

## Seal Coat Design for Unbound Granular Pavements Carrying Heavy Axle Loads

Bryan D. Pidwerbesky  
University of Canterbury  
Christchurch, New Zealand

Greg Arnold  
Logging Industry Research Organisation  
Rotorua, New Zealand

### ABSTRACT

Virtually all of the public highway pavements in New Zealand are comprised of usually one or more coats of a sprayed seal over unbound granular layers. The standard New Zealand design and construction techniques are being applied to heavy-duty forest roads. Seal coats are an attractive economic alternative for low-volume roads but existing design procedures are inappropriate for the loadings that are experienced on the arterial forest roads.

The advantages and limitations of seal coat design with respect to forest roads are discussed in this paper. Experimental work which has been instigated to further the development of seal coat design, construction techniques, and specialized materials suited to the special requirements of forest roads sustaining heavy loads of up to 160 kN per single axle is described and discussed. Results of field trials thus far have shown that enhanced quality control during construction, reduced bitumen application rates, and use of polymer-modified bitumens are providing the required performance.

**Keywords:** seal coats, polymer-modified bitumen.

### INTRODUCTION

The forestry sector is a major export earner for New Zealand. Forestry companies construct and maintain networks of high-quality private arterial roads because logging trucks travelling at speeds of up to 100 km/h, or more, over smooth, all-weather surfaced roads provide the most economical means of hauling logs from plantation forests to processing and port facilities.

*The authors are respectively a Lecturer in Civil Engineering and a Research Engineer.*

In New Zealand, asphalt pavements are used for some urban streets and motorways, and some rigid pavements were constructed 50 years ago, but virtually all highway traffic is carried by thin surface treatments over unbound granular pavements. The log transport industry takes advantage of the unique highway pavement design techniques and practices used in New Zealand, but some aspects needed to be investigated and modified to suit the needs of forest roads. The background to the surfacing design and construction methods and practices is discussed first, followed by the field study, current trials in progress, and results to date.

### SEAL COAT DESIGN METHODS

In New Zealand, surface treatments are called seal coats or chip seals; common types of seal coats are illustrated in Figure 1. The functions of the seal coat are to provide (i) an impermeable membrane over the basecourse, (ii) a skid-resistant surface, and (iii) a wearing surface. The design of New Zealand seal coats is based on the theory and mechanisms proposed by Hanson [2], who related the bitumen application rate to the size of the stone chip, the ratio of the chip's average, least, and greatest dimensions, and the residual void space within the single layer thickness of the aggregate cover. The major assumptions are [6]:

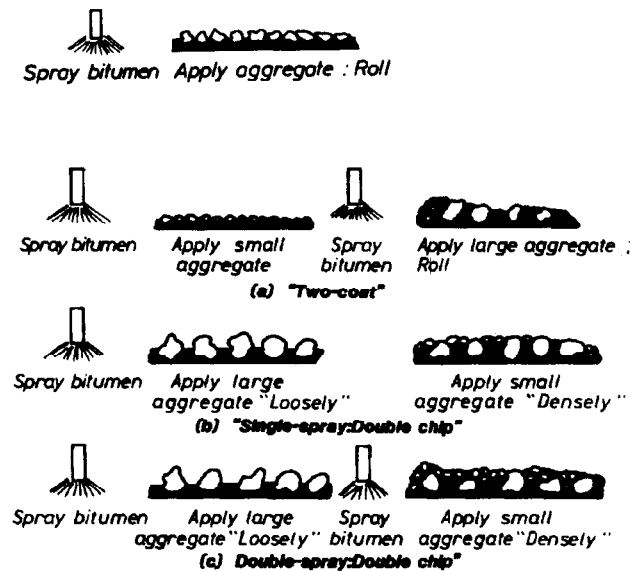


Figure 1. Seal coat systems (after [13]).

