Engineering the Forestry Road Pavement

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1. Abstract

The paper provides an overview of the engineering issues involved in providing and maintaining aggregate-surfaced pavements in forests. After a brief background foray into the history of aggregate-surfaced pavements, the desirable and failure behaviours of forest pavements are considered. Then the engineering behaviour of the constituent granular material is described and, hence, its contribution to the pavement response is explained. The implications of this understanding for aggregate selection, specification and testing are discussed and conclusions drawn for the better application of aggregates in forestry pavements.

2. Introduction

In importance to the forestry operation, forestry roads are probably second only to the trees! Without roads it is impossible to get the timber from its source to its processing centre and thence to the market. Furthermore, the abstraction and transport of timber from its point of felling to the mill generates a major proportion of the costs to the industry. Yet the economics of the forest industry are so limited that it is not practicable to invest heavily in the forest pavements lest the savings in more efficient transport are swamped by pavement construction and maintenance costs. Instead, the task of the forestry civil engineer is to optimise his pavement design, material selection, construction and maintenance within a very tight budget.

The purpose of this paper is to set out the engineering principles concerning the pavement and its constituent materials in order that optimum use of natural resources may be encouraged.

3. Definitions

In this paper the expression "Granular Material" is used to describe the compacted assemblage of stone particles (usually of a wide range of sizes) which is in an unbound condition except for suction forces deriving from moisture contained in the materials pores and from interlock. The word "Aggregate" is used to describe the crushed stone, or other source material, before compaction to form the granular material.

4. Some History

4.1 Roman Roads

The Romans, some 2000 years ago, were arguably the only society before our own which purposely constructed a substantial road network with fully engineered pavements. Much of the European road network still owes something to the Roman engineers who developed the roads that provided this most essential part of the infrastructure of the Roman Empire. Roads were constructed as far North as Scotland and as far South as North Africa and from the Atlantic to the Middle East. This effort, in itself, is remarkable but more remarkable, perhaps, is the engineering skill they showed in constructing their pavements.

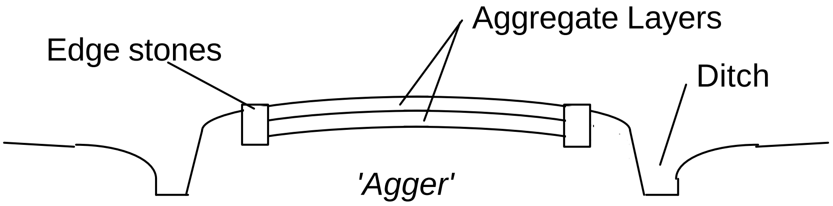


Figure 1 Typical Roman Pavement in Cross Section

A typical cross section is shown in Figure 1. It exhibits many features of a 21st century aggregate-surfaced pavement! Material (particularly stone) was dug from side ditches to form a well-drained central mound (the "*agger*" - from which the word aggregate also derives) which was capped with hand-placed stones, often restrained between kerb stones to help hinder lateral displacement. The pavement itself is comprised of two or more granular layers performing a load spreading rôle. The designer, thus, understood about the necessity of shedding surface and sub-pavement water in order to maintain the performance of the aggregate and about developing frictional interlock by maintaining a high horizontal stress within the pavement. Thus the importance of drainage, stone interlock, horizontal stress and a smooth running surface were all implicitly recognised circa 2000 years ago.

The assessment methods used by the engineers of the time is not known but was probably entirely empirical, relying on experience to predict behaviour. Construction was dominated by military needs and thus it is probable that the engineers had the ultimate incentive to get their assessments right - the death penalty! Furthermore they could call upon slave labour to keep costs down. It may be argued that their design and assessment methods were unnecessarily conservative if some roads can still be seen two millennia later!

4.2 Macadam and Telford

In modern times the re-emergence of engineered pavements was spear-headed by Trésauget in France and by Macadam and Telford in the UK. Once again experience was the main technique for performing aggregate assessment although both Macadam and Telford introduced crude specifications to ensure that their aims in construction were met. It is clear from the literature of the time (Macadam 1823, Telford 1838) that they had a clear idea of the purpose and behaviour of their selected material - although they differed somewhat in their detailed views. Macadam was pre-eminently concerned to produce a material with a high resistance to shear and thus strength and load spreading ability. Thus the word 'macadam' has passed into technical English to mean any continuously graded aggregate mix which has these properties. Telford, on the other hand, seems to have recognised the deleterious effects of ground water on these basic properties and attempted to provide some more open-graded material to assist in drainage. It may be that he understood the particular contribution of water to the rutting phenomenon.

4.3 20th Century

This century has seen the advance of the scientific approach in all areas. For assessing pavement aggregates the engineer's heel (essentially a strength assessment) was replaced first by the California Bearing Ratio (CBR) (good aggregate = 100%) , then by the plate bearing test for in-situ assessment (essentially a stiffness assessment by determining a modulus of reaction) and more recently by laboratory tests in which the stress conditions are more readily controlled.

