CIVIL AVIATION AUTHORITY

CAA PAPER 2000/1

REVIEW OF RUNWAY FRICTION LEVELS

CIVIL AVIATION AUTHORITY, LONDON

Price £18.00

CAA PAPER 2000/1

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CIVIL AVIATION AUTHORITY, LONDON, SEPTEMBER 2000

ISBN 0 86039 781 5

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Printed and distributed by
Westward documedia Limited, 37 Windsor Street, Cheltenham, England

Preface

This report has been prepared in support of the new CAP 683 Procedures for Runway Friction Classification and Monitoring. It was commissioned by the Civil Aviation Authority Safety Regulation Group (CAA-SRG) to provide the background information to some of the guidance provided in CAP 683.

In particular the derivation of the published levels for Minimum Friction Level, Maintenance Planning Level and Design Objective Level are given.

The information set out in this Report is intended to be applied by those with experience in the measurement and interpretation of runway friction data.

The Author

Mark Oliver is a Chartered Civil Engineer with 10 years of experience in airfield pavement evaluation design, construction and maintenance. He is currently Division Manager of GIBB Airports, a Division of GIBB Ltd, and since 1994 has provided support to the Civil Aviation Authority on a number of airfield pavement related projects.

During this time he has been responsible for drafting the new CAP 683 Procedures for Runway Friction Classification and Monitoring, as well as managing the new Runway Friction Analysis System (RFAS) software which is compatible with the CAP document.

Acknowledgements

GIBB gratefully acknowledge the assistance provided by Cranfield University and the Defence Estates (DE) in the supply of data used as a basis for this report. GIBB also acknowledge the valuable comments contributed by members of the Expert Review Panel which included representatives from the CAA, Cranfield University, DE, Findlay Irvine Ltd and Douglas Equipment Ltd.

Executive Summary

This document has been prepared in support of the new CAP 683 Procedures for Runway Friction Classification and Monitoring. CAP 683 supersedes previous advice given in CAP 168 Licensing of Aerodromes in respect to runway friction. This Report provides details of the background to some of the new information provided in CAP 683 including:

- Review of the derivation of existing criteria defining Friction Levels for runways.
- Establishment of new Minimum Friction Levels for runways tested with the Mu-Meter and GripTester machines.
- Review of the procedures for the measurement of friction.
- Review of the methods of analysis and reporting of friction data.

The document is provided to both inform and assist the users of CAP 683 with the interpretation of runway friction surveys.

Contents

1 INTRODUCTION

1.1 General

This Report was prepared by GIBB Ltd (GIBB) for the Civil Aviation Authority (CAA) under Contract No.7D/5/937/1. The Report was requested by the CAA's Safety Regulation Group following a meeting with Cranfield University and the Defence Estates (DE) of the Ministry of Defence on 16 June 1998. At the meeting the Friction Levels specified at that time by the CAA for civil runways were compared with those proposed by the DE for military runways. As the values were found to differ, concern was expressed that this may lead to confusion in the UK airport industry, particularly when the majority of data from which both sets of Friction Levels were derived, originate from testing carried out by Cranfield University.

In addition, it was considered that due to the safety implications associated with the publication of Friction Levels in CAP 683 Procedures for Runway Friction Classification and Monitoring, there should be a rigorous analysis of the data, with a clearly identified audit trail. It was also recognised that the findings should be subject to a peer review by a body of recognised experts in the field of friction, prior to reaching agreement on any revision to the current Friction Levels.

In view of the matters mentioned above, it was agreed that GIBB would undertake to combine and analyse all available data supplied by both Cranfield University and DE in order to recommend Friction Levels to be adopted by the CAA in CAP 683. It was also agreed that GIBB's findings would be subject to peer review by an Expert Review Panel. This Report outlines those findings and the recommendations of the Expert Review Panel.

2 BACKGROUND

2.1 Historic

The Authority has been collecting friction data on runways in the UK since 1982. Historically the Mu-Meter manufactured by M L Douglas has been used to measure friction values using a self-wetting system, discharging a calculated water depth of 0.5mm and travelling at 135 km/h (80 mph). Later the GripTester, manufactured by Findlay Irvine Ltd, was recognised by the Authority discharging a calculated water depth of 0.25mm. Subsequently the standard test speed for a Classification Survey was reduced to 65 km/h (40 mph) in order to maximise the extent of measurement coverage at the ends of runways.

Prior to the publication by the CAA of NOTAL 2/94 on the subject of Wet Friction Measurement, friction measurements at the UK civil airports were undertaken at a test speed of 130km/h (80mph). The specified Friction Levels at this speed for the Mu-Meter were as given in Table 2.1.

Table 2.1 Mu-Meter Friction Levels @ 130km/h (80mph)

Equipment	Design Objective Level (DOL)	Maintenance Planning Level (MPL)	Minimum Friction Level (MFL)	Water Depth (mm)	Test Speed (km/h)	Tyre Type
Mu-Meter	0.65	0.45	0.39	0.5	130	DICO 16 x 4 – 8

The Friction Levels at 80mph were originally derived by Cranfield University among others, based on empirical feedback and performance. A review of the origin of these values is outside the scope of this report.

NOTAL 2/94 introduced a test speed of 65km/h (40mph) primarily because this allowed greater coverage to be achieved at the runway ends by reducing the distances required for acceleration and deceleration.

Prior to the CAA deciding to change the test speed from the 80mph to 40mph, all the data then available from Cranfield University and the Property Services Agency (PSA), were reviewed and the results summarised by Cranfield University in Report FS-2349, Runway Friction Classification Surveys: The Case for Reducing the Mu-Meter Test Speed, dated 20/11/1996. An extract of the report is given as Figure 2.1. The report recommended that the Friction Levels be chosen on the following basis:

For Minimum Friction Level (MFL):	Take the lowest value relationship given by the Cranfield data hence 0.39 @ 80mph = 0.47 @ 40mph
For Maintenance Planning Level (MPL):	Take the highest value relationship given by MOD data hence 0.45 @ 80mph = 0.57 @ 40mph
For Design Objective Level (DOL):	Take the highest value relationship given by MOD and PSA data hence 0.65 @ 80mph = 0.72 @ 40mph

It is understood that subsequently the equivalent friction levels for the GripTester at 40 mph were determined from tests undertaken by NASA.

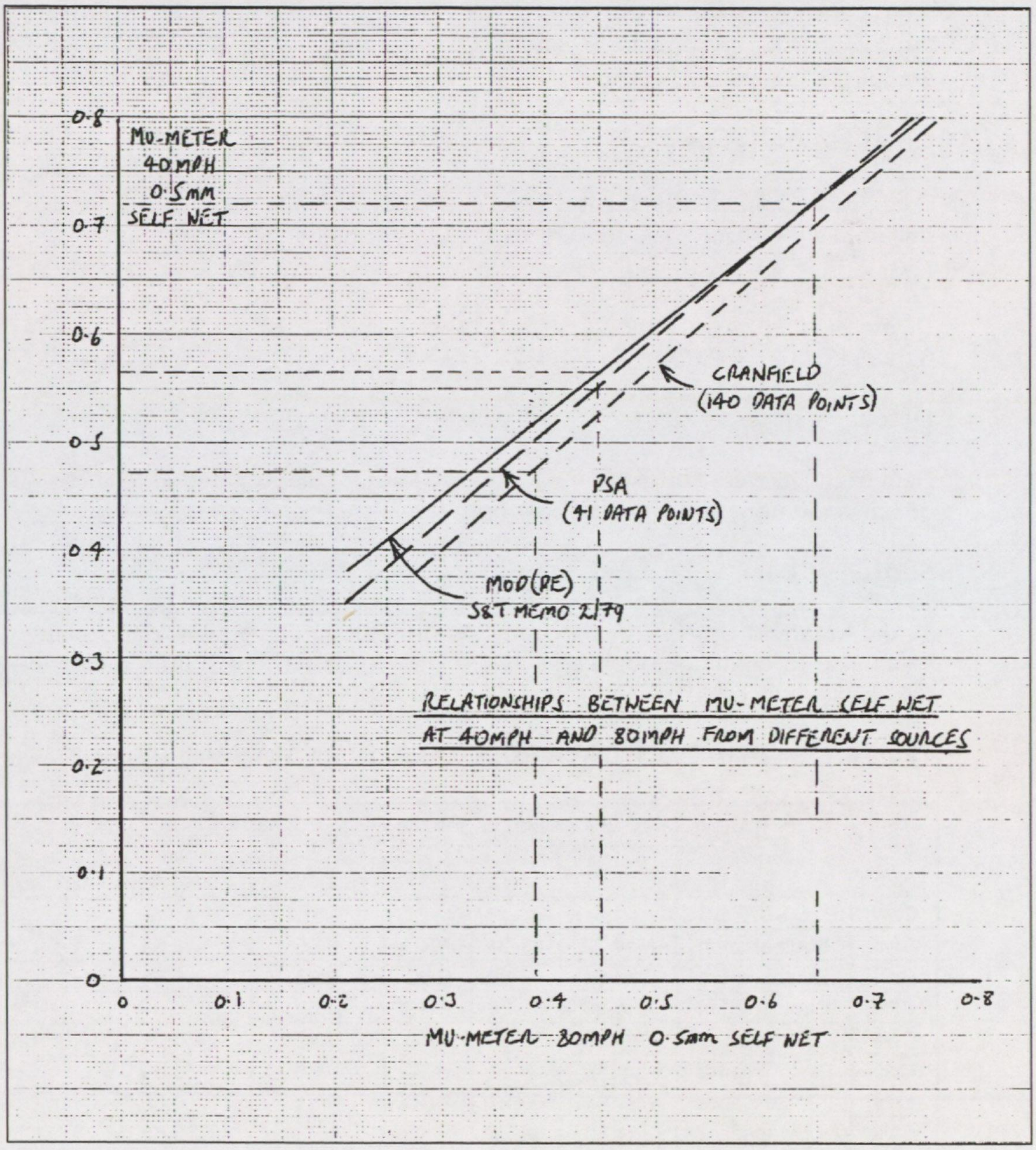


Figure 2.1 Extract from FS-2349

The following sections of this report take the opportunity to review the findings of report FS-2349 and reassess the Friction Levels in the light of all available friction data.

3 SOURCES OF DATA

3.1 General

The data analysed in this report were obtained from two sources, Cranfield University and the Defence Estates (DE).

3.2 Cranfield University

Data from Cranfield University were supplied in a Microsoft Excel spreadsheet and included all available data from historic surveys on civil and military runways.

As not all friction surveys included tests at both 65 km/h (40mph) and 130 km/h (80mph), a subset of the data has been used where tests at both speeds were undertaken.

3.3 Defence Estates

Data from DE were supplied in a hardcopy format that included all data points at both 65 km/h (40mph) and 130 km/h (80mph).

3.4 Sorting of Data

As the Cranfield University source represented the larger pool of data, a careful check was made to eliminate duplicates in the DE source. The resulting combined pool of data is given in Table 3.1.

Table 3.1 SUMMARY OF DATA POOL USED IN ANALYSIS

Status	Airport	Date	Runway	Surface	Friction Values		Source
					130km/h (80mph)	65km/h (40mph)	
CONCRETE SURFACES							
Civil	Southampton	May-82	03-21	BRC	0.55	0.55	Cranfield
Civil	Southampton	Dec-90	02-20	BRC	0.60	0.65	Cranfield
Civil	Southampton	Aug-93	02-20	BRC	0.57	0.61	Cranfield
Civil	Cambridge	Sep-82	06-24	BRC	0.47	0.57	Cranfield
Civil	East Midlands	Jun-82	09-27	BRC	0.63	0.64	Cranfield
Civil	East Midlands	Mar-91	09-27	BRC	0.61	0.65	Cranfield
Civil	Swansea	Jun-82	04-22	BRC	0.63	0.69	Cranfield
Civil	Filton	Mar-95	09-27	C	0.50	0.55	DE
Civil	Heathrow	Apr-75	05-23	C	0.50	0.58	Cranfield
Civil	Heathrow	Sep-80	05-23	C	0.50	0.55	Cranfield
Civil	Heathrow	Jun-83	05-23	C	0.50	0.56	Cranfield
Civil	Heathrow	Sep-85	05-23	C	0.49	0.51	Cranfield
Civil	London City	Aug-87	10-28	C	0.64	0.73	Cranfield
Civil	Leeds/Bradford	Jun-82	15-33	C	0.65	0.72	Cranfield
Military	M1	n/a	n/a	C	0.53	0.71	DE
Military	M2	n/a	n/a	C	0.47	0.60	DE
Military	M3	n/a	n/a	C	0.49	0.68	DE
Military	M4	n/a	n/a	C	0.43	0.54	DE
Military	M5	n/a	n/a	C	0.68	0.74	DE
Military	M6	n/a	n/a	C	0.62	0.71	DE
Military	M7	n/a	n/a	C	0.6	0.7	DE
Military	M8	n/a	n/a	C	0.55	0.71	DE

Table 3.1 continued

Status	Airport	Date	Runway	Surface	Friction Values 130km/h (80mph)	Friction Values 65km/h (40mph)	Source
SLURRY SURFACES							
Civil	Gatwick	Mar-91	08L-26R	Crs S	0.61	0.72	Cranfield
Civil	Exeter	Jun-82	08-26	CSS	0.77	0.76	Cranfield
Civil	Benbecula	Aug-82	07-25	SS	0.77	0.79	Cranfield
Civil	Blackpool	Aug-82	10-28	SS	0.62	0.67	Cranfield
Civil	Bournemouth	Jun-82	17-35	SS	0.66	0.73	Cranfield
Civil	Bournemouth	Jun-82	08-26	SS	0.71	0.75	Cranfield
Civil	Islay	Aug-82	13-31	SS	0.66	0.70	Cranfield
Civil	Prestwick	Jun-83	03-21	SS	0.75	0.76	Cranfield
Civil	Stornoway	Aug-82	01-19	SS	0.57	0.74	Cranfield
Military	M9	n/a	n/a	SS	0.78	0.82	DE
Military	M10	n/a	n/a	SS	0.69	0.76	DE
Military	M11	n/a	n/a	SS	0.60	0.69	DE
Military	M12	n/a	n/a	SS	0.70	0.77	DE
Military	M13	n/a	n/a	SS	0.76	0.80	DE
Military	M14	n/a	n/a	SS	0.67	0.76	DE
Military	M15	n/a	n/a	SS	0.65	0.77	DE
Military	M16	n/a	n/a	SS	0.76	0.80	DE
Military	M17	n/a	n/a	SS	0.72	0.81	DE
Military	M18	n/a	n/a	SS	0.67	0.78	DE
Military	M19	n/a	n/a	SS	0.69	0.74	DE
Military	M20	n/a	n/a	SS	0.76	0.80	DE
Military	M21	n/a	n/a	SS	0.68	0.78	DE
Military	M22	n/a	n/a	SS	0.77	0.83	DE
Military	M23	n/a	n/a	SS	0.75	0.78	DE
Military	M24	n/a	n/a	SS	0.75	0.81	DE
Military	M25	n/a	n/a	SS	0.72	0.71	DE
Military	M26	n/a	n/a	SS	0.71	0.7	DE
Military	M27	n/a	n/a	SS	0.73	0.74	DE
Military	M28	n/a	n/a	SS	0.75	0.78	DE
Military	M29	n/a	n/a	SS	0.75	0.77	DE
Military	M30	n/a	n/a	SS	0.59	0.71	DE
Military	M31	n/a	n/a	SS	0.76	0.77	Cranfield
Military	M32	n/a	n/a	SS	0.66	0.72	Cranfield
Military	M33	n/a	n/a	SS	0.65	0.77	Cranfield
GROOVED ASPHALT SURFACES							
Civil	Bristol	Sep-90	09-27	GASP	0.62	0.70	Cranfield
Civil	Edinburgh	Jul-92	07-25	GASP	0.70	0.75	Cranfield
Civil	Edinburgh	Nov-96	13-31	GASP	0.60	0.69	DE
Civil	Blackpool	Mar-91	10-28	GASP/A	0.70	0.78	Cranfield
Civil	Aberdeen	Nov-87	17-35	GAS	0.47	0.54	Cranfield
Civil	Aberdeen	Jul-88	17-35	GAS	0.54	0.60	Cranfield
Civil	Birmingham	May-82	15-33	GAS	0.68	0.72	Cranfield
Civil	Birmingham	May-82	06-24	GAS	0.69	0.72	Cranfield
Civil	Birmingham	Jul-87	15-33	GAS	0.49	0.63	Cranfield
Civil	Gatwick	1990	n/a	GAS	0.36	0.46	DE
Civil	Teesside	Jul-82	05-23	GAS	0.72	0.72	Cranfield
Civil	Teesside	Mar-91	05-23	GAS	0.73	0.76	Cranfield
Civil	Birmingham	Jan-93	15-33	GASP	0.62	0.70	Cranfield

Table 3.1 continued

Status	Airport	Date	Runway	Surface	Friction Values		Source
					130km/h (80mph)	65km/h (40mph)	
Civil	Stansted	May-92	05-23	GASP	0.66	0.69	Cranfield
Civil	Aberdeen	Mar-92	16-34	GASP	0.69	0.74	Cranfield
Civil	Exeter	Jun-94	08-26	GMA	0.50	0.64	DE
Civil	Gatwick	Jun-89	08R-26L	GMA	0.63	0.72	Cranfield
Civil	Heathrow	Apr-94	05-23	GMA	0.62	0.70	DE
Civil	Luton	May-89	08-26	GR MA	0.57	0.62	Cranfield
Military	M34	n/a	n/a	GMA	0.76	0.79	DE
Military	M35	n/a	n/a	GMA	0.32	0.49	DE
Military	M36	n/a	n/a	GMA	0.52	0.64	DE
Military	M37	n/a	n/a	GMA	0.47	0.6	DE
Military	M38	1991	n/a	GAS	0.58	0.67	DE
Military	M39	1991	n/a	GAS	0.61	0.74	DE
Military	M40	Jun-92	08/26	GAS	0.68	0.74	DE/Cranfield
Military	M41	Dec-93	08/26	GAS	0.69	0.72	Cranfield
Military	M42	1991	n/a	GAS	0.40	0.57	DE
Military	M43	1996	n/a	GAS	0.56	0.69	DE
Military	M44	1991	n/a	GAS	0.43	0.58	DE
Military	M45	Sep-96	85-22	GAS	0.45	0.60	DE
Military	M46	1991	n/a	GAS	0.47	0.70	DE
Military	M47	1996	n/a	GAS	0.47	0.70	DE
Military	M48	Feb-93	16/34	GAS	0.72	0.74	DE/Cranfield
Military	M49	Feb-93	10/28	GAS	0.74	0.76	DE/Cranfield
Military	M50	1991	n/a	GAS	0.78	0.78	DE
Military	M51	Jul-92	04/22	GAS	0.72	0.79	DE/Cranfield
Military	M52	0/0/96	n/a	GAS	0.76	0.83	Cranfield
Military	M53	Jun-96	09/27	GMA	0.71	0.80	Cranfield
Military	M54	Aug-96	04/22	GMA	0.62	0.72	Cranfield
Military	M55	Aug-96	08/26	GMA	0.66	0.76	Cranfield
Military	M56	Oct-96	77-31	GMA	0.29	0.42	DE
POROUS FRICTION COURSE (PFC) SURFACES							
Civil	Belfast	Nov-82	08-26	PFC	0.77	0.80	Cranfield
Civil	Cardiff	Jun-82	12-30	PFC	0.58	0.59	Cranfield
Civil	Cardiff	Oct-92	12-30	PFC	0.61	0.68	Cranfield
Civil	Edinburgh	Jul-82	07-25	PFC	0.69	0.71	Cranfield
Civil	Gatwick	Sep-83	08R-26L	PFC	0.61	0.65	Cranfield
Civil	Gatwick	Sep-85	08R-26L	PFC	0.62	0.67	Cranfield
Civil	Glasgow	Sep-82	05-23	PFC	0.55	0.55	Cranfield
Civil	Glasgow	Nov-87	05-23	PFC	0.72	0.67	Cranfield
Civil	Guernsey	Oct-82	09-27	PFC	0.62	0.65	Cranfield
Civil	Heathrow	Apr-75	10L-28R	PFC	0.74	0.77	Cranfield
Civil	Heathrow	Apr-75	10R-28L	PFC	0.73	0.78	Cranfield
Civil	Heathrow	Sep-80	10L-28R	PFC	0.63	0.72	Cranfield
Civil	Heathrow	Sep-80	10R-28L	PFC	0.66	0.73	Cranfield
Civil	Heathrow	Jun-83	10L-28R	PFC	0.62	0.67	Cranfield
Civil	Heathrow	Jun-83	10R-28L	PFC	0.62	0.65	Cranfield
Civil	Heathrow	Sep-85	10L-28R	PFC	0.59	0.62	Cranfield
Civil	Heathrow	Sep-85	10R-28L	PFC	0.60	0.60	Cranfield
Civil	Heathrow	Jun-89	09L-27R	PFC	0.61	0.66	Cranfield

