Session 6
Paper (b)

FUNDAMENTALS OF CHIP SEAL DESIGN FOR FORESTRY ROADS

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ABSTRACT

Seal coats are the most attractive economic alternative for providing all-weather forestry roads, so the log transport industry takes advantage of the unique highway pavement design techniques and practices used in New Zealand, but existing design procedures are inappropriate for the loadings that are being experienced on the arterial forestry roads. The advantages and limitations of seal coat design with respect to the forestry roads are discussed in this paper. The background to the surfacing design and construction methods and practices is discussed first. Experimental work which has been instigated to further the development of seal coat design, construction techniques, and specialised materials suited to the special requirements of forestry roads sustaining heavy loads is described and discussed. Results of field trials thus far have shown that enhanced quality control during construction, reduced application rates of bitumen, and use of polymer-modified bitumens are providing the required performance.

SEAL COAT DESIGN METHODS

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 objective is to spray just enough bitumen to hold the chips in place and provide the impermeable layer, but not too much so as to minimise the eventual flushing.

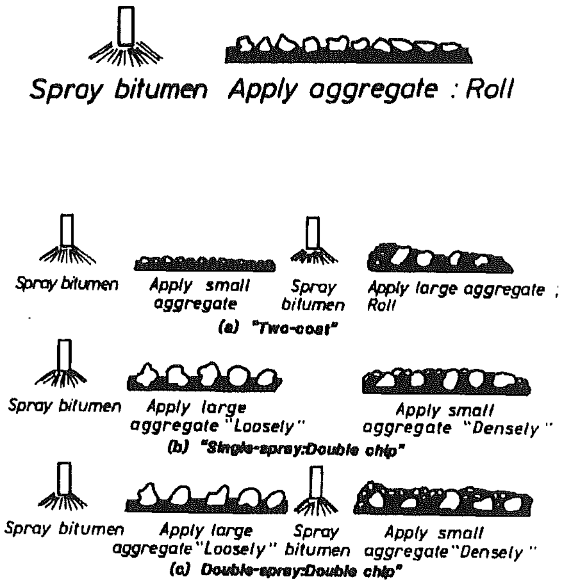

Figure 1 Seal Coat Systems

The design of seal coats is based on the theory and mechanisms proposed by Hanson [2], who was the first to relate 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, as a result of laboratory experiments and field experiences. The major assumptions are [6]:

1. When one-size cover aggregate is spread over a bitumen film, the particles lie in random 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.

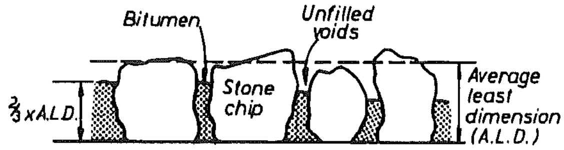

Figure 2 Cross-section of a Seal Coat

5. The residual bitumen should fill about 67 % of the voids, under typical public highway traffic volumes and vehicle mix.

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:

$$R = (0.138\ ALD + e)\ T_f$$

where:

R = residual (after diluent evaporates) bitumen application rate at 15°C $[\ell/m^2]$

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

e = adjustment for the texture of the surface to be coated $[\ell/m^2]$

T_f = 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 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 forestry roads, a formula converts the HCV to a standard mix of vehicles. The surface texture is quantified by the sand circle test, which is the diameter achieved when 45 ml of sand (300 µm to 600 µm) is spread by revolving a straight-edge until the sand is level with the tops of the cover aggregate. Additional design algorithms have been developed for two-coat seals and emulsified bitumens.

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, tyre characteristics and the other unique conditions found on the forestry 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] presents a comprehensive review of surface treatments. Road Note 39 [11] and Southern [13] 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 [10] proposed that seal coat design should be based on: (i) hardness (resistance to embedment) of the layer under the seal coat and (ii) traffic loading. Their paper provides the initial basis of such a design approach, but emphasizes 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.

However, none of the above design procedures are applicable to the heavy axle loads and trafficking conditions experienced on the arterial forestry roads.

Factors Affecting Seal Coat Performance

Bitumen consistency is quantified by a number of tests, but the most common is the penetration test. In the penetration test, the bitumen is heated to a specified temperature (normally, 25°C) and then maintained at a constant temperature in a water bath. A standard sized needle, of a specific weight (normally, 100 g), is positioned at the surface of the bitumen and released to penetrate the bitumen sample for exactly 5 seconds. Two standard penetration grade bitumens - 45/55 and 180/200 - are used as is or blended to create bitumens of intermediate viscosities. A blend, 80/100, 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 and for temporarily softening it with kerosine 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 kerosine) was adjusted accordingly to produce a target viscosity at the time of spraying.
Subsequently, the viscosity-temperature-cutback relationships for bitumens was enhanced by field measurements of air and subsurface pavement temperatures [9], but the basic principles have remained the same.