5. The Forest Road as an Engineering Structure

5.1 Functional Aims of the Pavement

Figure 2 illustrates the cross-section through a simple pavement. A granular material layer is placed and compacted over the naturally occurring (or fill) subgrade soil. A good forest pavement should meet the following requirements:

1 It should provide a smooth running surface so as to aid efficient driving and low tyre wear.

2 Transient (resilient) deformations under the vehicle wheels should be small. Douglas and Valsangkar (1994) have argued that the resilient response of the pavement is more important for the operating costs of vehicles over unsurfaced roads than rutting. They argue this as a very resilient pavement will, in effect, result in a vehicle travelling in a transient deflection bowl of its own making, continually climbing uphill to attempt to get out of this bowl - thus leading to fuel inefficiency.

3 Permanent deformation - seen as rutting - should not be of any significance. Rutting effectively thins the pavement leading to failure by some secondary method, hinders drainage, makes steering more difficult (and, hence, dangerous) and increases fuel consumption by frictional contact between tyre and pavement.

4 There must only be a limited dust problem in dry weather, so as to provide safe driving conditions, environmentally acceptable air quality and very limited effects on tree growth adjacent to the pavement.

5 Aggregate loss from the surface should be limited in order to maintain the pavement thickness and, thus, helping to meet requirements 2 and 4 above.

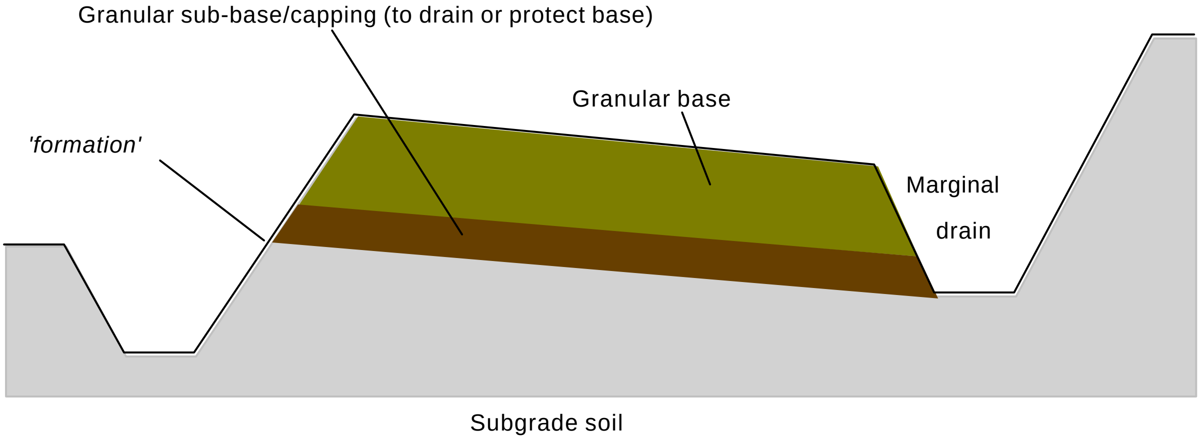


Fig. 2 Desirable granular-surfaced forest pavement

5.2 Pavement Surface Loading

In order to provide efficient transport of timber from the forest, vehicles are becoming heavier and their wheel arrangements simpler. The legal axle load vehicles can place on the public highway has risen to 11.5t. This has resulted in pavements being loaded by tyres which are getting higher in pressure, wider and in multi-axle combinations. The tyres place one or more vertically stressed zones on the surface of the pavement. These zones may also receive horizontal shear stresses due to traction, cornering and braking forces. At the surface the stresses imposed from each tyre are, essentially, independent of one another except in so far that the suspension system of the vehicle redistributes load from one wheel to another. The increasing contact stresses (especially due to higher tyre pressures) make greater demands on the granular material - demands which cannot always be met without incurring damage to the pavement.

5.3 Loading within the Pavement

The overall purpose of the pavement is to spread the applied loads so that by the time the stresses reach the subgrade soil they will have diminished to such a degree that the subgrade can cope without undergoing any significant displacement. Efficient load spreading requires a high modular ratio between overlying and underlying layers. Thus a stiff granular layer over a soft subgrade means that the granular layer spreads load well. However, in so doing, it experiences high shear stresses within itself and the confining stresses which hold the aggregate together are diminished at the bottom of the layer. Thus a good granular layer needs not only to be stiff so as to provide stress protection to the underlying subgrade, but must also be resistant to internal shear itself.

For vehicles with large tyre prints and/or multiple axles, there will be less opportunity for the granular layer to spread the loading. A larger tyre print will take a greater thickness of granular material for the stress to be reduced at all points on the subgrade to the same level as would have been achieved under a smaller print. Within the granular material the stresses will remain higher for longer - necessitating good quality aggregate for a greater depth. Under multiple axles the conditions near the surface will be unchanged from those under single axles of the same loading, but at some depth, where the stress ‘cones’ under each wheel overlap, the stresses are higher than before and better material may be required at this depth.

