Granular and bituminous planings mixtures for capping

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Executive Summary

There are continuing pressures on DTLR to increase the usage of recycled materials and industrial by-products in road construction. One such area is in capping layers, where previous studies at TRL have led to the introduction of Class 6F3 covering the use of recycled bituminous planings and granulated asphalt into the Specification for Highway Works. This project has extended the previous studies to look at mixtures of planings with other recycled roadbase layers and granular materials. The key objectives of the project were:

- to maximise the use of bituminous planings by mixing them with unbound materials;
- to increase the compaction thickness for planings mixtures;
- to minimise the disposal of bituminous planings and other materials;
- to implement the findings by suggesting modifications to the current Specification for Highway Works;
- to provide data for the assessment of performance specifications for capping.

The project was carried out in two phases. Phase 1 covered the literature review into published works on the use of recycled bituminous planings, primarily in the UK, Europe and the USA. Also included were relevant data from previous TRL research projects for HA, relating to material specifications, compaction, settlement and creep properties for unbound bituminous planings. Discussions were held with HA regional geotechnical engineers, relevant local authorities, and consultants where planings mixtures have been used in road or other constructions, and the findings reported.

In Phase 2, laboratory trials were carried out on a range of bituminous planings and granular material mixes, designed to study the effects of varying the bitumen content on compaction and settlement. In addition to standard laboratory compaction testing, Rowe cell tests were used to study creep settlements over time, at relevant overburden pressures, on samples compacted to typical field densities as per SHW Class 6F3. Following the laboratory testing, limited pilot-scale trials were carried out on large samples compacted to representative densities, to enable the stiffness of typical mixtures to be measured *in situ* with a number of performance testing devices. Such devices are being evaluated for pavement foundation testing as part of a performance specification.

This is the final report of the project. Sections 1 and 2 provide a brief introduction and background to the work. The literature review is summarised in Section 3, whilst Sections 4 and 5 cover the laboratory testing and its application. The pilot scale trial is described in Section 6, followed by a discussion of the results and the main conclusions. These were:

- The literature review resulted in only a limited amount of data on the use of recycled bituminous planings, and no significant technical data on the use of bituminous planings and granular material mixtures. Discussions within the industry have shown that there is some experience of using blacktop and granular material blends successfully.
- Laboratory test data, generated from a comprehensive suite of standard compaction tests, particle size distributions, and compressibility testing using a Rowe cell, have been used to identify a lower bitumen content of 2% which enables mixtures containing bituminous planings to be classified into a new capping sub-class within SHW. An outline of the classification and compaction requirements for this proposed Class 6F4 is presented in the report.
- A pilot scale trial of certain mixtures used in the laboratory work was constructed and assessed using compaction and stiffness based methodologies. The benefits and disadvantages of each method are discussed: overall it is considered that a compaction based method is more applicable to the proposed Class 6F4 material.

The results of this project may be implemented by the inclusion of a new Class 6F4 material into the current Specification for Highway Works. This would allow mixtures of bituminous planings and granular materials having the same grading as Class 6F3, but with maximum bitumen contents of 2% to be compacted using the same method as for Class 6F3, but in layers up to 250mm thickness, rather than the 200mm limit imposed for Class 6F3. An outline of the proposed amendment is given in the report.

1 Introduction

There are continuing pressures on DTLR to increase the usage of recycled and industrial by-products in highway construction. This requires material specifications and site control procedures to be developed to ensure that satisfactory long-term performance of the pavement is achieved. Significant environmental benefits can also be achieved by reducing disruption to the local environment caused by taking highway waste to tips and opening borrow pits to excavate natural fills. Use of recycled materials reduces the pressure on natural materials, which are a scarce resource, and are better utilised in more demanding applications.

Whilst Class 6F3 (recycled asphalt planings and granulated asphalt) was introduced into the Specification for Highway Works, SHW (MCHW 1), primarily to cover the material acceptability requirements for planings only, it is highly probable that requests will arise from contractors to use planings mixed with other recycled roadbase layers and granular materials. Current advice would be to classify such materials as Class 6F3, which must be compacted in thinner layers when compared to Class 6F1 and 6F2 granular materials. This is required due to a reduction in compaction plant efficiency at depth on unbound layers incorporating materials containing bitumen. However, it may be possible that mixed materials could be adequately compacted in thicker layers, thus reducing construction costs. Also, it would allow planings to be mixed with other granular materials or industrial by-products, which would currently be deemed as unacceptable within the SHW, to provide an acceptable capping material.

Before any recommendation could be made to increase the compacted layer thickness, the effects of bitumen content on the performance of mixed materials would need to be ascertained. Therefore, the primary aim of this study was to determine the lower limit of bitumen content that influences the compaction and settlement of mixtures of recycled planings and granular materials. The findings from this research would permit the reclassification of such mixed materials, with bitumen contents below this new lower limit, from Class 6F3 to Class 6F1 or Class 6F2. The maximum compacted layer thickness specified for such mixtures would then increase from 200mm to 250mm.

2 Project background

The key objectives of this project to be addressed by the research were:

i to maximise the use of bituminous planings, by mixing them with unbound (recycled or natural) materials;

ii to increase the compaction thickness for planing mixtures;

iii to minimise the disposal of bituminous planings and other materials;

iv to implement the findings via modifications to the current SHW (MCHW 1);

v to provide data for the assessment of performance specifications for capping.

The project was carried out in two phases. Phase 1, as reported by MacNeil *et al*,. (1999), consisted of a literature review into published works on the use of recycled bituminous planings, primarily in the UK, Europe and the USA. Also included were relevant data from previous TRL research projects for the Highways Agency (HA), relating to material specifications, compaction, settlement and creep properties for unbound bituminous planings. Discussions were held with HA regional geotechnical engineers, relevant local authorities, and consultants where planings mixtures have been used in road or other constructions, and the findings reported.

In Phase 2, laboratory trials were carried out on a range of bituminous planings and granular material mixes, designed to study the effects of varying the bitumen content on compaction and settlement. In addition to standard laboratory compaction testing, Rowe cell tests were used to study creep settlements over time, at relevant overburden pressures, on samples compacted to typical field densities as per SHW Class 6F3. Following the laboratory testing, limited pilot-scale trials were carried out on large samples compacted to representative densities, to enable the stiffness of typical mixtures to be measured *in situ* with a number of performance testing devices. Such devices are being evaluated for pavement foundation testing as part of a performance specification.

3 Literature review

The initial strategy was to review the literature available at TRL, which encompasses unpublished TRL Project Reports, and published TRL Research and Contractor Reports. National standards, advice notes and guides, collated as part of previous TRL research, were also reviewed. The breadth of the review was then widened with the assistance of the TRL Library, and the International Road Research Database (IRRD) was searched to assist in the identification of other significant international references on the subject.

Despite reviewing a considerable body of information, only a limited amount of significant information relating to the use of recycled bituminous planings was identified (MacNeil *et al.*, 1999). With regard to the use of recycled planings mixed with other granular materials, no references with substantial technical information were identified. The main findings of the literature review are summarised in the following sections.

3.1 UK based work

In a comprehensive literature review, Ellis and Earland (1998) compiled existing information on the re-use of planings in sub-bases. The reported data were divided into three categories; existing work in the UK, overseas work, and health and safety aspects related to the re-use of planings.

In terms of pavement engineering, the existing UK research, predominately undertaken by TRL, has involved construction of trials and investigations of material characteristics. Individual construction trials have been reported by Chaddock and Earland (1992), Chaddock and

Coyle (1994), and Coyle (1995). These trials concluded that asphalt planings could perform similarly to Type 1 sub-base. The conclusions from this research formed the basis of a draft specification for the use of asphaltic planings as Type 4 sub-base material, and the draft specification was first trialed in August 1998 (MacNeil *et al.*, 1998). Significantly, the recycled planings used in this trial failed to meet the performance criteria, as revealed via a trafficking trial, due to poor mechanical interlocking of the gravel within the planings. Further development and trialing of the draft specification is to be undertaken by TRL.

The use of alternative materials, including recycled bituminous planings, in haunch repairs to county roads has been reported by Earland (1995) and Potter (1996). The research, supported by the County Surveyors' Society (1997), confirmed that recycled planings performed as well as Type 1 control sections. The performance of recycled bituminous planings and granular material mixes was not investigated.

In terms of ground engineering, research into the use of recycled bituminous planings as capping material (Toombs *et al*, 1994) concluded that planings could provide a suitable platform for pavement construction, providing the maximum compacted layer thickness was reduced from 250mm to 200mm; this work facilitated the inclusion of Class 6F3 in Table 6/1 of the SHW (MCHW 1). Steele and Snowdon (1995) reported that the performance of planings as capping layers was only marginally lower than that of Type 1 granular sub-base material.

An investigation into the use of recycled bituminous planings as Class 6N/6P structural fill yielded the most notable compilation of data on material properties and testing characteristics:

i Permeability testing (Brookes, 1995).

ii Shear strength testing (Steele, 1996).

iii Structural fill (MacNeil *et al.*, 1997).

iv Compressibility testing (Brookes and MacNeil, 1998).

This research culminated in the construction of a full-scale trial abutment, which was thoroughly tested for compliance during construction, and monitored for external settlement and internal settlement and displacements during construction and afterwards. The overall conclusion was that recycled bituminous planings can meet the majority of the SHW (MCHW 1) acceptability requirements for structural backfill. However, due to the occurrence of excessive settlements over long periods, the potential for differential settlements, the possibility of further settlement when a structure is loaded, and prolongation of the creep mechanism by the seasonal temperature cycle, bituminous planings were not recommended for use as structural backfill.

With regard to the use of recycled planings mixed with other granular materials, a follow up to an article in Highways (1995) resulted in discussions with Hyder Environmental Laboratories (ex Bucks County Council materials laboratory). As part of the reconstruction of the A41 Aylesbury Bypass, recycled bituminous planings and crushed concrete (dry lean-mix) were mixed to form a Class 6F1 capping material. Some data were available on optimum moisture content, maximum dry density and grading of the planings, the crushed concrete and the mixed material. The mix design consisted of one bucket of planings to one bucket of crushed concrete, i.e. a 50:50 by volume mixture; this probably halved the bituminous content from 5 - 7% (base and wearing courses) to about 3%, though no actual values were measured. This blended 'Class 6F1' was then placed and compacted to Method 6, in 150mm layers, although some layers were only 80mm thick (probably to accommodate the many services in this section of the road). Water was generally added at the time of mixing and topped up, during compaction on hot days, using the spray bars on the compactor. Some Clegg hammer values were recorded to identify soft areas, but no *in situ* densities or California Bearing Ratios (CBRs) were taken.

The reconstruction of the A41 provides a good example of effective use of a mixture of recycled bituminous planings and other waste materials, as it is performing well under heavy traffic. However, the available site control data are limited and, other than providing an indicator to the characteristics of the mixture, do not significantly assist in the determination of a lower limit of bituminous material that influences compaction and settlement.

The sub-contractor involved with the reconstruction of the A41, Kevin Oliphant Ltd (now Quest Devon Ltd), has considerable experience of using blacktop planings as Class 6F capping. The company has also used a blacktop planings and Type 1 mixture as a Type 1 material on the M6 (Penrith), blacktop planings and recycled granular materials on the M62, and blacktop planings and quarry scalpings on the M5. Discussion with the sub-contractor revealed that, for these applications, particle size distribution was considered the most significant material characteristic; the 'gap' at the bottom end of the Class 6F grading of the blacktop planings was filled using fine graded granular material. Once the gradings of the mix materials achieved the Type 1 grading, the mixed materials appeared to perform at least as well as Type 1. For the sites detailed, the reduction of bitumen content was not considered. This should not be regarded as significant, as the addition of fine graded granular materials will dilute the bitumen content of the blacktop planings.

With the focus on achieving a Type 1 grading, no significant compaction characteristic data are available for each of these blend materials. However, the sub-contractor did confirm that small volumes of water were added, prior to compaction, to assist with minimising air voids, and, due to the inability to predict a grading for a particular *in situ* blacktop and planer combination, trial blends were manufactured prior to reconstruction.

3.2 International work

Only a limited number of international references relating to the re-use of planings has been identified. In particular, at least sixteen States in the USA have used reclaimed asphalt pavement as an unbound aggregate; planings are described as frequently used waste material and have a proven in-service record (TRB, 1994). In Denmark, Danish Road Institute documents give guidelines, and material and construction specifications, for the use of crushed asphalt as unbound roadbase (Berg *et al.*, 1992 and 1994). In Switzerland, the national standards permit the use of unbound asphalt planings as a direct replacement for gravel sub-bases, providing the asphalt does not contain tar (Hirt, 1993).

3.3 Environmental considerations

Health concerns with asphalt and tarmacadam relate to the content of polycyclic aromatic hydrocarbons (PAHs, some of which are carcinogenic) and metals. Published research shows that a problem with leachates occurs only if tar is present in bituminous planings. As tar contains significant amounts of carcinogenic PAHs, the specification for Class 6F3 does not permit planings with any tar content.

Whilst tar is used in significant amounts in Europe, the level of tar used in pavement construction in the UK is believed to be minimal. The amount of tar bound pavement materials used since the mid-1970s on UK motorways and trunk roads is probably less than 0.1%, and should not therefore cause a pollution problem in the use of recycled planings (Toombs *et al.*, 1994). Because of their resistance to oil, small volumes of tar binders may still be used in paving vehicle lay-bys.

MacNeil *et al.* (1997) reported on the analysis of contaminants and PAH content of four sources of bituminous planings materials used in previous TRL research; the results show that the levels of PAHs and contaminants, apart from the slightly higher cadmium contents in two samples, fell well below the DOE Interdepartmental Committee for the Reclamation of Contaminated Land (ICRCL, 1987) threshold trigger concentration values and, therefore, should not present a contaminant problem. Further references regarding methods for the analysis of impurities in planings are presented by Ellis and Earland (1998).

4 Laboratory trials

4.1 Background to laboratory trials

The laboratory trials were undertaken on a range of bituminous planings and granular mixtures, designed to investigate the effects of varying the effective bitumen content on compaction and settlement characteristics. In order to reduce any potential problems associated with non-representative samples, bulk samples of recycled planings were sourced from four sites. This permitted a typical range of planings at different bituminous contents to be studied, thus enabling the effects of bitumen content on the mixed materials to be identified. Details of all the materials are presented in Table 1. Whilst all the granular materials used for the initial stage 1 mixtures were typical materials that would meet the suitability and acceptability requirements for SHW Class 6F1 or 6F2 capping, the non-bituminous granular additives used in the second stage of the testing were too fine to meet these grading requirements and could not therefore be used as capping on their own.

The initial stage of the laboratory trials involved assessing compaction and settlement performance across the bitumen content range of the four bituminous planings samples. The Class 6F2 control material was also used as the granular additive to the planings. The material mixtures initially investigated are detailed in Table 2.

The characteristics of the mixtures were assessed via standard BS1377 (BSI, 1990) laboratory compaction testing, namely:

i vibrating hammer compaction tests;

ii particle density tests;

iii particle size distributions, undertaken on air dried samples.

All the test mixtures were prepared on a weight basis and it was assumed for example that the bitumen content

Table 1 Materials

Material	*Code*	*Bitumen content (%)*	*Description*	*Source*
Class 6F2	6F2	na	Crushed limestone	Torr Work, near Shepton Mallett
Redlands	R	5.9	Planed wearing course, including a small component of base course. Course aggregate granite, fine aggregate sand.	Maintenance work at the junction of M25 and A404.
Pryors	P	4.2	Planed wearing course. Coarse aggregate granite and gravel, fine aggregate sand.	Improvement work on the M10.
Walblack	WB	5.4	Planed wearing course (fine).	Reconstruction work on the A404M near Maidenhead.
Walgrey	WG	5.6	Planed wearing course.	Reconstruction work on the A404M near Maidenhead.
Sand	S	na	Well graded sand.	TRL reference material.
Crushed brick	CB	na	Fletton crushed brick. (fresh bricks used to produce sample)	Hanson Recycling.
Quarry waste	QW	na	Granite dust.	Mountsorrel Quarry, Leicestershire.

Table 2 Granular materials and mixtures used in laboratory trials

	Mixture		
Materials	*Planings (%)*	*Granular (%)*	*Test ID*
Stage 1			
Class 6F2	–	100	1006F2
Redlands + Class 6F2	25	75	25R_756F2
	50	50	50R_506F2
	100	–	100R
Pryors + Class 6F2	25	75	25P_756F2
	50	50	50P_506F2
	100	–	100P
Walblack + Class 6F2	25	75	25WB_756F2
	50	50	50WB_506F2
	100	–	100WB
Walgrey + Class 6F2	25	75	25WG_756F2
	50	50	50WG_506F2
	100	–	100WG
Stage 2			
Walgrey + sand	25	75	25WG_75S
	50	50	50WG_50S
	100	–	100S
Walgrey + crushed brick	25	75	25WG_75CB
	50	50	50WG_50CB
	100	–	100CB
Walgrey + quarry waste	25	75	25WG_75QW
	50	50	50WG_50QW
	100	–	100QW

of a 50:50 mixture was 50% of that of the bituminous planings. The actual bitumen contents of the mixtures were confirmed by Surrey County Council Materials Laboratory at a later date, using bitumen content analysis undertaken on small samples in accordance with BS 598 (BSI, 1996).

Following laboratory compaction tests, samples were also prepared and tested for CBR and penetration resistance, in accordance with BS1377 (BSI, 1990) and the Dynamic Cone Penetrometer (DCP) instruction manual (Overseas Unit, 1986). These data were generated to enable laboratory scale relations to be established with any forthcoming performance requirements, in terms of strength, stiffness etc, for pavement foundations. Such data will be important, as previous research has shown that the current correlations between performance measuring devices do not apply to unbound materials containing bitumen (Toombs *et al.*, 1994).

Based on previous experience, it was considered that compressibility (creep) testing was the most reliable, and cost effective, laboratory based method of determining relative performance of bituminous planings materials; it was also likely that compressibility testing would effectively determine the relative performance of mixtures. Accordingly, settlement of the mixtures was assessed using a Rowe cell, as reported by Brookes and MacNeil (1998). The test samples were prepared by compacting to typical field densities, as per SHW requirements. Suitable overburden pressures were selected to reflect typical *in situ* capping conditions.

The second stage of laboratory testing investigated the performance of mixtures comprising bituminous planings and fine granular materials. The test regime was identical to that used for the stage 1 testing. The Walgrey planings were selected for use as the control material. The materials and mixtures investigated in stage 2 are detailed in Table 2.

4.2 Laboratory compaction testing

The most significant material properties for initial acceptability of the recycled bituminous planings were considered to be those in Class 6F3 of the Specification for Highway Works (MCHW 1) which relate directly to compaction, namely grading, bitumen content and moisture content.

Particle size distributions for the mixtures, undertaken following BS1377 (BSI, 1990) on air dried samples, are summarised in Table 3 and plotted in Figures 1a and 1b. All stage one mixtures, comprising the four bituminous planings and eight planings and Class 6F2 granular mixtures, met the Class 6F3 grading requirements, which are identical to the Class 6F2 grading requirements. The stage 2 mixtures, comprising bituminous planings and fine granular materials, all failed to meet the lower limits of the Class 6F3 grading requirements. The results of bitumen content analysis, to BS598: Part 102: Clause 5.2.5.2 (BSI, 1996), are presented in Table 3. All bitumen contents for the trial mixtures were below the upper limit of 10% specified for Class 6F3.

The results of the laboratory compaction tests, undertaken following BS1377: Part 4: Method 3.7 (vibrating hammer) (BSI, 1990), and particle density tests, are summarised in Table 4; test data and associated plots are presented in Appendix A. Previous experience had shown that measurements of moisture contents using the standard oven drying method (at 105°C) presented difficulties, as the low melting point of bitumen results in the loss of volatile constituents from the test sample. Consequently, the moisture contents of all the test samples were determined using a microwave oven on a low power setting for 20 to 30 minutes, as described by Toombs *et al.* (1994).

Many of the dry density versus moisture content plots do not exhibit the classical peak which enables a maximum dry density and associated optimum moisture content to be specified. This is often the case for bituminous planings (Toombs *et al.*, 1994; MacNeil *et al.,* 1997). Another factor which may contribute to the absence of the classical peak is that, for many of the materials and mixtures, the vibrating hammer test at the highest moisture content levels resulted in excess free water ponding on top of the sample, and therefore a representative moisture content proved difficult to measure reliably. In the absence of peaks, best fit straight lines have been used and the point at which the regression line intersects the 5% air voids line has been taken to be the optimum for that particular material or mixture. If 5% air voids was not attained, the intersection with the 10% air voids line was used.

Table 3 Particle size and bitumen content details

Materials	*Test ID*	*Coefficient of uniformity C_U*	*Effective particle size D_{10}*	*Median particle size D_{50}*	*Bitumen content (%)*
Stage 1					
Class 6F2	1006F2	60.0	0.20	9.0	–
Redlands + Class 6F2	25R_756F2	25.0	0.60	11.0	1.5
	50R_506F2	21.4	0.70	11.0	3.5
	100R	23.3	0.60	10.0	5.9
Pryors + Class 6F2	25P_756F2	20.0	0.70	11.0	1.0
	50P_506F2	20.0	0.60	9.5	2.6
	100P	17.8	0.90	11.0	4.2
Walblack + Class 6F2	25WB_756F2	20.0	0.65	11.0	1.5
	50WB_506F2	17.3	0.75	11.0	2.8
	100WB	12.0	1.00	10.0	5.4
Walgrey + Class 6F2	25WG_756F2	20.0	0.70	11.0	1.9
	50WG_506F2	18.6	0.70	10.0	2.7
	100WG	16.0	1.00	12.0	5.6
Stage 2					
Walgrey + sand	25WG_75S	10.9	0.35	2.2	1.5
	50WG_50S	36.7	0.30	6.0	2.7
	100S	na	na	0.4	–
Walgrey + crushed brick	25WG_75CB	17.6	0.17	2.0	1.4
	50WG_50CB	30.0	0.15	2.8	2.2
	100CB	20.0	0.10	1.5	–
Walgrey + quarry waste	25WG_75QW	18.8	0.08	1.0	1.4
	50WG_50QW	25.0	0.10	1.5	2.7
	100QW	18.6	0.07	0.9	–

Table 4 Compaction data summary table

Materials	*Test ID*	*Optimum moisture content (%)*	*Maximum dry density (Mg/m^3)*	*Particle density (Mg/m^3)*
Stage 1				
Class 6F2	1006F2	5.3	2.344	2.74
Redlands + Class 6F2	25R_756F2	5.0	2.050	2.68
	50R_506F2	7.0	2.053	2.55
	100R	6.9	1.968	2.42
Pryors + Class 6F2	25P_756F2	7.0	2.075	2.60
	50P_506F2	6.2	2.150	2.65
	100P	6.7	2.005	2.46
Walblack + Class 6F2	25WB_756F2	6.3	2.170	2.66
	50WB_506F2	5.3	2.020	2.61
	100WB	7.6	1.860	2.45
Walgrey + Class 6F2	25WG_756F2	5.5	2.100	2.68
	50WG_506F2	5.6	2.080	2.57
	100WG	5.6	1.870	2.42
Stage 2				
Walgrey + sand	25WG_75S	6.1	2.200	2.54
	50WG_50S	7.0	2.140	2.52
	100S	7.3	2.190	2.69
Walgrey + crushed brick	25WG_75CB	19.5	1.580	2.47
	50WG_50CB	16.5	1.710	2.53
	100CB	24.0	1.460	2.62
Walgrey + quarry waste	25WG_75QW	5.5	2.140	2.58
	50WG_50QW	5.0	2.120	2.50
	100QW	8.8	2.060	2.66

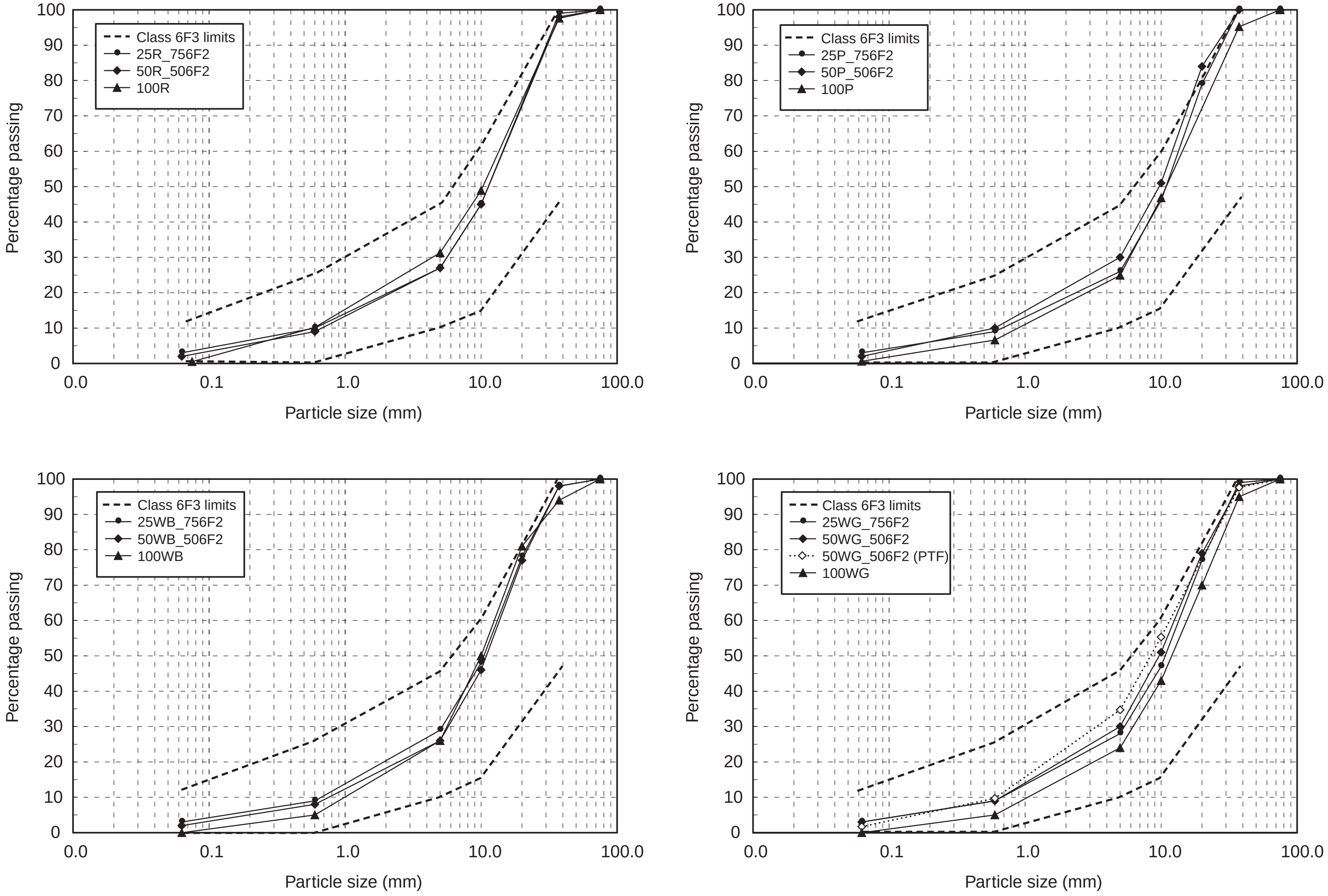

Figure 1a Particle size distributions

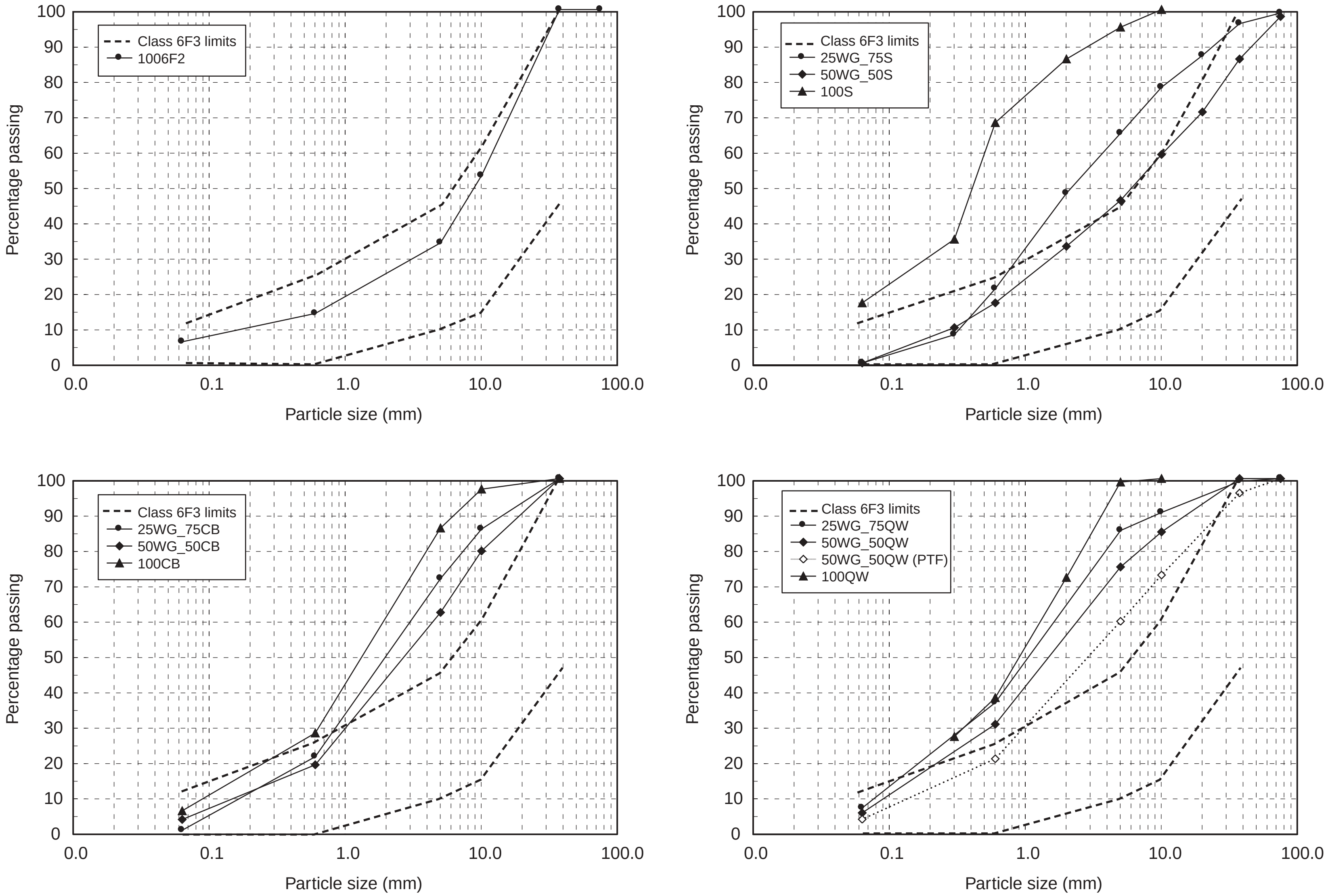

Figure 1b Particle size distributions

4.3 Laboratory strength testing

Laboratory California Bearing Ratio (CBR) tests were carried out to BS1377: Part 4: Method 3.7 (BSI, 1990); sample preparation was undertaken using the vibrating hammer compaction method. CBR tests were undertaken on all materials and mixtures at nominal relative compaction values of 85%, 95% and 105%. The relative compaction data are the dry densities of the test specimens expressed as percentages of the appropriate maximum dry density, determined using the appropriate laboratory compaction test (Parsons, 1992). This range of relative compaction encompasses poorly compacted material (85%), compaction typically to the current requirement (95%), and a value approaching the maximum achievable, i.e. refusal compaction, using standard laboratory compaction methods (105%).

