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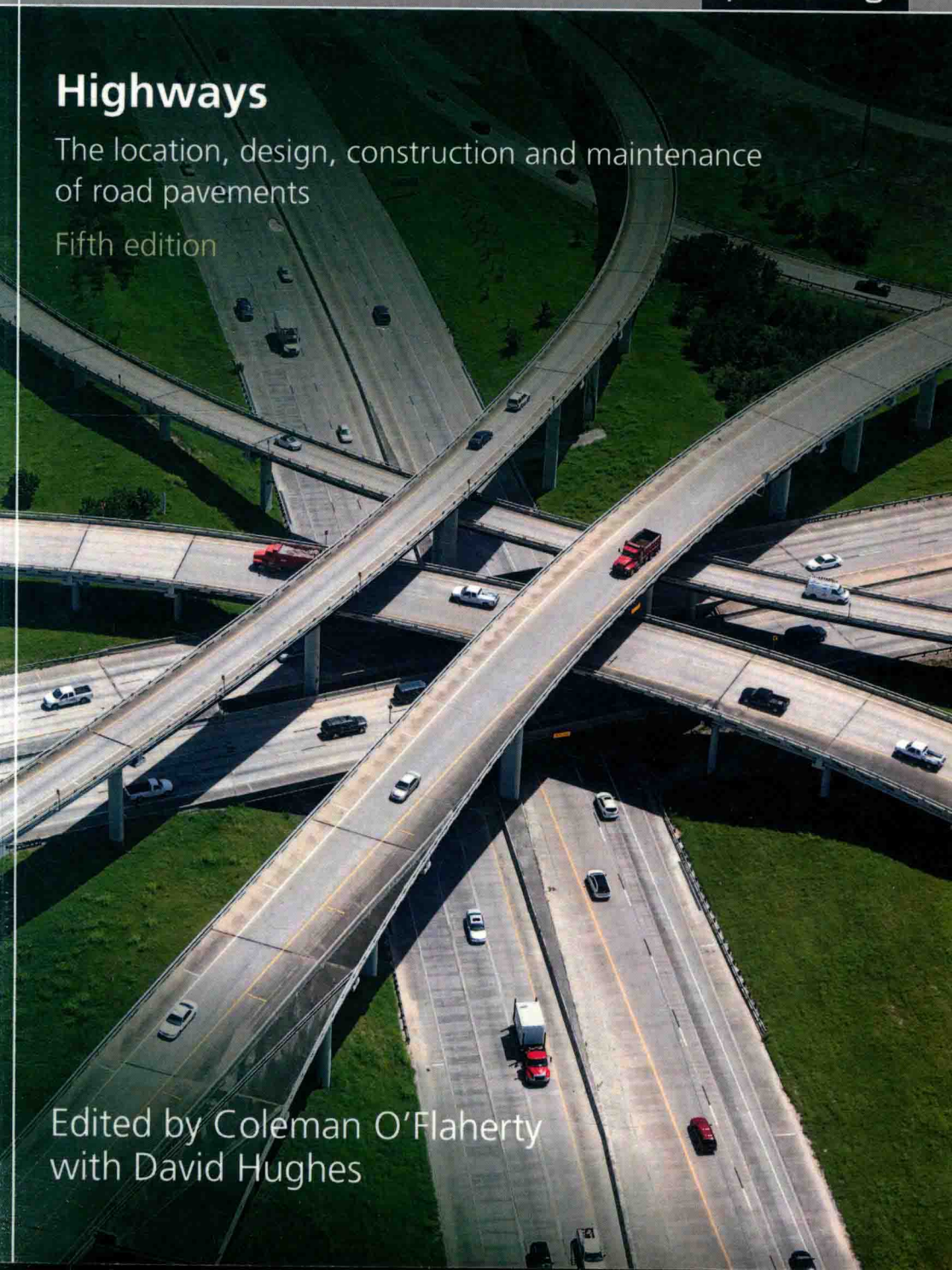
Highways

The location, design, construction and maintenance of road pavements

Fifth edition



Edited by Coleman O'Flaherty
with David Hughes

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Highways

Fifth edition

This book is dedicated to

Nuala Rose O'Flaherty

In memoriam

About the editors

Coleman O'Flaherty AM, BE (NUI), MS, PhD (Iowa State), Hon LLD (Tas), CEng, FICE, FIEI, FIEAust, FIHT