In addition to material properties and environmental factors, seal coats are very dependent on operator skills 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 ± 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 minimise loss of cover aggregate.

Unlike most North American and European practices, the cover aggregate used in New Zealand seal coats is always crushed stone chips of uniform size and a cubic shape, even though this is more expensive than a graded cover aggregate (of a range of particle sizes). The range of sizes and shapes of particles are tightly specified and controlled, so that a good mosaic is produced in the cover aggregate. The design procedure assumes that the void volume is still twenty percent, as prescribed by Hanson [2], though modern stone crushing plants produce a more cubic chip than the norm of fifty years ago.

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 tyre action [8]. Roque *et al*[12] found that no more than one pass of a 8 tonne pneumatic roller was needed to compact cover aggregate.

In spite of the theoretically rigid requirements, it is not uncommon practice for contractors 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 minimise 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. However, experience and research have 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]. Excess cover aggregate interferes with particle placement and early alignment under trafficking, both of which are essential for proper embedment at low bitumen contents.

Vehicle Loading and Pavement Design

At present the vehicle configuration for public roads is limited to a total maximum length of 20 metres 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 tyres.

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 tyre pressure in the EDA model is 580 kPa.

FIELD STUDIES

Typically, the first coat seal consists of 180/200 or 80/100 (depending on the location and climatic conditions) penetration grade bitumen, cutback with kerosine, and cover aggregate of A.L.D. 5.5 to 8 mm. The application rate of the bitumen for a first coat ranges between 1.0 and 1.5 ℓ/m^2 (at 15°C), depending on traffic volumes and surface texture.

One or two years later, normal practice is to apply a second seal coat. The application rate of the bitumen (at 15°C) ranges between 1.5 and 2.5 ℓ/m^2, depending on conditions. The aggregate is normally a larger size of stone chip of A.L.D. of 9.5 to 12 mm.

A Typical Scenario

In too many cases, only a few months after the second seal coat is applied, bitumen in the wheel paths of the loaded lane is flushed to the extent that free bitumen is present on the surface. The cover aggregate can still be in place and particles is not being removed by vehicle tyres, except at intersections where severe turning is necessary. Surface excavations reveal that the second coat of larger particles are being pushed down into the lower layer of smaller particles. The first coat of cover aggregate and bitumen has apparently bonded well to the basecourse. The basecourse has a firm, distinct surface, which indicates that the chips were not punching into the basecourse and that the bitumen was not being absorbed into the base. The basecourse surface is dense and well-compacted, and appears to have the normal moisture content of approximately 2%. The basecourse is sound and is composed of quality aggregate.

The bitumen is mobile, which confirms the absence of fine particles at the bottom of the seal coats. Patching is usually only necessary in the few places where the whole chip-seal system has been removed by a tyre after a parked vehicle has moved away.

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

Causes of the Flushed Bitumen

Samples should be taken from both flushed and non-flushed seal coat sections; extracted bitumen can be tested and aggregate examined for quantity and dimensions. The substantial diluent contents remaining after two or three years can suggest that either, initially, the actual contents were higher than those recorded due to 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 often deviate substantially from specified values. Contractors confirm that application rates are adjusted on-the-spot based on visual assessment of the road surface and experience.

The flushing, even if it is severe, differs only in degree from that of normal seal coats made with an excess of bitumen. The prime cause of flushing in forestry roads is usually a seal coat which is 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 usually reveals that flushing occurs over most of the surface, but is not as big 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 that months or years after construction it becomes *"lively"* in hot weather.

The most probable causes are [7]:

- Poor load distribution between the axles in groups.
- The adoption of wide single tyres in place of dual-tired wheels. In the worst case, the load can approach 5 tonnes per tyre.
- Higher average tyre inflation pressures that now range from 730 to 860 kPa.

Oliver [7] 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, tyre 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 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.

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

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

Possible Remedies

After the flushing has started, a variety of remedies can be considered. Burning off the excess bitumen is one option, but may not be feasible. Proprietary products are available that are supposed to rehabilitate flushed surface treatments, but their performance in New Zealand field trials has been unsatisfactory.