Thus ‘super-single’ tyres, which have higher pressures than conventional ones, can be expected to be more damaging to the granular material near the surface than conventional twin tyres, somewhat more damaging to the granular layer at its mid depth but to necessitate similar granular material thickness for the same stress to be placed upon the subgrade. However, closely spaced axles are likely to increase the stress at depth, necessitating a thicker granular layer if the stress placed onto the subgrade is not to be exceeded. Central Tyre Inflation (CTI) systems in which tyre pressures may be reduced while travelling at slow speeds on unsurfaced roads will help near the surface, but not at depth. So CTI has most to contribute when travelling on pavements containing poor quality aggregates or ones which, because the subgrade is of moderate quality, are rather thin.

5.4 Incremental Effects - Rutting

Being unbound, forest pavement material does not suffer fatigue as cycles of traffic loading pass over it (unlike, say, asphalt). However, it is incrementally damaged as loads are repeatedly applied. Damage is seen in the incremental build up of plastic deformation over many cycles. This is a feature of every layer and is greater if the applied stress level is higher. The result is seen as rutting.

Rutting can be seen as the consequence of three types of behaviour:

Mode 0 Compaction of non-saturated materials in the pavements can be a contributor to rutting. Normally compaction prior to trafficking is considered sufficient to prevent further compaction under trafficking. Furthermore this mode is self-stabilising - i.e. compaction under trafficking hinders further compaction (Fig. 3). It also causes the material to stiffen (Fig. 4; Dawson et al, 1996) and hence to spread load better (Chan et al, 1989) with the beneficial effects discussed above. Rutting is also seen as a narrow depression relative to the original surface. The material affected is mostly near the wheel. Particle damage (attrition/abrasion) can be a contributor to such rutting.

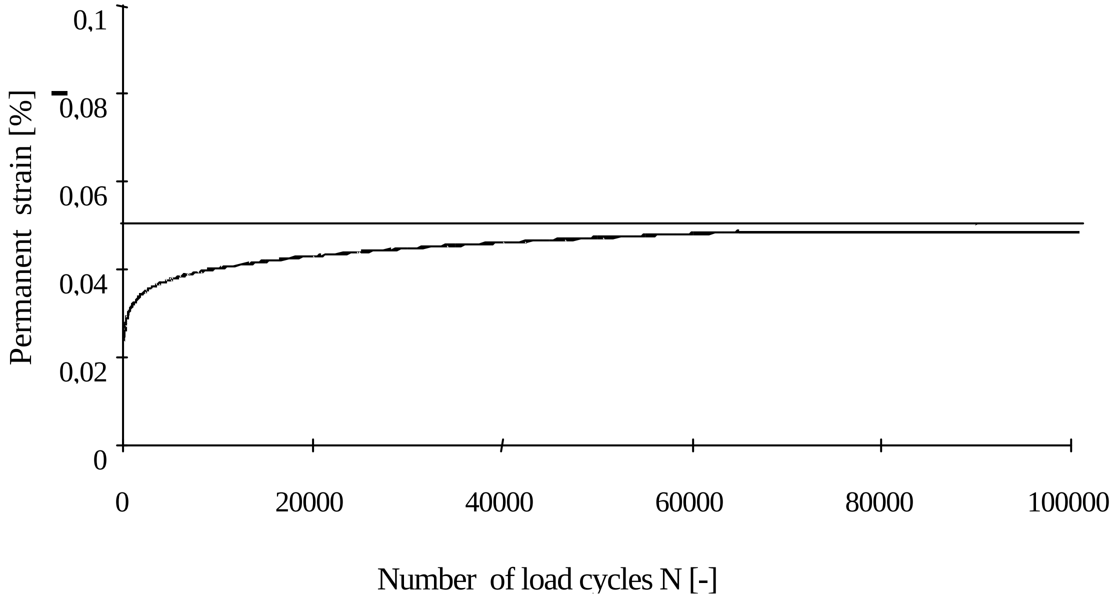


Fig. 3 Permanent strain v. no. of cycles, Granodiorite.
σ_D = 35 kPa, σ_3 = 70 kPa (after Werkmeister et al, 2001)

