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Future rehabilitation and maintenance & cost-benefit study of alternative solutions

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Project Coordinator
University of Nottingham, UK

ZAG, Slovenia

VTT, Finland

SINTEF, Norway

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Authors:
Carl Thodesen, SINTEF, Trondheim (Norway)
Alessandra Carrera, University of Nottingham
Andrew Dawson, University of Nottingham

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Table of content

1 Introduction

In this report, the future changes in rehabilitation and routine maintenance regimes necessary for the road infrastructure to economically support the impacts of climate changes will be identified. These will depend on the main problems that can be expected to arise, and will be different depending on whether they concern the asphaltic surface or the base/subbase. It is considered that the maintenance and rehabilitation methods are the same ones that are used nowadays, as at present it is not possible to foresee what new technologies will be developed in future years.

Also a cost-benefit analysis of the reformulated materials and treatment methods of construction of the road asset has been performed. Again, this is merely based on the costs at present, and the future increase or decrease of the costs can only be guessed at. This section includes all those treatment methods and technologies that have been arisen mainly from the research described in the technical reports No. 5 (which describes the effect of water and, generally, of climate on asphalt and porous asphalt and methods to decrease deterioration rate) and No. 3 (which describes alternative materials needed as a response to the climate change in sub-surface layers). A quantitative analysis of the road life cycle costs (LCCA) could not be performed, as this would be based on data that are not available. Life cycle cost analysis (LCCA) is a process that allows calculating the total cost of an asset by analyzing initial costs and discounted future expenditures, such as maintenance and repair costs, over the service life of the asset (Rahman & Vanier, 2004), and is an important tool to analyse differential costs among alternative construction and/or maintenance and rehabilitation methods. However, very few researches can be found that quantify the improvements, as a matter of time, of new, reformulated materials for road construction. Therefore, a LCCA to compare different construction and rehabilitation alternatives in the light of the future climate changes could not be assessed, but rather a simple analysis of the costs of the modern road construction materials was performed.

It is worth noting that the LCCA considers a period of 30 to 40 years to analyse the road design. This period represents the average expectation of life for a road surface. It is a relatively short time span to actually observe possible changes in climate, and for this reason it was observed, during this research project, that, at present, the decision tools for pavement surface maintenance are not to be changed in the light of climate change. Rather, the climate and its evolution has to become an integral part of the decision making. For this reason, a list of the most common problems that arise during a pavement's life and the consequent maintenance and rehabilitation procedures commonly used are here analysed in an attempt to see what aspect of the climate has to be taken into consideration. Section 2.1 deals with paved roads, Section 2.3 with gravel roads.

A different question concerns the unbound/lightly bound base and subbase layer below the road surface. These layers are supposed to have longer life than the surface..In practice (depending on the jurisdiction), this might be 60 years. Therefore, a subbase that is constructed today, might still be in use when the climate has noticeably changed in a considerable way. Section 2.2 will analyse the life of these layers.

2 Maintenance and rehabilitation of roads

Road deterioration over time is due to the combined effect of traffic loading above it and of environmental factors such as rain, sun, frost. Which of the two factors has most influenced depends on how the road was built, on the traffic, on the severity of the weather, etc. Pavements deteriorate at a rate that increases with time: this is because, as distresses develop, they function as triggers for subsequent distresses to develop. If a crack appears on the surface, at first it has little consequence on the overall health of the road, but, as time passes, water infiltrates through the crack, reaching the subbase and subgrade, which, consequently, weaken. Deterioration can only be slowed down with proper and rapid intervention, but cannot be blocked.

For the purposes of this research, only that deterioration that is weather-related is of interest[1], however, the ways to intervene are the same as they depend on the effect and not on the cause. The possible interventions are of two types: maintenance actions that slow down the rate of the deterioration process by acting on specific pavement deficiencies; rehabilitation, instead, resets the condition of the road surface by removing and replacing those portions of pavement that are too damaged to be repaired by normal maintenance (Pavement Tools Consortium, undated). Maintenance operations can be needed rather often during a road's lifetime, and consist, most of the time, in crack sealing, joint sealing and patching by the application of surface treatments such as chip seals, asphalt emulsion sealcoats, slurry seals, and bituminous crack sealants; these methods prevent the entry of water through the surface into the aggregate below, improve skid resistance and, more generally, allow a longer pavement life. Rehabilitation generally happens once or twice over the course of a road's lifetime. Rehabilitation techniques for asphalt include patching, surface milling, overlays of new asphaltic (AC) wearing surface and, in some countries, overlays of Portland Concrete (PCC) directly on top of existing AC (usually called "whitetopping"); rehabilitation techniques for PCC include diamond grinding, full- and partial-depth repair, overlays of new PCC wearing surface, and AC overlays directly on top of existing PCC (Ting et al., 2001), although PCC maintenance and rehabilitation is not the topic of this report..

2.1 Maintenance and rehabilitation of asphaltic roads in the light of the effect of climate changes

As, on average, the life cycle of a pavement surface is relatively short, climate will unlikely change to such an extent during that period that it can actually increase or decrease the deterioration process in a not negligible way. Instead, as the climate evolves, newly built roads should be designed and constructed taking into account climate-related factors as well as traffic factors. However, present road construction design techniques can be still used in the future, provided that maintenance and rehabilitation changes according to the change in climate. In particular, these operations will likely need to be planned more often if materials and processes remain the same. Table 1 describes how the future climate will interfere with the different types of distress that are the main reasons for maintenance actions.

Maintenance is necessary to slow down the deterioration process, but cannot stop it. When the effects of deterioration are too large, or if the environmental/climatic conditions have

[1] Of course, traffic loading may be the driver – e.g. stripping of asphalt material during wet weather needs traffic to force the water into the asphalt. But our interest, in this report, is the deterioration resulting from a weather pattern difference caused, in turn, by climate change as compared to a deterioration under the same traffic and an unchanging climate.

changed to such an extent that maintenance operations need to be performed too often, thus becoming uneconomical, rehabilitation has to take place. Deterioration consists of adding, or replacing, material in the existing pavement; this way, the road deterioration will start again as if the road was new or, at least, as though it is relatively new[2]..

It is important to stress that not only the pavement design of a new asset, but also the overlay design of rehabilitation operations should allow for climatic/environmental conditions such as the Mechanical-Empirical Pavemet Design Guide (the MEPDG) (AASHTO, 2008). Mechanical-empirical design methods allow designers to evaluate different materials in different environmental as well as different traffic conditions and are, therefore, to be preferred.