Dynamic Cone Penetrometer (DCP) tests (Kleyn, 1975) were performed on the samples after CBR testing, with the cone of the DCP penetrating the indentation left by the CBR plunger following the CBR test carried out on the bottom surface of the sample. Both CBR and DCP tests were carried out on bituminous material passing the 20mm sieve as stipulated in BS1377 (1990).

CBR and DCP data are presented in Appendix A, and are summarised in Figures 2a and 2b. For comparative purposes, the standard Kleyn laboratory calibration line for granular materials, and the Toombs *et al.* (1994) laboratory calibration for bituminous planings at moisture contents of between 2 and 3%, are also plotted. Linear regression data for the calibration lines are presented in Table 5.

The DCP/CBR relation for the 100% planings is significantly different to the Kleyn relation for natural granular materials, but is close to the calibration line presented by Toombs *et al* (1994). The difference to the Kleyn relation can generate considerable variance in the estimation of CBR for planings via DCP testing. For example, a typical DCP value of 10mm/blow is equivalent to a CBR of 22% using the Kleyn line, and a CBR of 7.5% using the planings line. Whilst this appears to suggest that the 100% planings are not able to meet the 15% CBR typically required from capping, it must be remembered that bituminous planings behave differently to granular material under dynamic point load tests, such as the DCP. This is discussed by Toombs *et al*, (1994).

The DCP/CBR line for 50% planings and 50% other granular mixtures lies approximately half way between the 100% planings line and the Kleyn line. The calibration line for mixtures comprising 25% planings and 75% other granular materials coincides with the Kleyn line, and the DCP/CBR data for the 100% sand, crushed rock and quarry waste are broadly similar to the Kleyn line (see Figures 2a and 2b).

4.4 Rowe cell compressibility testing

Consolidation theory, normally applied to cohesive soils, is based on the principle that consolidation occurs as a result of the reduction of voids between soil particles, i.e. the soil particles are incompressible. Whilst the aggregates within recycled bituminous planings meet this requirement, bituminous binders are both plastic and compressible, and display temperature dependent behaviour. Consequently, the magnitude of consolidation and the time for consolidation to occur are significantly dependent on factors beyond the scope of consolidation theory. For this reason, the application of consolidation theory to these materials is not appropriate.

The laboratory investigation of settlement of the mixtures relied on compressibility testing, which simply links change in voids ratio with increasing overburden. As compressibility is not specified within the SHW, or within BS1377 for granular materials, testing was undertaken following the best practice described by Head (1986). The compressibility testing was undertaken using three large (254.4mm internal diameter) Rowe hydraulic cells, as shown in Figures 3a and 3b. The Rowe cell comprises a shallow, heavy gauge metal cylinder into which the test sample is compacted to about two-thirds depth. Load is then applied to the top of the sample by pressurized water or air acting on a rubber diaphragm attached to the top plate of the cell. The load is monitored by a pressure transducer mounted on the top plate, and settlement by a displacement transducer. All Rowe cell tests were undertaken in a laboratory maintained at a nominal temperature of 20°C by an air conditioning system.

As the median particle size, D_{50}, ranged between 0.9mm and 12.0mm for the test mixtures (see Table 3), resulting cell diameter to median particle size ratios ranged from 21.2 to 282.7. It was therefore considered appropriate to test the samples with the full range of particle sizes present, rather than to scalp of the larger particles.

Initial preparation involved conditioning the mixtures to appropriate moisture content levels, nominally selected as optimum moisture content minus 2%. Prior to testing, all samples were adjusted to the required moisture content and allowed to stand for several days in a sealed container to allow moisture to equilibrate. Prior to

Table 5 DCP/CBR calibration lines

Material	*Linear regression*	*Regression coefficient, R^2*
Granular (Kleyn, 1975)	Log CBR = 2.62 - 1.27 log (DCP)	–
100% non-bituminous granular materials	Log CBR = 2.95 - 1.50 log (DCP)	0.77
Granular mixtures comprising 25% planings	Log CBR = 2.80 - 1.49 log (DCP)	0.74
Granular mixtures comprising 50% planings	Log CBR = 2.51 - 1.38 log (DCP)	0.84
100% planings	Log CBR = 1.83 - 0.95 log (DCP)	0.72
100% planings (Toombs *at al*., 1994)	Log CBR = 1.81 - 0.86 log (DCP)	–

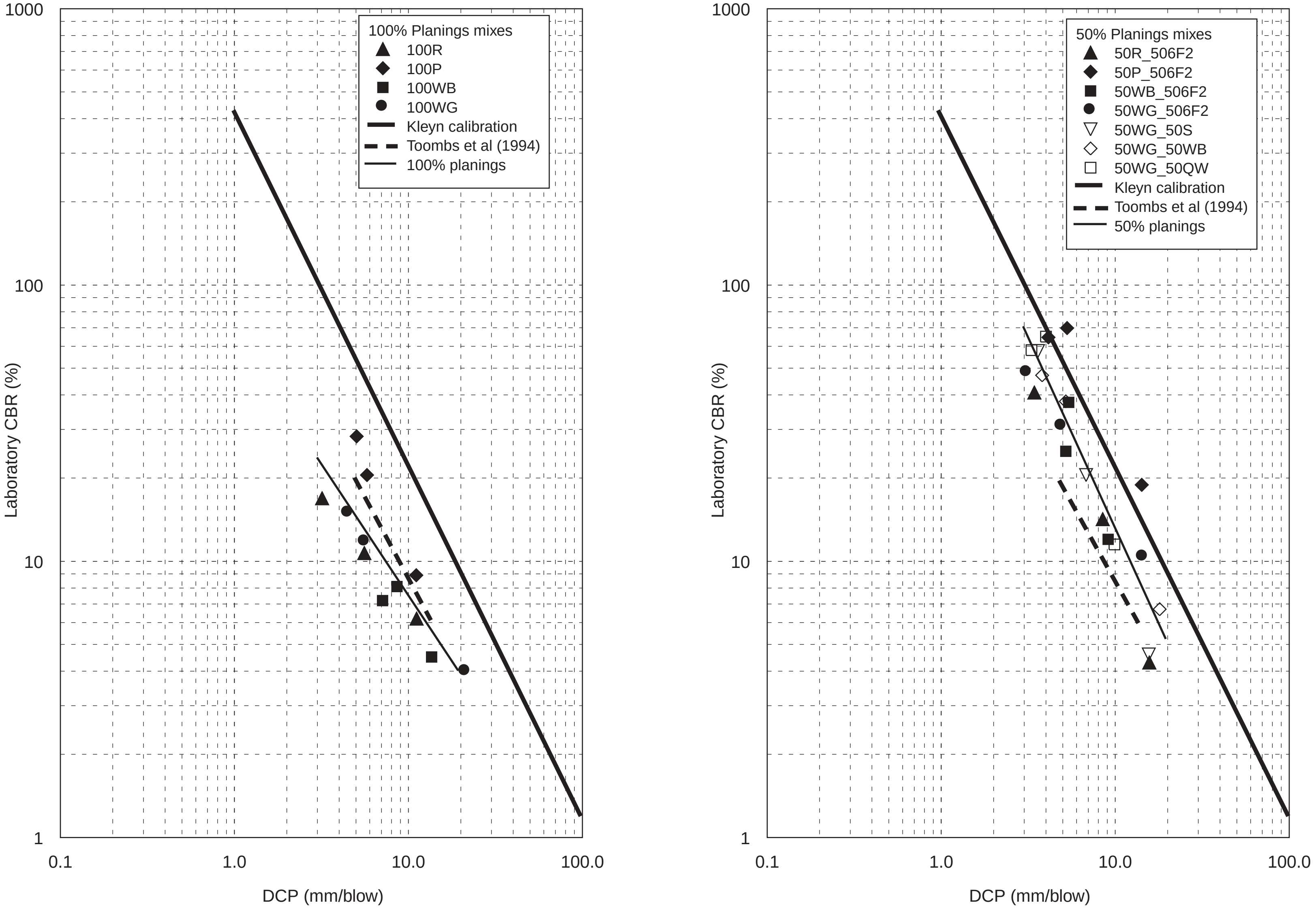

Figure 2a DCP versus CBR plots

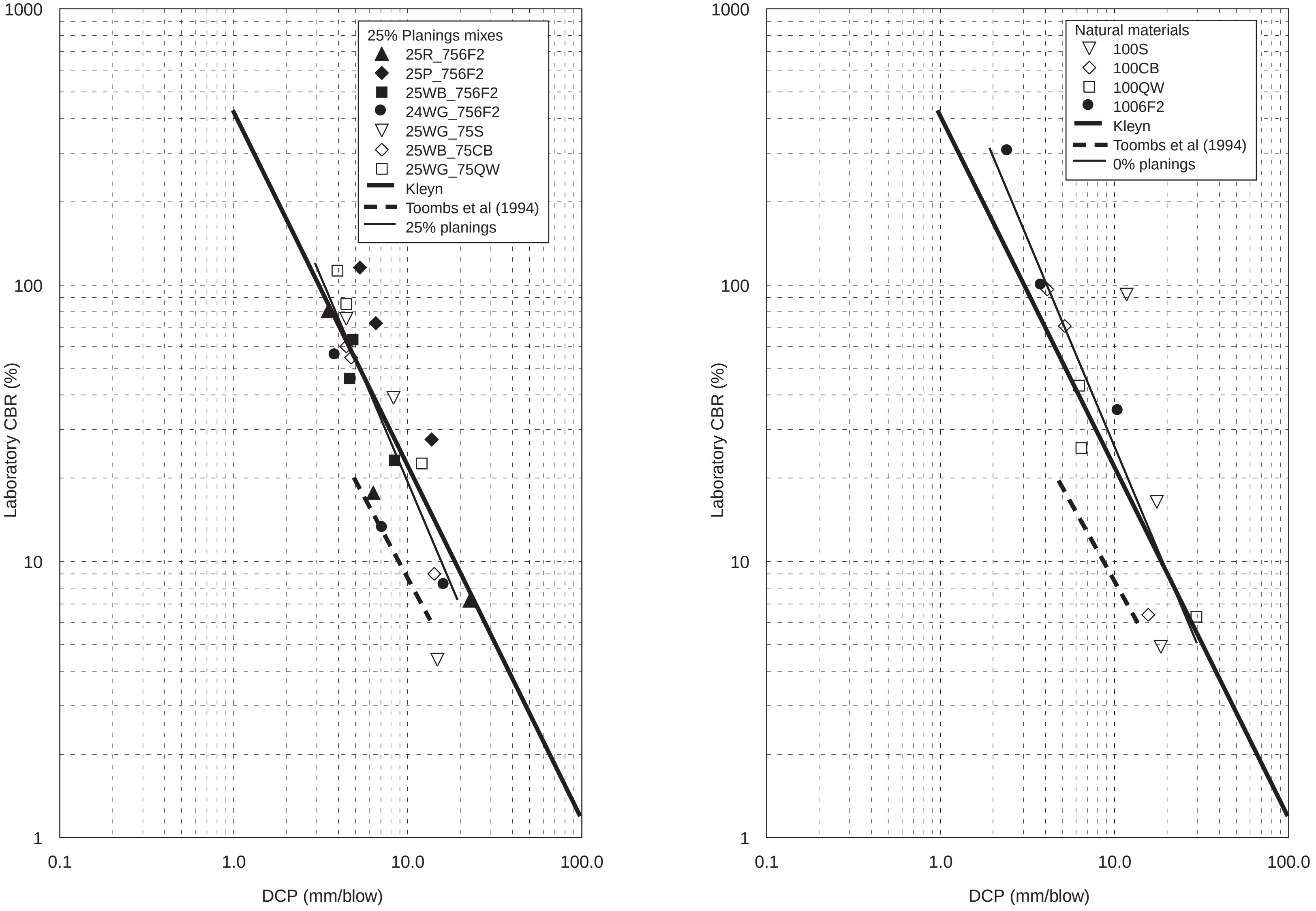

Figure 2b DCP versus CBR plots

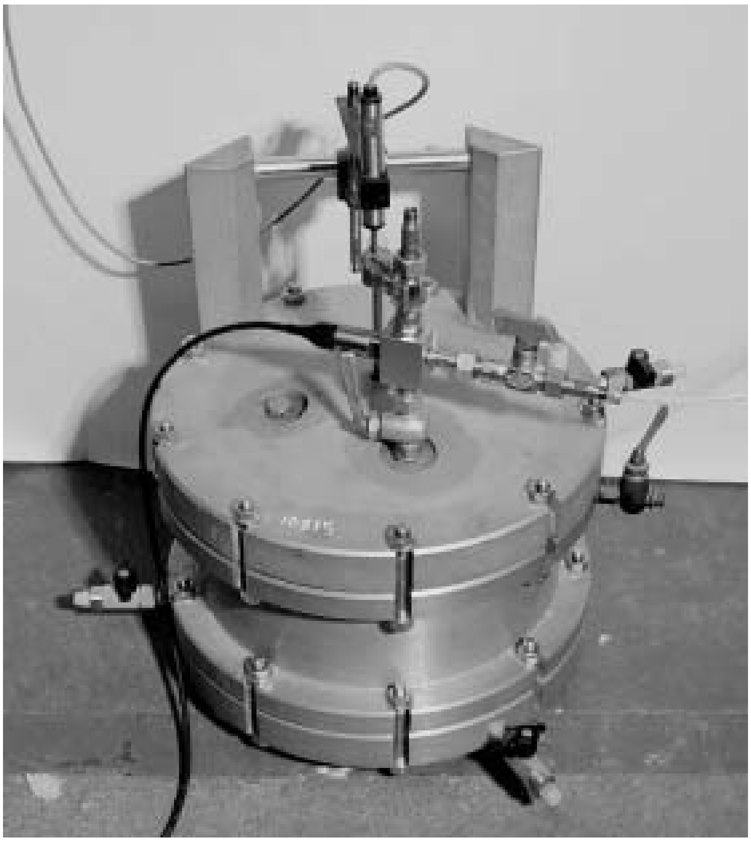

Figure 3a Rowe cell

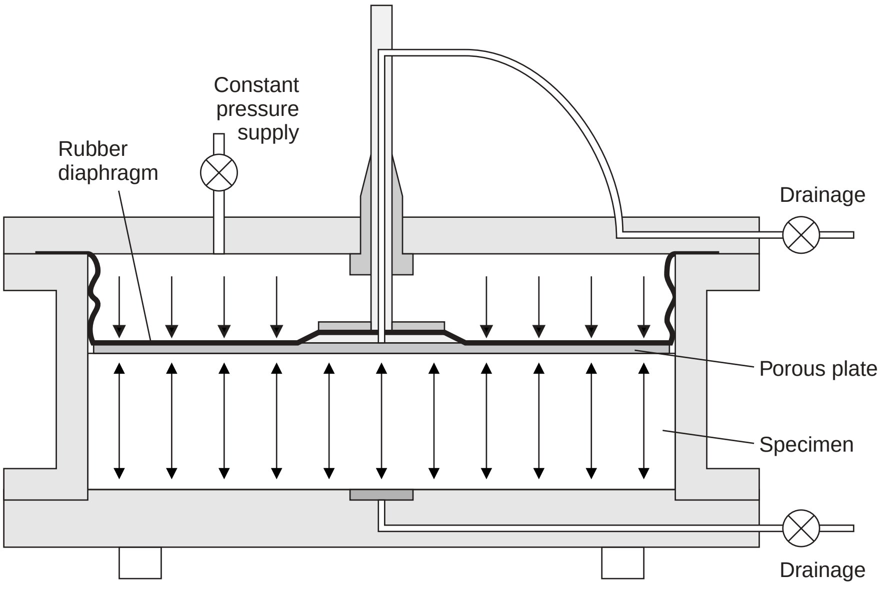

Figure 3b Rowe cell schematic

compaction, the walls of the Rowe cells were liberally coated with silicon grease to reduce friction. The test samples were compacted into the Rowe cells in three equal layers, using a vibrating hammer. The thickness of each layer was tightly controlled to ensure the required bulk density was achieved throughout the sample. The nominal relative compaction target for the Rowe cell samples was 95%, and the final thickness of each test specimen was between 90 and 95mm. Details of the states of compaction achieved are presented in Table 6. Of note is the fact that whilst the range of relative compaction values were close to the nominal target of 95%, the resulting air void contents showed values ranging from 7.8% to 21.4%.

As the Rowe cell tests were conducted in free-strain mode, as opposed to equal strain mode, a flexible rather than rigid sintered bronze plate was placed on each specimen before the top plate complete with diaphragm was lowered into position and secured (Head, 1982). An initial load of 10kPa was specified for the tests. Once the initial load had been achieved, it was maintained until all settlement was observed to have ceased. The load was then increased to 20kPa, 40kPa or 70kPa (or some sequence of these), and was maintained until all settlement had again ceased. Each cell was tested for compliance, using a solid steel dummy, and subsequent test results adjusted accordingly.

Compressibility plots from individual Rowe cell tests are reproduced in Appendix B. As the data are presented in material/mixture sequence, which was not always the chronological test order, some plots have more than one overburden sequence. A summary of the data, including the calculated coefficient of volume compressibility, m_v (see for example Smith, 1978), is presented in Table 7.

A summary plot of overburden versus settlement is presented in Figures 4a and 4b. In terms of overburden likely to be encountered by capping *in situ*, the pavement layers above capping will typically form a 0.5 to 1m composite layer. Such a layer would typically exert an overburden pressure of between 10 and 20kPa. These values only account for static load, and do not consider dynamic traffic loads. The compressibility testing was therefore continued to overburdens of up to 70kPa, which were beyond those expected for capping. This ensured that no sudden loading anomalies occurred across the bitumen content range of the mixtures.

4.5 Discussion on laboratory testing

In comparing the laboratory performance of the bituminous materials and mixtures, care must be taken when considering the effects of the state of compaction of the test sample at the beginning of the test. This is further complicated by the fact that relative compaction alone does not indicate the state of

Table 6 Compressibility sample preparation data

Materials	*Test ID*	*Moisture content (%)*	*Dry density (Mg/m³)*	*Relative compaction (%)*	*Air voids content (%)*
Stage 1					
Class 6F2	1 1006F2	2.9	2.253	96.1	11.2
	2 1006F2	2.6	2.264	96.6	11.5
	3 1006F2	2.8	2.215	94.5	13.0
	4 1006F2	4.2	2.262	96.5	7.9
Redlands + Class 6F2	25R_756F2	2.8	1.959	95.6	21.4
	50R_506F2	5.5	1.965	95.7	12.1
	100R	4.3	1.886	95.8	14.0
Pryors + Class 6F2	25P_756F2	7.0	1.981	95.5	9.9
	50P_506F2	6.6	2.057	95.7	8.8
	100P	7.9	1.847	92.1	10.3
Walblack + Class 6F2	25WB_756F2	4.4	2.145	98.8	9.9
	50WB_506F2	7.5	1.995	98.8	8.6
	2 100WB	6.6	1.807	97.2	14.3
Walgrey + Class 6F2	25WG_756F2	5.5	2.050	97.6	12.2
	50WG_506F2	6.0	1.977	95.0	11.2
	100WG	6.5	1.750	93.6	16.3
Stage 2					
Walgrey + sand	25WG_75S	4.7	2.046	93.0	9.8
	50WG_50S	4.5	2.013	94.1	11.1
	100S	6.5	2.110	96.3	7.8
Walgrey + crushed brick	25WG_75CB	17.6	1.540	97.5	10.5
	50WG_50CB	14.5	1.654	96.7	10.6
	100CB	21.5	1.397	95.7	16.6
Walgrey + quarry waste	25WG_75QW	6.3	2.033	95.0	8.4
	50WG_50QW	5.0	2.042	96.3	8.1
	100QW	9.5	1.945	94.4	8.4

Table 7 Compressibility data

Materials	*Test ID*	*Bitumen content (%)*	*Total settlement (%)*				*Coefficient of volume compressibility, m_v (m^2/MN)*	
			0 to 10kPa	*0 to 20kPa*	*0 to 40kPa*	*0 to 70kPa*	*0 to 20kPa*	*0 to 70kPa*
Stage 1								
Class 6F2	1 1006F2	–	0.16	–	0.90	–	–	–
	2 1006F2	–	0.21	–	1.02	–	–	–
	3 1006F2	–	0.02	–	0.76	–	–	–
	4 1006F2	–	0.19	0.31	0.51	0.70	0.166	0.103
Redlands + Class 6F2	25R_756F2	1.5	0.31	0.55	–	1.14	0.277	0.162
	50R_506F2	3.5	0.52	0.93	–	1.66	0.468	0.236
	100R	5.9	0.15	2.52	–	3.84	1.273	0.547
Pryors + Class 6F2	25P_756F2	1.0	0.57	0.97	–	2.00	0.438	0.278
	50P_506F2	2.6	0.65	1.05	–	1.57	0.474	0.218
	100P	4.2	0.94	3.19	–	5.69	1.436	0.791
Walblack + Class 6F2	25WB_756F2	1.5	0.36	0.91	1.33	1.56	0.492	0.227
	50WB_506F2	2.8	0.77	1.26	1.75	–	0.608	-
	100WB	5.4	0.98	2.51	5.10	7.04	1.356	1.030
Walgrey + Class 6F2	25WG_756F2	1.9	0.36	0.77	1.13	1.36	0.366	0.193
	50WG_506F2	2.7	0.66	1.49	2.35	2.72	0.708	0.386
	100WG	5.6	2.71	3.55	5.51	5.87	1.609	0.833
Stage 2								
Walgrey + sand	25WG_75S	1.5	0.47	1.15	1.63	1.97	0.582	0.283
	50WG_50S	2.7	0.54	0.98	1.50	1.92	0.492	0.275
	100S	–	0.04	0.62	1.52	1.91	0.312	0.274
Walgrey + crushed brick	25WG_75CB	1.4	1.18	1.76	2.08	2.27	0.854	0.325
	50WG_50CB	2.7	0.74	1.12	1.37	1.50	0.546	0.215
	100CB	–	0.17	0.98	1.82	2.15	0.479	0.307
Walgrey + quarry waste	25WG_75QW	1.4	0.27	0.49	0.75	0.98	0.268	0.146
	50WG_50QW	2.2	0.26	0.48	0.70	0.87	0.266	0.128
	100QW	–	0.04	0.22	0.58	0.94	0.119	0.139

compaction achieved; for the compressibility testing of the four planings materials, relative compaction values of 95.8, 92.1, 97.2 and 93.6% were achieved, but the resultant air void contents were 14.0, 10.3, 14.3 and 16.3%, respectively. These data do not appear readily conformable, and highlight the problem of comparing the performance of different granular materials and mixtures on the basis of one test procedure. Furthermore, other factors such as grading, moisture content, aggregate characteristics, and the stiffness of the bituminous material within the materials/mixtures will play significant roles in compressibility performance. Notwithstanding these factors, it is considered likely that, for compressibility assessment, air voids content is a more suitable indicator of state of compaction than relative compaction.

As discussed in Section 1, the objective of the laboratory trials was to identify whether a lower limit of bitumen content that influences the compaction and settlement of granular mixtures could be identified. In terms of grading, all four bituminous planings used in stage 1 met the Class 6F3 grading. Unsurprisingly given that the stage 1 mixtures also comprised two materials meeting the Class 6F3 grading, the gradings of the mixtures also met the Class 6F3 grading.

Bitumen content versus settlement data from compressibility testing are presented in Figures 5a and 5b. The performance of the SHW standard Class 6F2 crushed rock may be assumed to represent acceptable performance. As such, an acceptable settlement at 10kPa is less than 0.25%, less than 0.4% at 20kPa, and of the order of 1% at overburdens between 40 and 70kPa. Rather than applying multiple criteria to the data, it is considered suitable to apply one settlement limit. Using engineering judgement, specifying a 1% settlement as the acceptability criterion is considered appropriate. Table 8 presents the results of applying this criterion to the compressibility data presented in Table 7; a tick is used to indicate settlements below the 1% settlement criterion and a cross for each percentage point the settlement was above 1% (i.e. two crosses represents a settlement of 3%).