Professor Emeritus Coleman O'Flaherty graduated from the National University of Ireland (Galway) in 1954 and worked in Ireland, Canada and the USA before joining the Department of Civil Engineering, University of Leeds, UK, in 1962. He was Foundation Professor of Transport Engineering and Foundation Director of the Institute for Transport Studies at Leeds University before being invited to Australia as, initially, Commonwealth Visiting Professor, University of Melbourne, and, then, as First Assistant Commissioner (Chief Engineer) of the National Capital Development Commission, Canberra. Since retiring as Deputy Vice Chancellor at the University of Tasmania, he has been made a Professor Emeritus of the university, and awarded the honorary degree of Doctor of Laws. In 1999, he was appointed a Member of the Order of Australia for services to education and the community.

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Dr David Hughes graduated from Queen's University Belfast with a BSc (Hons) in civil engineering in 1982, and completed his doctorate with the Pavement Research Group at the University of Nottingham in 1986. He then worked with Roughton International Consulting Civil Engineers as a pavement and materials specialist on many road construction projects across the world, ranging from Nepal to Suriname. In 1990 he took up an academic position at Queen's University Belfast, where he is now Director of Education and Senior Lecturer in Geotechnical and Highway Engineering. His research is focused on pavement design and assessment, and on the performance of geotechnical infrastructure, in particular predicting and assessing the impact of climate change on infrastructure slopes.

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Professor Gordon Airey graduated from the University of Cape Town with a first-class honours degree in civil engineering in 1989, and worked for the Council for Scientific and Industrial Research in South Africa before taking a research associate position at the University of Nottingham, UK, in 1994. He obtained his doctorate from the University of Nottingham in 1997 before being appointed to the academic staff in the Department of Civil Engineering in 1998. Professor Airey is currently Director of the Nottingham Transportation Engineering Centre (NTEC) and a former director on the board of the International Society for Asphalt Pavements (ISAP).

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Andrew Boyle graduated from the University of Cambridge in 1967, and worked on motorway and trunk road design and construction, before joining the UK Department for Transport in 1974. There, he worked on the management and maintenance of trunk roads in the West Midlands, before later managing the planning, design and construction of major schemes in the Midlands and London. After managing computer software development, he became Head of the Engineering Policy Division at the Highways Agency, where he had responsibility for the development of policy on value for money, quality, specifications, innovative traffic control systems and enforcement, and road safety, as well as European and international affairs. Since 1997 he has been an independent consultant, and has worked in the UK, Bahrain, Israel, Poland and Palestine, advising on a variety of highway matters. He is currently Chair of the UK National Committee of the World Road Association.

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Dr Michael Brennan graduated with first class honours from the National University of Ireland in 1970, and subsequently obtained a master's degree in transportation engineering at the University of Leeds. He worked with Ireland's national transport company (CIE) and as a

research assistant at the Institute for Transport Studies at Leeds University, before starting a teaching career at University College, Galway, where he was appointed Statutory Lecturer in 1980. He spent sabbatical years at Purdue University in 1979–1980, and at Laboratoire Central des Ponts et Chaussées in 1987–1988. In 2000, the University of Ulster conferred the degree of DPhil upon him for his published research. Dr Brennan has collaborated with the asphalt industry in Ireland on research work into asphalt mix design and performance for four decades.

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Dr Seósamh Costello graduated from University College, Galway in 1993 before going on to obtain a master's degree in international highway engineering from the University of Birmingham in 1996. He worked as a research associate and then a research fellow at the University of Birmingham while simultaneously reading for his doctorate, which was conferred in 2001. He joined the lecturing staff at the University of Auckland in 2002, later serving as Associate Dean (Postgraduate) in the Faculty of Engineering. He has published widely in the field of transportation asset management, and has also consulted widely, having worked for a number of consultancies in the UK and Ireland.

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Andrew Dawson commenced his career as a technician with major civil engineering contractors before attending the University of Lancaster and Imperial College London. He then spent 5 years with civil engineering consultants as a geotechnical engineer working on the design of earth dams, mine pit slope stability assessments, highway schemes, water resources and hydraulic studies. Since 1983 he has been Lecturer, Senior Lecturer and Associate Professor in Civil Engineering at the University of Nottingham, where he lectures in geotechnics and pavement engineering. His research interests have concentrated on pavement foundations and low-volume and unsealed road pavements, extending to the study of geosynthetics, repeated loading effects, pavement sub-drainage, secondary aggregates in un-, cement- and

bituminous-bound pavements, trench reinstatement, effects of climate change, and pavements as solar energy collectors.