Table 3.1 continued

Status	Airport	Date	Runway	Surface	Friction Values		Source
					130km/h (80mph)	65km/h (40mph)	
Civil	Heathrow	Nov-90	09R-27L	PFC	0.68	0.78	Cranfield
Civil	Humberside	Jan-92	03-21	PFC	0.78	0.80	Cranfield
Civil	Inverness	Jul-82	06-24	PFC	0.60	0.70	Cranfield
Civil	Inverness	Dec-90	06-24	PFC	0.59	0.59	Cranfield
Civil	Isle of Man	Apr-84	09-27	PFC	0.70	0.74	Cranfield
Civil	Isle of Man	Sep-94	08-26	PFC	0.74	0.76	DE/Cranfield
Civil	Jersey	Sep-90	09-27	PFC	0.71	0.75	Cranfield
Civil	Liverpool	Jan-89	09-27	PFC	0.77	0.79	Cranfield
Civil	Luton	May-82	08-26	PFC	0.70	0.69	Cranfield
Civil	Manchester	Aug-82	06-24	PFC	0.72	0.72	Cranfield
Civil	Manchester	Mar-91	06-24	PFC	0.65	0.66	Cranfield
Civil	Prestwick	Jun-83	13-31	PFC	0.75	0.76	Cranfield
Civil	Prestwick	Dec-90	13-31	PFC	0.71	0.72	Cranfield
Civil	Southend	May-89	06-24	PFC	0.43	0.44	Cranfield
Civil	Southend	Nov-89	06-24	PFC	0.39	0.45	Cranfield
Civil	Southend	Mar-90	06-24	PFC	0.51	0.54	Cranfield
Civil	Southend	Jan-91	06-24	PFC	0.44	0.48	Cranfield
Civil	Southend	Apr-92	06-24	PFC	0.36	0.43	Cranfield
Civil	Southend	May-92	06-24	PFC	0.47	0.51	Cranfield
Civil	Southend	Nov-92	06-24	PFC	0.41	0.50	Cranfield
Civil	Southend	Oct-93	06-24	PFC	0.40	0.50	Cranfield
Civil	Stansted	Sep-82	05-23	PFC	0.74	0.75	Cranfield
Civil	Sumburgh	Jul-82	09-27	PFC	0.68	0.73	Cranfield
Civil	Manchester	Jul-93	06-24	PFC	0.59	0.60	Cranfield
Military	M57	n/a	n/a	PFC	0.80	0.83	DE
Military	M58	n/a	n/a	PFC	0.76	0.79	DE
Military	M59	n/a	n/a	PFC	0.67	0.70	DE
Military	M60	n/a	n/a	PFC	0.72	0.76	DE
Military	M61	n/a	n/a	PFC	0.59	0.68	DE
Military	M62	n/a	n/a	PFC	0.63	0.70	DE
Military	M63	n/a	n/a	PFC	0.72	0.77	DE
Military	M64	n/a	n/a	PFC	0.54	0.58	DE
Military	M65	n/a	n/a	PFC	0.60	0.68	DE
Military	M66	n/a	n/a	PFC	0.63	0.68	DE
Military	M67	n/a	n/a	PFC	0.62	0.65	DE
Military	M68	n/a	n/a	PFC	0.63	0.66	DE
Military	M69	n/a	n/a	PFC	0.66	0.73	DE
Military	M70	n/a	n/a	PFC	0.56	0.61	DE
Military	M71	n/a	n/a	PFC	0.56	0.59	DE
Military	M72	n/a	n/a	PFC	0.76	0.79	DE
Military	M73	n/a	n/a	PFC	0.62	0.69	DE
Military	M74	n/a	n/a	PFC	0.52	0.57	DE
Military	M75	n/a	n/a	PFC	0.56	0.62	DE
Military	M76	n/a	n/a	PFC	0.75	0.80	DE
Military	M77	n/a	n/a	PFC	0.55	0.65	DE
Military	M78	n/a	n/a	PFC	0.58	0.65	DE

Table 3.1 continued

Status	Airport	Date	Runway	Surface	Friction Values		Source
					130km/h (80mph)	65km/h (40mph)	
Military	M79	n/a	n/a	PFC	0.65	0.70	DE
Military	M80	n/a	n/a	PFC	0.60	0.69	DE
Military	M81	n/a	n/a	PFC	0.70	0.77	DE
Military	M82	n/a	n/a	PFC	0.66	0.75	DE
Military	M83	n/a	n/a	PFC	0.70	0.72	DE
Military	M84	1991	n/a	PFC	0.63	0.67	DE
Military	M85	n/a	n/a	PFC	0.52	0.67	DE
Military	M86	n/a	n/a	PFC	0.51	0.65	DE
Military	M87	n/a	n/a	PFC	0.61	0.69	DE
Military	M88	n/a	n/a	PFC	0.55	0.65	DE
Military	M89	n/a	n/a	PFC	0.69	0.70	DE
Military	M90	n/a	n/a	PFC	0.58	0.68	DE
Military	M91	n/a	n/a	PFC	0.68	0.78	DE
Military	M92	n/a	n/a	PFC	0.49	0.52	DE
Military	M93	n/a	n/a	PFC	0.49	0.51	DE
Military	M94	n/a	n/a	PFC	0.63	0.70	DE/Cranfield
Military	M95	n/a	n/a	PFC	0.58	0.63	DE
Military	M96	n/a	n/a	PFC	0.59	0.67	DE
Military	M97	n/a	n/a	PFC	0.69	0.76	DE
Military	M98	n/a	n/a	PFC	0.67	0.76	DE
Military	M99	n/a	n/a	PFC	0.47	0.58	DE
Military	M100	n/a	n/a	PFC	0.63	0.69	DE/Cranfield
Military	M101	n/a	n/a	PFC	0.48	0.62	DE/Cranfield
Military	M102	n/a	n/a	PFC	0.66	0.72	DE/Cranfield
Military	M103	n/a	n/a	PFC	0.58	0.61	DE/Cranfield
Military	M104	n/a	n/a	PFC	0.61	0.69	DE/Cranfield
Military	M105	n/a	n/a	PFC	0.52	0.52	DE/Cranfield
Military	M106	n/a	n/a	PFC	0.56	0.64	DE/Cranfield
Military	M107	n/a	n/a	PFC	0.64	0.72	DE/Cranfield
Military	M108	n/a	n/a	PFC	0.62	0.68	DE/Cranfield
Military	M109	n/a	n/a	PFC	0.66	0.73	DE/Cranfield
Military	M110	n/a	n/a	PFC	0.65	0.74	DE/Cranfield
Military	M111	n/a	n/a	PFC	0.64	0.77	DE/Cranfield
Military	M112	n/a	n/a	PFC	0.6	0.62	DE/Cranfield
Military	M113	n/a	n/a	PFC	0.63	0.7	DE
Military	M114	n/a	n/a	PFC	0.63	0.74	DE/Cranfield
Military	M115	n/a	n/a	PFC	0.63	0.84	DE
Military	M116	n/a	n/a	PFC	0.68	0.74	DE
Military	M117	n/a	n/a	PFC	0.58	0.75	DE
Military	M118	n/a	n/a	PFC	0.62	0.74	DE
Military	M119	n/a	n/a	PFC	0.76	0.8	Cranfield
Military	M120	n/a	n/a	PFC	0.55	0.58	Cranfield
Military	M121	n/a	n/a	PFC	0.68	0.77	Cranfield
Military	M122	n/a	n/a	PFC	0.55	0.68	Cranfield
Military	M123	n/a	n/a	PFC	0.54	0.7	Cranfield

Key to Table 3.1

Surface type key	
PC	*Precoated Chippings*
GSS	*Grooved Slurry Seal*
GAS	*Grooved Asphalt*
ASP	*Asphalt*
Conc	*Concrete*
SS	*Slurry Seal*
CrseASP	*Coarse Asphalt*
GASP/A	*Grooved Asphalt & Asphalt*
BRC	*Brushed Concrete*
PCC	*Pre-coated Chippings*
CSS	*Coarse Slurry Seal*
GMA	*Grooved Marshall Asphalt*
Crs S	*Coarse Slurry*
SSS	*Slurry Seal Surfaces*
Source Key	
Cranfield	Cranfield University
DE	Defence Estates

Note: The use of the term M49 or similar denotes a military airfield for which the precise location has been de-identified.

4 SUMMARY OF ANALYSIS

4.1 General

This Section provides a summary of the analyses carried out on the data pool given in Table 3.1. It is assumed that all survey data were collected on the following basis:

- Mu - Meter : Mark 1 - 5
- Water Depth : 0.5mm
- Tyre Type : 16 x 4 - 8
- Tyre Pressure : 10psi ± 0.5

Subsequent to the completion of analyses it has been established that there was a change in tyre types from Dunlop tyres to DICO tyres around 1993. Unfortunately the date of introduction of the new tyre for each Mu-Meter in use at the time is not known. Nevertheless the new tyres were calibrated such that there was a convergence in measured readings in the region of the Minimum Friction Level. As this region is the critical area of most interest to the reporting of friction values it has been assumed that the change in tyre types would not alter the key conclusions of this report.

All analyses presented in this Section and in Appendix A were performed using the standard tools and functions available with Microsoft Excel 97.

4.2 Friction Levels from the Original Cranfield Report FS-2349

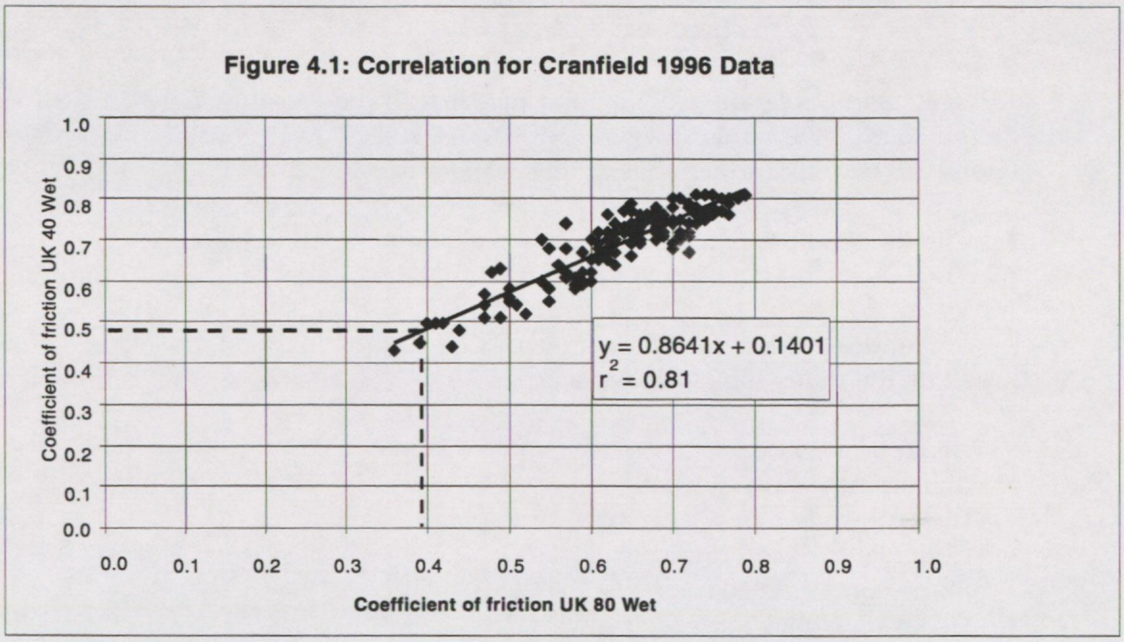
The original data used by Cranfield in FS-2349 have been re-analysed. Figure 4.1 includes all the data points used by Cranfield as part of the analysis presented in the report. This indicates that utilising the equation of the best-fit line, the precise value of the Minimum Friction Level equivalent to 0.39 at 130km/h (80mph) is 0.48 at 65km/h (40mph). This varies 0.01 from the published value in NOTAL 2/94 of 0.47.

The full comparison of Friction Levels is given in Table 4.1

Table 4.1 Comparison of Cranfield FS-2349 Correlation v NOTAL 2/94

Level	Friction Level @130km/h Cranfield FS-2349 (Figure 4.1)	Friction Level @65km/h Cranfield FS-2349 (Figure 4.1)	Friction Level @65km/h NOTAL 2/94
MFL	0.39	0.48	0.47
MPL	0.45	0.53	0.57
DOL	0.65	0.70	0.72

It must be recognised that the values for MPL and DOL in NOTAL 2/94 were in fact not derived from the Cranfield data, but from MOD/PSA data as shown in Figure 2.1 and discussed in Section 2.



The data represented in Figure 4.1 include all data points for all surface types available to Cranfield in December 1996. This analysis takes no account of the following factors:

- More recent survey data.
- Other available data held by MOD.
- The relative friction performance of different surface types
- The frequency of surveys on each runway.
- Date of survey.
- Time of survey after resurfacing.

These matters are reviewed in more detail in the following sections.

4.3 Friction Levels Based on the Friction Data Pool

A review of all available friction data provided by Cranfield University and DE has been analysed in a similar manner to that of the Cranfield FS-2349 data.

Figure 4.2 includes all 207 available data points for all surfaces of the following types: concrete, slurry seal, grooved asphalt and porous friction course (PFC). Data on a limited number of more obscure surfaces has been ignored.

This graph is similar to the original Cranfield graph discussed in Section 4.2 above and gives the following correlation's, using the equation of the best fit line, compared to NOTAL 2/94.

Table 4.2 Correlation using all Data Points

Level	Friction Level @130km/h (Figure 4.2)	Friction Level @65km/h (Figure 4.2)	Friction Level @65km/h (NOTAL 2/94)
MFL	0.39	0.51	0.47
MPL	0.45	0.56	0.57
DOL	0.65	0.71	0.72

The results in Table 4.2 show a good match with the existing values in NOTAL 2/94 at the MPL and DOL but a difference of 0.04 at MFL. This is considered to be significant enough to warrant further analysis given the following:

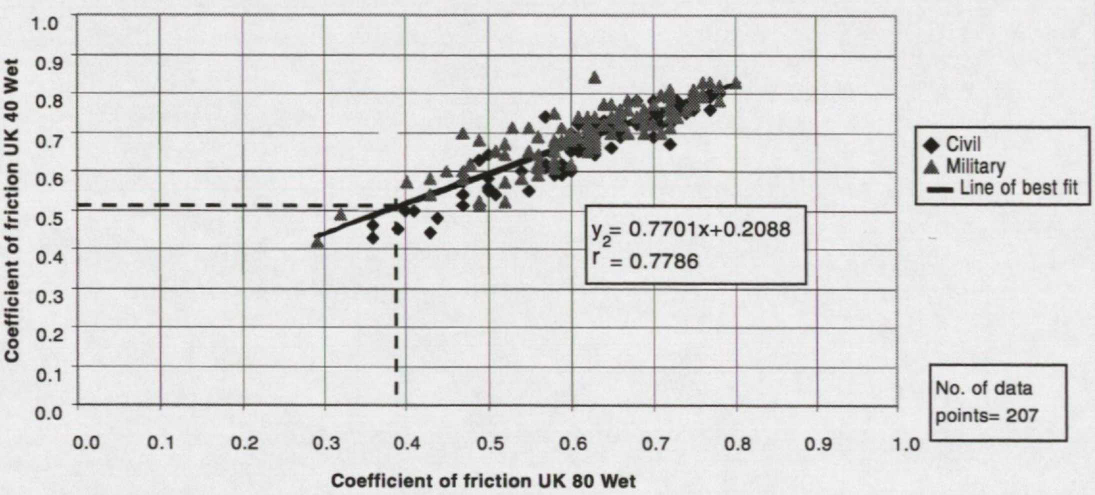
- The difference is considered to be outside equipment tolerance.
- The results in Table 4.2 would suggest that the current MFL of 0.47 to be incorrect.

In view of these findings, the data have been further analysed to isolate Friction Levels based on the following characteristics:

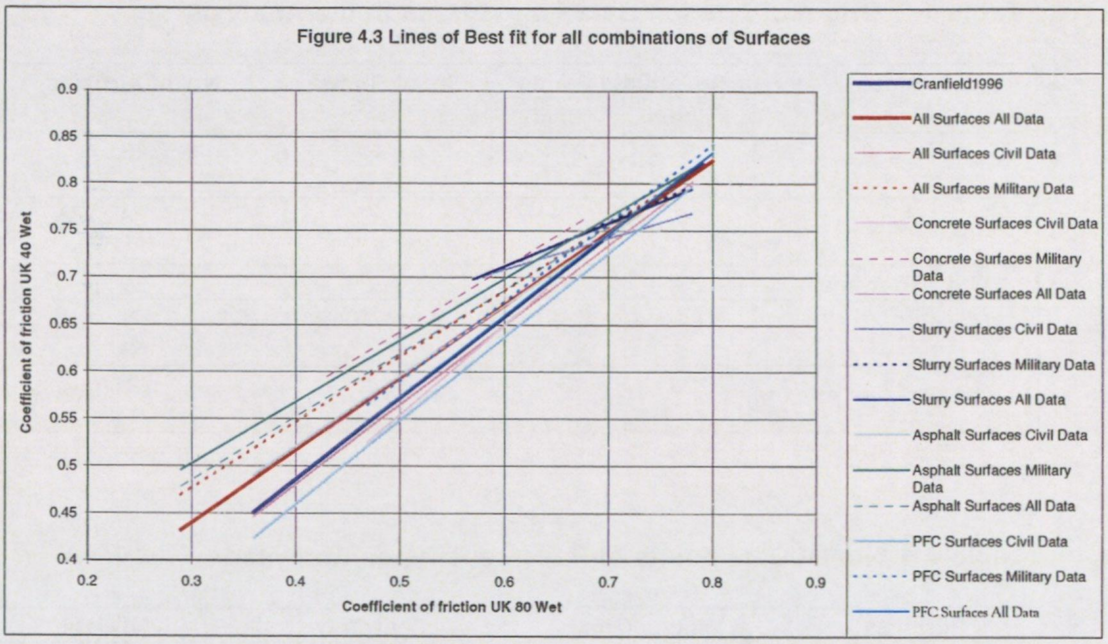
- All surfaces, all data.
- Military runways.
- Civil runways.
- Concrete surfaced runways.
- Slurry seal surfaced runways.
- Grooved asphalt surfaced runways.
- PFC surfaced runways.

This is illustrated graphically by runway type in Figure 4.2.

Figure 4.2: Correlation for All Surfaces (Concrete, Slurry, Asphalt, PFC) : All Data



The same data is presented by surface type in Figure 4.3.



4.4 Overview of Analysis

Table 4.3 shows that of the 207 data points, 59% of data are from military airfields and 41% from civil airfields. The data include surveys on 147 runways at 134 airfields. Some 53% of the data comprise the PFC surface type, by far the largest amount on any surface type. The analysis shows the values which would be yielded by the data if analysed in a similar manner to the FS-2349 Cranfield correlation, plotting a line of best fit through data at 65 km/h (40mph) versus data at 130 km/h (80mph), both in self-wetting conditions. Various combinations have been considered, as presented in the summary data in Tables 4.3 to 4.9, and presented in detail in Appendix A.

Closer inspection of this data shows that when considering the graphs of military and civil data separately, the equation of the line of best fit, and hence the 40mph friction values calculated are consistently different.