For stage 1 compressibility testing to an overburden of 10kPa, 15 of the 16 mixtures met the settlement acceptability criterion, with only the 100% Walgrey planings failing. The differences between the compressibility performances of the mixtures are more apparent for the 20kPa overburden; only 6 of the 13 mixtures passed the acceptability criteria. Of significance, the mixtures passing were the one Class 6F2 tested at 20kPa, all four of the 25% planings/75% Class 6F2 mixtures and one of the 50% planings/50% Class 6F2 mixtures. Indeed, interpolating the settlement data for the 10kPa and 40kPa overburdens for the initial three Class 6F2 tests gives estimated settlements of 0.41, 0.48 and

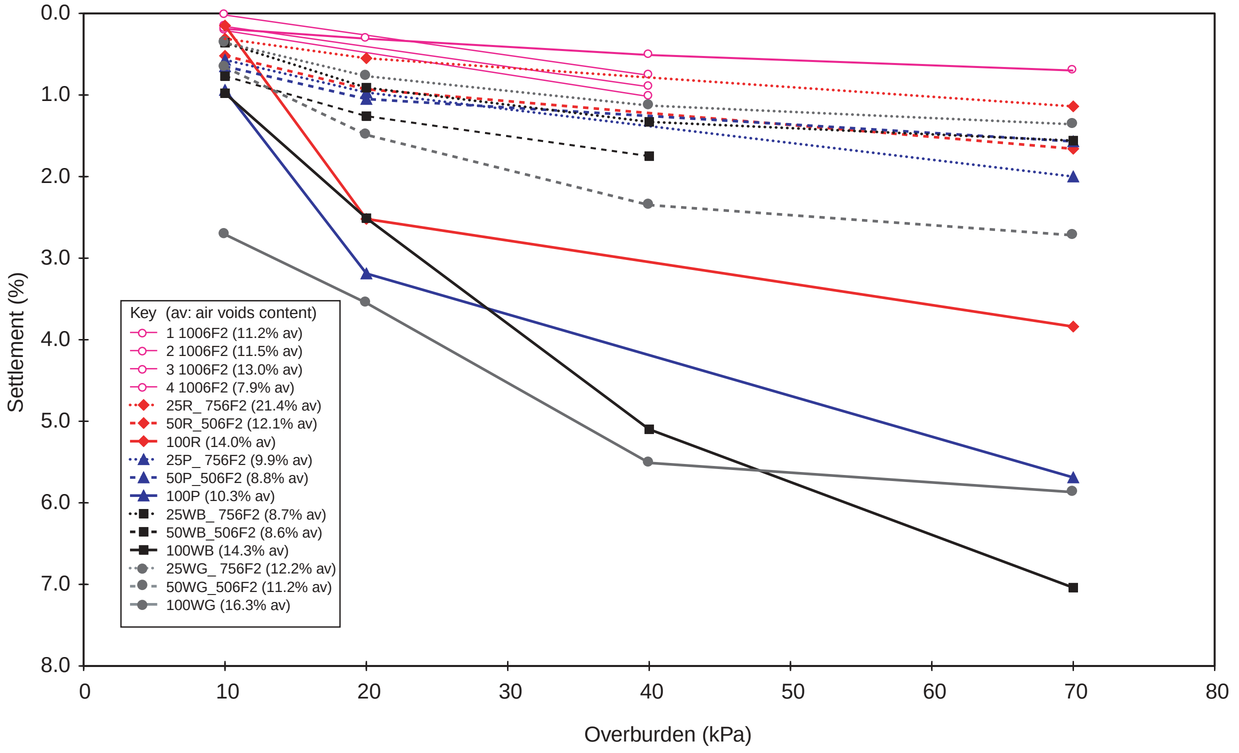

Figure 4a Overburden versus settlement plot

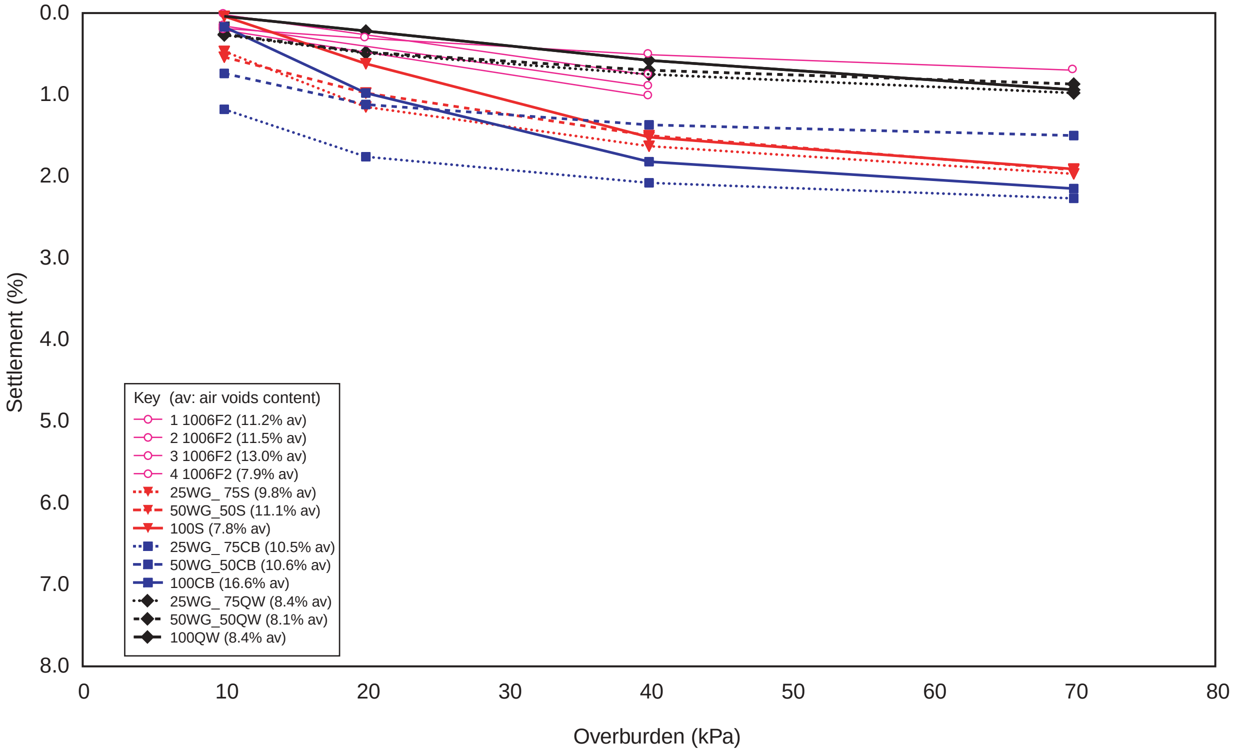

Figure 4b Overburden versus settlement plot

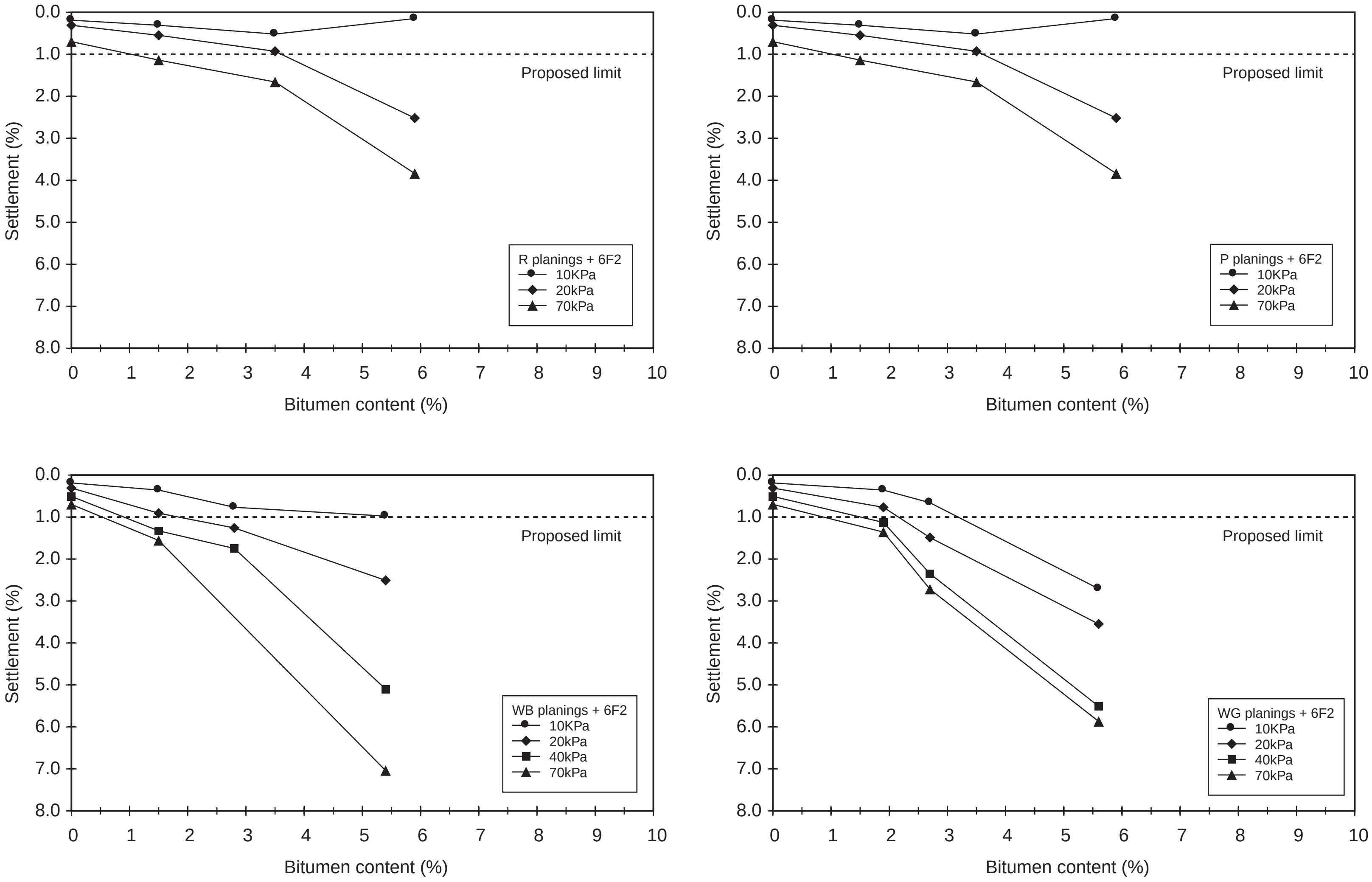

Figure 5a Bitumen content versus overburden plots

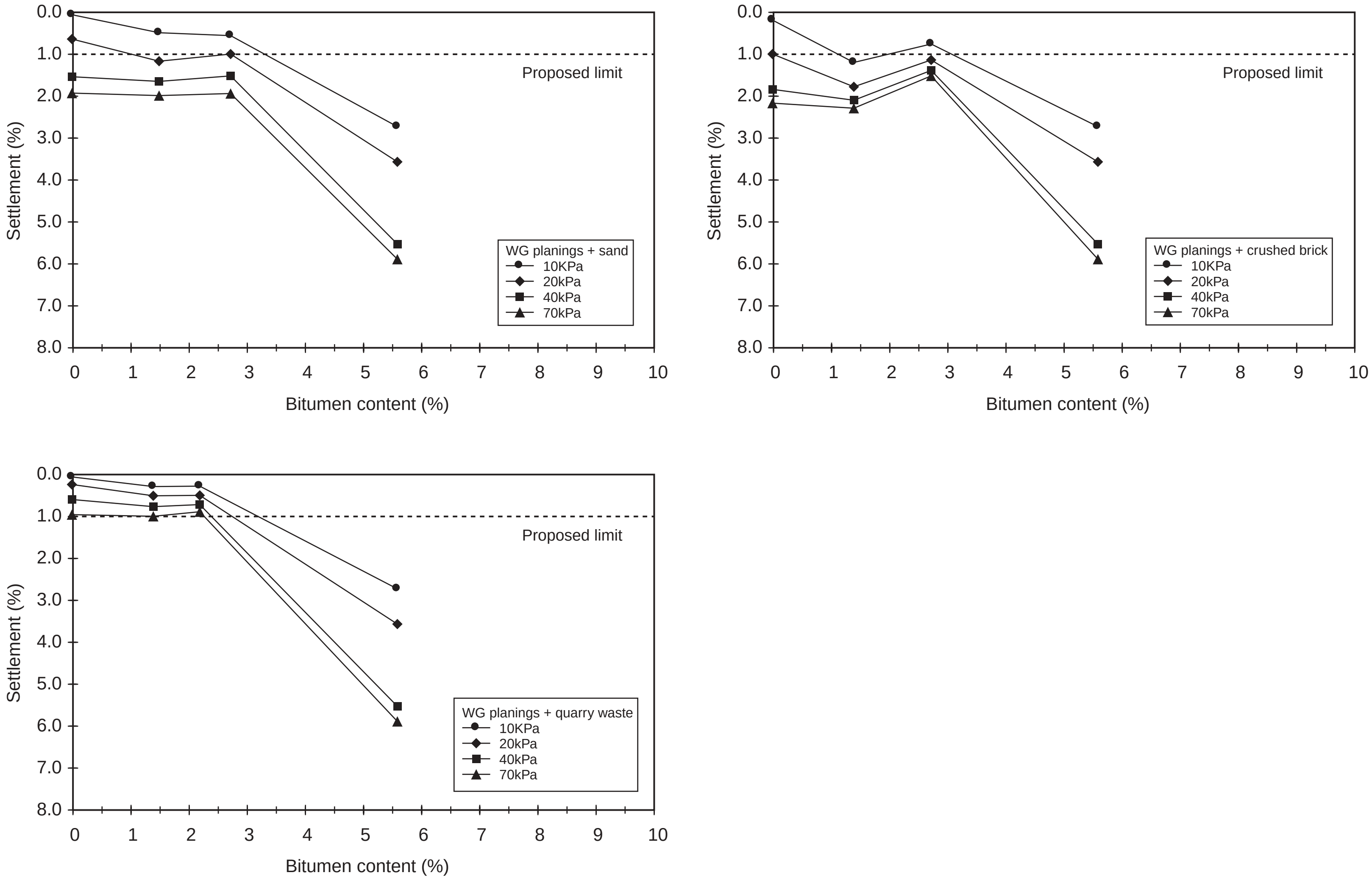

Figure 5b Bitumen content versus overburden plots

Table 8 Compressibility data versus 1% settlement criterion

Materials	*Test ID*	*Bitumen content (%)*	*Total settlement (%)*			
			0 to 10kPa	*0 to 20kPa*	*0 to 40kPa*	*0 to 70kPa*
Stage 1						
Class 6F2	1 1006F2	–	✔	–	✔	–
	2 1006F2	–	✔	–	✘	–
	3 1006F2	–	✔	–	✔	–
	4 1006F2	–	✔	✔	✔	✔
Redlands + Class 6F2	25R_756F2	1.5	✔	✔	–	✘
	50R_506F2	3.5	✔	✔	–	✘
	100R	5.9	✔	✘✘	–	✘✘✘
Pryors + Class 6F2	25P_756F2	1.0	✔	✔	–	✘
	50P_506F2	2.6	✔	✘	–	✘
	100P	4.2	✔	✘✘✘	–	✘✘✘✘✘
Walblack + Class 6F2	25WB_756F2	1.5	✔	✔	✘	✘
	50WB_506F2	2.8	✔	✘	✘	–
	100WB	5.4	✔	✘✘	✘✘✘✘✘	✘✘✘✘✘✘
Walgrey + Class 6F2	25WG_756F2	1.9	✔	✔	✘	✘
	50WG_506F2	2.7	✔	✘	✘✘	✘✘
	100WG	5.6	✘✘	✘✘✘	✘✘✘✘✘	✘✘✘✘✘
Stage 2						
Walgrey + sand	25WG_75S	1.5	✔	✘	✘	✘
	50WG_50S	2.7	✔	✔	✘	✘
	100S	–	✔	✔	✘	✘
Walgrey + crushed brick	25WG_75CB	1.4	✘	✘	✘✘	✘✘
	50WG_50CB	2.7	✔	✘	✘	✘
	100CB	–	✔	✔	✘	✘✘
Walgrey + quarry waste	25WG_75QW	1.4	✔	✔	✔	✔
	50WG_50QW	2.2	✔	✔	✔	✔
	100QW	–	✔	✔	✔	✔

✔ *shows less than 1% settlement,*
✘ *used for each percentage point above 1% settlement.*

0.27% at a 20kPa overburden. All four tests on the Class 6F2 were therefore in reasonable agreement, with the acceptability criterion of a 1% settlement being approximately 50% greater than the actual recorded data at an overburden of 20kPa. For stage 1 testing, the data for overburdens of 40 and 70kPa show that the majority of the mixtures failed to meet the acceptability criterion. This is particularly evident for the 100% planings.

To summarise the stage 1 data, Table 8 indicates that an overburden of 20kPa is an effective test level for discriminating between the performances of the granular materials and mixtures. Applying the 1% settlement criterion results in all four 25% planings/75% Class 6F2 mixtures having compressibilities broadly similar to the standard Class 6F2. For this reason, it is proposed that capping materials, or mixtures of materials, with bitumen contents equivalent to these mixtures could perform in a manner similar to the standard Class 6F2 crushed rock. As the bitumen content of the 25% planings/75% Class 6F2 mixtures were 1.5, 1.0, 1.5 and 1.9%, it is proposed that specifying a upper bitumen content of 2% would be appropriate for materials comprising bituminous planings and crushed rock.

In terms of Stage 2 testing, undertaken to assess the performance of mixtures comprising planings and fine granular materials, the gradings of all the test samples either fell outside the capping requirement, or met the requirements of the fine Class 6F1 capping. The states of compaction of the compressibility test samples, as indicated by air voids content, were acceptable (see Table 6). The conclusions to be drawn from the application of the 1% settlement criterion (Table 8) are less clear. At an overburden of 20kPa, mixtures 25WG_75S, 25WG_75CB and 50WG_50CB failed, whilst all mixtures of planings and quarry waste passed at all overburdens. On the basis of the data presented in stage 2 for mixtures with grading outside the Class 6F3 grading, it was not possible to define a bitumen content which would result in the acceptance of a mixture of planings and quarry waste, whilst rejecting mixtures of planings and sand or crushed brick.

The bituminous planings to granular material ratios used in all of the test samples were selected to permit investigations of the performance of mixtures with low bitumen contents. This necessitated the use of ratios comprising 25% and 50% planings. Whilst it was not the intention to examine the addition of small volumes of bituminous planings to fine materials, (the sand, crushed brick and quarry waste all had d_{50} values between 0.4 and 1.5mm), this is in effect what occurred during stage 2 testing. Ideally, the stage 2 testing would have also encompassed mix ratios of say 66% and 75% planings; this would have generated data which would have typified adding fine granular materials to dilute the effect of the bitumen content of the planings which comprised the bulk of the mixture.

5 Application of findings from laboratory trials

All planings tested to date by TRL have met the Class 6F3 grading, and require limits on compacted layer thicknesses. As such, it is considered appropriate to continue to specify the Class 6F3 grading for mixtures comprising bituminous planings and other granular materials. Whilst the encouragement of the use of other fine granular materials for capping is clearly desirable, care must be taken to ensure that all permitted combinations of such mixtures are fit for use as capping. This is best achieved by rejecting the use of such mixtures comprising bituminous planings with gradings which do not comply with Class 6F3.

In terms of the application of these finding in the SHW (MCHW 1), it is recommended that the current bitumen content for Class 6F3 should be maintained at 0 -10%. At the same time, a new Class 6F4, specifically for mixtures of bituminous planings and granular materials, should be included in the SHW. The material properties recommended for the proposed Class 6F4 are presented below; they are identical to the current Class 6F3 requirements, with the exception that the permitted bitumen content range would be 0 to 2%.

Classification and compaction requirements for proposed Class 6F4

				Material properties required for acceptability				
						Acceptable limits within:		
Class	*General material description*	*Typical use*	*Permitted constituents*	*Property*	*Defined and tested in accordance with:*	*Lower*	*Upper*	*Compaction requirements in Class 612*
6F4	Selected granular material (coarse grading)	Capping	Combinations of recycled bituminous planings and granular asphalt, and granular materials other than unburnt colliery spoil and argillaceous rock. Materials containing tar or tar-bitumen binders shall be excluded	(i) grading	BS 1377: Part 2	Tab 6/2	Tab 6/2	Tab 6/4 Method 6
				(ii) optimum mc	Clause 613	–	–	
				(iii) mc	Clause 613	Optimum mc -2%	Optimum mc	
				(iv) bitumen content	BS 598: Part 102	0	2	

Applied in this manner, Class 6F3 would continue to apply to 100% bituminous planings and Class 6F4 would apply to mixtures of bituminous planings with other granular materials. It is considered highly unlikely that any 100% bituminous planings would have a bitumen content less than 2%, but such a material could be treated as Class 6F4 by the addition of a token amount of granular material. By applying the same grading as Class 6F3 to Class 6F4, the performance of the mixtures will be similar to Class 6F3. In terms of compaction, by limiting bitumen content to a 2% upper limit, compacted layer thicknesses of up to 250mm may be allowed and so the requirements of Table 6/4 Method 6 can be applied without qualification to Class 6F4.

The testing undertaken for this project has shown that Class 6F2 crushed rock performs well as the diluting material for the proposed Class 6F4. However, using Class 6F2 crushed rock in the proposed Class 6F4 would be an expensive option; clearly economics would prevail and the likelihood would be that the planings would be placed as Class 6F3. The project has also demonstrated that other granular materials could have potential use in the proposed Class 6F4.

In particular, quarry waste would be particularly suited to this application. It is considered that using lower quality granular materials as the diluting materials within the proposed Class 6F4 would form a more viable option than using Class 6F2 crushed rock. It should be noted that these lower quality granular materials do not need necessarily to comply with the Class 6F2 grading, although it should be possible to produce mixtures which do meet the proposed Class 6F4 grading whilst also meeting the proposed bitumen content limits. Thus, the materials mixed with bituminous planings to form the proposed Class 6F4 capping could comprise a wide range of traditional and more innovative granular materials.

The method of producing the proposed Class 6F4 capping will depend on whether the mixtures are to be produced on or off site. Clearly, in terms of environmental consideration such as number of haulage movements, more benefits would arise from production on site, though it is likely that larger scale operations, and therefore larger production capabilities, would be available off site (see Quarry Management, 2000). The processes and plant used to blend the mixtures need not be specified, although guidance may be required to advise on achieving consistent mixtures.

6 Pilot scale trial

6.1 Introduction

In order to assess the *in situ* performance of granular and bituminous mixtures, a small, pilot scale trial was designed and constructed in the Pavement Test Facility (PTF) at TRL. The objective of the trial was to evaluate the states of compaction which could be achieved on large representative samples of the bituminous planings and granular mixtures, prepared using Method 6 compaction, as specified in the SHW (MCHW 1). The state of the subgrade was selected to represent the condition which would require a capping layer to enable construction of the pavement sub-base. The typical *in situ* performance of a Class 6F2 material, a Class 6F3 material and two planings and granular material mixtures, the performance of which had been assessed previously in the laboratory test regime, were evaluated in this manner.

At the same time, performance data were generated using a range of performance evaluating devices. These devices are designed principally to measure stiffness, although a surface modulus for the material under test can be derived. Tests using these devices were conducted on the heavy clay subgrade, a nominal 150mm thick capping layer, and a nominal 350mm thick capping layer, which was constructed by placing a nominally 200mmm thick capping layer on top of the first layer.

6.2 Trial design

In order to assess the performance of each of the test materials, the trial was designed to simulate a typical capping construction over a clay subgrade. The subgrade in the PTF comprised a stiff heavy clay, with plastic limit of 22%, liquid limit of 62% and plasticity index of 40%. The optimum moisture content (omc) and maximum dry density (mdd) of the clay, determined in accordance with BS1377: Part 4 (BSI 1990), were 23% and 1.630 Mg/m^3 respectively.

The trial was constructed within the test pit of the enclosed PTF, and was therefore not influenced by varying weather conditions. The area selected for the construction was 6m wide by 10m long. This area was divided into six separate bays, four of which were used for the trial. Each bay was approximately 3.3 metres long by 3.0 metres wide. The layout of the trial is presented in Figure 6.

Prior to commencing the trial, the previous pavement construction in the trial area was excavated and the clay exposed and graded to approximately 350mm below pit edge. The subgrade was then sealed by compacting with a vibrating plate compactor. The *in situ* California Bearing Ratio (CBR) of the subgrade was estimated using a MEXE cone penetrometer, fitted with a small cone. As the penetrometer is marked in Imperial units, these units are used for the presentation of these data. Cone Index (CI) values were recorded over the exposed subgrade area. The CI values for penetration depths of 0, 6, 12, 18 and 24 inches, converted to CBR using CI divided by 20 (Black, 1979) are presented in Table 9. The data showed the subgrade strength to be resonably consistent across the trial area.

In total, a 350mm thickness of capping was specified in accordance with Table 10/1 of HA 44 (DMRB 4.1.1), to be placed in nominal 150mm and 200mm layers. Details of the four test mixtures selected for evaluation are presented in Table 10.

6.3 Trial construction

6.3.1 Material preparation

Due to the small scale of the trial, rather than use specialised processing plant, each of the test mixtures was mixed on the concrete apron in front of the PTF building. Mixture production was carried out on a volumetric basis, and blending undertaken using both the front and back actor of a JCB, as shown in Figure 7. Each mixture was blended until a uniform consistency was achieved. During the blending process, moisture was added to each material to achieve compliance with the Series 600 requirement of omc to omc - 2% (MCHW 1). Results of material acceptability testing are presented in Table 11. Moisture contents of the bituminous mixtures were measured in accordance with BS1377 (BSI, 1990), with the exception that the oven temperature was reduced to 40-50°C (Toombs *et al.*, 1994). Bitumen content analysis was carried out in accordance with BS598 (BSI, 1996). Particle size distribution analyses were carried out in accordance with BS1377 (BSI, 1990) on each of the mixtures and are presented in Figures 1a and 1b. Whilst the 1006F2, the 100WG planings and the 50WG_506F2 mixture all met

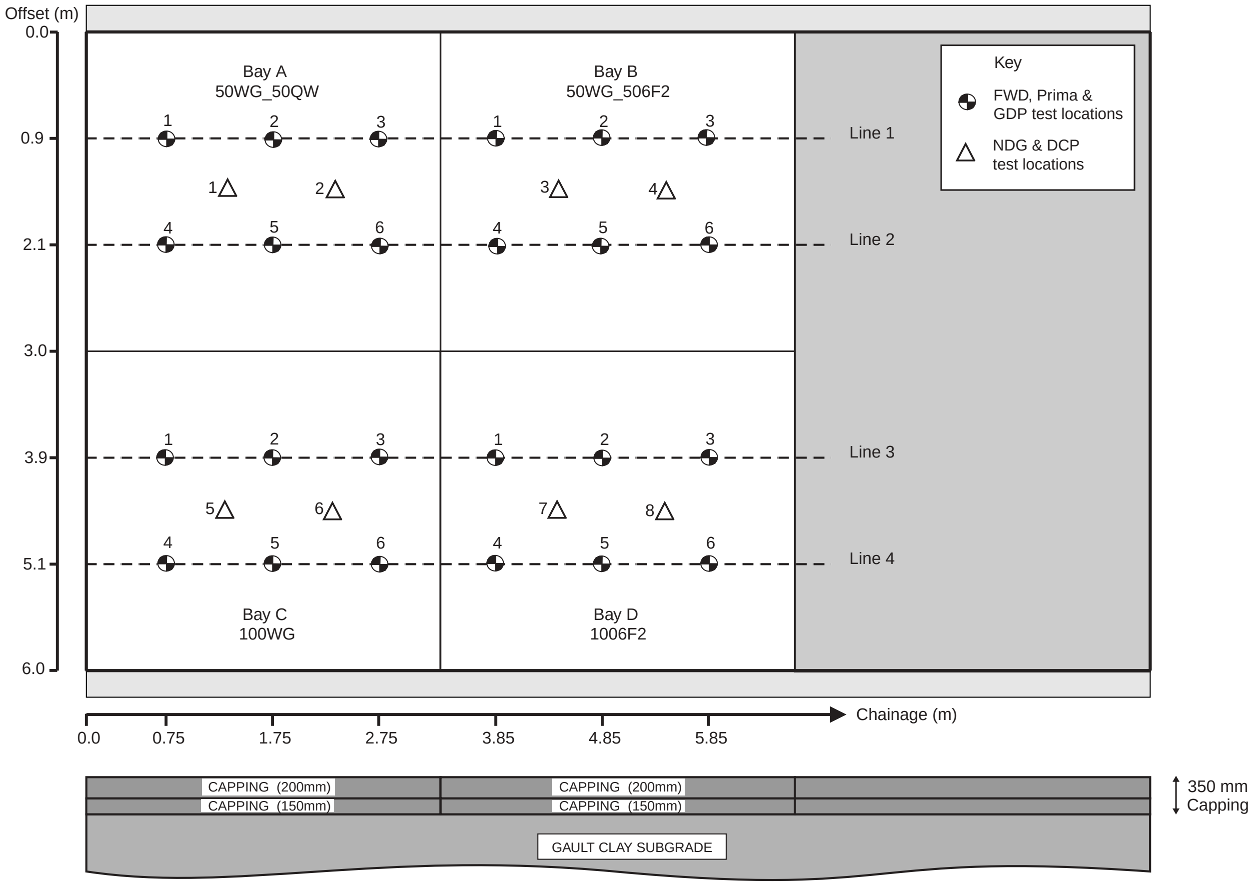

Figure 6 Layout of trial in PTF

Table 9 Subgrade strength for trial area (MEXE cone)

	CBR (%)						
	Depth						
Test position	*0*	*6"*	*12"*	*18"*	*24"*	*Mean*	*Overall mean*
Bay A							
1	2.8	4.4	5.0	4.7	4.5	4.6	4.4
2	3.8	4.4	4.8	4.9	4.4	4.6	
3	4.3	4.5	4.6	4.3	4.2	4.4	
4	4.0	3.5	4.6	4.5	4.5	4.3	
5	4.1	4.3	4.7	4.0	4.5	4.4	
6	3.6	3.3	4.8	4.4	3.9	4.1	
Bay B							
1	3.5	4.2	4.5	4.3	4.8	4.4	4.4
2	4.0	3.8	3.0	5.6	5.3	4.4	
3	4.0	4.4	4.5	4.3	4.0	4.3	
4	3.8	4.3	4.6	4.5	4.4	4.4	
5	3.5	3.9	6.1	4.7	4.2	4.7	
6	4.3	3.9	4.1	4.7	4.0	4.2	
Bay C							
1	4.0	4.8	5.8	5.8	4.8	5.3	4.9
2	5.0	4.6	5.1	4.3	3.9	4.5	
3	4.3	4.6	4.8	4.5	4.5	4.6	
4	5.8	5.3	5.8	5.0	5.0	5.3	
5	4.8	5.2	5.3	5.0	4.5	5.0	
6	4.5	4.8	5.3	5.2	4.4	4.9	
Bay D							
1	3.9	4.8	4.3	4.3	4.4	4.4	4.6
2	4.0	4.1	4.5	4.1	3.8	4.1	
3	3.4	4.8	4.4	4.3	4.3	4.4	
4	5.5	4.5	4.9	4.5	4.3	4.5	
5	5.4	4.5	5.3	10.0	3.5	5.8	
6	4.3	4.5	5.2	4.5	4.3	4.6	
Overall subgrade mean							4.6

Table 10 Description of material blends used in trial

Material	*SHW material class*	*Test ID*
Bay A		
Walgrey + quarry waste	na	50WG_50QW
Bay B		
Walgrey + Class 6F2	na	50WG_506F2
Bay C		
Walgrey	6F3	100WG
Bay D		
Class 6F2	6F2	1006F2

the Class 6F3 grading requirements, the 50WG_50QW mixture fell below the lower bound. From Figure 1b, it can be seen that the grading of the 50WG_50QW mixture used in the PTF was coarser than that used in the laboratory testing. This is reflected in the bitumen content of 3.5%, which is 1.3% higher than that of the laboratory sample. This may have been due to the fact that the PTF sample was mixed on a volumetric basis, whilst the laboratory sample was mixed on a weight basis.

