Water Repellent Treatment of Building Materials
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Ecological Aspects of Water-Repellent Treatment

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Abstract

The use of deicing salts on roads may lead to chloride ion induced corrosion. This deterioration mechanism has become one of the most frequent reasons for repair measures within the planned service-life of concrete structures. One way of reducing the risk of chloride ion induced corrosion is the prevention of the penetration of dissolved chloride into the concrete. By water repellent surface treatment the water and chlorid penetration rate can be substantially slowed down. As the water repellent treatment has a limited service-life and its performance and durability depend on many parameters, no standard performance criteria for the water repellent treatment could be defined yet. This study compares the economical and ecological impact of a water repellent treatment with the impact of repair measures. Results are meant to be used to define standard performance criteria. These criteria must take into consideration not only the performance with respect to the reduction of chloride penetration rate, but also garantee the required durability.

The expected life-time of an untreated reinforced concrete element can be estimated by modelling the mechanism of chloride ion induced corrosion. Based on this value the frequency of repair measures within a planned service-life of 100 years can be determined.

Comparing the ecological and economical impact of a water repellent treatment with the corresponding impact of repair measures allows us to the formulate performance criteria concerning the durability and the minimum required service-life of a water repellent treatment. The water repellent treatment has to prevent repair measures within the planned service-life of a structural concrete element. Technical criteria concerning the performance of a water repellent treatment within the minimum required service-life can be formulated.

Keywords: life cycle assessment, durability, water repellent treatment, restoration, chlorides

1 Introduction

For several decades, the winter maintenance of streets and roads in regions where temperature during wintertime drops below zero necessitated the use of deicing salts (usually NaCl, sometimes $CaCl_2$). Meanwhile these deicing salts have become one of the major reasons for restoration of reinforced concrete elements. If a concrete surface gets into contact with water containing chlorides, solved chlorides are transported through the pore system into the concrete. If these chlorides get onto the surface of the reinforcement bars and if their concentration exceeds a critical threshold concentration, steel corrosion can under certain conditions be initiated. The penetration rate of chlorides into the concrete structure depends on both the decisive transport mechanism of water into the concrete and on the pore size distribution. If intervening measures are not undertaken in due time, corrosion damage is, when noticed, often too advanced to allow a further safe use of the construction. A restoration measure might become necessary.

One way of drastically reducing the probability of chloride induced corrosion and of the necessity of a complete restoration is to hinder the penetration of water containing solved chlorides into the concrete structure. One appropriate surface technological measure is the water repellent treatment.

This paper evaluates the possible ecological benefits of a repeated water repellent treatment aiming at the prevention of a restoration measure. It is based on a former publication [1] and further elaborates the method of life cycle assessment used to determine the ecological impact of both the restoration measure and the water repellent treatment.

2 Water repellent treatment and durability

A water repellent treatment reduces the water uptake of the concrete element. On one hand, it thereby increases the frost resistance of the concrete element [2], on the other hand it reduces the penetration rate of solved aggressive substances into the structure element.

This paper focuses on the property of a water repellent treatment to reduce the penetration rate of chlorides into a concrete element. As experience has shown, a properly applied water repellent treatment enhances the resistance against chloride penetration, thereby retarding the date at which a restoration becomes necessary [3]. Table 1 sums up results found in [3] concerning the effect of a water repellent treatment on the chloride penetration.

Latest experience shows, that various factors must be taken into account for the evaluation of a water repellent treatment [4]. A decisive criteria for a water repellent treatment is the distinctive reduction of the water uptake. As chlorides are most frequently solved in water when transported into the concrete element, a reduction of the water uptake increases the resistance of the treated structure element against chloride penetration. Experience shows, that the efficacy of a water repellent treatment applied with currently used application technology decreases with time, so that the application has to be repeated after a certain period. Müller and Wittmann [5] showed in investigations concerning traffic structure elements that the time period leading to a significant reduction of efficacy may vary from less than 3 to more than 14 years. These results show that strict requirements concerning the efficacy and durability of a water repellent treatment are necessery if the aims set are to be met.

The performance of a water repellent treatment depends next to other parameters on the penetration depth of the water repellent agent into the concrete as well as the distribution of the agent in the surface layer. These values themselves depend on parameters like the conditions during application (as the humidity of the concrete) or the properites of the concrete (as the porosity) or of the water repellent agent (as the molecular size and content of active agent) or on the application technology. Latest investigations [6] have shown, that an application with a new technology (the box technology introduced in [6]) considerably improves the penetration depth of the water repellent agents.

The complex interdependence clearly shows that the planning engineer has to elaborate a whole requirement profile for an intended water repellent treatment. Next to well defined technical requirements and economical criteria these requirements should also contain ecological aspects.

From a technical point of view a water repellent treatment is a surface technological measure, that can be used for the protection against chloride induced corrosion. It should hinder the chloride penetration at least to such an extent, that a repeated water repellent treatment can prevent a costly restoration during the planned useful life of the structure element.