It can be seen in Figures E to J that extrapolation is required to obtain the 40mph friction values for Concrete and Slurry Seal surfaces. This is because the data points at 80mph are not in the region of 0.39. Thus, for this reason, and because these two surfaces have a very small number of data points, the reliability of the contribution of these two surfaces to the overall analysis is brought into question.

It would therefore appear prudent to base the new values for the Minimum Friction Level on the Grooved Asphalt and PFC surfaces. The average of the combined data sets for these two surface types gives a value 40mph = 0.5055, which has been rounded to 0.51.

Table 4.3 Origin of Friction Data Points Used in the Analysis

Surfaces	No. of Data Points		No. of Runways	No. of Airfields
	Military	Civil		
Concrete	8	14	14	13
Slurry	25	9	39	28
Grooved Asphalt	23	19	33	29
PFC	67	42	61	64
All	123	84	147	134
% of Total	59%	41%		

Table 4.4 No. Of Data points of Pavement Types Analysed

Surfaces	Military Only		Civil Only		All Data	
	Data Only	% All Surfaces	Data Only	% All Surfaces	All Data	% All Surfaces
Concrete	8	7%	14	16%	22	11%
Slurry	25	20%	9	11%	34	16%
Grooved Asphalt	23	19%	19	23%	42	20%
PFC	67	54%	42	50%	109	53%
All	123	100%	84	100%	207	100%

Table 4.5 Equations for Line of Best Fit

Surfaces	Military Data Only	Civil Data Only	All Data (Military and Civil Data)
Concrete	y=0.68x+0.30	y=0.96x+0.07	y=0.78x+0.20
Slurry	y=0.48x+0.43	y=0.34x+0.51	y=0.46x+0.44
Grooved Asphalt	y=0.65x+0.31	y=0.75x+0.22	y=0.67x+0.28
PFC	y=0.84x+0.17	y=0.89x+0.10	y=0.87x+0.14
All Excluding Slurry	y=0.70x+0.26	y=0.86x+0.13	y=0.77x+0.21
All Excluding PFC	y=0.62x+0.33	y=0.82x+0.17	y=0.70x+0.27
Grooved Asphalt and PFC	y=0.72x+0.25	y=0.85x+0.14	y=0.77x+0.21
All	y=0.70x+0.27	y=0.85x+0.14	y=0.77x+0.21

Table 4.6 Values for Correlation Coefficient (r^2)

Surfaces	Military Data Only	Civil Data Only	All Data (Military and Civil Data)
Concrete	0.70	0.83	0.57
Slurry	0.44	0.48	0.46
Grooved Asphalt	0.87	0.89	0.85
PFC	0.71	0.92	0.79
All Excluding Slurry	0.73	0.89	0.77
All Excluding PFC	0.83	0.85	0.80
Grooved Asphalt and PFC	0.74	0.89	0.78
All	0.76	0.87	0.78

Table 4.7 Friction Levels at 65 km/h (40 mph) corresponding to a value of 0.65 at 130 km/h (80 mph)

Surfaces	Military Data Only	Civil Data Only	All Data (Military and Civil Data)	Current value NOTAL 2/94
Concrete	0.74	0.70	0.71	0.72
Slurry	0.74	0.73	0.74	0.72
Grooved Asphalt	0.73	0.71	0.72	0.72
PFC	0.72	0.68	0.70	0.72
All Excluding Slurry	0.72	0.69	0.71	0.72
All Excluding PFC	0.73	0.70	0.72	0.72
Grooved Asphalt and PFC	0.72	0.69	0.71	0.72
All	0.72	0.69	0.71	0.72

Table 4.8 Corresponding 65 km/h (40mph) friction values from 130 km/h (80mph) = 0.45

Surfaces	Military Data Only	Civil Data Only	All Data (Military and Civil Data)	Current value NOTAL 2/94
Concrete	0.61	0.51	0.55	0.57
Slurry	0.64	0.66	0.64	0.57
Grooved Asphalt	0.60	0.56	0.59	0.57
PFC	0.58	0.52	0.55	0.57
All Excluding Slurry	0.61	0.54	0.58	0.57
All Excluding PFC	0.58	0.52	0.55	0.57
Grooved Asphalt and PFC	0.55	0.50	0.53	0.57
All	0.58	0.52	0.56	0.57

Table 4.9 Corresponding 65 km/h (40mph) friction values from 130 km/h (80mph) = 0.39

Surfaces	Military Data Only	Civil Data Only	All Data (Military and Civil Data)	Current value NOTAL 2/94
Concrete	0.57	0.45	0.51	0.47
Slurry	0.61	0.64	0.62	0.47
Grooved Asphalt	0.56	0.51	0.55	0.47
PFC	0.50	0.45	0.48	0.47
All Excluding Slurry	0.54	0.47	0.51	0.47
All Excluding PFC	0.57	0.49	0.54	0.47
Grooved Asphalt and PFC	0.53	0.47	0.51	0.47
All	0.54	0.47	0.51	0.47

4.5 Discussion

The results presented in the preceding sections of this report were considered by an Expert Review Panel consisting of representatives from the equipment manufacturers Findlay Irvine Ltd and Douglas Equipment Ltd, the CAA, Cranfield University and DE.

It was the opinion of the Expert Review Panel that the Design Objective Level and Maintenance Planning Level should remain at the values given in NOTAL 2/94 as the new values were sufficiently close not to warrant a change.

It was also the opinion of the Expert Review Panel that with respect to the Minimum Friction Level:

- Concrete surfaces have a very small data set, with significantly different behaviour, and were not considered typical for the purpose of analysis.
- Slurry seal and concrete surfaces were also considered unsuitable because extrapolation is required to determine the result and the data sets do not include Friction values in the 0.39 region.
- From interpretation of Figure 2.1 and Figure 2.2 the value of the Minimum Friction Level must be raised from the present value of 0.47 given in NOTAL 2/94.
- A single value for the Minimum Friction Level should be published that would be applicable to all surfaces.
- The choice of the value for Minimum Friction Level should acknowledge the recent experience with low friction values encountered on a number of runways with grooved asphalt surfaces.

In view of these findings it was the opinion of the Expert Review Panel that the value for the Minimum Friction Level for the Mu-Meter under self-wetting conditions, with a calculated water depth of 0.50mm should be set at 0.50. The choice of this value reflects the concerns of the Expert Review Panel that:

- Current value of 0.47 is incorrect in the light of the present information and that a higher value is appropriate.
- The average of all surfaces and all data is calculated at 0.51.
- Considering Grooved Asphalt and PFC surfaces only, an average value of 0.51 is applicable.
- 0.50 reflects an appropriate level of accuracy in the second decimal place.
- 0.50 maintains a reasonable separation from the value of 0.57 retained for the Maintenance Planning Level.

Accordingly the value of 0.50 for the Mu-Meter has been incorporated in Table 3.2 in CAP 683.

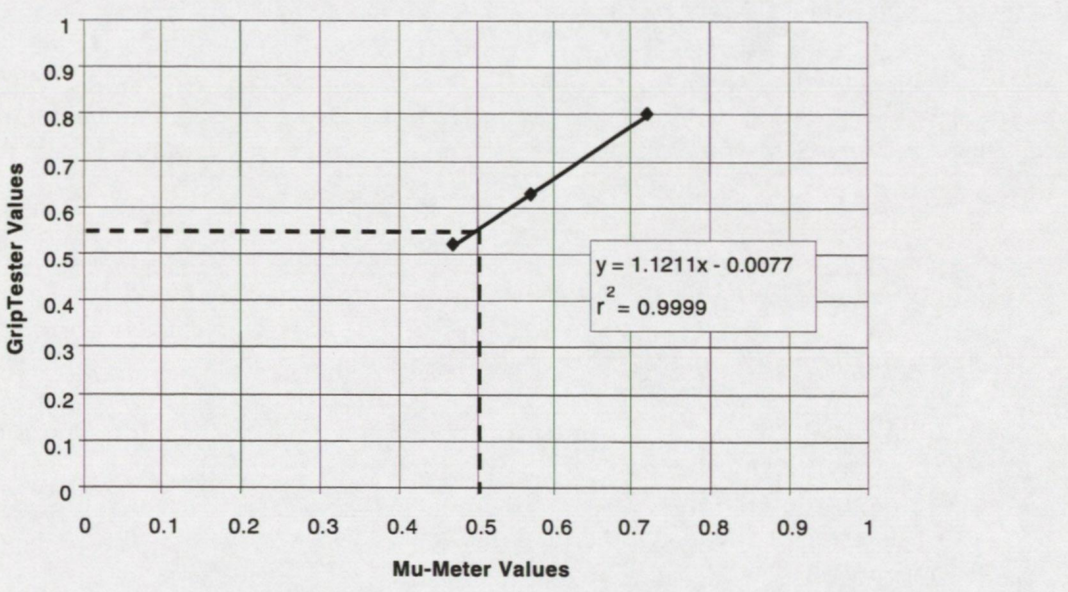
5 CORRELATION WITH THE GRIPTESTER

Having established a new value of 0.50 for the Minimum Friction Level when using the Mu-Meter it is necessary to correlate this value to the GripTester. The original study of the correlation between the Friction Levels recorded by the Mu-Meter and those recorded by the GripTester are unavailable, and beyond the scope of this Report. However, it is possible to obtain the corresponding value for the GripTester by interpolation using a best-fit line through the values given in NOTAL 2/94.

This correlation is shown in Figure 5.1 and indicates that the corresponding value of the Minimum Friction Level for the GripTester under self-wetting conditions with a calculated water depth of 0.25mm, is 0.55.

Accordingly, the value of 0.55 for the GripTester has been incorporated in Table 3.2 in CAP 683.

Figure 5.1: Correlation between Mu-Meter and GripTester Friction Levels



6 OTHER CONSIDERATIONS IN FRICTION MEASUREMENT AND REPORTING

6.1 Introduction

In the process of drafting CAP 683 the opportunity was taken to review a number of issues relating to measurement and reporting of friction values. These included:

- Definition of a 'portion of a runway'.
- The impact of water depth.
- The variation of friction with speed.
- Areas for future development.

These issues are discussed in more detail in the following sections.

6.2 Definition of a 'Portion of a Runway'

The International Civil Aviation Organisation (ICAO) International Standards and Recommended Practices for Aerodromes, Annex 14, Volume 1, Aerodrome Design and Operations, makes a number of statements in respect to runway friction including the following:

> "9.4.6 Corrective maintenance action shall be taken when the friction characteristics for either the entire runway or a portion thereof are below a minimum friction level specified by the State.
>
> *Note – A portion of runway in the order of 100m long may be considered significant for maintenance or reporting action.*
>
> *9.4.7 **Recommendation**. – Corrective maintenance action should be considered when the friction characteristics for either the entire runway or a portion thereof are below a maintenance planning level specified by the State."*

These statements require some interpretation as there is no clear definition given of the 'portion of a runway' except the reference to '100m long'. It has been suggested that the 100m portion could relate to any of the following:

- The full width of the runway.
- A half width of the runway one side of the centreline.
- The trafficked area of the runway.
- A single test run by continuous friction measuring equipment (CFME).

It is also not stated as to whether the 100m relates to:

- A 100m increment.
- A rolling 100m average.
- A minimum of possible 100m rolling averages.
- An average of some or all of the runs by a CFME.

The resolution of these issues is particularly important when it comes to the issue of a NOTAM defining the runway as 'liable to be slippery when wet'. This has particular safety, as well as operational and economic implications, and must be determined without any room for doubt or dispute. In view of this 'the portion' of a runway has been more clearly defined in CAP 683 as:

Areas of runway, the width of which should be taken as the following:

1 A central trafficked portion, taken as the area up to and including 7.5m either side of the runway centreline.

2 Two outer untrafficked portions either side of the centreline making up the remainder of the width of the declared runway.

This definition is illustrated in Figure 6.1.

In addition the 100m average has been taken as the minimum 100m rolling average as described below.

6.3 Calculation of Minimum 100m Rolling Average

In the absence of any guidance from ICAO a methodology for calculating the minimum 100m rolling average has been developed. This is outlined below and illustrated in Table 6.1. This methodology is used in the Runway Friction Analysis System (RFAS).

Data are collected by the continuous measuring friction equipment (CFME) along the line of the survey run and reported as an averaged value for each 10m increment along the run. Over a distance of 100m an average can be calculated as the average of 10 inclusive increments. However, away from the ends of the runs at the position of each increment there are 10 possible applicable 100m rolling averages. This is best visualised by the use of a sliding 100m cursor passing over the surface. This cursor can be moved to 10 different positions whilst still including the 10m increment in question. An additional complexity is that at times there may be data at any or several of the 10m increments that should be excluded. This could be due to a variety of reasons but most commonly it will be because the speed of survey was out of tolerance at this point. If this is the case then this data is ignored as being invalid. However, it is important to make the most of the valid friction data obtained and not reject it entirely on account of the occasional data point which is out of tolerance.

In view of this it has been decided that the minimum 100m rolling average should comprise of at least eight readings within the 100m length being evaluated. If there are less than eight readings, no average friction value should be assigned to the relevant 10m increment because the lack of data will unduly affect the reported result. If there are at least eight readings, it is necessary to temporarily assign the average of all the friction values in that 100m length to the 10m increment at the beginning of the 100m length.

The next step is to evaluate friction values for the next 100m of the run starting 10m from the previous increment and assign the average friction value to the 10m increment at the beginning of the 100m length being evaluated. This process is repeated until the distance to the end of the run is less than 100m.

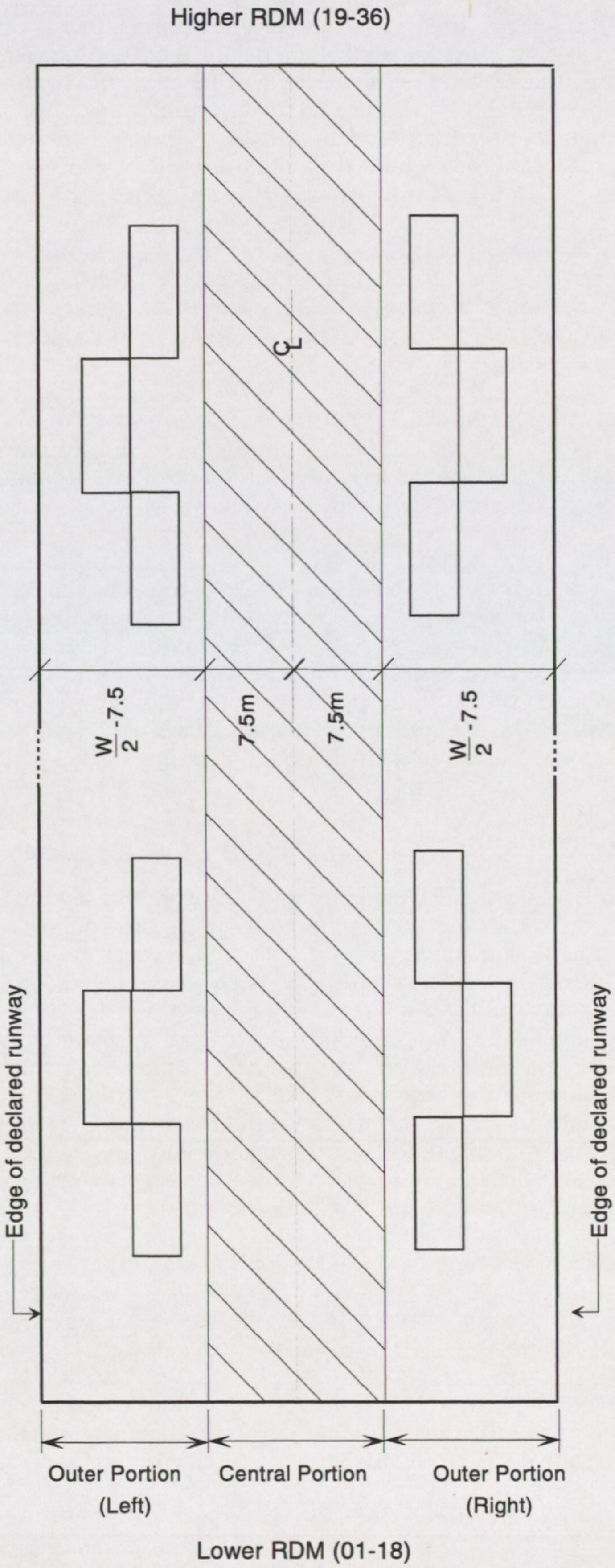


Figure 6.1 Schematic layout defining portions of a runway. (W = runway width)

After an average friction value is assigned to every 10m increment of the run it is necessary to sift the average friction values and select the lowest of these averages, excluding those areas with no data. Hence at a distance of 0 only the average from 0 to 100m is included in the calculation so there will be only one value to select from. However, at 10m there will be two values to select from, one for the calculation at 0 m and one for the calculation at 10m, and the lowest of the two values will be selected. This selection is performed through all the data in order to select the minimum 100m rolling average at any one position on the runway. This process is illustrated in Table 6.1 and a typical calculation of the rolling average is illustrated in Figure 6.2.

The procedure for calculating the rolling average for each run is repeated in a similar fashion for each of the three portions across the runway. In each case the applicable runs across the width of each portion are first averaged before undertaking the rolling average calculation as described above.

In addition to calculating 100m rolling averages it is necessary to undertake a critical area analysis. A critical area is defined as a continuous section of pavement where the minimum rolling average friction value is below the specified threshold for the friction level for a distance of greater than 100m. However, it must be remembered that the threshold values are dependent on the type of friction test device used. A search must be made of each run and group of runs for areas where the minimum rolling average friction is below the Minimum Friction Level. In RFAS this information can be reported in two ways: by run or by portion. The Critical Area by Run report looks at the rolling average friction for each run in a survey and reports areas where the friction falls below the Minimum Friction Level. The Critical Areas by Portion looks at the rolling average friction for each of the three portions of the runway (left, right, and centre) and reports areas where the friction falls below the Minimum Friction Level. A typical set of maps and reports, generated by RFAS, illustrating these matters are given in Figure 6.3 and 6.4.

6.4 The Impact of Water Depth

Research in the UK by Cranfield University and Transport Research Laboratory (TRL) into the issue of water depth used for self-wetting purposes found that this was not a significant factor in assessing runway friction. For this reason, the GripTester and Mu-Meter have historically used self-wetting water depths of 0.25mm and 0.50mm respectively. These water depths are based on a theoretical calculation of the flow rate, speed and wetted area. ICAO recommends the use of a water depth of 1.0mm. A principal reason for retaining the water depths used in the UK is that there are a large amount of historical data and experience using these water depths. An immediate move to using 1.0mm water depth would require the CAA to publish applicable Friction Levels. However, at this time there are insufficient data in the UK to make such a recommendation. In addition there is concern that on low texture surfaces water depth could significantly affect the findings of a friction survey.

In view of these matters, it is recommended that the UK should:

1 Consider moving towards establishing Friction Levels long term at a calculated water depth of 1.0mm.

2 Where possible Friction Levels should be checked at a water depth of 1.0mm, in addition to the use of the current water depth, particularly on runways which are known to have a low surface texture.

In view of these recommendations CAP 683 includes two additional runs at a water depth of 1.0mm to allow data to be gathered on Friction Levels at this water depth so that a correlation can later be established with the existing water depths.

