some bridge elements, e.g. edge beams & parapets, supports, slopes & embankment ends, slopes and bridge deck & surfacing, are more exposed than others and show more damages [6], [7]. Different bridge elements of same type or different parts of the same bridge element do not necessarily need the same maintenance. Swedish research [7] shows that, e.g. the casting month and the point of the compass influence the service life of the bridge element.

A strategy for the optimum selection of maintenance measures may consist of the following steps:

1. Analyse the bridge and divide it into parts with similar properties, mechanical stresses and environmental loading.
2. Establish alternative strategies for inspection type and intervals, maintenance, repair and replacement.

3. Investigate which strategy that is technically, economically and environmentally most suitable for every one of the defined parts.
4. Determine which combination of measures is most beneficial for the bridge or a system of bridges.

A simple example of an active maintenance is the repainting of a Swedish summerhouse. Due to the sun exposure the paint on the south and west facades is found to peel while the north and east facades are found in good shape. The owner that selects an active maintenance strategy repaints the south and west facades. His neighbour selects (unconsciously) a passive maintenance strategy and paints all four walls.

Bridges are much more complex than summerhouses. The establishment cost and the cost of detour might overshadow the advantages by selecting active bridge maintenance. If, e.g., a thorough analysis shows that the edge beams on the south side of the bridge need to be exchanged every 15th year while the north one will sustain 20 years without exchange, the bridge manager might select a compromise and exchange both every 16th year. The pilot study [5] contained an extensive survey between Vägverket (Swedish Road Administration) and Banverket (Swedish Rail Administration). The establishment cost was repeatedly mentioned as an obstacle against active bridge maintenance. The authorities' interest in preventive maintenance has, however, increased during recent years.

3 Examples of active bridge maintenance

The pilot study [5] focused on the following eight measures that might be parts of an active bridge maintenance system:

- Inspection and maintenance intervals,
- Cleaning and drainage,
- Surface protection,
- Crack repair,
- Bridge deck heating,
- Cathodic protection and chloride removal,
- Intermittent transversal removal of traffic, and
- Intelligent bridges.

Most West European countries as well as USA and Canada have an inspection system containing perspicuous, general and main inspections [8]. In Sweden the intervals for these three inspection types are 6 months, 3 years, and 6 years, respectively [6]. There are a lot of research on how to select optimum intervals for inspection and maintenance [9], [10]. An annual cleaning of the bridge superstructure is a simple and cost-effective measure to prolong the service life. The cost has been estimated to 0.4 $/(m^{2}year) [11]. The same report states that silane impregnation costs 5 $/m^2 and sustains seven years resulting in 0.7 $/(m^{2}year). This indicates that impregnation also is a cost-effective maintenance measure.

4 Surface protection

Water and de-icing salt are the cause of several deterioration processes in concrete [12]:

- Frost damage in pure water,
- Frost damage in saline water,
- Alkali-silica reactions (ASR),
- Secondary damages due to the calcification of the entrained air system,
- Carbonation initiated reinforcement corrosion and
- Chloride initiated reinforcement corrosion.

If the concrete can be protected from water and salt, the deterioration risk and degree will diminish substantially. A dense and crack-free concrete does not need any protection, but such concrete structures are difficult to produce. Some methods to reduce permeability increase the crack risk. High cement content may increase the risk of early-age thermal cracking while silica fume may enhance the risk of plastic shrinkage cracking. The Swedish road authorities have concluded that concrete elements, e.g. edge beams and columns in the splash-zone, ought to be protected. In order to prevent frost damage, outdoor concrete structure must be able to breath. Vapour has to be able to leave the concrete surface while liquid water has to be prevented from penetrating into the concrete. Consequently, diffusion open systems must be selected. Water-repellent systems based on silane and siloxane fulfil these demands and have successfully been used by the Stockholm City [12], [13].

During several decades, various kinds of superficially applied surface protections have been used to protect concrete in severe environments. Examples are paints, plastics, oils, epoxies, and silanes [14]. In USA, surface treatments have been used since the 1970’s. Two field tests on deep polymer impregnation were carried out in 1975 and 1985, respectively, in Pennsylvania [15]. Test areas were impregnated with methyl methacrylate to a depth of 100 mm. The impregnation was shown to have a retarding effect on the reinforcement corrosion rate. After nine years, the corrosion rate was reduced to 10 to 40 % in impregnated areas compared to the rate in untreated ones.

In Sweden – especially in the Stockholm area – the use of de-icing salt is extensive since the temperature from mid November through March is oscillating around 0° C. A number of 58 salt occasions was registered during the winter 1996-97 [16]. Consequently, the road authorities in Sweden and Stockholm City are very interested in surface protection.

In order to secure a proper function of the impregnation, a sufficient amount water repellent agent has to penetrate into the concrete to a sufficient depth. Silane and siloxane are deteriorated if they are exposed to direct ultra violet sunlight. The siloxane molecule is larger than the silane molecule and has on account of this greater difficulty to penetrate the concrete. The use of siloxane should therefore be limited to concrete elements with course-porous surface structures. A good impregnation result is dependent on a clean surface without oil, dust and other contaminations at the moment of application. The water repellent agent can either be applied in a liquid or gel. The impregnation depth increases with decreasing humidity in the concrete, increasing permeability and increasing capillary suction time. The possibility to increase the suction time increases if the water repellent agent is a part of a gel, usually based on bentonite [12].

