Design and Performance of Sprayed Seal Coats for Unbound Granular Pavements Carrying Heavy Logging Trucks

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Virtually all of New Zealand's highway pavements usually consist of 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 forestry roads. In a recent case study, a private forestry arterial road carrying heavily loaded logging trucks was examined. The advantages and limitations of New Zealand's approach to seal coat design with respect to the forestry roads are discussed. Bitumen application rates calculated from national highway design algorithms resulted in flushing in the arterial forestry roads because the surface treatment contains excess bitumen for the axle loads. Experimental work that has been instigated to further the development of seal coat design, construction techniques, and specialized equipment suited to the special requirements of forestry roads sustaining heavy loads is discussed. The concept of cover aggregate embedment and surface hardness is also considered.

Forestry companies are constructing and maintaining networks of high-quality private arterial roads, which are justified economically because logging trucks traveling at speeds of 80 to 100 km/hr over a smooth, all-weather surfaced road can haul logs at a lower cost per unit payload than would the railways. The logging industry takes advantage of New Zealand's unique highway pavement design techniques and practices, but some aspects need to be investigated and modified to suit the needs of the forestry roads. The background to the surfacing design techniques and practices is discussed first, followed by a case study.

BACKGROUND

The total population of New Zealand is 3.4 million. The majority live in five major cities, only one of which is inland. More scattered are rural towns supported by agricultural and pastoral industries that are still New Zealand's largest exporters. The road system that has evolved to serve these communities consists of long, sparsely trafficked lengths. Asphalt-bound aggregate systems are used for some urban streets and interurban motorways, and some rigid pavements were constructed 50 years ago, but virtually all highway traffic is carried by sophisticated unbound granular pavements. The main links between the population centers are classified as national highways and are funded by fuel taxes and heavy-vehicle road user charges. The national highways are managed by a national highway agency, Transit New Zealand [before 1989 the agency's title was the National Roads Board (NRB)]. The pavement engineering design and construction practices have been described elsewhere (*1–4*); the seal coat design, performance, and construction practices are discussed herein.

Current Techniques for Designing Seal Coats

In New Zealand, surface treatments are called seal coats or chip seals; common types of seal coats are shown in Figure 1. The functions of the seal coat are to provide an impermeable membrane over the base course and a skid-resistant surface, as well as a wearing surface. The design of New Zealand's seal coats is based on the theory and mechanisms proposed by Hanson (*5*), 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. Later, the major assumptions were refined by McLeod (*6*):

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 percent.
2. Rolling partially reorients the aggregate particles and reduces the voids to about 30 percent.
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 percent.
4. Because 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. For good performance, under the typical traffic volume of 500 to 1,000 vehicles per day, the quantity of asphalt binder used should fill about 70 percent of the voids.

In New Zealand, the basic precepts have been refined by experience into a semiempirical design procedure that provides corrections for existing surface texture and vehicle loading, culminating in the *Seal Design Manual* (*8*). The seal design algorithm is shown in Figure 3. The algorithm is based on observations and studies involving public highways carrying normal traffic, which typically consists of 10 to 15 percent heavy commercial vehicles with an average axle load of about 5 tonnes. The surface texture is quantified by the sand circle test, which is the diameter achieved when 45 ml of sand (300

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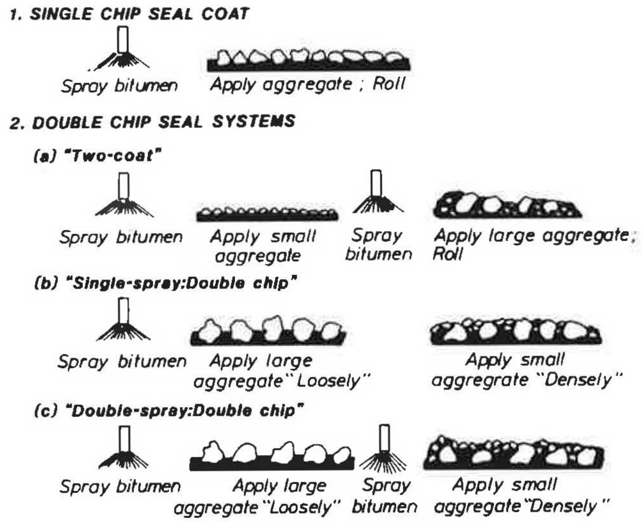