Next to the efficacy requirements the water repellent treatment should also fulfill requirements concerning its durability. These requirements have to be defined for the bidding and controlled during the quality control after the application of the water repellent treatment. The quality control is meant to determine mainly the penetration depth, the content of water repellent agents and the reduction of water uptake due to the water repellent treatment. The values determined during the quality control are to be compared to the values required in the bidding documents. There is no absolute clarity or concordance concerning the requirement profile. Bidding documents differ sometimes significantly regarding the tests and requirements requested for a water repellent treatment [8].

A unique quality control does not give direct hints regarding the long term behaviour of a water repellent treatment, so that it is very difficult to

Table 1: Influence of a silane based water repellent treatment on the chloride penetration depth [3]. The chloride content in kg/m^3 is indicated for a depth of 13 and 25 mm after 10, 20 and 30 weeks respectively.

exposure ration weeks	**penetration depth mm**	**chloride content kg/m^3**			
		horizontal surface		vertical surface	
		untreated	with water repel. treatm.	untreated	with water repel.treatm.
10	13	1.1	0.0	1.9	0.1
	25	0.1	0.0	0.2	0.0
20	13	2.2	0.0	3.4	0.1
	25	0.1	0.0	0.1	0.0
30	13	4.1	0.1	4.5	0.1
	15	0.6	0.0	0.7	0.0

include requests concerning durability in the requirement profile and to control them in the quality control after application. Nevertheless the durability and resistibility of the water repellent treatment strongly influences the operational expenses for renewal during the life time.

Detailed investigations that might allow the elaboration of a model to estimate the long term resistibility of water repellent treatment are not yet available.

In order to define the requirements for the life span of a water repellent treatment, the following approach has been adopted:

It can be stated that a repeated water repellent treatment makes sense if it is both economically and ecologically more advantageous than a restoration that would become necessary without protecting measures.

A goal of this study is therefore to elaborate an approach for the formulation of the minimum needed life time of a water repellent treatment by using the example of a reinforced concrete pillar exposed to chloride penetration. From the requirements regarding durability, the criteria for the efficacy of a water repellent treatment are to be derived. In order to determine the needed durability, the water repellent treatment as a surface technological measure is compared to a realistic restoration regarding its ecological and economical impact.

The planned life time of the structure element is set to 100 years. The number of ecologically and economically justifiable repetitions of a water repellent treatment during that period will be determined. Additionally the technical requirement, meaning the efficacy of the water repellent treatment concerning the reduction of chloride penetration, is to be estimated, presuming that, if there is need, a regular renewal of the application of a water repellent treatment can prevent a restoration.

The costs can be determined relatively easily by ascertaining the execution costs from the industry, whereas the impact of a restoration or a water repellent treatment on environment can be estimated using a socalled life cycle assessment.

3 On Life Cycle Assessment

3.1 General remarks

The life cycle assessment is a methode used to determine the impact of a process, a measure or product on the environment "from the cradle to the grave", meaning the whole life cycle from the raw materials and the necessary converting processes over the use of the finished product to its (partial) recycling or disposal.

Over this life cycle, both the input to the different stages (i.e. the energy and raw materials needed for the production of compounds as well as infrastructure) and the output (emissions into air, water and ground as well as waste) are thoroughly determined. It can therefore be said that the life cycle assessment consists of a quantitative input/output-analysis.

The use of energy and raw materials together with the emissions produced over the whole life cycle are afterwards evaluated accordingly to their impact on the environment.

3.2 The systematics of life cycle assessment

The life cycle assessment is carried out in 4 steps:

In the goal definition, the aim of the life cycle assessment (whether it is meant to be used for comparison, for optimization or just for information) as well as the object and the depth of the investigations have to be defined.

The definition of the object of the life cycle assessment includes next to the description of the object of investigation itself the definition of the spatial and temporal representativeness and the definition of the functional unit which the results refer to. For the case of the water repellent treatment, the object was defined as a bridge pillar with given dimensions in the splashing zone of a road in vicinity. The spatial or geographical definition (in this case Switzerland) gives indications f.e. on the climatic circumstances to which the pillar is being exposed or on the building standards and norms applied, whereas the temporal definition gives clues f.e. regarding the standard technologies used at that time.

The system boundaries indicate, which phases of the life cycle are taken into consideration. For a structure element, these phases can be the construction, use, restoration or waste management of the building materials. Model presumptions like the energy model which defines the energy mix (the share of energy that constitutes nuclear or hydraulic energy or that is gained from fossile fuels) or the waste model (that indicates the share of recycled or deposed materials) have to be included in the boundary system. This is due to the fact that f.e. the production of hydraulic energy usually involves less emissions than the production of energy from fossile fuels. As one of the major requests for a life cycle assessment is its reliability and representativeness, these presumptions have to be clearly formulated.

