1. Overview

This document is a summary of the work performed by the ‘COST351 Action’ known by its acronym “WATMOVE”.

Following a programme lasting almost 3½ years the study team from 18 European countries has researched just about every aspect of Water Movement in road pavements and in the earthworks of highways constructed to allow roads to cross the landscape. As water in the construction is one of the main causes of deterioration and premature distress of pavements and their supporting geo-technical structures, the project has concentrated:

- firstly on understanding water movement, water contents and their effects on the materials that comprise the highway construction,
- secondly on how contaminant migration is associated with water in the pavement and near-pavement hydrological environment,
- thirdly on measuring and describing the water location, quality and movement,
fourthly on setting out possible mitigation strategies.

The principle output of the WATMOVE project is a book, to be published soon by Springer, entitled “Water in Roads”. In almost 400 pages, with the help of many illustrations, it gives full coverage of basic principles and more advanced theory, it sets out methods of measuring water and water flow, it describes best-practice in the collection of water samples, it explains modern laboratory tests and their interpretation, it shows how the value of and changes in the water condition effect soil and aggregate behaviour, it provides an introduction to the tools that are available to model water flow and its impact on the pavement and soil materials and ends with chapters that concentrate on practical solutions to ensure good drainage and control of contaminant migration.

2. Introduction

Roads have been constructed for more than 2000 years. Even the earliest engineers practiced drainage of the pavement’s sub-surface layers in order to keep the highway functioning.

Nowadays, many billions of euros are spent on road construction and maintenance each year, and road transport is the primary method of mobility for European people and goods. Transport constitutes about 10% of the Gross National Product of the European Union and more than 80% of the total transport of people and goods is provided by the road infrastructure. Investment in road construction and maintenance in Europe is therefore at a very high level and any improvements can have a significant effect on the European economy.
Not only will well-maintained roads and highways contribute economically, for they are also essential for social development of Europe. On the other hand, the deterioration of roads can have serious consequences for the safety and comfort of road users.

In many countries premature break-down, especially of low-volume asphalt roads, is an accelerating problem. Increasing traffic and traffic loads demand higher performance levels from pavement if premature rutting and cracking is to be avoided. At the same time climate change means that highways are likely to be exposed to more rain and to greater thermally induced cracking that can lead the runoff into the structure. Once in the pavement or embankment, water plays a primary role in giving shorter service life and in increasing the need of rehabilitation measures.

A further problem that is becoming of more and more concern, is the possibility that the road is a source of contaminants that are having an undesirable effect on the hydrological environment. Two sources are possible:

- leaching of contaminants from the road construction materials and earthworks,
contaminant in runoff from rainwater or snowmelt that flows over the top of the pavement and then soaks into the ground.

3. **COST351**

For these reasons, in 2002, the COST programme (now administered by the European Science Foundation) agreed to a proposal to study these problems and to provide best guidance for road owners, designer, maintainers and contractors. The programme was given the number 351 and the title “Water Movements in Road Pavements and Embankments”, with the acronym “WATMOVE”. The concerted Action commenced work in December 2003 and finished in April 2007.

The membership quickly grew, as the problem areas it addressed are common to all countries, so that it soon had 18 members (see box). The work was performed in three major working groups (on Modelling and Monitoring, on Environmental Aspects, and on Performance-Related Aspects). Additional supporting work was performed by two other working parties, one of which dealt with defining the state-of-practice and one of which handled dissemination.

### Members of the COST351 Action with dates of joining

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4. **Aims & Objectives**

To help ensure that valuable and applicable findings were obtained from the study, the main objective of the Action was defines as an increase in the knowledge required to improve the highway performance and to minimise the leaching of contaminants from roads and traffic. The overall goal will be appreciated by the users of roads just as much as by pavement engineers as it is to improve pavement performance allowing less road closures, better use of the road network, longer service lives and more effective transportation of goods and people.

The detailed objectives of the Action have been:

- to identify water movement and moisture conditions in unbound pavement layers and subgrade for different types of road constructions in various climatic conditions,
to investigate the relationship between the mechanical behaviour of materials/soils and their hydraulic conductivity and moisture condition,

to implement finite element modelling based on laboratory analysis and field studies in order to simulate water movement and moisture conditions in road construction,

to identify, investigate and control contaminants leaching from soils, natural aggregates and by-products.