Table 1: Maintenance of asphalt pavements - types of distress, effects of climate change, and maintenance suggestions (adapted from Asphalt Institute, 2009).

Type of distress	**Possible cause**	**Possible contributing factors due to climate change[3]**	**Maintenance suggestions[4]**
Fatigue (Alligator) Cracking	• Excessive loading • Weak surface, base, or subgrade • Thin surface or base • Poor drainage • Any combination of the above 4 causes	• Temperature decrease in winter time • Precipitation increase • Increased freeze-thaw cycles • Increased sea level (coastal areas)	Full-depth patch
Edge Cracks	• Lack of lateral support • Settlement of underlying material • Shrinkage of drying out soil • Weak base or subgrade layer • Poor drainage • Frost heave • Heavy traffic or vegetation along edge	• Annual temperature increase • Temperature decrease in winter time • Temperature increase in summer time • Precipitation decrease • Precipitation increase • Increased freeze-thaw cycles	Improve drainage. Remove vegetation close to edge. Crack seal/fill (with asphalt emulsion slurry or emulsified asphalt)
Longitudinal (Linear) & Transverse Cracking	• Poorly constructed paving joint crack • Shrinkage of the asphalt layer • Daily temperature	• Temperature decrease in winter time • Temperature increase in summer	Improve drainage by removing the source that traps the water Seal crack or fill

[2] For further details on maintenance and rehabilitation operations, the 'Pavement Guide Interactive' (Pavement Tools Consortium, undated) is suggested.

[3] These relate to those previously identified in Report No. 6 of this project.

[4] Sometimes removal of the failed layer might also be required.

	cycling • Cracks in an underlying layer that reflect up through the pavement • Longitudinal segregation caused by the improper operation of the paver	time • Change in the number of events per annum in which the change of temperature within six hours is greater than 15 °C • Precipitation increase	with asphalt emulsion slurry or light grade of asphalt mixed with fine sand. Provide side drainage ditches Crack seal/fill
Reflection Cracking	• Differential movement between the asphalt and concrete layers • Can deteriorate further under heavy traffic • Localized crack widening under traffic and/or temperature cycles	• Annual temperature increase • Temperature increase in summer time • Precipitation increase • Colder winters as indicated by change in the number of events per annum in which the change of temperature within six hours is greater than 15 °C	Crack seal/fill Controlled debonding of new overlay using Stress Anbsorbing Membrane Interfaces (SAMIs) or overlay reinforcement
Slippage Cracks	• Lack of a good bond between surface layer and the course beneath due to dust, oil, dirt, rubber, water and other non-adhesive material • Tack coat has not been used • Mixture has a high sand content • Vehicular turning or stopping movements in pavements with a low-strength surface mix	• Annual temperature increase • Precipitation increase • Increased wnter temperature cycling through 0°C	Partial or full-depth patch
Corrugations & Shoving	• Mixtures too high in asphalt • Low air voids • Fine aggregate content too high • Excessive moisture or contamination in the granular base • Smooth or rounded aggregate • Incorrect asphalt grade	• Annual temperature increase • Temperature increase in summer time • Precipitation increase	Deep or full-depth patch
Rutting	• Consolidation or lateral movement of	• Annual temperature increase	Cold mill and overlay or thin

	any of the pavement layers or the subgrade under traffic • Insufficient design thickness • Lack of compaction • Weaknesses in the pavement layers due to moisture infiltration • Asphalt mixtures too soft • Mixtures too high in asphalt	• Temperature increase in summer time • Precipitation increase	surface patch
Settlement/Grade Depressions	• Settlement or failure in the lower pavement layers • Improper construction techniques	• Precipitation increase • Increased freeze-thaw cycles • Decreased freeze-thaw cycles	Cold mill and overlay Thin surface patch Infrared patch
Upheaval/Swell	• Expansive soils (which swell in the presence of moisture) • Frost heave (in which ice lenses grow beneath the pavement, causing the pavement to crack)	• Temperature decrease in winter time • Precipitation increase • Increased freeze-thaw cycles	Full-depth patch
Pot Hole	• Continued deterioration of another type of distress, such as thawing of a frozen subgrade, cracking, raveling, or a failed patch after pieces of the original pavement surface have been dislodged • Poor surface mixtures • Weak spots in the base or subgrade • Severity of the surrounding distress and traffic action accelerate potholes	• Annual temperature increase • Temperature decrease in winter time • Temperature increase in summer time • Precipitation increase • Increased freeze-thaw cycles • Decreased freeze-thaw cycles	Partial, full-depth or injection patching
Raveling/Weathering	• Asphalt binder has hardened excessively • Poor-quality mixture • Usually requires the presence of both traffic and water to occur	• Annual temperature increase • Precipitation increase • Increased freeze-thaw cycles	Any surface treatment or thin overlay

Bleeding	• Improperly constructed seal coat • Too much asphalt in a mix • Too heavy a prime or bond/tack coat • Excessive sealant in the cracks or joints under an overlay • Traffic can contribute to bleeding if the asphalt layers become overcompacted and excess asphalt is forced to the surface	• Precipitation increase • Temperature increase in Summer	Chip Seals, Sandwich Seals, thin overlay

2.1.1 Mean Temperature Change as an Example

As an example, suppose temperature increase, is anticipated at the pavement section of interest. As the life cycle of the pavement surface is relatively short, the mix design of the asphalt material can be changed by the designer according to the climatic conditions anticipated. At the time of each re-surfacing, the asphalt mix used can be selected so as to sustain higher temperatures than before. However, mixes that work well at higher temperatures may be more costly. Also, it might happen (especially in the southern part of Europe) that the temperatures reached by the pavement surface become very high, and, even though the asphalt mix is designed properly, such heat may considerably accelerate the deterioration of the pavement. Because of reducing viscosity with temperature, asphalt stiffness decreases exponentially (Hunter, 1994) and, for the same reason, rutting also increases. Aging, too, is faster when temperature is high (with asphalt becoming stiffer and more brittle with time)...