The next stage of the life cycle assessment is the inventory analysis, where the actual data are collected and listed. As the inventory analysis can be considered as an input-ouput-analysis Schematic example for the inventory analysis of a structure element.

For a process, the input to the process, which consists of both the use of raw materials and energy, as well as its output, which consists of products and side-products as well as waste and emissions, have to be determined.

Figure 1 gives a schematic example for the inventory analysis of a structure element.

The list of data should be as complete as possible. This request immediately leads to the problem of infinite regression: for the inventory analysis to be complete the data collected for each input would f.e. have to include data on the construction and maintenance of the production site, with all the inputs and outputs for the materials used for the construction and maintenance of the production site and so on. In order to keep the effort for the data collection in sensible limites relevant and irrelevant processes have to be distinguished. The criteria for the choice of the relevant processes has to be carefully indicated. The inventory analysis is an objective collection of data on material and energy flows during the whole defined life cycle and does not include an evaluation.

The third step of the life cycle assessment consits of the classification according to ecological problem types. The emissions determined in the inventory analysis are classified qualitatively (according to their effect) and quantitatively (depending on the intensity of the emissions). Before the actual classification can start, the « classes » to be considered, meaning the ecological problems that are of interest, have to be defined. The ecological problems listed in the model elaborated by the Centruum voor Milieukunde Leiden (CML), on which this study is based, consists of effects like the depletion of abiotic ressources, the depletion of biotic ressources, the depletion of the ozone layer, the enhancement of the greenhouse effect, human toxicity

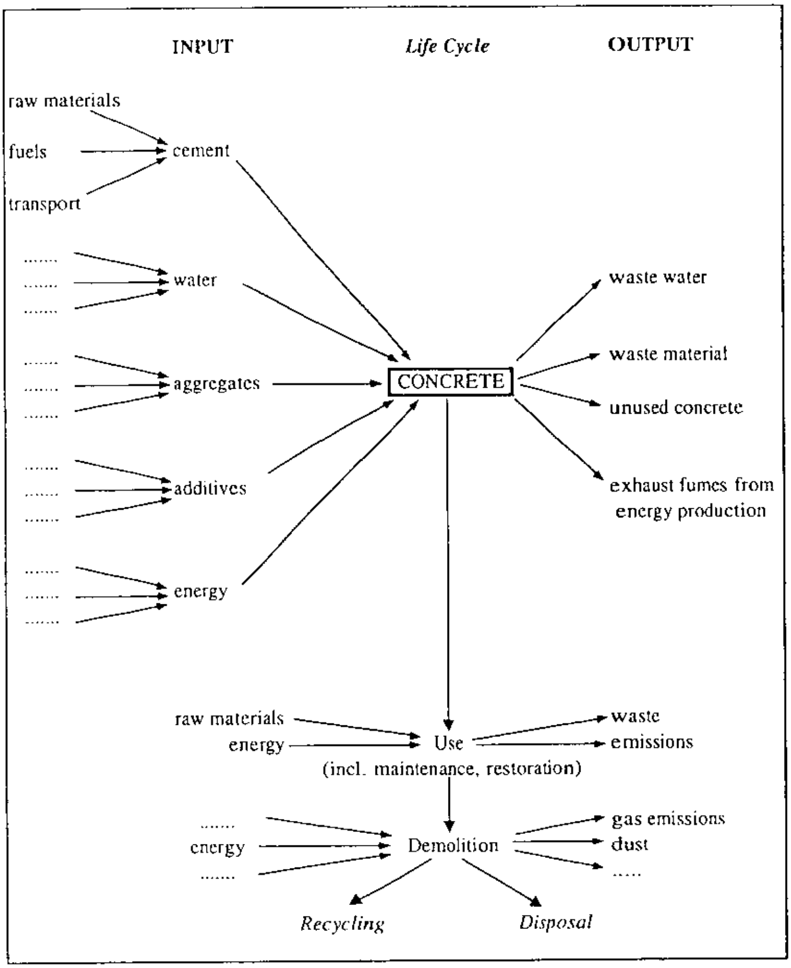

Figure 1: Schematic example for the inventory analysis of a structure element.

and ecotoxicity, the photochemical oxidant formation, the acidification of soils, the nutrification of surface water and ordour.

The emissions of a process are then classified according to their effect on the environment in the selected ecological problem types. One substance can be relevant in several ecological problem types. After the effect to which an emission contributes has been identified (qualitative classification), the intensity of the effect has to be determined (quantitative classification). For that purpose the CML model defines for each ecological problem category a reference substance. The amount of the reference substance, that has the same effect regarding the ecological problem considered than the amount of the specific substance emitted, has to be determined. The equivalent amounts of the reference substance can afterwards easliy be summed up and their sum gives an indication on the environmental effect of a whole process regarding a specific ecological problem category .

