AGGREGATES FOR ROAD PAVEMENTS

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AN IMPORTANT NOTE FOR THE READER

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CONTENTS

EXECUTIVE SUMMARY

This report is a review of the most recent available information about research into the properties and performance of unbound mineral aggregates used in the construction of road pavements. The review highlights the different approach taken in New Zealand to the design and construction of highway pavements, compared to that used in the United Kingdom, the United States, Australia and Europe.

The technical and practical information on aggregates is made available to roading practitioners so that designers may select pavement materials with more confidence and attention to their true cost, and contractors can use materials with greater care and skill. A greater awareness of this information will result in better utilisation of a valuable resource and better pavements for the dollars expended.

The arterial road pavement in New Zealand has unbound basecourse as the main load-bearing component. This material is separated from the tyre of the vehicle by a thin film of bitumen covered with aggregate chippings. The quality requirements of unbound basecourse as a structural component of the pavement has therefore always been important.

In Europe and United States, bitumen and cement-bound materials are used more extensively than in New Zealand, and layered bound systems are normal in pavement design. Research in these countries tends to concentrate on the behaviour of unbound aggregates as the less important member of the system, with more emphasis given to the properties of the overlying structural layer.

The first part of the report (Sections 1,2 and 3) provides the results of the review of New Zealand and international research papers that have been published, mainly in the last ten years. This research has concentrated on the following topics:

- Characterisation of basecourse by geological and mechanical means
- Development of repeated loading tests for the characterisation of basecourse for use in pavements
- Utilisation of unbound material as a construction material
- Performance evaluation

The review describes the following aspects of research:

Characterisation of basecourse by geological and mechanical means
- Geological characteristics
- Mechanical characteristics
- Grading and shape of particles
- Density
- Strength characterisation
- Permeability

Performance Monitoring
- Highway pavements
- Experimental pavement test sections
- Accelerated trafficking tests

Selection of aggregates for unbound pavements
- Selection by experience
- Selection by theoretical approach

The second part (Section 4) provides a commentary on the production of aggregate, the design, construction and maintenance of pavements, and on their performance, to assist practitioners.

The following topics are discussed:
- Function of the structural layers in a pavement
- Characteristics of aggregates
    including grading; density; plasticity; stability; clay index test
- Factors influencing performance of basecourse
- Selection of pavement aggregates
- Aggregate production
    including quality of resource; process control; quality control
- Construction
    including subgrade preparation; handling; laying; water content; compaction methods

The advice given is that all the theory at present available is based largely on experience and by no means should an engineer apply one particular method without considering all the options. Understanding and applying both the science and a certain amount of "art" are required to devise the most economical and effective method of pavement construction. This is the challenge for present and future roading engineers.

ABSTRACT

A review has been made of literature describing the results of research into the properties and performance of unbound mineral aggregate used in the construction of road pavements. This review highlights the different approach taken in New Zealand to the design and construction of highway pavements, compared to that used in the United Kingdom, the United States, Australia and Europe. In New Zealand, unbound aggregate is used as a structural layer immediately under a thin bitumen seal.

The geological characteristics of an aggregate determine the way it will perform as a roading material. Petrographic analysis, combined with some mechanical tests, can provide a good guide of durability.

Structural properties are related to density which is a function of particle-size distribution, particle shape, compactive effort and water content.

Recent research into the theory of shakedown and in the use of the laboratory shear-box has provided a much clearer appreciation of the factors which influence the performance of an unbound aggregate pavement.

1. INTRODUCTION

Mineral aggregates are literally the base of the New Zealand transport system. They are the materials that are used in road making to separate the natural soil foundation of the road from the tyres of our transport vehicles.

The engineering effort that has been expended on the design and construction of road transport vehicles is enormous. The engineering input to the pavement system, by comparison, is minimal. Even of that input it is probably true to say that 10 to 100 times more effort goes into the geometric layout of a new road than into the design and selection of the materials that make up the pavement. It is also of concern that many of our road builders have learnt their construction skills only by experience. Some have acquired good practices, others bad. The present state of the industry is such that when a skilled practitioner retires, most of that skill is lost.

Transit New Zealand, formerly the National Roads Board (NRB), has spent a significant part of its research budget each year on an investigation of the properties and use of pavement materials, particularly of unbound mineral aggregate. It has accumulated an array of technical and practical information on aggregates which should be made available to the roading practitioner so that designers may select pavement materials with more confidence and attention to their true cost, and contractors can use materials with greater care and skill. A greater awareness of this information will result in better utilisation of a valuable resource and better pavements for the dollars expended.