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Dr Gareth Hearn is an independent consultant geomorphologist who was previously with Scott Wilson/URS as Technical Director for International Geotechnics and Geohazards. He graduated from Kingston Polytechnic, UK, with a first-class honours degree in geography, geology and pedology in 1981. In 1987 he completed his doctorate at the London School of Economics, following research undertaken in the Himalayas on the design and construction of mountain roads. Since then, he has been involved in environmental, geotechnical and geohazard assessment for infrastructure development projects in over 30 countries, focusing especially on the selection and design of alignments for road, rail and pipeline schemes through difficult terrain.

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Professor Kim Jenkins practised as a consultant in civil engineering for 12 years after qualifying from the University of Natal, South Africa, in 1983. His career in the private sector included investigations and design projects in geotechnical engineering, materials and pavement engineering. He then immersed himself in full-time research into pavement rehabilitation and recycling technologies, with a focus on performance of materials. The research was conducted at Stellenbosch University, South Africa, and Delft University of Technology, the Netherlands, culminating in a doctoral degree in 2000. He collaborates globally in pavement recycling and stabilisation technology. Professor Jenkins is currently the incumbent of the SANRAL Chair in Pavement Engineering at Stellenbosch University.

Alan Kavanagh BE (NUIG), MEngSc (NUIG), CEng, MIEI, MIAT
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Alan Kavanagh graduated with first-class honours in 1997 from the National University of Ireland, Galway, where he was subsequently also awarded the degree of

Master of Engineering Science. Since graduation, he has worked for the Colas Ireland Group of companies. In his current capacity as Technical Manager, he is responsible for the quality assurance and control of surface dressing, micro-surfacing and in situ recycling operations, the supply of bitumen for the production of hot-mix asphalts, and the supply of chemical emulsifiers, additives and adhesion agents for worldwide use. He also manages the Colas R&D Laboratory in Oranmore, Co. Galway. In the period 2001–2003, Alan Kavanagh was seconded to the parent company, Colas Inc., in Maryland, USA, to work as an estimator/project manager on highway maintenance.

Hussain Khalid BSc (Baghdad), MSc, PhD (Birmingham), CEng, MICE, MIAT
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After completing his PhD at the University of Birmingham in 1985, Dr Hussain Khalid worked for 2 years at the University of Newcastle upon Tyne on research into modular pavements before moving to the University of Liverpool, where he is currently Senior Lecturer in Civil Engineering in the Centre for Engineering Sustainability. In 2008–2009 he worked on an industrial placement with A-one+ Managing Agent Contractor, where he was involved in the maintenance and management of the motorway network in north-west England. In 2010–2011, Hussain Khalid was Visiting Professor at Texas A&M University, where he investigated surface free energy and asphalt fatigue. Dr Khalid's research interests are in the characterisation and modelling of asphaltic materials behaviour, focusing on rheology, fatigue and fracture.

John Knapton BSc, PhD (Newcastle), DSc (Kwame Nkrumah), CEng, FICE, FIStructE, FCIHT
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Professor John Knapton graduated in civil engineering from Newcastle University in 1970, and obtained his doctorate there in 1973. He has divided his career between academia and consulting, specialising in pavement engineering. He is the author of all four editions of the British Ports Association manual – *The Structural Design of Heavy Duty Pavements for Ports and Other Industries* – and was Chairman of the PIANC Working Group 165 that prepared guidelines on container terminal pavements. He established his

consulting business in 1981, mainly as an expert witness in pavement disputes, and he held the Chair of Structural Engineering at Newcastle University from 1991 to 2001. Professor Knapton is currently Chair of the Small Element Pavement Technologists Council, which perpetuates a series of international conferences on concrete block paving. He is the author of three books on concrete floors, and sits on many committees in the British Standards Institution.

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Derek McMullen graduated from Queen's University Belfast in 1976, completing a master's degree by research (on the applications of pavement analysis) in 1978. Early experience was gained with UK consulting engineers in southern England, working on the design and construction supervision of major roads. Following admission to the Institution of Civil Engineers in 1984, he was engaged on the design of pavement rehabilitation schemes and the implementation of pavement management systems in the Middle East, Africa and the UK. Since 2000, he has been based in the English Midlands, involved with highway asset management and pavement design in the UK, Eastern Europe and the Middle East.

