FRACTURE IN HIGH PERFORMANCE FIBRE REINFORCED CONCRETE PAVEMENT MATERIALS

ERIK DENNEMAN

A thesis submitted in partial fulfilment of the requirements for the degree of PHILOSOPHIAE DOCTOR (ENGINEERING)

In the

FACULTY OF ENGINEERING

UNIVERSITY OF PRETORIA

May 2011

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An innovative pavement system known as Ultra Thin Continuously Reinforced Concrete Pavement (UTCRCP) was recently developed in South Africa. The technology is currently being implemented on some major routes in the country. The system consists of a high performance fibre reinforced concrete pavement slab with a nominal thickness of approximately 50 mm. The material has a significant post crack stress capacity compared to plain concrete. Current design methods for UTCRCP are based on conventional linear elastic concrete pavement design methodology, which does not take into account post crack behaviour. Questions can be raised with regards to the suitability of conventional approaches for the design of this high performance material.

The hypothesis of the study is that the accuracy of design models for UTCRCP can benefit from the adoption of fracture mechanics concepts.

The experimental framework for this study includes fracture experiments under both monotonic and cyclic loading, on specimens of different sizes and geometries and produced from several mix designs. The aim is to quantify size effect in the high performance fibre
reinforced concrete material, to determine fracture mechanics material parameters from monotonic tests, and to investigate the fatigue behaviour of the material.

As part of the study a method is developed to obtain the full work of fracture from three point bending tests by means of extrapolation of the load-displacement tail. This allows the specific fracture energy ($G_f$) of the material to be determined. An adjusted tensile splitting test method is developed to determine the tensile strength ($f_t$) of the material.

The values of $G_f$ and $f_t$ are used in the definition of a fracture mechanics based cohesive softening function. The final shape of the softening function combines a crack tip singularity with an exponential tail. The cohesive crack model is implemented in finite element methods to numerically simulate the fracture behaviour observed in the experiments. The numerical simulation provides reliable results for the different mixes, specimen sizes and geometries and predicts the size effect to occur.

Fracture mechanics based models for the prediction of the fatigue performance of the material are proposed. The predictive performance of the models is compared against a model representing the conventional design approach.

It is concluded that the findings of the study support the thesis that design methods for UTCRCP can benefit from the adoption of fracture mechanics concepts. This conclusion is mainly based on the following findings from the study:

- The high performance fibre reinforced concrete material was found to be subject to significant size effect. As a consequence the MOR parameter will not yield reliable predictions of the flexural capacity of full size pavement structures,
- In contrast to the MOR parameter, the fracture mechanics damage models developed as part of this study do provide reliable predictions of the flexural behaviour of the material,
- The fatigue model developed based on fracture mechanics concepts, though not necessarily more precise, is more accurate.
ACKNOWLEDGEMENTS

The author gratefully acknowledges the financial support provided by CSIR and the University of Pretoria (UP), which made this thesis work possible. The author further wishes to thank all those who have contributed to this study, in particular:

- Mr. Derek Mostert of UP for the mix designs and the preparation of specimens tested as part of this study,
- Mr. Derek Mostert, Mr. Herman Booysen and Mr. Johan Scholtz for the production of test fixtures and the execution of the tests on fibre reinforced concrete at UP,
- Dr. Rongzong Wu of the University of California at Davis (UC Davis) for the mentoring provided on the use of the OpenSees finite element software and on the embedded discontinuity method implemented in that software by Dr. Wu,
- Mr. Bill Sluis and Mr. Daret Kehlet, for the support provided during the mix production and testing performed at UC Davis,
- Mr. Benoit Verhaeghe (CSIR), Prof. Wynand Steyn (formerly CSIR) and Prof. John Harvey (UC Davis), for creating a work environment that allowed the author to complete the bulk of the thesis work during office hours,
- Dr. James Maina (CSIR) who acted as a mentor for this study,
- Prof. Elsabe Kearsley and Prof. Alex Visser, for the advice, guidance and valuable input provided to this document and the papers published as part of the study.
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NOMENCLATURE