5. Achievements

The chief achievement is a nearly 400 page book to be published soon by Springer. The chapter outline is shown alongside. A total of 13 chapters, plus annexes, have allowed the WATMOVE team to cover the topic matter in considerable detail so that students, researchers, practitioners and policy makers will all find sections of value to them. There is something of a tension developed when trying both to define the state-of-the-art for researchers at the front of their fields of study and also to provide a best-practice guide to lead engineers, more generally, into applying scientific and technological advances in their own businesses and duties. Nevertheless, the Action team believes that it has gone a long way to meeting this self-imposed goal by the coverage provided in the different chapters. In essence, the earlier chapters explain theory, the central chapters seek to apply that in more advanced ways and the final chapters describe the practical out-workings. Thus best-practice is described both with respect to the latest modelling techniques and also with respect to in-situ application. A summary of the chapter titles appears alongside.

This represents something of an expansion beyond the original proposal made to the COST organisation. Early on in the study, the team identified, that heat flow is a very important driver of moisture content and moisture movement (for example, in connection with water movements causing frost heave). Therefore, particular and specific attention was given to this aspect. Also, regarding the movement of contaminants in the pavement construction, subgrade, embankments and adjacent earthworks, it was quickly realised that the water driving such
seepage comes, largely, from run-off and will already be contaminated before it enters the pavement / embankment structure. The WATMOVE team therefore concluded that the book should also address contaminated water run-off, albeit with the emphasis on percolating water in the substructure.

6. **Summary of Technical Coverage & Findings**

After a brief history, the book introduces the topics to be covered in an introductory chapter. Water flow theory is then described in more detail. In addition to the conventional description of saturated flow, water flow under partially saturated flow is considered and the relationship between partially saturated soil and the suction that, in part, controls water content and movement is described and tools presented for its description. Of course, a major reason for doing this is to provide to the user the tools that will help him or her to benefit from the remainder of the book. A further purpose is to clearly define the fundamental issues that have such a major influence in every aspect of the topic area.

Conventional and modern test methods for determining water content are described, particularly those that are non-destructive and, therefore, may be used in-situ for control and monitoring purposes. Given the importance of suction, as mentioned above, techniques for measuring this are also covered. There are a wide range of permeability tests available. Six are selected for detailed study and review and their appropriate application is described.
Comparison between laboratory soil suction measurements achieved using a tensiometer and achieved using a Thermal Conductivity Matric Suction sensor (#18).

Next the book addresses heat flow issues. Temperature highly affects pavement performance. High and low temperature not only affect viscosity of asphalt concrete but can also have very significant impact on moisture flow within pavements. At temperatures below 0°C the freezing of pavements drastically changes permeability and frost heave might occur forcing water to flow upwards to the freezing front. Heat transfer in soils involves convection, radiation, vapour diffusion and conduction. For pavements, conduction is the most important factor. During warm and sunny summer days though, it has been determined that natural convection should not be neglected.

Frost susceptible soils always experience frost heave and freezing but drainage will lower the heave by reducing the water content. Nevertheless, a frost susceptible soil will always hold enough water for a significant heave to be occur, therefore other techniques than drainage alone must be employed in such circumstances.

Following these introductory sections on water movement and its driving agency, temperature gradient, the book addresses the sources, transport pathways and targets of road and traffic contaminants. Given the wide range of sources of pollution (including traffic and cargo, pavement and embankment materials, road equipment, maintenance and operation, as well as external sources) it is impossible to prevent the presence of contaminants. Heavy metals, hydrocarbons, nutrients, particulates and deicing salt are among the contaminants needing the greatest attention. Runoff, splash/spray and seepage through the road construction and the soil are major transport routes of pollutants.
In saturated media, diffusion, advection and dispersion are the major processes of mass transport whereas, in unsaturated soil, this strongly depends on the soil-moisture distribution inside the pores. Sorption/desorption, dissolution/precipitation and exchange reactions are the most significant chemical processes governing pollutant transport in soils with redox conditions and acidity having a major influence on heavy-metal mobility. Plants close to heavily trafficked roads accumulate traffic-derived pollutants that can disturb biological processes in themselves as well as in animals, microorganisms and other biota. Even though the pollution of such flora and fauna can be severe, European legislation chooses to emphasise the protection of water bodies (rivers, lakes, groundwater) against pollution, partly because of the greater ease of policing their pollution levels. Another reason for protecting water bodies is the dependence that human life and commerce has on supplies of clean water.

Including consideration of measures for environmental protection at an early planning stage is much more cost-efficient than retrofitting measures and installations afterwards. To judge the need for prevention and mitigation measures, chemical and biological characterization of soil and water is often required. For this reason a separate chapter of the book is set aside to describe contaminant sampling and analysis.

