Frost Resistant Design and Construction of Pavements in Central Otago

Tonkin & Taylor Ltd, 2004. Revised 2009.

1.0 Introduction

Frost damage is a significant factor in the premature demise of unbound granular pavements in Central Otago. During the 1970s and 1980s, extensive lengths of new and rehabilitated pavements were constructed in the Cromwell Gorge and Lindis Pass (where frost penetration to 600 mm was noted). Experience obtained in these projects was documented at the time under research grants addressing both construction in schist and the frost resistance of pavement materials. The work was carried out for the National Roads Board to provide guidelines for the frost resistant design and construction of unbound pavements in similar terrain where schist and glacial deposits are the principal soil types. This update is intended for local practitioners involved with design and/or construction supervision and quality assurance of pavements in frost prone regions.

2.0 Characteristics of Frost Damage

Frost heave is caused by ice expansion with loss of strength on thawing. It may occur in the basecourse, subbase or subgrade and is manifested as premature rutting and cracking, and, in extreme cases, as shoving and pot-holing.

If the basecourse of an unbound granular pavement with chip-seal is formed of frost susceptible material, distress can develop very rapidly as trafficking during thaw will result in chip being driven down into the binder, leading to flushing and loss of skid resistance. Areas of cracked pavement may seep melt-water during thaw and form black ice in wheelpath ruts in the next freeze. Seal may be laterally displaced or inflated, having lost adhesion to the basecourse.

3.0 Design for Frost-Resistant Pavements

3.1 Depth of Frost Penetration

With one night of freezing, the zero isotherm may penetrate about 100 mm. If the one night is followed by day temperatures above freezing, temperatures below freezing point persist for only a few hours. However, with 3 days of day temperatures below freezing point, frost may penetrate 300 mm. With 10 days below freezing point, frost penetration may exceed 450 mm (Ref. 3).

For Central Otago, favourable sites may experience frost penetration of not much more than 200 mm, while values for high altitude highway passes were found to exceed 600 mm. Hence, site specific pavement depth and material requirements should be applied. Quantitative estimates of the depth of frost penetration may be made from the frost index. The frost index, I, is defined as the product of the number of days of continuous freezing and the average amount of frost (in degrees Celsius) on those days. The depth of frost penetration (H) is estimated as:

$$H = 40\sqrt{I} \text{ mm} \qquad \text{Eqn (1)}$$

3.2 Particle Size Distribution and Permeability

Silt size particles have been shown to be the most frost susceptible soils. Silts are a characteristic of Central Otago because most of its subgrade soils and aggregate sources are derived from glacial scouring in relatively recent times. Till, inter-glacial lake sediments and loess are predominately silt and these are three of the principal soils. A fourth is schist debris mantling most of the alpine slopes, and again silt forms its matrix. The other major unit is outwash alluvium, which contains minimal silt but frequently is mantled by silt (loess or floodplain deposits).

Basecourse

The TNZ Supplement to the Austroads Pavement Design Guide states that "Specific construction techniques and materials are required when freeze/thaw conditions prevail, but there is no change to the pavement design philosophy …. all aggregates used must not be susceptible to freeze/thaw collapse. Also, good drainage must be provided to minimise the quantity of water which can enter the pavement and subsequently freeze". A laboratory test is indicated (Ref. 2), in which basecourses with access to water are subject to freezing conditions for 4 days. The laboratory criteria proposed, based on limited sample numbers, are:

- Freeze-Thaw Heave < 14 mm
- Sand Equivalent > 50
- Fines (<0.075 mm) < 5 %

Historically, one of the more fundamental criteria for frost susceptibility has been the percentage of material passing 20 microns, with 3% set as the limit for the type of mineralogy in Central Otago. As this criterion requires an extended particle size distribution to be determined, many other specifications (including TNZ M/4) adopt the percentage passing 75 microns as their criterion of convenience. Most use between 5 and 10% as a maximum (Ref. 1) comparing reasonably with the M/4 limit of 7% for basecourse. However, in M/4, the limit is based on stockpile condition, not in-situ (after loading, trucking, spreading, trimming, compaction and trafficking). Recent QLDC practice has been to sample after spreading.