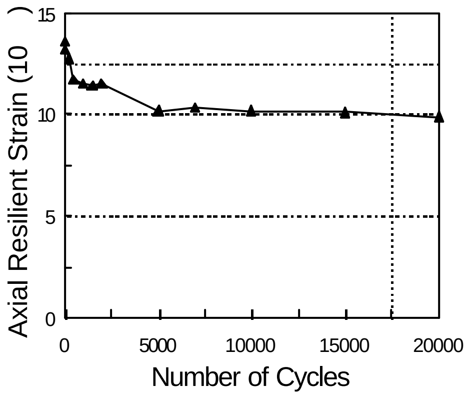
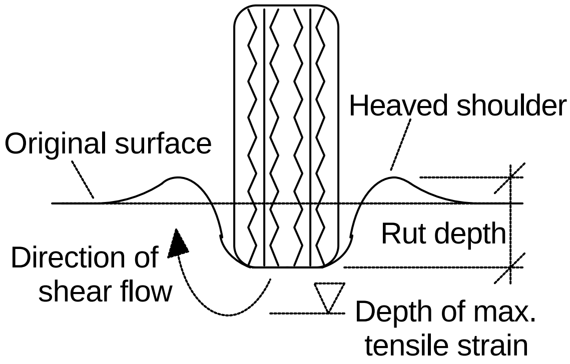


Fig. 4 Stiffness versus number of cycles (after Dawson *et al*, 1996)

In weaker granular materials, local shear close to the wheel may occur. This gives rise to dilative heave immediately adjacent to the wheel track (Figure 5) in which granular material has undergone large plastic shear strains and consequent dilation, leading to relatively loose material. This rutting is thus largely a consequence of inadequate granular material shear strength (Brown and Chan, 1996). In this mode, ideally, there would be no deformation at the subgrade surface. At first sight the only remedy for such rutting seems to be to improve the aggregate or reduce the tyre imposed stresses as the subgrade will have no effect on this mode of rutting (but see the discussion below). The granular material may be improved by compaction (within limits) or if further compaction is deemed difficult or impossible, by the use of a geosynthetic reinforcement. Many authors (e.g. Bathurst *et al*, 1986) have noted that the optimum position to place a geosynthetic to prevent rutting is at a depth of about a third of the width of the loaded area (for a dual tyre pair this is around 0.3m)(Fig. 5). This must be the depth at which the tensile strain (and hence reinforcement contribution) will be a maximum, confirming that it is granular material strain near the surface which is the cause of this movement.

Further evidence for this shallow shear strain were found in some Scottish trials (Fig. 6) performed under the author's supervision, in which rutting in thick granular layers was as much, or greater, than in thin granular pavements (Little, 1993).

Mode 2 When aggregate quality is better, then the pavement as a whole may rut. Idealised, this can be viewed as the subgrade deforming with the granular layer(s) deflecting bodily on it (i.e. without any thinning). This is the assumption made in many unsurfaced haul road design methods (e.g. Giroud and Noiray, 1981) in which a certain frictional resistance in the aggregate is deemed to wholly prevent Mode 1 rutting. The surface deflection pattern is of a broad rut with slight heave remote from the wheel (as it is the displacement of the soil which causes this).



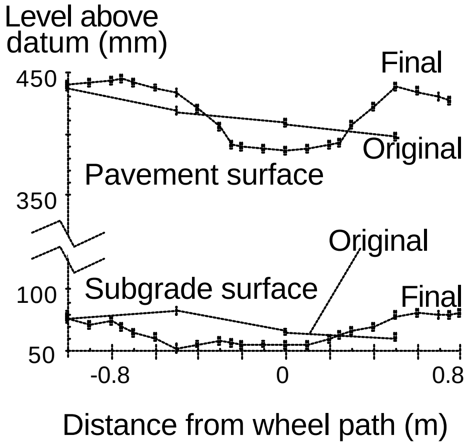


Fig. 5 Observed shape of heave (Mode 1 rutting)

Fig. 6 Rut observed on exhumation (after Little *et al*, 1994)

Combined Modes In practice rutting will be a combination of the above mechanisms. Data from the Scottish trials on exhumation (Fig. 6) shows both the thinning of the granular layer (Mode 1) and depression of the subgrade (Little *et al*, 1994). It is expected, and to some extent observed, that Mode 1 will be more evident with canalised trafficking (e.g. as is the case with many forest roads) where wheel wander is not available to displace-back, and generally compact, aggregate (Mode 0). Furthermore, canalised trafficking will repeatedly apply a maximum stress to the same location thus encouraging the less desirable type of stress level/permanent deformation shakedown relationships discussed by Werkmeister et al (2001). Conversely, Mode 2 is expected to be more evident under wandering traffic with Mode 0 more likely to make a contribution in this case as the "kneading action" of a wandering tyre is more effective in achieving compaction.

6. Forest Aggregate as an Engineering Material

The properties of the unbound granular materials which form the engineered levels of any forest pavement derive, principally, from three characteristics - the inter-particle contacts, the pore network and the water contained within that pore network. Note that particle strength is not one of these (though it may have an effect on the first two of them). Each of these will now be briefly considered.

