A geomechanics view on heavy duty pavements

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ABSTRACT

This paper outlines my journey from an initial PhD on “Effects of Basecourse Saturation on Flexible Pavement Performance” to research on the deflection bowl due to wheel loading, the use of time-temperature effects on concrete curing, the influence of clay minerals to New Zealand aggregates and the effects of the geology of rocks source on pavement friction characteristics. This work has lead to consideration of the intricacies of design using different pavement materials including mix designs for Asphaltic Concrete (AC) and Portland Cement Concrete (PCC). Different methods of stabilising existing materials, including innovative use of very soft marine sediments for structural use in pavements and the application of underground injection to extend the life of damaged pavements are also described. Project examples are used to illustrate the interesting challenges of real problems and the fun of developing solutions.

1 INTRODUCTION

Pavement engineering is more typically the concern of highway engineers or transportation specialists rather than geotechnical engineers. My interest in geomechanics began in undergraduate courses sparked by Professor Peter Taylor whose excellent lectures on the complexity of soils, water and air offered challenges for youthful minds. Professor Geoff Martin offered me the chance to look into the interaction between a typical aggregate mix of crushed rock, sands and silts used in road construction, under a partially saturated state and subjected to dynamic wheel loadings. Back then I thought the topic straightforward only to find out how daunting it would prove to be and the older I get the more complex the topic is. So that was good fun.

With Beca, I have had opportunities to apply some of the pavement knowledge I gained. In the days when most pavement design was not in private engineering consultancies, we took the opportunity to look at some interesting tropical soils e.g. swelling clays, coralline rocks and floating islands. The government agencies did offer roading research that progressed NZ’s understanding in the effects of geological provenance of crushed rocks on the longevity of our highways. My interests then gravitated towards the heavy-duty applications of both bound or stabilised and unbound aggregates and the challenges our residual, alluvial and volcanic soils present as the subgrade on which our roads are built. I now spend a significant part of my time looking into pavements for the heaviest if not the fastest man made machines that use our pavements.

2 HEAVY DUTY PAVEMENTS

2.1 Design today

Pavement design is practised by a large number of engineers in the roading industry. It is often only a small part of a highway engineer’s focus; geometric design, traffic volume, speed of operation and safety aspects are all consuming. For the standard truck axle loads of 8.2 tonnes (which consists of two sets of 2 tonne dual tyres) we use design charts from codes/guidelines. However digging further into this science, this is more empirical, really an art rather than science. For example we do not often effectively test for or measure the stiffness of pavement materials and subgrade that are used in the design programmes. The stiffnesses of the granular components of a pavement structure depend on both confining stresses away from the wheel loads and on the speed of loading.

The CBR test pushes a 50 mm plunger into the soils to cause a dent of 2.5 – 5.0 mm. Yet the pavement loads only induce much smaller deflections, and we hope only elastically not permanent deformations; such large plastic deformations would rapidly cause deep ruts. With more sophisticated tests, e.g. a plate load test we run into the stress levels and confinement effects problem. The stiffnesses we measure on exactly the same pavement profile differ depending on the size of the loading plate. The larger the plate, the greater stiffness we obtain.

Further complications come with the multi-layered elastic programmes often used for analyses e.g. CHEVRON, ELSYM5, CIRCLY, APSDS etc. all derived from the assumption that pavement materials all behave in a linear elastic manner. Well they do not. Their stiffnesses vary depending on the level of confinement. For instance, the shape of a deflection bowl cannot be predicted by CIRCLY. We do better using a finite element programme that allows for non-linear soils behaviour, but there has been no widespread database of non-linear material characteristics.

So our road designs generally work well, by dint of experience i.e. empirical design. When we face loads that are much higher than 8.2 tonnes, our empirical design methods require application of sound judgment and a degree of innovation.

2.2 Heavy duty pavements

When wheel loads reach 25 – 30 tonnes with axles of up to 120 tonnes, it all becomes interesting and quite challenging. The general principles still apply. The materials we use just become stressed, a lot more.

One of the simple views is: with most well designed roading pavements for 8.2 tonnes axles (2 tonne per wheel) the factor of safety against failure is not a lot higher than about 2.0. So if the axle is 16.5 tonne, that road pavement is likely to suffer significant distress i.e. premature rutting, shoving, or cracking of the concrete slabs. Based on the Portland cement charts, a road slab designed for a 0.5 tensile stress factor would fail when loaded with twice the weight. The basic reason is that unreinforced pavement slabs would last under repeated flexural loading only if the failure tensile strain is not exceeded. A fully reinforced unjointed pavement slab would be cracked but such cracks would be fine and regularly distributed keeping aggregates interlock between the cracks.

Some pavement designers assume that criteria used for highways are applicable to heavy duty pavements, only to their sorrow; when the “design life” was thought to be “infinite”, the pavements was found to fail only months after completion.

So for heavy duty pavements we need to address the heaviest likely wheel load and not just the most frequent vehicle/aircraft. (Figure 1 and Figure 2 show examples of airport pavements of different types, using AC or PCC compared with some typical roading pavements). The next step would be to realistically consider the number of passes for the intended pavement life i.e. allow the wander factor. It is also essential to use a suitable software e.g. CIRCLY (ref.: Wardle 2007) or APSDS (ref.: Rickards and Wardle 2003) to allow a more economical design of the pavement required. Such software would also allow predictions of deflections at various stages of progress to allow the design to be verified using a Benkelman Beam during construction.

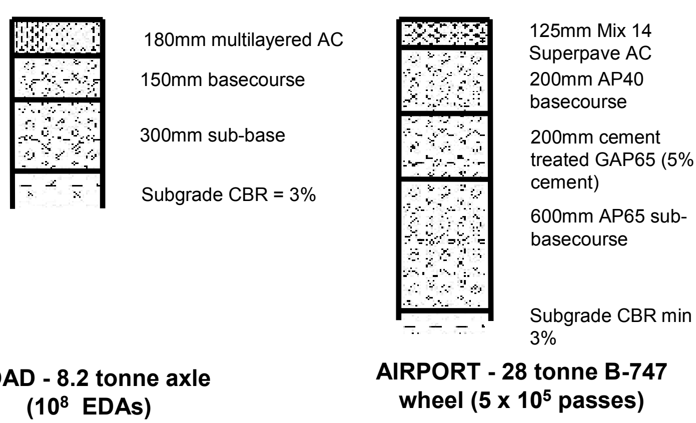


Figure 1: AC pavement

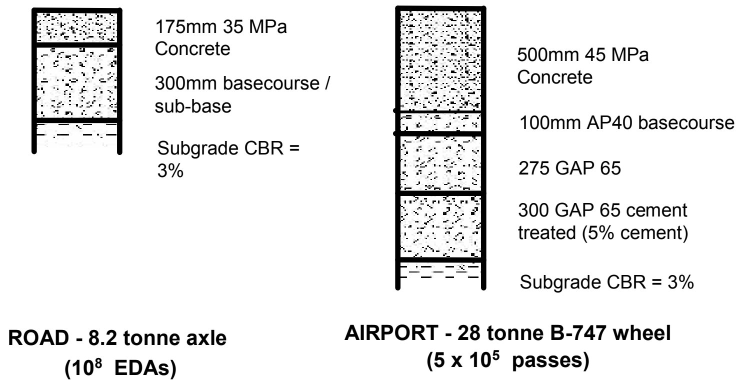


Figure 2: Concrete pavement

To design heavy-duty pavements economically it is necessary to dig deeper into the science (or art of pavement design) and look for alternative material sources and solutions to the problems we face.