The effect of a process regarding a certain ecological problem can therefore be calculated as follows:

$$EE = \sum_i SEE_i \tag{1}$$

with EE: Ecological effect [kg/functional unit]

SEE_i: specific ecological effect of a substance i [kg of the reference substance/kg of the substance i]

m_i: mass of the substance i [kg of the substance i /functional unit]

The ecological problem categories considered in this study are represented in Table 2

By determining the environmental effect according to the ecological problem types an overview over the environmental impact can be elaborated. This overview does not represent an evaluation. The environmental effect categories can not be compared to one another, as it is not possible to determine which environmental problem among these completely different effects will in the short or in the long run, globally or locally cause the biggest damage. Therefore this method does not allow to combine different environmental categories like the green house effect or the depletion of the ozone layer to one common value expressing the environmental impact of a sub-

Table 2: Environmental problem categories considered

ecological effect	reference
greenhouse effect (global warming)	CO_2-equivalent
depletion of the ozone layer in the stratosphere	CFC-11-equivalent
formation of photo-oxidants (smog formation)	C_2H_2-equivalent
acidification of the soils through acid rain	SO_2-equivalent
eutrophication (over-fertilisation of surface water)	PO_3-equivalent
energy (embodied energy and process energy incl. waste heat)	MJ

stance. Instead of reducing the whole range of effects to one "eco-point" the resulting product profile allows a representation of the environmental impact regarding different ecological areas.

While comparing products influencing different ecological problem categories, it can be very difficult to deduce one absolute and valid evaluation. In short the purpose of the brievly presented model for life cycle assessments elaborated mainly by the CML Leiden is to represent of the ecological impact of products or processes without subsequent evaluation. It is especially used for the optimization of processes and procedures. Further information concerning the life cycle assessment can be found in [7].

4 Scenario restoration

Data concerning the realisation of the different steps constituting a restoration measure were taken from literature or determined with the support of executing enterprises.

The restoration measure analysed in this study consists of the following steps:

- removal of the covercrete and uncovering of the reinforcement bars by high pressure hydrojetting,
- cleaning of the steel surface using sandjetting,
- corrosion protection of the reinforcement bars using epoxy sealers,
- pre-treatment of the concrete surface by sprinkling with water,
- application of a shotcrete layer,
- curing of the surface of the applied shotcrete layer.

A more detailed description of the considered restoration steps is given in [9]. For a better understanding of the results of the life cycle analysis should be noted, that the sandjetting and highest pressure hydrojetting machines both use a compressor run by diesel fuel. The removal of the covercrete and the cleaning of the steel surface of the reinforcement bars are the restoration steps with the highest energy consumption.

5 Scenario water repellent treatment

The data regarding the production of a water repellent agent (in this case a silane) were determined both from specifications from the producer and from literature.

The main compound of the water repellent agent is the tetrachlorsilane (TCS). The production process has been reconstructed from literature specifications following the Müller-Rochow process. With an efficiency of about 80 %, TCS can be obtained from silicon and allyl chloride (CH_3Cl) during a highly exothermic reaction. It has been presumed, that $(CH_3)_3SiCl$, which amounts to about 20% of the output, is burnt in an incineration plant for special waste.

The actual production process and production energy for silane from TCS was provided by a producing company. The compounds that are important for the ecological discussion are TCS (about 21 weight-% referring to the original materials), the hydrocarbons n-e-octene and olefines (about 17 w.-%) as well as ethanol (about 30 w.-%). The ethanol is used as a solvent. It is partly set free through hydrolysis after the application of the water repellent agent. This emission of ethanol after the application of the silane must also be taken into consideration for the ecological evaluations.

Before the water repellent agents are being applied the concrete surface has to be cleaned from major soilings. For this purpose it is usually sufficient to thoroughly brush the concrete surface. If the surface shows intense soilings or incrustations, it can be cleaned by steam jetting. The application of the water repellent agents should in this case only be carried out after the concrete surface has sufficiently dried. Afterwards the water repellent agent is applied without pressure to the surface.

For the ecological and the economical considerations, as well the cleaning of the concrete surface as the production and application of the water repellent agents have to be considered.

6 Model presumptions and boundary conditions

6.1 Object specifications

The structure element used as an example for the investigations is an existing reinforced concrete bridge pillar on the highway N9 between Lausanne and St. Maurice in Switzerland. For the estimation of the risk of corrosion, a thickness of the covercrete of 3 cm over the first row of reinforcement bars was presumed. This value corresponds to the requirements of the Swiss building norms SIA. The chloride concentration was then calculated at the presumed depth of the point of gravity of the reinfrocement bar, i.e. at a depth of 3.5 cm beyond the concrete surface.

The stage of the life cycle on which this study concentrates, is the useful life time of the structure element. Both production and waste management of the bridge pillar have not been taken into account, because the ecological impact of these phases are virtually identical regarding the considered environmental problems for both scenarios water repellent treatment and restoration. The energy consumption and the emissions due to traffic diversion or traffic congestion due to restoration measures have not been considered either. Here should nevertheless be noted, that these emissions can possibly be considerable.