1. When one-size cover aggregate is spread over a bitumen film, the particles lie in unarranged positions and the voids between the particles are approximately 50%.
2. Rolling partially reorients the aggregate particles and reduces the voids to about 30%.
3. Finally, after considerable traffic, the particles become oriented into their densest positions, with all lying on their flattest sides, and the voids are reduced to approximately 20%.
4. Since the particles lie on their flattest sides, the average thickness of a surface treatment is the Average Least Dimension (ALD) of the stone chips, as shown in Figure 2.
5. The residual bitumen should fill two-thirds of the voids, under typical public highway traffic volumes and vehicle mix.

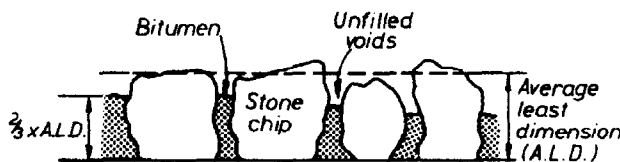


Figure 2. Typical seal coat cross-section.

In New Zealand, the basic precepts have been refined by experience into a semi-empirical design procedure which provides corrections for existing surface texture and vehicle loading, culminating in the Bituminous Sealing Manual [1]. The seal design algorithm for single-coat first seals and re-seals of cutback bitumen is:

$$R = (0.138 \text{ ALD} + e) T_f$$

where:

R = residual (after diluent evaporates)  
bitumen application rate at 15°C [l/m<sup>2</sup>]

ALD = Average Least Dimension of the single-sized, cubic, crushed aggregate [mm]

e = average texture depth of the surface to be sealed [l/m<sup>2</sup>]

T<sub>f</sub> = adjustment for compaction due to trafficking [unitless]

The goal of the above is to obtain a bitumen film thickness sufficient to provide a durable, impermeable membrane and to hold the cover aggregate in place, but insufficient to completely fill the voids in the cover aggregate. The surface texture is quantified by the sand circle test, in which 45 ml of sand (particle sizes are between 300 μm to 600 μm) is spread by revolving a straight-edge until the sand is level with the tops of the cover aggregate particles, and the diameter of the sand circle is measured. Dividing the volume by the area of the circle gives the average texture depth. Additional design algorithms have been developed for two-coat seals and emulsified bitumens.

The algorithm is based on observations and studies involving public highways carrying traffic that typically consists of 10% to 15% heavy commercial vehicles (HCV), with an average axle load of about 5 tonnes. When the proportion of HCV exceeds 15%, as in the case of private forest roads, the HCV are converted to a "standard" mix of Equivalent Light Vehicles (ELV) using [1]:

$$\text{ELV} = V_t + [10V_t(m-0.15)]$$

where:

V<sub>t</sub> = total traffic volume

m = proportion of HCV (decimal fraction)

A review of international literature was undertaken to determine if any other surface treatment design techniques may have been developed that take into account heavier axle loads, tire characteristics, and the other unique conditions found on the forest roads. Houghton [3] evaluated a variety of New Zealand and French design techniques to derive a suitable method for heavily trafficked urban arterials, and Khandal [4] presented a comprehensive review of surface treatments. Road Note 39 [11] and Southern [13] considered commercial vehicles of unladen weights over 1.5 tonnes and apply a

subjective description of the surface hardness of the road. Potter and Church [10] proposed that seal coat design should be based on traffic loading and the hardness (resistance to embedment) of the layer under the seal coat, but emphasized that long term data are still required to evaluate the embedment of the cover aggregate in the underlying layer under trafficking. Also, the results were limited to first coat seals using a 16 mm stone chip. Due to the reasons explained later in this paper, none of the above design procedures are applicable to the heavy axle loads and trafficking conditions experienced on the arterial forest roads.

### Factors Affecting Seal Coat Performance

In New Zealand, two standard penetration grade bitumens are commonly used in seal coats. 80/100 penetration grade bitumen is preferred in the warmer regions north of central North Island, and the softer 180/200 grade bitumen is used throughout the remainder of the country.