The following sections outline a number of these challenges I have enjoyed solving.

3 PAVEMENT RESEARCH

3.1 Pavement structure

Typically a pavement would consist of a frictional, hardwearing seal that does not yield significantly under rolling loads. Frictional qualities help vehicles steer and stop or accelerate. This upper surface should not wear or deteriorate too fast, it needs to last 10 – 20 years or more, although our financers and government tax officers would prefer 100 + years. The aspect not often focussed on is the need to minimise the cost of rolling resistance; rolling resistance is the effort a motor needs to overcome tyre deformation and the slope caused by the small hollow due to the deflection of a pavement under the wheel load. Minimising this deflection is the combined function of the surface seal be it asphaltic concrete or Portland cement concrete or just plain packed earth. Equally important is the longevity required of the pavement.

3.2 Influence of water

Even a very well drained and sealed pavement could not remain “dry”. The materials under the seal will almost always be damp. Moisture is attracted to a sealed pavement by vapour transport due to the diurnal effect of being heated during the day and then cooling during the night causing condensation to collect under the seal. Saturation could be caused by seepage through the seal, from rain onto the grass verge beside the seal or simply by a high ground water level.

It was commonly known that saturation would shorten the life of a pavement but understanding has not always been translated into action. For example, the US federal funding agency for airport development did not recognise subsoil drainage as part of the funding package until the last few years. In NZ early runway design included a soft bituminous seal surrounding the whole pavement structure to avoid water from the subgrade entering the pavement. However this didn’t work, as over time, the pavement was found to be in a “bath tub”; water entered, via moisture vapour condensation or seepage though the asphaltic concrete (yes, AC has low but finite permeability, not waterproof). Water that entered did accumulate above the soft bitumen seal, which we found to be well above the local water table under quite dry weather conditions.

3.3 Saturated basecourse

After much reading, as all PhD students do, we sketched out the research programme, the equipment and set about to find in some quantitative way how saturation would shorten the life of an unbound aggregate. In the early days of NZ history, rock aggregate was plentiful and typical pavements consisted of a thin seal, be it thin asphaltic concrete layer or more usually a chip-seal over thick compacted rock aggregates. The unbound rock aggregate did most of the work to spread the wheel loads and avoid deforming the subgrade too quickly. Equipment developed for my PhD research is shown in photo, Figure 3.

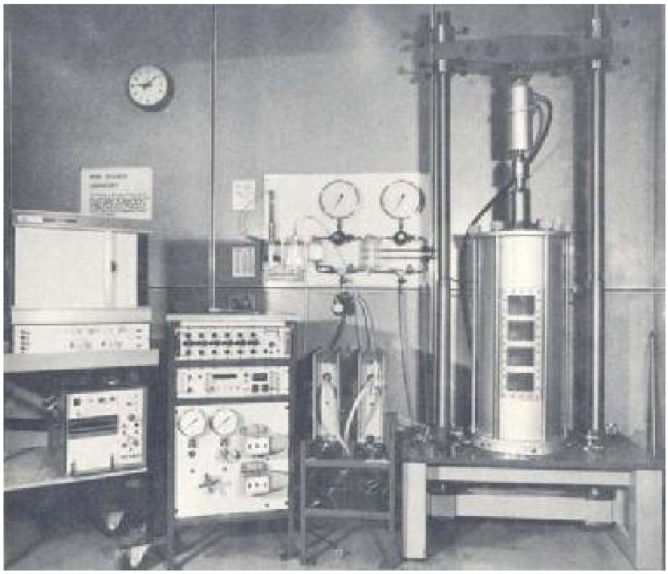


Figure 3 Dynamic triaxial apparatus

Drainage was not always efficient.

A saturated basecourse was found to be less stiff than a drained one, by 30%- 50% (the resilient modulus halved under low confining pressure or under a chipseal). It was also found that the creep rate in the basecourse increased by a factor of 2 – 5 when saturated. These two effects combined to accelerate the accumulation of rut depth and shortening of the fatigue life loading to both cracking of the surfacing and causing shallow depressions along the wheel path.

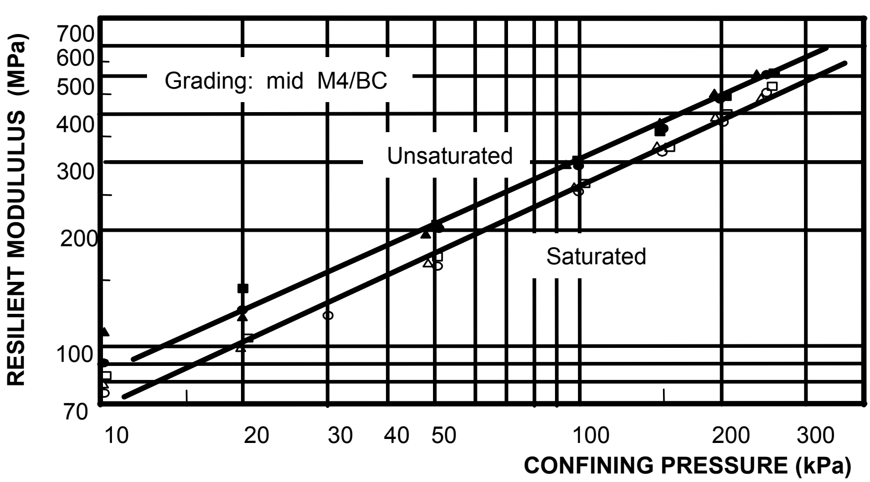


Figure 4: Resilient modulus vs confining pressure

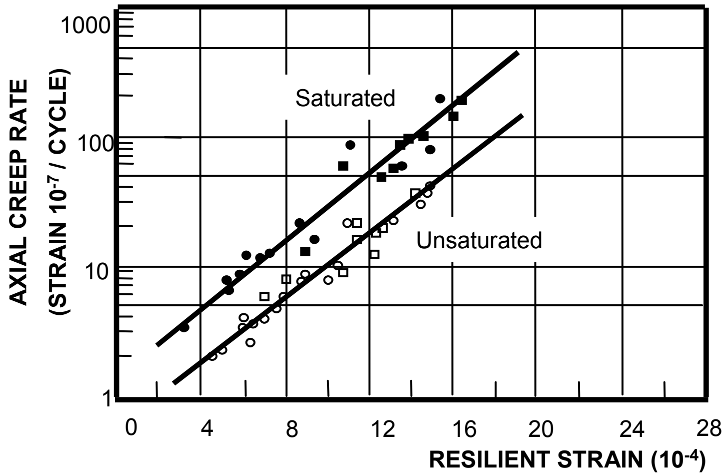


Figure 5: Effect of resilient strain on creep rate

3.4 Basecourse permeabilities

Findings I realised much later to be of interest to ground water flow studies were: basecourse permeability reduces significantly when fines are transported by ground water, and as flow velocities increase with increasing hydraulic gradients there exists a level at which the flow velocities would level out (refer to Figure 6), this was due to change in flow characteristics in the pore spaces.