Also, it should be appreciated that the overseas criteria are mostly based on pavements which will have a thick structural asphaltic surfacing (protecting the deeper unbound layers) as opposed to thin chip seal used in NZ. For unbound granular basecourses with thin chip seal surfacing, aggregates which are marginal in one or more of the M/4 requirements should be used with caution. The 4 principal parameters relevant to the mixed schist and greywacke aggregates of Central Otago are: Crushing Resistance, Weathering Resistance, Sand Equivalent, and Fines (percentage passing 75 microns). In Otago, all four may approach the M/4 limits to varying degrees, particularly where the percentage of greywacke is low. The Wakatipu Basin has a lesser proportion of its catchment composed of greywacke sources than Wanaka; hence somewhat poorer aggregate performance is generally found in the former area. For any marginal M/4 it is suggested that supplementary or more restrictive criteria be introduced to ensure the completed basecourse product is checked for frost resistance. Sand equivalent has not been proven to be a good indicator in local basecourses. Post-compaction grading, voids, permeability, and freeze-thaw heave should provide the most effective controls.

Basecourse gradings may be simply characterised with the grading exponent given by Talbot and Richart (1923) for the gradient of the particle size distribution curve plotted logarithmically. A mid M/4 grading has a gradient (n) of 0.5 with ranges of 0.41 to 0.63 approximately, defining the fine and coarse limits of the envelope. At the coarse limit, high permeability and no problems with frost resistance will be experienced, but obtaining a well-interlocked surface will be more difficult. The compacted dry density typically achieved in a mid-M/4 basecourse (n=0.5), is typically about 86% of solid density. An approximate target percentage of solid density (D_{max} %) for other gradings (Ref. 4) is:

$$D_{max}\ \% = 86 + 20(0.5-n) \qquad \text{Eqn 2}$$

Alternatively the following regression may be adopted:

$$D_{max}\% = 83.6 - 8.8n + 13.6SGE + 0.1P_{19mm} - 0.018C - 0.9(P_{4.75mm}/P_{0.15mm}) \quad \text{....Eqn 3}$$

Where:

- n is the average grading exponent of the full particle size distribution
- SGE is the sand grading exponent (defined below)
- P_{19mm} $P_{4.75mm}$ and $P_{0.15mm}$ are the percentages of the aggregate (by weight) passing the 19, 4.75 mm and 0.15 mm sieves, respectively.
- C is the percentage (by weight) of broken faces in the aggregate but adopt 200% if the aggregated is quarried rock rather than crushed alluvial gravel.

(Note: $D_{max}\%$ is a percentage of solid density, as distinct from percentage of maximum dry density or relative density.)

Therefore, an additional design consideration in frost prone areas is to prefer aggregate sources which have compaction curves exhibiting relatively low values of D_{max} at the maximum laboratory dry density (ie not more than about 86% of solid density). The best performing basecourses in the Wakatipu basin exhibit about 85% of solid density.

Grading shape control is an important part of the M/4 specification that relates to frost resistance because it precludes gap gradings that have a deficit of void creating, medium to coarse sand in relation to moisture holding fines. However, M/4 particle size distribution is a pre-compaction requirement. An approximate way to simulate post-compaction characteristics is to determine the particle size distribution after laboratory vibrating hammer compaction. From that, an effective grading shape control (Ref. 4) that minimises the risk of either frost damage or shear instability (shoving) developing within an aggregate is to specify that Talbot's n value in the sand fraction is generally greater than 0.40.

A quantitative measure of this is here termed the sand grading exponent (SGE) which is described further in Appendix A, ie

$$SGE >= 0.40 \qquad \text{Eqn 3}$$

This is slightly more restrictive than the M/4 grading shape control limits and can be achieved by adding sand to South Island alluvial sources which are traditionally short of medium to coarse sand sizes.

If this criterion is satisfied, it is likely that fines (passing 0.075 mm) could be increased from the 5% limit proposed above to the standard M/4 acceptance criterion of 7%. (Either value is much lower than values around 13% generated in some local roads after basecourse compaction.)