Figure 7 Mixing materials

6.3.2 Construction method

On completion of subgrade testing, each of the four materials was delivered to the test area using a small, 2 tonne capacity dumper truck. In order to protect the subgrade from rutting, boarding was placed to allow the delivery of material to both bays A and B (see Figure 8). This boarding was then removed and materials for Bay C and D placed. Each material was then spread with the back actor bucket of the JCB, to a loose layer depth sufficient to achieve a nominal compacted layer depth of 150mm.

The 150mm layers of the four capping materials were compacted using a Bomag BPH 80/65/S vibrating plate compactor (see Figure 9), which has a mass per square metre of baseplate of 2182 kg. This machine complies with the ‘over 2100kg m^2’ category of the SHW (MCHW 1). For the nominal 150mm layer, compaction was carried out in accordance with Table 6/4, Method 6, of the SHW, which requires 6 machine passes.

On completion of compaction of the 150mm layer, and subsequent testing, the second nominally 200mm thick layer of each of the four materials was placed and compacted in the same manner, with the exception that, as specified in Table 6/4, Method 6 of the SHW for a nominal 200mm layer, compaction was carried out using 12 machine passes.

6.4 Effectiveness of method specification for trial materials

6.4.1 States of compaction

For each layer, the layer thicknesses were recorded at 24 locations on each bay, using an optical level. The mean compacted thicknesses of each layer are presented in Table 12. Whilst the mean overall layer thickness for Bays A, B and C were close to the 350mm target, the overall mean for Bay D was somewhat lower than ideal.

A Troxler 3411B nuclear density gauge (NDG), operated in direct transmission mode, was used to measure bulk density and moisture content at two locations in each bay, on the subgrade, the 150mm layer and the final 350mm combined layer. The NDG test locations are shown in Figure 6. Two separate sets of measurements

Table 11 Material acceptability testing

Material	*Test ID*	*Target moisture content (%)*		*Moisture content (%)*	*Bitumen content of laboratory mixture (%)*	*Bitumen content of pilot scale mixture (%)*
		OMC	*OMC - 2*			
Bay A						
Walgrey + quarry waste	50WG_50QW	5.0	3.0	6.0	2.2	3.5
Bay B						
Walgrey + Class 6F2	50WG_506F2	5.6	3.6	5.4	2.7	2.4
Bay C						
Walgrey	100WG	5.6	3.6	5.0	5.6	na[*]
Bay D						
Class 6F2	1006F2	5.3	3.3	5.0	–	–

[*] *Not determined separately, but assumed to be equal to the laboratory value*

Figure 8 Delivery of materials

Figure 9 Compaction of four bays

Table 12 Mean compacted layer depths for each of the trial bays

Material	*Test ID*	*Mean compacted layer depth (mm)*		
		Layer 1	*Layer 2*	*Overall*
Bay A				
Walgrey + quarry waste	50WG_50QW	155	211	366
Bay B				
Walgrey + Class 6F2	50WG_506F2	135	206	341
Bay C				
Walgrey	100WG	127	212	339
Bay D				
Class 6F2	1006F2	133	188	321

were taken at each location; the second set taken with the gauge rotated 180° compared to the first set. The results of NDG tests are presented in Table 13.

The data recorded by the NDG is normally corrected on two counts. Firstly, for all soils, the recorded NDG bulk densities are corrected using a field calibration (Troxler, 1984). However, due to the limited extent of this trial, this was not possible for these data. For bituminous planings, previous work (Steele and Snowdon, 1995; MacNeil *et al.*, 1997) indicates that the NDG bulk density reading underestimates the field corrected bulk density by typically between 0.05 and 0.1Mg/m^3, for a bulk density range of 1.9 to 2.1Mg/m^3. For a Type 1 crushed rock, Steele and Snowdon (1995) showed that the NDG bulk density reading requires no amendment, as the relation is very close to 1:1. Accordingly, the data recorded in Table 13 should be viewed as accurate for the Class 6F2 (Bay D) material, potentially under reading the NDG bulk density of the two 50:50 mixtures (Bays A and B) by between 0.025 and 0.05Mg/m^3, and potentially under reading the NDG bulk density for the Walgrey bituminous planings (Bay C) by between 0.05 and 0.1Mg/m^3. The effect of

Table 13 Compaction data from pilot scale trial

Layer description *Mixture*	*Test ID*	*NDG moisture content (%)*	*NDG bulk density (Mg/m³)*	*Oven moisture content (%)*	*Dry density (Mg/m³)*	*Air voids (%)*	*Relative compaction (%)*
Subgrade							
Bay A	1	29.7	1.927	30.1	1.481	0.6	90.9
–		29.2	1.904		1.463	1.7	89.8
	2	28.0	1.943		1.493	-0.3	91.6
		32.7	1.854		1.425	4.3	87.4
Bay B	3	28.0	1.916	27.9	1.498	2.7	91.9
–		28.2	1.932		1.511	1.9	92.7
	4	29.0	1.891		1.478	4.0	90.7
		29.3	1.917		1.499	2.7	92.0
Bay C	5	28.8	1.914	28.2	1.493	2.6	91.6
–		26.8	1.939		1.512	1.3	92.8
	6	29.7	1.933		1.508	1.6	92.5
		29.5	1.908		1.488	2.9	91.3
Bay D	7	29.3	1.954	29.1	1.514	-0.1	92.9
–		28.9	1.915		1.483	1.9	91.0
	8	29.9	1.896		1.469	2.9	90.1
		30.9	1.905		1.476	2.4	90.5
Layer 1 (150mm)							
Bay A	1	8.6	2.075	4.9	1.978	11.2	93.3
50WG_50QW		8.7	2.070		1.973	11.4	93.1
	2	8.7	2.065	5.0	1.967	11.5	92.8
		8.3	2.054		1.956	12.0	92.8
Bay B	3	9.0	2.178	4.7	2.080	9.3	100.0
50WG_506F2		8.2	2.228		2.128	7.2	102.3
	4	7.4	2.199	4.7	2.100	8.4	101.0
		7.5	2.119		2.024	11.7	97.3
Bay C	5	10.7	1.941	3.9	1.868	15.5	99.9
100WG		10.5	1.930		1.858	16.0	99.3
	6	11.6	1.976	4.9	1.884	12.9	100.7
		10.6	1.937		1.847	14.6	98.7
Bay D	7	5.3	2.352	4.0	2.262	8.4	96.5
1006F2		5.7	2.333		2.243	9.2	95.7
	8	4.8	2.337	3.7	2.254	9.4	96.1
		4.9	2.243		2.163	13.1	92.3
Layer 2 (200mm)							
Bay A	1	9.6	2.060	5.2	1.958	11.5	93.2
50WG_50QW		8.3	2.079		1.976	10.7	93.2
	2	9.4	2.052	4.5	1.964	12.6	92.6
		8.5	2.132		2.040	9.2	96.2
Bay B	3	7.0	2.147	3.9	2.066	11.5	99.4
50WG_506F2		6.9	2.165		2.084	10.8	100.2
	4	7.6	2.176	3.8	2.096	10.5	100.8
		7.6	2.191		2.111	9.8	101.5
Bay C	5	9.9	1.945	3.9	1.872	15.3	100.1
100WG		10.1	1.959		1.885	14.7	100.8
	6	10.0	1.926	3.3	1.864	16.8	99.7
		9.2	1.945		1.883	16.0	100.7
Bay D	7	4.7	2.439	3.5	2.357	5.7	100.5
1006F2		4.5	2.375		2.295	8.2	97.9
	8	4.8	2.341	3.6	2.260	9.4	96.4
		4.8	2.394		2.311	7.3	98.6

increasing the bulk density in this manner would be to increase the associated dry density, reduce air void content, and increase relative compaction.

The second correction to the NDG data is due to the NDG's inability to record moisture contents of bituminous materials accurately. The NDG's moisture monitoring system relies on the slowing down of neutrons by the hydrogen molecules in water. As bitumen binders also contain hydrogen molecules, the NDG records erroneously high moisture contents, compared to the equivalent oven dried moisture contents. An approximation to the oven dried moisture content can be obtained by subtracting the bitumen content from the NDG moisture content of bituminous planings (Berg *et al.*, 1992; Yuille, 1996). Rather than use this approximation, oven dried moisture contents, measured in accordance with BS1377 (BSI, 1990), with the exception that the oven temperature was reduced to 40-50°C, were used in the calculation of dry density. The particle density and maximum dry density data generated for the equivalent laboratory materials and mixtures have been used to calculate air voids contents and relative compaction values.

Notwithstanding the absence of a field calibration for the NDG bulk density data, the compaction data indicate that the states of compaction achieved using the compactive effort of 6 and 12 machines passes for the 150mm and the 200mm layers respectively varied by a noticeable amount. For the Walgrey and quarry waste mixture (50WG_50QW), a large majority of the relative compaction values were below 95%, whilst the air voids content ranged between 9.2 and 12.6%. The states of compaction achieved for the Walgrey and Class 6F2 mixture (50WG_506F2) were slightly improved; relative compaction values ranged between 97.3 and 102.3% and air voids contents ranged between 7.2 and 11.7%. For the Walgrey planings (100WG), the relative compaction values were consistently high, indicating that the maximum density for the compactor used in the trial was likely to have been achieved. However, the associated air voids contents were significantly above the 10% value typically associated with a well compacted granular material. Previous research (Steele and Snowdon, 1995; MacNeil *et al.*, 1997; MacNeil *et al.*, 1998) has shown that, for bituminous planings, air voids contents of up to 20% can be achieved for relative compaction values ranging between 95 and 100%, (see Section 4.5). For the Class 6F2 (1006F2) material, which was in effect the standard control material, the compactive effort generally produced an excellent state of compaction; the exception was the final reading on Layer 1.

It is evident that the application of method specification for all four materials resulted in states of compaction which are broadly in agreement with the current requirement of the SHW (MCHW 1).

6.4.2 Bearing capacity

Whilst there are no bearing capacity related acceptability requirements specified in the SHW for capping, Clause 10.6 of HA 44 (DMRB 4.1.1) advises:

> *'The materials permitted for capping have been chosen to meet the requirement for a formation of CBR of greater than 15%.'*

To permit an evaluation of bearing capacity, DCP measurements were carried out on completion of construction and testing of the second capping layer. The DCP tests were performed close to the locations of the NDG tests, to a depth of approximately 600mm. A summary of the DCP data, analysed for each layer, is presented in Table 14. For the subgrade and the Class 6F2 material, the data have been converted to CBR using the Kleyn calibration for granular materials (Kleyn, 1975), whilst the DCP/CBR calibrations generated during the laboratory trials for this project have been used to convert the DCP data for the Walgrey bituminous planings and the two mixtures.

Table 14 Bearing capacity data from pilot scale trial

Layer description *Bay ID*	*Material/ mixture*	*DCP value (mm/blow)*	*Equivalent CBR (%)*
Subgrade			
Bay A	–	66.9	2.0
		76.9	1.7
Bay B	–	51.1	2.8
		88.5	1.4
Bay C	–	77.0	1.7
		94.0	1.3
Bay D	–	76.0	1.7
		74.5	1.7
Layer 1 (150mm)			
Bay A	50WG_50QW	7.5	20.1
		6.5	24.4
Bay B	50WG_506F2	6.4	25.0
		4.6	39.4
Bay C	100WG	9.0	8.4
		10.8	7.1
Bay D	1006F2	5.7	45.7
		4.4	63.5
Layer 2 (200mm)			
Bay A	50WG_50QW	7.8	19.0
		7.6	19.7
Bay B	50WG_506F2	6.3	25.5
		6.4	25.0
Bay C	100WG	7.9	9.5
		9.2	8.2
Bay D	1006F2	5.9	43.8
		5.9	43.8

From DCP testing, the estimation of CBR of the subgrade is typically less than half the value measured using the MEXE cone at the start of the construction of the trial (see Table 9). This is likely to be a result of the quasi-static loading applied by the MEXE cone, where a steady rate of penetration is applied throughout the test.

For each bay, both the DCP and CBR data are broadly consistent for layers 1 and 2. The highest bearing capacity of over 40% was calculated for the control Class 6F2 material (Bay D). Both the planings and fine granular mixtures (Bays A and B) resulted in CBR values typically ranging from 19 to 25%, values well above the recommended bearing capacity for capping. As discussed in Section 4.3, bituminous planings behave differently to granular material under DCP testing. For the Walgrey planings (Bay C), a bearing capacity of 8 to 9% is estimated from DCP testing, for what are considered to be well compacted bituminous planings.

6.5 Performance assessment devices

Three stiffness measuring devices were used for the performance assessment of the test materials. These were the Falling Weight Deflectometer (FWD), the German Dynamic Plate (GDP) and the Prima 100 (Prima). All these devices are basically 'falling weight devices', and are described in the following sections.

6.5.1 Falling Weight Deflectometer (FWD)

The Falling Weight Deflectometer (FWD), shown in Figure 10, consists of a dynamically loaded plate of either 0.45m or 0.3m diameter and associated geophones. The entire assembly is mounted on a trailer and operated from a suitable towing vehicle. The magnitude of the applied load can be adjusted either by changing the mass of the falling weights, or the height from which they are dropped. The geophones can be set at various distances from the centre of the circular plate.

Figure 10 FWD

The surface modulus, E (MPa), can be calculated from the FWD results using:

$$E = \frac{\pi q r \left(1 - \nu^2\right)}{2d} \qquad (1)$$

where: q = maximum pressure under plate (MPa)

r = radius of plate in metres (m)

ν = Poisson's ratio (assumed to be 0.45)

d = maximum deflection under centre of plate (m)

6.5.2 German Dynamic Plate (GDP)

This device, as shown in Figure 11, has a number of names, including the Dynamisches Plattendruckgerät, Light Weight Drop Tester and German Dynamic Plate. For ease of reference, this device is referred to herein as the German Dynamic Plate (GDP). The GDP essentially consists of two parts; the first is a loading plate and the second a loading device. The loading plate comprises the plate, acceleration sensor (geophone), protective rubber hood and a centring ball. The loading device consists of a dropping weight of 10kg mass, guide rod and release device. The dropping mass provides an impact force of 7.07kN, assuming a free falling mass. This impact is transmitted, via the centring ball, to the load plate which has a diameter of 300mm. The data acquisition system assumes that the stress imparted by each impact is equivalent to 100kPa. It is worth noting that the acceleration sensor cannot read beyond approx 2.54mm, thus on weak subgrades, typically below 5% CBR, the device reports a constant minimum value.

Figure 11 GDP

6.5.3 Prima 100 (Prima)

The Prima 100 (Prima), shown in Figure 12, is a more up to date version of the GDP. Building on experience gained in the design and use of the larger Falling Weight Deflectometer (FWD), the device is described by the manufacturers as a 'hand held FWD'. The Prima is of similar proportions to the GDP, having a drop mass of 10kg and a 300mm diameter load plate. Both the drop mass and plate diameter can be changed for different applications.

Figure 12 Prima

6.5.4 Comments on test devices

The main differences between these falling weight devices are in the positioning of sensors, extra data acquisition hardware and the information provided by the software. The Prima, in addition to a geophone to measure dynamic deflection, also has a load cell to measure actual impact forces, whereas the GDP assumes certain impact force parameters. The Prima data acquisition software, if required, can also collect time history data for each impact in addition to providing deflection, force and stress values for each drop. The geophone on the Prima is mounted through a hole in the plate, whereas the GDP transducer is mounted onto the plate itself. As the Prima transducer is in intimate contact with the ground, the transducer records the movement of the test material rather than the movement of the load plate. This has benefits, as the actual deflection of the material in response to an impact is measured, as opposed to the average deflection of the plate, which may be not be in flush contact with the test surface.

Some difficulties were encountered with the operation of the Prima whereby the device recorded data when no drops had taken place. The cause of this problem was eventually identified as the data cable connecting the device to the portable logging computer. Fortunately, the spurious data were highly evident in the data file, and were erased.

Equation 1 presented in Section 6.5.1 was used to derive the surface modulus for the FWD data. For the Prima and GDP, the surface moduli reported by these devices have been reported without further analysis. It should be noted that the surface modulus reported by both the Prima and the GDP are different to those which would be calculated by using the reported deflections and stresses in Equation 1. However, as the outputs of these systems tend to be reported in most literature on end performance testing, it was considered more appropriate to use the directly reported values.

6.6 Performance testing

As the specified performance tests were effectively non-destructive, on completion of sealing the subgrade, and compaction of both capping layers, these tests were carried out prior to undertaking the relatively destructive NDG tests (in direct transmission mode) and DCP tests detailed in Section 6.4. All performance tests were carried out at 6 locations in each bay; these location are shown on Figure 6.

At each location, a fixed sequence of testing was applied; the details are presented in Table 15.

Table 15 Test devices and testing order

Test order	Device	Subgrade	*1st 150mm* layer	*2nd 200mm* layer
1	MEXE cone penetrometer	✔	–	–
2	Falling Weight Deflectometer	✔	✔	✔
3	Prima 100	✔	✔	✔
4	GDP	✔	✔	✔
5	Falling Weight Deflectometer	✔	✔	✔
6	Nuclear Density Gauge	✔	✔	✔
7	Dynamic Cone Penetrometer	–	–	✔

In order to assess whether material stiffness properties had been altered by using the FWD, the Prima and the GDP, the FWD testing was repeated at the end of the test sequence. All testing was carried out in the plate footprints created by the initial FWD tests.

The FWD testing was initially undertaken on the subgrade using a 300mm diameter plate. However, even at the lowest stress level, the resultant deflections were above the minimum of the geophones calibrated range. Accordingly, a larger 450mm diameter plate was used on the FWD to assess the subgrade. The 300mm diameter plate was replaced for the subsequent testing on each of the capping layers.

Both the FWD and Prima testing was carried out at three drop heights. This enabled the surface modulus value at three stress levels to be calculated and any stress dependency of the material under test to be evaluated. The GDP is designed to operate at only one nominal stress level. The lowest stress achieved by the FWD coincided with the highest stress achievable with the Prima and the nominal stress for the GDP.

6.7 Analysis of performance testing

Full results of the performance testing undertaken using the falling weight devices are presented in Appendix C and the data are summarised in Table 16. From the data set presented in Appendix C, it is evident that the individual surface modulus values obtained from the initial and final FWD tests were broadly similar. This confirms that initial FWD testing, followed by both Prima and GDP testing, did not significantly alter the stiffness characteristics of the materials under test.

Table 16 Summary of performance testing

		Surface modulus, E, for Subgrade (MPa)					*Surface modulus, E, for Layer 1 (MPa)*					*Surface modulus, E, for Layer 2 (MPa)*			
Device		*A*	*B*	*C*	*D*		*A*	*B*	*C*	*D*		*A*	*B*	*C*	*D*
Test position	*Mean stress (kPa)*	*50WG_ 50QW*	*50WG_ 506F2*	*100WG*	*1006F2*	*Mean stress (kPa)*	*50WG_ 50QW*	*50WG_ 506F2*	*100WG*	*1006F2*	*Mean stress (kPa)*	*50WG_ 50QW*	*50WG_ 506F2*	*100WG*	*1006F2*
FWD (After other plate tests)															
1	76	11.3	10.0	12.2	8.9	103	14.9	11.3	16.7	10.9	112	43.9	36.6	46.2	37.4
2		6.5	7.9	9.0	8.3		13.0	11.4	15.4	13.1		43.2	37.3	46.0	36.8
3		7.5	6.6	6.7	6.4		13.0	11.2	8.8	12.6		37.8	34.1	36.8	31.9
4		8.7	9.2	13.2	6.7		16.2	12.1	17.7	13.2		44.7	40.7	55.5	43.3
5		8.8	7.2	6.8	8.5		16.7	11.3	14.8	15.1		47.0	40.8	52.2	41.5
6		7.0	7.3	9.0	7.0		13.0	12.0	15.5	17.3		41.8	36.9	53.2	40.8
	Mean	8.3	8.0	9.5	7.6	Mean	14.5	11.5	14.8	13.7	Mean	43.1	37.7	48.3	38.6
Prima															
1	85.6	6.6	3.0	16.1	11.4	92.4	14.7	11.5	17.7	13.3	97.2	52.3	45.7	70.7	43.1
2		4.6	6.7	11.6	6.8		13.4	12.8	19.3	15.3		48.7	53.2	69.2	46.7
3		4.8	4.7	5.8	3.6		13.4	11.4	9.7	16.6		45.9	46.2	48.1	36.7
4		5.9	6.7	12.2	6.0		17.7	15.6	17.9	15.5		64.7	61.9	73.4	64.4
5		5.9	7.6	5.1	5.0		18.8	13.6	14.8	17.1		71.6	59.7	73.7	55.7
6		3.1	N/A	12.3	11.9		12.9	15.3	16.3	19.7		62.2	59.7	75.1	59.5
	Mean	5.2	5.7	10.5	7.4	Mean	15.1	13.4	15.9	16.3	Mean	57.5	54.4	68.3	51.0
GDP															
1	100	8.9	8.9	10.1	10.2	100	15.8	12.6	19.1	15.0	100	54.9	50.0	62.5	46.9
2		8.9	8.9	9.8	8.9		14.5	13.1	21.6	18.0		56.3	50.0	97.8	34.6
3		8.9	8.9	8.9	8.9		14.9	12.2	8.9	16.9		48.9	40.2	56.3	38.8
4		8.9	8.9	8.9	8.9		20.3	15.8	16.2	18.6		68.2	56.3	64.3	44.1
5		8.9	8.9	8.9	8.9		21.6	14.2	17.3	20.1		54.9	52.3	64.3	52.3
6		8.9	8.9	8.9	8.9		13.6	15.7	17.6	25.0		54.9	54.9	75.0	44.1
	Mean	8.9	8.9	9.2	9.1	Mean	16.8	13.9	16.8	18.9	Mean	56.4	50.6	70.0	43.5

Plots of surface modulus for the three falling weight devices are presented in Figures 13a, 13b and 13c. In terms of the relatively weak subgrade, differences in the surface modulus recorded with the three falling weight devices are minor; typical surface modulus values ranged from 5 to 10MPa. It should be noted that only 3 of the 24 readings taken with the GDP were above its lower recording limit of 8.9MPa. As such, the GDP could not be used to evaluate the stiffness of the subgrade in a meaningful way. The data for the 150mm capping layer also shows consistency between the data recorded using all three of the falling weight devices; typical surface modulus values ranged from 10 to 20MPa. However, for the combined 350mm capping layer, it is clear that the FWD consistently recorded the lowest modulus values, typically ranging from approximately 37 to 48MPa. Data recorded using both the Prima and the GDP typically ranged between 44 and 70MPa. Differences between the data generated using the Prima and the GDP were generally small, but the contours of Prima data were more similar in shape to the FWD data than to the GDP data.

To highlight the range of data recorded by the three falling weight devices, stress versus surface modulus data are plotted in Figures 14a to 14d. Data are plotted for the three drop heights for both the FWD and the Prima, whilst the GDP operates at one stress level. The data for the subgrade are reasonably consistent for all four bays. The main point of note is the wider scatter typically generated using the Prima, particularly for layer 2. Prima and GDP versus FWD modulus values are plotted in Figure 15. Linear regression produces good fits and is in agreement with data reported by Fleming *et al.* (2000).

A summary of the data recorded during the pilot scale trial is presented in Figure 16. Of some note is the fact that the performance testing highlights the improvement in surface modulus as a result of the addition of the second, nominal 200mm, layer. This improvement was consistent for all four bays and may reflect the fact that falling weight devices record material performance over a depth greater than that of the layer being tested. Hence, the recorded modulus of the layer 1 material may be lower because of the presence of the subgrade. From the compaction related data, it was evident that the control Class 6F2 could arguably be judged as the most sound material for use as capping. For all the bays, the compaction data do not accurately reflect the trends in the performance data. This is not surprising, as the performance and the traditional compaction assessments record entirely different aspects of the material under test. For example, the compaction assessment for the planings appears to be poor, though experience suggests that the state of compaction of the planings could not be significantly improved. Conversely, the performance assessment suggests that the planings performance may be assumed to be as good as the other three test materials.