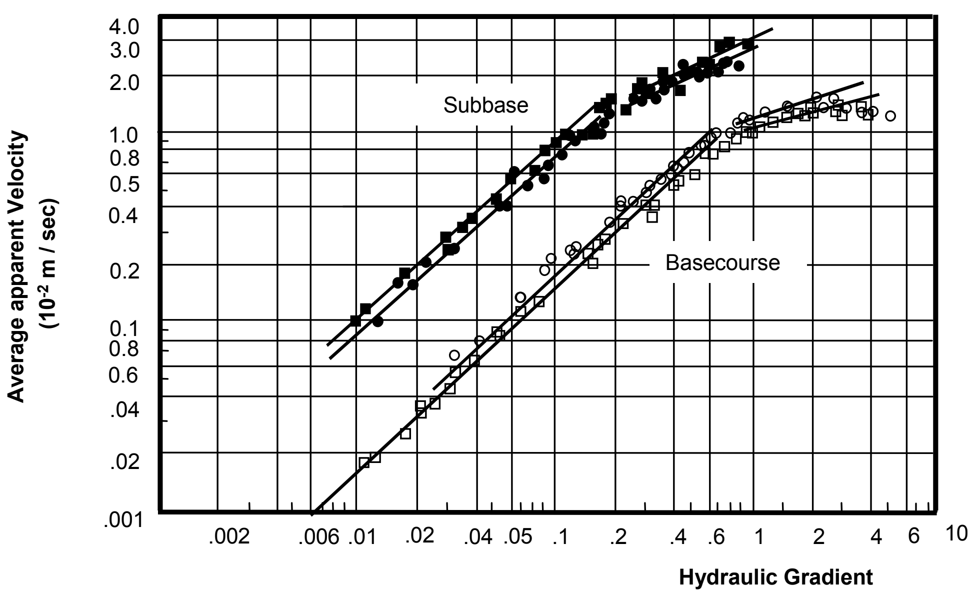


Figure 6: Relationship between velocity vs hydraulic gradient

It is surprising to note that fine sand particles were transported at lower hydraulic gradients as low as 0.1 compared to the commonly understood threshold of piping failure at 0.2. The transport was observed in a large permeameter with a clear window (Figure 7).

This window panel was made of steel to allow the aggregates to be compacted then carefully removed and replaced with a clear window panel of exactly the same shape. Once saturated, water flow was gradually increased to find the cause of reduction in permeability in some basecourse gradings, which appeared to have a high initial permeability. The reduction was caused by transport of the smaller particles, stopping in the smaller pore spaces, reducing the overall permeability by a significant factor. Better-graded aggregates tend to be less permeable initially but do not suffer such reduction once water flows are established, even if the hydraulic gradients applied were quite high.

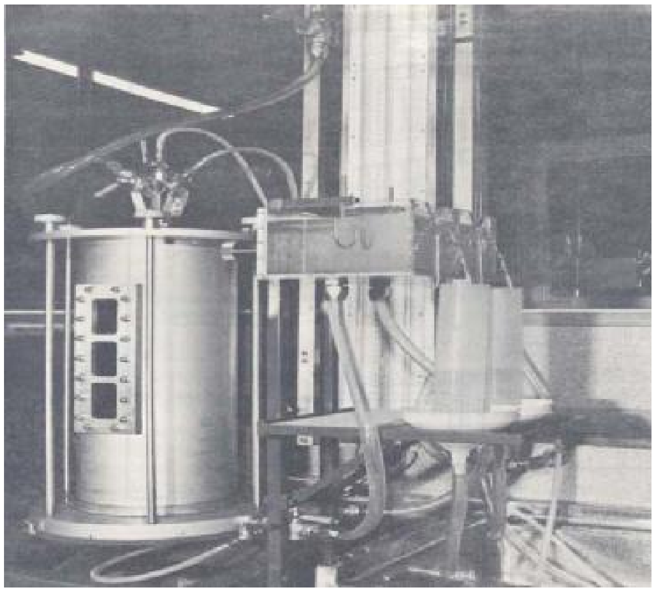


Figure 7: Permeameter & outflow measuring system

The provision of effective subsoil drainage is the key to the longevity of unbound pavements. (Even with the most permeable aggregates, placing those in a “bath” cut in clayey subgrade would not give longevity). With much of the upgrade work for our existing urban pavements, we found often the cause of poor performance have been either disrupted subsoil drainage due to poor trench backfilling or there was no subsoil drains.

Assuming that subsoil drains were provided, it is important to use a clean and well graded aggregate. As found in my research work, a small percentage of clays or silts in the aggregate mix would be sufficient to make a poorly graded material not “free-draining”; this would allow pore pressures to build up on a busy road thereby severely shortening the pavement life. The key aspect of pavement design is in material selection and specification, and the need to check during construction that the fines included in the aggregate mix are as low as specified.

3.5 Pavement bowl deflections

An intriguing finding I made was in one of the NZ National Roads Board research briefs into deflection bowl characteristics. Figure 8 shows beam deflections versus basecourse thicknesses and subgrade stiffnesses. The subgrade stiffness appears to be independent of the pavement structure, giving an effective tool to assess the stiffness of the subgrade more accurately than a large number of test pits and field tests. For the range of basecourse thicknesses there were the corresponding range of central deflections, however, at about 0.6m from the tyre, deflections remain relatively unchanged, reflecting the subgrade stiffness (refer to Figure 8).

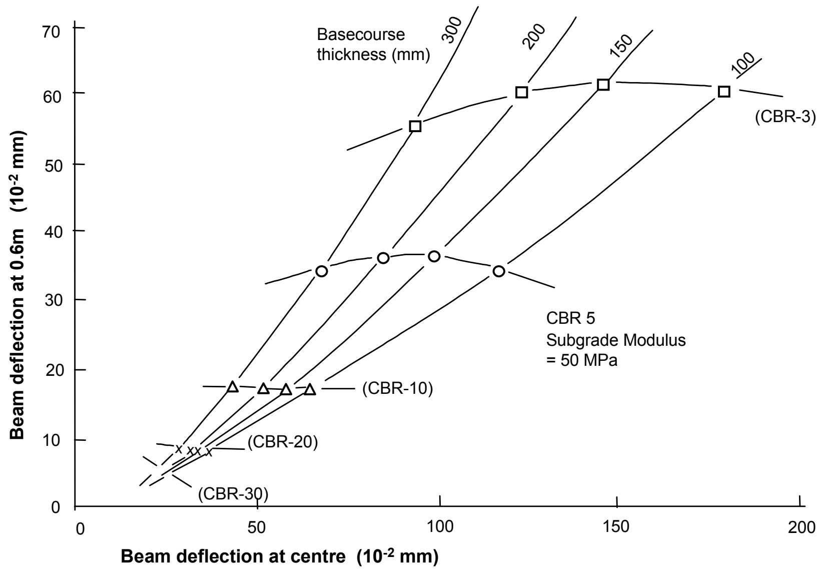


Figure 8: Beam deflections vs basecourse thickness & subgrade modulus

3.6 Time challenge of concrete curing

Working on concrete airport runways, we often face the frustrating pressure of having to wait for the concrete to set and become sufficiently strong to allow landing and takeoff. The standard 28 days used in the concrete industry is way too long and even the 14 days sometimes adopted is too costly in terms of down time. I heard comments made while I was attending a conference and found references in old concrete papers to the “Time-Temperature” technique to evaluate the strength achieved in the concrete. With some follow up laboratory testing of concrete cylinders immersed in a warm water bath, I soon found that the high curing temperatures expected in the typically 500 mm thick new airport slabs would allow the curing period to be significantly shortened.