The structure element is an uninhabitated reinforced concrete element exposed to deicing salts. Because the structure element is not inhabitated, the energy consumption due to the usage of the structure, such as heating energy, can be omitted.

The following investigations mainly focus on aspects of durability and the ecological and economical effect of certain measures taken during the useful life in order to extend the life time of a concrete element. The measures analysed are the restoration measure and the water repellent treatment. For the described structure element, the requirement profile for a water repellent treatment strongly depends on the intensity of exposure to chlorides. The more intense the exposure is, meaning the concentration of chlorides and the frequency of contact with water containing chlorides, the higher the risk of chloride induced corrosion for an unprotected structure element becomes.

6.2 Restoration measure

In order to be able to estimate the life time of an unprotected structure element exposed to solved chlorides, a certain number of model assumption have to be taken. For a structure element in cyclic or unregular contact with water containing deicing salts the transport of chlorides has not yet been described in a generally accurate way. In [10] a model for the estimation of the life time for road elements is explicitly described, which distinguishes three different exposure conditions:

- for horizontal structure elements: exposure to a solution of deicing salts standing on the surface,
- for vertical or inclined structure elements: exposure to splashing water,
- exposure to mist.

It could be shown in [10], that the chloride content in case of a standing solution of deicing salts is about 40 times higher than in case of exposure to mist and about 7.5 times higher than in case of exposure to splashing water.

In the present study, a method using an "effective" diffusion coefficient has been used for the estimation of the life time for a structure element not protected with a water repellent treatment. The calculations rely on data from literature [11].

In [12], criteria have been found that use the concentration of chlorides on the surface of the reinforcement bars as an indicator for the approximative estimation of the condition of the reinforced concrete element.

- 1st criterion
  The time at which the corrosion reaction is initiated depends on the content of free chlorides on the steel surface. The share of free chlorides depends on a multitude of parameters such as type and quantity of additives and admixtures or the cement content and cement composition. To be on the safe side it has been assumed that corrosion can be initiated at chloride concentrations at the steel surface of 0.4 w.-% (referring to the cement weight) and above.
- 2nd criterion
  Significant damage due to the corrosion of reinforcement bars can be expected in the presence of the necessary humidity around a concentration of 6 kg Cl^- per m^3 of concrete, which corresponds to 0.25 w.-% Cl^- referring to the concrete weight [12], or 1.71 w.-% referring to the cement weight (with 350 kg cement/m^3).

From the applied literature data [11] (for a bridge pillar with water/cement-ratio of 0.4 under cyclic exposure to splashing waves in a costal area) and according to the above criteria, corrosion can be induced after about 6 years, whereas after about 40 years major damage has already occurred, so that a further use becomes too risky. It can therefore be said that under such extreme conditions a restoration can be necessary after a time period of only 15 years.

The considered example constitutes a worst-case-example, which indicates that even for less extreme conditions (like a less intense exposure to chlorides) there is considerable risk that a one-time restoration of a structure element without surface technological protection may become necessary within the planned useful life.

The quality of the restoration measure and therefore the resistibility of a structure element after restoration is very hard to estimate. There are very little investigations on the resistibility of reinforcement steel covered *at post* with an epoxy coating, that would directly relate the quality of the coating to its performance in protecting against corrosion. An epoxy coating can constitute a durable protection against chlorides if it is free of cracks or defects. On the other hand, if the application has not been carried out thoroughly enough, a local corrosion reaction can be accelerated.

6.3 Water repellent treatment

The performance of a water repellent treatment has been measured for a bridge pillar on the Gotthard route in Switzerland, which was treated with a water repellent treatment and exposed to splashing water containing chlorides [13]. The content of chlorides found are represented in table 3. Even though data were not available for untreated samples exposed to the same environmental conditions, the low concentration of chlorides point to a very good action of the water repellent treatment. At the time of the measure

Table 3: Chloride concentration in bridge pillars 11 years after the application of a water repellent treatment [13]

structure element	depth from surface	chloride concentration Cl_C [M.% ref. to concrete]	chloride concentrationCl_{PC}[1] [M.% ref. to cement]	remarks
pillar1	10-20	0.016	0.106	average
pillar2	20-30	0.023	0.153	single value

[1]estimation for a cement use of 350 kg/m^3

ments the water repellent treatment had already been applied for 11 years. Whether the water repellent treatment is still active has not been controlled. Neither on pillar 1 nor on pillar 2 has corrosion been observed.

This example shows that a water repellent treatment allows in practice to significantly retard the necessity of a restoration measure.

6.4 Analysed life cycles

The following scenarios have been considered:

- a structure element treated with a water repellent treatment and where a restoration is not necessary during the useful life,
- an untreated structure element, that has to be restorated once,
- an untreated structure element, that has to be restorated twice because the first restoration was not carried out carefully enough.