The function of the surface protection is dependent on the quality of the impregnation. A total of 1224 test specimens have been tested in the laboratory to investigate the influence of relative humidity (*RH*), water cement ratio (*w/c*) and absorption time on the penetration depth [17]. The water repellent agent – an octylsilane – was applied as liquid (1116 specimens), gel (54) or cream (54). The investigation covered eleven different combinations of concrete quality and application method, three different *RH* values and ten different absorption times from 20 s to 7 days. Both *w/c* and *RH* had a substantial influence on the penetration depth. The penetration depth ratio between the most beneficial combination (*w/c* = 0.70, *RH* = 65 %) and the less beneficial one (0.40, 90) was 30. Application with gel and cream worked well. Cream and gel applications equal a liquid absorption time of 10 minutes and 24 hours, respectively.

The effect of impregnation (with silane) on moisture profile, chloride ingress and frost resistance in two different concrete mixes (*w/c* = 0.40 and 0.70) have been investigated on 36 laboratory test specimens [18]. 20 mm from a rain-exposed surface, the impregnation has a significant effect on the moisture level in both concrete mixes. At 60 mm depth, the effect is smaller than 2 %. Silane impregnation has a beneficial effect on both chloride ingress and frost resistance in the low quality concrete (w/c = 0.70), but hardly any effect on high quality concrete (0.40). The authors concluded that impregnation might not be necessary in cases with low *w/c* ratios and thick covers, i.e. in civil engineering structures designed and constructed according to modern recommendations. The tests were, however, limited to 3 months, why long-term tests are needed before more definitive conclusions can be drawn.

One important question is the long-term performance of surface protections such as impregnations. An American estimation [11], citied in Chapter 3, estimated the service life tom 7 years. Swedish field tests show that the impregnation has a substantial effect on the water absorption even after 9 years [19]. In total 27 Stockholm objects were investigated. The water absorption of impregnated surfaces was only 25 % of corresponding value for untreated surfaces. The water repellent agent was applied to the surface through a liquid containing 20 % silane and siloxane and 80 % ligroin. Ligroin and other solvent were disposed in 1994. Presently the Stockholm City uses gel. The investigation referred above [17] shows that gel is more effective than liquids. Consequently, nothing contradicts the statement that the impregnations applied today will function properly during at least 10 years.

5 Proposed research projects

Based on the pilot study [5], five Ph.D. projects were proposed. One of these concerns impregnation of concrete structures. In the research application problems, research significance, aim and method were described as follows:

The research on impregnation has mostly been experimental. The theoretical research has not reached the same level. Why does impregnation with gel and cream lead to much better results than impregnation with liquids, why does impregnation in dry concrete lead to the best results, why is the impregnation depth greater in normal strength concrete than in high performance concrete? Some of these questions may be given easy answers based on empirical studies and logical reasoning. In order to quantify the differences and benefit as much as possible from the advantages of the products, you have to conduct phenomenological studies on the transport mechanisms of impregnation substances into concrete, how they influence and interact with the concrete's microstructure and to investigate the interaction between microstructure, transport processes and the surface protection of the impregnated concrete. The project aims at analysing how common impregnation substances work in concrete and find explanation models to the promising results that have been obtained from the research during the last decade. The academic goal is a doctoral degree. The work will be divided into six phases: (i) a literature study, (ii) analyses of test specimens, (iii) selection of models, (iv) testing of these models, (v) refinement of the most promising models and (vi) testing and verification of the new models.

In February 2004 a Ph.D. project based on the description above was inaugurated at the Swedish Cement & Concrete Research Institute (CBI) and Royal Institute of Technology (KTH), both in Stockholm, Sweden. The Swedish Research Council for the Environment, Agricultural Sciences and Spatial Planning financially supports the project. Mr. A. Johansson, M.Sc., is the Ph.D. student. The author supervises the project with assistance by Dr. J. Trägårdh and Dr. M. Janz, both CBI. The project is described in detail in [20] and the first test results will be presented soon [21].

6 Concluding remarks

In a pilot study by the author [5] active bridge maintenance is defined as effective and optimum preventive bridge maintenance. The hypothesis is that the preventive bridge maintenance could be optimised through thorough analyses of properties of the bridge element, actual mechanical stresses and ambient microclimate. The Swedish road authorities have used impregnation as a measure of active bridge maintenance without using this term. However, since impregnation with silane and siloxane successfully have been used primarily to bridge elements exposed to severe environments, it might be possible to denote it active bridge maintenance. This paper summaries some promising field experiences of impregnation and shows that empirical investigations predominates the research overwhelmingly. Against this background a Ph.D. project has been proposed to theoretically explain the promising field experiences. Satisfactorily such a Ph.D. project has also been inaugurated in Stockholm, Sweden.

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