One remedy involves spreading stone chips pre-coated with bitumen; this has been successful in some situations on public roads but can be less successful when the stone chips are larger and the seal coats do not need more bitumen. Applying small aggregate (ALD of 3 mm) in thin layers is unsuccessful because the truck tyres throw the particles off the surface, but increasing the thickness of the layer has yielded a more successful, though temporary, remedy. However, this remedy is too expensive, so a research program has been initiated to find a more economical, long-term solution.

TRIALS OF NEW SEAL COAT DESIGNS

Initially, construction records were reviewed and a detailed description of the road compiled. Annual visual appraisal surveys, including photographic logs, of the surface condition were completed.

The goal of the research is the development of a new seal coat design procedure suitable for the loading conditions, so test sections have been constructed on an arterial road to trial new seal coat designs and types of bitumens. All test sections must have the same, uniform conditions: vehicle loading, longitudinal and transverse slopes, the underlying unbound granular pavement, and surface deflection response.

Research has proven that the application rates of the residual bitumen can be reduced substantially and still retain the cover aggregate, but standard penetration grade bitumen by itself is 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 tyre action. The liquid synthetic elastomeric rubber - a styrene-butadiene-styrene (SBS) polymer - is first mixed with bitumen at 30% concentration, then the mixture is added to the bitumen to be sprayed. The final concentration of the thermoplastic rubber in the bitumen is 6% by weight. The polymer-modified bitumen is then applied using standard spraying equipment.

The results of some trials are presented in Table 1. 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).

Test Section	Polymer Content	Residual Bitumen Rate	Cover Aggregate ALD	Flushing, after		Cover Aggregate Loss
				1 year	2 years	
	(%)	(ℓ/m^2)	(mm)	(Relative Severity)		(Area %)
D	6	1.34	12.1[1]	Negligible	Negligible	30
E	6	1.30	12.1	Negligible	Negligible	0
F	6	1.76	12.1	Negligible	High	0
G	0	1.70	12.1	High	Very High	0

Table 1. Second Set of Seal Coat Trial Sections (polymer-modified bitumen)

In Sections D and E, the bitumen viscosity is remaining 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, so heat alone is not contributing to flushing.

Modified Seal Coat Design

Field studies have confirmed that an alternative design method is required to satisfy the specific needs of the sealed forestry roads. A set of test sections has been implemented; the aim is to establish a suitable seal coat design procedure which provides adequate serviceability under the environmental and vehicle loading conditions being experienced. The objectives are to:

Develop a standard procedure for monitoring and evaluating test sections, which could eventually be adopted for the entire forestry 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,

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

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[1] Followed with a second layer of graded aggregate ranging in size from 75 μm to 13.2 mm.

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 application rates of bitumen, ranging from 1.04 to 1.64 ℓ/m^2 @ 15 ° C, were sprayed for each type of bitumen, adjusted for the texture of the surface being sealed (e = 0.10 ℓ/m^2). All test sections are carrying fully-laden logging trucks. The application rates of the bitumen and chips (A.L.D. of 13.1 mm) were determined using the public highway design procedure then modified to compensate for the high axle loads. Because the application rates of bitumen are so low, polymer-modified bitumen, adhesion agents and pre-coated chips are necessary to prevent loss of the chips.

The test sections are being monitored by condition surveys using walkover inspections and photographs. A Falling Weight Deflectometer (FWD), a Mu-Meter, and a Mini-Texture Meter are being used in the annual measurement of pavement structural capacity, skid resistance and surface micro-texture, respectively, to quantify the performance of each test section and underlying pavement. The sand circle test is being done four times per year on each test section, to measure seasonal variations in surface texture.

Road Management

In New Zealand, the arterial roads used by the logging industry carry loadings considerably in excess of those currently allowed on public highways. The forestry road operators need to build an on-going data base of experience and experimentation. More specifically, comprehensive pavement management systems for monitoring and documenting the planning, design, construction, performance and maintenance of arterial forestry roads should be implemented. Substantial attention and resources are required to monitor existing roads and document activities. The feasibility of providing financial incentives to truck operators to use less damaging axle load, suspension and tire configurations should also be investigated.

CONCLUSION

The requirements of private arterial forestry roads subjected to heavy axle loads is superior to those acceptable for public highways. Seal coats determined from existing public highway design procedures result in flushing in arterial forestry roads because the residual bitumen rates are too high and the rheological properties of unmodified bitumens are inadequate for the loading conditions. The current seal coat design procedures and construction practices are unsuitable for arterial forestry roads carrying axle loads of up to 16 tonnes or twice the 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 forestry road networks could be used to improve public highway design procedures for heavier loads.

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