In 1965, a rational basis for both modifying the bitumen with diesel oil and for temporarily softening it with kerosene was introduced [5]. Laboratory trials established the upper viscosity at which the various types of stone chip could still firmly adhere to a freshly sprayed bitumen film. At first, the road surface temperature was assumed to be a simple function of the ambient air temperature, and the percentage of cutback (usually kerosene) was adjusted accordingly to produce a target viscosity at the time of spraying. Subsequently, the viscosity-temperature-cutback relationship for bitumens used in New Zealand was enhanced by field measurements of air and subsurface pavement temperatures [9]. Nevertheless, the basic principles have remained the same.

In addition to material properties and environmental factors, seal coats are very dependent on operator skill and equipment precision. Historically, the main causes of incorrect bitumen application were incorrect bar heights and worn, misaligned slot jets (slot jets predominate in New Zealand, for both cutback and emulsion spraying), but now stringent specifications and monitoring ensure an application rate precision in the order of  $\pm 2.5\%$ . Fortunately, under normal traffic loadings, "errors" in bitumen application arising from incorrect design assumptions, departures from theoretical binder formulation, irregularities in sprayer performance or

minor departures from specified practices tend to negate the effects of each other. Moreover, a typical seal coat subjected to common public highway loading conditions has considerable inherent tolerance. Also, adhesion agents are always added to the bitumen, to minimize loss of cover aggregate.

The cover aggregate used in New Zealand seal coats always consists of crushed stone particles of uniform size and a cubic shape, even though this material is more expensive than a graded cover aggregate. The range of sizes and shapes of particles are tightly specified and controlled, so that a good mosaic is produced. The design procedure assumes that the desirable voids volume is 20%, though modern stone crushing plants produce a more cubic chip, which tends to reduce the volume of voids, than the norm of 50 years ago [2].

Until recently, heavy rollers were considered to be essential to chip embedment, but this apparently self-evident premise has been disproved. The mass of the roller compactor is less important in creating a tightly locked mosaic of the stone chips than tire action [8]. Roque et al. [12] found that no more than one pass of an 8-tonne pneumatic roller was needed to compact cover aggregate. Excess cover aggregate interferes with particle placement and early alignment under trafficking, both of which are essential for proper embedment at low bitumen contents.

In spite of the theoretically rigid requirements, it is not uncommon practice for contractors to exercise judgement, based on experience, in determining the appropriate bitumen and aggregate application rates for specific, localized situations. The application rates of bitumen tend to be higher than specified to minimize the risk of loss of cover aggregate. As a precaution against loss of chips by traffic action, the actual application rates of cover aggregate also tend to be higher than the rates derived from theoretical design procedures, even though research has confirmed that the application rates of the bitumen and the cover aggregate must be tightly controlled to produce good seal coats because correct application rates and aggregate retention are the most important contributors to seal coat performance [12].

### Vehicle Loading and Pavement Design

At present the vehicle configuration for public roads is limited to a total maximum length of 20 m for an A- or B-train, hauling no more than one trailer behind a tractor/semi-trailer combination.

The maximum weight for the vehicle is limited to 44 tonnes, and the maximum loads permitted on dual-tired single, tandem, and tri-axle groups are 8.2, 15.0 and 18.0 tonnes, respectively. The maximum allowable inflation pressure is 825 kPa for radial ply tires.

Heavy vehicle loading is quantified for highway pavement design purposes in terms of Equivalent Design Axles (EDA); actual axle loads are related to reference loads by the "fourth-power rule" (the exponent is 4.0) to determine the pavement life design loading in terms of EDA. The reference loads for single-tired and dual-tired axles, for example, are 6.7 and 8.2 tonnes, respectively; the tire pressure in the EDA model is 580 kPa.

### FIELD STUDIES

In order to establish a suitable seal coat design procedure which provides adequate serviceability under the environmental and vehicle loading conditions being experienced, a series of field trials are underway. The research involves an 83 km long, private arterial forest road (called the Kawerau-Murupara off-highway) constructed in the Central North Island region during 1987-88, south of Kawerau (shown in Figure 3).



Figure 3. Location of Kawerau Murupara off-highway.