FIGURE 1 Types of seal coat systems (*7*).

to 600 μm) is spread by revolving a straightedge until the sand is level with the tops of the cover aggregate.

Factors Affecting Sprayed Seal Coats

Virtually all of New Zealand's bitumen is produced at the country's sole refinery, at Marsden Point, which uses crude petroleum from various sources to produce two standard penetration (pen.) grade bitumens—45/55 and 180/200 pen. A blend, 80/100 pen., is preferred in the warmer regions north of central North Island, and 180/200-pen. grade bitumen is used throughout the remainder of the country.

A rational basis for both modifying the bitumen with diesel and for temporarily softening it with kerosine was introduced in 1965 (*9*). Laboratory trials established the upper viscosity at which the various types of stone chip could still firmly adhere to a freshly sprayed bitumen film. The road surface temperature was assumed to be a function of the ambient air temperature and the percentage of cutback (usually kerosine) was adjusted accordingly to produce a target viscosity at the time of spraying.

Subsequently, information on the viscosity-temperature-cutback relationships for bitumens used in New Zealand has been extended, and modern instruments have enhanced measurement of the true surface temperature. Field measurements have shown that the relationship between air and road temperature is rather more complex (*10*). Nevertheless, the basic principles have remained the same.

In addition to material properties and environmental factors, seal coats are dependent on operator skills and equipment precision. 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 loading conditions has considerable inherent tolerance. Adhesion agents are usually added to the bitumen.

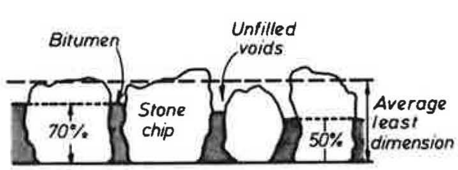

FIGURE 2 Cross section of a seal coat system.

Generally, there have not been serious problems on most public roads, though occasionally excess bitumen flushing from old seals has had to be burned off. However, beginning in the early 1970s, an increase in the occurrence of flushing in pavements under increasing traffic volumes led to a growing awareness of sprayer maladjustments. The main causes were incorrect bar heights and worn, misaligned slot jets (slot jets predominate in New Zealand, both for cutback and emulsion spraying). *The Performance of Bitumen Distributors* (*11*) was introduced to ensure an application rate precision in the order of ±2.5 percent. Subsequent testing of sprayers indicated that some did not have the precision essential for producing uniform-bitumen films at low application rates, principally because the sprayers had not been designed for such duties.

The cover aggregate used in New Zealand seal coats is always crushed-stone particles of uniform size, even though this is more expensive than a graded-cover aggregate. Particle size range and shape has been tightly specified and controlled for many years, so that a good mosaic is produced in the seal coat cover aggregate. The design procedure assumes that the void volume is still 20 percent, though modern stone-crushing plants produce a more cubic chip than the norm of 50 years ago.