2. OBJECTIVE

The principal objective of this Transit New Zealand project is to provide the practitioner with the most recent information about unbound aggregates available and on the efficient use of mineral aggregates in the construction of roads.

Stage 1 of the project involved a survey of practitioners to identify the current extent of their knowledge and their needs in the future. The results are described in Transit New Zealand Research Report No.2, by Bartley & Cornwell (1991a).

Stage 2, described in this report, involved the assembly of the results of international and local research covering the production, placement and performance of aggregates, and the preparation of a text identifying the important aspects of pavement construction.

The first part of this report provides the results of the literature search of papers which have been published, mainly in the last ten years. The second part provides a commentary on the production of aggregate, the construction of pavements and their performance.

3. LITERATURE REVIEW

3.1 Introduction

New Zealand is well endowed with sources of quality rock suitable for road building. The rock types range from acid and basic volcanic rocks, through the weakly metamorphosed "greywacke" rock types to sedimentary and chemically bound limestones. Many alluvial deposits have been formed from the erosion and the transportation of a variety of rock types.

Many New Zealand quarries are located relatively close to urban areas where the demand for aggregate is sufficient to support a strong industry. However, in rural areas, the industry tends to consist of small, widely spread operations. The operation of a quarry or pit requires a large investment of capital for plant and machinery. Wear of plant can be severe, particularly that used for greywacke rock types, and maintenance costs are often high. Good quality aggregate is therefore frequently expensive to produce.

The owners of some small quarries which operated in rural areas in the 1930s to 1950s have not been able to keep up with the cost of the developments and, in many areas, a locally produced basecourse is no longer available.

The historical development of basecourse specifications in New Zealand was reviewed by Bartley et al. (1988). In the early years of road construction, most roads were unsealed and it was necessary to use aggregates which were bound with clay-rich fines. Since the 1930s however several changes in particle-size distribution requirements and the development of sealed pavements have been made. Changes have also been made to the methods for controlling the particle strength and clay content. The object of these changes has been to improve the quality of the basecourse for sealed pavements. However, in some instances, the reason for a change was based on an inappropriate philosophy and this has led to some confusion within the industry as to what should be specified, particularly for lightly loaded pavements.

The literature available on aggregate research and use in New Zealand indicates that the research has followed a similar trend to that recorded overseas, but that significant differences exist in the manner in which unbound materials are utilised in pavements. Traditionally, the New Zealand arterial road pavement has been built using unbound basecourse as the main load-bearing component. This material is separated from the loaded tyre of a vehicle by a thin film of bitumen which is covered with aggregate chippings. The quality requirements of unbound basecourse as a structural component of the pavement have always been emphasised and it is only natural that efforts to upgrade specifications have been given priority in New Zealand research. Field trials of pavements constructed using local aggregates have provided useful information on the basecourse produced from a broad range of rock types, while laboratory modelling has provided further data on the behaviour of basecourse as a load-bearing material.

The literature from Europe, Canada and the United States indicates that bitumen and cement-bound materials are used more extensively in road construction there than in New Zealand, and that layered bound systems are regarded as normal in pavement design. As multi-lane highways carry large volumes of traffic, taking lanes out of service for maintenance is difficult and expensive. Thus pavements are designed to perform under high loads without maintenance and for this reason thick asphalt-bound or cement-bound layers are commonly used as the main structural component. Unbound basecourse is generally used as a capping layer over the subgrade to provide a working platform for construction equipment or used with concrete pavements as a drainage course. Aggregate research in these countries has tended to assess the behaviour of unbound aggregates as the less important member of the system and emphasis is given to the properties of the overlying structural layer.

Jones and Dawson (1989) mention that many engineers in the United Kingdom find a conflict between the drainage requirement and the structural requirements of the aggregate layers in a flexible pavement, i.e. open versus dense grading. They consider the structural contribution of the unbound layer below a bound pavement is modest and for this reason unbound basecourses are often avoided. The use of unbound aggregates as a medium through which water is conveyed contrasts strongly with the New Zealand approach of using such material as a structural layer. The prevailing view in the UK is that the two functions are not compatible.

Economic considerations, which in part arise from the price increases in the petroleum industry that seriously effect the cost of a bitumen-bound pavement, are now forcing European engineers to re-evaluate the function and use of unbound materials as a major contributor to pavement performance.

3.2 Available Literature

The literature available to the authors indicates that New Zealand and international research over the last 10 years has concentrated on the following topics:

- Characterisation of basecourse by geological and mechanical means
- Development of repeated loading tests for the characterisation of basecourse for use in pavements
- Utilisation of the unbound material as a construction material
- Performance evaluation

A collection of papers useful to aggregate users was presented at the International Symposium on Unbound Aggregates in Roads in 1989 (UNBAR 3, Jones and Dawson, Editors, 1989). These symposia are held at four-year intervals.