The thicknesses of the pavement layers in the arterial road were designed using the *State Highway Pavement Design and Rehabilitation Manual* [14]; the design life was 15 years. Most of the road consists of a 200 mm thick granular basecourse and 100 mm thick granular subbase over a subgrade stabilized with lime or soil cement. The region is in an active earthquake and volcano zone, so the subgrade material is usually pumice. During construction, the subgrade condition was measured by Benkelman Beam deflection and dynamic cone penetrometer (DCP) tests. Where rebounds exceeded 1.6 mm, the upper 200 mm of the subgrade was stabilized by mixing in Portland cement (2% by mass), to achieve a California Bearing Ratio of at least 30% before the unbound granular cover was placed. A total pavement thickness of 310 mm was specified for the road, based on the performance of existing sealed roads in the same forest. The 200 mm deep basecourse layer was specified to be a well-graded aggregate of crushed river gravel with a crushing resistance of at least 130 kN and a maximum particle size of 40 mm. However, the as-built design, material properties and construction details, such as compaction and weather conditions, were not documented, so exact details are unknown. Later, excavations revealed that quality control during construction was deficient. Often, the granular pavement was placed directly on the topsoil, which should have been removed first. Below the topsoil, the *in situ* soil was usually pumice, but was occasionally a saturated sand.

Typically, the first coat seal consisted of 180/200 penetration grade bitumen, cutback with 7% kerosene, and cover aggregate of A.L.D. 5.5 to 8 mm. The application rate of the bitumen for the first coat ranged between 1.15 and 1.24 l/m<sup>2</sup> (at 15°C). One year later, in accord with normal public highway practice for the region, the road received a second seal coat designed according to the standard procedure. The bitumen was 180/200 penetration grade, cutback with 3% to 4% kerosene. The actual application rate of the bitumen (at 15°C) ranged between 1.97 and 2.36 l/m<sup>2</sup>, depending on the surface condition. The aggregate was a larger size of stone chip of ALD of 9.5 to 12 mm.

Less than two months after the second seal coat had been applied, bitumen in the wheel paths of the loaded lane had flushed to the extent that free bitumen was present on the surface. The cover aggregate was still in place and particles were not being removed by vehicle tires, except at intersections

where severe turning was necessary. Surface excavations revealed that the second coat of larger particles was being pushed down into the lower layer of smaller particles. The first coat of cover aggregate and bitumen had apparently bonded well to the basecourse. The basecourse had a firm, distinct surface, confirming that the chips were not punching into the basecourse and that the bitumen was not being absorbed into the base. The basecourse surface was dense and well-compacted.

The bitumen was mobile, which confirmed the absence of fine particles at the bottom of the seal coats. Patching was only necessary in the very few places where the whole chip-seal system had been removed by a tire after a parked vehicle had moved away.

The lane carrying unloaded vehicles was also flushing but only to a minor degree. The surface of untrafficked areas exhibited the locked mosaic of particles expected of a well-constructed seal coat.

Benkelman Beam tests under an 80 kN single axle load were conducted in the inner and outer wheelpaths of both lanes every 50 m along the entire length of the road. Most of the road exhibited deflections of 0.5 to 1.2 mm, which is typical for New Zealand highways, but about 10% of the road length had deflections of 1.2 to over 2 mm. Sections of the road with surface distress or surface deflections greater than 1.5 mm were either reconstructed or their drainage improved, depending on the specific situation at each site. The most common deficiency in the pavement was poor drainage. In some sections, berms had been constructed to prevent trucks from leaving the road if the drivers fell asleep; these berms also trapped the water on and in the road. Excavations revealed excess moisture in the granular layers. Side drainage was improved by cutting large sloping shoulders and grading them, which allows excess water to freely drain from the pavement and subgrade layers. Due to the improved drainage, the surface deflections of the improved sections of road are less than 1.5 mm, thereby reducing the horizontal tensile stresses in the bitumen film in the seal coat.