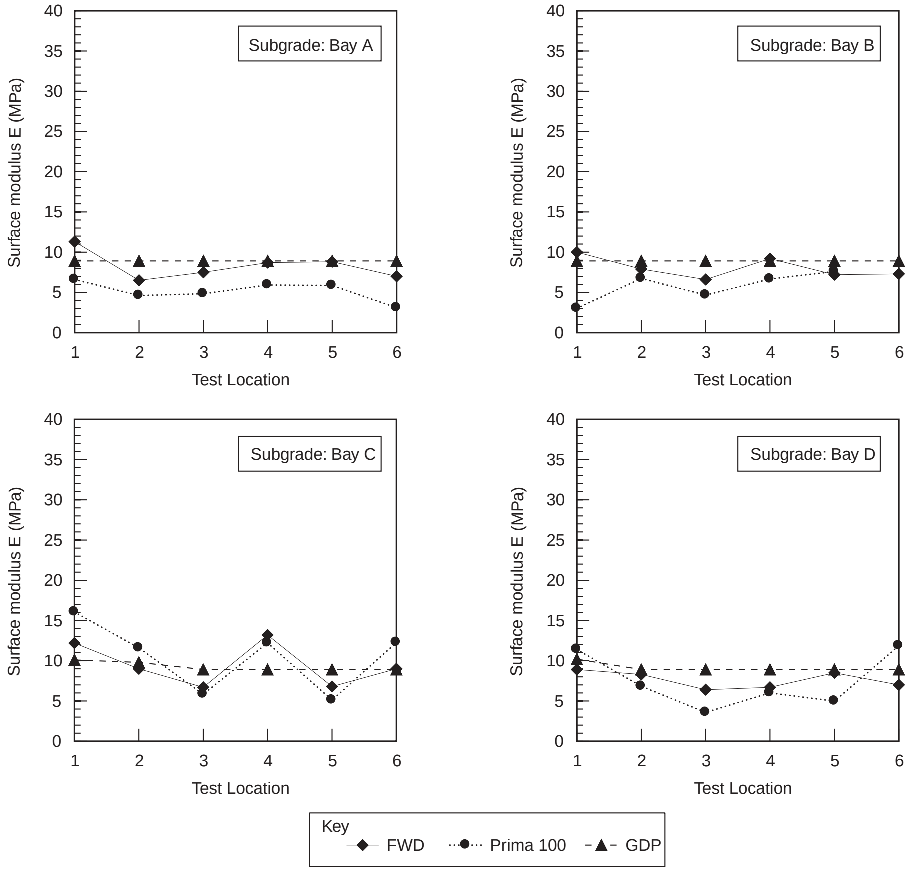

Figure 13a Subgrade surface modulus

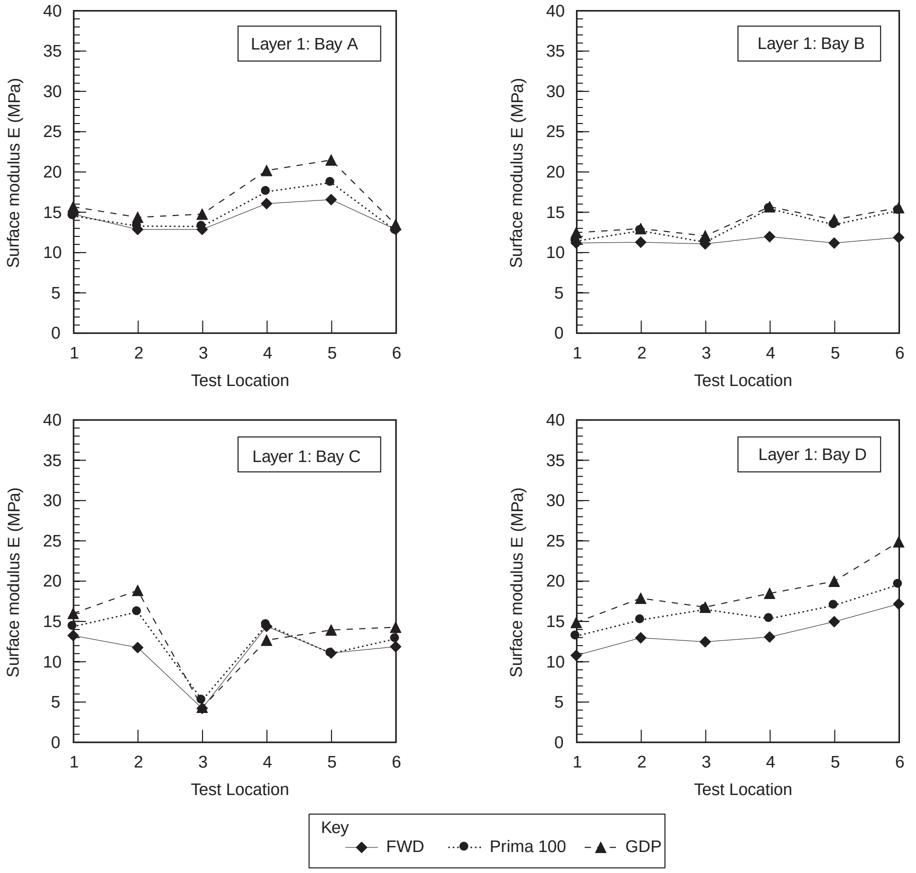

Figure 13b Layer 1 surface modulus

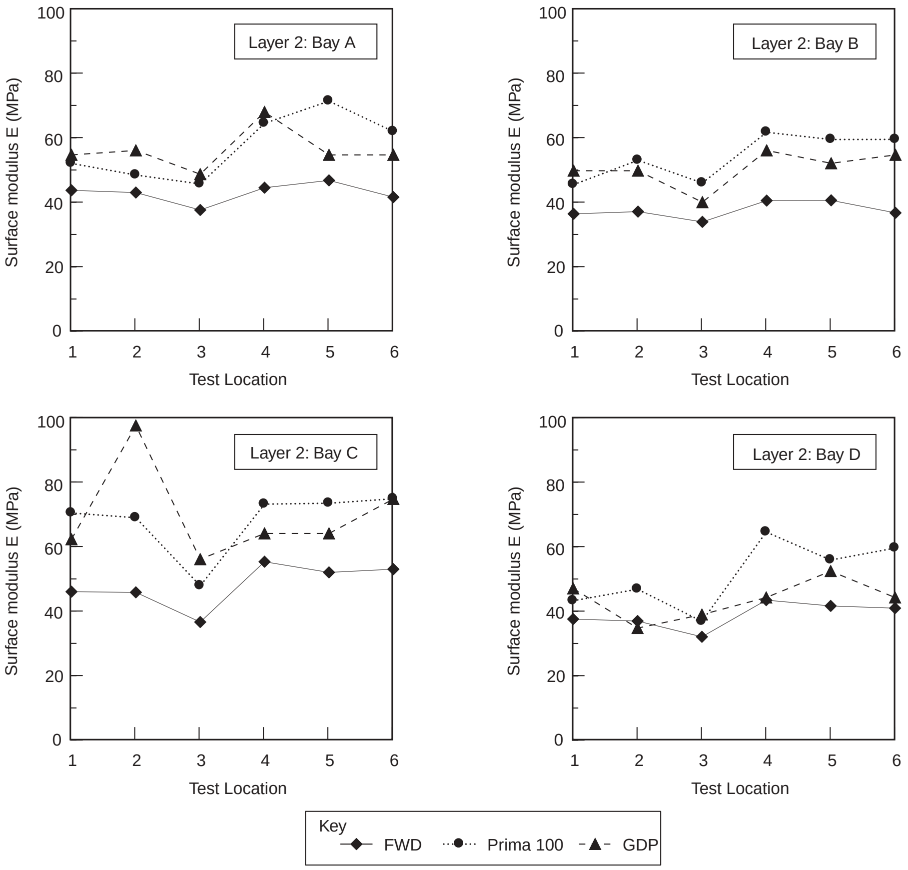

Figure 13c Layer 2 surface modulus

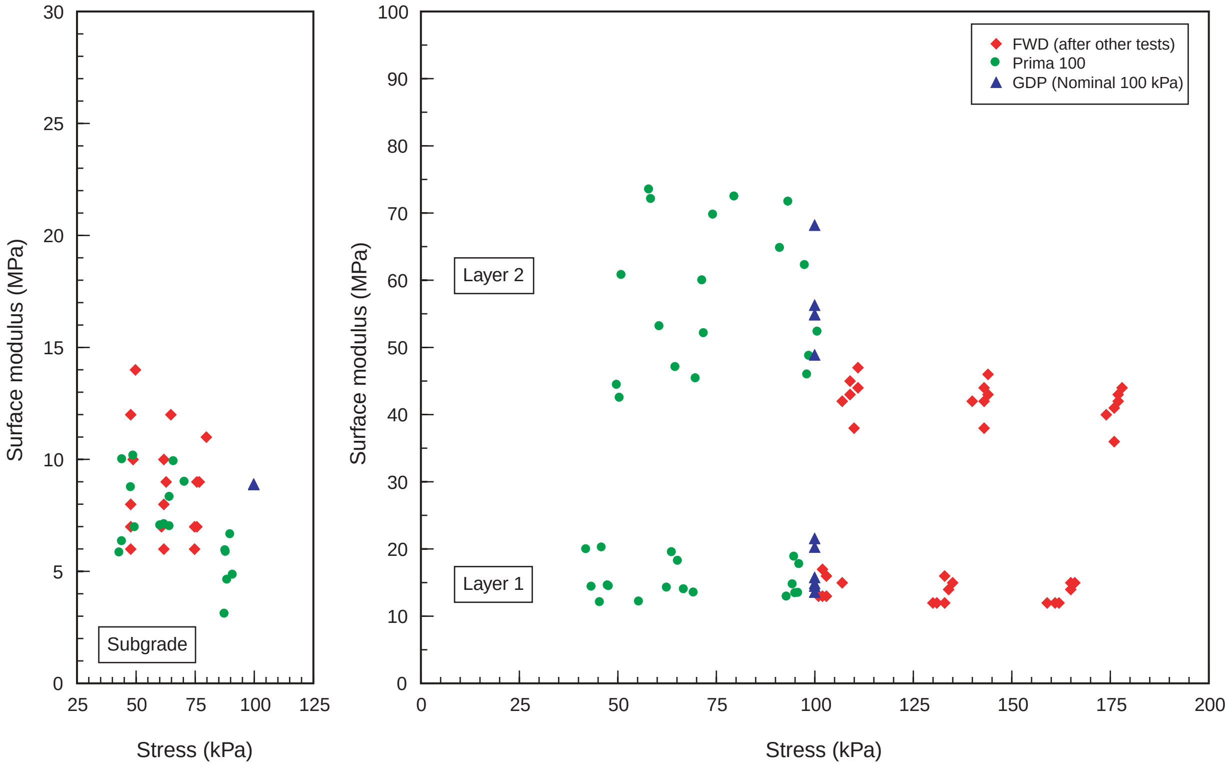

Figure 14a Variation of surface modulus with stress for Bay A

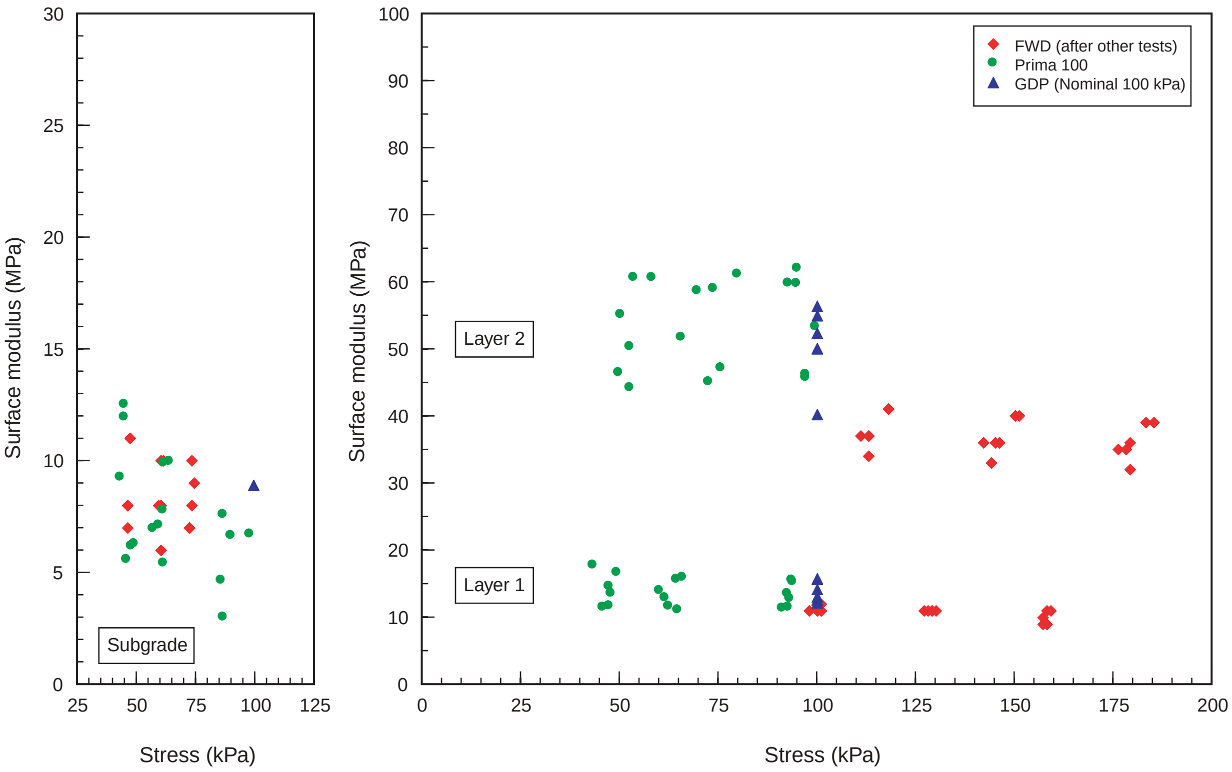

Figure 14b Variation of surface modulus with stress for Bay B

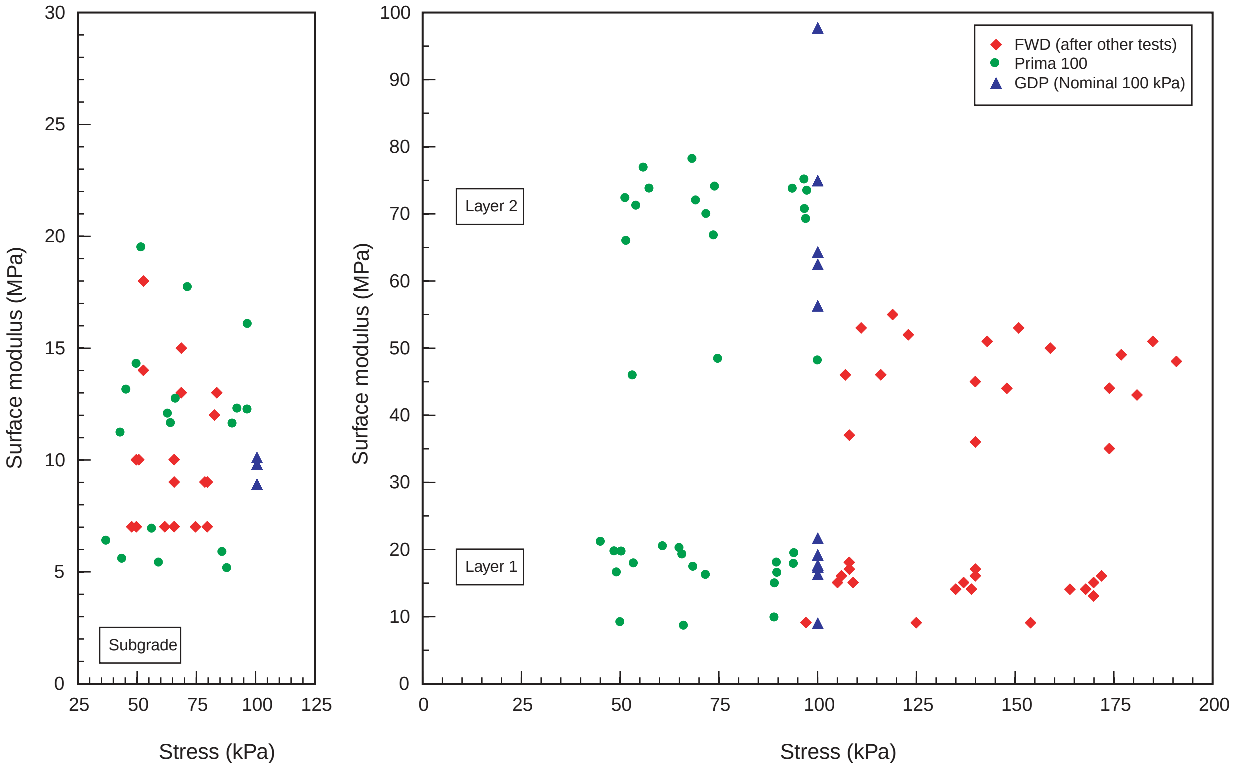

Figure 14c Variation of surface modulus with stress for Bay C

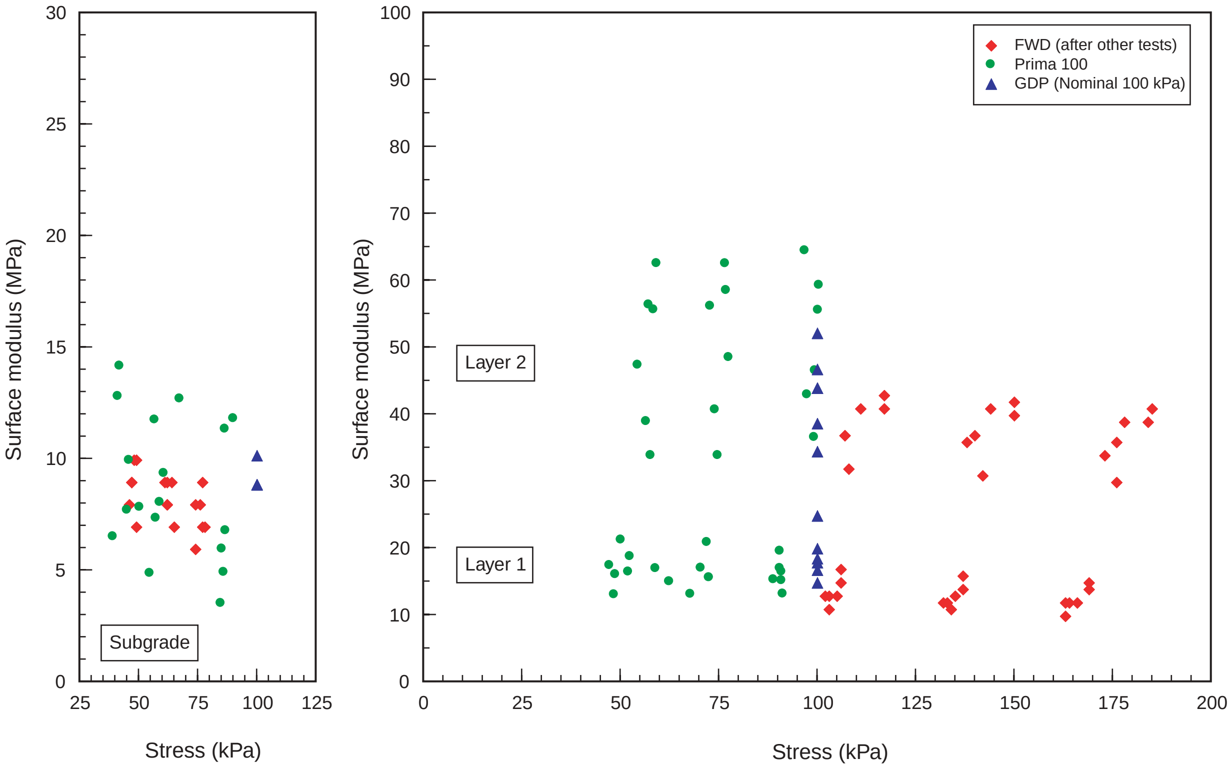

Figure 14d Variation of surface modulus with stress for Bay D

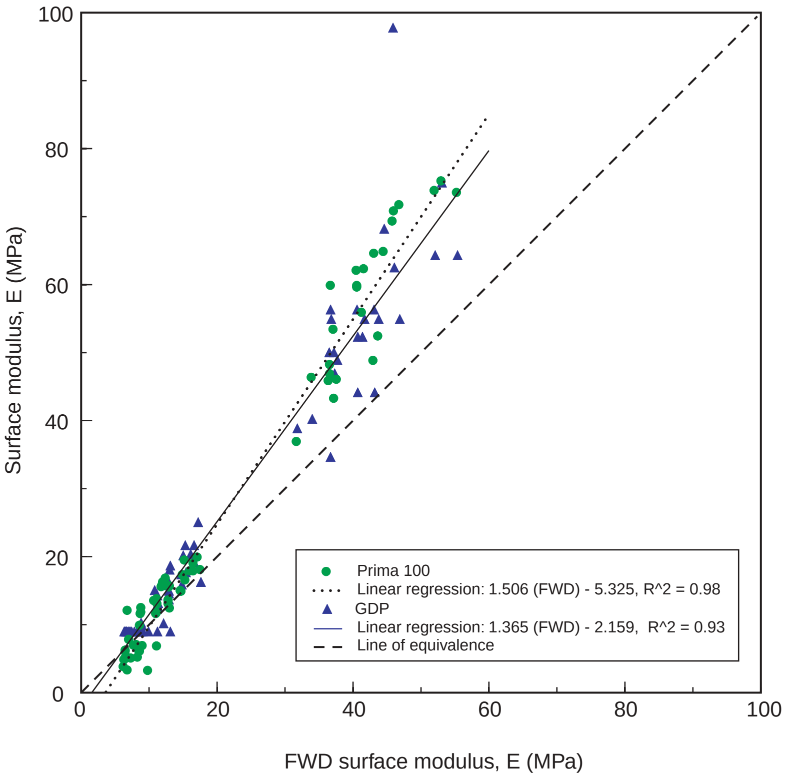

Figure 15 Prima and GDP versus FWD surface modus

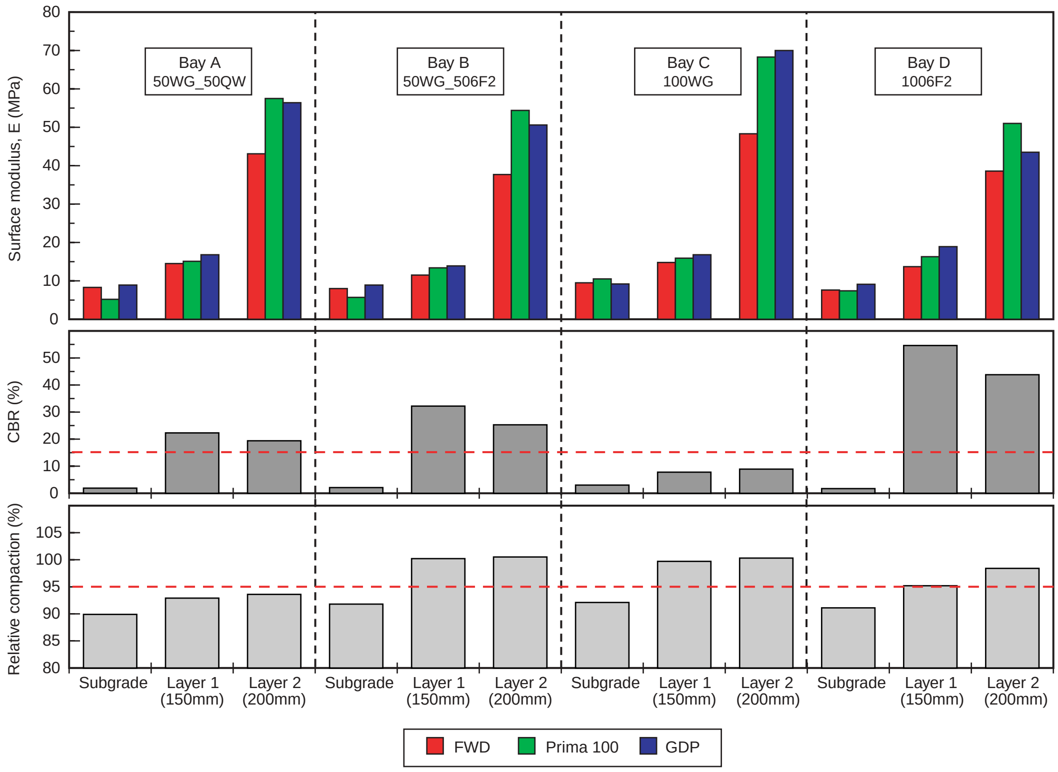

Figure 16 Summary of data from pilot scale trial

7 Discussion

The application of either a compaction or a performance based assessment methodology for formation applications clearly has strengths and weaknesses; some of the issues highlighted by the testing undertaken for this project are briefly discussed below.

In a compaction, or method based approach, reliance is placed on the formation to provide a sufficient platform on which to place and compact sub-base (see LR 1132, 1984) and the designer needs to assess the bearing capacity of the subgrade. CBR is described in HA 44 (DMRB 4.1.1) as an index of bearing ratio used to indirectly measure soil strength and stiffness. It is well recognised that soil type and condition influence the ability of the CBR test to measure these attributes (Croney and Croney, 1991). The test is more effective on fine-grained soils, as the laboratory test samples are more representative of *in situ* conditions. In HA 44, CBR is described as being 'not wholly satisfactory', probably due to poor correlations between laboratory data and *in situ* data, especially for coarse granular materials, and the fact that the data generated do not feed directly into theoretical models for pavement design. The difficulty of assessing CBR via DCP testing was highlighted during the pilot scale trial. However, the benefits are that the CBR test is simple and inexpensive, and has well established methods of correlation to other significant soil properties. Following an evaluation of subgrade strength, the combination of specified capping materials and thicknesses, and prescribed states of compaction, are intended to produce the required bearing capacity at formation level. State of compaction is best assessed by air voids content and relative compaction, which is a measure of the *in situ* dry density relative to maximum dry density, measured by the appropriate laboratory compaction test (Parsons, 1992).

A particular benefit of the method specification is that the performance of different compaction plant types, for different earthwork applications, have been assessed in the development of the specification. Providing material properties have been assessed correctly during suitability and acceptability testing, and the appropriate type and class (measured via mass per metre width of drum roll) of compactor is used, in accordance with the manufacturer's instructions and following the number of passes specified in Table 6/4 of the SHW (MCHW 1), an appropriate state of compaction will be produced. An apparent drawback of using a method specification is that the data specifying the level of compaction required for individual applications have conservative margins built in. This is a consequence of the level of compaction being specified to reflect compaction requirements of the materials at the dry end of the acceptable range of moisture content: achieving an appropriate air voids content requires more compactive effort at the dry end compared to the wet end, where moisture acts as a lubricant between soil particles. It may be argued that this apparent drawback ensures that satisfactory states of compaction are achieved for all soils within their acceptable moisture content ranges, and thereby benefits the long term durability of earthworks.

It is often considered that the method specification in its current form has been developed solely with the aim of ensuring adequate states of compaction for the materials which meet the specified suitability and acceptability requirements. This however is not the only aim of the method specification. As described in HA 44 (DMRB 4.1.1):

> *'The main objective of acceptability assessment is to enable the scheme to be constructed to a satisfactory standard of design and longevity for the minimum cost. This requires the maximum use of on-site or locally available materials, and setting specifications for imported materials which are adequate for performance but not unnecessarily restrictive thereby incurring increased costs.'*

As such, the current emphasis for construction of earthworks is based on achieving:

i a minimum short-term performance, which is basically achieving sufficient shear strength to permit continuation of construction. In Clause 4.14 of HA 44, a lower limit shear strength of 30-50kN/m^2 is recommended for cohesive materials; this limit is based on trafficability for construction plant and stability of the capping material,

ii an acceptable state of compaction, to ensure long-term durability. In this context, durability refers to:

  a the resistance of the material to changes in its moisture and pore water pressure regime; typically, the main concern is wetting up, which often will result in softening and/or swelling of cohesive materials, and

  b the resistance to deformation of the earthwork as a consequence of long-term settlement, via consolidation of cohesive soils, and, to a lesser extent, granular soils.

Whilst earthwork materials are of low quality, and should be viewed as highly variable, heterogeneous materials, current requirements specify that earthworks should have a design life of 60 years, i.e. earthworks are not designed for short term replacement. It is possible that any significant problems with earthworks, due either to poor construction control, or inadequate design, could result in expensive remedial works. In contrast, non-earthwork materials used in the pavement structural layers are high quality, homogeneous engineering products. In the past, the sub-base layer had a design life of 20 years; this requirement has recently been increased to 40 years. The economic consequences of a sub-base failure, compared to a significant earthwork failure below formation, are relatively modest.

The prescriptive method based approach may be considered to restrict the use of more innovative materials in capping applications. However, experience has shown that the method specification can be readily adapted to include new materials (e.g. recycled bituminous planings) and techniques (e.g. treatment with lime and cement). Also, inherent in the method specification is the feedback of many years of site experience of materials which perform well. Whilst the use of innovative materials is desirable, until such materials have a proven performance record, there will be an associated increase in risk in using such materials, which may be sufficient to discourage their use.

The performance, or stiffness measurement approach to formation is driven principally by the desire to apply a performance specification in the upper layers of the pavement. In terms of whole pavement analysis, a common application of elastic stiffness modelling may be desirable.

The use of performance criteria may encourage a wider use of marginal and recycled materials and, provided the client is assured of the quality of the product prior to the subsequent construction of the structural layers of the pavement, may permit innovative approaches to the construction of pavement foundations.

Compared to materials used in the structural layers, a considerably wider range of natural and man-made materials are used in formation applications, and have associated with them a wide range of performance. The most obvious environmental influence on performance is weather related. Wetting up or drying out of moisture from a compacted layer may occur; this would have most influence at the top surface of a compacted layer. This has significant implication for performance testing, which is significantly dependent on boundary conditions between the test device and the material under test. Performance testing also needs to cover the issue of cross correlating the multiple devices currently available; variances between the devices were highlighted during the pilot scale trials and are widely recognised in the literature on performance testing. At present, it could be said that there is a lack of consensus as to which method most closely measures a representative value of modulus. Unlike CBR and shear strength, very few engineers have a hands-on feel for estimating stiffness or modulus values (Ground Engineering, 1999).