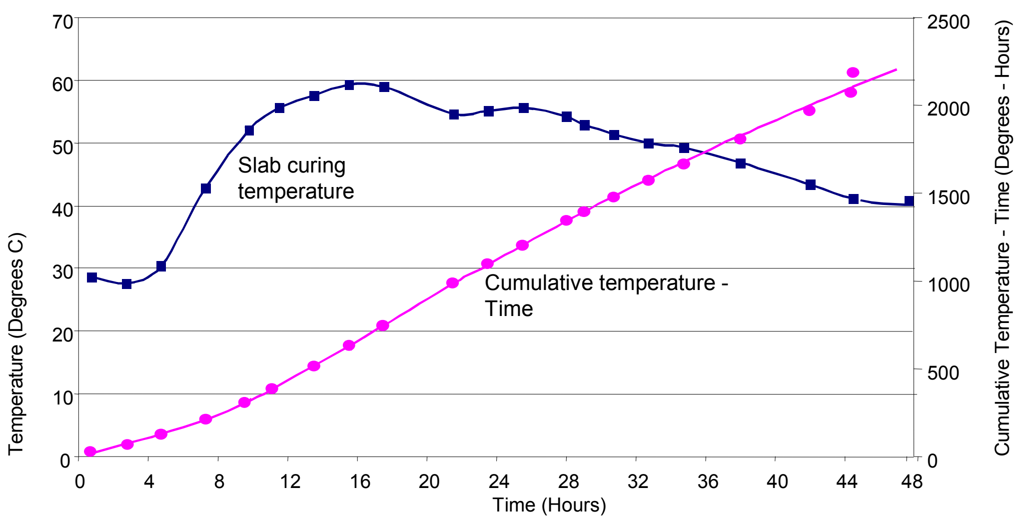


Figure 9: Concrete temperature - time

Figures 9 and 10 show the typical temperatures measured using digital thermo probes embedded in the concrete. The time-temperature graphs developed long ago proved quite correct. This allowed us to shorten the curing period to 4 days, allowing the 400 tonne aircraft to land on the recently poured slabs (not without some trepidation from those involved!).

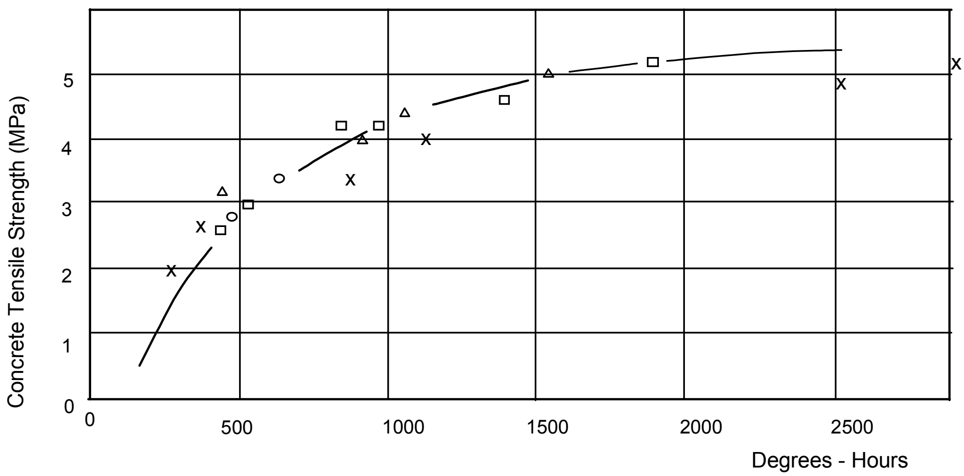


Figure 10: Concrete maturity testing in a heated water bath

4 GEOLOGICAL SOURCES AND MATERIAL PROBLEMS

4.1 Engineering geology

The appreciation of geology in pavement design has improved much in NZ today. A number of newsworthy failures have forced this upon us. In construction engineering we recall some painful cases that underlie our difficulties in bridging the geological and geotechnical sciences. Mostly geologists working together in close cooperation with geotechnical and civil/structural engineers, have now bridged this gap. These experienced geologists become “engineering geologists” that interpret the collected wisdom from the geological field to alert the engineers to aspects not always apparent.

4.2 Swelling clays

The first motorway section in NZ failed prematurely. This was caused by the presence of swelling clay minerals (smectites and montmorillonite) in the greywacke aggregates. These swelling minerals came from thin bands of argillite in the rock mass. When monitored during construction the quarried and crushed greywacke passed all the specified criteria for strength (high), grading (good), fines content (low), plasticity (low) etc. However the motorway paving failed in fatigue after only 2-5 years. When tested the aggregates showed high levels of plastic clays, rich in swelling clay minerals. These were released from the fine crushed particles on exposure to moisture over a very short time (short for the expected life of a crushed rock). Since then a number of steps have been adopted to control the risk of such failure:

- Geological inspection of quarries to assess the existence of advance weathering that may yield swelling clay minerals;
- Use of the Clay Index test to gauge the level of swelling clay materials in the aggregates mix;
- Use of stabilisation (cement or lime or both) to control the plasticity of the fines.

4.3 Aggregates sources

Various rock sources in NZ and the Pacific Islands have resulted in surprises in terms of pavement longevity.

a. Greywacke: greywacke is wide spread in the NZ North Island and has been a low cost resource for our building industry. Sufficient experience with the unfortunate inclusion of the finer grained thinner bands of argillite has allowed the use of resource with rare mishaps. However they still occur where the bad experiences above have been overlooked, resulting in the swelling clay minerals turning the basecourse/subbase plastic in a matter of months.

b. Andesite: Some andesites that are moderately weathered also contain swelling clay minerals, which similarly result in short-lived pavements.

c. Coralline materials: I was surprised to find the humble coral debris, which did not comply with typical roading specification laboratory tests produced quite serviceable roads for 20 – 30 years, the secret being the natural cementation of the carbonate rich coral. However the coral particles tend to abrade quickly or breakdown under higher stresses from heavy duty uses and are not readily applicable in asphaltic concrete for high repetitions (i.e. ≥ 10^6 passes)

d. Gneiss: NZ's South Island provides plentiful aggregate supplies from the various alpine rivers. Greywacke, basalt, andesite and dacites cobbles and boulders well tumbled by flood flows (naturally selected) were ideal for roading with the exception of gneiss. Gneiss tends to release mica which does not yield the high strength associated with good compaction from other crushed gravels. Allowance for the existence of mica would allow its use on low traffic roads or as subbase i.e. well below the surfacing layer or by using stabilisation measures.

