Ooms
Avenhorn Holding bv

P.O. Box 1
1633 ZG Avenhorn
The Netherlands

Phone +31 229 547700
Fax +31 229 547701
Internet www.ooms.nl

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M.R.A van Vliet, C.A.P.M van Gurp
A.H. de Bondt, W.T. van Bijsterveld

STRUCTURAL VIABILITY OF SHALLOW DEPTH HOLLOW SYSTEMS IN AIRFIELDN PAVEMENTS

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Structural viability of shallow depth hollow systems in airfield pavements

M.R.A. van Vliet
TNO Building and Construction Research, Delft, The Netherlands

C.A.P.M. van Gurp
KOAC•NPC, Apeldoorn, The Netherlands

A.H. de Bondt & W.T. van Bijsterveld
Ooms Avenhorn Holding bv, Scharwoude, The Netherlands

ABSTRACT: The growing interest in pavement energy collectors, data communication systems and fuel pipe assemblies embedded at shallow depths at airfield pavements has led to the need to investigate the structural adequacy of these 'hollow systems' under critical aircraft loading. Especially pipe systems and porous layers of pavement energy collectors may be a structural hazard, because these layers should be constructed at shallow depth for efficient use of solar and geothermal energy. The paper presents the results of a risk analysis organised among experts in the field of asphalt energy collectors and airfield pavements. The paper also addresses the various numerical analyses conducted to quantify the stresses, strains and failure ratios near the discontinuities in the structural layers. The study has shown that shallow depth hollow systems may be applicable for structural reasons as long as enough attention is given to adequate structural properties and behaviour to carry aircrafts with heavy gear loading or high tyre pavement surface contact pressures.

KEY WORDS: discontinuities, energy collection systems, finite elements, risk analysis

1. INTRODUCTION

1.1. Motive of the research

Since 1998 various systems for the generation of thermal energy from asphalt pavements have been developed in the Netherlands. These systems can either consist of an asphalt or cement concrete layer with pipes (comparable with floor heating systems) or a porous asphalt layer enclosed in two impermeable layers. The generated energy (both heat and cold) is stored in aquifers and can be used for heating and cooling of buildings and pavements. Though feasibility of asphalt energy collector systems in public roads has been shown in various projects, there existed a lack of knowledge on the long term effects of the presence of discontinuities (e.g. pipes) in asphalt layers at shallow depth in airfield pavements with respect to structural behaviour and deterioration of the surface.

By the end of 2002 the co-ordination committee Airfield Pavements of the Dutch National Technology Platform for Infrastructure, Transport and Public Space (CROW) initiated the investigation of the research needs with regard to 'Discontinuities in Airport Pavements'. This study resulted in an overview of possible discontinuities in pavements ranging from data communication systems to asphalt solar collectors. The committee furthermore presented a list of recommendations and a research plan for the further investigation of this subject. This paper describes the work and the results of the research carried out in this second phase (CROW, 2004).

1.2. Goals of the second research phase

According to the research plan recommended in the first phase, the research consists of the following points:

- risk analysis of the aspects that can not be calculated or where practical experience is not available in the public domain;
- (finite element) model calculations related with laboratory material testing;
- set up of a list of minimum requirements for documentation, which a producer of pavement energy collectors should provide.

The outline of the paper is in accordance to these points.

The research question in this phase can be stated as follows: *'Are discontinuities such as asphalt solar collectors allowable in airfield pavement structures and which structural aspects are relevant when making the choice between various systems?'* The study explicitly focuses on pavement energy collectors since at the start of the research no experience was available with application of these systems in airfield pavements. Furthermore, because of the novelty of such systems, there is no long-term experience.

The final result of the working group is a guideline for Airfield (or Highway) Administrations for a proper assessment of the risks and opportunities involved when incorporating an energy collector in a pavement structure.