The colour of the asphalt has a major role on its temperature: the darker its colour the greater the energy absorbed and transformed into temperature increase. For this reason, the use of the so called “cool pavements” technologies is suggested when rehabilitating a road that suffered high temperature-related deteriorations. These technologies are, of course, valid also when designing a newly built road. Pavements more reflective of sunlight deteriorate more slowly, and they also help avoiding the so-called “Heat Island effect” in the urban areas, a phenomenon in which surface and air temperatures get very high due to the retention and emittance of solar heat from roads and other structures (see EPA, 2008).

Methods to overcome the problem of hot pavement surfaces are:

- Chip seals: consist of spraying either bitumen or emulsified bitumen immediately followed by an aggregate cover that is approximately the thickness of one stone. Chip seals are often used as maintenance techniques to resurface low-volume asphalt roads and sometimes more major highways. The use of light coloured aggregate increases the albedo of asphalt-paved surfaces. The cost of such treatment depends on the local availability of suitable aggregate but is relatively economic compared to many other treatments (see Section 3).
- Slurry seals: consist of a mixture of emulsified asphalt, aggregate, water and other additives. The mixture is applied over the existing pavement to seal surface cracks, stop ravelling and loss of aggregate from the underlying asphalt matrix, make surfaces more impermeable and improve skid resistance. Also, in this case, the use

of light colour aggregate can help cooling of the surface. Because aggregate covers a smaller percentage of the surface area compared to chip seals, the temperature reduction is likely to be smaller.

- Whitetopping: a layer of concrete, usually greater than 10 cm thick, applied over an existing asphalt pavement as a form of maintenance or resurfacing. The cooling effect comes from the lighter colour of concrete compared to asphalt. Slag (a byproduct of processing iron ore) and fly ash (a byproduct of coal burning), mixed with cement, not only reduce material costs and avoid sending wastes to landfills, but also increase the reflectivity of the finished pavement thanks to their lighter colour.
- Ultra-thin whitetopping: similar to whitetopping, but is only 5 to 10 cm thick. It often contains fibres for added strength.
- Microsurfacing: is a thin sealing layer used for road maintenance. Light coloured materials can be used to increase the solar reflectance of asphalt. For example, one manufacturer (PolyCon Manufacturing, Inc.) makes a light-coloured microsurfacing material known as E-Krete® that consists of cement, sand, other fillers and a liquid blend of emulsified polymer resin, and whose solar reflectance is comparable to that of new concrete.
- Pavement paint coatings: high reflectivity coatings, especially in the infrared region. A layer of durable paint coating with high albedo and low brightness is applied to the surface of conventional asphalt pavement, thus reducing the pavement's surface temperature. This coating is also applicable on already existing roads, making it suitable also for simple maintenance operations.
- Overlaying with water-retaining layers: these are pavement layers designed to be somewhat porous so as to "absorb" and retain water within them. Solar heating of the pavement surface causes evaporation of the water stored within such pavements while latent heat effects draw energy from the pavement to allow such evaporation, leading to the temperature dropping..

(sources:Graniterock;; EPA, 2008; Cambridge Systematics Inc., 2005; Tran & Powell, 2009).

A few pavements, are designed to be "perpetual" (designed to last longer than 50 years (Timm & Newcomb, 2006)). For such pavements re-surfacing will probably be incurred in the manner already described. However, the relative permanency of the underlying base necessitates that new perpetual pavements should be designed with a higher mean operating temperature than current whilst existing pavements will need checking against future mean temperature increase. If their long-term performance is then found to be compromised, a thicker overlay at the time of the next resurfacing might be a sensible action. Perhaps, this might be a partial inlay so as to remove the uppermost part of the old base which is most prone to temperature effects deriving from increased air temperatures and solar gain.

2.1.2 Responses to Other Changes Caused by Climate Change

While temperature increase, as covered in the last section, is far from the only consequence of climate change that is of concern (as this, and other reports, show), the principle of responding at maintenance/resurfacing intervals with solutions that allow for each anticipated change in climate impact is equally valid. We emphasize, again, that this is because the cycle time for significant remedial activity is substantially less, for most activities, than the time-scale over which climate change effects may be reliably observed. Of course, climate change is ongoing but the mean change from one year to the next will be masked by natural year-to-year variations in weather.

Once again, perpetual pavements will likely need a special study to ensure their longevity against these other changes. However, perpetual asphalt pavements are not the only pavements of concern. Unbound pavements and the bases and sub-bases of flexible pavements also need reviewing in the light of anticipated climate change impacts. Theses are now discussed.

2.2 Maintenance and rehabilitation of bases and subbases under the effect of climate changes

Maintenance of bases and subbases is usually not possible, because any maintenance operation on this part of the road involves the removal of the road surface. For this reason, it is more common to talk about rehabilitation, although, even in this case, a subbase that fails almost certainly means that the road needs to be rebuilt from the foundation upwards.

While it is unlikely that the climate will change considerably in 20 years, an common assumption of the rehabilitation cycle time for re-surfaced, the situation is rather different for the layers underneath. In fact, the life cycle of the base and subbase layers is commonly considered much longer than that of a road surface (often considered to be higher than 40 years), and thus the effect of climate change may influence that deterioration process.

The present study has shown that changes in rainfall and temperature will affect the base and subbase with rainfall events likely to become more intense, and with more rain in the northern part of Europe. These will have negative consequences for the lower layers of the road, whereas temperature changes are important only in the case of subgrades usually subject to frost during winter, and, generally, the effect will be positive thanks to the temperature increase that is foreseen. This study has also found that only if rainfall events become extreme (and thus more unlikely) can they be seriously harmful for the road health, and only a proper design (especially of the drainage system) can slow down the resulting deterioration.

Due to their inaccessibility, regular maintenance of the road pavement below the surface is mainly related to the maintenance of the drainage system. This consists on ensuring that all ditches adjacent to the highway and culverts allow water to flow freely, clearing anything that can block the flow of water. A well-constructed and working drainage system keeps the base and sub-base drained, increasing the effective stress and, thus, increasing the resistance to rutting and increasing the stiffness, so that the overlying asphaltic layers suffer from fatigue more slowly. This is why it is so important to inspect the condition of the drainage and to do undertake proper maintenance regularly. To ensure inspection and maintenance operations, drainage systems have to be designed allowing accessibility to the pipes. Given the increasing rainfall and the increasing intensity of rainfall events that are frequently anticipated due to climate change, such inspection and maintenance is likely to become more important. Unlike surfacing repair, this must be performed before the consequences become apparent if complete pavement reconstruction is to be avoided. However, because distress consequent on poor drainage is seldom seen until significant damage to the lower layers of the pavement has resulted, there is always (an understandable) tendency to relegate priority to other, more immediately visible, defects. Such practice will become less and less tenable.