It is likely that the most effective way forward in terms of formation construction and assessment will rely on a combination of compaction and performance methodologies. There is no direct relation between density and stiffness/modulus, and therefore any relation will be highly conditional and exist only within the context of other parameters such as moisture content, void ratio and stress. Based on stiffness gain with accumulated compactive effort, which is in effect a measure of relative stiffness, Main (2000) proposed a useful method of utilising performance testing to evaluate optimum compaction:

> *‘At the beginning of a job, establish a nominal roller pattern for each material layer by monitoring the stiffness gain with each pass or set of passes using the end performance device. When the percentage gain in stiffness relative to the first pass remains approximately constant, the compaction is optimised as much as the supporting material below will allow. Applying compactive effort beyond this point will most likely damage or degrade the layer and the layers below as most of the stress is going into something other than compacting the top layer.*
>
> *This same method can be used to control the compaction of each highway section. Using the nominal pattern as a guide, passes can be added or subtracted from the pattern as indicated by the rate of stiffness gain of each section. In this way the compaction process can be controlled to assure optimum compaction the first time. If the compaction is done at optimum moisture content, then the maximum dry density, the required percent compaction and the required void ratio could be achieved. This method of controlling compaction should work for soils, aggregates and asphalt.’*

It is considered important that the application of any performance methodology for formation considers engineering requirements not only from a structural perspective of the pavement, but also in terms of the limitation of the materials commonly used as subgrade and capping. To avoid potential long term problems, the good practise used to build the method specification for earthworks in its current form should not be wholly abandoned.

8 Conclusions

A study has been undertaken to assess both the laboratory and *in situ* performance of mixtures of recycled bituminous planings and other granular materials. The findings of the study are:

1. A literature review resulted in only a limited amount of data on the use of recycled bituminous planings, and no significant technical data on the use of bituminous planings and granular material mixtures. Discussions within the industry have shown that there is some experience of using blacktop and granular material blends successfully.
2. Laboratory test data, generated from a comprehensive suite of standard compaction tests, particle size distributions, and compressibility testing using a Rowe cell, have been used to identify a lower bitumen content of 2% which enables mixtures containing bituminous planings to be classified into a new capping sub-class within the SHW. An outline of the classification and compaction requirements for this proposed Class 6F4 is presented in the report.
3. A pilot scale trial of certain mixtures used in the laboratory work was constructed and assessed for compliance using compaction and stiffness based methodologies. The benefits and disadvantages of each method are discussed: overall it is considered that a compaction based method is more applicable to the proposed Class 6F4 material.

9 Acknowledgements

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Appendix A: Laboratory compaction, CBR and DCP data

Table A1 Class 6F2 compaction data

Material	*Test ID*	*Particle density (Mg/m^3)*	*Test level*	*Moisture content (%)*	*Dry density (Mg/m^3)*	*Air voids (%)*
Class 6F2	1006F2	2.74	1	1.5	2.166	17.7
			2	2.0	2.126	18.1
			3	3.3	2.203	12.3
			4	4.9	2.329	3.6
			5	5.9	2.344	0.7

Table A2 Redland planings and Class 6F2 compaction data

Materials Test ID	*Particle density (Mg/m^3)*	*Test level*	*Moisture content (%)*	*Dry density (Mg/m^3)*	*Air voids (%)*
Redlands + Class 6F2					
25R_756F2	2.68	1	1.6	2.017	21.5
		2	3.4	2.045	16.7
		3	3.7	2.012	17.5
		4	5.2	2.027	13.9
		5	6.0	1.997	13.5
		6	6.3	2.008	12.5
50R_506F2	2.55	1	1.4	1.992	19.1
		2	3.0	1.954	17.5
		3	4.7	2.000	12.2
		4	5.7	2.044	8.2
		5	7.8	2.021	5.1
100R	2.42	1	0.9	1.848	22.0
		2	2.3	1.849	19.3
		3	3.2	1.866	16.9
		4	3.8	1.888	14.8
		5	5.2	1.949	8.7
		6	5.3	1.963	8.5
		7	7.4	1.959	4.6
		8	12.7	1.868	-0.9

Table A3 Pryor planings and Class 6F2 compaction data

Materials Test ID	*Particle density (Mg/m^3)*	*Test level*	*Moisture content (%)*	*Dry density (Mg/m^3)*	*Air voids (%)*
Pryors + Class 6F2					
25P_756F2	2.60	1	2.6	2.066	15.2
		2	3.5	2.102	11.9
		3	4.9	2.067	10.5
		4	5.4	2.099	8.0
		5	7.4	2.075	4.9
		6	7.6	2.071	4.5
50P_506F2	2.65	1	1.6	1.998	21.3
		2	3.4	2.040	16.1
		3	4.2	2.089	12.5
		4	5.1	2.132	8.8
		5	5.2	2.131	8.5
		6	8.0	2.100	4.0
100P	2.46	1	2.0	1.883	19.7
		2	4.8	1.983	9.9
		3	7.0	2.003	4.6
		4	7.7	2.024	2.1
		5*	10.3	1.991	-1.4

Table A4 Walblack planings and Class 6F2 compaction data

Materials Test ID	*Particle density (Mg/m^3)*	*Test level*	*Moisture content (%)*	*Dry density (Mg/m^3)*	*Air voids (%)*
Walblack + Class 6F2					
25WB_756F2	2.66	1	2.3	2.056	17.9
		2	2.6	2.088	16.1
		3	3.7	2.129	12.2
		4	4.6	2.079	12.4
		5	5.2	2.141	8.4
		6	6.1	2.147	6.1
50WB_506F2	2.61	1	2.3	1.999	18.7
		2	3.7	1.969	17.3
		3	4.3	2.016	14.1
		4	5.5	2.002	12.2
		5	6.5	1.968	11.9
		6	7.4	1.941	11.4
100WB	2.45	1	2.2	1.844	20.7
		2	2.2	1.828	21.3
		3	3.5	1.829	18.9
		4	4.7	1.814	17.4
		5	4.8	1.855	15.4
		6	6.0	1.845	13.6
		7	7.4	1.826	11.9

Table A5 Walgrey planings and Class 6F2 compaction data

Materials Test ID	*Particle density (Mg/m^3)*	*Test level*	*Moisture content (%)*	*Dry density (Mg/m^3)*	*Air voids (%)*
Walgrey + Class 6F2					
25WG_756F2	2.68	1	2.2	2.100	17.4
		2	3.3	2.079	15.8
		3	4.0	2.051	15.6
		4	5.2	2.113	10.4
		5	6.0	2.053	11.5
		6	5.3	2.078	11.8
50WG_506F2	2.57	1	2.2	2.002	17.8
		2	3.1	2.069	13.1
		3	3.4	2.047	13.5
		4	4.7	2.071	9.6
		5	4.9	2.077	9.1
		6	7.1	2.042	6.1
100WG	2.42	1	1.5	1.838	21.3
		2	2.6	1.820	20.0
		3	3.7	1.840	17.2
		4	4.0	1.861	15.6
		5	4.6	1.861	14.6
		6	7.5	1.819	11.1

Table A6 Walgrey planings and sand compaction data

Materials Test ID	*Particle density (Mg/m^3)*	*Test level*	*Moisture content (%)*	*Dry density (Mg/m^3)*	*Air voids (%)*
Walgrey + sand					
25WG_75S	2.54	1	3.6	1.969	15.4
		2	6.1	2.202	-0.2
		3	6.8	2.170	-0.1
		4	8.3	2.136	-1.8
		5	10.3	2.083	-3.4
50WG_50S	2.52	1	3.5	2.010	13.2
		2	4.0	2.066	9.9
		3	4.9	2.118	5.5
		4	7.1	2.138	0.3
		5	8.5	2.126	-2.5
100S	2.69	1	5.0	1.995	15.9
		2	5.8	2.061	11.4
		3	7.7	2.188	1.8
		4	9.0	2.099	3.0
		5	11.0	1.993	4.1

Table A7 Walgrey planings and crushed brick compaction data

Materials Test ID	*Particle density (Mg/m^3)*	*Test level*	*Moisture content (%)*	*Dry density (Mg/m^3)*	*Air voids (%)*
Walgrey + crushed brick					
25WG_75CB	2.47	1	9.2	1.595	20.8
		2	12.1	1.575	17.1
		3	14.9	1.518	15.6
		4	15.1	1.557	13.8
		5	19.6	1.566	5.9
		6	21.6	1.575	2.2
50WG_50CB	2.53	1	6.4	1.695	22.2
		2	9.9	1.671	17.4
		3	9.8	1.678	17.3
		4	12.4	1.670	13.3
		5	12.9	1.639	14.1
		6	16.6	1.695	4.9
100CB	2.62	1	8.8	1.420	33.3
		2	13.2	1.412	27.4
		3	17.4	1.379	23.4
		4	21.4	1.388	17.3
		5	25.4	1.482	5.9

Table A8 Walgrey planings and quarry waste compaction data

Materials Test ID	*Particle density (Mg/m^3)*	*Test level*	*Moisture content (%)*	*Dry density (Mg/m^3)*	*Air voids (%)*
Walgrey + quarry waste					
25WG_75QW	2.58	1	1.9	2.008	18.3
		2	3.5	2.013	14.8
		3	4.9	2.106	8.0
		4	5.1	2.127	6.6
		5	5.5	2.155	4.5
50WG_50QW	2.50	1	2.1	1.997	15.9
		2	3.7	2.005	12.4
		3	3.9	2.118	6.9
		4	4.4	2.081	7.5
		5	4.9	2.162	2.8
100QW	2.66	1	4.7	1.897	19.7
		2	5.9	1.977	14.0
		3	7.6	2.071	6.4
		4	8.6	2.037	5.9
		5	9.1	2.080	2.9

Table A9 Class 6F2 CBR and DCP data

Materials		*Moisture content (mix)*	*Dry density*	*Air voids content*	*Moisture content (after test)*	*CBR*		
Test ID	*Test level*	*(%)*	*(Mg/m^3)*	*(%)*	*(%)*	*Top (%)*	*Base (%)*	*DCP (mm/blow)*
Class 6F2								
1006F2	85	3.8	2.038	20.8	3.8	35.3	34.8	10.8
	95		2.293	10.9	3.9	125.0	99.6	3.9
	105		2.443	5.1	4.0	305.0	na	2.5

Table A10 Redlands planings and Class 6F2 CBR and DCP data

Materials		*Moisture content (mix)*	*Dry density*	*Air voids content*	*Moisture content (after test)*	*CBR*		
Test ID	*Test level*	*(%)*	*(Mg/m^3)*	*(%)*	*(%)*	*Top (%)*	*Base (%)*	*DCP (mm/blow)*
Redlands + Class 6F2								
25R_756F2	85	3.8	1.786	26.6	3.7	6.3	7.2	23.00
	95		1.955	19.7	3.7	15.5	17.7	6.43
	105		2.123	12.8	3.6	73.9	80.5	3.53
50R_506F2	85	6.5	1.757	19.7	5.7	4.8	4.3	15.70
	95		1.915	12.5	6.3	13.2	14.2	8.47
	105		2.105	3.8	6.1	32.4	40.8	3.43
100R	85	6.1	1.702	19.3	6.3	5.9	6.2	11.15
	95		1.854	12.2	6.5	12.5	10.7	5.58
	105		1.948	7.7	6.5	16.6	16.9	3.19

Table A11 Pryors planings and Class 6F2 CBR and DCP data

Materials		*Moisture content (mix)*	*Dry density*	*Air voids content*	*Moisture content (after test)*	*CBR*		
Test ID	*Test level*	*(%)*	*(Mg/m^3)*	*(%)*	*(%)*	*Top (%)*	*Base (%)*	*DCP (mm/blow)*
Pryors + Class 6F2								
25P_756F2	85	3.5	1.904	20.1	4.1	9.3	27.6	13.9
	95		2.136	10.3	3.7	67.9	72.7	6.65
	105		2.193	7.9	3.5	67.9	115.6	5.39
50P_506F2	85	5.2	1.890	13.1	3.0	26.2	18.9	14.2
	95		2.010	13.6	2.8	51.7	64.6	4.13
	105		2.023	18.8	2.6	53.3	69.8	5.29
100P	85	6.4	1.829	19.1	3.6	9.3	8.9	11.1
	95		2.012	12.3	3.0	23.1	28.3	5.04
	105		2.024	11.2	3.2	23.5	20.5	5.78

Table A12 Walblack planings and Class 6F2 CBR and DCP data

Materials		*Moisture content (mix)*	*Dry density*	*Air voids content*	*Moisture content (after test)*	*CBR*		
Test ID	*Test level*	*(%)*	*(Mg/m^3)*	*(%)*	*(%)*	*Top (%)*	*Base (%)*	*DCP (mm/blow)*
Walblack + Class 6F2								
25WB_756F2	85	na	2.018	11.0	6.5	28.8	23.2	8.5
	95		2.114	7.8	6.0	49.6	45.9	4.7
	105		2.126	9.9	4.8	48.7	63.4	4.9
50WB_506F2	85	na	1.857	15.7	7.1	14.2	12.0	9.1
	95		1.849	16.0	7.1	14.5	25.0	5.2
	105		1.944	12.9	6.5	27.3	37.6	5.4
100WB	85	na	1.654	21.3	6.8	4.9	4.5	13.6
	95		1.766	15.7	6.9	7.6	7.2	7.1
	105		1.759	16.6	6.6	7.5	8.1	8.6

Table A13 Walgrey planings and Class 6F2 CBR and DCP data

Materials		*Moisture content (mix)*	*Dry density*	*Air voids content*	*Moisture content (after test)*	*CBR*		
Test ID	*Test level*	*(%)*	*(Mg/m^3)*	*(%)*	*(%)*	*Top (%)*	*Base (%)*	*DCP (mm/blow)*
Walgrey + Class 6F2								
25WG_756F2	85	na	1.857	20.8	5.5	6.2	8.2	16.5
	95		2.106	9.7	5.7	17.7	13.2	7.3
	105		2.219	4.4	5.9	56.2	55.6	3.9
50WG_506F2	85	na	1.868	15.2	6.5	8.8	10.4	14.4
	95		2.038	8.9	5.8	38.3	31.0	4.9
	105		2.115	4.6	6.2	51.7	48.4	3.1
100WG	85	na	1.624	21.9	6.8	3.2	4.0	21.2
	95		1.859	11.3	6.4	13.3	11.8	5.6
	105		1.887	10.5	6.1	10.8	15.0	4.5

Table A14 Walgrey planings and sand CBR and DCP data

Materials		*Moisture content (mix)*	*Dry density*	*Air voids content*	*Moisture content (after test)*	*CBR*		
Test ID	*Test level*	*(%)*	*(Mg/m^3)*	*(%)*	*(%)*	*Top (%)*	*Base (%)*	*DCP (mm/blow)*
Walgrey + sand								
25WG_75S	85	6.4	1.837	16.0	6.8	4.3	4.4	15.0
	95		2.103	3.9	6.4	48.3	39.0	8.4
	105		2.145	1.9	6.3	47.5	75.4	4.5
50WG_50S	85	6.1	1.821	16.7	5.2	7.3	4.6	15.6
	95		2.049	6.2	5.6	29.1	20.5	6.8
	105		2.111	3.4	5.0	50.8	57.7	3.6
100S	85	8.8	1.856	14.7	8.9	6.3	4.9	18.9
	95		2.031	6.7	8.6	28.6	16.4	17.9
	105		2.243	-3.1	7.7	50.0	92.3	12.0

Table A15 Walgrey planings and crushed brick CBR and DCP data

Materials		*Moisture content (mix) (%)*	*Dry density (Mg/m^3)*	*Air voids content (%)*	*Moisture content (after test) (%)*	*CBR*		*DCP (mm/blow)*
Test ID	*Test level*					*Top (%)*	*Base (%)*	
Walgrey + crushed brick								
25WG_75CB	85	14.3	1.360	25.4	15.9	16.7	9.0	14.4
	95		1.498	17.9	15.5	42.2	54.6	4.8
	105		1.550	15.1	17.0	35.9	59.9	4.5
50WG_50CB	85	14.4	1.457	21.5	14.2	9.6	6.7	18.0
	95		1.678	9.5	14.9	33.9	37.9	5.2
	105		1.774	4.3	13.5	34.1	47.1	3.8
100CB	85	20.7	1.216	28.5	20.3	9.7	6.4	16.0
	95		1.380	18.8	20.5	26.4	71.0	5.3
	105		1.434	15.7	20.7	42.3[*]	96.4	4.2

Table A16 Walgrey planings and quarry waste CBR and DCP data

Materials		*Moisture content (mix) (%)*	*Dry density (Mg/m^3)*	*Air voids content (%)*	*Moisture content (after test) (%)*	*CBR*		*DCP (mm/blow)*
Test ID	*Test level*					*Top (%)*	*Base (%)*	
Walgrey + quarry waste								
25WG_75QW	85	4.9	1.810	21.0	5.1	14.9	22.6	12.2
	95		2.026	11.6	4.8	73.7	85.3	4.5
	105		1.994	13.0	4.9	67.7	112.7	4.0
50WG_50QW	85	5.7	1.803	17.5	5.1	9.6	11.5	9.9
	95		1.999	8.6	5.1	49.8	65.0	4.0
	105		1.978	9.5	5.1	54.9	58.1	3.3
100QW	85	9.1	1.767	17.4	8.9	19.1	6.3	30.2
	95		2.004	6.4	9.0	35.4	43.2	6.4
	105		2.060	3.7	8.4	31.0	25.7	6.6