7 Costs

The costs for both the complete restoration and the water repellent treatment represented in Table 4 have been determined together with the engineering company Ernst Winkler und Partner AG [13] and are based on the specifications regarding the dimensions of the structure element and the extent of the restoration.

Table 4: comparison of the costs of different measures

measure	standard price [CHFr/m^2]
restoration	891.-
water repellent treatment	35.-

8 Ecological evaluation

8.1 Procedure

The life cycle assessment has been generated with the model from the CML Leiden and using the database as well as the software EMIS by Carbotech [14]. Further explanations on the software can be found in [9]. A major problem for the generation of life cycle assessments are the frequently missing process data, especially for chemicals. The data used in this study has been determined from information from the industry and from research on published literature. The data for secundary materials and raw materials that are used in low quantities during the process are replaced by chemically similar compounds. The final results are only very slightly influenced by these approximations.

8.2 comparison of the water repellent treatment to the restoration

8.2.1 General remarks

As a general and summarizing evaluation of the environmental impact does not seem very useful in this context, the different ecological effect categories will in the following be compared seperately.

As it has turned out that both the processes pre-treatment of the concrete surface with sprinkling water and curing have only very little impact on the environment (they mainly use water and only very little energy), these steps will not be discussed any further in the evaluation of the ecological impact of a restoration.

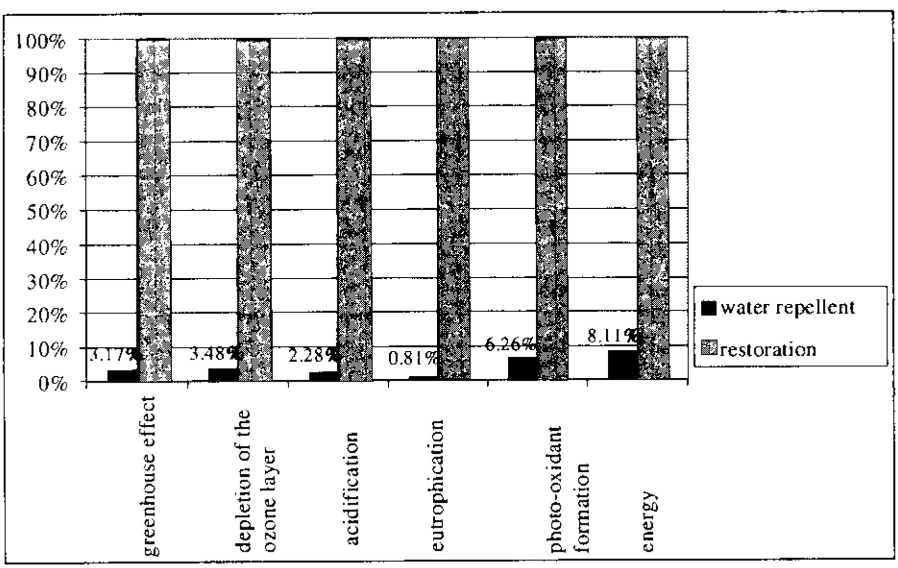

Figure 2: comparison of the ecological impact of a water repellent treatment to the impact of a restoration

In [9] the restoration steps hydrojetting, pre-treatment and application of a shotcrete layer and curing have already been analysed using the example of a restoration due to carbonation of the covercrete. For the analysis of a water repellent treatment, the production of the water repellent agents and the cleaning of the concrete surface together with the application of the water repellent agents have been considered. It could be shown, that the influence of the steps cleaning and application is so small compared to the effect of the production process, that these steps will not be discussed any further.

The results are represented in Figure 2. The following remarks on the results focus on the ecologically most significant elements or compounds for the specific measure.

8.2.2 greenhouse effect

- Restoration measure

  The impact of a restoration measure regarding the green house effect corresponds to the effect of 71.85 kg CO_2 per square meter peripheral surface of the pillar. The major part (about 60 %) of these emissions are due to the combustion of fossile fuels in this case diesel for sandjetting or hydrojetting. The energy necessary for the production of cement for the shotcrete represents another 40 % of the impact. The main greenhouse gas produced is CO_2.

- Water repellent treatment

  The measure water repellent treatment is responsible for emissions of the equivalent of 2.28 kg CO_2 of greenhouse gases, which corresponds approximately to 3.2 % of the emissions due to a restoration. The major share is caused by the use of energy from fossile fuels for the production of ethanol (35%) as well as the production of silicon for the basic material trichlorsilane.

8.2.3 Ozone depletion in the stratosphere

- Restoration measure

  The ozone depletion stems to about 90 % from the combustion of diesel for the sandjetting rsp. hydrojetting. As the laughing gas (N_2O) emitted during the combustion of diesel is very slow in reacting it can ascend onto the stratosphere, where it contributes to the depletion of the ozone layer. The effect of these emissions corresponds approximately to 53 mg chlorfluorocarbon CFC-11 CO_2 per square meter peripheral surface of the pillar.