4.4 Friction properties in aggregates

Table 1 shows typical friction values measured on a range of NZ aggregates. These NZ aggregates have been found sufficient in the past, as our traffic was relatively light. In any case the use of chip seal did not exploit the friction properties of our rock aggregates to their full potential. With our increased traffic and the inconvenience caused by closing heavily trafficked sections of road for maintenance or reconstruction, our central roading authority (Transit New Zealand) is looking for better products. TNZ is looking for high friction values, but such high levels in Polished Stone Values (e.g. PSV ≥ 65) are rare in NZ. Only few natural sources would comply: the Moutohura aggregate in NZ meets these frictional values but it has not proven to last in terms of wear by disintegration (instead of polishing).

Table 1 – Typical NZ Aggregates

Description	Age (m. yrs)	SG (kN/m^3)	UCS (MPa)	Wear (PSV)	CBR (%)	Permeability (m/sec) [Rock Mass]	Crushing Resistance (kN)
Basalt	0.001 – 2	29 - 32	80 – 160	45 – 50	30 – 100+	$10^{-2} – 10^{-4}$	80 – 180
Andesite	10 – 20	26 - 28	50 – 200	40 – 55	20 - 80	$10^{-6} – 10^{-9}$	60 – 100
Greywacke	140 – 200	26.5	150 – 300	50 – 55	30 – 100+	$10^{-6} – 10^{-8}$	100 – 200
Argillite	140 – 200	26.5	0.5 – 100	NA	10 - 20	$10^{-7} – 10^{-9}$	NA
Scoria	0.001 – 2	20 - 25	0.5 – 50	-	10 - 30	$10^{-2} – 10^{-4}$	40 – 80
Tuff	<1	19 - 21	0.5 – 20	-	7 - 20	$10^{-3} – 10^{-6}$	NA
Parnell Grit	20 – 24	19 - 22	0.5 – 25	-	5 - 15	$10^{-6} – 10^{-8}$	NA
Onerahi Chaos	21 [55-100]	18 - 25	0.1 – 50	-	-	$10^{-6} – 10^{-9}$	NA
Waitemata Group	20 – 24	19 - 22	0.5 – 20	-	5 - 15	$10^{-7} – 10^{-8}$	NA
Ignimbrite	<1	20	0.2 – 0.5	30 – 40	10 - 20	$10^{-6} – 10^{-9}$	20 – 60
Rhyolite	<1	22	0.5 – 2	35 – 50	15 - 30	$10^{-7} – 10^{-8}$	40 – 80
Coralline Limestone	0.1 – 10	17 - 25	0.5 -5	20 – 30	15 - 30	$10^{-3} – 10^{-4}$	30 – 60
Limestone	21-100	19 - 26	0.5 – 100	20 – 40	10 - 20	$10^{-6} – 10^{-9}$	60 – 100

Focus on friction surfaces on NZ roads is recent. Friction is not understood in detail. For example a chip seal may look coarse and highly frictional but in fact could be quite poor. If the exposed coarse aggregates become polished, however "rough" the surfacing looked, it would behave like a pavement made of fixed polished marbles. Good friction requires both good micro texture (the roughness felt by hand as a coarse sand paper) for velocities below 60 km/hr and good macrotexture (visible texture – for velocities above 60 km/hr). Macrotexture in AC is a function of the grading of the aggregates used in the mix. An improvement to the traditional TNZ mixes would be the use of Superpave mixes developed in the USA. Superpave mixes have a number of advantages, namely a better texture, a higher stiffness, easier to place and it costs less, as the mix requires less bitumen. (Refer to Figure 11 showing a comparison of a Superpave grading and a grading currently specified by TNZ; it is noted that the Australian guide (ARRB Transport Research 2004) recommends gradings very similar to the Superpave without the “no-go” zone).

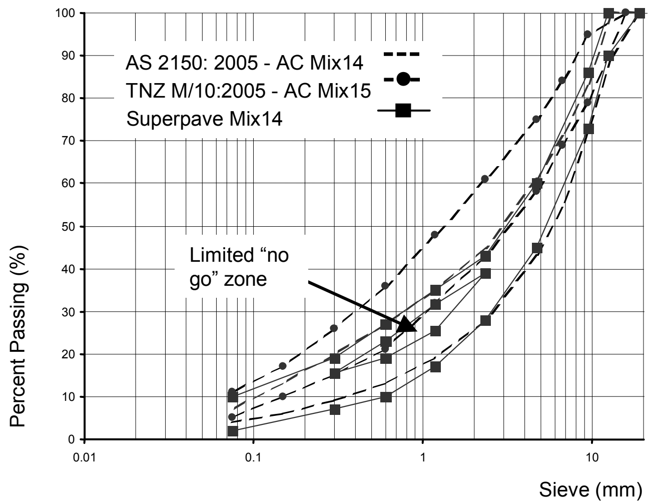


Figure 11: Comparison of asphalt Mix 14 – grading curve

The challenge in NZ is to produce a pavement surface with coarse crushed stones, having large textural depth that retains its sharp edges. For a reliable surfacing we had to import the aggregate e.g. calcined bauxite product from Japan, China or Germany!)

A method of adding texture to improve high friction at speeds greater than 60km/hr is to use grooving. Airports have applied this technique i.e. by cutting 6 mm x 6 mm slots at about 35mm spacing on the pavement surface. Grooving is used on roads too in particular in regions affected by snow and sleet, albeit with faster rate of wear. The rate of wear is exacerbated by the need to remove snow by mechanical means. Similarly on airports the build up of rubber deposits from landing aircraft regularly requires removal, which accelerates the wear of the pavement surfacing. The pavement industry is plagued by a set of difficult compromised choices!

Refer to Figure 12 showing some of the texture that relates to good macrotexture.

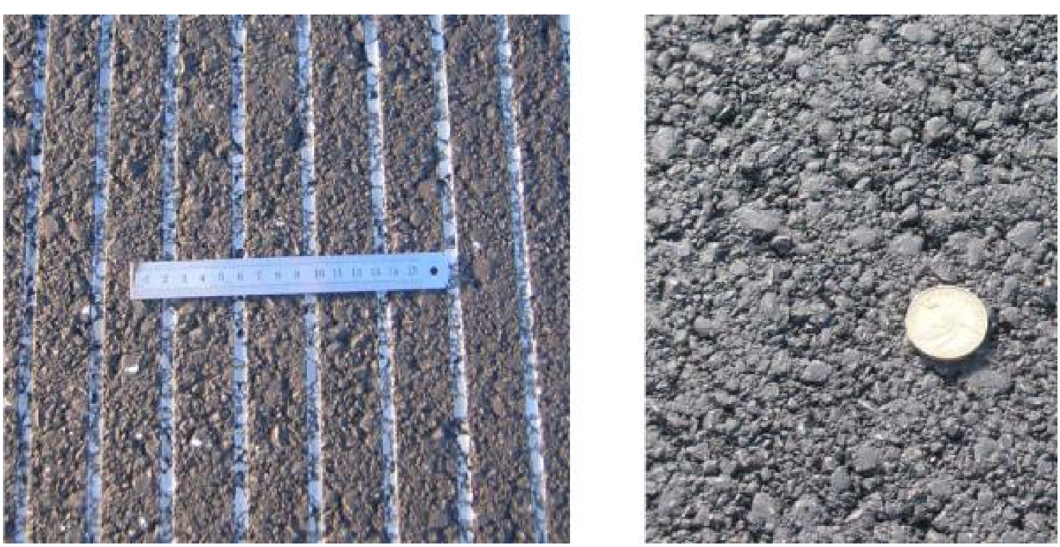


Figure 12: Grooved superpave Mix 14 pavement

4.5 Difficult NZ volcanic soils

NZ does not have the notoriously difficult swelling 'black' clays found in the tropical areas. However our volcanic soils produce puzzling and sometimes nasty surprises for the construction industry.