Michael Maher MA, BAI, PhD (Dub), PEng, CEng, MIEI, Eur Ing
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After completing a doctorate in geotechnical engineering and pavement design at Trinity College Dublin, Michael Maher moved to Ontario, Canada, in 1978 to join Golder Associates. He is currently Golder's regional leader for large public infrastructure. In his 36 year career he has worked from Golder's offices in London and in St John's and Toronto, Canada, as well as in Qatar and Ireland. His practice areas span geotechnical and materials engineering, pavement design, construction aggregate performance, asset management and sustainability, highway drainage, and forensic engineering investigations. Michael Maher has undertaken assignments in North and South America, the Caribbean, Europe and the Middle East. His current emphasis is on the resolution of construction disputes, investigating premature failures, leading highway research studies, and acting as an expert witness.

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Paul Nowak is Technical Director at Atkins Ltd, with over 35 years' experience of the design and construction of infrastructure projects in the UK and overseas. He has been responsible for the investigation and design of new earthworks and existing earthworks assets. Latterly, he has been involved in design–build and public–private partnership schemes, predominantly as a designer to constructors and advisor to the lenders technical advisor.

Martin O'Connell BE (Hons), MEngSc (NUI), CEng, MIEI
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Martin O'Connell graduated from the National University of Ireland (Dublin) in 2008 with an honours degree in civil engineering. He subsequently undertook a two year research master's degree on the performance of concrete incorporating ground granulated blastfurnace slag in aggressive wastewater environments, graduating in 2010. Martin has worked in the USA and the UK, latterly in the area of airport infrastructure construction and design with Amey plc. He has been involved in the development of Heathrow Airport's new Terminal 2 and has also undertaken consulting roles at a number of other British airports, including Glasgow, Stansted, Southampton and Cambridge. His interests include pavement design and the development of concrete and asphalt technology.

Dan Raynor BSc (Cardiff), MSc (Leeds) CEng, MICE, FGS
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Dan Raynor graduated from Cardiff University in 1999 with an honours degree in geology and from the University of Leeds in 2001 with a master's degree in engineering geology. Following graduation, he worked as an engineering geologist at Hyder Consulting, where he focused on site investigations for various UK highways schemes before being seconded, in 2004, to Mowlem Civil Engineering and working as a site engineer during the construction of the Cwm Relief Road in South Wales. Since 2005, Dan Raynor has

worked with the Arup Group. During this time he has provided geotechnical leadership for a wide variety of civil engineering, building and infrastructure projects, including ground investigations and geotechnical design for major highway schemes.

Martin Snaith OBE, MA, BAI, MSc (Dub), PhD (Nott), ScD (Dub), FREng, FICE, FCIHT
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Professor Emeritus Martin Snaith graduated from Trinity College, Dublin, in 1968 with a first-class honours degree in engineering and a pass degree in arts. For most of his career he specialised in university teaching and research, particularly addressing the needs of roads in developing countries. Recently retired from the University of Birmingham, where he was Pro Vice Chancellor, he now advises a number of organisations in the UK and around the world on asset management issues. He is a director of Highway Management Services, which develops road management systems for use in countries as diverse as China and Cyprus. He is also Chair of the multinational consortium HDMGlobal, which is responsible for the development and dissemination of HDM-4, the de facto world standard economic evaluation model for roads, and still teaches aspiring and practising highway engineers in the UK and overseas.

Nick Thom MA (Cantab), PhD (Nott), MICE, MCIHT, MPWI
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After joining Scott Wilson in 1978, Nick Thom worked both in the design office and on a highway construction site before carrying out his doctoral research into road foundations. He then joined Scott Wilson Pavement Engineering, continuing as a consultant until 2014. During this time he worked on the design and evaluation of highways, ports and airfields in many parts of the world. Since 1991 he has also been a member of the academic staff at the University of Nottingham, where he specialises in the analysis and design of pavements and rail track. In addition to teaching highway, airfield and railway engineering, his role at the university includes research on subjects as diverse as cold-mix asphalt, pavement management, fibre-reinforced concrete, railway track beds, and energy loss from rolling wheels.