Until recently, it was also believed that heavy rollers were essential to chip embedment but this apparently self-evident

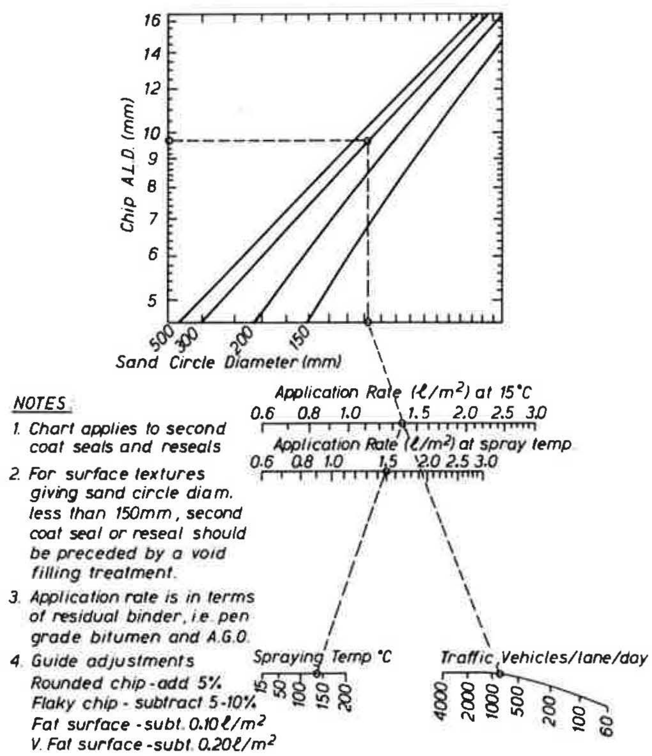

FIGURE 3 New Zealand seal coat design algorithm.

premise has been disproved (*12*). The research indicates that the mass of the roller compactor is less important in creating a tightly-locked mosaic of the stone chips than tire action. The research also showed that 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 in New Zealand for contractors on private work to exercise an appreciable degree of experience-based judgment in determining the appropriate bitumen and aggregate application rates for specific situations. The application rates of bitumen tend to be higher to avoid risking loss of stone chip. 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.

Vehicle Loading

The tradition of a strong central government has resulted in uniformity of pavement design and construction as well as a concomitant enforcement of heavy vehicle load limits. At present, the vehicle configuration 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-semitrailer combination. The maximum weight for the vehicle is limited to 44 tonnes, and the maximum loads permitted on single, tandem, and triaxle groups are 8.2, 15.0, and 18.0 tonnes, respectively.

Heavy-vehicle loading is quantified for highway pavement design purposes in terms of equivalent design axles (EDAs). The NRB reference loads for single- and dual-tired axles are 6.7 and 8.2 tonnes, respectively; the standard tire pressure is 580 kPa. Actual axle loads are related to the reference loads by the fourth-power rule (the exponent is 4.0). Currently, transport operators are lobbying to have the load limits relaxed, but the existing data base is inadequate and pavement engineers are reluctant to extrapolate the present pavement design techniques for untested loadings.

In recent years, increasing lengths of private roads have been built by logging companies in the radiata pine forest plantations of New Zealand. The heavy haulage vehicles for which these roads are built are not subject to the load limits imposed on the national highway systems and some seal coats over unbound granular pavements are subjected to axle loads of up to twice the current national limits. The following case study illustrates how inappropriate the semiempirical national highway design approaches are for seal coats subjected to such loads. Conversely, empirical data derived from such conditions could be used to enhance the national highway design procedures.

CASE STUDY

The case study involves a 50-km forestry road constructed in the scenic northeastern region of the North Island. In 1987, a major forestry company calculated that private truck haulage would be more economic than public rail haulage to transport logs between a major assembly depot and its pulp and paper mill (the largest in the southern hemisphere).

The thicknesses of the pavement layers in the arterial road were designed using the state highway pavement design manual (*4*); the selected design life was 15 years. Most of the road consists of a 200-mm-thick granular base course and 100-mm-thick granular subbase over a subgrade stabilized with lime or soil cement. The first coat seal consisted of 180/200-pen. grade bitumen, cutback with 7 percent kerosine, and cover aggregate of ALD 5.5 to 8 mm. The seal coat was applied in stages during the period December 1986 to March 1988. The application rate of the bitumen (at 15°C) ranged between 1.15 and 1.24 L/m^2. All materials and construction practices followed national highway specifications (*13–18*).