Another source of information is the Proceedings of the International Symposium on Aggregates held in 1984 (International Association of Engineering Geologists (IAEG) Bulletin 29 1984). Progress in the study of New Zealand aggregates, to 1983, was summarised at that symposium by van Barneveld et al. (1984) who divided the topic into the following categories:

- Geological and petrographic characteristics
- Water movement
- Elastic characterisation
- Performance monitoring:
    - Experimental test sections
    - Accelerated trafficking
    - Normal highway pavement observations
- Construction techniques

For many years, throughout the world, assessment of pavement materials and pavement design methods has been based on observed performance of pavements. Sets of empirical rules have been established to guide practitioners in the use of available material. However, in many western countries new planning regulations restrict both the use of existing quarries and the development of new quarries.

As a conservation measure, the regulations also encourage the use of aggregates manufactured from low grade rock, furnace slag and recycled material, such as concrete and brick. The search for a low cost, but effective, construction material has accelerated the necessity for characterising materials on which there is little performance data. Suss (1989) points out that, in Germany, many kinds of building and road materials have been recycled as aggregates because regulations prohibit them being dumped.

Processing these materials and industrial waste products presents problems for the pavement designer but may also pose problems for the environmentalist because of the potential for the release of toxic agents. Identification of the chemical as well as the engineering characteristics is now an essential part of research of aggregates.

3.3 Geological and Mechanical Characteristics

3.3.1 Introduction

The importance of the geological characteristics of a rock on its performance in a pavement is well established and the evaluation of rock deposits for aggregate production has been successfully researched. In many instances, the assessment of geological characteristics requires carrying out a wider range of mechanical tests or a modification of a standard test. However some deviations from the standard test procedures have not been well documented and results obtained from such tests may be misleading.

Overall however, no major advances have been made in the manner in which the geological and mechanical properties of rock are evaluated, except in assessing elastic characteristics. For elasticity, test methods have been developed, with significant progress, in the use of both the cyclic triaxial and shear-box apparatuses.

3.3.2 Geological Characteristics

Many countries in the northern hemisphere, as well as New Zealand, have resource management legislation that covers the use of aggregate resources. Guizol (1984) draws attention to not only the high cost of investment in the quarrying industry, but also to the high operational, maintenance and depreciation costs. Quarries may be considered a nuisance within an urban area and for reasons of popularity politicians frequently wish to close existing production sites. However, re-establishment of a quarry elsewhere may be detrimental for reasons of quality and cost. Thus Guizol believes that resource management strategies should be based on a comprehensive knowledge of the country's total aggregate resource (extent, quality, extraction cost, environmental hazards).

Throughout the world, research on the durability of aggregates has incorporated petrological studies. Certain minerals are considered to adversely influence the performance of a basecourse and may be described as undesirable, unsuitable, detrimental, etc. A number of index values (or criteria) have been assigned to aggregates based on the degree of weathering, and these values may be indicated by standard tests such as crushing values, plasticity, porosity. For example, Dearman et al. (1984) successfully related the degree of alteration of a dolerite in the UK using durability index values proposed by Weinert (1984) in South Africa.

Frequently, a rock which displays significant differences in its "lustre", "hardness", and "state of crystallisation" within the deposit will produce an aggregate which can exhibit varying characteristics in laboratory testing. For example, it is not unusual for the absorption or porosity to differ when mineralogical alteration is apparent in the rock. Several Canadian provinces use a Petrographic Number (PN) index to evaluate aggregate, particularly in relation to its resistance to frost and to impact. Hudec (1984) suggests that such a system of PN values is probably applicable to specific climatic regions.

In New Zealand, Sameshima and Black (1979) studied the weathering of local andesites and greywacke and introduced the **Clay Index Test** as a measure of the presence of swelling clay minerals. The test involves the use of methylene blue as an indicator but positive identification of the clay mineral present would normally be undertaken by X-ray procedures carried out on the crushed rock. In France, a methylene blue test uses a turbidimetric method employing light absorption spectra to assess the cleanness of aggregate (Ngoc Law and Millon-Devigu 1984).

Both the New Zealand and French test methods identify the presence of clay minerals but results may differ quantitatively. The presence of clay minerals in the fines of an aggregate may indicate contamination by clay from overburden or joints in the rock. The clay index test is used in New Zealand on aggregate fines and on crushed rock powder to measure contamination. Crushed rock powder gives results that relate to aggregate performance rather than to production of a basecourse.