- Water repellent treatment

  The ozone depletion potential of a water repellent treatment corresponds approximately to 3.5 % of the potential of a restoration, i.e. to the effect of about 1.9 mg CFC-11 per square meter of treated surface. About 35% of the risk can be referred to the trichlorsilane used for the water repellent agents and about 30% to the n-e-octene. The ozone depletion potential comes from the emission of very stable gases during the production of refinery products, that become reactive only in the stratosphere to deplete the ozone layer.

8.2.4 Acidification

- Restoration measure

  The acidification of the soil is to about 80 % due to nitrogen dioxide emitted during the diesel combustion for sandjetting and hydrojetting. The acidification potential of the emissions caused by a restoration corresponds to about 666 g SO_2 per square meter of surface.

- Water repellent treatment

  The acidification potential of a water repellent treatment per square meter corresponds to about 15.17 g SO_2, i.e. about 2.3 % of the effect due to a restoration measure. The effect can mainly be referred to nitrogen oxides (NO_x) emitted during the energy generation from fossile fuels for the production of ethanol (about 35%) as well as silicon (40%) used for the production of trichlorsilane.

8.2.5 Eutrophication

- Restoration measure

  The "over-fertilisation" of surface water due to a restoration measure corresponds in its effect to 102 g of phosphates per square meter of surface. About 90 % of this effect is due to the emissions of nitrogen oxides from the combustion of diesel both for sandjetting and for hydrojetting.

- Water repellent treatment
  The "over-fertilisation" of water due to a water repellent treatment corresponds approximately to the effect of 0.82 g of phosphates per square meter, which is about 0.8 % of the effect of a restoration measure. The major part (40%) can be referred to the production of trichlorsilane and more specifically of silicon. A lesser amount of about 20 % can be referred to the nitrogen oxide emissions from the energy production for the production process of ethanol.

8.2.6 Oxidant formation

- Restoration measure
  The restoration process causes emissions per square meter with a potential for oxidant formation corresponding to the effect of about 750 g ethylene. About 90 % of these emissions are combustion gases from the diesel combustion for sandjetting and hydrojetting.
- Water repellent treatment
  Regarding the formation of oxidants in the troposphere the effect of the water repellent treatment corresponds approximately to the effect of 46.9 g ethylene, which is about 6.3 % of the effect of a restoration measure. A significant part (about 40%) can be referred to the energy use for the production of silicon further used in trichlorsilane production and about 30% to the energy intensive production of ethanol.

8.2.7 Energy

- Restoration
  The energy necessary for a restoration measure amounts to about 908 MJ per square meter of surface to be restored. The major share (about 50%) can be attributed to the very energy intensive removal of the covercrete by hydrojetting. The energy consumption for the coating of the reinforcement (incl. the jetting with sand rays) amounts to about 30%. The production of cement is only responsible for about 20% of the energy consumption.
- Water repellent treatment
  The production as well as the application of the water repellent

agents consume about 73.7 MJ per square meter of treated surface, which corresponds approximately to 8.1 % of the energy necessary for a restoration measure. The most energy intensive process is the production of trichlorsilane with about 35% of the total energy consumption of the water repellent treatment. About 25% of the total energy use are needed for the production of ethanol.

9 Discussion

9.1 Costs

When the water repellent treatment is compared to the restoration measure regarding their resp. costs per square meter, it becomes clear that 25 water repellent treatments could be applied before a restoration becomes more profitable for the building owner than a repeated water repellent treatment, as long as its requirements concerning the efficiency, i.e. the reduction of the chloride penetration, are fulfilled.

Comparing these results with the life scenarios considered for an unprotected structure element, the following technical requirements can be derived:

- case 1: one restoration necessary during the planned useful life of the unprotected element

From the economical perspective, the minimum required life time for a water repellent treatment amounts to 4 years. During this life time, an accumulation of chloides that in the useful life may end up to cause significant damage to the structure element, so that the planned use is no longer safe, has to be prevented. It is relatively complicated to derive the progress of the corrosion reaction from a reliable model. Applying the criteria defined in [12] for the estimation of significant damage at the structure element and presuming, that in case of a repeated application of a water repellent treatment a constant quality can technically be realized, leads to the following request: a water repellent treatment has to prevent that the increase within 4 years of the chloride concentration above the reinforcement bars exceeds a maximum of 0.01 weight-%, referring to the concrete.

After testing the request on the chloride contents observed according to [13] (Table 3), it becomes clear that the request is met in that particular case.

- case 2: twofold restoration during the planned useful life of the unprotected element

If a second restoration can be supposed to be neccesary during the useful life time of the unprotected structure element,a minimum life time for the water repellent treatment of only 2 years could be required from the economical point of view. During this life span a maximum increase of the chloride concentration above the reinforcement bars of about 0.005 weight-% should not be exceeded.