Subbase and Subgrade

With the transition from the State Highway Pavement Design and Rehabilitation Manual (TNZ, 1989) to the Austroads Pavement Design Guide in the 1990s, thinner pavements are now being designed. It is likely that the Australian experience relates to pavements which are less frequently experiencing either fully soaked subgrade conditions or deep frost penetration than their NZ counterparts. There is no formal M/3 Specification, but it is suggested that for subbases the general requirements of TNZ M/3 Notes for thickness and permeability requirements are followed strictly and incorporated in specifications for all frost prone pavements. For heavily trafficked pavements this requires a minimum thickness of 225 mm of free draining aggregates.

With regard to preventing frost penetration below subgrade level, the surface distress is likely to be less dramatic than frost heave originating in the basecourse or subbase. Accordingly, some judgement for the cost-benefit of an additional depth of pavement will need to be assessed based on subsoil drainage conditions (water sources), availability of frost resistant subbase materials, and required reliability. It is suggested that a qualitative evaluation be made of the above factors in relation to likely frost penetration depths in Section 3.1 for all pavements in frost prone regions.

3.3 Drainage

Drainage is a primary consideration, especially for the silt subgrades common in Otago.

Flushable, underfill drains are only recommended where they are able to be constructed at depths below the level of frost penetration. This depth of cover may require manufacturing during road building to ensure the drain works in the extremes of freezing temperatures.

4.0 ConstructionTechniques

4.1 Objectives

- Avoid segregation
- Minimise degradation
- Maximise permeability

- Provide effective drainage

4.2 Subgrade Preparation

- Ensure any water sources are collected

- Use large diameter subsoil drains to minimise ice blocking

- When constructing during dry periods, assess likely winter watertable levels to install adequate drainage for more adverse conditions

- Maintain largest practical gradients on drains with frequent culverts and wide shoulders so that melting snow will not feed water back under the pavement

4.3 Basecourse Stockpiling and Loading

- Stockpile in layers and avoiding tipping over high steep faces
- Wet the stockpiles to promote adherence of particles of differing size and minimise segregation. Wetting should occur a day or two prior to load-out, thus allowing sufficient time for aggregate to absorb water and for excess water to disperse
- Load selectively to avoid excesses of dry or segregated areas

4.4 Placement of Subbase and Basecourse

- Scarify any existing seal layers (or remove to form shoulders if the scarified product does not comply with M/3 Notes - see below), then compact as subbase to B/2 requirements
- Place carefully from slow-moving vehicles to prevent segregation
- Minimise grading of rough spreads
- Grade as near to the final shape as possible, avoiding reworking. This requires a high degree of skill by the grader driver forming true to grade and level with the first pass
- Obtain refusal with non-vibrating compactors prior to applying any vibrating compactor
- Minimise vibrating compaction by using the compactor directly behind the watercart
- Ensure water is evenly distributed through each layer and adequate to achieve required density with minimum passes
- Remove crusts of fines from haul roads or areas of frequent temporary tracking during construction
- Minimise use of superficial crusher fines for locking up, reworking large segregated or out of shape areas only. Ensure any fines applied have less than 5% passing 75 microns and are from the same source (of proven Crushing Resistance) as the basecourse
- High density is imperative for a strong basecourse, yet it is important to cease compaction as soon as B/2 density requirements are met to minimise particle breakdown if Crushing Resistance is marginal. Very high densities may be achievable, but are counter-productive for frost resistance, and there is currently no appropriate control check for degradation induced by compaction in the B/2 Specification
- Prime promptly. The basecourse surface texture produced in a frost resistant basecourse will be prone to ravelling or segregation under light traffic - particularly in aggregates that tend to have smooth and rounded surfaces and become dry. To retain the constructed surface texture to the design surface shape, level and line where drag brooming is inadequate, an asphaltic binding agent should be considered