The main problems that are usually encountered when inspecting the draining systems are (Watmove, 2008):

1. Clogging of the system, usually due to fine materials
2. Roots penetrating into the soil and blocking drains or even breaking the drainage pipes
3. Generation of ferrous oxide and calcium carbonate sediments and precipitates
4. Crushed pipes
5. Poor outlet conditions of pipes and ditches
6. Insufficient volumetric flow capacity

7. Inadequate water velocity.

The first four issues depend mainly on the environment, and, even if a good design of the drains can help, nonetheless they require the system to be subject to periodical maintenance to clear ditches pipes. The last two problems, instead, are mainly due to inadequate design. Problem 6 is affected by both.

The new climatic conditions that will be found in Central-Northern Europe in the next hundred of years are unlikely to affect the number of crushed pipes, or the formation of rust and calcareous sediments with consequent clogging of the holes. A more spread roots system can be hypothesised, caused by the temperature increase and by the small increase in precipitations, however, the effect of climate change on this problem is probably so small that it can be considered negligible. However, the need to transport more water (or, at least, more water per unit time) will cause these problems to have greater impact.

A non-negligible increase in transportation of the finer material into the draining system, instead, is likely to occur as the rainfalls will become more intense; this because the flow of water through the soil and on the surface will be stronger, and thus more soil is going to be eroded and dragged towards the drains. It will also be more probable to find material of larger dimensions, especially blocking the surface drainage. As a consequence of a thunderstorm, stones, vegetation and other material of foreign nature can fall on the road or be transported and eventually accumulate at the sides of the road, clogging the lateral superficial drains. In extreme cases, rivers can overflow their banks and flood the roads, causing not only their temporary inaccessibility, but also introducing large quantities of material, mostly mud and vegetation. On the other hand, because of the higher occurrence of events such as these, a drainage system that works properly becomes of primary importance to allow early accessibility of a road after rain, and to ensure a longer life of the asset.

The unclogging of the drainage systems from fine soil and vegetation will therefore become more necessary in the future, as a consequence of climate change. At present, it is common and suggested practise to perform the inspection and maintenance operations of the roads draining system at least every 5 years, the inspections possibly during speing (when the situation is supposed to be at its worst) and the maintenance during summer (Watmove, 2008). Inspections should, however, be intensified in periods of high precipitation. In the future, every 5 years might be too infrequent to perform satisfactory maintenance, and costly rehabilitation might be then be needed. A shorter time interval between maintenance actions is suggested, or, even better, an (inspection and) maintenance time interval that is not fixed, but rather depends on the intensity and quantity of the rainfall (or thaw) events during the year. Also, small regular interventions after particularly heavy rainfalls and thunderstorms to clear the drains in the main roads would be recommended and thus considered part of the intervention plan.

Regarding those maintenance works that are needed to solve problems related to inadequate design of the drainage system, only those due to insufficient capacity of the drainage pipes and ditches are likely to increase noticably as a consequence of future climate change. This is true especially for those roads whose design has not taken into consideration the future probable increase in rainfall intensity. If rainfall events become more intense, as is likely in most areas, insufficient pipe or ditch capacity may become a problem. For this reason it is of primary importance, when designing a pavement asset, that the drainage systems are calculated taking into account extraordinary precipitations and flows, including in the return period an allowance for the worsening of weather conditions.

If rehabilitation of the drainage system is needed, the drainage should be re-designed at the same time as the other rehabilitation measures (e.g. re-surfacing). The locations where poor drainage is the major cause of road damage should be recognised and proper countermeasures should be applied – e.g. ditch widening and/or deepening..

The maintenance of a subbase weakened subsequent to a rise in water table level is very difficult and, most of the time, a total rehabilitation will be needed. For this reason, an investigation of the risk of water table increase in the 40 years after the road construction should be taken before the road is designed. For the design purposes, it should be born in mind that the water table has an oscillating movement from winter to summer, and thus the highest water table conditions (corresponding to the weakest subgrade) should be considered (http://www.highwaysmaintenance.com/drainage.htm).

A fairly common problem is inadequate falls to outlets (or sections with reverse gradients). These may be difficult to avoid in flat topography and the increased difficulty in getting discharge permissions on the grounds of environmental protection is exacerbating the problem. Such problems cannot be easily overcome, but should be the object of redesign and correction at the time of the next major rehabilitation.

2.3 Rehabilitation of unsealed roads under the effect of climate changes

Unsealed roads tend to rut more easily than paved roads, in wet weather (Skorserth & Selim, 2000). Gravel tends to be displaced from the centre of the surface towards the shoulder as a consequence of the weather (mostly rainfall) and of the traffic (also during the dry period). Other common problems are slippery or dusty surfaces due to the presence of excessive fines at the pavement surface.

It is responsibility of the operator to perform routine maintenance in order to reshape the road surface and shoulder and to keep the drainage system working properly. When the displacement and the erosion of gravel consequent to traffic and heavy rain reaches a level that affects the drainage (e.g. by changing the surface profile or by filling drainage ditches with displaced paving material) maintenance may be insufficient. Then rehabilitation is necessary. Differently from paved roads, base layers of unsealed roads can undergo rehabilitation through processes of reblading, recompacting and regravelling (only the last of which involves importing new materials; the others, just work on existing material). Details of the methods of maintaining and rehabilitating gravel roads are found in Skorseth & Selim (2000) a. In this report, only, the effects of future climate are taken into consideration.

Gravel roads are strongly affected by wet conditions. Heavy rains can displace aggregate, and also change the initial grading by transporting fine material into and from the road surface. As a result the pavement may become slippery, dusty, difficult to drain or unstable under traffic. Climate affects the erosion through the frequency, intensity, and duration of rainfall. In addition, in northern climates, soil erosion can be worsened from the compounding effects of frozen ground, saturated soil and snow melt (see Skorseth & Selim (2000)). It has already been said that rainfall may increase or decrease in quantity according to the zone in Europe, whilst the increase of the intensity will be commonly found everywhere. The effect of frozen ground, instead, should decrease.