9.2 Ecology

Figure 2 shows that in average the environmental effect of a water repellent treatment corresponds to about 4 % of the ecological impact of a restoration (the effect of the restoration being set to 100% for each environmental problem.

The energy use for a water repellent treatment corresponds with slightly more than 8 % of the energy used for a restoration and has thereby the highest percentage rate, referring to the effect of the restoration measure. This is due to the high energy use for the production of the water repellent agents. These results indicate that a water repellent treatment, even when repeated up to 12 times, is both ecologically and economically more interesting than a restoration.

With the environmental problem categories defined as above, the actual harmful emissions related to the production and use of energy are included in the different categories, so that the observable harmful influence (the emissions) due to the use of energy is already taken into account in the remaining categories.

A surplus of energy use might therefore be accepted (with the emissions still included in the remaining categories). In this case, the water repellent treatment could be repeated up to 16 times, before the effect of the repeated water repellent treatments approaches in another environmental problem category the level of the ecological impact of a restoration. After the 16^{th} application of a water repellent treatment, the potential for oxidant formation of the water repellent treatment reaches the level of the effect of the restoration measure.

It can therefore be concluded, that up to the 16^{th} water repellent treatment the surface technological measure causes less ecological damage than a restoration measure. This leads from the ecological perspective to a minimum renewal period of 6.25 years.

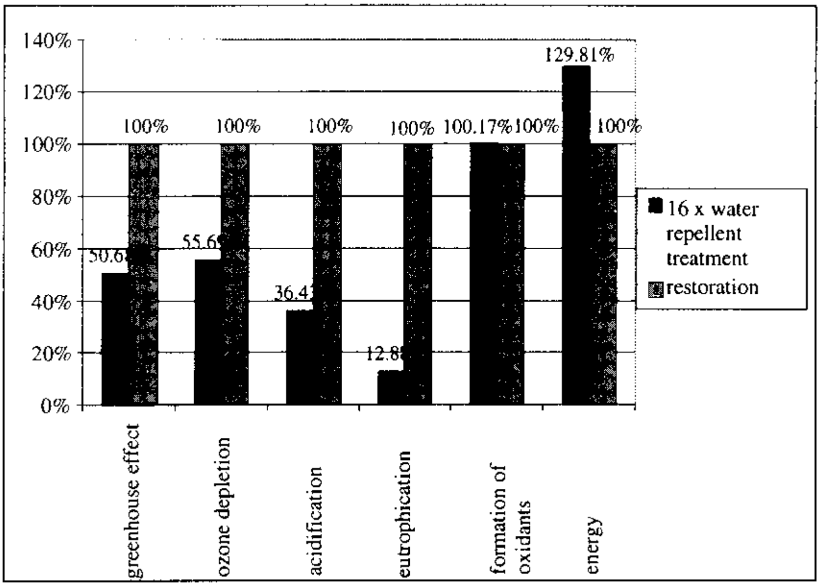

Figure 3: comparison of the ecological effects of a bridge pillar after 16 water repellent treatments to the effects of a bridge pillar after restoration

During this period of 6.25 years the increase of the chloride concentration around the reinforcement bars should not exceed 0.016 weight-% referring to the concrete, under the presumption that the performance of the water repellent treatment is independent of the number of applications carried out. In case a second restoration measure becomes necessary, the minimum required life time from the ecological perspective even amounts to about 3 years. From the technical point of view, the average yearly increase of the chloride concentration on the surface of the reinforcement bars should not exceed 0.0025% referring to the concrete weight.

10 Conclusions

The following conclusions can be drawn from the presented results:

- If a adequate database is available, it is possible to estimate the ecological effects of a water repellent treatment and to optimize the specific process steps regarding ecological aspects.

- A water repellent treatment leads to a reduction of the water and chloride uptake and thereby reduces the risk of chloride induced corrosion.
- Based on ecological and economical considerations, the comparison between a water repellent treatment and a restoration executed according to current standards allows to determine requirements regarding the durability of the water repellent treatment.
- The water repellent treatment aims at preventing the necessity of a restorating measure during the planned useful life of a concrete structure element. Based on this premise and after certain model assumptions have been set, technical requirements concerning the performance of a water repellent treatment over the period of the minimum determined life time can be formulated.
- Setting requirements concerning the performance and durability of a water repellent treatment may represent a starting point for the definition of a requirement profile for bidding documents.

11 Finishing remarks

The system boundary defined did deliberately not include the ecological influence of the construction site, such as the traffic congestions and deviations due to the construction work, because those aspects are very difficult to grasp in life cycle assessments. Nevertheless it is interesting to note that the equipment used for the preparation and the application of a water repellent treatment is small and very flexible compared to the machines that are necessary for a restoration. These aspects may become significant in tunnels, which have to be closed much longer for a restoration measure than for a water repellent treatment. The consideration of traffic related aspects can have a significant influence on the ecological impact in favour of the water repellent treatment.

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