6.1 Particle contacts

The condition of the particle contacts provide the chief control over the mechanical properties of the bulk material [Thom, 1989]. When there is a strong interaction between one particle and another high strength, high stiffness and good resistance to permanent deformation under repeated traffic loading are likely to be experienced. Such interaction is achieved due to many factors - mineralogy of aggregate particles, particle roughness, particle interlock (partly achieved by compaction), grading and the overall applied *effective* confining stress level (which will tend to press contacts together, hindering their sliding). A summary of the effects on granular material behaviour of several factors are given in Table 1. This table lists each effect *individually*. In reality, the interaction of these factors makes for a complex variation of mechanical response from one material to another.

Table 1 Effect of intrinsic and manufactured properties of aggregates as controlling factors on engineering properties of granular material in pavement layers

Property: Controlling Factor	**Stiffness**	**Susceptibility to Permanent Deformation**	**Strength**	**Permeability**	**Durability**
Type - Gravel instead of Crushed Rock	↑	↑	↑	none	usually ↑
Grading - Well graded instead of Single-sized	minor ↑	↓	↑	major ↓	↓
Fines content	↓?	↑	varies	major ↓	↓
Maximum Size - Large instead of Small	↑	↓?	minor ↑	↑	↓?
Shape - Angular/Rough instead of Rounded/Smooth	↑	↓	↑	minor	minor
Density	↑	↓	↑	↓	minor
Moisture Content	major ↓	major ↑	major ↓	major ↑	varies
Stress History	↑?	major ↓	minor ↓	none	?
Mean Stress Level	↑	↓	↑	minor ↓	↓

↑ = Value of property increases with increase (or indicated change) in controlling factor.
↓ = Value of property decreases with increase (or indicated change) in controlling factor.

Thom and Brown (1989) reported strength, stiffness and permanent (plastic) deformation from laboratory repeated load triaxial tests assessments of granular material from a wide range of aggregates and ranked them accordingly. Table 2 gives a summary of this information from which it will be seen that each property does indeed need separate determination and that, while there is a broad correlation between strength and resistance to permanent deformation, it is by no means absolute. Certainly, it should be noted that high strength is not always associated with high stiffness.

Table 2 Rankings of Granular Material Performance (after Thom & Brown 1989)

Elastic Stiffness	11	14	1	2	6	5	4	7	9	8	12	13	19	17	15	16	18
Shear Strength	11	1	9	8	19	12	5	2	4	18	14	6	7	17	13	16	15
Permanent Deformation Resistance	12	6	9	2	4	5	7	1	19	11	8	17	14	18	13	16	15

Each number indicates a particular aggregate. ‘Best’ to left, ‘worst’ to right.

6.2 Pore network

The grading and packing of the aggregate assemblage also affects the pore sizes, their continuity and their tortuosity. These attributes are largely responsible for the water drainage and water retention capabilities of the granular material. Thus the coefficient of permeability is controlled by the pore network, but so, too, is the amount of water which remains in the layer due to capillary effects [McEnroe, 1994] upon full-drainage. The amount of water in a granular material has a very large effect on behaviour as is now shown.

6.3 Water content

In broadly-graded mixes the amount of drainable water may be quite a small percentage of the pore space - potentially leading to problems of frost heave, for example. Of even more importance to the pavement engineer, however, is the effect that pore water has on suctions acting in the pores and therefore, effectively, adding confining stress between particles. Thus granular materials have mechanical properties which tend to be extremely sensitive to water condition, particularly when broadly graded (i.e. small pore sizes). Figures 7 and 8 show some stiffness and some permanent deformation results as a function of moisture content (the data was obtained from repeated load triaxial testing). It is well-known that there is an optimum water content for compaction (when water almost fills the pores, thereby reducing suction and facilitating compaction), but it is less well-known that there is an optimum moisture content for mechanical performance which may be several percent less (the suction is then higher and the particles more intimately in contact with each other).

6.4 Implications

It follows from the above description that successful, optimal use of an aggregate material into a granular pavement layer will depend on both the raw material and the water, density and stress conditions under which it is to be used. This implies that an assessment of a material’s potential contribution to the successful operation of a pavement must be made at conditions which replicate the water, density and stress conditions likely to be experienced in-service. As these may well be affected by the drainage provision (and its maintenance) and the climatic conditions to be experienced, it will be very difficult to provide a reliable yet non-conservative assessment.

It will also be evident that the packing is just as important as the condition of the individual stones which make up the mixture. Thus particle-based tests must, generally, be rejected in favour of mix-based tests where the interaction aspects can be properly examined.

It will also be apparent that drainage of a granular material layer can be a key factor in its satisfactory behaviour.