Axle weights and gross weights of all the logging vehicles using the private forest road were measured. The average number of fully laden vehicles travelling over the road was 140 per day. The gross vehicle weights ranged from 40 tonnes to 220 tonnes (the latter is a twin-powered unit); the

maximum axle loads were 16 tonnes per axle, in tandem or tri-axle groups. Cold tire pressures ranged from 650 kPa on trailers to 730 kPa on truck driving axles.

### Causes of the Flushed Bitumen

Samples were taken of the seal coat from both flushed and non-flushed seal coat sections; extracted bitumen was tested and aggregate was examined for quantity and dimensions. The actual application rates of the bitumen and the cover aggregate deviated substantially from specified values; the contractors confirmed that application rates were adjusted on the spot based on visual assessment of the road surface and experience.

The flushing, although severe, differed only in degree from that of normal seal coats made with an excess of bitumen. The prime cause of flushing was a seal coat which was inappropriate for such a major departure from the orthodox highway loadings, on which the normal seal design and construction procedures are based.

If the excess is small, and the rate of chip consolidation slow, then surface oxidation will keep pace with the flushing so that over the years the bitumen, although it becomes level with the top of the chips, never reaches the stage of open flushing. An inspection of the public highways in the same region showed that flushing occurred over most of the surface, but was not a problem.

The problem has also been noted in Australia. Oliver [7] reports that, although Australian bitumen quality has remained relatively constant, there are complaints that:

- seal coats which would not previously have bled in the wheelpaths are now doing so, and
- bitumen remains "lively" for longer periods before "setting-up," or long after construction, the bitumen becomes "lively" in hot weather.

The most probable causes are [7]:

- poor load distribution between the axles in groups.
- the adoption of wide single tires in place of dual-tired wheels. In the worst case, the load can approach 5 tonnes per tire.

- higher average tire inflation pressures that now range from 730 to 860 kPa.

Oliver [7] concluded that the degree of embedment of chips will depend on the numbers of and characteristics of the heavy vehicles, such as gross weight, suspension type, and tire characteristics, as well as the resistance of the underlying layer to embedment. The forces and mechanism are such that the properties of the bitumen will have negligible effect on the process. When embedment occurs, bitumen is forced to the surface and flushing occurs in the wheelpath. If a reseal is applied to correct the problem, then the reseal is likely to be affected in the same way.

For arterial forest roads, the axle loads are considerably in excess of the values on which public highway designs are based. The design input values, such as ALD, surface texture, and vehicle intensity, used to derive the bitumen application rates, were based on public highway practice for orthodox vehicle loadings. A softer 180/200 penetration grade bitumen was used for the second coat seals in the belief that the bitumen normally used in the region (80/100 pen. grade) would be too brittle in the winter. Local experience indicates that cracking does not occur in the 80/100 bitumen provided the pavement deflection basin shape is shallow, and that the minimum temperatures ( $-8^{\circ}\text{C}$ ) do not cause cracking.

Another contributing factor may be that the arterial forest road had to carry the full working load immediately following construction. Older sealed forest roads in the same region, whose traffic loadings, with respect to both axle numbers and load magnitude, have increased at a lower rate over many years, have performed well.

The geometry of the arterial forest road is excellent, to enhance the efficiency of the trucking operation; consequently, heavily loaded vehicles of similar configurations travel at speeds in excess of 80 km/h along a common wheelpath as undeviating as a rail line. The intensity of the wheelpath use is much greater than that of a public highway where overtaking, varying vehicle dimensions and tire spacings, and driver behaviour provides random deviation of the wheelpaths, yielding a broader transverse distribution.

## Remedial Work

After the flushing started, a variety of remedies were considered. Burning off the excess bitumen was not attempted in the heavily forested area. Proprietary products are available that are supposed to rehabilitate flushed surface treatments, but their performance in New Zealand field trials has been unsatisfactory.

The first remedy tried involved spreading stone chips pre-coated with bitumen, which has been successful in some situations on public roads but was unsuccessful in this particular case, because the stone chips were too large and the seal coats did not need more bitumen. Applying small aggregate (ALD of 3 mm) in thin layers was unsuccessful initially because the truck tires threw the particles off the surface, but increasing the thickness of the layer yielded a more successful, though temporary, remedy. However, this remedy was too expensive, so a research program was initiated to find a more economical, long-term solution.