Woodside and Woodward (1989) carried out extensive work on basalt aggregate in Ireland where they found that geological factors such as secondary mineralisation, oxidation and weathering control the durability of the basalt rock. They developed a **Durability Index** using the relationship of the results of the methylene blue absorption value (MBA), porosity, and wet 10% Fines Test, which are three quick, simple and standard tests.

Porosity was calculated as follows:

$$Porosity\ \% = \left(\frac{ssd\ RPD\ x\ WA}{100 + WA}\right)\ x\ 100$$

where *ssd RPD* = Saturated surface dry Relative Particle Density
WA = Water Absorption

Results of the three tests can be used in the following equation to predict the potential for in-service failure and can be obtained in two days:

$$Basalt\ Durability\ Index = \left(\frac{Porosity}{10\%\ Fines}\ x\ 100\right)\ MBA$$

Other researchers found that durability was not entirely related to mechanical test results. Goswami (1984) studied acid igneous rocks and found that petrographic features such as grain size and pore space were also important. In Finland crystalline rocks that were tested for hardness and brittleness complied with specifications but in use were affected by frost action. These rocks were shown by Niemineu and Uusiwoka (1986) to have high specific surface areas which are related to the quality of the fine fraction of the aggregates. The high specific surface area is mostly caused by the presence of clay minerals and probably of sulphides associated with alteration products. In addition, microfracturing of feldspar and mica crystals, which can occur during blasting, will reduce durability.

The geological assessment of rock deposits and crushed rock products is an essential part in the assessment of durability. Applying this philosophy to research in New Zealand has provided an understanding of the importance of the fabric of rock particles. Further work on the relationship of the Clay Index to other parameters such as porosity and absorption may improve the knowledge of durability.

3.3.3 Mechanical Properties

Techniques used to determine the petrography of a rock or rock particles provide knowledge on its origin and fabric. Many aspects of petrography, such as the mineral and/or grain-size, texture, microfracturing and weathering, are related to mechanical or physical properties such as hardness, resistance to abrasion, and absorption.

Physical test methods have been developed as a result of experience with the performance of aggregates. For example, testing for hardness and resistance to abrasion probably originated from experience gained in railway engineering where the performance of rail ballast could be observed during walkover field inspections. Resistance of the ballast to disintegration, particularly under freezing, was an important property to assess as was its hardness. The cyclic concept, occurring naturally in freezing and thawing, wetting and drying cycles, is the basis for many durability tests, the most common test for which involves cyclic wetting, using saturated sodium or magnesium sulphate solution, and drying.

There has been considerable growth throughout the world over the last forty years in the number of tests used to define the mechanical properties of aggregate. Many test methods have local variations introduced to evaluate local aggregate types or satisfy specific changes in climate, precedent, traffic loading or other environmental conditions. The list of tests for durability or soundness is extensive and the prefixing of a geographical name records both the apparent necessity for local testing and the establishment of new tests for that locality, e.g. *Oregon* air degradation test, *Washington* degradation test, *Idaho* rattler test, *California* durability test, etc.

A range of mechanical tests, to provide information on strength, have been developed. These involve impact loading, continuous loading and cyclic loading. Other mechanical tests are undertaken to assess the particle-size distribution, shape, texture, cleanness, density and absorption.

The concepts of plasticity introduced by Atterberg in 1913 were related to soils classification and road aggregate performance in the USA in the late 1930s to mid-1940s. As a result pavement performance was related to the plasticity index of the basecourse among other factors. Measurements of plasticity and cleanness are still considered to be important in basecourse construction and are undertaken in many parts of the world.

Many engineers experience difficulty when evaluating a new source of rock because of the wide range of parameters that need to be considered. In general, they will rely on the requirements for a premium quality product rather than try to evaluate the geological information of an available or new rock in terms of its potential performance in a road pavement.

Reviews of test methods and specifications are continuously carried out, particularly in Europe and the USA, to rationalise basecourse characterisation tests.

Almost invariably, specifications for grading, particle strength and control over the percentage of fines or degree of plasticity are required for evaluating aggregates. Dawson (1989) uses the term "particle integrity" which is determined by crushing, abrasion, tumbling, polishing or impact tests.

Bulk strength on the other hand may involve density, California Bearing Ratio (CBR), triaxial or shear-box testing. Triaxial or shear-box testing may be of a cyclic nature. Tests to determine content of fines will normally involve sieving processes although the Sand Equivalent is often also used as a measure of cleanness. The presence of clay minerals may be measured in terms of plasticity tests or by using methylene blue as an indicator. Some specifying road authorities vary the details of a test method to suit their own use and this can lead to confusion in comparing the results of such tests.