1.3. Working group 'Discontinuities in Airfield Pavements'

The co-ordination committee Airfield Pavements was advised and supported by TNO Building and Construction Research and KOAC•NPC. This consortium is expert on the relevant disciplines in this matter, such as finite element analyses, pipe systems and energy collectors in asphalt and airfield pavement loading conditions. The intermediate results were discussed within the working group 'Discontinuities in Airfield Pavements' formed in the first phase out of members of Airfield Administrations interested in procurement of an asphalt collector and experts in (airfield) pavement design and analysis with 3D finite elements.

The working group consisted of:

A.H. de Bondt Ph.D. M.Sc.	Ooms Avenhorn Holding BV
A.J. van Leest M.Sc.	CROW
W.F. Stas M.Sc.	VBW-Asfalt (Dutch Asphalt Pavement Assoc.)
R. van der Tang B.Sc.	Dutch Royal Airforce
J.P. Verbeek M.Sc.	Infrastructural Facilities Dutch Royal Airforce
J.T. Vermeulen B.Sc.	Dutch Royal Airforce
M.J. Voorwinde B.Sc.	Amsterdam Airport Schiphol

2. RISK ANALYSIS

2.1 Approach

Due to the novelty of pavement energy collectors there is only limited experience available in the public domain. Moreover, not all the risks are of structural nature and can therefore not mathematically be calculated. By forming a team of experts on each of the components of the system, completed with project leaders of the Dutch road administration who conducted experiments in two trial sections with energy collection systems, optimal use was made of all experience available (at start experts from manufacturers were not invited to prevent any bias). The team was invited to a brainstorm session to devise all possible events with a negative effect on the functionality of the pavement. After this session for each of the events the chance that it actually occurs and the consequence of an occurrence was established using classes as presented in table 1. In the consequences a difference is made between non-availability and costs of repair. This distinction is made because the costs of non-availability of the pavement is highly dependent on the airport size and the type of use (runway, taxiway or platform).

table 1: Classes of chances and consequences

	chance of occurrence	**consequence of occurrence**	
class		non-availability	costs
1	> once in 10 years	> 1 month	> € 10 million
2	once in 10 years	1 week to 1 month	€ 1 – 10 million
3	once in 25 years	1 day to 1 week	€ 100.000 – 1 million
4	once in 100 years	2 hours to 1 day	€ 10.000 – 100.000
5	< once in 100 years	< 2 hours	< € 10.000

Finally, the *risk* of each event, defined as *chance x consequence*, is determined in terms of non-availability and costs. Due to the logarithmic nature of the classes, the final risk number is acquired by addition.

2.2. Results of the risk analysis

The working group presented a top 10 of risks in terms of non-availability and costs. These risks are based on a properly planned, designed and constructed pavement structure. The decision whether a risk is acceptable or not is left to the airport authorities and subject to the intended use of the pavement and the environmental conditions.

The events with the highest risk are thought to be (the number in brackets represents the risk number, note that high risk numbers represent a small risk!):

- reduction of the bearing capacity/cracking due to inhomogeneity of the structure (4)
- non-availability due to animals (birds) attracted by the heated pavement (in winter) (4)
- damage to the pipe system due to repairs in and around the pavement structure (5)
- cancellation of the permit to use the aquifer for heat and cold storage (5)
- damage to the pipe system due to an extremely cold period (6)

3. FINITE ELEMENT MODEL DEVELOPMENT

3.1. Goal

One of the conclusions of the explorative study (CROW, 2003) was that 3D finite element analysis is needed for the investigation of the effects of an energy collector system in the pavement. Moreover, this study resulted in a list of minimum requirements for documentation which a producer of such a system should provide to the airfield administration. One of the requirements is a finite element analysis of the producer's system. In the following paragraphs the analysis of typical pavement structures is described. Special attention is paid to the dimensions of the model, allowable simplifications and boundary conditions.

3.2. Dimensions

The dimensions of the mesh in horizontal directions are 10 m, based on modelling experience. To determine a suitable depth of the finite element mesh, the depth has been varied in a 2D mesh from 10 m, 20 m, 30 m to 40 m. Although the absolute value of the surface deflection due to a single wheel load increases with increasing depth, the shape (curvature) of the deflection does not change after 20 m. Therefore a depth of 20 m is considered to be sufficient.