Allophanic Soils: when soils contain more than 7% allophonic clay minerals, we cannot readily establish compaction curves for fill compaction control. The usual way is to wet up or dry down soil samples to establish the optimum moisture content for a specific compactive effort. However with allophane, the soil samples change their behaviour as they dry down, becoming less plastic or sandier. This soil type is just a trick for the inexperienced.

Weathered volcanic soils: when cut these volcanic soils look firm, but when disturbed they often behave as soils close to their liquid limit. This is due to the puffy soil structure, which collapses on disturbance (as if "releasing" the water it holds). This makes it behave as a very soft, sensitive silt, a mud. To condition it requires much drying, from the near liquid limit state towards the plastic state (which would be then amenable to compaction). The difference between a typical near liquid limit natural moisture content of 60 – 80% and a suitable optimum moisture content for compaction i.e. near the plastic limit of 25 – 30% takes a long time to dry. Yet when dried these allophonic volcanic soils behave well and yield very strong fill with c' up to 10 – 15 kPa and ø' of 34°-36° (like a well compacted clayey sand – a rare soil in NZ).

When not well understood and not carefully provided for in contract documents in terms of construction season and work method (time and work area for drying), these highly sensitive soils can result in large cost and time overruns with many legal wrangles to resolve.

Similar problems are encountered with micaceous gravely/sandy soils and loess (wind deposited moraine silts found in the South Island of NZ).

5. STABILISATION AND INNOVATIONS

5.1 Range of stabilisation measures

With the increased rate of aggregate resource usage, and the greater difficulties surrounding the resource consent to develop new quarries (due to the increasing awareness of environmental effects) spring the need to use lower grade aggregates or recycle existing pavement material. This is an interesting set of challenges that has been fun to delve into.
Stabilisation has various techniques with a range of target levels e.g.

- Removing only the plasticity of the fines from an aggregate;
- Improving the stiffness of a weak aggregate to service a more demanding application;
- Providing a degree of cementation to increase the load spreading capacity;
- Allowing the reuse of old pavement material.

All these targets allow reduction in the use of the available resource instead of relegating them to land fill dumps.

These techniques include the use of lime, cement, bitumen and the more complex injection of epoxy plus hardener with a precisely targeted viscosity and set timing to cement the chosen pavement zone.

5.2 Common usages

Lime is often used from 1% up to about 3% targeted to reduce the plasticity in the fines in an aggregate grading. It is worth remembering that the use of burnt lime, which costs the same as hydrated lime by weight, but is three times more effective. Attention to adequate provision for health and safety measures must be taken when using burnt lime.

Lime at 2% to 4% is customarily effective to improve the strength of a weak plastic clayey subgrade.

At low percentages of 2% – 3% cement could "condition" a poor aggregate and at 5% – 9%, cementation could be achieved. To ensure that a cemented aggregate behaves properly, a more complex fatigue analysis is required to be considered in design besides the simple requirement of sufficient degree of compaction.

Lower percentages of lime or cement as low as 1% - 3% or in combination have been used by some designers in the industry; these values showed high CBR values when tested in the laboratory; however in some instances, I had the sad task of investigating the cases of early failures where such low percentages were used. The reasons were:

- Benkelman Beam tests on the still intact parts of the failed pavement showed the deflections to be large indicating the stiffness assumed from the laboratory tests not to be realistic – this meant that the laboratory CBR did not reflect as field stiffness. I have not found the CBR test to be an effective method of evaluating the effect of stabilisation due to the nature of gravel size particles confined in a steel mould, a simple UCS would reveal the effect of the low percentages used. The low percentages serve only to "condition" the aggregates and reduced the plasticity of the fines, but provided no real cementation that would correspond to the high laboratory CBR;

- Another cause of the poor performance of some of the cement stabilisation cases is the lack of cementation due to the small clay content in the aggregate, which neutralises the small percentages of cement used;

- The lack of effectiveness of low lime content was found to be not so beneficial in silty aggregates with low plasticity in some other cases.

Bitumen is used in an aggregate mix as the main ingredient to make AC; when used in recycled AC it achieves a degree of saving plus the environmental benefits of less transportation and quarrying energy used. About 15% of recycled milled AC is to be adopted in Auckland to be used in new seal. Higher proportions of recycled AC have been used elsewhere but often as material below the wearing course.

Foam bitumen is a technique to allow the use of mixed basecourse and milled AC to construct in situ a recycled stronger structural pavement layer.

Recycled crushed concrete is viewed as a premier recycled material as it offers a relatively adequate grading and a degree of self-cementation.

5.3 Mudcrete

Born from the challenge of disposing of contaminated very soft harbour mud and the difficulty of constructing a pavement for port operation we "invented" Mudcrete. However it is not a new concept. Very soft marine sediments have been stabilised by subsurface cement injection (e.g. in northern Europe and Japan) to stabilise soft seabed materials to construct new port reclamation or a whole new airport. However our novel application is the simplicity of the technique that allows a very undesirable construction material (recent very soft marine sediments, which are a variable mix of mainly silts with some clays and sands) to be used. The addition of judicious percentage of Portland Cement (80 – 110kg/m^3) was found to produce a cemented material not too different from the tertiary sandstone and siltstone from our own Waitemata Harbour cliffs; the grain sizes are similar being eroded from these cliffs, the only difference is the lower dry densities as no compaction was applied.

Figure 13: Fergusson Wharf reclamation

This simple approach yielded a product with strengths in the range of 150 kPa up to 1000 + kPa (and corresponding moduli in the range of 80 MPa to 150 MPa, all for about $45/m^3. It also saves the cost of dumping the contaminated mud. This needs to be compared with the $300/m^3 when undersea injection is used. No complex plant is used. The mud is excavated using diggers from a barge, mixed in a container using a mechanically activated paddle mixer. The percentage of cement could be optimised (read reduced) when more efficiently mixing could be carried out e.g. in a pugmill (ref.: Priestley 1995, 1999 and 2001).

The technical aspects that needed to be resolved are the variable grain size distribution of the mud and the considerable variations in seawater content. A sandy mud can be made into Mudcrete on land but cannot be dropped in the sea, as it would “dissolve” in the seawater, losing much of the cement. Mud needs a degree of clay content to yield a “cohesive” Mudcrete to withstand being dropped in seawater without being “washed”.

Mudcrete was first used for the reconstruction of the Whitbread Race stopover wharf in the Viaduct Basin and then the America’s Cup base wharves; this significantly reduced the lateral loads and hence the cost of the wharf walls. Mudcrete was also used for the duplication of the Upper Harbour Highway embankment for the second bridges; this allowed the fill slopes to be made steep to avoid the loss of the environmentally important mangrove stand. The site where Mudcrete has been recently placed is Fergusson Wharf extension in Auckland (Refer Figure 13).