## TRIALS OF NEW SEAL COAT DESIGNS

Starting in November 1989, various aspects of the arterial forest road have been investigated as part of an on-going research project. The goal is the development of a new seal coat design procedure suitable for the loading conditions. Test sections have been constructed on the arterial road to trial new seal coat designs and types of bitumens. Initially, construction records were reviewed and a detailed description of the road was compiled. Annual visual appraisal surveys, including photographic logs, of the surface condition are also being done.

### Lower Rates of Residual Bitumen

Three adjacent test sections (A, B, and C), each 500 m long, were sealed in January 1990; the site is 20 km southwest of Murupara, as shown in Figure 4. The purpose of this experiment was to determine the effect of reducing the residual bitumen application rate and the ALD of the cover aggregate. All three sections had the same, uniform conditions, with respect to vehicle loading, longitudinal and transverse slopes, subgrade, unbound granular pavement, and surface deflection response. Standard 180/200 penetration grade bitumen cutback with

7% kerosene and 1% adhesion agent was used for all three sections.

Section A had a single seal coat of larger (ALD) cover aggregate, Section B had a single spray: double aggregate (two nominal sizes) coat, and Section C had a single seal coat of smaller (ALD) cover aggregate. The characteristics and performance of the three test sections is shown in Table 1. The only form of surface distress in Sections A and B was flushing, and

thetic elastomeric rubber, a styrene-butadiene-styrene (SBS) polymer, was first mixed with bitumen at 30% concentration, then the mixture was added to the bitumen to be sprayed. The final concentration of the thermoplastic rubber in the bitumen was 6% by weight. The polymer-modified bitumen was then applied using standard spraying equipment. The bitumen viscosity was temporarily reduced by adding kerosene (4%), and aggregate retention was enhanced by an adhesion agent (0.7 %).

**Table 1.** First set of seal coat trial sections (standard 180/200 penetration grade bitumen).

Test section	Residual bitumen rate (l/m <sup>2</sup> )	Cover aggregate ALD (mm)	Flushing, after	
			1 year (area %)	2 years (area %)
A	1.89	12.0	Moderate	Moderate
B	1.97	12.0 <sup>1</sup>	Moderate	High
C	1.03	6.0	Low	Very High

<sup>1</sup>On top of a first layer of graded aggregate ranging in size from 75 µm to 13.2 mm.

and Section C also exhibited alligator cracking, probably due to the lower durability resulting from the thinner film of bitumen in that section.

After only three years, the test sections were resealed because of severe flushing, but the test sections showed that the application rates of the residual bitumen could be reduced substantially and still retain the cover aggregate. Standard penetration grade bitumen by itself was insufficient.

### Polymer-modified Bitumen

Polymer-modified bitumens enhance retention of cover aggregate, reduce fatigue cracking in the bitumen film, support higher volumes of traffic, perform better in colder service temperatures, and withstand the higher stresses induced by tire action. For these reasons, a second set of four test sections (D, E, F and G) was established to evaluate a polymer-modified bitumen in January 1992. The liquid syn-

The test sections were 200 m long and 4 m wide; the sections were separated by 50 m to minimize proximity effects. Sections D and E are 22 km south of Kawerau; Sections F and G are 7 km further south along the same road (Figure 4). The subgrade, pavement, gradients and vehicle loading are the same for all four sections.

Test section D has a single spray: double coat of aggregate; the second layer of graded aggregate is intended to "lock-in" the cover aggregate, by filling some of the interstices between the larger particles. Test sections E, F, and G have single seal coats. The residual bitumen rates in sections F and G are the normal rates determined from the standard design method, whereas the residual bitumen rates in D and E are the minimum feasible rates (considering the environment, the texture of the existing surface, and vehicle loading). The details are presented in Table 2.