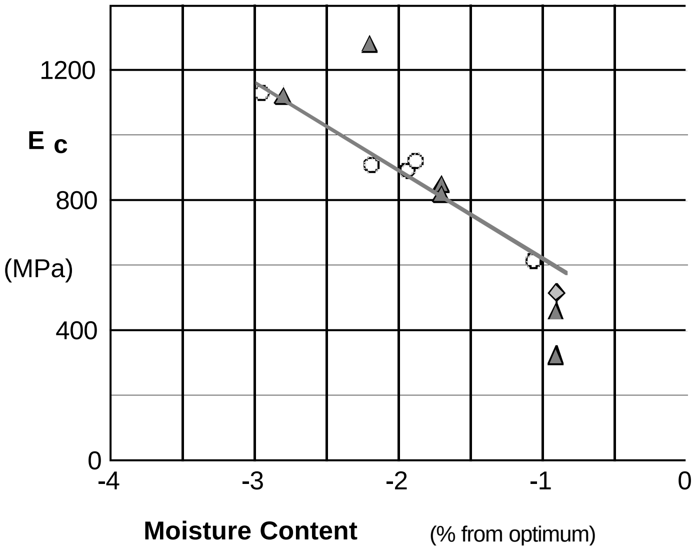


Fig. 7. Resilient Modulus determined on well graded weak limestones showing reduction with increasing moisture content (Dawson et al, 1996).

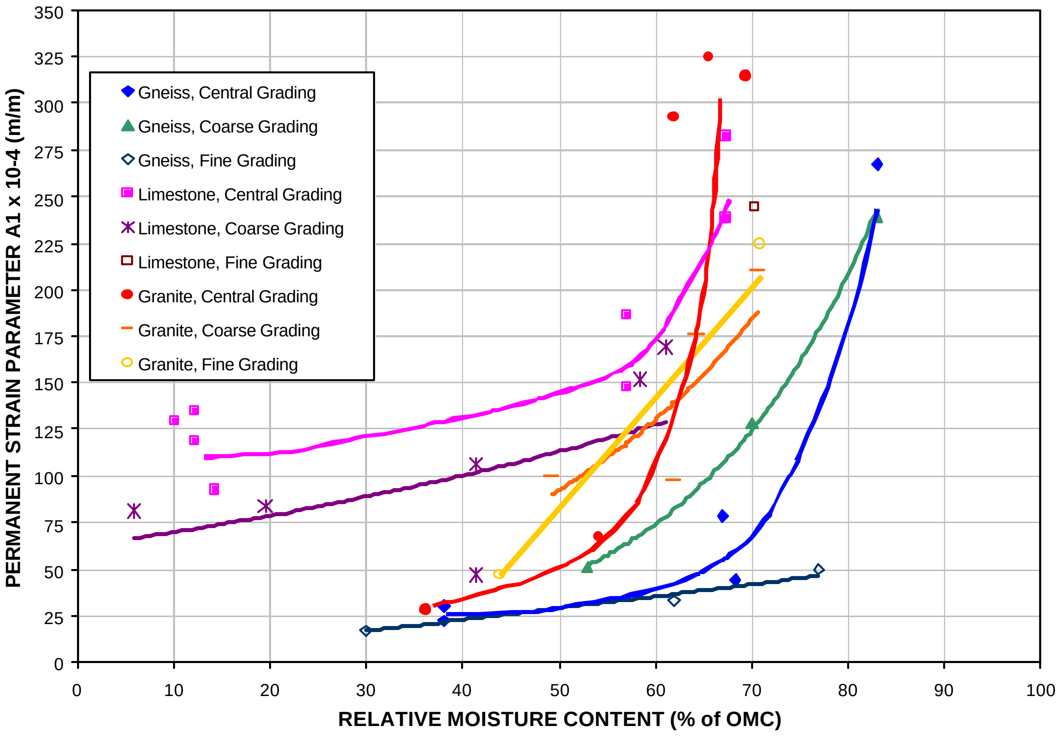


Fig. 8. Permanent strain rate as a function of moisture content for 9 granular materials (Mundy & Dawson, 1999)

7. Limitations of Present Specification Practice

In common with many other countries, the UK has consistently used a 'Yes-No' specification for its pavement materials for the public road network. A material is either in-specification and is deemed an appropriate candidate to deliver the required performance or is out-of-specification and is deemed unsuitable. There is no half-way house. Conversely, the forestry engineer has to use what he has available, locally (usually within the forest). Conventional specifications are not helpful in this situation.

A further hindrance to optimum use of aggregates within the forest pavement is their traditional reliance upon index properties which have little relationship to the properties required for successful *in-situ* performance. Thus it is conventional to measure stone strength, plasticity of fines, optimum moisture content, etc., but to be worried about the likelihood of rutting, stone loss, dust generation, etc. For 'well-behaved' aggregates there may be some empirical (although never explicitly stated) relationships between the measured properties and the desired performance. Nevertheless, there are, at least, two problems with this approach:

1) Because the relationship between index properties and performance requirements isn't 1:1, it will be necessary to over-specify index properties in most cases in order to ensure that the performance is almost always provided.
2) Many of the aggregates available to the forestry engineer will not be 'well-behaved' as he/she has to use local materials whose quality would preclude their exploitability in a commercial quarrying operation. In such a situation, those empirical:performance relationships which do exist will be less reliable.