There is also the potential of excessive shrinkage on drying. However the degree of shrinkage was surprisingly low for Mudcrete placed in harbour reclamations, because when placed a few metres above sea level, the Mudcrete gained sufficient moisture by capillary pull to achieve a near ideal curing condition with very little shrinkage.

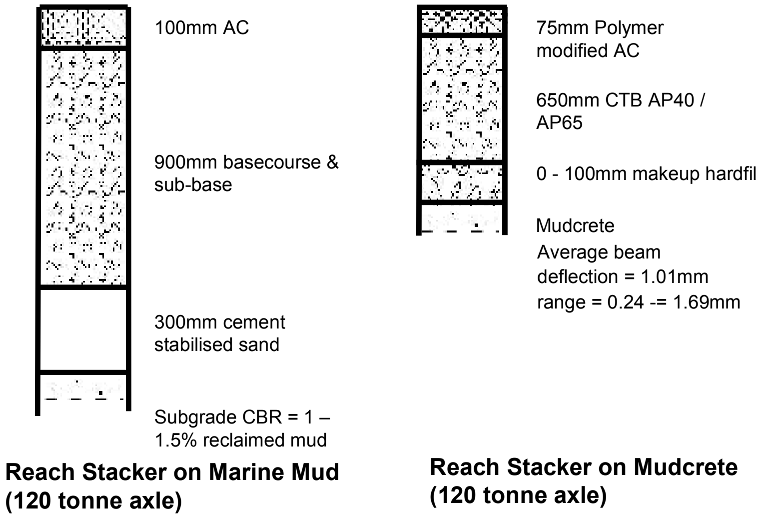


Figure 14: Container port pavements

The low densities inherent in a cemented mud (without compaction) make Mudcrete “tender” or easy to crush in pavement construction turning it back to a mud. But with a small increase in cement percentage and sufficient time to cure, Mudcrete can yield CBRs well in excess of 10% for pavement support. (Figure 14 shows an example of a port pavement with axle loads of 120 tonnes on Mudcrete, and Figure 15 and Figure 16 depict Mudcrete in a cut face and as a pavement subgrade).

Figure 15: Trenching in mudcrete

Figure 16: Completed mudcrete subgrade

Figure 17 shows the Mudcrete strength gain with time for the various cement dosages used for the Fergusson Wharf reclamation design. Experience with these various projects since the early 1990 has proven our confidence in the process and the use of more efficient mixing using a pugmill allowed us to use lower cement levels.

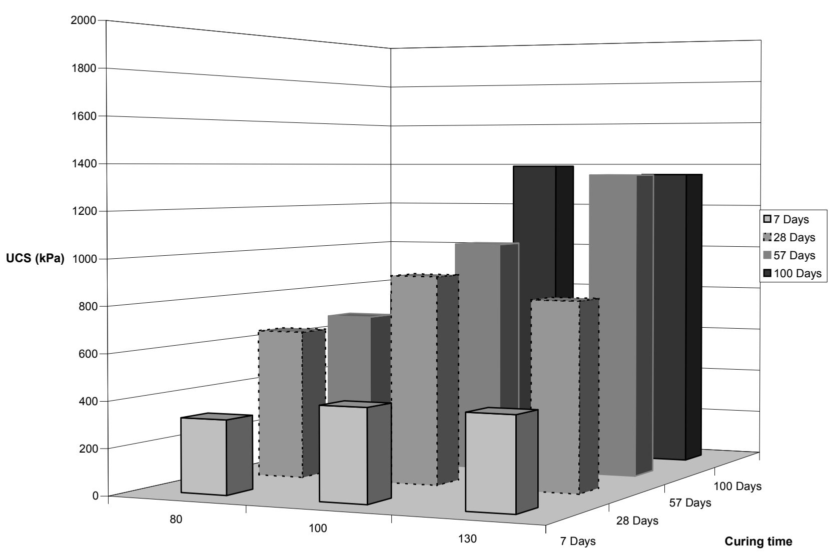


Figure 17: UCS v binder content v curing time

5.4 Underslab injection

Concrete used in buildings would have a 100-year "life" (according to the NZ Inland Revenue Department in terms of depreciation). Concrete structures could last much longer, 200 years or more. However on an airport, a runway pavement life made of concrete would rarely last more than

30 years. Airport concrete pavement slabs tend to be un-reinforced. These slabs flex each time they are loaded by the 25 – 30 tonne wheels from jet aircraft with an all-up weight of around 400 tonnes for the Boeing B-747. Failure in fatigue ensues, with first, longitudinal cracking, then spalling, with dire consequences in terms of debris that could be sucked into the jet engines. Once one slab cracks, damage rapidly extends longitudinally from slab to slab. 2 – 3 years after the onset of initial cracking, the slabs tend to break into quarters or smaller pieces with much increased FOD (Foreign Object Damage – Refer to Figure 18).

Figure 18: Fatigued slabs

The challenge offered to us by Auckland International Airport was to research the use of epoxy injection to repair these cracks. It was claimed that a product was available to fill and rebind the cracks to repair the broken slabs. The bonding strength was claimed to be better than 60 MPa even for wet concrete. This claim was found sustainable for dry concrete; alas with damp concrete the bond strength achieved was quite poor.

The complication is due to the fatigue mechanism that induces cracking in a slab. The repeated bending stresses affected a wide zone on the underside of a slab. Once a crack forms it rapidly propagates upwards to expose a visible crack at the ground surface. As one fatigue crack is repaired e.g. by adequate bonding (in dry conditions) a new crack soon appears alongside. The reason is: the concrete next to the original crack has already suffered near terminal fatigue, so the magic 60 MPa epoxy is not a solution.

The existing pavement profile at Auckland International Airport is shown in Figure 19.

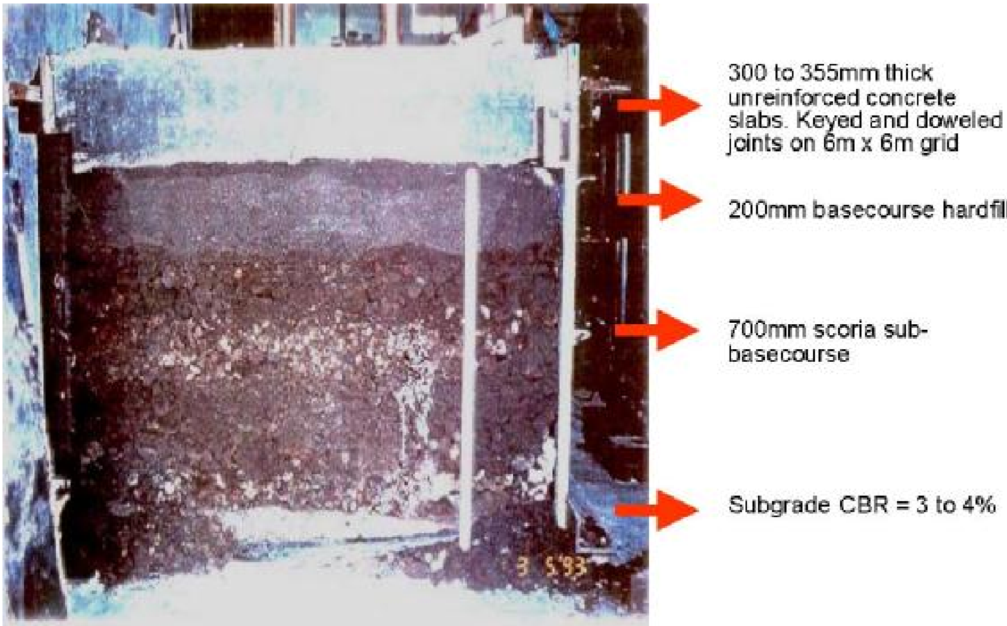


Figure 19: Old pavement structure (courtesy of Tom Watford, Auckland International Airport)

The concept developed was to form by injection a cemented beam under the crack, just as formed and poured concrete beams have been used to support the free edge of a slab. (Figure 20 explains the theory of underslab injection).