Before any soil or water sampling regime is contemplated and before any specimens are analysed, it is essential that a systematic sampling programme and network is designed and
planned with its purpose and constraints clearly in view. Therefore, both the available techniques and their best deployment is described in some detail, not only listing the instrumentation devices that are available, but also giving advice on design of sampling schemes and frequencies, data handling and sample storage. Bibliographic information points the user to more extensive supporting materials.

A substantial section of the book is given over to introducing and advancing the knowledge of the interaction between water and the performance of highway construction materials (specifically aggregates and subgrade soils). Initially this is achieved by summarising in-situ observations of road behaviour as a function of water condition. It is shown that water content in the construction is very sensitive to the influences of climate – especially rainfall and freezing and thawing – and that the influence of rain is most marked nearest the edge of the pavement.
pavement. As an example of the utility of such information is the recommendation that low-volume road owners may manage trafficking of their to maximise performance of while minimising inconvenience to users.

In general, field observations indicate clear and significant variations of moisture in subgrades. This is true both for moderate climates as well as for cold regions where it is related to temperature. In particular, thawing may induce strong increases in moisture. The mechanical behaviour, as observed in situ, is strongly affected by moisture variations: the wetter the state the lower the stiffness (up to a factor 2 or more), the lower the strength and the higher the deflection. Therefore we may conclude that an efficient drainage system is crucial in order to reduce the road structure’s ageing.

Monthly average water contents in the granular base, at the centre and near the edge of a pavement.

Rut depth development in an accelerated test. Note how added water accelerates deterioration by a factor of 4.
Clearly, the impact of water on pavement performance can be very significant indeed. The research team believes that there is much room to improve the engineering approach to the subject matter. Whilst traditional experience, historical practice and the application of time-proved rules-of-thumb have much value, their continued use without taking notice of the major theoretical and analytical developments of the subject is inimical. For this reason the book seeks to present the latest research developments in the area of modelling of moisture movement under gravitational and temperature drivers, coupling this with mechanical behaviour by means of comprehensive aggregate and subgrade constitutive relationships.

Although a plethora of models are available in the literature, it is concluded that the constitutive models suitable for routine pavement design and advanced pavement design can be classified as follows:

- **resilient models** (suitable for stress analysis and fatigue computations) such as the k-θ model and Boyce models,
- **long-term elastoplastic models** (suitable for rutting studies) can be split into four categories (see box alongside).

It is shown that routine pavement design is based on an elastic calculation, with a resilient modulus. Usually, the design criterion is a limitation of the maximum vertical strain. However, a too simple understanding of pavement and earthworks behaviour is liable to mean that the range of possible material responses is not fully considered. Partly for this reason, more elaborated models take into account the other behaviours, particularly irreversible behaviour (e.g. the Chazallon-Hornych model, the
Suiker model and the Mayoraz elasto-visco-plastic model) are introduced. A particular advantage of some of these newer approaches is their ability to take into account suction and suction variation.

The coupling of mechanical behaviour, water content, water movement and heat in pavement and earthworks structures is at the forefront of current research. Developments in this field allow us to:

- describe geo-materials using a non-linear solids mechanics framework incorporating elasto-visco-plasticity and then to implement this for design purposes,
- describe both saturated and non-saturated water flow and to link this description to material condition,
- to consider both the mechanical and fluid processes as a function of, and an influence on, the movement of heat,
- to model the transport of pollutants by and in the fluid, noting that they may modify the fluid’s properties if concentration is high enough.

Cleary this is a tough proposition. It is impossible to cover all the complexities involved but the relevant chapter in the book gives a detailed overview of the computational approach that is necessary and then presents typical computational results comparing them with in-situ measurements. By this means the power of the techniques are illustrated and their take-up encouraged.

Having introduced a theoretical framework for the relationships between water and material performance, it is now time to describe these by means of materials testing. Therefore a chapter is set aside to present laboratory and in-situ experimental techniques used to describe mechanical behaviour of pavement material at different saturation stages. Repeated load triaxial testing was used to obtain both stiffness characteristics and a description of the ability to withstand accumulation of permanent deformation during cyclic loading. As pavement engineers are dealing with unsaturated soils, techniques for the control of moisture/suction are
A lightweight falling weight device for assessing modulus, in-situ. It can easily be used to assess materials at different moisture contents.

particularly emphasised with the goal of obtaining sound estimates of material parameters that are so necessary for reliable modelling and prediction of in-situ performance. Of course, no laboratory assessment can hope to replicate all in-situ conditions, so the topic of model calibration has been introduced.