Andrew Todd BSc, CEng, MICE, CMIWEM
Principal Engineer, Jacobs Ltd, UK

Andrew Todd graduated in 1977 and worked for 12 years in UK local government, mainly on the design and construction of major sewerage schemes: this included 8 years of construction supervision as a resident engineer. Following 6 years with consultants designing motorway drainage and sewerage schemes, he was appointed Research Principal for Pipelines and Drainage at the Transport Research Laboratory (TRL). At the TRL he undertook trials of innovative highway drainage systems, and wrote the guidance and specifications for their design and construction, as well as significantly contributing to the development of highway drainage asset condition determination and management. Andrew Todd is presently a consultant with Jacobs, working on the development of technical guidance for, and the design of, highway drainage systems.

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Dr David Woodward graduated from the Ulster Polytechnic in 1982. He became involved with research into highway engineering materials at the University of Ulster, where he was appointed Lecturer in 1998 and Reader in Infrastructure Engineering in 2005. He is currently Head of the Highway Engineering Research Group, and in 2015 became Director of SABER (Studies Allied to Built Environment Research) at Ulster University.

Acknowledgements

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Last, but far from least, I pay tribute to my wife Nuala, who helped me immeasurably in the development and preparation of the previous editions of this textbook. Her love, support and forbearance will never be forgotten by me.

Coleman O'Flaherty

Launceston, Tasmania
August 2015

Abbreviations and terminology

AADF	average annual daily flow
AADT	annual average daily traffic
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
AAV	aggregate abrasion value
AFNOR	Association Française de Normalisation
AGS	Association of Geotechnical Specialists
APL	actual point load
ASTER	Advanced Space-borne Thermal Emission and Reflection Radiometer
ASTM	American Society for Testing and Materials
AUTL	asphalt for ultra-thin layers
BBA	British Board of Agrément
BGS	British Geological Survey
BIM	building information modelling
BoQ	bill of quantities
BSI	British Standards Institution
CAD	computer-aided design
CBA	cost–benefit analysis
CBGM	cement bound granular material
CBR	California bearing ratio
CEC	cation exchange capacity
CEN	Comité Européen de Normalisation (European Committee for Standardization)
COBie	Construction Operations Building Information Exchange
CPIC	Construction Project Information Committee
CPT	cone penetration test
CRCB	continuously reinforced concrete base
CRCP	continuously reinforced concrete pavement
CT	circular texture
c_u	shear strength
D&B	design-and-build
DBFO	design, build, finance and operate
DCP	dynamic cone penetrometer
DEM	digital elevation model
DIN	Deutsches Institut für Normung, German Institute for Standardization
DfT	Department for Transport
DLP	Determinate-life pavement
DoP	declaration of performance
DUPV	dry unpolished value
EAL	equivalent axle load
ECI	early contractor involvement
EFTA	European Free Trade Association
EIAs	environmental impact assessments
EME	Enrobé à module élevé

EOTA	European Organisation for Technical Approvals
ESAL	equivalent standard axle load
ESPL	equivalent single point load
EVA	ethylene vinyl acetate
FAP	friction after polishing
FBA	furnace bottom ash
FEA	finite-element analysis
FPC	factory production control
FWD	falling-weight deflectometer
GGBS	ground granulated blast furnace slag
GIR	ground investigation report
GISs	geographical information systems
GNCA	granular base with no cementing action
G_{sa}	apparent specific gravity
G_{sb}	bulk specific gravity
G_{se}	effective specific gravity
HAGDMS	Highways Agency geotechnical database management system
HAPAS	Highway Authorities product approval scheme
HAPMS	Highways Agency pavement management system
HAWRAT	Highways Agency water risk assessment tool
HBM	hydraulically bound mixture
HCV	heavy commercial vehicle
HDM	heavy duty macadam
HFS	high-friction surfacing (BBTM, from its French name 'béton bitumineux très mince')
HMB	high-modulus base
HRA	hot rolled asphalts
HSE	Health and Safety Executive
I_c	consistency index
ICL	initial consumption of lime
ICS	initial consumption of stabiliser
I_d	density index
I_L	liquidity index
Ip or PI	plasticity index
IRI	international roughness index
ISO	International Organization for Standardization
ISOHDM	International Study of Highway Development and Management
ISSA	International Slurry Surfacing Association
ITT	initial type test
JRC	jointed reinforced concrete
LiDAR	light detecting and ranging
LLP	long-life pavement