The number of elements of the obtained mesh in 2D has subsequently been reduced resulting in a courser mesh, thereby optimizing the calculation time. The coarsest mesh which still results in acceptable results has been extended to a 3D mesh with 20-noded cubic elements. In the mesh some local refinements have been made to incorporate the modelling of the pipes. The circumference of the pipe is surrounded by 16 elements. The actual plastic pipe has not been modelled since the structural contribution of the material is considered not to be relevant. Therefore an empty space has been created in the asphalt with the outer dimension of the pipe. A calculation has been performed with a hydraulic pressure on the inside of the 'pipe' to investigate the effect. It was found that the inside pressure is a slightly favourable condition and is therefore left out.

3.3. Boundary and loading conditions

The boundary conditions in both the 2D and the 3D models were the same. The bottom nodes were supported for all translations, whereas the vertical boundaries were only supported for the translations perpendicular to the boundary. The remaining translations could freely occur. In the 2-dimensional mesh the effect of a multiple wheel load versus a single wheel load has been investigated. With respect to the vertical displacement the distance between the wheels in a landing gear are big enough to not influence each other. Considering the horizontal stress conditions, interference does occur. A further investigation of the influence of multiple wheel loads in a 3D mesh resulted in the conclusion that the analysis of a single wheel load is sufficiently accurate. If the results indicate that the stress conditions are such that damage to the structure might occur, then refinement of the mesh and modelling of the complete landing gear is recommended to acquire a higher accuracy.

4. STRUCTURAL ANALYSIS OF SHALLOW DEPTH HOLLOW SYSTEMS

4.1. Modelled geometries

For the 3D finite element analyses, four basic structures (numbered I to IV) have been defined with the boundary conditions as described previously. The structures are based on the standard design for an asphalt concrete taxiway on Amsterdam Airport and a cement concrete platform respectively (see figure 1). In the semi-rigid case (asphalt concrete on CTB), the asphalt concrete has a thickness of 200 mm whereas in the rigid case the thickness of the cement concrete (without construction joints) is 380 mm. Structure I and II represent a system with pipes at a depth of 50 mm and 100 mm respectively. The pipes have an external diameter of 30 mm and a spatial distance of 100 mm. Structures III and IV have a porous asphalt concrete layer with a thickness of 50 mm at a depth of 50 mm and 100 mm respectively. This layer serves as a water conducting medium and has only been analyzed with asphalt concrete properties. A perfect bond is assumed between all layers. Due to time limitations, no cracks or joints in the CTB are included in the model, which means that reflective cracking issues are not considered in this study.