Techniques for determining soil and pavement material behaviour are not limited to the laboratory, as evaluation of pavement structural capacity is often based on deflection measurements with non destructive testing equipment. For this reason, these approaches have also been presented and typical responses are illustrated both for laboratory and in-situ evaluations. The deleterious effect of water is very clearly shown from these results.

Roadowners and their maintenance agents are responsible for ensuring that the construction and use of roads is not detrimental to the quality of natural waters. Strategies for the protection of the environment from road and traffic pollutants should primarily be directed towards limiting the generation of pollutants. As a complement to source-based measures, mitigation measures aim at reducing the dispersal of pollutants to the roadside environment and detrimental effects on soil, water and biota. Principles of road and traffic pollution prevention and mitigation are therefore outlined. Pollution prevention and mitigation is connected with several constraints that can be classified in five major groups (see next page).

As the final sections of the book dealing with the practical aspects of drainage were prepared, it became apparent that pollution mitigation techniques are integrally involved with the techniques for draining water from the pavement substructure and embankment. The holistic approach to management of a
pavement is needed to maintain the strength of the road structure, to provide long service life, safe traffic conditions and the environmentally acceptable handling of water in the highway environment .... and to achieve this for optimum economy.

Therefore the study team presents general principles for the design and choice of a drainage system, the measures to adopt during construction and maintenance phases and considers the control of surface and subsurface water contamination, in order to minimize the possible detrimental effect to existing aquifers and habitats. Apart from drainage itself, the techniques presented also aim at preventing ground waters from entering the superficial layers of pavement. Sometimes this can occur where the highway geo-hydrological environment is not properly appreciated and/or where an inappropriate or inadequate drainage system is provided. This can induce an inversion in the direction of water flow, allowing water to re-enter the earthworks or pavement structure.

Constraints to Prevention & Mitigation of Pollution
- site sensitivity and vulnerability,
- risk and hazard to pollution,
- traffic characteristics,
- economic constraints
- legislative constraints

Longitudinal drainage for an embankment on “½ a hillside”
As well as providing a comprehensive review of both traditional and state-of-the-art drainage systems, with copious illustrations, the final section of the book gives a basis for decision making in the selection and design of the sub-surface drainage system together with typical material properties and dimensions required to ensure successful use.

7. Workshops, Newsletters & Web-site

Although you will need to buy the book, much of the work is also available on-line at our web site. There you will find copies of the presentations made at our three well-attended seminars/workshops – Madrid (2005), Constantza (2006) and Athens (2007) – together with copies of our newsletters and questionnaire results.

8. Conclusions

When the WATMOVE project started in late 2003, it seemed that it would be difficult for a European group to spend three or more years studying the movement of water in road layers and in the adjacent earthworks. It turns out that the subject is far more complex and extensive than any member of the WATMOVE study team realised. Despite having produced a substantial book, it seems that, in many respects, the task of advancing the topic of sub-surface drainage is hardly started! Like many other subjects, once you begin to investigate "how", "why" and "where", you find that there are many aspects that are little understood and that no-one has ever tried to answer some of these questions. Certainly there are many areas that are, as yet, unresearched by anyone and we have tried to enumerate these in the book.

Although there is much more to be discovered and written, the study team has produced a book with an original concept – it brings together engineering theory, geological constraints, and best-practice into a book that covers scientific aspects, engineering principles and design solutions. The initial scope, set down at the start, has been substantially expanded so that we can explain seepage flow, temperature induced water
movements, flow and quality monitoring, geo-environmental aspects and highway sub-surface water control in all of their interacting connectivity.

9. Acknowledgements

To produce a book like “Water in Roads” requires a huge amount of effort. So this summary report must end with a very big “thank you” to everyone who’s co-operated during the life of the project. Every one of the authoring team gives thanks to colleagues, past and present, in their own institutions and in the WATMOVE team, for all their many and varied contributions. The WATMOVE Management Committee and its working groups have given a great deal of time, energy and, above all, enthusiasm to the task. We also acknowledge the debt to the COST office in Brussels and to the dedicated team of scientific and administrative officers who’ve helped the project in so many ways, not least in funding our meetings. Thanks too, to the publisher of the “Water in Roads” book – Springer. Final thanks are reserved (in anticipation) for you – the work will have been worthwhile when you start using the findings to increase your knowledge and to build better roads!