Table 6.1
Selection of 100m Rolling Friction Average and Minimum 100m Rolling Friction Average

CFME Data at 10m Increments	100m Rolling Friction Average					Minimum 100m Rolling Friction Average
	RA_1	RA_2	RA_3	RA_4	RA_n	
D_1	RA_1					MRA_1
D_2	RA_1	RA_2				MRA_2
D_3	RA_1	RA_2	RA_3			MRA_3
D_4	RA_1	RA_2	RA_3	RA_4		MRA_4
D_5	RA_1	RA_2	RA_3	RA_4	RA_n	MRA_5
D_6	RA_1	RA_2	RA_3	RA_4	RA_n	MRA_6
D_7	RA_1	RA_2	RA_3	RA_4	RA_n	MRA_7
D_8	RA_1	RA_2	RA_3	RA_4	RA_n	MRA_8
D_9	RA_1	RA_2	RA_3	RA_4	RA_n	MRA_9
D_{10}	RA_1	RA_2	RA_3	RA_4	RA_n	MRA_{10}
D_{11}		RA_2	RA_3	RA_4	RA_n	MRA_{11}
D_{12}			RA_3	RA_4	RA_n	MRA_{12}
D_{13}				RA_4	RA_n	MRA_{13}
…etc						…etc

Where:

RA_1 = average of values D_1 to D_{10} over distance 0 to 100m
RA_2 = average of values D_2 to D_{11} over distance 10 to 110m
RA_3 = average of values D_3 to D_{12} over distance 20 to 120m
…etc

$MRA_1 = RA_1$
MRA_2 = minimum of RA_1 and RA_2
MRA_3 = minimum of RA_1, RA_2 and RA_3
…etc

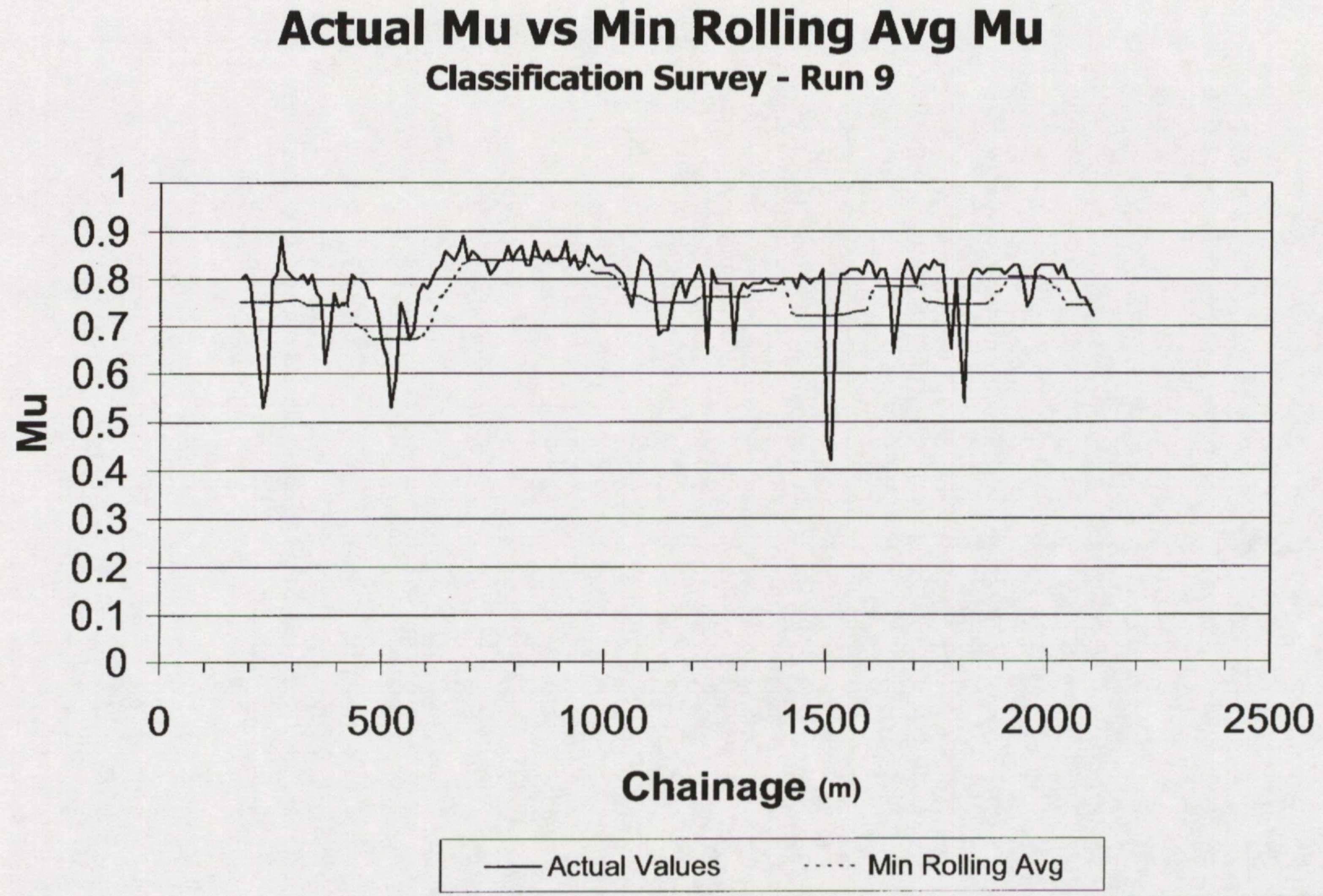


Figure 6.2 Typical Rolling Friction Average Calculation

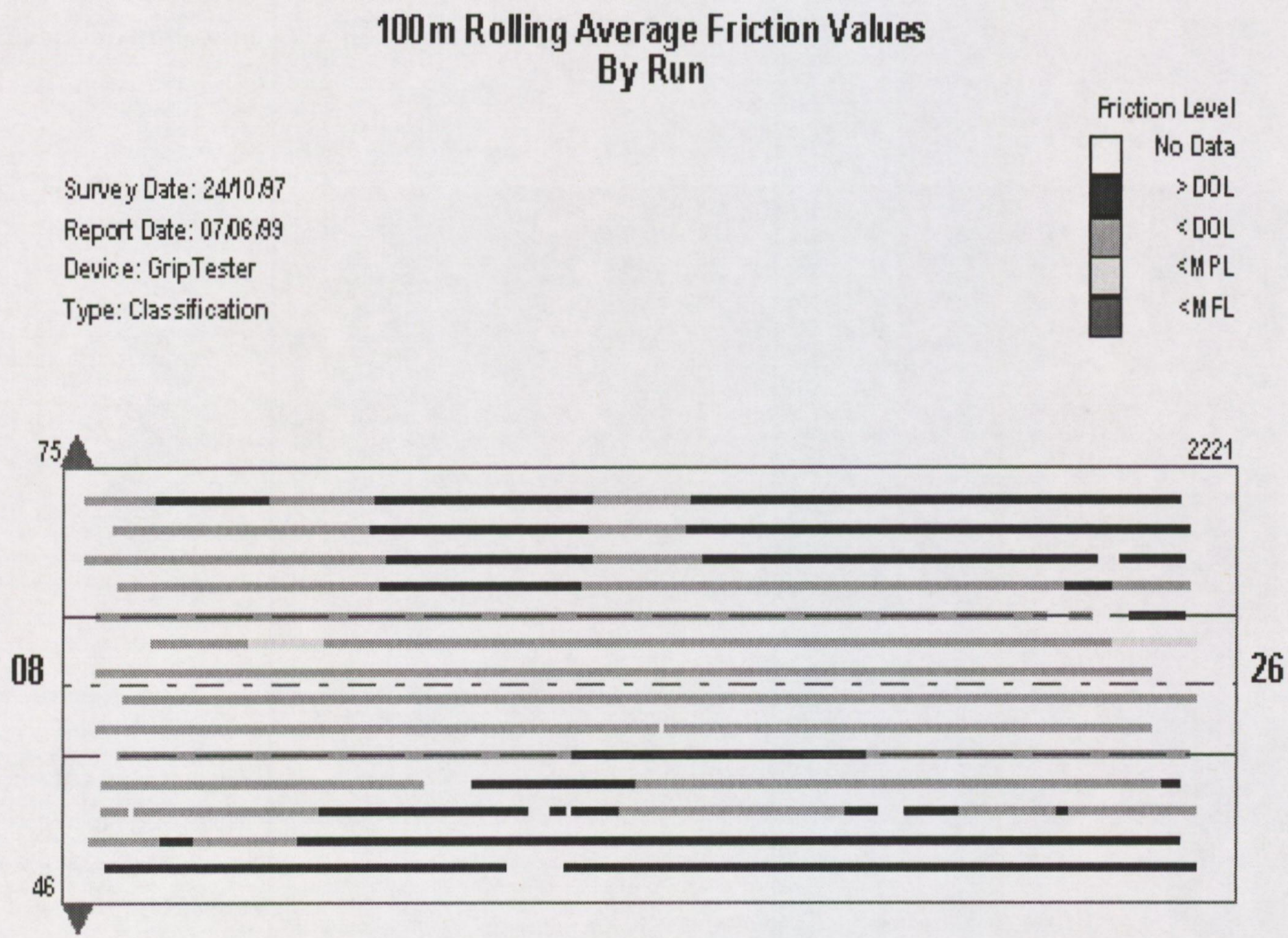


Figure 6.3 Typical Rolling Average Friction Values by Run

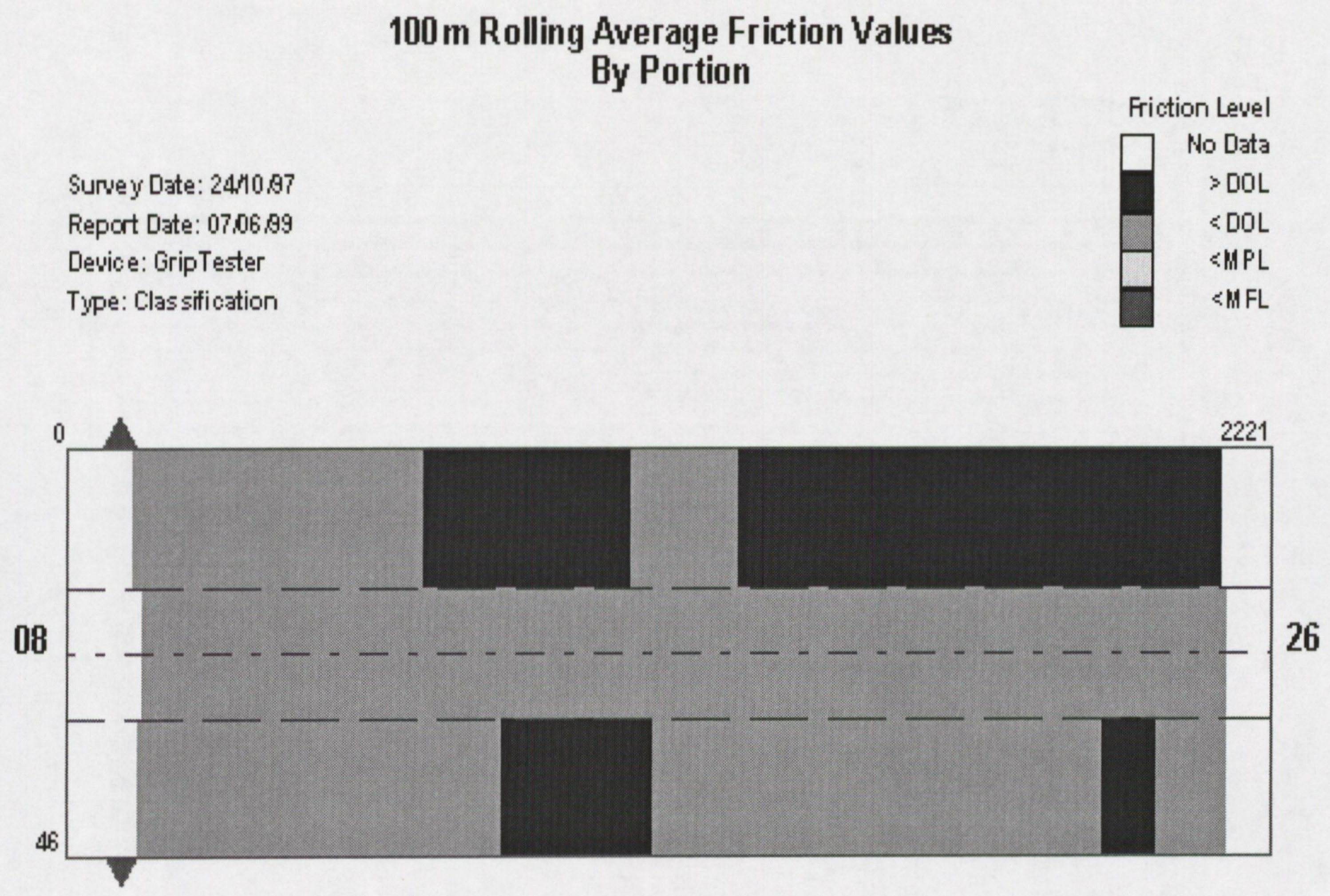


Figure 6.4 Typical Rolling Average Friction Values by Portion

6.5 The Variation of Friction with Speed

The variation of friction with speed is a useful indicator of the properties of a pavement surface. In particular it is known to be an indicator of surface texture, however, at this time it is not possible to give quantitative advice from this information.

It is also a recommendation of ICAO in Annex 14, that friction characteristics be tested at more than one speed. Table A-1 in Attachment A of Annex 14 suggests test speeds of 65km/h and 95km/h.

In view of this guidance from ICAO the run pattern for friction measurements in CAP 683 have been refined by dropping the speed runs at 30km/h and 130km/h as these were considered less practicable and of limited value. However, Speed Runs at 95km/h have been retained in addition to the standard 65km/h runs, and new Speed Runs at 80km/h introduced at the midpoint between the other two speeds. From these data a speed v friction curve can be established which in time, it is hoped, will allow some quantitative interpretation to be made. It is also hoped that the gathering of the data will in future also allow CAA to establish and publish friction values at the ICAO suggested speed of 95km/h.

7 CONCLUSION AND RECOMMENDATIONS

Comprehensive analysis of available data and subsequent peer review by the Expert Review Panel has resulted in a recommendation on the Friction Levels to be included in CAP 683 Procedures for Runway Friction Classification and Monitoring.

This recommendation has been based on the comparison and assessment of all available friction data on all common types of runway surface found in the UK. The line of best fit through these data plots was then used with the criteria that the Minimum Friction Level at 130 km/h (80mph) = 0.39 in order to find the corresponding value at 65 km/h (40 mph) for the Mu-Meter. Subsequently a value for the Minimum Friction Level for the GripTester was also established by interpolation of historic data. The recommended values for the Minimum Friction Levels for the two types of friction testing equipment commonly used in the UK have been defined as:

- Mu-Meter = 0.50
- GripTester = 0.55

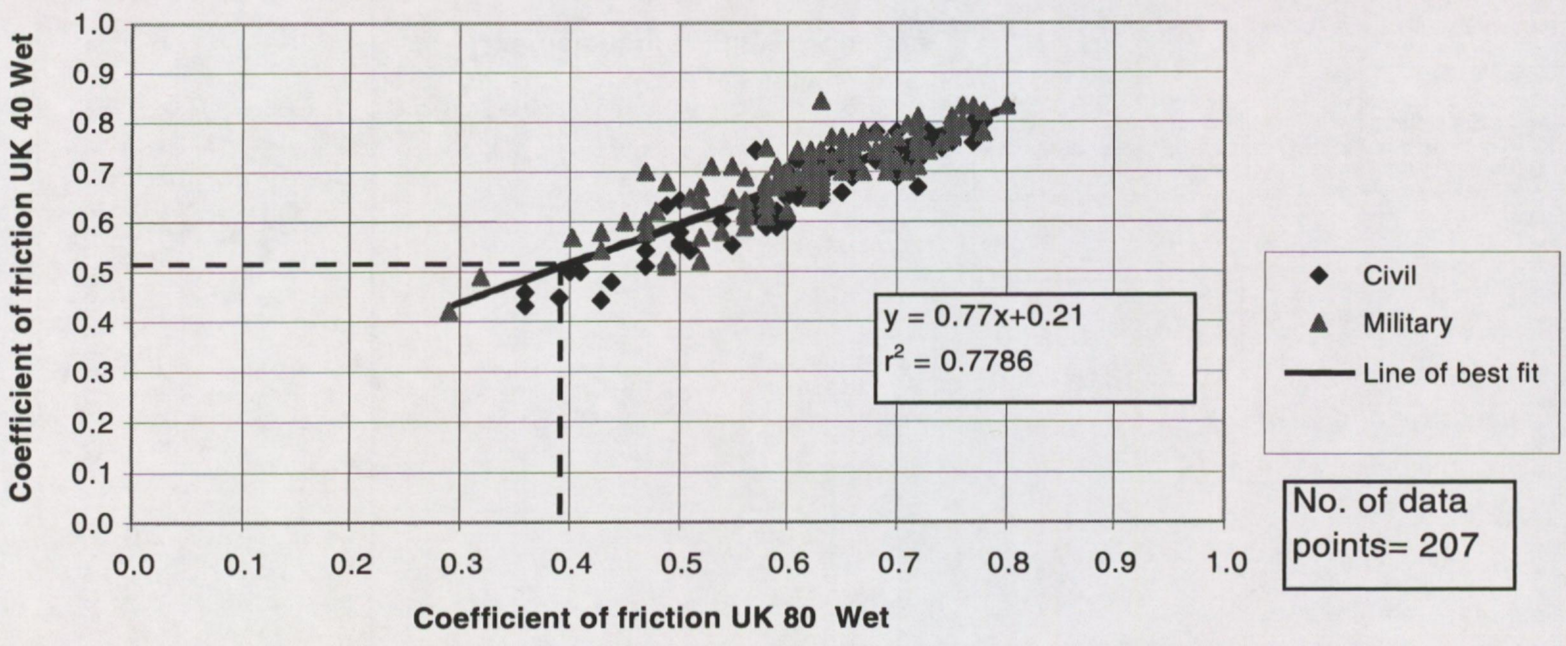
It was further decided to leave the values for the Mu-Meter and GripTester at Maintenance Planning Level and Design Objective Level at the previously defined levels given in NOTAL 2/94. These are 0.57 and 0.72 respectively for the Mu-Meter and 0.63 and 0.80 respectively for the GripTester.

It should be noted that these recommended values are entirely dependent on the quality of the data that have been analysed and could be subject to periodic review in the light of new information.