7.1 Performance-related Material Assessment

In order for the *in-situ* engineering potential of a pavement base or sub-base material to be estimated before being used, it must be subjected to a loading(s) which simulates the loading condition to be experienced in the pavement and in which the type of response(s) measured is closely related to the type of response(s) of concern *in-situ.* Thus the traditional testing of aggregate particle strength (e.g. by the Ten percent Fines Test) is not satisfactory unless the primary reason for the unsatisfactory performance of pavement bases is due to premature particle breakage.

As discussed above, in practice the two responses of concern are:

- the generation of excessive plastic deformation under repeated traffic loading (manifested as pavement rutting) and
- inadequate load spreading leading either to excessive resilience of the pavement (resulting in increased rolling resistance and thus higher fuel costs) or to subgrade over-stressing and foundation rutting or other damage.

To assess these characteristics at the laboratory testing stage requires new procedures. The repeated load triaxial test (RLT) is the most popular world-wide (Figure 9). The resilience of the granular material is measured by monitoring the resilient strain under a rapidly pulsed actual loading simulative of that due to a passing vehicle. The plastic behaviour is determined by noting the cumulative axial deformation developing after thousands of such repetition of such a load pulse. An Australian test procedure is available and has been in use for several years [Standards Australia, 1995]. A draft CEN standard [CEN, 2000] has been drafted and should be made available for public use in 2003.