One year later, in accord with normal national highway practice for the region, the road received a second seal coat. The bitumen was 180/200-pen. grade, cutback with 3 to 4 percent kerosine. The application rate of the bitumen (at 15°C) ranged between 1.97 and 2.36 L/m^2, depending on the surface condition. The aggregate was a larger size of stone chip of ALD 9.5 to 12 mm.

Less than 2 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 stone chips were still in place and 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 base course. The base course had a firm, distinct surface, which implied that the chips were not punching into the base course and that the bitumen was not being absorbed into the base. The base course surface was dense and well compacted, and appeared to have the normal moisture content of approximately 2 percent. The bitumen was mobile, which confirmed the absence of fine particles at the bottom of the seal coats. Patching was only necessary in the 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 flushing also but only to a minor degree. Apparently, the effects of weathering had kept pace with flushing so that no bitumen from a broken skin was apparent. The surface of untrafficked areas exhibited the locked mosaic of particles expected of a well-constructed seal coat.

Remedial Work

After the flushing started, a variety of remedies was attempted. The first trial involved spreading stone chips precoated with bitumen. This process is successful in some situations on public roads but was unsuccessful in this particular case, probably because the stone chips were too large and the seal coats did not need more bitumen. A second trial that involved applying thin layers of small aggregate (ALD of 3 mm) was unsuccessful because the truck tires threw them off. Burning off the excess bitumen was not attempted in the heavily forested area.

A more successful solution has been the application of a thicker layer of 3 mm (ALD) cover aggregate. The lower chips in the layer are pressed into the seal and stick to the binder while being protected by the covering chips. But, to determine the most suitable long-term solution, a comprehensive investigation was undertaken by a team of four final-year engineering students from the University of Canterbury.

Subsequent Investigation

During the summer period of November 1989 to February 1990, various aspects of the arterial forestry road were investigated in detail. Initially, construction records were reviewed and a detailed description of the road was compiled. A visual appraisal survey and photographic log of the surface condition were done for the whole road.

Benkelman beam tests under an 80-kN 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; about 10 percent of the road length had deflections of 1.2 to 1.9 mm, which is acceptable for public highways subjected to typical commercial vehicle loads.

Axle weights and gross weights of all the logging vehicles using the private forestry road were measured; a relationship between vehicle configuration and payload efficiency, with respect to potential damage to the road, was developed. The average number of fully laden vehicles traveling over the road was 140 per day. The maximum gross vehicle weights of the trucks ranged from 40 to 120 tonnes; the maximum axle loads were 15 tonnes per axle, in tandem or triaxle groups. Cold tire pressures ranged from 650 kPa on trailers to 730 kPa on truck driving axles (of Mack trucks).

The bearing capacity of the subgrade and the pavement and subsurface drainage were evaluated. The excavations revealed that the base course had a sound, hard surface, and was composed of quality aggregate.

Samples were taken of the seal coat from both flushed and nonflushed seal coat sections; extracted bitumen was tested for diluent content (see Table 1) and aggregate was examined for quantity and dimensions. The substantial diluent contents remaining after 2 or 3 years suggests that either, initially, the actual contents were higher than those recorded because of imprecision in the mixing or the diluent is remaining in the bitumen much longer than is normally assumed. 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 on the basis of visual assessment of the road surface and experience.

TABLE 1 PROPERTIES OF RETRIEVED BITUMEN SAMPLES

Age of each seal coat		Diluent Content
First (years)	Second (years)	%
2	1	2.2[a]
3	2	2.2[b]
5	3	2.1[c]

[a] Average of 3 samples.
[b] Average of 6 samples.
[c] 1 sample.

A theoretical model describing the performance of bitumen in seal coats was also derived, and will be calibrated using actual field data. The final analysis and report were incomplete at the time of the writing, so specific details and references are unavailable.