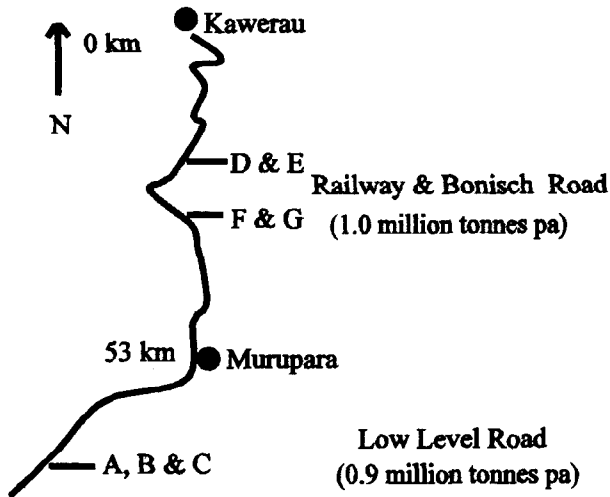


Figure 4. Location of test sections A-G.

### Modified Seal Coat Design

The test sections confirmed that an alternative design method is required to satisfy the specific needs of the arterial forest roads. A third set of test sections have been sealed, to:

- develop a standard procedure for monitoring and evaluating test sections, which could eventually be adopted for the entire forest road network;
- establish a relationship between residual bitumen rate and different forms of resulting surface distress, to determine the optimal rate;
- determine the most effective (with respect to cost and technical performance) type of bitumen for the level of stress expected; and,

Table 2. Second set of seal coat trial sections (polymer-modified bitumen).

Test section	Polymer content (%)	Residual bitumen rate (l/m <sup>2</sup> )	Cover aggregate ALD (mm)	Flushing, after		Cover aggregate loss (area %)
				1 year (relative severity)	3 years	
D	6	1.34	12.11	Negligible	Moderate	30
E	6	1.3	12.1	Negligible	Moderate	0
F	6	1.76	12.1	Negligible	High	0
G	0	1.7	12.1	High	Very High	0

<sup>1</sup>Followed with a second layer of graded aggregate ranging in size from 75  $\mu$ m to 13.2 mm.

In Sections D and E, the bitumen viscosity remains high under loading and summer heat, thus flushing is negligible. However, the loss of cover aggregate in D confirms that the extra locking particles must interfere with the cover aggregate mosaic, leading to loss of cover aggregate. The performances of sections F and G confirm that the normal application rates are too high, whether the bitumen is modified or not. In December 1993, a layer of small aggregate had to be spread over section G to mitigate the effects of flushing, which results in tracking of bitumen along the wheelpaths. In all four sections, the seal coat condition outside of the wheel paths is satisfactory; solar heat alone is not contributing to flushing.

- determine whether the bitumen type and application rate must be adjusted for localized areas of increased stress, such as at corners and adverse gradients.

Forty test sections, each 50 m long, were sealed in January 1994. The variables were (i) level of stress (straight level road versus corners and adverse gradient), (ii) type of bitumen (two different, proprietary brands of polymer-modified bitumens and two standard penetration grade, 80/100 and 180/200, bitumens), and (iii) residual bitumen rate (five rates ranging from 1.02 to 1.73 l/m<sup>2</sup> for each type of bitumen, with minor compensation for



local variations in the texture of the surface being sealed). All test sections are carrying the same fully laden logging trucks. The application rates of the pre-coated cover aggregate (ALD of 12.4 mm) were determined using the public highway design procedure then modified to compensate for the high axle loads.

A detailed series of measurements was conducted on all the test sections prior to and immediately after sealing. The surface texture (using a Mini-Texture Meter and the sand circle test), structural integrity (using a Falling Weight Deflectometer), surface distress (using condition surveys of walkover inspections and photographs), and geometric characteristics were measured. The results are being analyzed to quantify the performance of each test section and underlying pavement.

Surface distress and texture measurements were repeated one year after sealing. The test sections on the adverse gradient with the 180/200 (softer) bitumen had all flushed and are deemed to have failed. All the other test sections are performing well with minor chip loss on the shoulder and centreline only. The test sections are being monitored annually for three years.