Appendix A

Data Analysis

Figure A: Correlation for all Surfaces: All Data



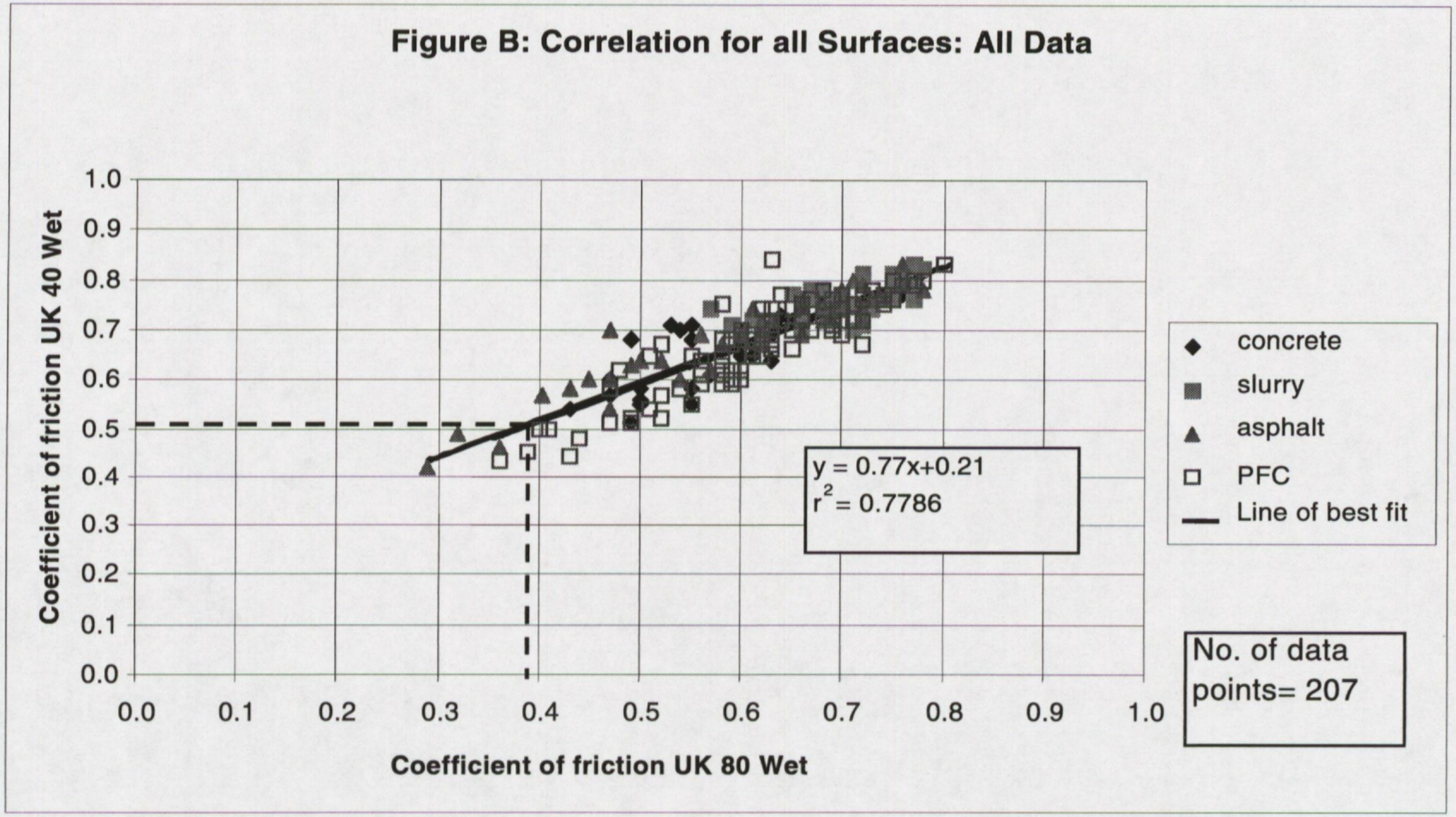


Figure B: Correlation for all Surfaces: All Data
Coefficient of friction UK 40 Wet
Coefficient of friction UK 80 Wet
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
y = 0.77x+0.21
r2 = 0.7786
concrete
slurry
asphalt
PFC
Line of best fit
No. of data points= 207

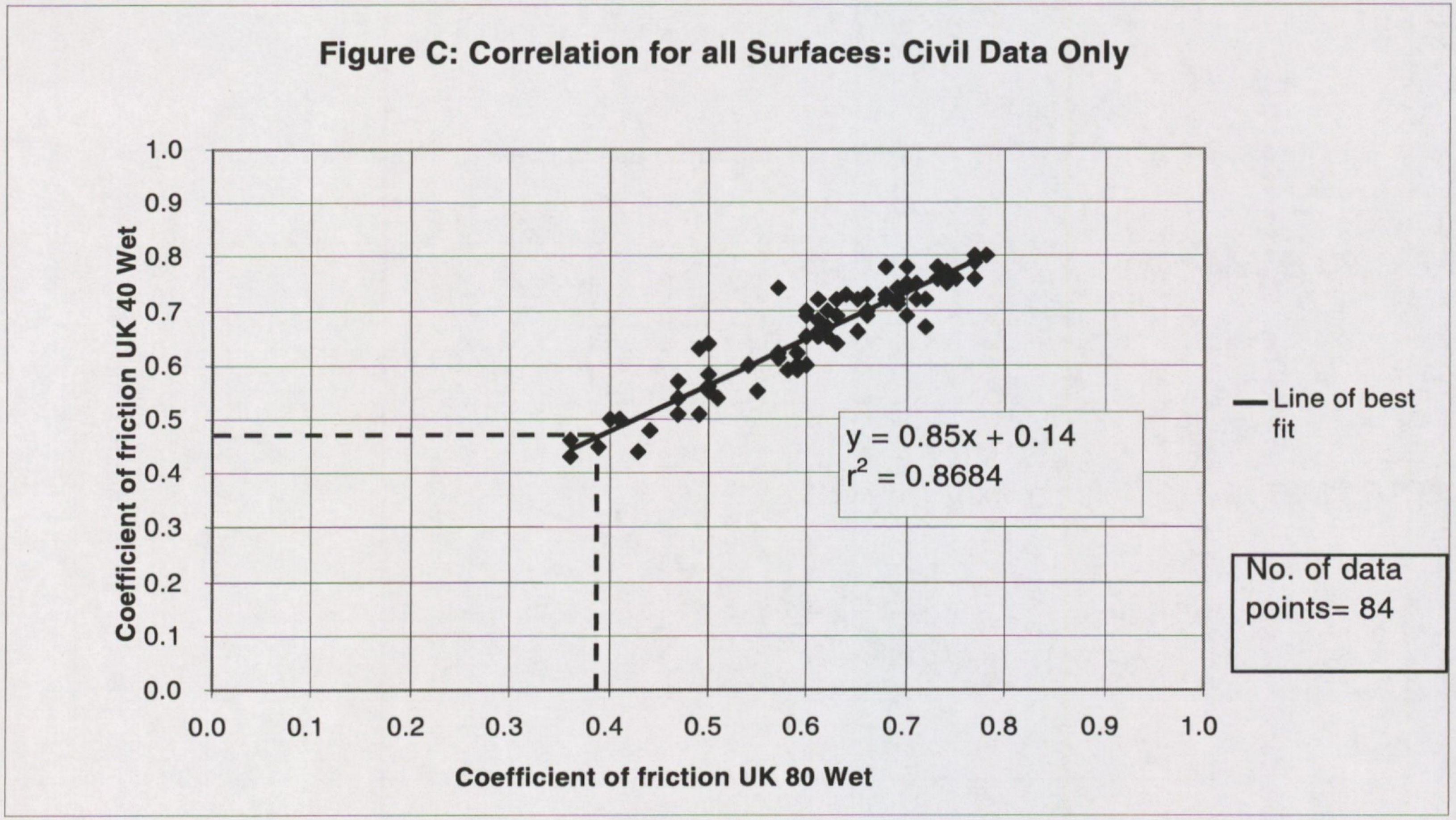


Figure C: Correlation for all Surfaces: Civil Data Only
Coefficient of friction UK 40 Wet
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
Coefficient of friction UK 80 Wet
y = 0.85x + 0.14
r2 = 0.8684
Line of best fit
No. of data points= 84

Figure D: Correlation for all Surfaces: Military Data Only

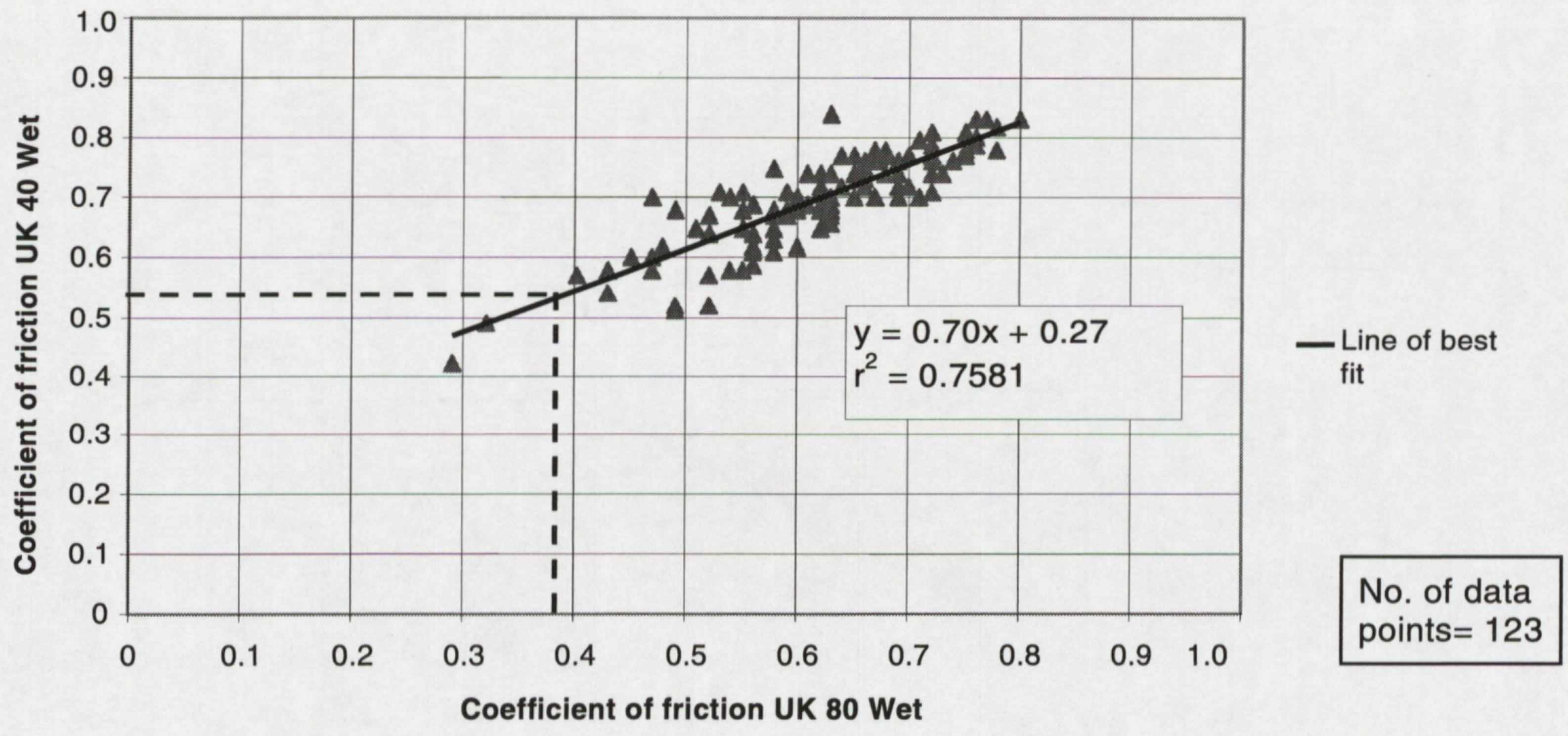


Figure E: Correlation for Concrete Surfaces: Civil Data Only

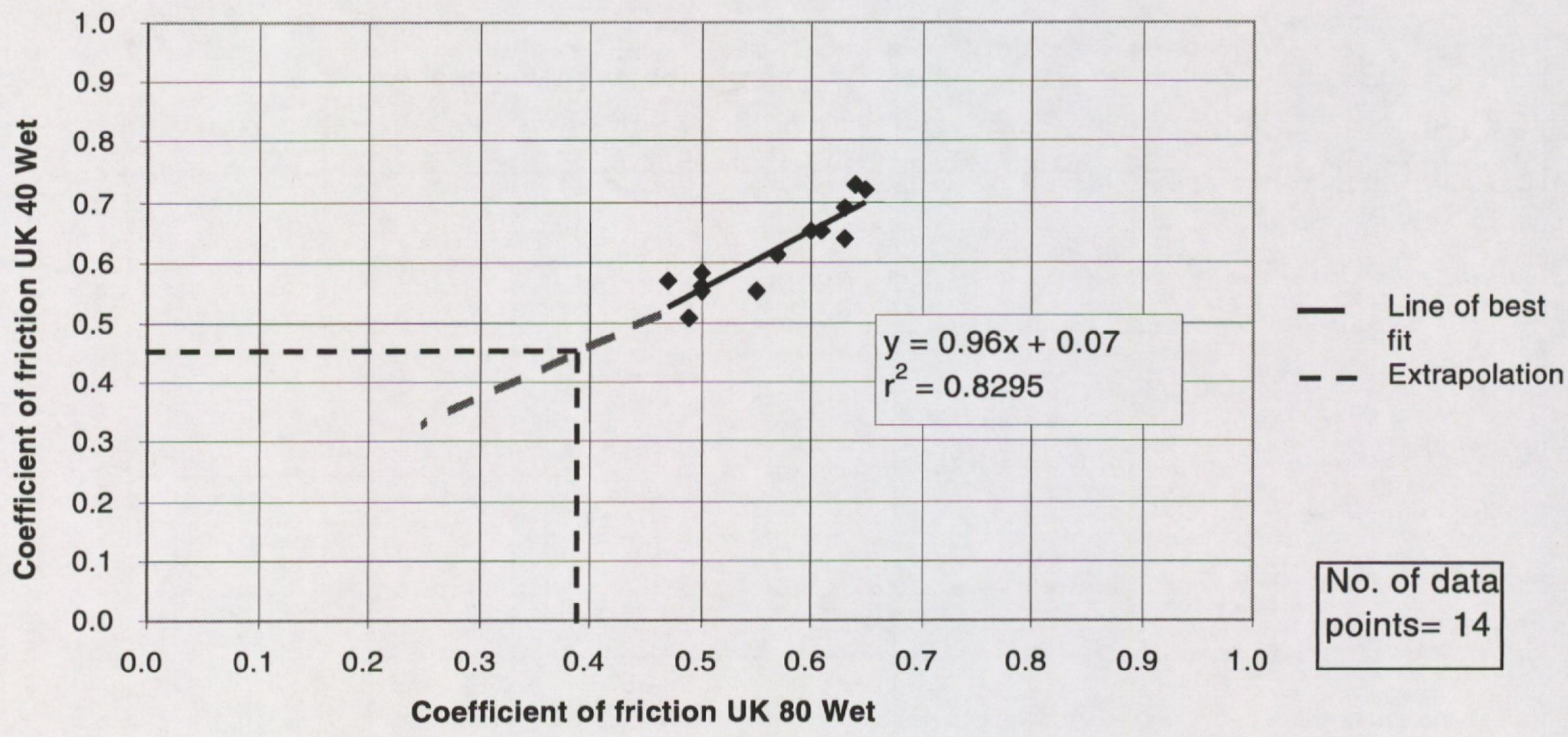
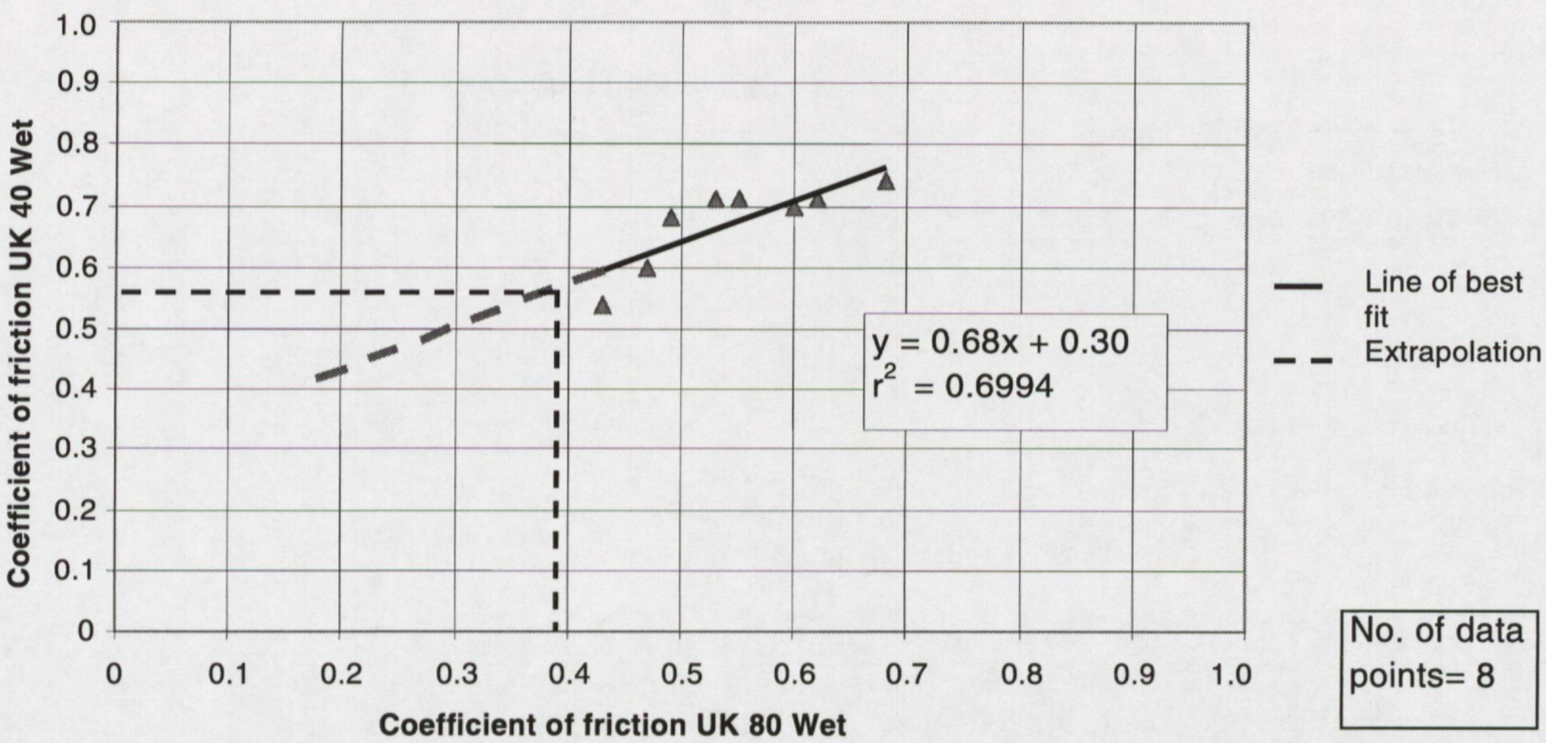