4.5 Acceptance Testing

- Prior to placement of basecourse (for rehabilitated as well as new pavements), ensure compliance of the subbase with TNZ M/3 Notes permeability requirements, and B/2 compaction
- Ensure compliance of supplied basecourse with M/4 and that grading shape control is tightened so that after laboratory vibrating hammer compaction the extracted samples pass at least one of the following "frost criteria":
  - Sand equivalent > 50 or;
  - Critical grading exponent >0.40 or;
  - Freeze-thaw Heave < 14 mm
- In marginal cases, investigate the sensitivity of breakdown to laboratory compaction water content, and consider whether field compaction is likely to induce greater breakdown than in the laboratory, in which cases basecourses may need repeated cycles of laboratory compaction before evaluating the "frost criteria"
- Compact to B/2 density requirements, but recognise that higher than that value may be counter-productive for aggregates with marginal Crushing Resistance. If B/2 conforming compaction exceeds the expected solid density of about 86% (Eqn 2), marginal material should be suspected. Assess for precedent performance before sealing
- Prior to sealing a marginal basecourse, check in-situ permeability
- A quick, practical, non-destructive test for permeability can be carried out readily by applying a cushioned flow from the watercart to any visually suspect point on the surface of the completed subbase or basecourse. A wetted area of not more than 1 square metre at steady state for 5 litres/minute flow is desirable but not always obtainable. Trial and adapt construction techniques to give the minimum steady state wetted area obtainable with any one aggregate source or use the test to compare the compacted state of alternative sources
- Where permeability is poor, sample the compacted basecourse selectively (preferably away from wheelpaths) to confirm the in-situ basecourse still complies with above "frost criteria". In marginal cases check there is less than 3% passing 20 microns
- Consider further treatment (eg cement or chemical stabilisation) of the basecourse if more than one of the above tests fail
- Ensure compliance with TNZ B/2 saturation requirements (< 80%) prior to sealing. Correct NDM water contents from laboratory determinations. Use measured, not assumed, solid density for calculation of saturation percentage as results are highly sensitive to this often assumed parameter. In frost regions, the 80% value must not be relaxed to 90% (as indicated in B/2 Notes) unless the season is appropriate and there is precedent proven performance and high permeability of both subbase and basecourse confirmed by test.

5.0 References

1. Chamberlain, E. (1981). Frost Susceptibility of Soil. US Army Cold Regions Research & Engineering Laboratory. FAA & FHA Washington, D.C.

2. Cheung, K.C., Dongol, D.M.S. (1996): Freeze-Thaw Effects in New Zealand Pavements. Transfund New Zealand Research Report No. 51. Transfund New Zealand, Wellington.

3. Croney, D. & Jacobs, J.C. (1967). The frost susceptibility of soils and road materials. RRL Report LR 90.

4. Salt, G. 1979. The performance of unbound basecourse under simulated traffic. University of Canturbury ME Thesis, summarised in NZ Roading Symposium, 1979. RRU NRB.

5. Talbot A.N. & Richart, F.E. (1923). The strength of concrete, its relation to the cement aggregates and water. University of Illinois, Eng. Exp. Station Bulletin 137.

6. TNZ Specifications: TNZ B/2, TNZ M/3 Notes, TNZ M/4: www.transit.govt.nz/technical_information/specifications.jsp

Applicability

This article is a combination of opinions from practitioners in the fields of design, materials testing and construction supervision and incorporates several decades of experience in Central Otago soils. It does not recommend any relaxation of NZTA specifications, ie the frost guidelines are additional to, rather than replacements of, NZTA (TNZ) B/2 and M/4 and M/3 Notes.

APPENDIX A: CALCULATING THE SAND GRADING EXPONENT

The sand grading exponent is a parameter that has been found to be closely related to basecourse performance and is a quantitative value for the Talbot's "n" grading exponent over the sand fraction. It is taken to be the average of the lowest two grading exponents within four "governing" sieve ranges. These four ranges are as follows:

4.75 mm-0.3 mm
2.36 mm-0.15 mm
1.18 mm-0.15 mm
0.6 mm-0.15 mm

The formula for calculating a grading exponent (the slope of the particle size distribution on a log-log plot) between the range of sieves size d1 and d2, with percentages passing P1 and P2, respectively, is as follows:

$$Incremental\ Grading\ Exponent = \frac{\log_{10}\left(\frac{P1}{P2}\right)}{\log_{10}\left(\frac{d1}{d2}\right)}$$

The exponents over the above four sieve intervals are first calculated, then the critical grading exponent is given by the mean of the two lowest values.

.