The information is being compiled into a data base for easy retrieval and updating.

Discussion

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 that 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.

In a research project conducted at the Canterbury Accelerated Pavement Testing Indoor Facility (CAPTIF) in Christchurch, New Zealand, during 1987, pavements similar to the case study road were subjected to 40-kN dual-tired wheel loads at an average speed of 40 km/hr until 1.4 million loads had been applied. Soon after loading began, the initial two-coat seal began flushing, even though there was no loss of chip and the base course was firm. After flushing became severe, the initial coats were removed and the base course lightly releveled. A single coat of bitumen sprayed at a lower-than-normal rate was coated with a first layer of larger stone chips (ALD of 12 mm) interlocked with smaller chips (ALD of 8 mm). This seal coat began exhibiting severe flushing after only a few thousand vehicle loadings. The flushing was attributed to excess bitumen of too low a viscosity for the high axle loads, the high rate of loading, and the absence of light-vehicle traffic that could have slowly conditioned the surfacing (*19*).

The problem has also been noted in Australia. Oliver (*20*) reports that, although Australian bitumen quality has remained relatively constant, there are complaints that

- Seal coats that would not previously have bled in the wheelpaths are now doing so, and
- Bitumen remains lively for longer periods before setting-up, or months or years after construction it becomes lively in hot weather.

The possible causes are (*20*) the following:

- The advent of triaxle configurations. These tend to have a poor load distribution between the axles in the group. For example, 1 in 10 trucks surveyed had a load variation exceeding 20 percent on individual axles of the triaxle group.
- The adoption of wide single tires in place of dual-tired wheels. In the worst case, the load can approach 5 tonnes per tire.
- At the time of the AASHO Road Test, typical truck tire pressure in the United States was 560 kPa (*21*). Average tire pressures now range from 730 to 860 kPa.

Oliver (*20*) concludes 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 the arterial forestry roads, the axle loads are considerably in excess of the values on which the national highway design tables are based. The design input, such as ALD values of the particles, surface texture, and vehicle intensity, used to derive the bitumen application rates were based on NRB practice for orthodox vehicle loadings. Bitumen of 180/200-pen. grade 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. (NRB experience indicates that cracking does not occur provided the pavement deflection is of the shallow-shaped bowl variety, and the minimum temperatures (−8°C) are not low enough to cause cracking.)

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

The geometrics of the arterial forestry road are particularly good. This factor enhances the efficiency of the trucking operation but, as a consequence, heavily loaded vehicles of similar configurations travel steadily at speeds in excess of 80 km/hr 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 behavior provide random deviation of the wheelpaths, yielding a broader transverse distribution.

REVIEW OF OTHER SEAL COAT DESIGN METHODS

The Transit New Zealand method is based on normal highway traffic; axle loads are limited to 8.2 tonnes per single axle carrying dual-tire wheels, and the maximum allowable tire pressure is 825 kPa for radials. A review of international literature was undertaken to determine if any other surface treatment design techniques may have been developed that do consider heavy-axle loads, tire characteristics, and surface hardness.

Houghton (*22*) evaluates a variety of New Zealand and French design techniques to derive a suitable method for heavily trafficked urban arterials, and Kandhal (*23*) presents a comprehensive review of surface treatments, but none consider the three critical parameters listed earlier. Southern (*8*) and Road Note 39 (*24*) consider commercial vehicles of unladen weights over 1.5 tonnes and take into account a subjective description of the surface hardness of the road. Potter and Church (*25*) proposed that seal coat design should be based on (a) hardness (resistance to embedment) of the layer under the seal coat, and (b) traffic loading. Their paper provides the initial basis of such a design approach, but emphasizing 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.

Seal coats are an attractive economic alternative for low-volume roads but none of the design procedures are appropriate to the loadings that are already being experienced on the arterial forestry roads.