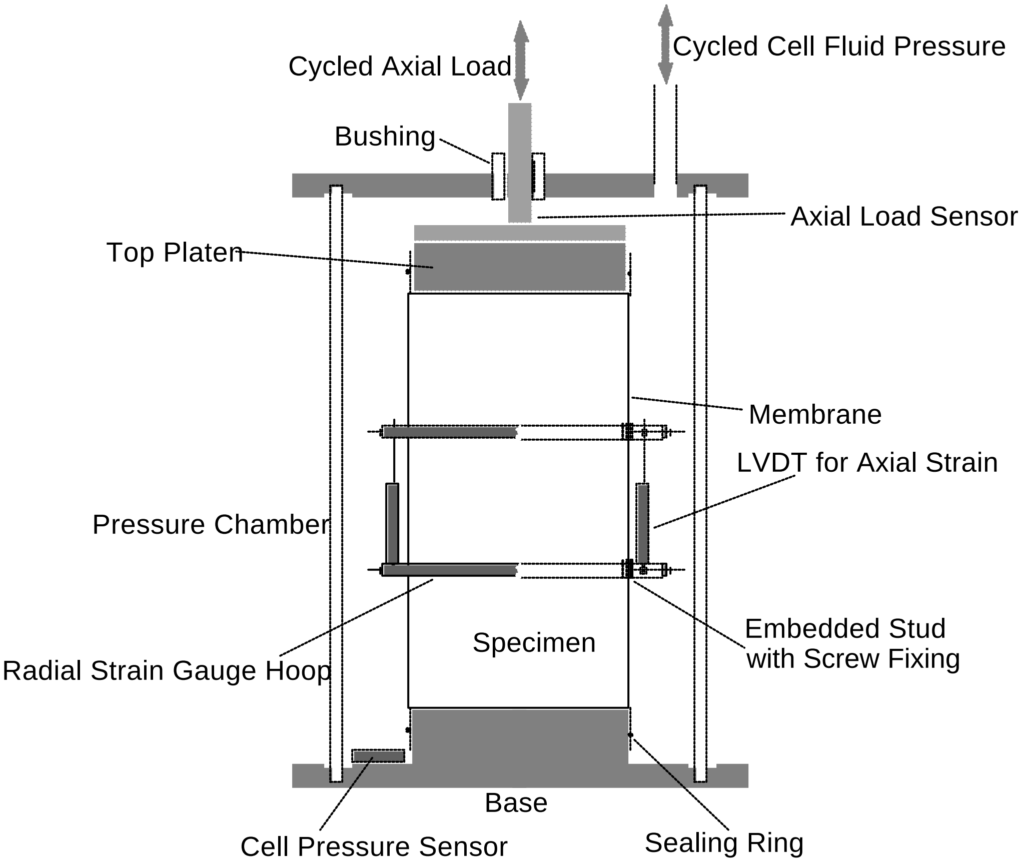


Fig 9 Repeated Load Triaxial Apparatus

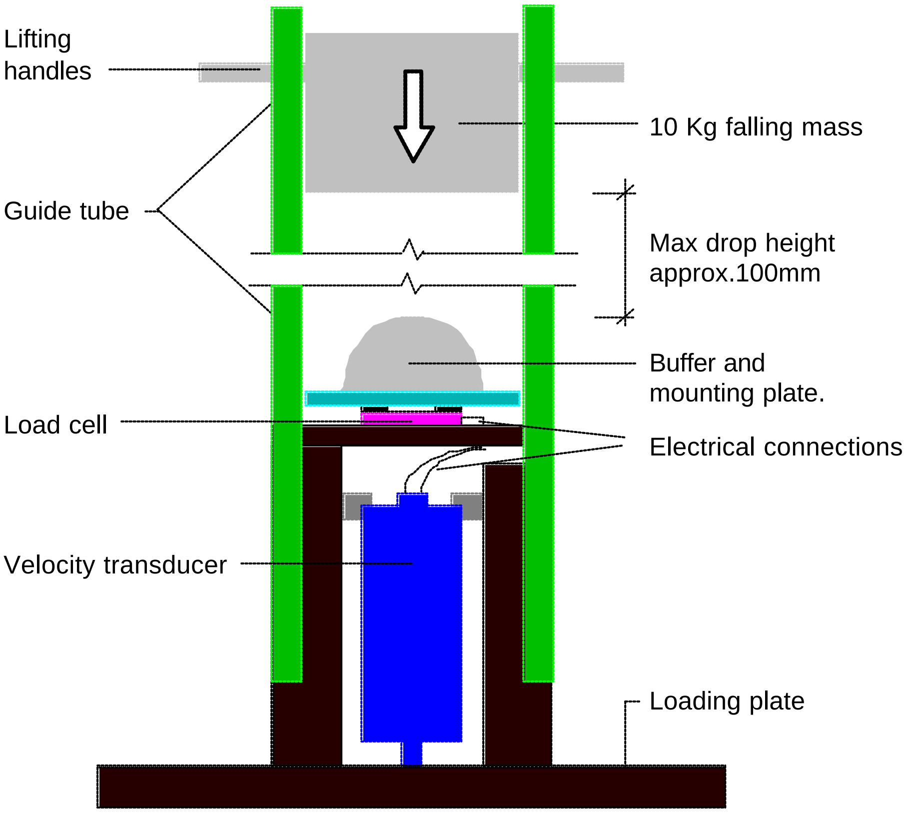


Fig 10 Line Drawing of a Typical Dynamic Plate Bearing Test Apparatus

Recent attempts [Fleming & Rogers, 1999] to provide standardised means of measuring the two responses *in-situ* have not been without problems. While dynamic plate bearing tests (e.g. Fig. 10) seem reasonably competent at measuring the stiffness characteristics of the pavement (and, in particular the top granular layer) they are still limited in that they cannot be used to directly estimate the future properties when moisture values may have changed. To measure rutting potential the best approach seems, still, to be to traffic the material a few times with a loaded truck and observe the response.

7.2 Performance-related Specifications

CEN standardisation of aggregates, is not yet moving in the direction of performance-related material assessment. Because the *raison d'être* of CEN standards is to control material quality at the point of sale and because this is taken to be at the quarry gates, there can be no possibility of CEN standards being written in performance-related terms either for laboratory or *in-situ* granular material purposes. However, there is no reason why industry shouldn't join together to produce their own.

8. Discussion and Conclusions

Aggregate-surfaced pavements have a very long history but the efficiencies now required of them in the forest environment demand a much more fundamental understanding and application of the engineering principles of the constituent granular material and its response to modern traffic loading than previously. Reliance solely on traditional approaches are likely to be either inefficient or unreliable. In particular, the interaction of resilient and plastic deformation and the stress imposed by modern forestry traffic needs to be better appreciated. Under the canalised traffic of the forest, on its narrow pavements, formed of locally won aggregate, and subjected to a wet climate, the chance of overloading the granular layers is relatively high - with rutting caused by excessive internal strain within the granular layer as a consequence - here called Mode 1 failure.

To overcome these difficulties (i.e. to reduce the risks of failure) a number of strategies are open to the forestry pavement engineer:

- better aggregate - *(often impossible),*
- underdrains & *maintained* marginal drains,
- open grading of aggregates employed (i.e. low fines) - perhaps achieved by screening off the fine fraction prior to use,
- clean fine fraction (i.e. low clay content so as to maximise the quality of the stone-to-stone contacts) - wash or screen off fine fraction,
- light stabilisation - although most binders (cement, lime, slag) are high pH so they could have an undesirable environmental impact. Binding should be modest in order that the pavement doesn't become too brittle and crack with large well-spaced cracks, and the temperature should be enough to ensure that the necessary reactions can proceed within a reasonable time-scale.
- geo-synthetic reinforcement *over soft spots*, placed at relatively shallow depths beneath the surface (typically 250mm-300mm)
- lower tyre pressures (perhaps achieved by a central tyre inflation system).

A thicker layer of the same granular material will only perform, where the original didn’t, if the reason for failure was inadequate protection of the subgrade - what is here called Mode 2 failure. This requires a relatively thin layer of good quality aggregate to be a possibility.

The choice of remediation method in any location will depend on both technical and economic factors, but must be set in the context of a realistic extraction economy which includes full vehicle operating costs as well as pavement construction and maintenance items.

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