Given the future changes of climate, it is probable that gravel roads maintenance operations will need to be planned more often. However, this situation can become rather uneconomic. In this case, a rehabilitation of the road that involves also the addition of binders (perhaps at low dosage rates) is suggested. Stabilisation can be performed in-place with cementitious or bituminous binders that will be mixed with the aggregate that is already forming the road surface and base. Dry Powdered Polymers (DPP) are another stabilisation method that is nowadays gaining importance, especially in Australia (Lacey, 2004; Vorobieff & Wilmot, 2001). For further details about the different stabilisation methods, please refer to Report No. 6. DPP works particularly well with fine material in presence of water, however, given the high prices (see Section 3), this method should be considered only for those parts of the road that are particularly important and also subject to supply of water, for example, close to the sea coast.

It should be borne in mind that traffic is also a very important issue for any road: its deterioration strongly depends on it. Deterioration due to traffic is indirectly affected by climate (e.g., see Report No. 1): as climate changes, populations relocate and, thus, the routes for transport of goods and people also change. This may have the consequence that roads that previously were sufficient to sustain a low volume of traffic, now face an increase in traffic and load that brings them to a rapid deterioration. This fact should be taken into account when deciding whether the road needs rehabilitation: if traffic is expected to increase, a full reconstruction of the road might be a better choice. Unpaved roads might be sealed. Paved roads might be overlayed. The indirect effects of climate change on pavement performance are very important. Indeed this present research indicates that, probably, the indirect effects are even more important than the climate change itself.

3 Cost-benefit study of alternative solutions to problems related to climate change

In Reports Nos. 3 and 5 and, partly, in the previous section, the use of different binders, materials and other solutions to improve or rehabilitate the condition of a road and make it more suitable to sustain any change in climate have been taken into consideration. An analysis of the costs related to such methods is now performed. It should be born in mind, however, that prices are very sensitive in the locality considered and can change considerably with time. For this reason, it is relatively hard to gather information that can apply well to all situations, and each situation has to be analysed based on the locality. Furthermore, at the time when climate will be sensibly different from nowadays, prices might well be very different, in part due to economic differences resulting, indirectly, from climate change induced effects. Ignoring this aspect (as any estimate would be far too conjectural), in this section, current prices are used and are generally be in U.S. Dollars ($), even if Euro is the most common money in Europe, as this is the standard value money in the international market. Prices can be given only for those products/technologies that are already sufficiently developed and on the market.

Below are shown the main climate-related problems and the most suitable solutions with an analysis of their costs. The effect of the temperature increase is considered to affect mostly the road surface, as the effects on the subsurface layers are small and mainly positive (see previous Reports).

❖ Increase in temperature at the surface	- anti-oxidation additives on asphalt - asphalt light reflecting coating - asphalt mix design to be improved - use of porous asphalt and asphalt-rubber
❖ Increase in rainfall intensity/quantity	- use of crushed, angular, aggregate with a large and steep grading - improve drainage system - use of sealing barriers/geotextiles to manage water - use of geogrids to reinforce aggregate layers - mix aggregate with hydraulic binders - mix aggregate with foam bitumen - real-time deflection measurements against thaw to manage use

The importance of cooling the asphalt surface was stressed in the previous section, where different rehabilitation and construction techniques to help cooling the road have been listed. The question is whether such cooling techniques are more costly than the lifetime cost savings. The answer depends strongly on the method used, but also on the region, the climate, the underlying soil, the size of the project and so on. However, it should be borne in mind that only a thin surface of chip seal, or paint, or anything else is needed, and thus the costly material needed is a usually small amount. According to Pomerantz et al. (2000), by reducing the maximum pavement temperature, an asphalt binder that works over wide temperature ranges (which is costly due, e.g., to polymer modification) is not needed anymore, and failure will also be delayed, with consequent additional savings due to a reduction in the lifecycle costs of maintenance and disposal. Thus, cool pavements reduce the costs in three ways:

1) reducing the rutting as the asphalt is less soft
2) decreasing aging, thus maintaining the flexibility for longer
3) allowing the use of softer (and thus, generally, cheaper) penetration grades of asphalt.

For these reasons, although there are insufficient direct data to provide a complete answer, the authors suggest that the resulting costs favour the use of cool pavements. Independently on the technique used, it must be considered that, according to the University of California, lowering roadway temperatures by 10°C extends pavement life from rutting failure by a factor of 10 (Pomerantz et al., 2000); this fact can be of extreme importance for the future construction and maintenance actions in the light of the climate change, in order to contain the costs.

Ting et al. (2001) calculated and compared the lifecycle costs of conventional asphaltic (AC) pavements due to those techniques that promote a decrease of the pavement temperature. These were

- Portland concrete (PCC),
- porous pavements (e.g. as currently used in vehicle parking areas),
- resin pavements,
- AC pavements covered with light-coloured chip seals and
- AC pavements using light-coloured asphalt emulsion additives.

They found that PCC can provide a cost-effective alternative to conventional AC when severely damaged pavements must be reconstructed. Also rehabilitation with thin overlays of PCC (whitetopping and ultra-thin whitetopping) can often provide a cost-effective alternative rehabilitation technique. Chip sealing that makes use of light coloured aggregate can, as well, be a cost-saving maintenance treatment for low volume roads, although the costs of light coloured chips are uncertain but likely to increase. According to the authors, porous pavements, considered only as a cooling method, have higher lifecycle costs than conventional AC, because they need frequent maintenance. However, as the authors themselves admit, only the temperature-related costs were considered, while other improvements brought by this asphalt were left out of the calculation. Resin pavements, based on a newly developed technique that uses clear tree resins in place of bitumen, were only slightly more expensive than conventional asphalt, but the calculation had large uncertainties in the cost and performance data. Finally, light coloured additives mixed in the asphalt emulsion were found to be more expensive than conventional AC, as their market is still not very developed.

EPA (2008) and Cambridge Systematic Inc. (2005) compared the costs of different cooling methods (see Table 2). It should be born in mind that, as already said, these costs are only rough estimates for initial construction or performing maintenance, and do not reflect life-cycle costs, and therefore they can vary considerably. In the table, new construction techniques are used: these consist of building roads with concrete or with asphalt that contains light-coloured aggregate. The report also stresses the fact that, although costs of cool pavements may be higher than conventional, these costs are often offset by savings from reduced requirements for grading, drainage, maintenance operations etc. .

Table 2: Comparison between costs of cool pavement methods (sources: EPA, 2008; Cambridge Systematic Inc., 2005; Saleh, 2006). Note: although it is reasonable to think that European prices are comparable, these prices are valid in U.S.