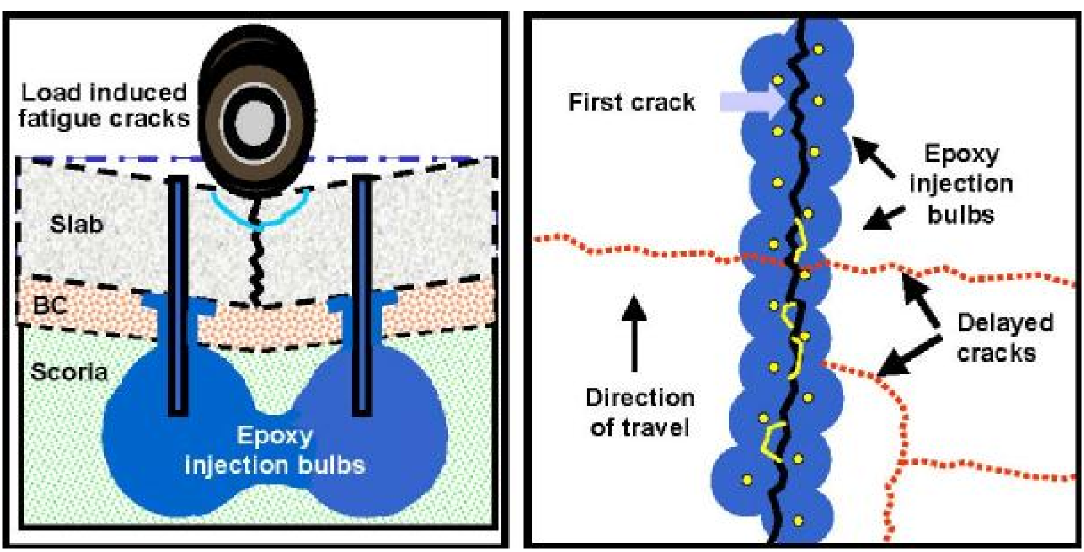
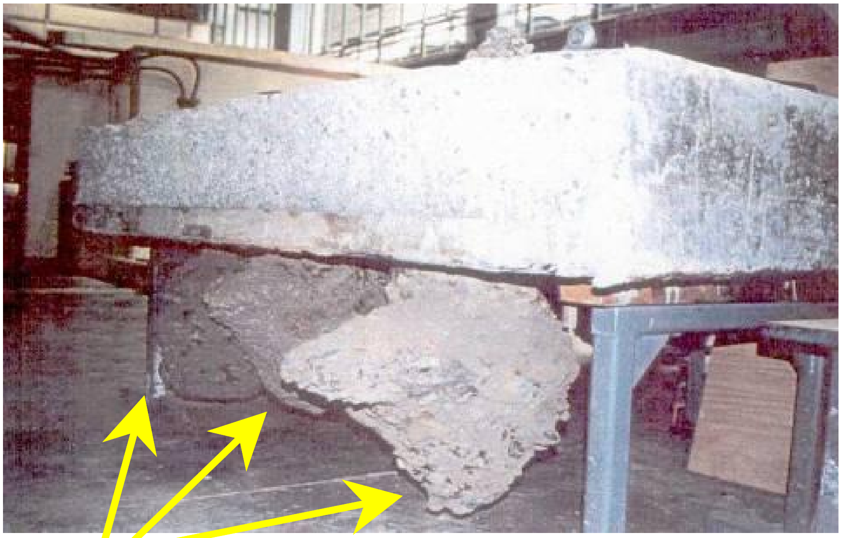


Figure 20: Reduce flexural stresses to delay further fatigue (courtesy of Tom Watford, Auckland International Airport)



Bulbs of cemented scoria
(University of Auckland test hall)

Figure 21: Epoxy underslab injection technique
(courtesy of Tom Watford, Auckland International Airport)

Semi-contiguous cemented bulbs
(NB. Concrete removed)

Figure 22: Epoxy underslab injection technique
(courtesy of Tom Watford, Auckland International Airport)

To achieve this we need to find a suitable product that penetrates damp or wet aggregates (the basecourse under the runway slab); sets to a high strength (like a roller compacted concrete); in a shape that forms a "beam". If the epoxy were too free flowing it would have gone to the bottom of the basecourse and spread out in a thin flat layer. If it were too viscous it would have risen and spread under the slab to form a thin plate of epoxy. With patient testing, we achieved a series of roundish bulbs that "held hands" to form a "beam" (see photos on Figures 21 and 22).

The underslab injection was highly successful; this technique halted further deterioration to the cracked slabs, and allowed their use by jet aircraft for a good 10 years before they were replaced. This was highly beneficial from a net-present-value expenditure perspective.

6 CONCLUSIONS

It has been an enjoyable and fulfilling experience facing the challenge of understanding the effects of water and the saturated state that reduced the life of a compacted crushed rock under dynamic loading in traffic conditions. It was satisfying to research and gain such an understanding. I recommend that any engineer with a technical bent undertake some advanced research, be it for a PhD or for a major project. It will give the engineer the confidence to face other problems. The majority of technical problems are solvable (or they have to be avoided if they cannot be economically solved).

For civil engineers, it is very important to get in touch with the geological side. We can easily miss seeing a problem that in hindsight would become evident.

Innovative thinking is the spice of an engineer's life. I was immensely pleased to be involved in the development of an apparently simple process to make Mudcrete that costs 1/7th of the industry's known method; is easy (for contractors) to apply and has so many environmental benefits. To find a way of extending for ten years the life of cracked slabs loaded by 390 tonne aircraft traffic has also given me pleasure.

ACKNOWLEDGEMENTS

I have been fortunate in my Auckland University days to have been taught and mentored by passionate and very capable engineers in particular Professor Peter Taylor and Geoff Martin. I particularly would like to thank Sir Ron Carter at Beca who gave me time and encouragement as well as the freedom and independence to develop my inclinations for my subsequent work.

I also acknowledge the importance of our clients in giving us the challenge and opportunities to explore the mechanics and engineering solutions for their assets. I very much appreciate those that understand the engineering challenges to question the advice they receive; that is the test of the engineer. Our clients at Auckland International Airport and at Ports of Auckland have provided me with many challenges to apply our innovative solutions and extend our understanding of materials, and for that I am greatly indebted.

Finally, I would like to thank the NZ Geotechnical Society for inviting me to share some of the more interesting experiences in my career.

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