Figure F: Correlation for Concrete Surfaces: Military Data Only



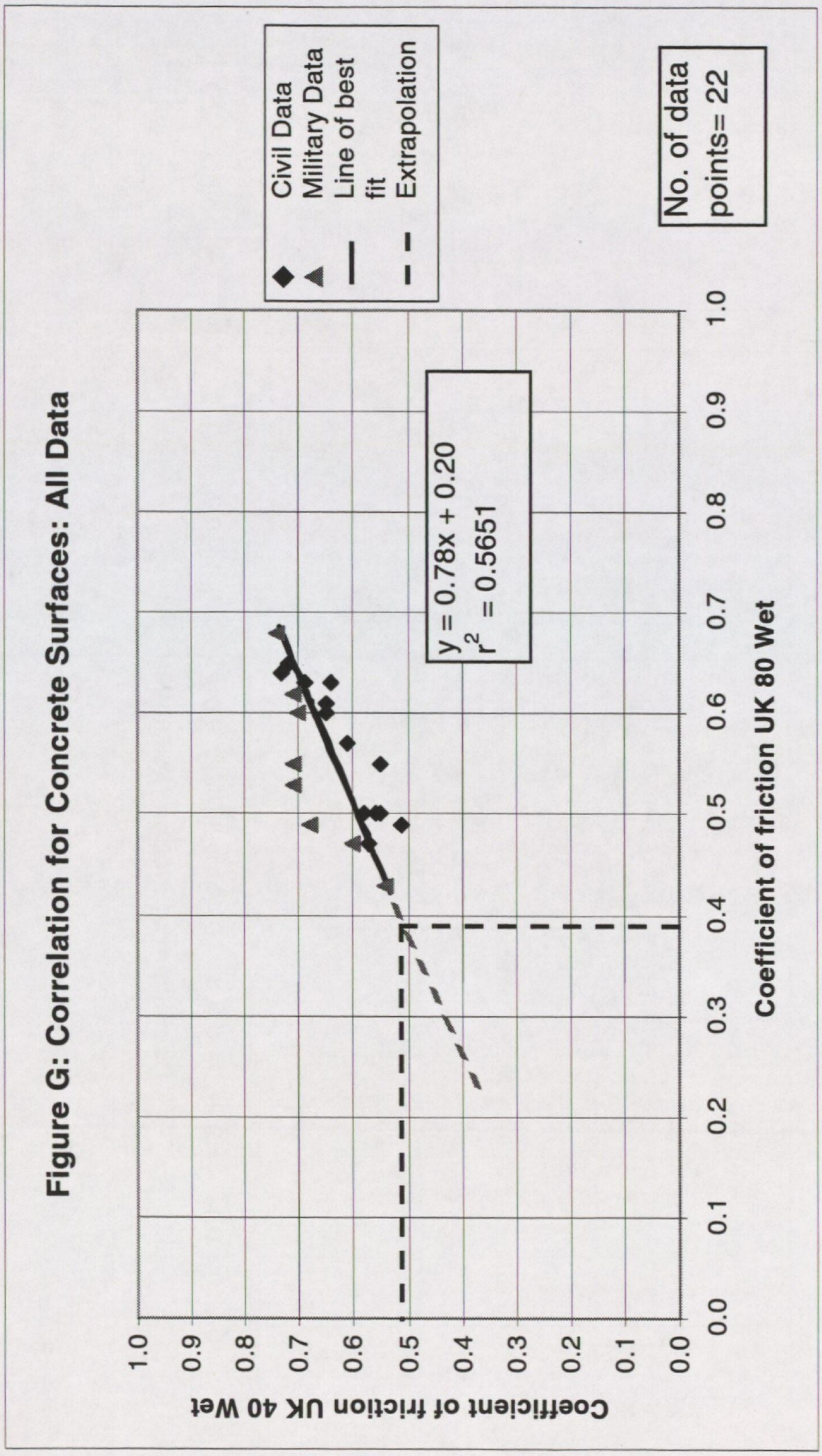


Figure G: Correlation for Concrete Surfaces: All Data

Figure H: Correlation for Slurry Surfaces: Civil Data Only

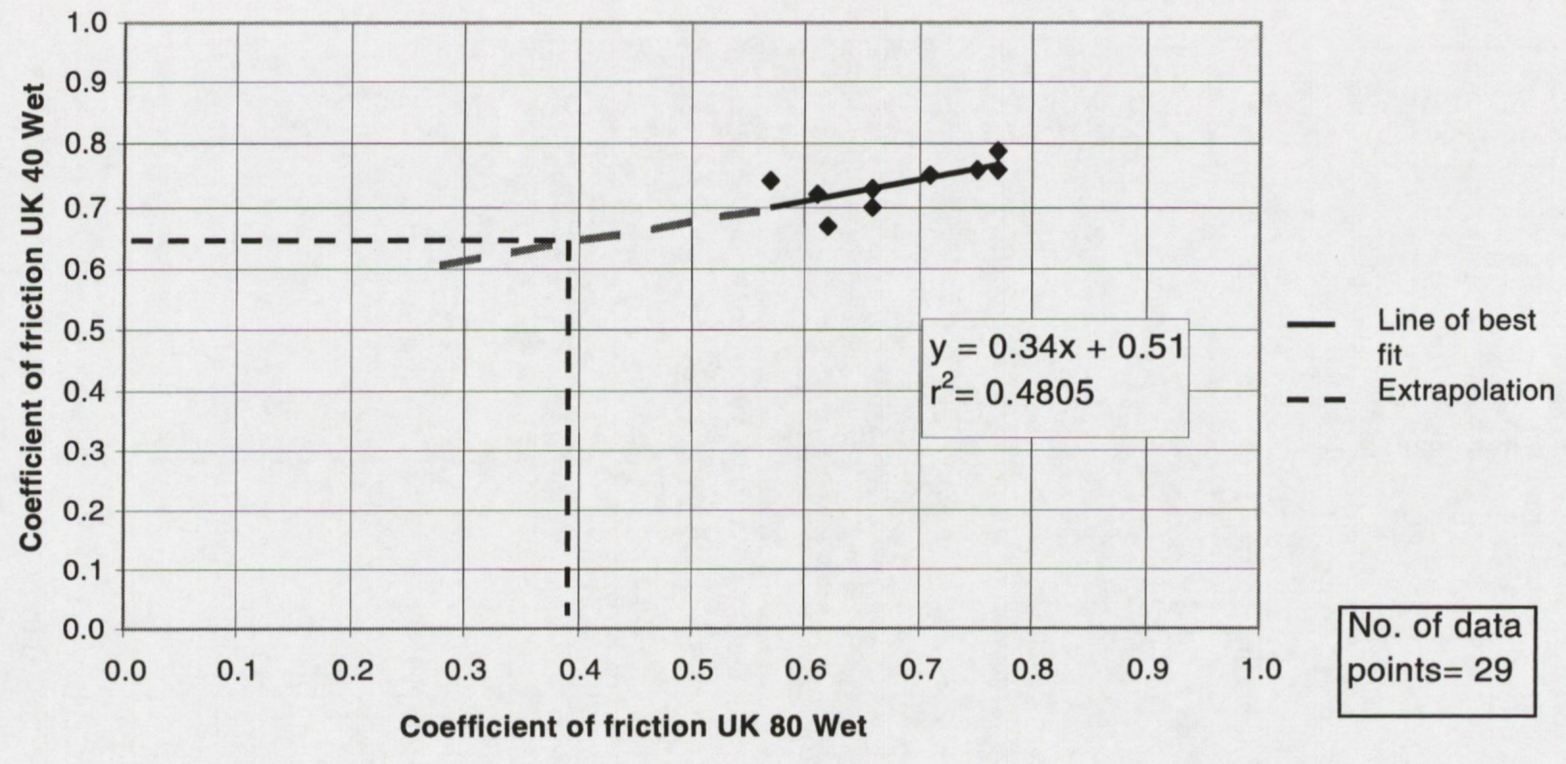


Figure I: Correlation for Slurry Surfaces: Military Data Only

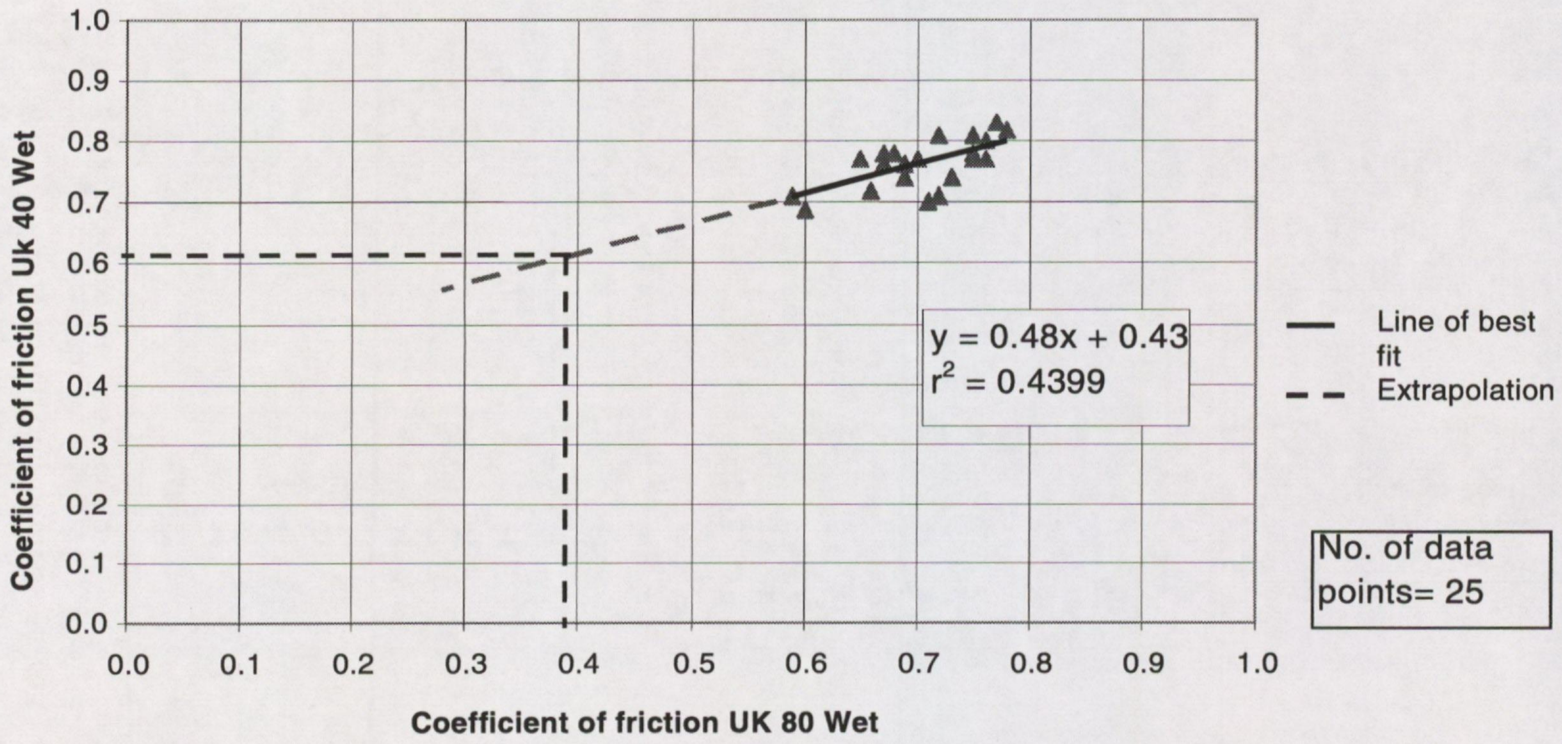


Figure J: Correlation for Slurry Surfaces: All Data

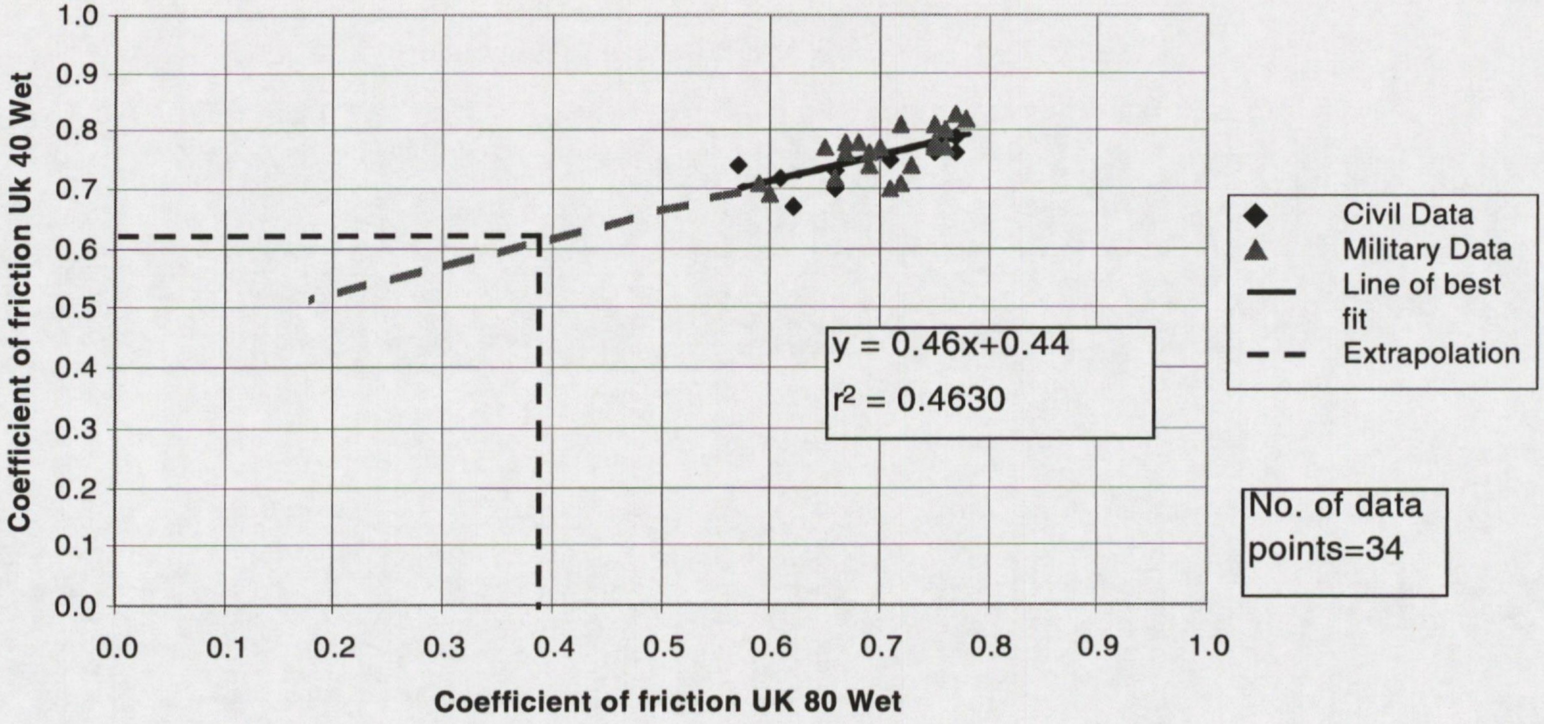


Figure K: Correlation for Grooved Asphalt Surfaces: Civil Data Only

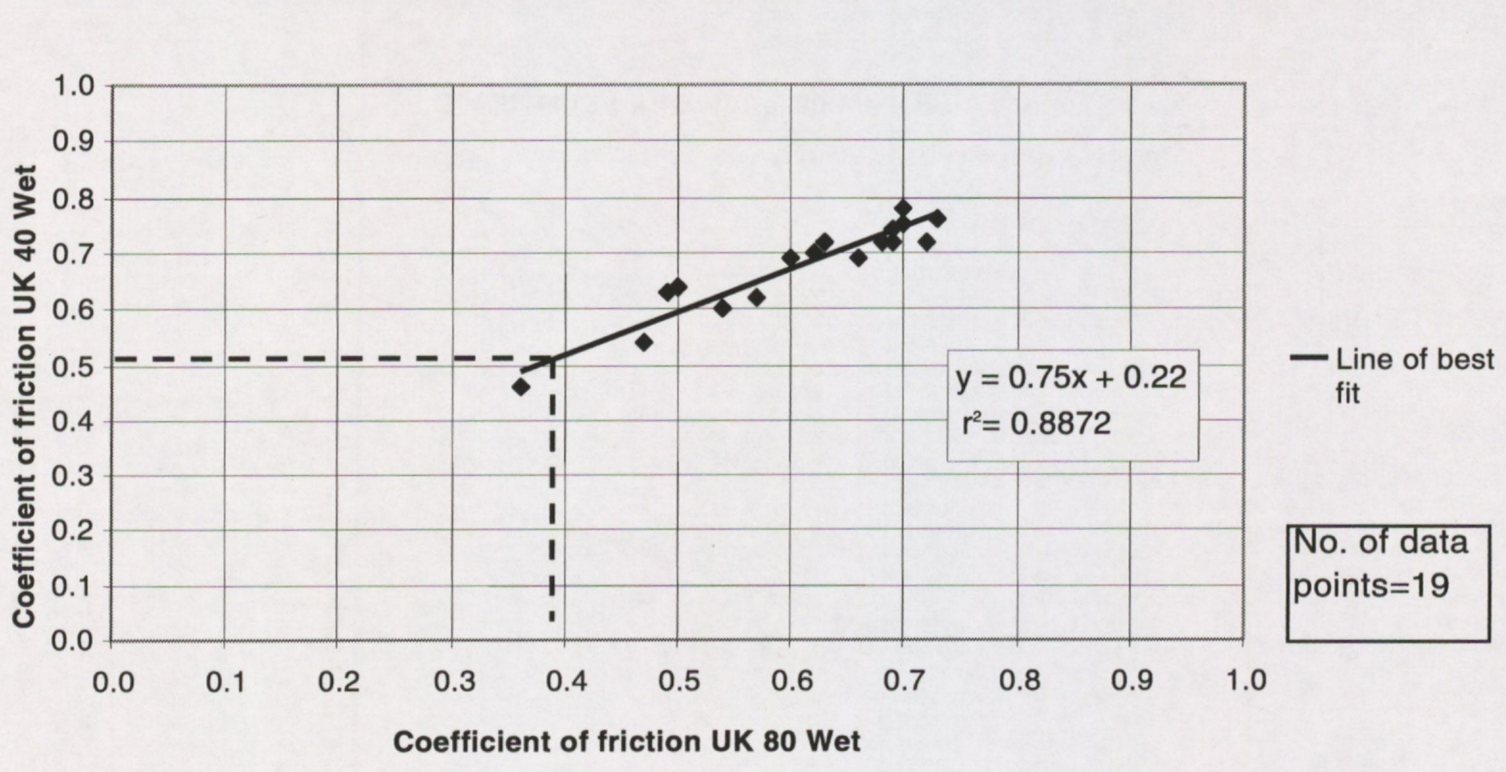


Figure L: Correlation for Grooved Asphalt Surfaces: Military Data Only

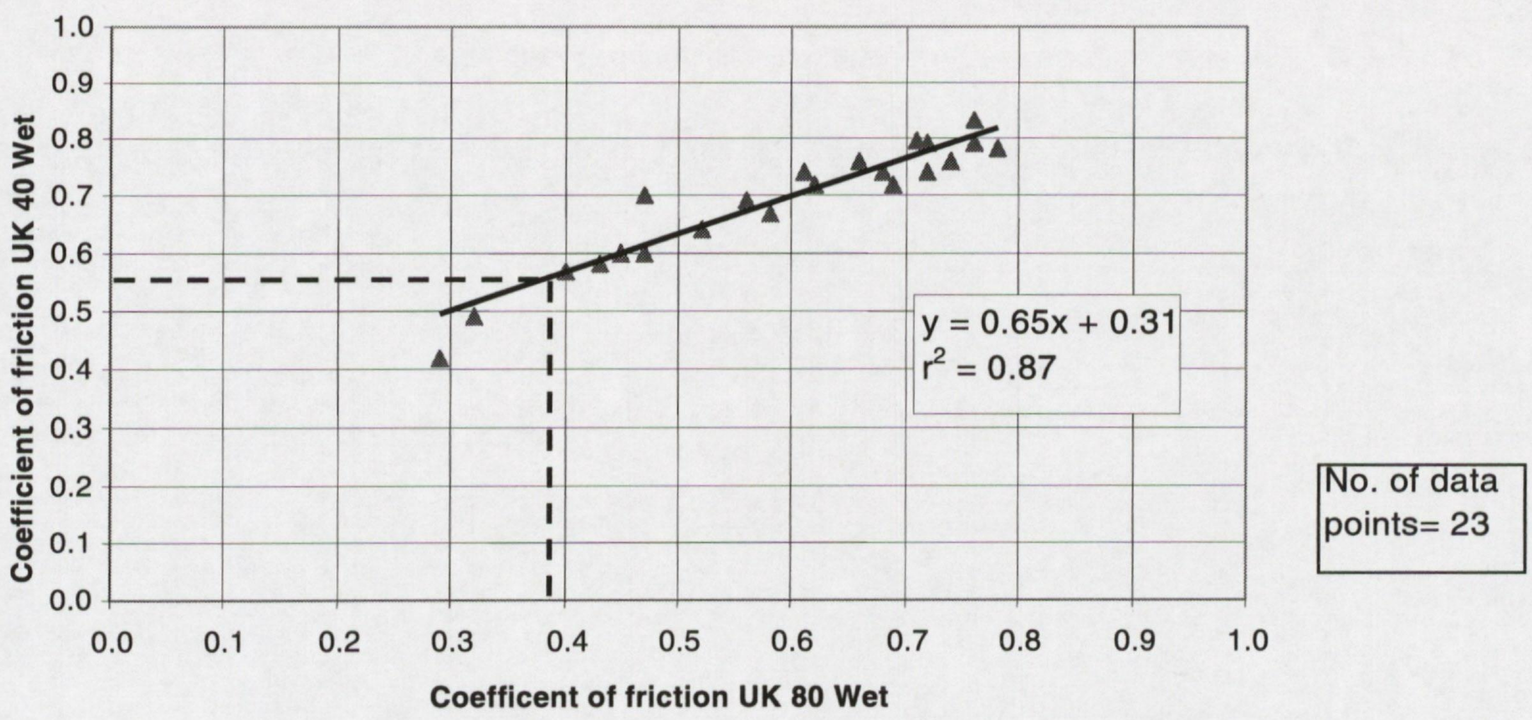


Figure M: Correlation for Grooved Asphalt Surfaces: All Data

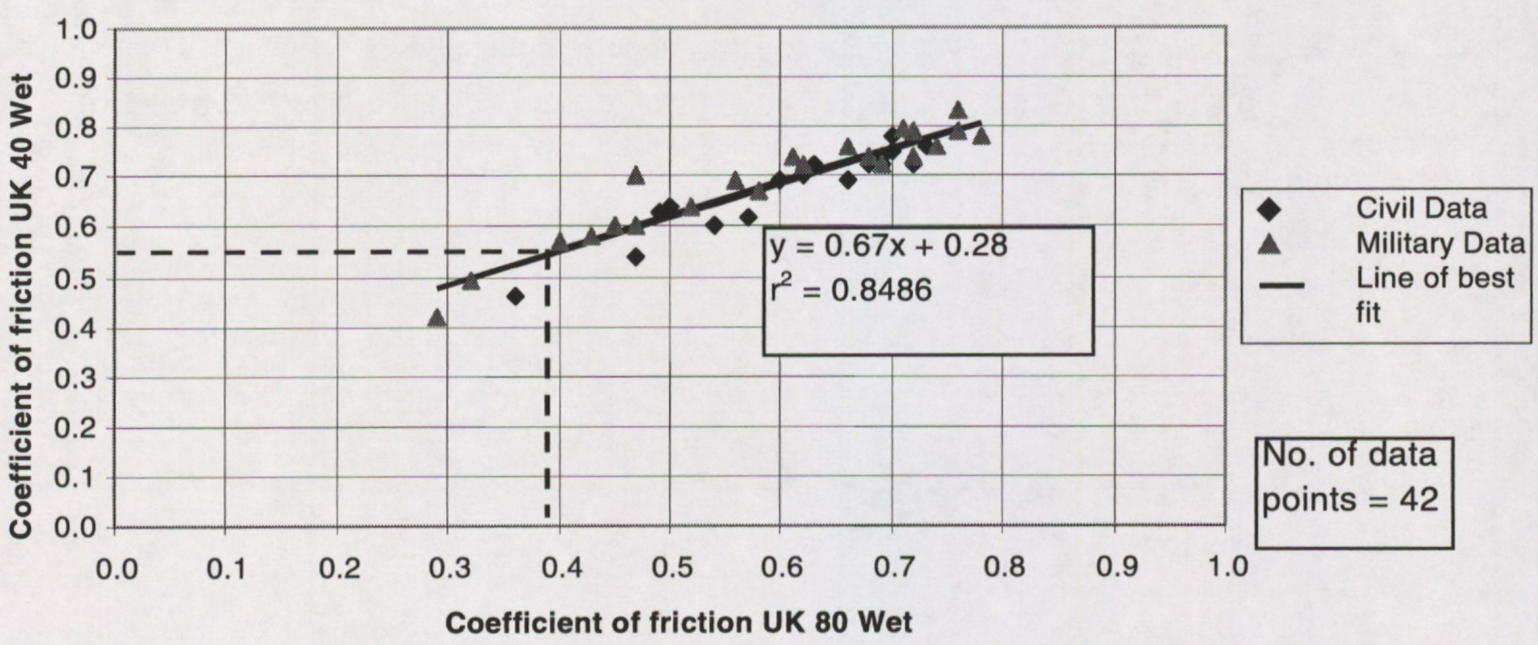


Figure N: Correlation for PFC Surfaces: Civil Data Only