Method	Installation cost ($/m^2)	Estimated service life (years)
Asphalt with locally available light aggregate	$ 1 – 1.8	7 - 20
PCC	$ 3 – 6	15 - 35
Porous asphalt	$ 22 - 28	7 - 10
Chip seals with locally available light aggregate	$ 1 – 4	2 - 8
Slurry seals with locally available light aggregate	$ 1.1	2 - 8
Microsurfacing	$1.5 – 7	7 - 10
Whitetopping	$ 3.5 – 6	10 - 15
Ultrathin whitetopping	$16 – 73	10 - 15

New pavement cooling techniques are nowadays being studied, especially new paint coatings and water retaining systems. Their price can vary considerably. An example is the high albedo pavement coating called "PerfectCool", a highly reflective pigment with hollow ceramic particles, developed by Nippo Corporation Co. and Miracool Co. Ltd. PerfectCool coating is highly reflective in the infrared region, but not in the visible light region. This allows the reduction of the heat without reducing the drivers' visibility of the lane markers, and thus without reducing safety. In general, the paint coating technique may also termed a Solar Heat-blocking Pavement.

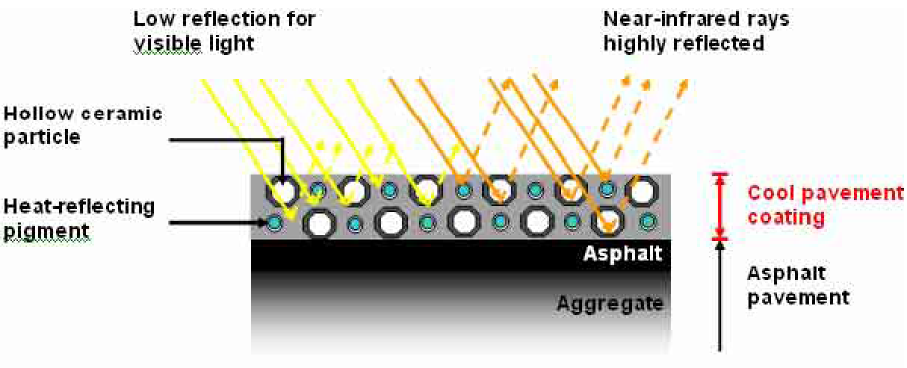

Figure 1: Scheme of the PerfectCool coating layer above the asphalt mixture (Source: www. Nippo-c.co.jp).

Laboratory and field tests showed that Perfectcool allowed a surface temperature reduction of up to 10^{o}C as compared to an asphalt surface without the pavement coating. The product also showed good weatherability, good adhesion with different pavement types, good torsional resistance, good resistance to rutting and good permeability (Iwama et al., 2006; Aloysius & Tan, 2009; Tan et al., 2009). The cost of this product depends on the order quantity, colour and application goods etc., and thus the price range is wide. Indicatively, the cost (where the application is spray) is $14.5 - 23.5/m^2,delivery from Japan included.

Other materials and methods have been shown to bring positive effects against climate change. Among these are rubberised asphalt and asphalt-rubber. Rubberized asphalt pavements have been found to be cooler at night than PCC pavements (Cambridge Systematic Inc., 2005), although detailed research on such benefits has not yet been performed. Although still not very common, both rubberised asphalt and asphalt-rubber materials are gaining in importance and are more and more used in every part of the world. At present they are mainly used for their noise reduction effects, but can also demonstrate a reduction in cracking. This is very important, as the study performed during this project and discussed in Report No. 1 showed that alligator cracking will be the type of distress most affected by climate change. Open asphalt-rubber friction courses can be placed on existing surfaces to enhance safety by reducing splash and spray: another important detail for many locations in view of the future increase in rainfall intensity expected there. According to Coomarasamy et al. (1996), the cost of rubber modified asphalt is, generally, between 60 and 150% higher than the cost of a conventional asphalt pavement. Since 1996 the margin has fallen, thanks largely to incentivization to recycle waste tyre rubber rather than to dump or incinerate it[5]. Consequently, more recent sources (e.g. Advanced Surfacing Technologies, Inc., 2008) give prices only slightly higher than hot-mix asphalt (HMA) (see Table 3). The higher initial cost will be easily absorbed because:

- Asphalt-rubber pavements, when designed and constructed properly, often last 50% longer and may last up to twice as long as conventional materials before needing maintenance or replacement,
- the decreased cracking means reduced maintenance costs, with consequent lower Life Cycle Costs,
- a reduced pavement thickness is needed,
- the increasingly high asphalt prices will favour the use of rubber.

Table 3: comparison between average prices of Hot Mix Asphalt and Asphalt Rubber mixes (Advanced Surfacing Technologies, Inc., 2009).

Mix	Bid Price per Ton	Cost per Square Meter/25 mm
HMA Dense	$79	$4.66
ARAC Gap	$94 (+16%)	$5.42 (+16%)
ACFC Open	$75	$3.72
ARFC Open	$82 (+9%)	$4.05 (+9%)

n.b. HMA = Hot mix asphalt, ARAC = Asphalt rubber base course material
ACFC = Asphatic friction surfacing course, ARFC – Asphalt rubber friction surfacing course

Porous asphalt is another product that is gaining more and more importance in the market. It is manufactured with the same material used for traditional asphalt pavement, but without "fine" materials, and incorporates void spaces to allow infiltration. It needs more maintenance because of the fines that tend to clog the pores; regular maintenance is usually done by industrial vacuums that suck up all the sediment. Also proper construction stabilization and erosion control are required to prevent clogging, thus increasing the costs. Another concern is durability. With less interparticle connection due to the open grading, the material is thought to last less long than conventional AC before stones in the mix debond and are lost

[5] This reduction in costs over a 15 years is an illustration of the future uncertainties of pricing of approaches that are, at present, unconventional. The high cost of special surface coatings is mentioned elsewhere in this section. Perhaps they, too, will reduce significantly in costs over the next 15 years. It's impossible to tell.

(Liu & Cao, 2009). Solutions are available. Better quality control or epoxy bitumens are two such solutions (Alabaster et al, 2008) but only at a cost increase.