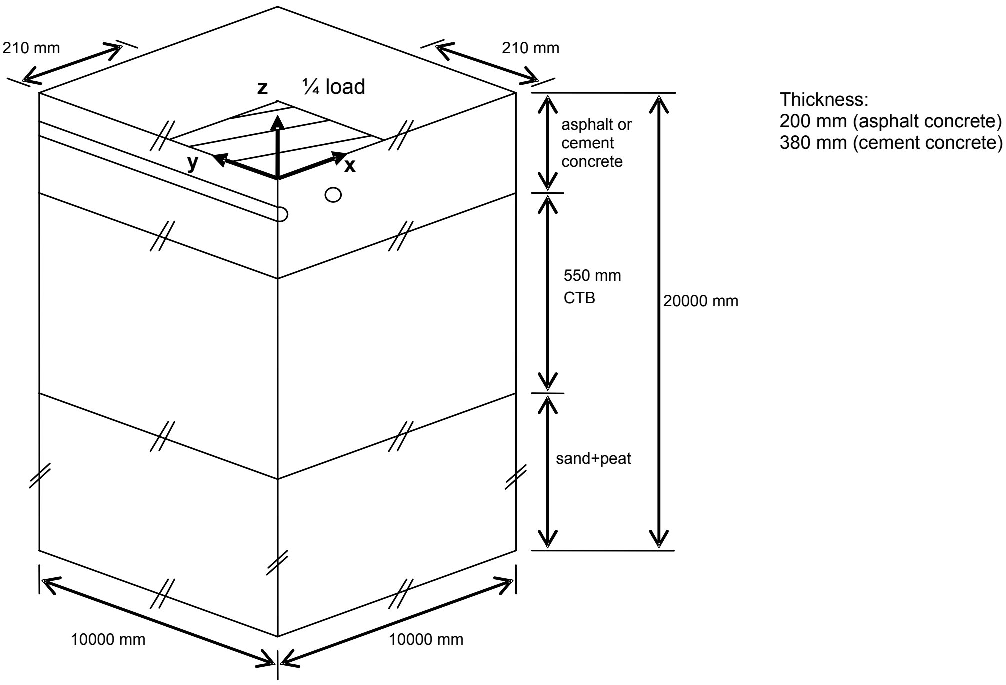

figure 1: Geometry of the basic structures I and II modelled in 3D finite elements

4.2. Material properties and loading conditions

The loading conditions are based on a single wheel load of a Boeing 777-300LR airplane, modelled as a uniformly distributed pressure of 1.51 MPa on a loading area of 210 x 210 mm². This is ¼ of the load, because of double symmetry of the model. The asphalt concrete properties depend on the loading frequency and the temperature. Therefore three situations have been defined:

- constant temperature (20 °C) + quasi dynamic load (8 Hz)
- temperature gradient asphalt (28.3 °C bottom, 44.6 °C top) + quasi static load (2 Hz)
- temperature gradient asphalt (28.3 °C bottom, 44.6 °C top) + quasi dynamic load (8 Hz)

The cement concrete pavements have only been subjected to a temperature gradient in combination with a static load.

The terms quasi-static and quasi-dynamic are applied because the analysis comprises a static load with linear elastic material properties based on the S78 asphalt mix characteristics (Shell, 1978) at the listed temperature and frequency. For the top layer and the water conducting layer 70% of the S78 values are taken. An overview of material properties is given in table 2.

table 2: Overview of material properties

Material	**Young's modulus (MPa)**	**Poisson's ratio (-)**
asphalt concrete	510 – 7 560	0.35
cement concrete	33 500	0.15
cement treated base	10 000	0.20
sand + peat	45	0.35

4.3. Interpretation of results

The four structures (I, II, III and IV) have been checked for their sensitivity to fatigue and to local shear failure. Fatigue occurs when the stress invariant is negative. The bulk stress is calculated by the equation $1/3(\sigma_1+\sigma_2+\sigma_3)$, where σ_1 is the highest (compressive) principal stress. The extent, to which fatigue occurs, can be calculated by using the F78 fatigue characteristics (Shell, 1978). If σ_1 exceeds the uniaxial compressive strength ($\sigma_{1,f}$) than local failure occurs, according to the Mohr Coulomb failure criterion. Therefore, the ratio $R = \sigma_1/\sigma_{1,f}$ is an important indicator for damage to the structure. $\sigma_{1,f}$ can be calculated from the angle of internal friction and the cohesion. Since it is not yet common practice to perform triaxial testing on asphaltic materials, limited information is available. Therefore values taken from literature (CROW, 1999) were used (see table 3) in this study.

table 3: Cohesion and friction angle values for asphalt mixtures

Temperature (°C)	**Cohesion c (MPa)**			**friction angle φ (degree)**
	DAC[1]	**OAC[2]**	**CSAC[3]**	
20	1,20	0,90	0,90	32
30	0,60	0,47	0,60	35
40	0,30	0,26	0,40	39
50	0,20	0,15	0,30	45
60	0,15	0,10	0,20	48

[1]*Dense Asphalt Concrete* [2]*Open Asphalt Concrete* [3]*Crushed Stone Asphalt Concrete*

4.4. Results of the analyses

In the model verification phase of this study a comparison was made of a 3D finite element model with a simulated pipe (at 50 mm depth) and a multi-layer reference model (without any simulated pipe). The graph in figure 2 shows the apparent effect of the presence of a cavity (pipe) on the stresses in the pavement. Another important observation is that due to the rigid base, the entire asphalt layer under the wheel load is in compression, even in the horizontal direction. The results of the four basic structures will be evaluated in terms of stress invariants, as described in the previous section.