PROPOSED DEVELOPMENTS

Seal Coat Design for Low-Volume Roads under Heavy Axle Loads

An important aspect deserving immediate attention is the matter of the exponent or relationship to be used in the load equivalency conversion factor. It is unlikely that the fourth-power law used on national highways is applicable to the forestry road loading conditions, especially in designing the seal coats.

The case study results confirm that the bitumen content must be kept low. The actual application rates in the case study were 1.15 to 1.24 L/m^2 for the first coat and 1.97 to 2.36 L/m^2 for the second coat. Using the NRB design algorithm and judgments of correction factors based on hindsight, the required bitumen application rate was calculated to be 0.8 L/m^2 (at 15°C) for the first coat seal. The application rate was also calculated by the Asphalt Institute method (*26*). Assuming that the base course was reasonably smooth and slightly porous, and the logging traffic applied tire loads equivalent to a normal public traffic mix of greater than 2,000 vehicles per day with about 10 percent heavy commercial vehicles, the first-coat application rate of residual bitumen was calculated to be 0.9 L/m^2 (at 15°C).

A computer-based expert system package, the Australian Road Research Board (ARRB) Sprayed Seal Advisor, was also used to calculate the required bitumen application rates:

- First coat of cold, residual bitumen of 0.8 L/m^2. (This value is equivalent to 0.86-L/m^2 cutback with 7 percent diluent.)
- Second coat of 1.2 L/m^2. (This value is equivalent to 1.25 L/m^2 cutback with 4 percent diluent.)

However, the theoretical values do not incorporate the necessary component of a visual appraisal of the condition of the surface before being sealed.

The feasibility of priming under arterial forestry road conditions should be examined. Emulsified bitumen could then be used even for the first seal coat. This would avoid the curing time of cutback diluents and wet the maximum particle surface area although the residual bitumen application is low.

A seal coat design that should be studied is a single-spray, double-chip seal incorporating a large chip braced and locked by a smaller top chip. With proper size selection, this design can produce a tight seal with a low total volume of bitumen. A double-spray, double-chip seal should also be considered, but the total bitumen content must be kept low.

These techniques are practical and available, and should be evaluated by field trials conducted on arterial forestry roads in use. which would yield results after many years, following preliminary trials at the Canterbury accelerated pavement testing facility. The test track trials, with the capability of applying 15 years of trafficking in a few months, will enable the evaluation of seal coat designs outside normal prudent limits because of the lower cost of test track utilization.

Road Engineering and Management

In New Zealand, the low-volume roads used by the logging industry carry loadings considerably in excess of those currently allowed on public highways. If modern-road engineering management techniques had been applied to the forestry road system, the problems highlighted by the road studied could probably have been predicted. The forestry road operators need to build an ongoing data base of experience and experimentation. Substantial attention and resources should be dedicated to monitoring existing roads and documenting activities. The pavement management techniques used by New Zealand's public road authorities are unsuitable because of the difference of loadings and users' needs. No road information and management system is known that is suitable for the forestry road situation. The logging industry should also investigate the feasibility of providing financial incentives to haul operators to use less damaging axle load and tire configurations.

CONCLUSIONS

The current seal coat design procedures and construction practices are unsuitable for low-volume roads carrying heavy axle loadings.

The requirements of low-volume arterial forestry roads subjected to heavy axle loads are superior to those acceptable for New Zealand national highways. Thus, sealing practices, especially with respect to bitumen and stone chip application rates, additions of cutback diluent, and adhesion agent, require supervision and equipment able to readily comply with the more rigorous requirements.

It is essential that the operators of low-volume roads build their own data base from experience and experimentation. More specifically, an ongoing system of monitoring and documenting the planning, design, construction, performance, and maintenance of arterial forestry roads should be implemented.

The performance of a single-spray, double-chip or double-spray, double-chip emulsion seal over a primed surface under heavy axle loads should be investigated. Long-term field trials, complemented by testing in an accelerated pavement testing facility, are recommended.

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