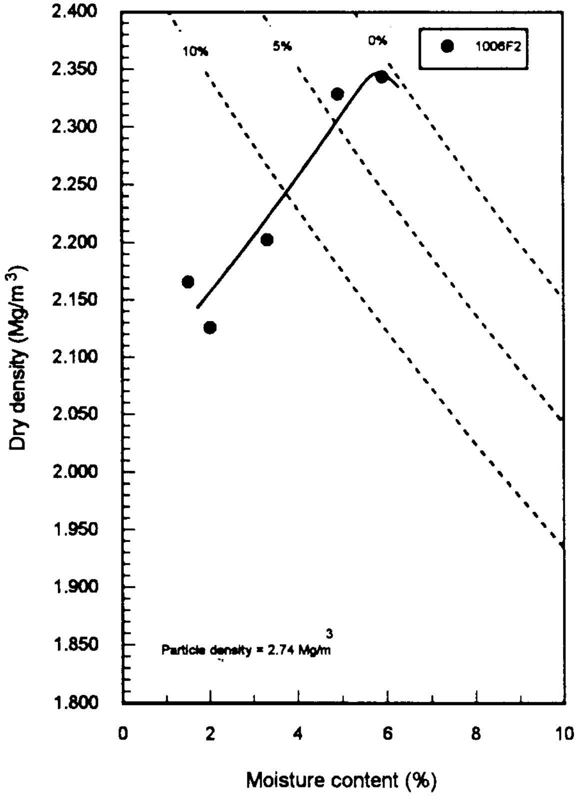

Figure A1 Class 6F2 compaction plot

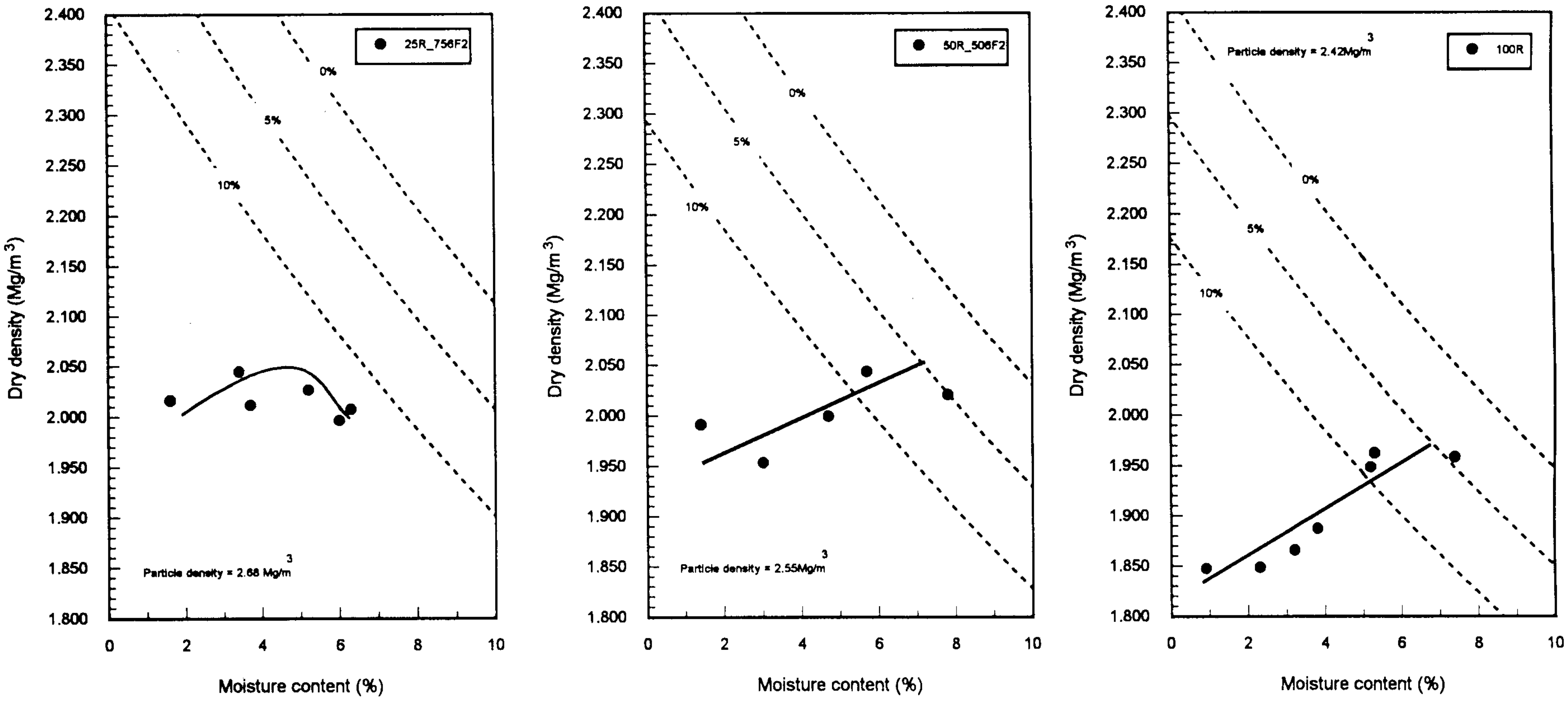

Figure A2 Redland planings and Class 6F2 compaction plots

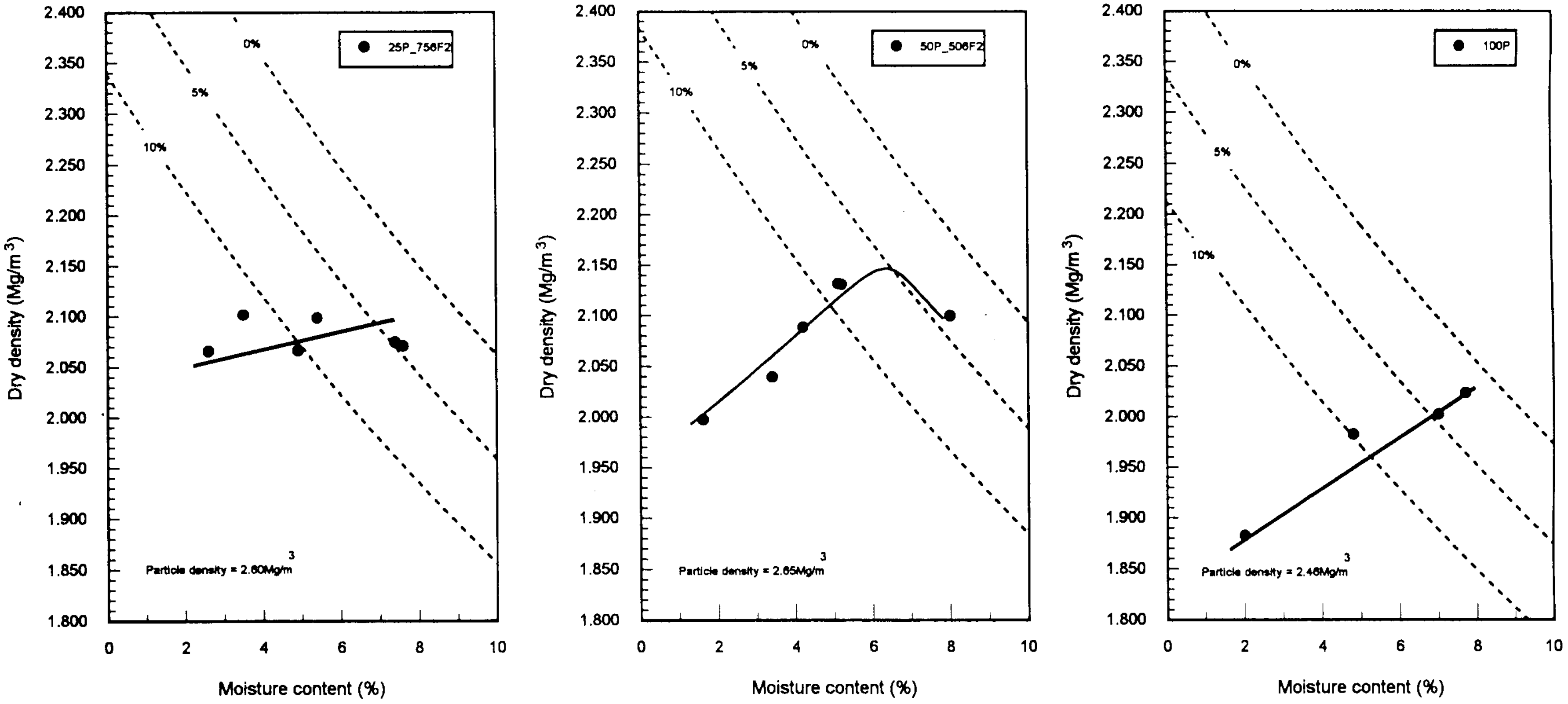

Figure A3 Pryor planings and Class 6F2 compaction plots

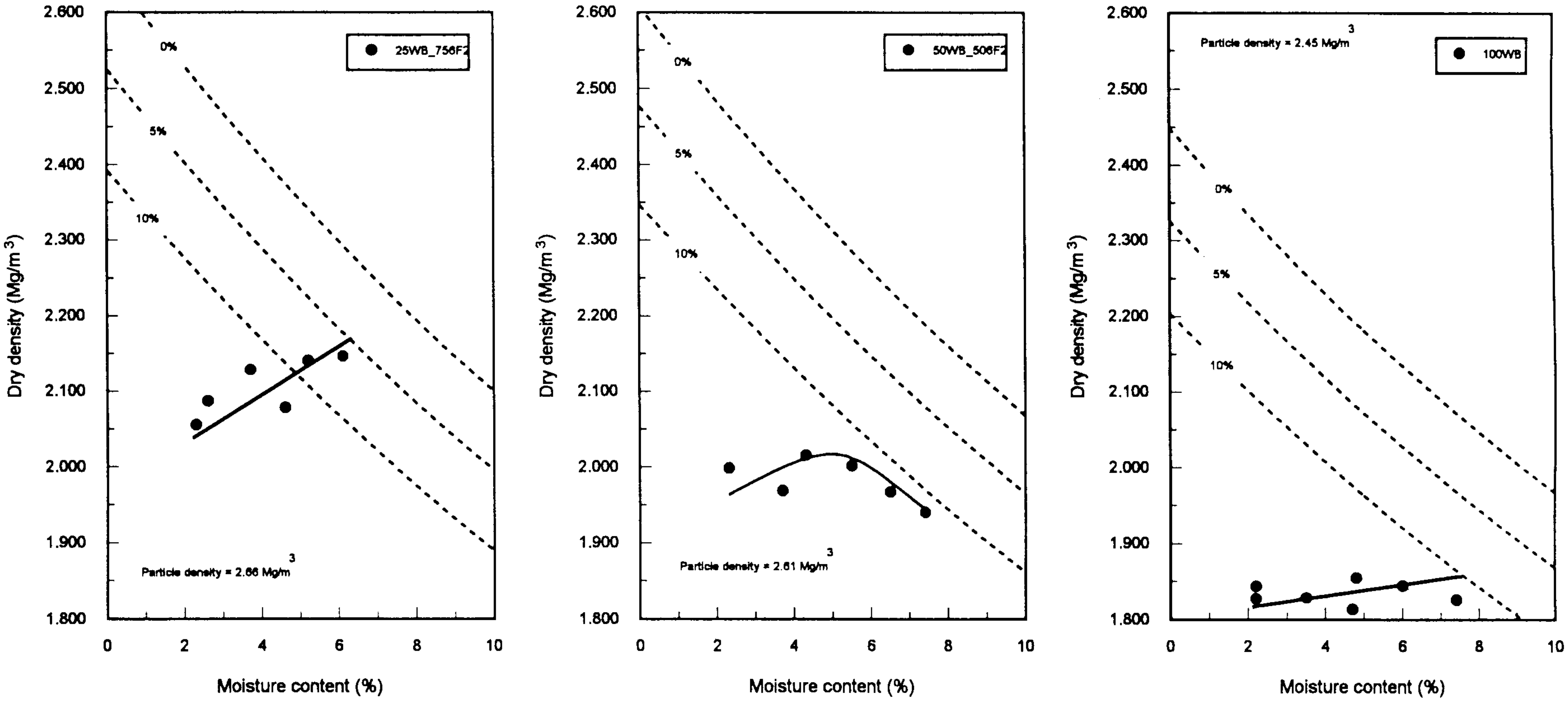

Figure A4 Walblack planings and Class 6F2 compaction plots

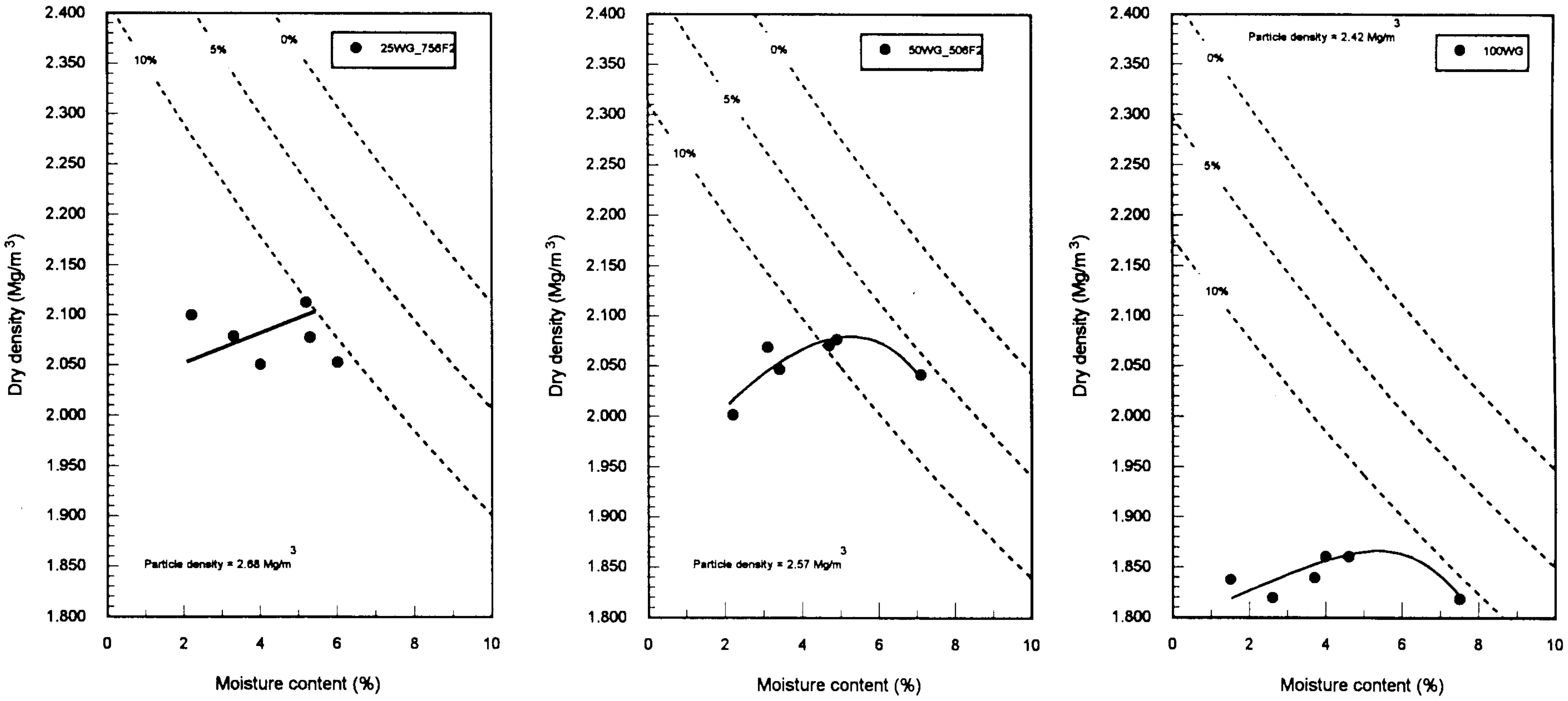

Figure A5 Walgrey planings and Class 6F2 compaction plots

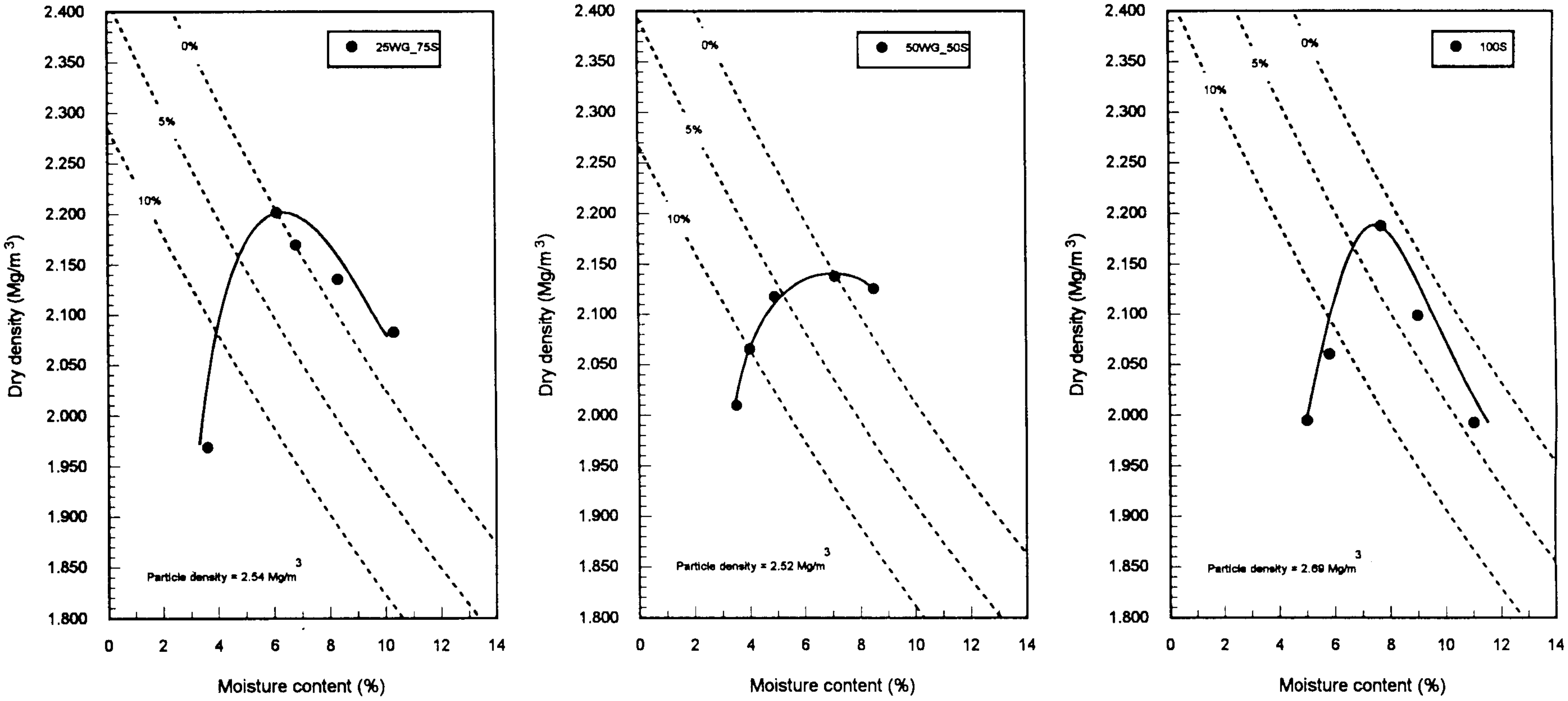

Figure A6 Walgrey planings and sand compaction plots

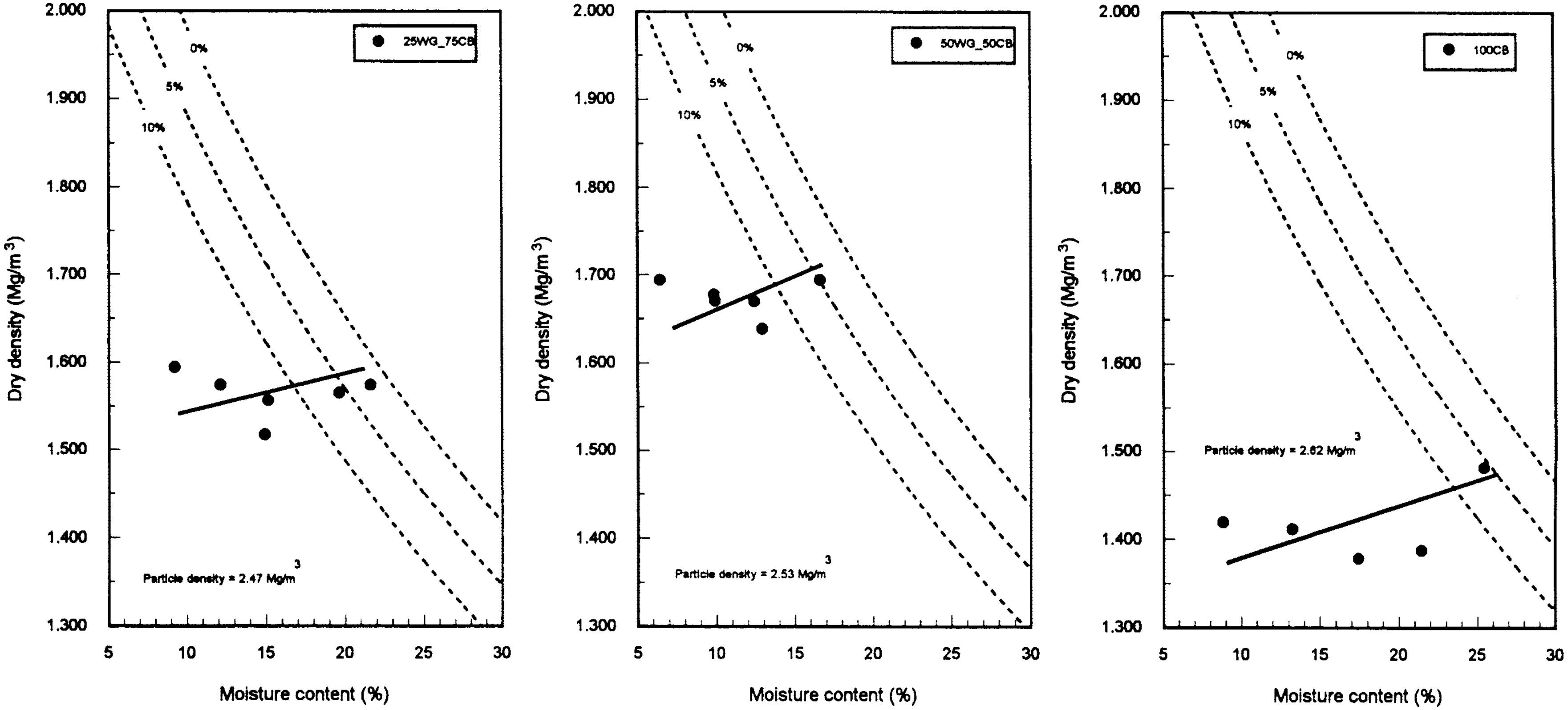

Figure A7 Walgrey planings and crushed brick compaction plots

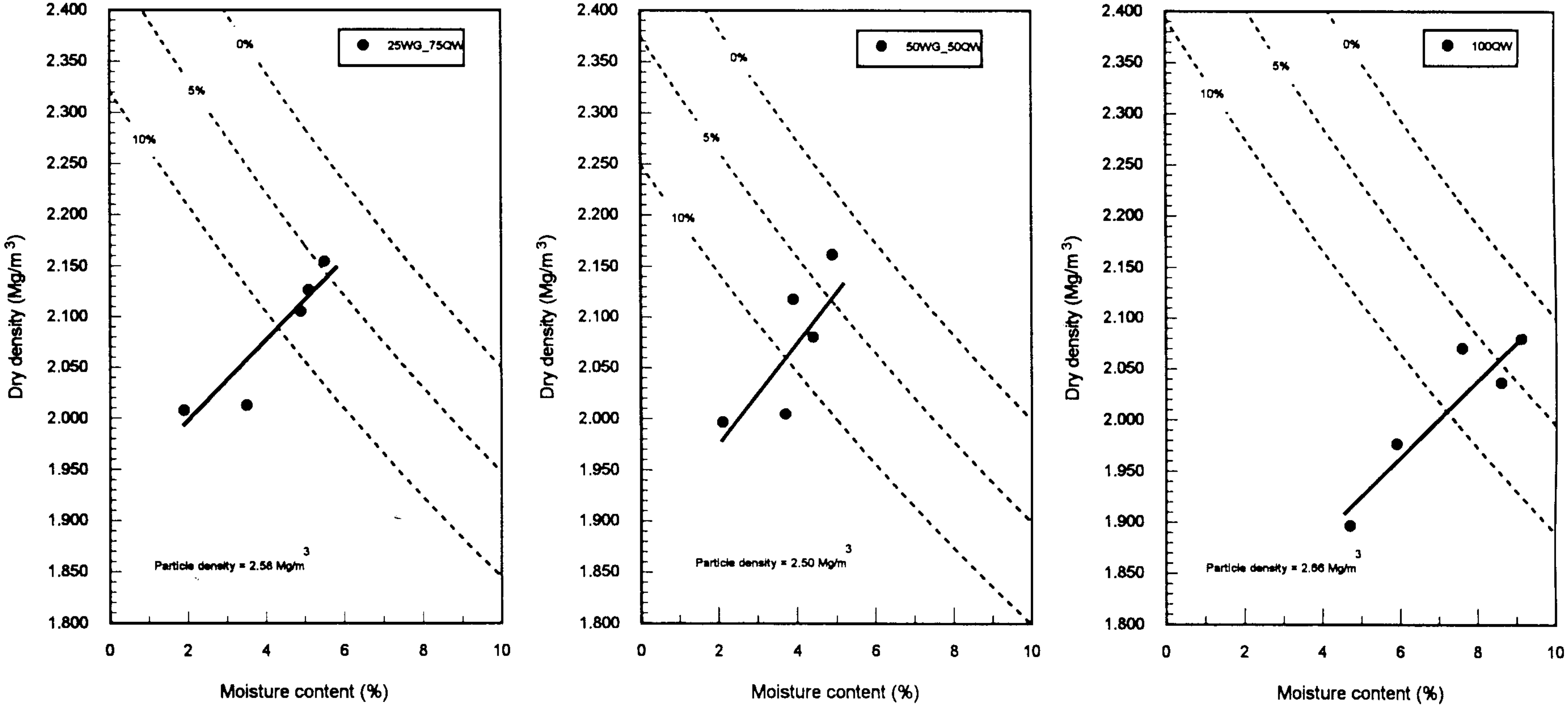

Figure A8 Walgrey planings and quarry waste compaction plots

Appendix B: Rowe cell compressibility data

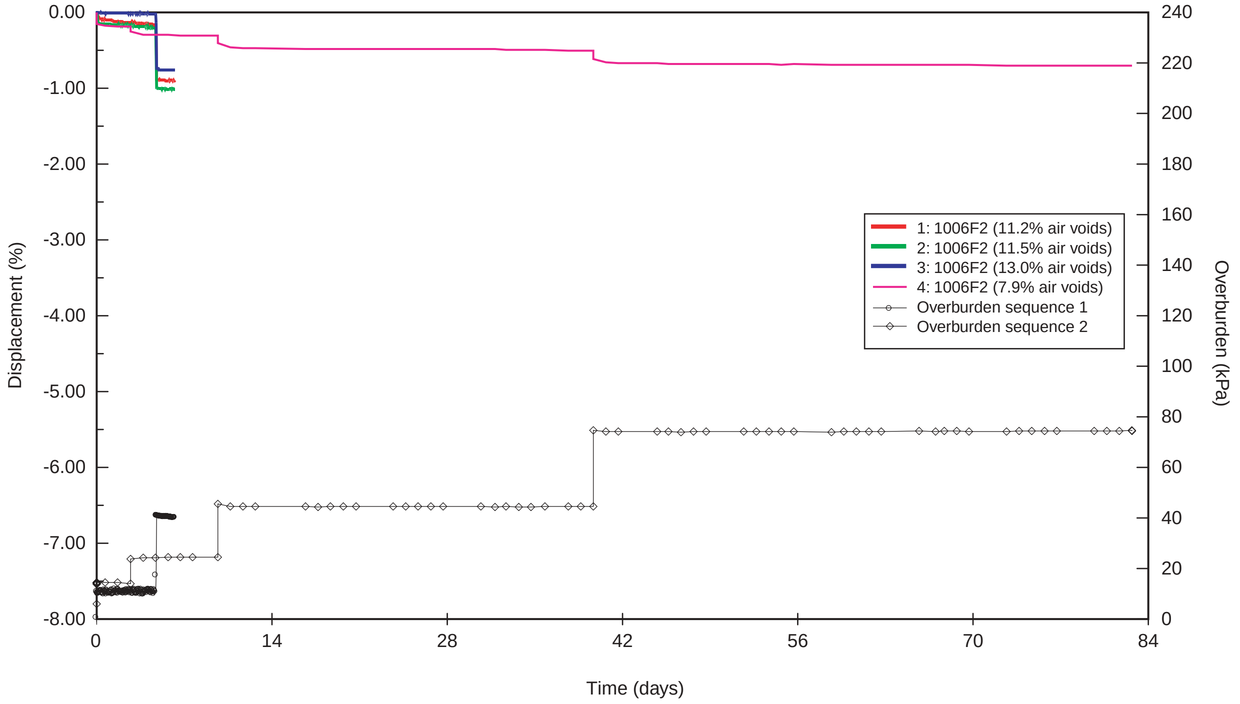

Figure B1 Granular and bituminous mixtures for capping: Class 6F2 at 95% relative compaction

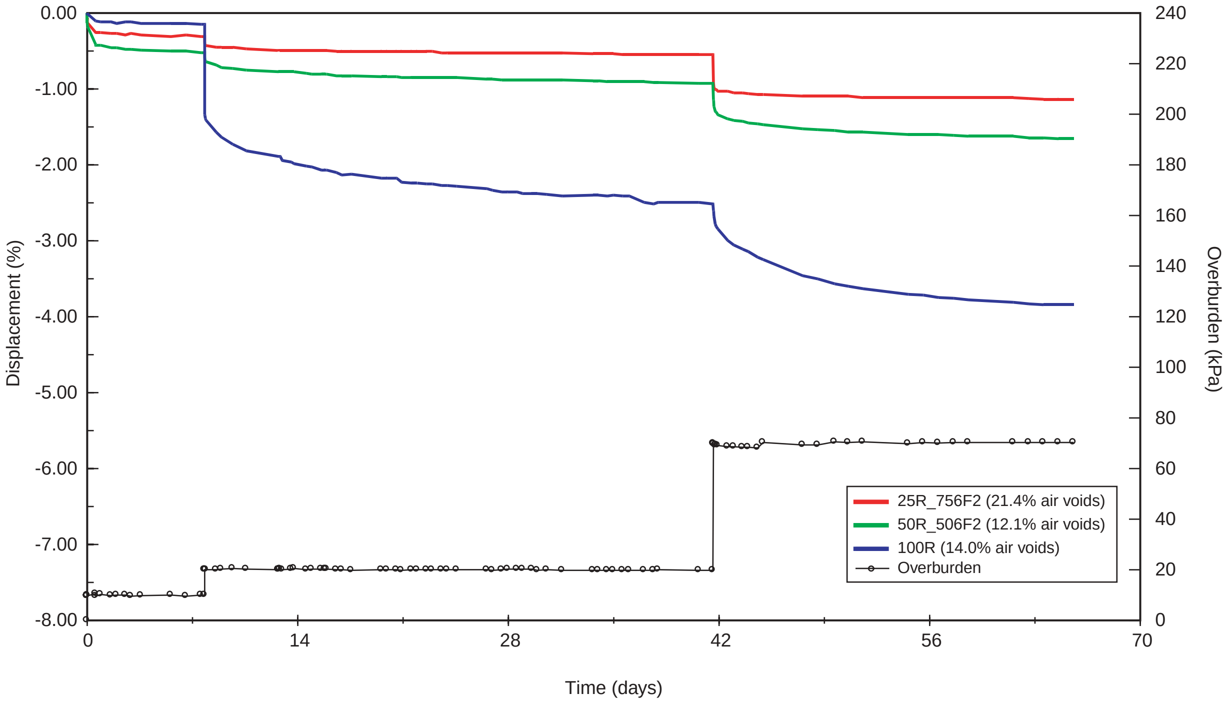

Figure B2 Granular and bituminous mixtures for capping: Redlands and Class 6F2 at 95% relative compaction

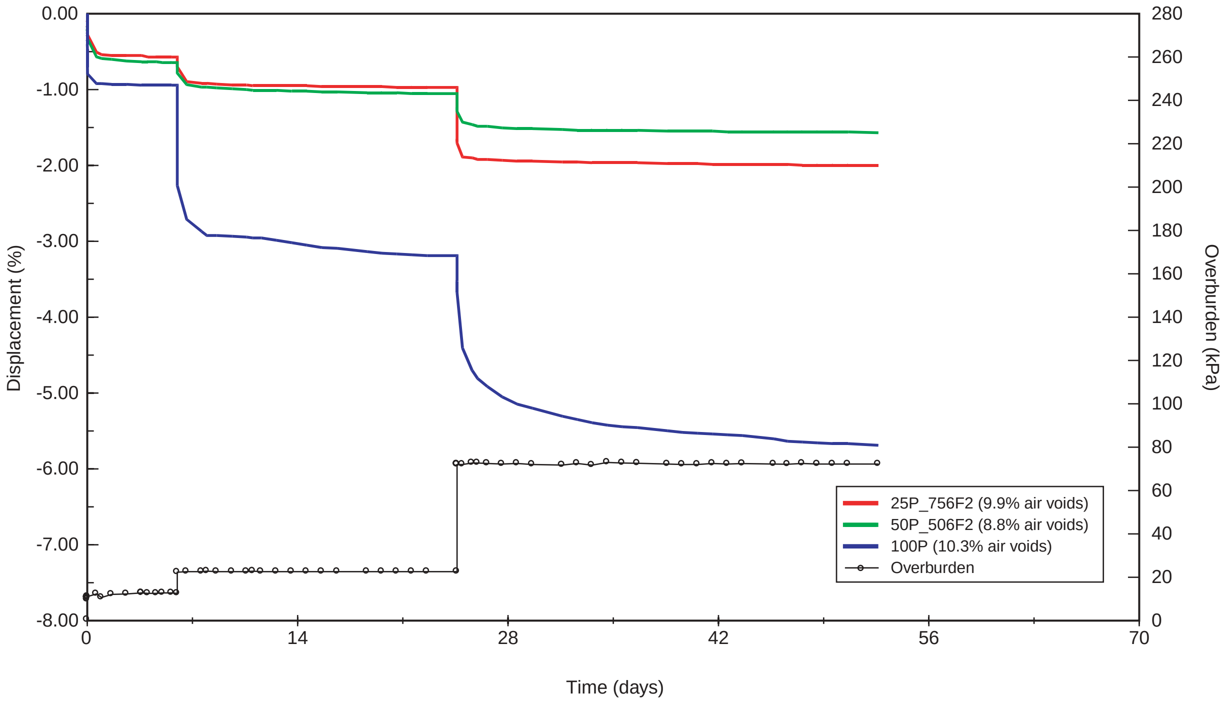

Figure B3 Granular and bituminous mixtures for capping: Pryors and Class 6F2 at 95% relative compaction

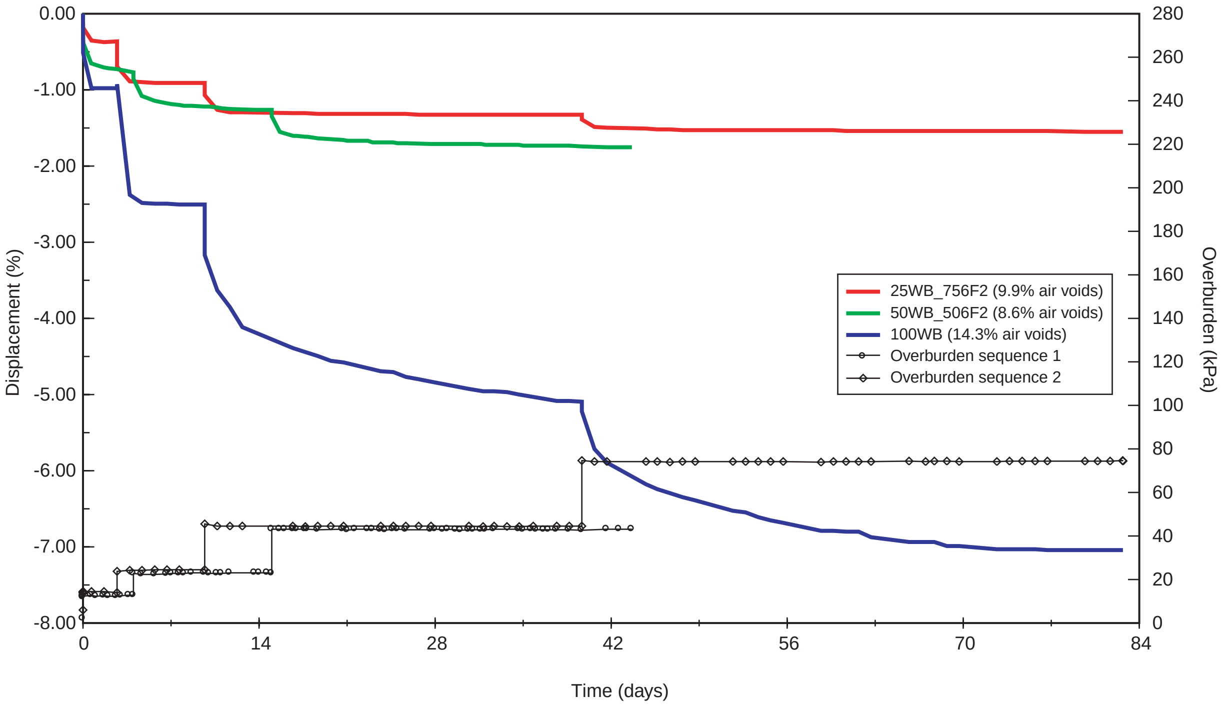

Figure B4 Granular and bituminous mixtures for capping: Walblack and Class 6F2 at 95% relative compaction

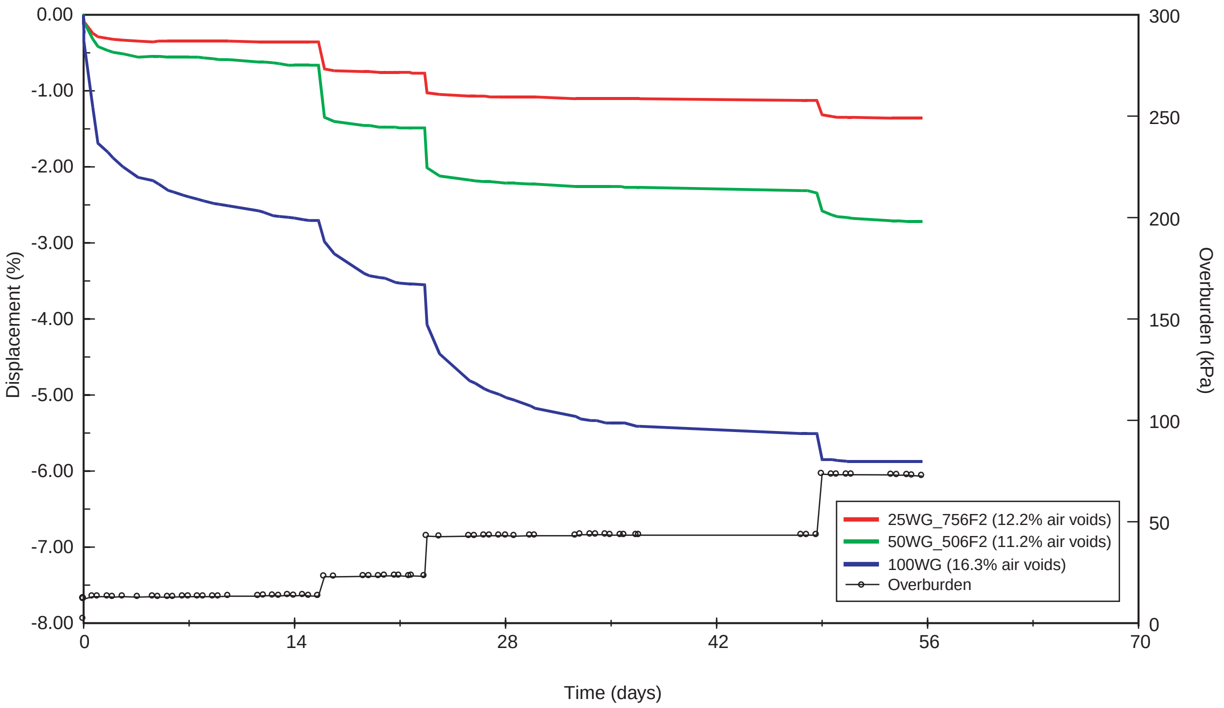

Figure B5 Granular and bituminous mixtures for capping: Walgrey and sand at 95% relative compaction