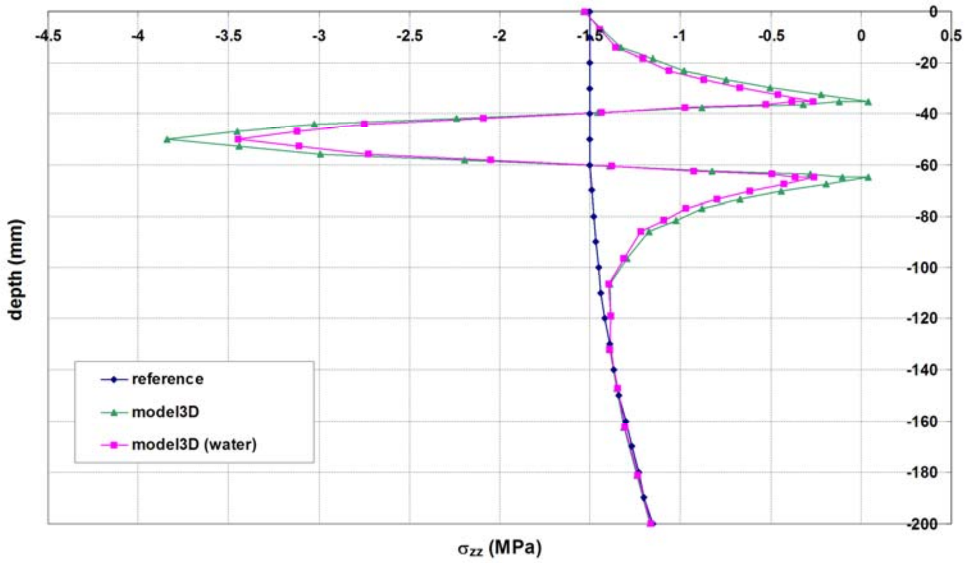

figure 2: Vertical stresses in the asphalt concrete near to a pipe

In figure 3 the stress invariant for the asphalt concrete structure with pipes at a depth of 100 mm is presented (basic structure II). On the basis of the highest value of σ_1 the highest ratio R is determined for various asphalt properties, as a function of the cohesion. In this way, figure 4 in combination with the values for c and φ in table 3 lead to the conclusion that damage around the discontinuity may occur under a B777 load. Asphalt mixtures with a higher stability, such as or high quality polymer modified asphalt are expected to show no damage.