The real costs of the porous asphalt are not easy to calculate – they change substantially from one source of information to the other, and they may or may not involve the costs of the drainage structure. According to the Federal Highway Administration (FHWA), porous asphalt costs approximately 10 to 15% more than regular asphalt (EPA, 2008). The cost of porous pavement is approximately the same of conventional asphalt according to Adams (2003), but the underlying stone bed is usually more expensive than a conventional compacted sub-base. However, as many other researches reveal, the cost difference is generally offset by the significant reduction in stormwater pipes and inlets needed. Many sources (e.g. UNH Stormwater center) report a material cost increase between 20 and 25%. Other sources, finally, report much higher costs, twice to three times higher, depending on the design (CWP, 1998), probably because they include the entire drainage structure that lies under and adjacent to the pavement.

However, there is a general agreement that the higher costs can be offset by benefits: in fact, porous pavement can create savings in terms of storm drain costs and land consumption. It is not necessary anymore to build other stormwater management features, nor other drainage features such as culvert pipes. Thus, their installation can, overall, be cost effective. Porous asphalt pavements have been shown to mitigate the urban heat island effect.

According to UNH, these are the principal advantages:

- Quantity and Flood Control (this is the main advantage on the light of the future climate changes)
- Water Quality Treatment
- Recharges Groundwater to Underlying Aquifers
- Allows for reduction of stormwater infrastructure (piping, retention ponds etc.)
- Suitable for cold-climate applications, maintains recharge capacity when frozen
- Allows for reduced salt and sand usage by not allowing the development of ice on the surface
- Maintains traction also while wet
- Reduced spray from travelling vehicles
- Reduced Roadway noise
- Extended pavement life due to well drained base and reduced freeze-thaw
- Increased safety for the drivers consequent to the flood and spray control.

In Report No. 5, the importance of the adhesion between asphalt binder and aggregate was stressed. Because of the limited binding of adjacent particles in a porous asphalt, due to its open grading, this is very important. The use of different additives to promote adhesion was suggested. Among these additives is hydrated lime to be mixed together with aggregates and bitumen in a quantity of approximately 1% of the total dry aggregate by weight. The cost of hydrated lime depends on the quantity; it ranges from $10/25 kg to $130/tonne. This is a rather cheap method for increasing adhesion. Other additives are more suitable for increasing not only adhesion, but also the overall quality of the asphalt. These other methods involve the use of liquid anti-stripping additives and polymer additives such as SBS. SBS is a thermoplastic rubber developed by the Shell Chemical Company; originally developed for use in the production of tyres, nowadays is suitable for the modification of bitumen. With the modification of asphalt by SBS, the high-temperature rutting resistance and temperature susceptivity of asphalt can be improved effectively. Prices were asked of the suppliers, and, again, they depend on the quantity. An example of price is $2500 – 3500 / tonne (Yumin Corporation, South Korea). Other anti-stripping additives, added in the proportion of 0.1 – 1% by weight of bitumen (various sources; e.g.: http://www.petrochemspecialities.com/anti-stripping-agent.htm), can have more contained costs. An example is represented by the Carlo-amine, added before mixing the asphalt to improve the adhesion, and thus the water resistance, with consequent reduced maintenance costs. Its price is found to be $50 to $100/tonne (Chengdu Hi-Tech Zone Zhaoming Auxiliary Factory). On the website http://www.thefreelibrary.com/Compounding+ingredients+price+list-a011347446 can be found a list of prices for anti-stripping agents, anti-oxidants and other additives useful for pavement strengthening. Many different anti-stripping additives at different costs can be found on the market.

The improvement of the subbase/subgrade layers relies on methods to reduce the moisture content of the aggregate or soil and/or methods to increase its stiffness. As already stated in Report No. 3, stabilisation through various binders is the main and most used means to achieve good results. Among these are cement, lime and bitumen. Other additives such as Dry Powdered Polymers (DPP) are also found in the market.

The use of cement as a subbase and subgrade binder is very common. This is due to its low price and ready availability. According to Wilmot & Roadway (1999), cement is, generally, the cheapest additive, and polymers are less expensive than bitumen. However, the initial costs depend on the location, and the cost of the total process depends on the stabilisation depths required for each additive and on the need of additional processes like, for example, special surfacing to combat reflection cracking. Despite its frequent use, cement is not necessarily the best candidate. In fact (see Report No. 3), its drying process can lead to shrinkage, a problem that can be limited by using fibres or fly ash mixed with the cement. It also raises sustainability issues that need to be considered. Lime is cheaper than cement, however its positive effect is observable only after long time, and is not always very appreciable.

According to Ramanujam and Jones (2000), the cost of foamed bitumen is higher than other stabilisation treatments, as it was shown in the table published by Kendall et al. (2000) (see Table 4 - once again, note that these prices are typical of the U.S. and not, necessarily, of Europe). Similar results were found by Saleh (2006), see Table 5. In this case, prices refer to New Zealand so they give only a qualitative indication, as they are in NZD (the conversion rate is currently 1 NZD = 0.726 USD).

Table 4: Costs of stabilisation (Kendall et al., 2000).

Treatment	Cost ($/m^2)
2-3% lime/flyash (200mm)	$6 - $9
Bitumen (2%) emulsion/cement (2%) (200mm)	$12 - $14
Ad-Base 4/cement (175mm)	$12 - $14
Foamed bitumen (250mm OWP, 200mm IWP)	$13- $15

Table 5: Costs of different stabilisation methods (Saleh, 2006).

Design alternative	Mix	M_r (MPa)	Thickness h (mm)	Quantity per lane—km (m^3)	Unit weight (t/m^3)	Quantity per lane—km (tonne)	Cost per tonne ($NZ)	Cost per lane-km including sub-base course and chipseal surfacing ($NZ)
1	Slag	420	245	894	2.0	1789	40	110960
2	Basalt	340	255	931	2.0	1862	40	113880
3	Greywacke	380	250	913	2.0	1825	40	112420
4	2% Lime	484	240	876	2.0	1752	45	118260
5	4% Lime	599	235	858	2.0	1716	47	120049
6	2% Cement	898	235	858	2.3	1973	52	142007
7	Foam stabilised	1000	235	858	2.3	1973	55	147925
9	HMA	3000	230	840	2.3	1931	135	285485

However, the comparison shows that the price of foamed bitumen is very close to that of cement treated base. The improvements of the use of foamed bitumen instead of cement are, however, multiple: foam bitumen's action is very fast, making the road quickly trafficable. Its resistance to moisture is higher. Also, the price is likely to decrease as the method becomes more common. This technique is also much cheaper than HMA bases.