## CONCLUSION

Forest road operators need to build an on-going data base of experience and experimentation, by monitoring and documenting the planning, design, construction, performance, and maintenance of arterial forest roads because the requirements of private arterial forest roads subjected to heavy axle loads can be more demanding than those acceptable for public highways.

Seal coats designed using existing public highway design procedures resulted in flushing in the arterial forest road in this study because the bitumen application rates were too high and the rheological properties of standard penetration grade bitumen were inadequate for the loading conditions. Existing seal coat design procedures and construction practices are unsuitable for arterial forest roads carrying axle loads of up to 16 tonnes (twice the New Zealand public highway limits) so new techniques are being developed.

Enhanced quality control during construction, reduced application rates of bitumen, and use of polymer-modified bitumens satisfy the more demanding conditions. Empirical data derived from the forest road networks could be used to improve public highway design procedures for heavier loads.

## ACKNOWLEDGEMENTS

The authors are grateful to Tasman Forestry Limited and Forestry Corporation of New Zealand for financially sponsoring the research, to J. Pollard and R. Lauder for their advice and comments, and to J. Hadley, W. Hatcher, M. Martin, T. Preston, J. Smith, B. Steven, A. Williams and T. Wylie for the information gathered during the summer field investigations.

## REFERENCES

- [1] Bituminous Sealing Manual, 2nd Edition. 1993. Wellington: Transit New Zealand.
- [2] Hanson, F.M. 1935. Bituminous surface treatment of rural highways. Proceedings of the New Zealand Society of Civil Engineers, Vol. 21. Pp. 89-179.
- [3] Houghton, L.D. 1987. Two-coat seals instead of two seal coats. Proceedings of the New Zealand Roading Symposium, Vol. 2. Wellington: National Roads Board. Pp. 265-275.
- [4] Khandal, P.S. 1983. Simplified design approach to surface treatments for low-volume roads. Transportation Research Record 898. Washington, D.C.: Transportation Research Board (TRB). Pp. 325-333.
- [5] Major, N.G. 1965. A basis for the selection of binders for seal coating. New Zealand Engineering, Vol. 20, No. 12, December, Wellington: N.Z. Inst. of Engineers. Pp. 521-528.
- [6] McLeod, N.W. 1974. Seal coat and surface treatment design and construction using asphalt emulsions. Presented at the First Annual Meeting of the Asphalt Emulsion Manufacturers Association, Washington, D.C. Pp. 12-13.

- [7] Oliver, J.W.H. 1988. What is happening to our seals? Proceedings of the 27th Regional Symposium. Melbourne: Australian Road Research Board.
- [8] Petrie, D.D., Sheppard, W.J. and Saunders, L.R. 1990. Towards more efficient rolling of chipseals. Proceedings of the Institution of Professional Engineers New Zealand (IPENZ), Vol. 1. Wellington: IPENZ. Pp. 291-300.
- [9] Pollard, J.S. 1967. The interrelation of atmospheric, binder, and road surface temperatures. Proceedings of the New Zealand Roading Symposium, Vol. 2. Wellington: National Roads Board. Pp. 803-839
- [10] Potter, J.L. and Church, M. 1976. The design of sprayed seal coats. Proceedings of the Australian Road Research Board (ARRB), Vol. 8. Melbourne: ARRB. Pp. 18-24.
- [11] Road Note 39. 1972. Recommendations for Road Surfacing Dressing. Crowthorne, U.K.: Transport and Road Research Laboratory.
- [12] Roque, R., Anderson, D. and Thompson, M. 1991. Effect of material, design, and construction variables on seal-coat performance. Transportation Research Record 1300. Washington, D.C.: Transportation Research Board. Pp. 108-115.
- [13] Southern, D. 1983. Premium surface dressing systems. Shell Bitumen Review 60. London: Shell International Petroleum Co. Ltd. Pp. 4-8.
- [14] State Highway Pavement Design and Rehabilitation Manual. 1987. Wellington: National Roads Board.