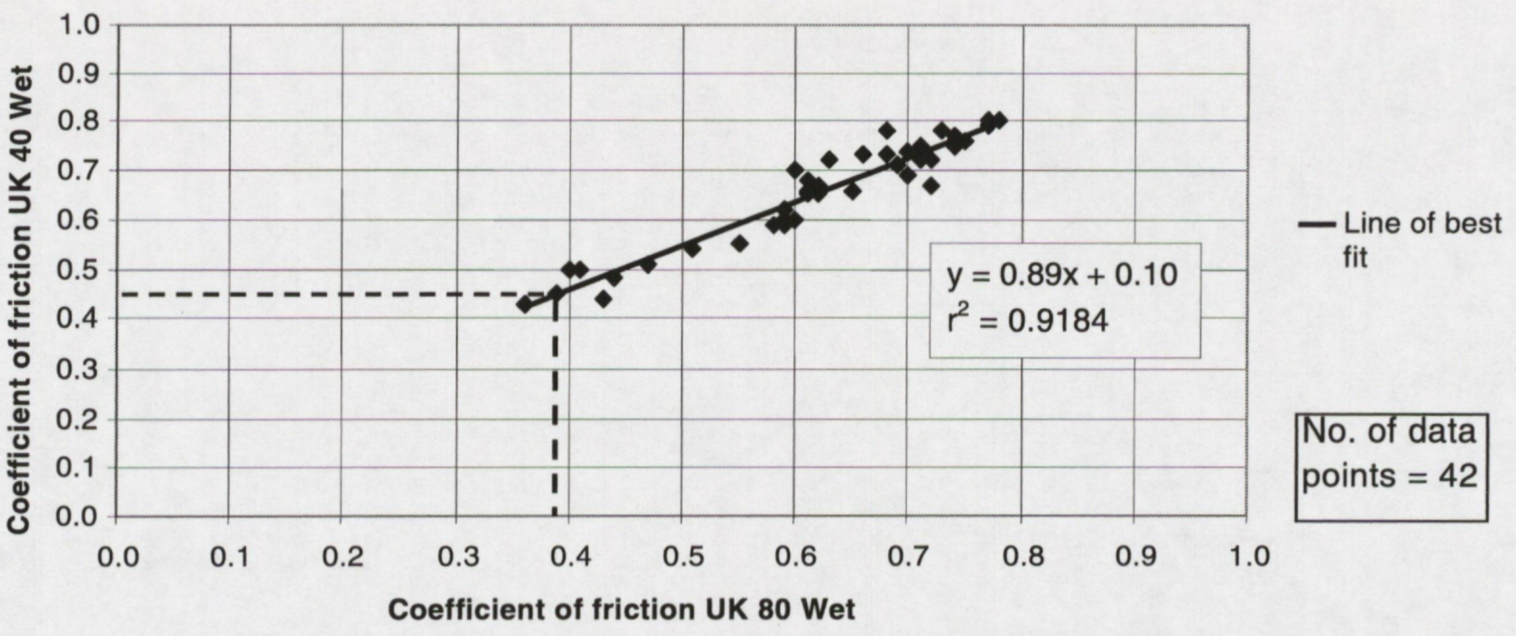
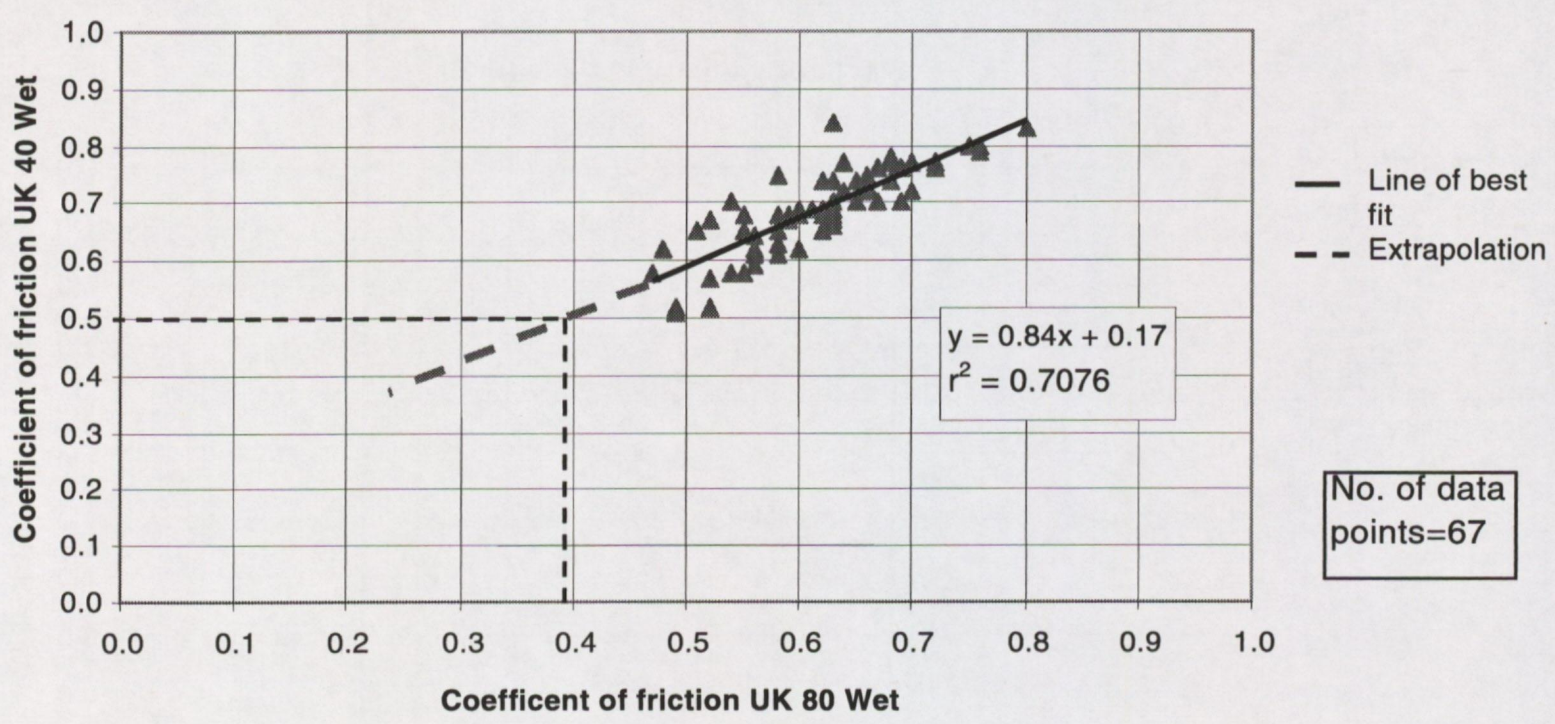


Figure O: Correlation for PFC Surfaces: Military Data Only



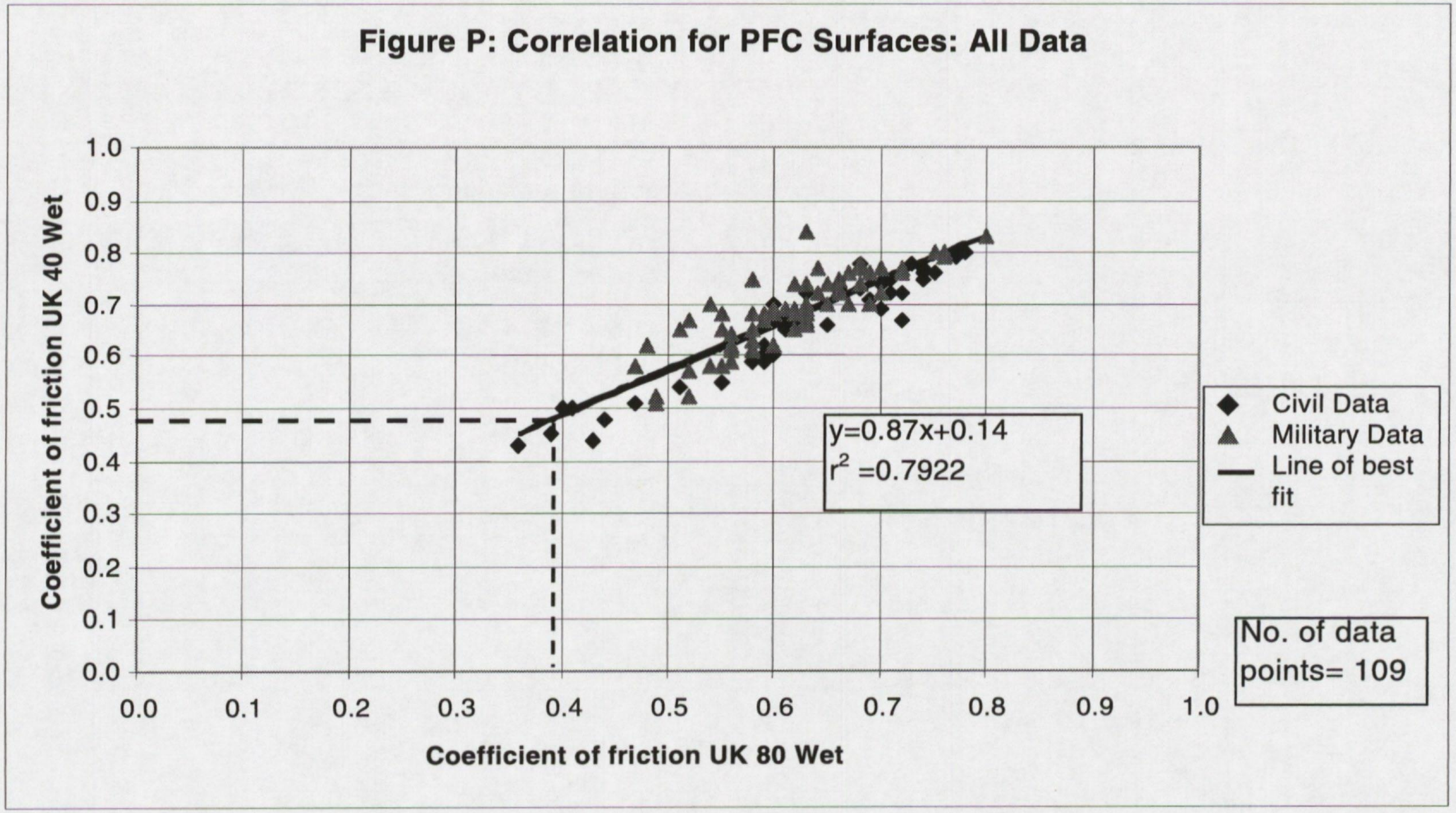


Figure P: Correlation for PFC Surfaces: All Data
Coefficient of friction UK 40 Wet
Coefficient of friction UK 80 Wet
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
y=0.87x+0.14
r2 =0.7922
Civil Data
Military Data
Line of best fit
No. of data points= 109

Figure Q: Correlation for Concrete, Slurry, and Grooved Asphalt Surfaces: Civil Data Only

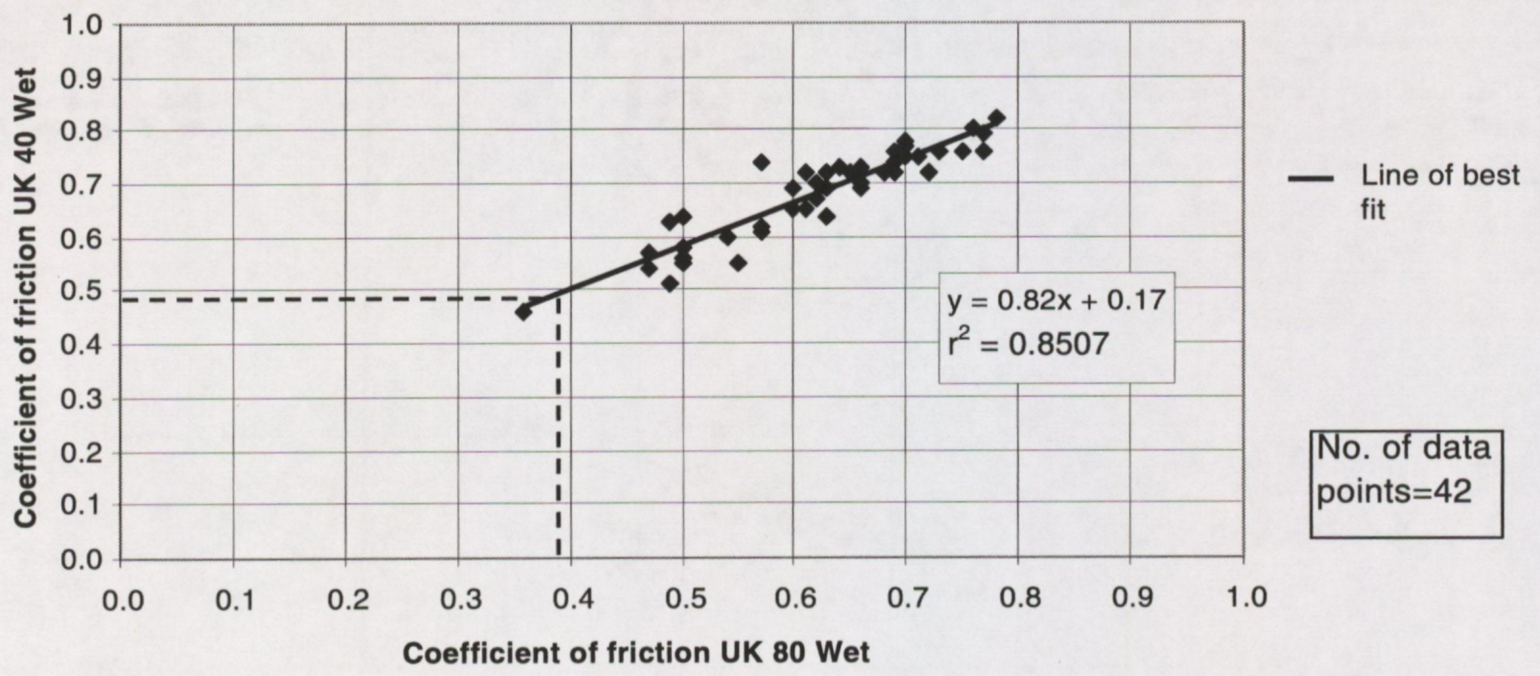


Figure R: Correlation for Concrete, Slurry and Grooved Asphalt Surfaces: Military Data Only

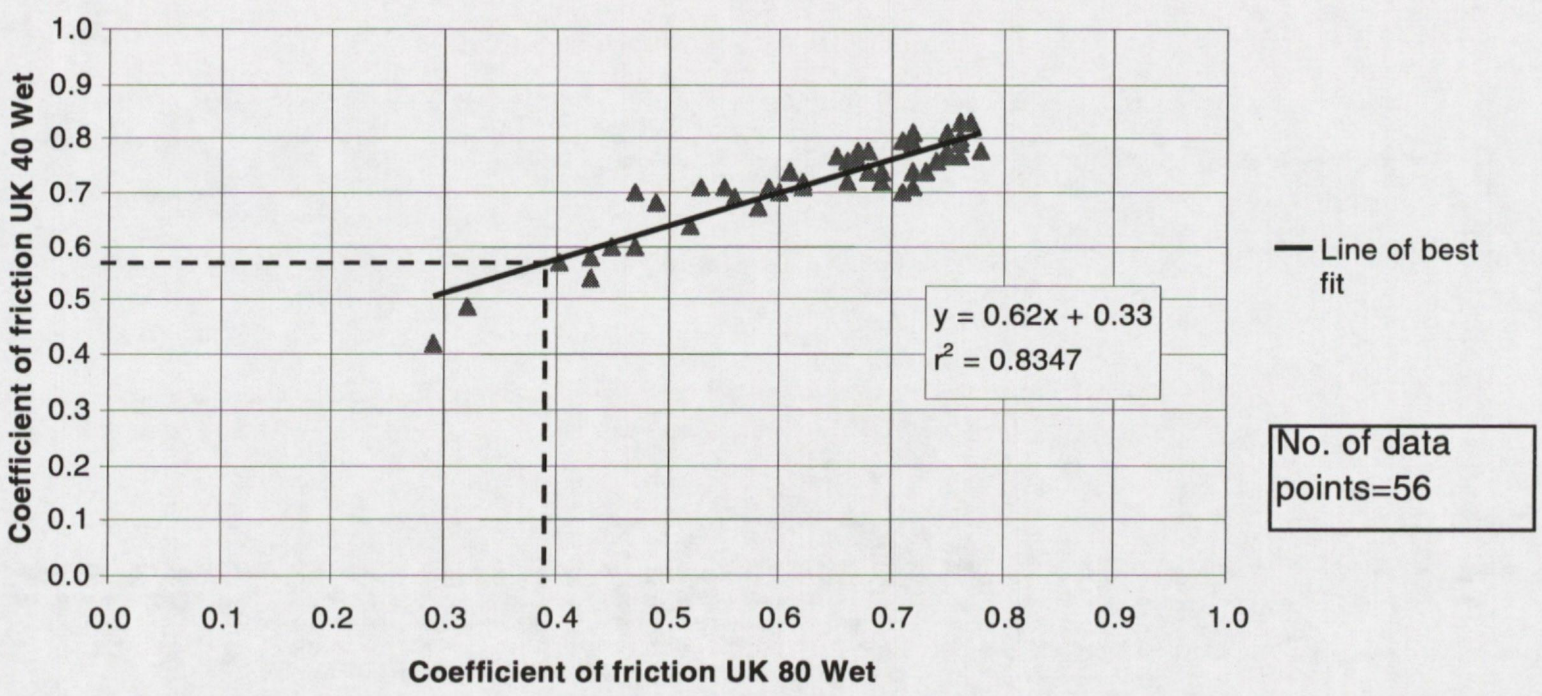


Figure S: Correlation for Concrete, Slurry and Grooved Asphalt Surfaces: Civil and Military Data