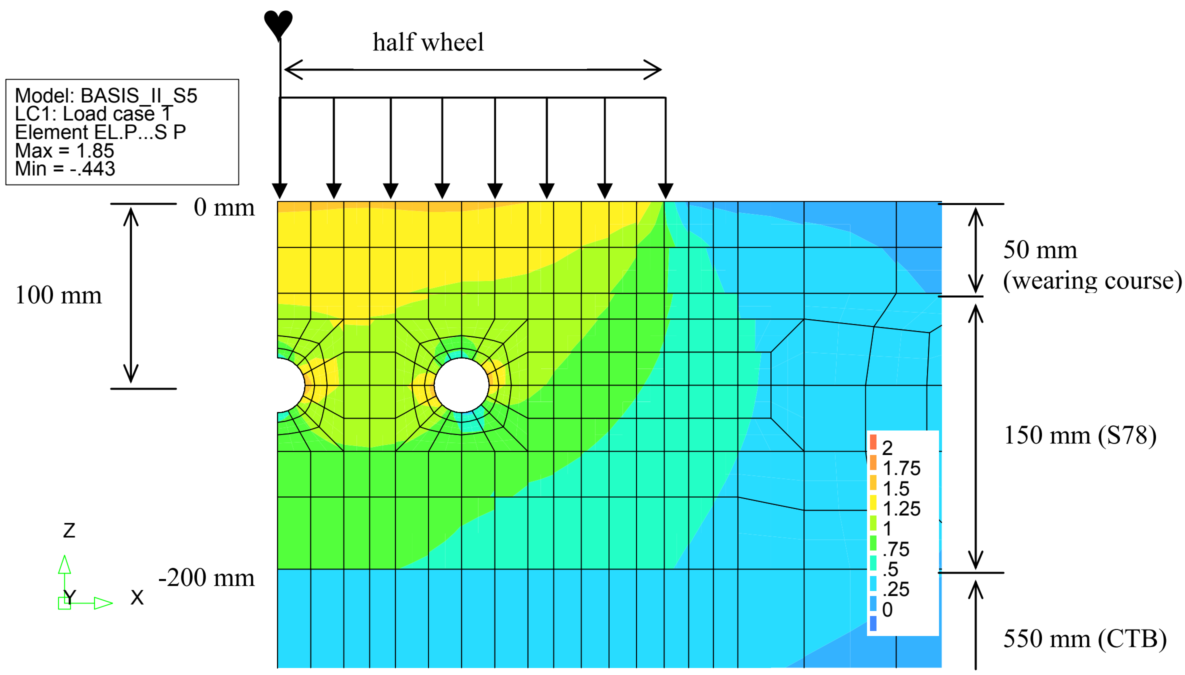

figure 3: Stress invariant for basic structure II (T = 20 °C, f = 8 Hz)

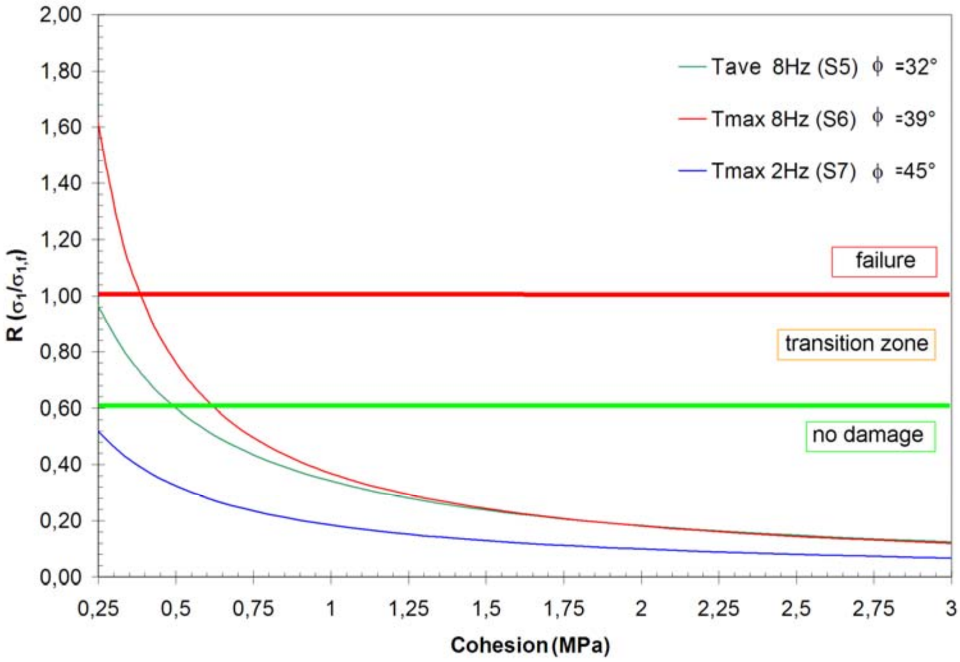

figure 4: Highest R-factor as a function of the cohesion for basic structure II

If the pipes are located higher up (< 50 mm) in the structure (structure I), damage can be expected in (nearly) any standard asphalt mixture.