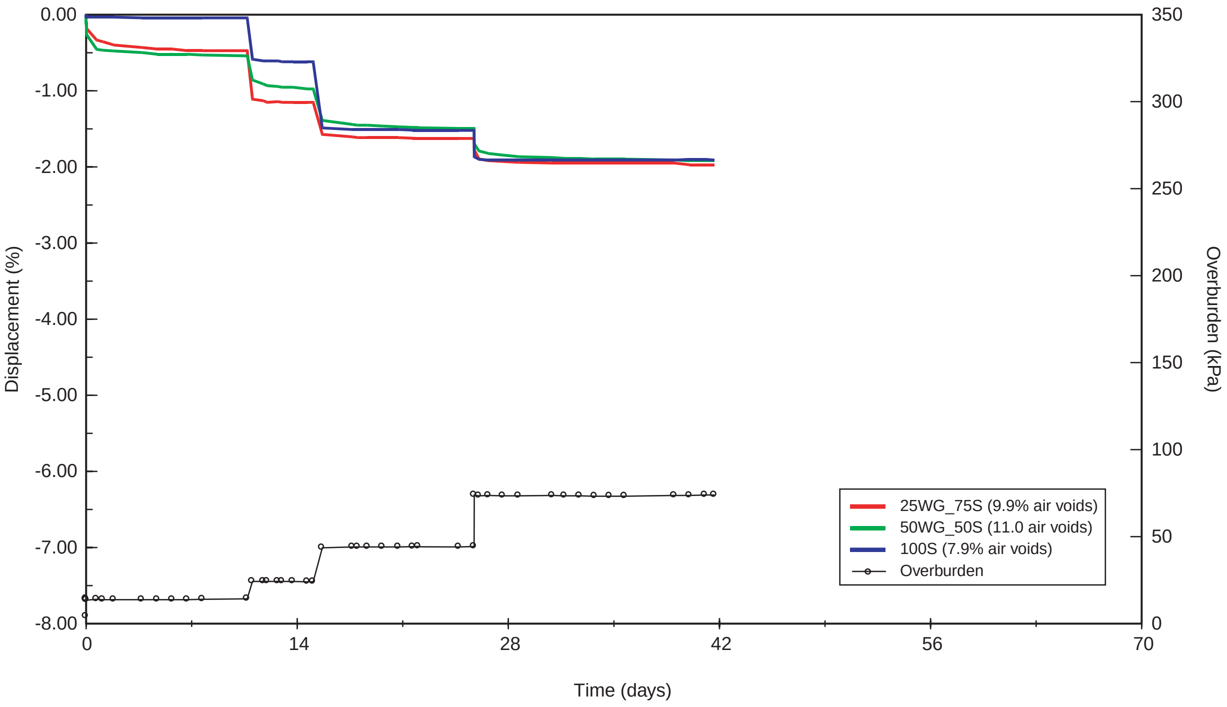

Figure B6 Granular and bituminous mixtures for capping: Walgrey and sand at 95% relative compaction

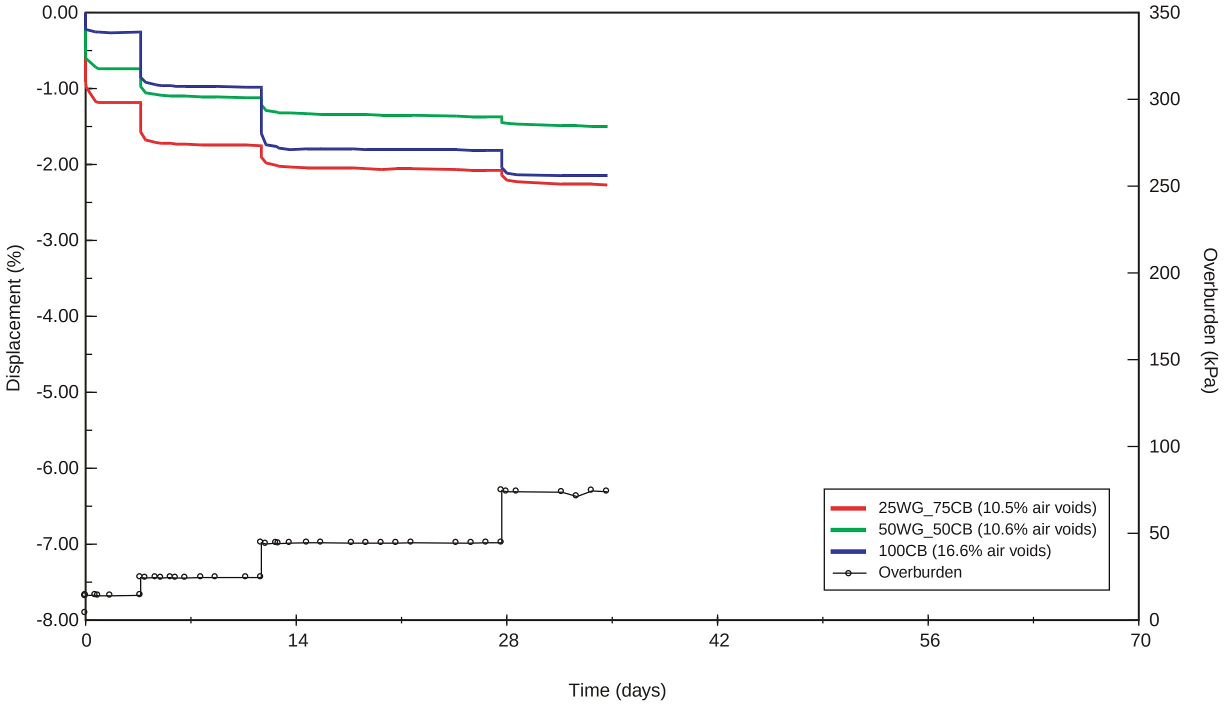

Figure B7 Granular and bituminous mixtures for capping: Walgrey and crushed brick at 95% relative compaction

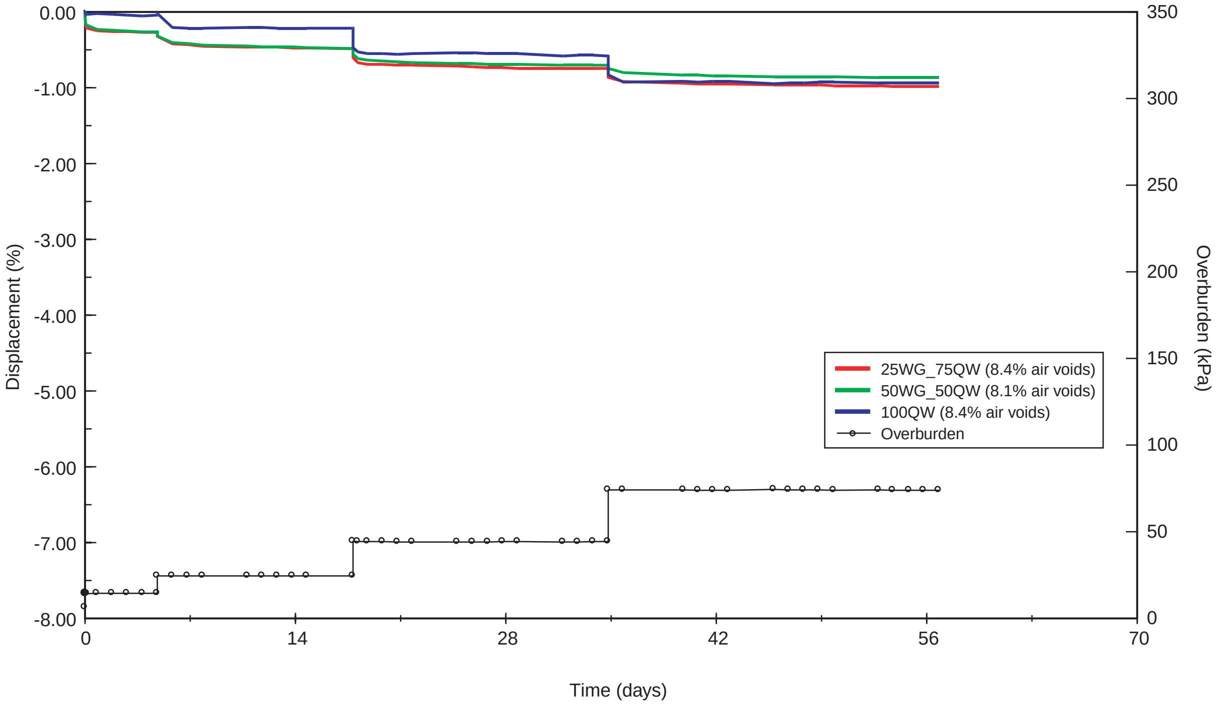

Figure B8 Granular and bituminous mixtures for capping: Walgrey and quarry waste at 95% relative compaction

Appendix C: PTF performance data

Table C1 Bay A subgrade

	FWD before		*FWD after*		*Prima*		*GDP*	
Test location	*Stress (kPa)*	*E modulus (MPa)*	*Stress (kPa)*	*E modulus (MPa)*	*Stress (kPa)*	*E modulus (MPa)*	*Stress (kPa)*	*E modulus (MPa)*
1	50	13.6	50	13.9	49.4	10.15	100.0	8.9*
	65	12.0	65	12.3	71.1	8.98		
	80	11.2	80	11.3	90.4	6.64		
2	48	6.7	48	5.7	43.5	5.82	100.0	8.9*
	62	6.7	62	5.8	62.4	7.09		
	76	6.6	75	6.5	89.1	4.61		
3	48	7.4	48	7.7	44.7	9.98	100.0	8.9*
	61	7.3	62	7.6	66.5	9.9		
	75	7.2	75	7.5	91.4	4.83		
4	49	7.7	49	9.8	44.6	6.33	100.0	8.9*
	63	7.5	63	9.1	60.8	7.03		
	77	7.4	77	8.7	88.3	5.92		
5	48	9.3	48	11.6	48.4	8.74	100.0	8.9*
	62	8.5	62	9.9	64.8	8.3		
	76	8.0	76	8.8	88.5	5.85		
6	48	6.6	48	6.9	50.0	6.95	100.0	8.9*
	61	6.4	61	6.6	64.7	7.00		
	74	6.7	76	7.0	88.0	3.09		

* *Lower recording limit of instrument*

Table C2 Bay B subgrade

	FWD before		*FWD after*		*Prima*		*GDP*	
Test location	*Stress (kPa)*	*E modulus (MPa)*	*Stress (kPa)*	*E modulus (MPa)*	*Stress (kPa)*	*E modulus (MPa)*	*Stress (kPa)*	*E modulus (MPa)*
1	48	9.4	48	11.3	45.6	11.9	100	8.9*
	61	8.8	61	10.4	64.6	10.0		
	75	8.4	74	10.0	87.3	3.0		
2	48	9.8	47	8.5	43.9	9.3	100	8.9*
	61	9.3	61	8.1	61.9	7.8		
	74	8.9	74	7.9	98.4	6.7		
3	47	7.1	47	6.5	46.6	5.6	100	8.9*
	60	6.8	61	6.3	57.7	7.0		
	73	6.5	73	6.6	86.4	4.7		
4	48	10.5	48	10.7	45.6	12.5	100	8.9*
	63	10.0	62	10.0	62.2	9.9		
	75	9.3	75	9.2	90.5	6.7		
5	47	8.4	47	8.3	48.6	6.2	100	8.9*
	61	7.9	60	7.6	62.1	5.4		
	73	7.3	73	7.2	87.2	7.6		
6	47	8.4	47	7.9	49.8	6.3	100	8.9*
	59	7.8	61	7.6	60.1	7.1		
	73	7.5	73	7.3	N/A	N/A		

* *Lower recording limit of instrument.*

Table C3 Bay C subgrade

	FWD before		*FWD after*		*Prima*		*GDP*	
Test location	*Stress (kPa)*	*E modulus (MPa)*	*Stress (kPa)*	*E modulus (MPa)*	*Stress (kPa)*	*E modulus (MPa)*	*Stress (kPa)*	*E modulus (MPa)*
1	53	14.6	52	14.2	51.4	19.5	100	10.1
	69	13.1	68	13.1	71.0	17.7		
	83	12.2	82	12.2	96.4	16.1		
2	49	11.1	49	10.2	45.1	13.1	100	9.8
	63	10.2	65	9.6	63.9	11.6		
	77	9.7	78	9.0	90.0	11.6		
3	46	6.0	47	6.7	43.3	5.5	100	8.9*
	60	6.1	61	6.6	58.8	5.4		
	73	6.6	74	6.7	85.7	5.8		
4	52	12.8	52	17.9	42.6	11.2	100	8.9*
	69	11.6	68	15.2	62.6	12.0		
	83	10.8	83	13.2	96.3	12.2		
5	51	6.6	49	6.7	36.6	6.3	100	8.9*
	66	5.7	65	7.3	55.9	6.9		
	80	6.9	79	6.8	87.7	5.1		
6	50	11.1	50	10.3	49.4	14.3	100	8.9*
	65	10.1	65	9.5	65.9	12.7		
	78	9.3	79	9.0	92.0	12.3		

* Lower recording limit of instrument.

Table C4 Bay D subgrade

	FWD before		*FWD after*		*Prima*		*GDP*	
Test location	*Stress (kPa)*	*E modulus (MPa)*	*Stress (kPa)*	*E modulus (MPa)*	*Stress (kPa)*	*E modulus (MPa)*	*Stress (kPa)*	*E modulus (MPa)*
1	49	10.0	49	10.0	42.0	14.2	100	10.2
	63	9.4	64	9.4	67.4	12.7		
	77	8.8	77	8.9	86.6	11.4		
2	48	11.2	47	9.4	39.2	6.6	100	8.9*
	62	10.3	61	8.9	54.8	4.9		
	74	9.3	74	8.3	86.9	6.8		
3	48	8.4	47	8.6	45.2	7.8	100	8.9*
	63	8.0	62	7.8	57.4	7.4		
	75	6.5	74	6.4	84.8	3.6		
4	49	8.9	49	6.8	46.1	10.0	100	8.9*
	64	8.5	65	6.8	60.7	9.4		
	78	8.1	78	6.7	85.3	6.0		
5	48	10.5	48	9.7	41.3	12.9	100	8.9*
	63	9.7	62	8.9	56.9	11.8		
	77	9.2	76	8.5	86.1	5.0		
6	47	13.4	46	8.0	50.5	7.9	100	8.9*
	62	11.6	62	7.8	59.0	8.1		
	77	10.9	77	7.0	90.2	11.9		

* *Lower recording limit of instrument.*

Table C5 Bay A layer 1

	FWD before		*FWD after*		*Prima*		*GDP*	
Test location	*Stress (kPa)*	*E modulus (MPa)*	*Stress (kPa)*	*E modulus (MPa)*	*Stress (kPa)*	*E modulus (MPa)*	*Stress (kPa)*	*E modulus (MPa)*
1	106	14.7	107	14.9	48.0	14.4	100	15.8
	136	13.9	134	14.2	62.7	14.2		
	165	13.1	165	13.5	94.6	14.7		
2	104	12.6	103	13.0	43.6	14.3	100	14.5
	133	11.9	133	12.5	67.0	13.9		
	161	11.2	162	11.8	96.0	13.4		
3	103	12.6	102	13.0	47.7	14.5		
	132	12.0	131	12.3	69.5	13.4		
	161	11.4	161	11.8	95.3	13.4	100	14.9
4	103	16.4	103	16.2	42.2	19.9	100	20.3
	134	15.5	135	15.4	65.5	18.2		
	165	14.5	166	14.7	96.3	17.7		
5	103	16.3	102	16.7	46.2	20.2	100	21.6
	134	15.5	133	16.0	64.0	19.5		
	164	14.5	165	15.1	95.0	18.8		
6	100	12.2	101	13.0	45.7	12.0	100	13.6
	128	11.5	130	12.3	55.6	12.1		
	158	11.0	159	11.7	93.1	12.9		

Table C6 Bay B layer 1

	FWD before		*FWD after*		*Prima*		*GDP*	
Test location	*Stress (kPa)*	*E modulus (MPa)*	*Stress (kPa)*	*E modulus (MPa)*	*Stress (kPa)*	*E modulus (MPa)*	*Stress (kPa)*	*E modulus (MPa)*
1	100	10.6	101	11.3	45.9	11.5	100	12.6
	128	10.2	129	10.7	64.8	11.1		
	157	9.0	158	9.1	92.7	11.5		
2	100	11.2	101	11.4	48.0	13.6	100	13.1
	131	10.7	130	10.8	61.6	12.9		
	158	9.1	158	9.4	93.1	12.8		
3	99	10.5	100	11.2	47.5	11.8	100	12.2
	128	10.2	129	10.7	62.5	11.7		
	156	9.7	157	9.0	91.2	11.4		
4	100	12.0	101	12.1	43.4	17.8	100	15.8
	130	11.4	129	11.4	66.0	16.0		
	158	10.8	159	11.1	93.6	15.6		
5	100	11.9	98	11.3	47.5	14.7	100	14.2
	127	10.9	127	10.8	60.2	14.0		
	156	9.9	157	10.4	92.5	13.6		
6	100	12.0	100	12.0	49.4	16.7	100	15.7
	129	11.2	128	11.2	64.5	15.7		
	157	10.6	158	10.9	93.8	15.3		

Table C7 Bay C layer 1

	FWD before		*FWD after*		*Prima*		*GDP*	
Test location	*Stress (kPa)*	*E modulus (MPa)*	*Stress (kPa)*	*E modulus (MPa)*	*Stress (kPa)*	*E modulus (MPa)*	*Stress (kPa)*	*E modulus (MPa)*
1	110	16.9	108	16.7	50.4	19.5	100	19.1
	141	15.8	140	15.7	65.8	19.1		
	171	14.5	170	14.7	94.1	17.7		
2	105	15.9	105	15.4	48.6	19.5	100	21.6
	136	15.0	135	14.5	60.9	20.3		
	165	13.8	164	13.7	94.2	19.3		
3	96	8.4	97	8.8	50.1	9.0	100	8.9*
	124	8.3	125	8.8	66.2	8.4		
	153	10.5	154	8.9	89.2	9.7		
4	109	18.4	108	17.7	45.1	21.0	100	16.2
	139	17.2	140	16.7	65.1	20.0		
	172	15.8	172	15.7	89.8	17.9		
5	108	14.9	109	14.8	49.2	16.4	100	17.3
	138	14.0	139	14.1	71.8	16.0		
	169	13.0	170	13.2	89.3	14.8		
6	106	15.2	106	15.5	53.5	17.8	100	17.6
	136	14.3	137	14.8	68.6	17.2		
	167	13.4	168	13.9	89.9	16.3		

* *Lower recording limit of instrument.*

Table C8 Bay D layer 1

	FWD before		*FWD after*		*Prima*		*GDP*	
Test location	*Stress (kPa)*	*E modulus (MPa)*	*Stress (kPa)*	*E modulus (MPa)*	*Stress (kPa)*	*E modulus (MPa)*	*Stress (kPa)*	*E modulus (MPa)*
1	103	10.8	103	10.9	48.5	13.2	100	15.0
	134	10.5	134	10.5	67.9	13.3		
	163	9.4	163	10.3	91.3	13.3		
2	103	13.1	103	13.1	52.1	16.6	100	18.0
	133	12.4	133	12.5	62.5	15.2		
	162	11.7	164	12.0	91.0	15.3		
3	102	12.7	102	12.6	47.3	17.6	100	16.9
	132	12.0	132	12.0	59.0	17.1		
	162	11.5	163	11.6	91.0	16.6		
4	104	13.3	105	13.2	48.8	16.2	100	18.6
	135	12.9	135	12.8	72.6	15.7		
	166	12.3	166	12.4	89.0	15.5		
5	106	15.2	106	15.1	52.5	18.9	100	20.1
	137	14.6	137	14.4	70.5	17.2		
	168	13.7	169	13.9	90.6	17.1		
6	106	17.3	106	17.3	50.2	21.4	100	25.0
	138	16.1	137	16.2	72.1	21.0		
	170	15.1	169	15.2	90.6	19.7		

Table C9 Bay A layer 2

	FWD before		*FWD after*		*Prima*		*GDP*	
Test location	*Stress (kPa)*	*E modulus (MPa)*	*Stress (kPa)*	*E modulus (MPa)*	*Stress (kPa)*	*E modulus (MPa)*	*Stress (kPa)*	*E modulus (MPa)*
1	114	42.6	111	43.9	60.8	53.1	100	54.9
	145	41.5	144	43.2	72.1	52.0		
	179	39.7	177	41.8	100.9	52.3		
2	109	42.4	109	43.2	50	44.3	100	56.3
	143	41.9	143	41.9	64.9	47.0		
	177	40.1	176	41.2	98.8	48.7		
3	113	37.6	110	37.8	50.7	42.4	100	48.9
	146	36.9	143	37.8	70.0	45.3		
	180	35.8	176	36.3	98.3	45.9		
4	109	43.5	109	44.7	58.7	72.0	100	68.2
	142	42.5	143	44.0	74.4	69.7		
	177	41.1	177	42.6	91.4	64.7		
5	112	45.1	111	47.0	58.2	73.4	100	54.9
	147	43.7	144	45.6	79.8	72.4		
	180	41.7	178	43.8	93.5	71.6		
6	109	41.7	107	41.8	51.2	60.7	100	54.9
	142	41.2	140	41.6	71.7	59.9		
	176	39.5	174	40.3	97.7	62.2		

Table C10 Bay B layer 2

	FWD before		*FWD after*		*Prima*		*GDP*	
Test location	*Stress (kPa)*	*E modulus (MPa)*	*Stress (kPa)*	*E modulus (MPa)*	*Stress (kPa)*	*E modulus (MPa)*	*Stress (kPa)*	*E modulus (MPa)*
1	116	34.4	113	36.6	52.7	44.2	100	50.0
	149	33.7	146	35.5	72.6	45.1		
	182	32.6	178	35.1	97.1	45.7		
2	116	36.2	113	37.3	52.7	50.3	100	50.0
	150	35.3	145	36.4	65.7	51.7		
	182	33.7	179	35.6	99.6	53.2		
3	113	30.3	113	34.1	49.9	46.4	100	40.2
	147	30.0	144	33.3	75.7	47.1		
	181	28.7	179	32.5	97.1	46.2		
4	119	37.5	118	40.7	53.7	60.6	100	56.3
	152	36.2	150	39.8	79.9	61.1		
	184	35.5	183	38.9	95.0	61.9		
5	120	37.9	118	40.8	50.4	55.0	100	52.3
	154	36.6	151	39.9	69.7	58.6		
	186	35.4	185	38.8	94.8	59.7		
6	109	39.3	111	36.9	58.3	60.5	100	54.9
	141	38.1	142	36.3	73.8	58.9		
	174	36.4	176	35.1	92.7	59.7		

Table C11 Bay C layer 2

	FWD before		*FWD after*		*Prima*		*GDP*	
Test location	*Stress (kPa)*	*E modulus (MPa)*	*Stress (kPa)*	*E modulus (MPa)*	*Stress (kPa)*	*E modulus (MPa)*	*Stress (kPa)*	*E modulus (MPa)*
1	114	45.1	116	46.2	54.1	71.1	100	62.5
	148	43.3	148	44.3	71.9	69.9		
	180	41.9	181	43.1	96.9	70.7		
2	111	44.6	107	46.0	51.6	65.9	100	97.8
	142	42.8	140	45.1	73.8	66.7		
	175	41.3	174	43.8	97.2	69.2		
3	110	35.9	108	36.8	53.2	45.8	100	56.3
	140	35.2	140	36.3	74.9	48.3		
	175	33.7	174	35.0	100.2	48.1		
4	116	51.5	119	55.5	51.4	72.3	100	64.3
	151	48.3	151	53.0	69.3	71.9		
	183	46.1	185	50.6	97.5	73.4		
5	124	49.5	123	52.2	56.0	76.8	100	64.3
	161	47.1	159	50.5	68.4	78.1		
	194	44.8	191	47.8	93.8	73.7		
6	114	48.9	111	53.2	57.5	73.7	100	75.0
	145	47.7	143	51.2	74.1	74.0		
	181	44.8	177	49.1	96.8	75.1		

Table C12 Bay D layer 2

	FWD before		*FWD after*		*Prima*		*GDP*	
Test location	*Stress (kPa)*	*E modulus (MPa)*	*Stress (kPa)*	*E modulus (MPa)*	*Stress (kPa)*	*E modulus (MPa)*	*Stress (kPa)*	*E modulus (MPa)*
1	109	35.4	107	37.4	56.6	39.1	100	46.9
	142	34.3	140	37.2	74.1	40.8		
	177	33.0	176	35.8	97.5	43.1		
2	108	35.4	107	36.8	54.5	47.5	100	34.6
	140	34.1	138	35.8	77.6	48.7		
	175	32.2	173	34.5	99.5	46.7		
3	111	30.7	108	31.9	57.8	34.0	100	38.8
	143	29.8	142	31.4	74.8	34.0		
	177	28.5	176	30.4	99.3	36.7		
4	117	42.8	117	43.3	59.3	62.7	100	44.1
	152	40.6	150	42.3	76.7	62.7		
	185	39.0	185	40.8	96.9	64.6		
5	113	40.1	111	41.5	58.5	55.8	100	52.3
	145	38.9	144	40.6	72.9	56.3		
	179	36.9	178	39.0	100.3	55.7		
6	119	40.1	117	40.8	57.3	56.5	100	44.1
	153	38.2	150	40.0	76.9	58.7		
	185	36.7	184	38.8	100.5	59.5		

Abstract

There are continuing pressures on DTLR to increase the usage of recycled materials and industrial by-products in road construction. One such area is in capping layers, where previous studies at TRL have led to the introduction of Class 6F3 covering the use of recycled bituminous planings and granulated asphalt into the Specification for Highway Works. This project has extended the previous studies to look at mixtures of planings with other recycled roadbase layers and granular materials.

The project was carried out in two phases. Phase 1 covered the literature review into published works on the use of recycled bituminous planings. In Phase 2, laboratory trials were carried out on a range of bituminous planings and granular material mixes, designed to study the effects of varying the bitumen content on compaction and settlement. Following the laboratory testing, limited pilot-scale trials were carried out on large samples compacted to representative densities, to enable the stiffness of typical mixtures to be measured *in situ* with a number of performance testing devices.

This is the final report of the project and makes recommendations for the inclusion of a new Class 6F4 material into the current Specification for Highway Works. This would allow mixtures of bituminous planings and granular materials having the same grading as Class 6F3, but with maximum bitumen contents of 2% to be compacted using the same method as for Class 6F3, but in layers up to 250mm thickness, rather than the 200mm limit imposed for Class 6F3. An outline of the proposed amendment is given in the report.

Related publications

TRL408 *Enabling the use of secondary aggregates and binders in pavement foundations* by V M Atkinson, B C Chaddock and A R Dawson. 1999 (price £35, code H)

TRL216 *Road haunches: a guide to re-usable materials* by J Potter. 1996 (price £35, code J)

LR901 *The strength of clay subgrades: its measurement by a penetrometer* by W P M Black, 1979 (price £20)

Recycling in transport infrastructure by J M Reid and J W E Chandler. 2001 (price £35)

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