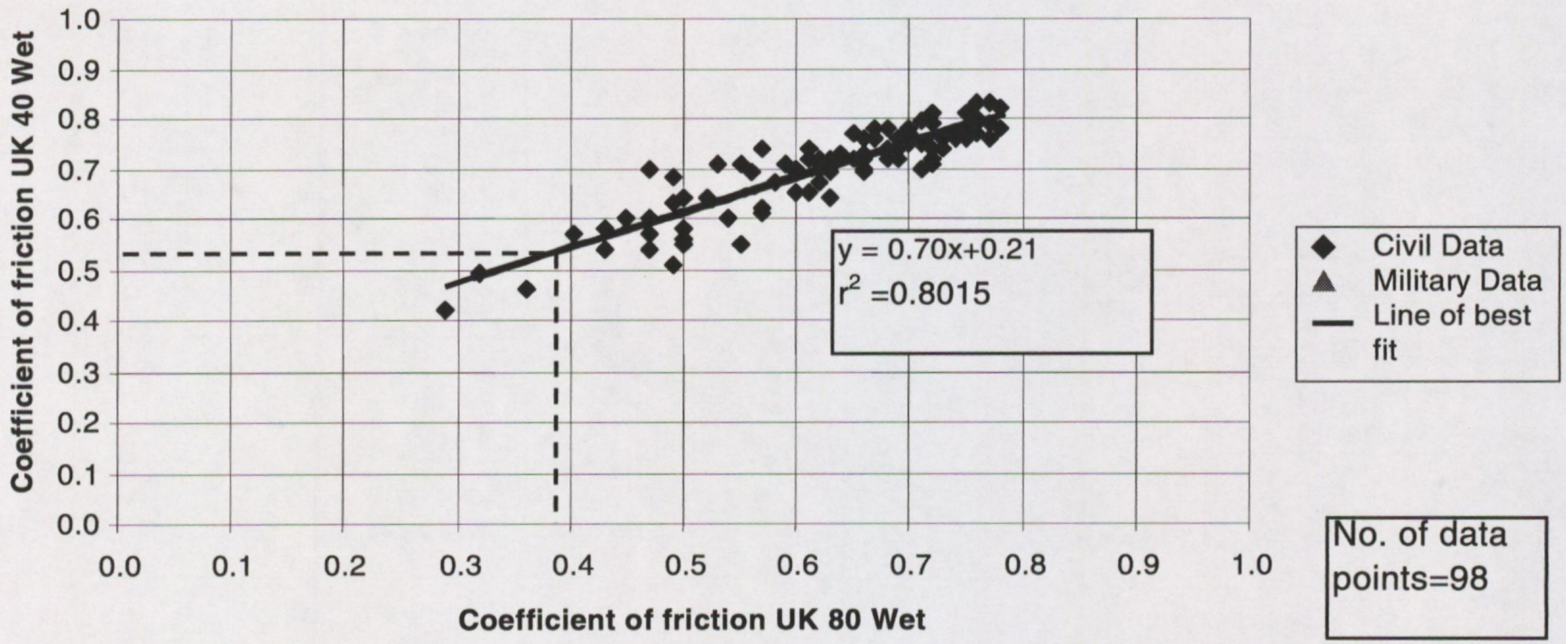


Figure T: Correlation for Concrete, Grooved Asphalt and PFC surfaces: Military and Civil Data

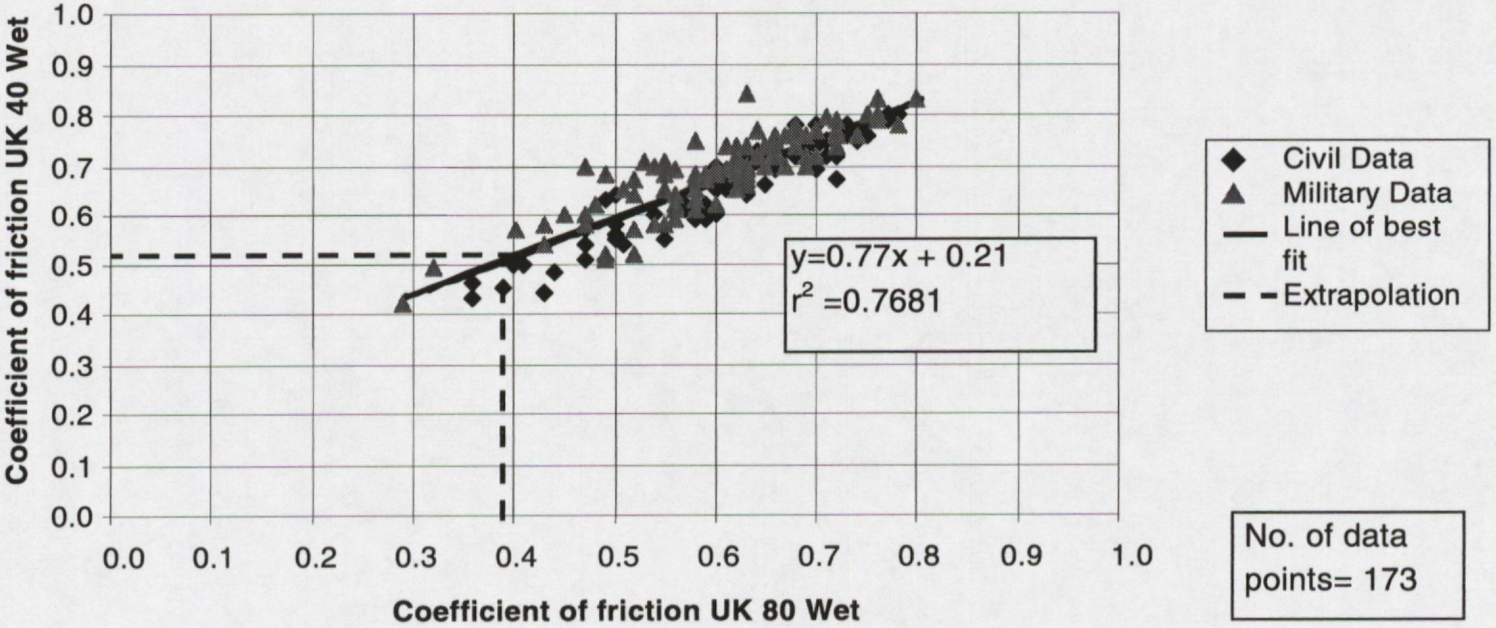


Figure U: Correlation for All Surfaces excluding Slurry Surfaces: Military Data

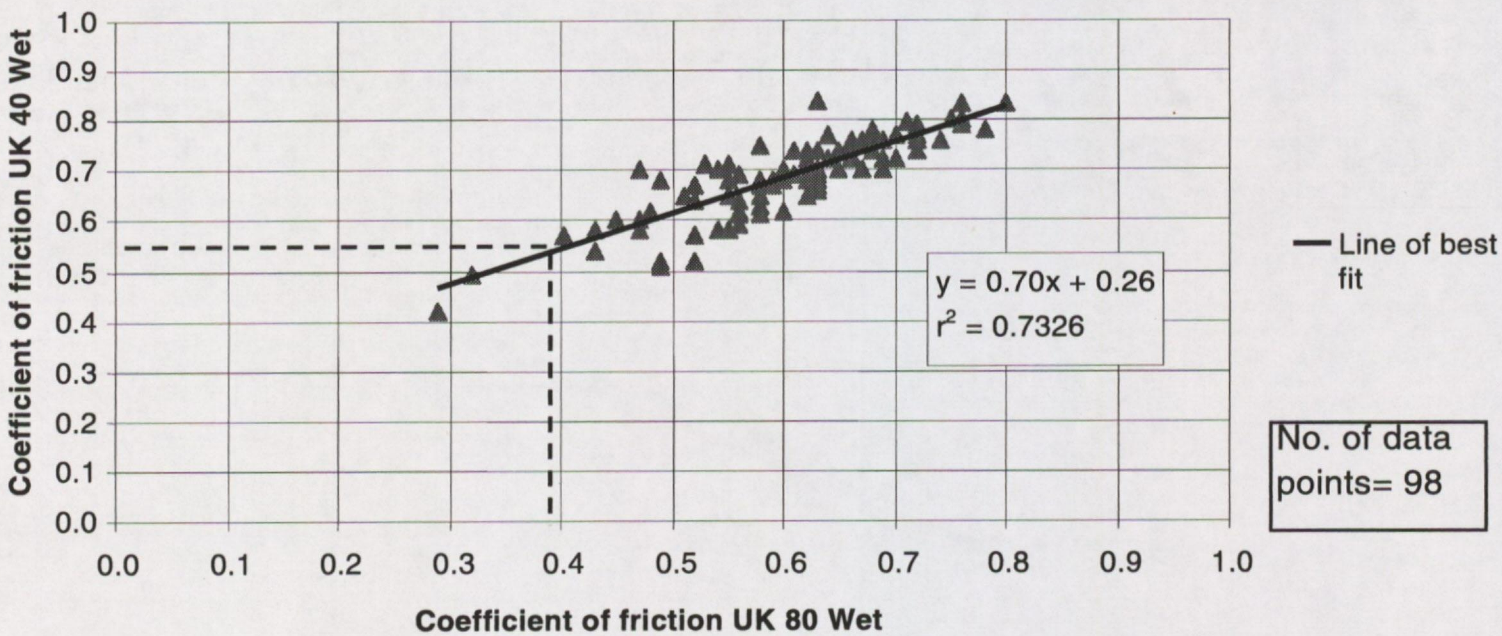


Figure V: Correlation for all Surfaces excluding Slurry Surfaces: Civil Data Only

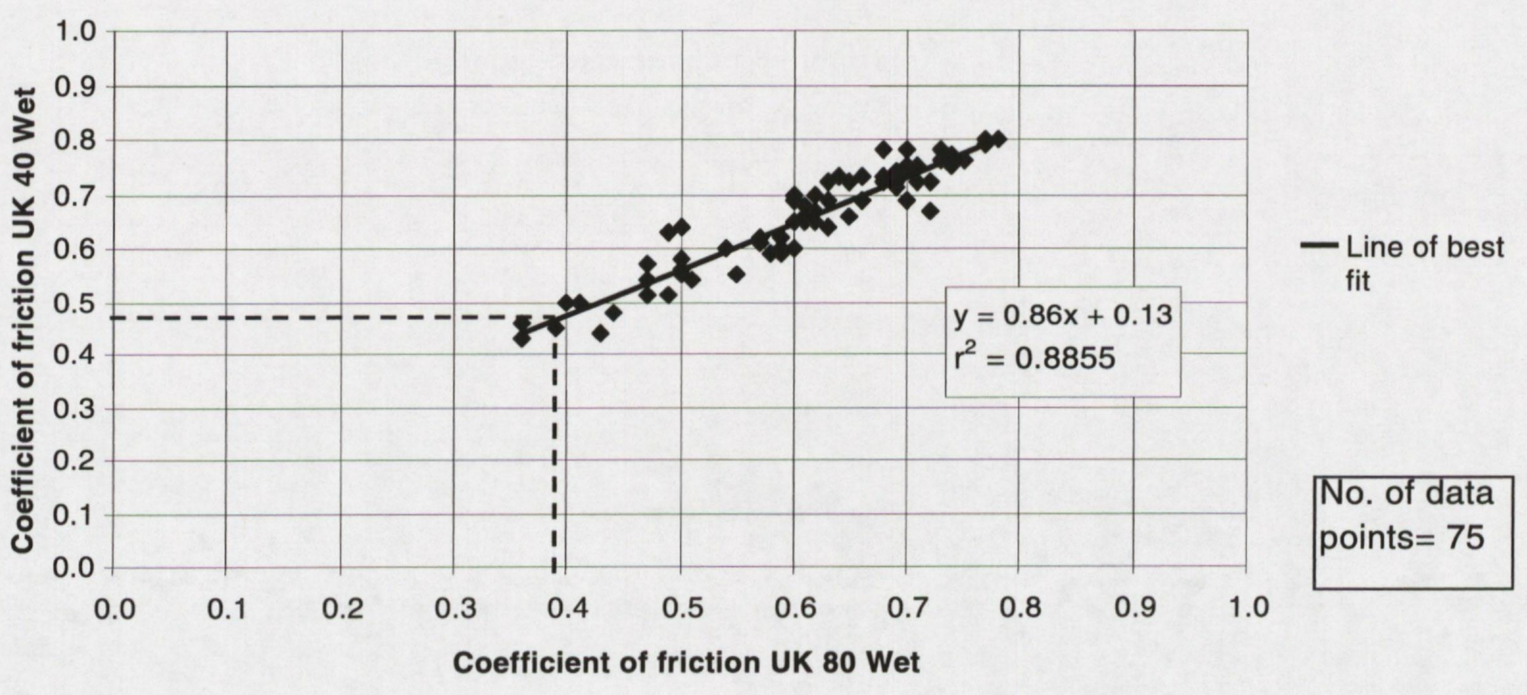
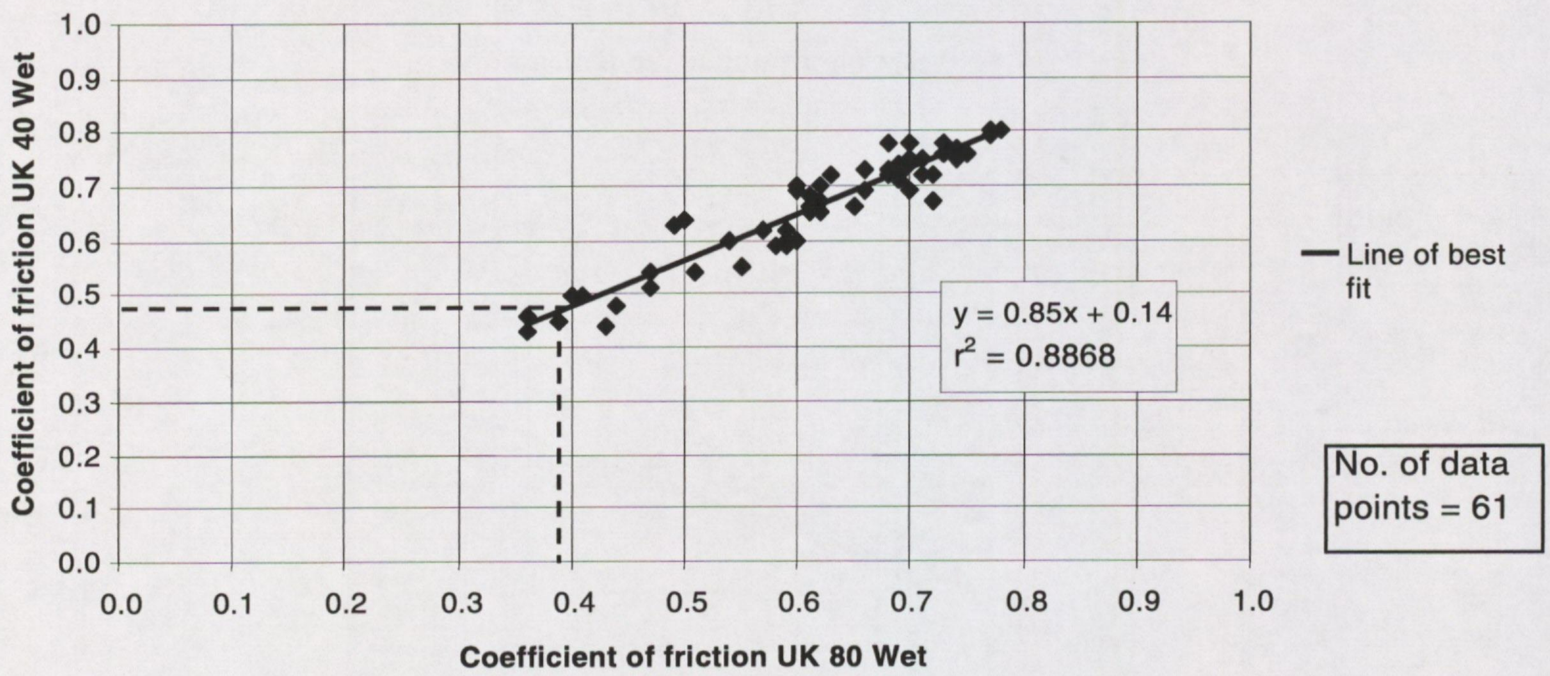


Figure X: Correlation for Grooved Asphalt and PFC: Civil Data Only



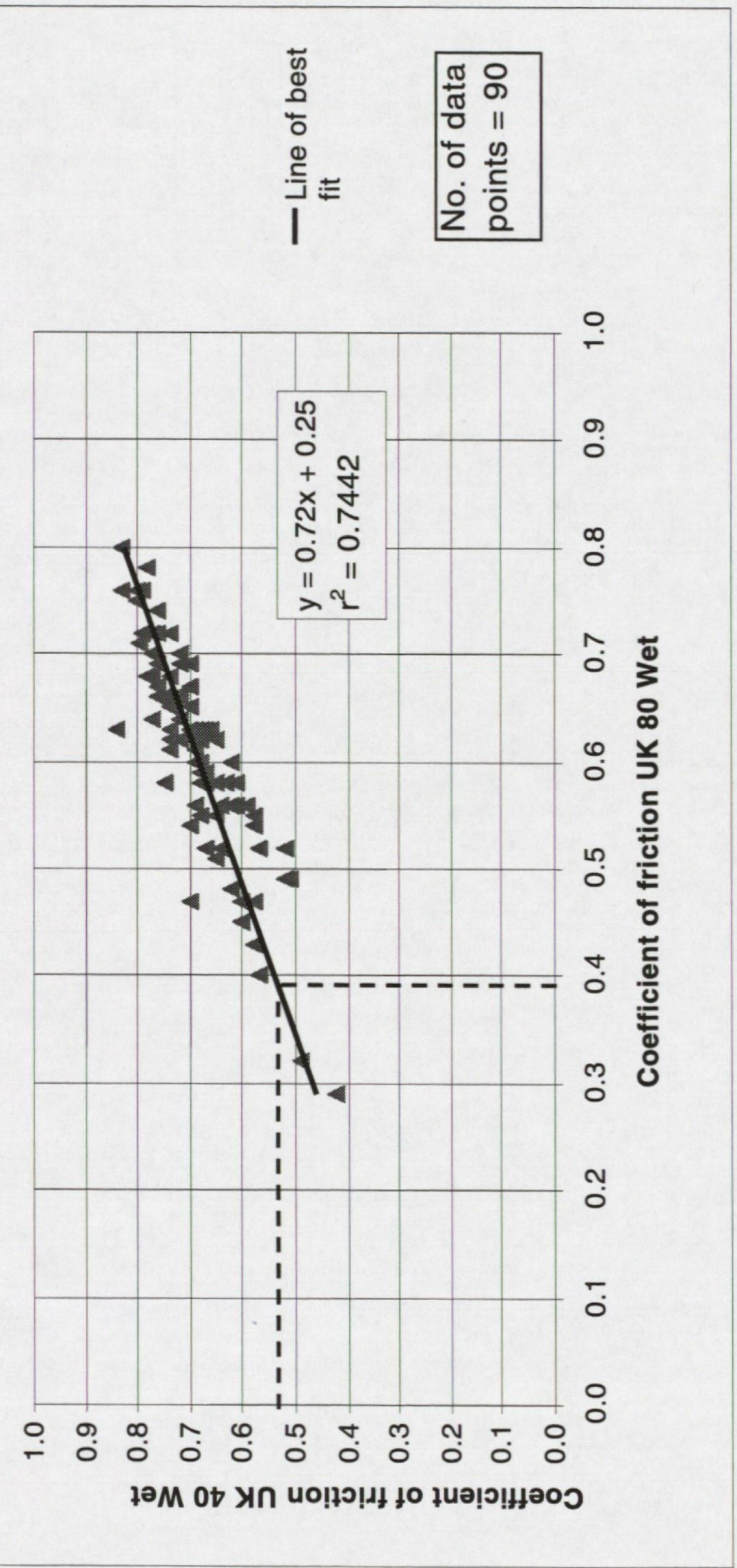


Figure Y: Correlation for Grooved Asphalt and PFC Surfaces: Military Data Only

Figure Z: Correlation for Grooved Asphalt and PFC Surfaces: Civil and Military Data