Abbreviations:

C&CI   South African Cement and Concrete Institute
CMOD  Crack Mouth Opening Displacement
CTOD  Crack Tip Opening Displacement
CTOD_{c}  Critical Crack Tip Opening Displacement
EDM   Embedded Discontinuity Method
FCM   Fictitious Crack Model
FEM   Finite Element Method
FPB   Four Point Bending
FPZ   Fracture Process zone
FRC   Fibre Reinforced Concrete
HVS   Heavy Vehicle Simulator
LE   Linear Elastic
LEFM  Linear Elastic Fracture Mechanics
LVDT  Linear Variable Displacement Transducer
MOR   Modulus of Rupture
SANRAL South African National Road Agency Limited
SDA   Strong Discontinuity Approach
TPB   Three Point Bending
UTCRCP Ultra Thin Continuously Reinforced Concrete Pavement
UC Davis University of California at Davis
UP   University of Pretoria

Symbols:

\gamma \quad \text{Specific surface energy} \quad [\text{N/mm}]
\delta \quad \text{Deflection} \quad [\text{mm}]
\varepsilon^f \quad \text{Fracture strain}
\nu \quad \text{Poisson’s ratio}
\sigma \quad \text{Stress} \quad [\text{MPa}]
\sigma_1 \quad \text{Major principal stress} \quad [\text{MPa}]
\sigma_{I} \quad \text{Stress at base of crack tip singularity} \quad [\text{MPa}]
\sigma_f \quad \text{Stress at fracture} \quad [\text{MPa}]
\sigma_d \quad \text{Design value of tensile stress} \quad [\text{MPa}]
\sigma_N \quad \text{Nominal stress} \quad [\text{MPa}]
\sigma_{Nu} \quad \text{Ultimate nominal stress} \quad [\text{MPa}]
\sigma_{xx} \quad \text{Horizontal normal stress} \quad [\text{MPa}]
\mu \quad \text{Shear modulus} \quad [\text{MPa}]
a \quad \text{Notch depth or crack length} \quad [\text{mm}]
a_1 \quad \text{Calibration constant}
a_2 \quad \text{Distance to corner of slab} \quad [\text{mm}]
a_c \quad \text{Critical crack length} \quad [\text{mm}]
a_e \quad \text{Equivalent effective elastic crack length} \quad [\text{mm}]
b \quad \text{Specimen width} \quad [\text{mm}]
b_1 \quad \text{Calibration constant}
f_t \quad \text{Tensile strength} \quad [\text{MPa}]
\( h \) Specimen height or slab thickness [mm]
\( h_c \) Width of fracture zone [mm]
\( k \) Subgrade stiffness [N/mm]
\( l \) Radius of relative stiffness [mm]
\( m \) Calibration constant
\( l_c \) Characteristic length [mm]
\( n_i \) Number of load cycles applied at stress level \( S_i \)
\( s \) Span [mm]
\( w \) Crack width [mm]
\( w_c \) Critical crack width [mm]
\( w_I \) Crack width at base crack tip singularity [mm]
\( E \) Young’s modulus [MPa]
\( C \) Paris’s constant
\( E' \) Effective Young’s modulus in plain strain condition [MPa]
\( E_t \) Tangent modulus [MPa]
\( G_f \) Specific fracture energy [N/m]
\( I \) Moment of inertia [mm^4]
\( K \) Bulk modulus [MPa]
\( K_I \) Crack tip stress intensity [MPa mm^{1/2}]
\( K_{lc} \) Critical crack tip stress intensity [MPa mm^{1/2}]
\( N \) Number of load cycles
\( N_i \) Number of cycles at stress level \( S_i \)
\( P \) Total of external loads [N]
\( P_u \) Peak load [N]
\( S \) Stress level [MPa]
\( S_I \) Surface energy [N m]
\( U^* \) Strain energy [MPa]
\( W_f \) Work of fracture [N mm]