The structures with a porous asphalt layer as a water conducting medium (structure III and IV) are not showing any damage due to permanent deformation under a B777 wheel load. Other damage mechanisms known for porous asphalt, which are not included in these finite element analyses, such as reflective cracking and physical wearing of the water conducting layer due to the permanent presence of warm flowing water, are probably determinative for the lifetime of these structures. Further investigation is therefore recommended into the bond between aggregate and binder in permanent wet conditions (stripping), ageing of the binder and crushing of the stone matrix

The cement concrete structures are showing small zones near the pipes with high tensile stresses caused by the thermal gradient (+ wheel load). A C45/55 concrete mix may show some crack initiation in these zones. Under the loading conditions applied in this analysis, the crack is not likely to propagate.

Some additional calculations indicate that for systems with pipes close to the surface of the pavement, other wheel loads with higher contact stresses but a smaller total load (e.g. F15 jet fighters) may result in higher stresses. Also horizontal (breaking) forces may be relevant.

RECOMMENDATIONS FOR PRACTICAL APPLICATIONS

To give a practical guide for airfield administrations and producers of energy collection systems, the working group set up a checklist with information a producer should provide. This list is divided in three parts. The first part requires a list of technical details about the system (e.g. diameter, distance and depth of the pipe) and the construction procedure. The second part requires documentation which shows that the system meets the structural

demands of an airport pavement. This documentation should deal with the aspects discussed in this paper, being:
- the design variables
- stiffness and failure properties of the materials
- description of the finite element model used for the analyses
- specification of the loading conditions (traffic and/or temperature loading)
- presentation of the results of the analyses

The last part of the checklist requires information about management and maintenance aspects of the system such as the frequency or probability of maintenance or repair works and the consequences in terms of non-availability and costs.

CONCLUSIONS

Energy collector systems in airfield pavements have not yet been applied, amongst others because the possible risks involved were not clear. With this study the structural aspects of collector systems in asphalt concrete or cement concrete with and without pipe systems have been analyzed for typical airfield pavement structures and loading conditions. Though no specific system of any manufacturer was analyzed in this study, let alone all possible configurations, a number of general conclusions can be drawn.

With respect to asphalt energy collectors with pipe systems:
- The application of energy collector systems with pipes in asphalt concrete at a depth of more than 50 mm is possible, provided that appropriate (high quality) materials are applied. With increasing depth, the chance of damage in the structure decreases, however this does influence the energy revenues.
- The most relevant damage mechanism is permanent deformation or (shear) failure of the asphalt around the discontinuity, caused by stress conditions close to or beyond the failure limits of the asphalt mixture. Triaxial material testing is needed to asses these limits properly.

Concerning systems with a porous asphalt layer as water conducting medium:
- No damage is expected under the conditions studied in this research.
- A lack of knowledge still exists concerning the lifetime determining mechanisms (e.g. mixture durability) of this system.

With regard to continuous cement concrete structures:
- The presence of a pipe in cement concrete structures has a very local influence on the stress conditions. The zones where damage may occur are very small and crack propagation is not expected.

In general it was concluded that the presence of a discontinuity does not influence the design thickness of the airfield pavement. It does however influence the specifications of the materials and structural details.

Damage mechanisms as uneven settlements and reflective cracking were not studied in this research.

Because of the lack of (long-term) experience with energy collecting systems in airfield pavements, the risks involved with such discontinuities in the pavement structure during the entire service-life were not sufficiently known or quantified. Therefore a team of experts analyzed a list of possible events for their chance of occurrence and the consequences of the event in terms of non-availability of the pavement and costs. The question whether these risks are relevant or acceptable is highly dependent on the use of the pavement (runway, taxiway or platform), the details of the system and in relation to that the possibilities to prevent the risk and the possible countermeasures. Therefore this decision is case dependent and left to the Airfield Administration.

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