The use of DPP as binders is practised somewhat in Australia and other Asian countries. Vorobieff & Wilmot (2001) list the average costs of binders around Australia (in $AUD) in Table 6):

Table 6: Average costs of binders in Australia (Vorobieff & Wilmot, 2001).

Binder	**Cost ($AUD)/tonne**	**Today's equivalent ($USD)**
Cement	150	138
Lime	140 - 180	128 – 166
Fly ash	30 - 60	27 – 55
Bitumen	500	460
DPP	*600 - 900*	*552 - 830*

The cost of DPP is rather high, compared to other treatment methods. These polymers work particularly well with finer soils (usually avoided in road construction). For these reasons, DPP should be considered in cases of particular necessity, e.g. when the subgrade soil is not very suitable for construction and importing better material would be costly; but, most of all, DPP is a valuable solution for zones where flood risk is particularly high, as in coasts. It may also offer environmental benefits, not introducing a high pH as does cement.

Geotextiles were shown to be give good results in increasing the strength and stiffness of the sub-surface pavement and subgrade in situations of moisture increase. In Report No. 3, a comparison between the different types of geotextiles and the cases in which they are more suitable was performed. There exist many different types of geotextiles, and prices can vary significantly. Currently, geotextiles cost between $ 0.50 and $ 2 per square meter, while geogrids cost $ 1 to $ 5 per square meter. The benefits are various:

- Reduced aggregate and excavation costs,
- Reduced rutting,
- Improved fill compaction,

- Reduced drainage system maintenance,
- Increased design life and improved life-cycle management and
- Thinner aggregate layers.

The importance of the drainage to reduce the moisture retention of the pavement structure has already been highlighted. An idea of the advantages that a good drainage brings to the road is given by Zaghloul et al. (2004): the authors performed a LCCA on a road with a good quality subsurface drainage system and with a poor drainage system. The results showed that a good drainage reduced the life-cycle costs by more than 50%, and also, a significant increase in the structural service life. The authors added other, more sophisticated, subsurface drainage systems to remove water more quickly from the subbase layer so as to enhance, further, the cost savings. These results are enough to justify the costs related to drainage layers and other related structures.

The different importance that subsurface drainage presence and base material used have on the performance of a road has been investigated by the National Cooperative Highway Research Program (NCHRP, Hall & Correa, 2003; Hall & Crovetti, 2007). As a result of the research, the authors suggest that, in presence of wet climates and poorly draining soils, although a subsurface drainage is important, a stiffer base (but not extremely stiff in case of a concrete road) could be a more cost effective design to be taken into consideration. They leave a little unanswered the question as to whether a stiffer base course can be achieved by use of a drainage underlayer!

4 Conclusions

This section of the research highlighted how the present maintenance and rehabilitation methods can still be used with the future climate conditions. The operations can remain more or less the same, although the interval of time between maintenance actions is likely to decrease. Operations such as crack sealing, joint sealing and patching by the application of surface treatments such as chip seals, asphalt emulsion sealcoats, slurry seals, and bituminous crack sealants will prevent the entry of water through the surface into the aggregate below, improve skid resistance and allowing a longer pavement life.

As the pavement surface cycle life is relatively short (on average, between 20 and 40 years?), it is unlikely that a change in the maintenance and rehabilitation practice will occur. Rather, it is important to start from now to include climate, both present and projected, into the pavement design, as, for example, the M-E PDG does. This will allow pavements to be more suitable, as an example, for an increase in temperature, and thus the total costs for maintenance would be reduced in the future.

New maintenance and rehabilitation techniques, especially addressed at avoiding deterioration due to climate change, are being developed nowadays, and many others will probably be developed in the future. It is not possible to predict the future techniques; however, important developments are being done in order to reduce the so called “Heat Island effect”. These methods consist in creating a high albedo road surface, for example by performing maintenance operations with light colour material, which absorbs less radiation, i.e. heats less. A lighter colour pavement is colder, and thus it ruts and ages more slowly. This topic is starting to develop now, but it will gain more and more importance in the future, when increased temperatures will increase the deterioration speed of asphalt.

Maintenance of road subbases and subgrades are based on maintenance operations on the drainage system. Also in this case, given the increase of rainfall intensity and of rainstorms that is predicted in the future, it is probable that drainage systems will get blocked more easily, and maintenance will occur more often. The methods will remain the same as today.

While pavement surface life is typically short, the sub-surface layers are designed to last for longer. This means that the road subbases that are built nowadays are likely to be still in function when climate-induced changes affect the deterioration of roads. This shows how important it is to include climate considerations in the pavement design. As these lower layers are not expected to suffer much from temperature effects, it is the water effects that require the longer-term assessment. Nevertheless, it should be noticed that the previous part of the research showed that the climate change will be unlikely to affect the road in a drastic way, and that present road construction methods should be able to face such climatic changes. Probably, the only important factor that might sensibly affect future road design, and should therefore be considered, is the possibility of water table rise: this might be not negligible in certain localities and could strongly reduce the subgrade and subbase strength, if there is no planned rehabilitation.

A type of road that can be strongly affected by climatic conditions is gravel road. Climate affects the erosion through the frequency, intensity, and duration of rainfall. The effect of frost should, instead, decrease, as higher temperatures are expected. Depending on locality, maintenance operations may be needed more often, and might end up being uneconomic to perform frequently. In these circumstances, a rehabilitation operation using binders could be a good solution. However, it is important to say that the indirect effects of climate change are likely to be more important than the direct effects. As a consequence of climate change, a road might become highly trafficked, or, vice versa, not trafficked, due to a relocation of the population.

The indirect effects are also likely to be most significant ones as concerning costs. An analysis of the costs and benefits of the different techniques to improve the asphalt design and maintenance showed that, although it is hard to quantify the real costs of the different techniques, they all showed savings during the life cycle that are greater than their initially higher costs. Among the subbase treatment methods, cement is shown to be the cheapest binder, but the drawbacks are not negligible. Foamed bitumen, although slightly more expensive than cement, gives better results, and the higher costs are easily absorbed thanks to lower design restrictions and the minor expenses during the lifecycle. Dry Powdered Polymers are shown to be too expensive for general treatment, and thus they are suggested to be considered as a treatment method only in situations of particular necessity or when other treatment methods are not very suited for the type of soil.

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