The presence of swelling clays in the rock fabric or in the clay-size fraction of a basecourse may be determined by the use of a methylene blue absorption test. The original test of Jones (1964) has been modified for use on powdered rock. It has also been modified for use in Ireland (Woodside and Woodward 1989) and in New Zealand (NZS 4407:Part 3.5:1991). Although variations may be minor in each revision, the accumulative changes may produce a different characteristic. A variation in test methodology is also apparent for the Sand Equivalent test when carried out in New Zealand, USA or in France. Because of such variations, one of the proposals made by the UNBAR Committee (1989) was for uniformity in specification and methodology in Europe in relation to specifications for road aggregates.

Degradation of basecourse particles within the pavement is stress-dependent. This is modelled by particle integrity tests, such as the crushing resistance test. However, many test procedures used to assess durability and degradation submit the aggregate specimen to considerably higher stresses than would normally be experienced in the pavement.

Bulk strength testing of the aggregate mass involves the interaction of all the particles and is also stress-dependent. However, the modulus is not linear and varies from aggregate to aggregate. The most effective method of testing the bulk strength is by repetitive test procedures. These provide data on the elastic and deformation properties which can be subsequently used for performance evaluation. Earland and Mayhew (1989) maintained that a ranking for basecourse in terms of the Peak Shear Stress ratio (PSSR) can be obtained from a simple shear box. The PSSR is the ratio of the peak shear stress at failure to the normal stress:

Strength	**PSSR**
Low	less than 1.9
Medium	1.9 to 2.8
High	above 2.8

3.3.4 Grading and Shape of Particles

Both the grading and shape of the aggregate particles are important in the packing arrangement of aggregates under compacting equipment. The principles of workability of concrete can also be applied to basecourse aggregates. For example, good compactability is generally achieved when the overall aggregate has a dense well graded particle size, i.e. the overall grading curve gives a Talbot "n" value of 0.45 - 0.55 (Bartley and Cornwell 1991b). Water will assist in the workability as will the presence of clay-size particles. However both water and clay can have an adverse effect on the shear strength of a basecourse.

The particle shape may range from smooth rounded gravel, through cubic to angular flaky crushed rock, depending on the manufacturing process involved and the geological origin of the rock. Many European countries emphasise the importance of particle shape and use a variety of methods such as direct measurement, sieving etc., to quantify it. Barksdale and Itani (1989) found that smooth rounded river gravels were more than twice as likely to be associated with the development of ruts in a pavement than angular flaky crushed aggregates. Flaky aggregate particles were not detrimental in a basecourse provided they did not degrade. Earland and Pike (1985) found many gravel materials performed as well as crushed rock under controlled trafficking but the shape characteristics were not given. Lees and Bindra (1982) found, during degradation studies, that equi-dimensionally shaped particles survived best at up to 30% strain, but flaky particles showed much higher rate of breakdown.

Particle shape can be classified as rod-shaped or disc-shaped. In the sieving process the rod-shaped particle can effectively pass a sieve of a size smaller than a flat disc-shaped particle. Tests to determine specific surface area available for water absorption, and the ability of the particles to fill the voids of a coarser size aggregate, cannot be properly carried out unless the particles are of good shape (roughly cubic).

Shape classification in terms of BS 812:1975 (British Standards Institution 1975) is as follows:

- Cubic (equidimensional)
- Disc
- Blade
- Rod

Lees (1964) considered that it was preferable to define a particle shape by flatness and elongation ratios rather than use the descriptive terms defined in BS 812:1975. He uses the following ratios but measurement details are not known. It is therefore not possible to establish how they would relate to the average, least and greatest dimensions used in New Zealand.

$$\textit{Flatness ratio } (p) = \frac{\textit{least/shortest dimension}}{\textit{intermediate length}}$$

$$\textit{Elongation ratio } (q) = \frac{\textit{intermediate length}}{\textit{greatest dimension}}$$

$$\textit{Shape Factor } (F) = \frac{q}{p}$$

Barksdale and Itani (1989) illustrated the influence of the combined effects of shape variables on the resilient modulus and permanent deformation. They introduced the Aggregate Influence Factor (AIF) which was taken to be a function of particle sphericity, roughness, roundness and angularity.

The AIF was empirically deduced and is given by the expression:

$$AIF = 2{,}500 \times (SV + R) - (A + SR)$$

where SV = average sphericity value
SR = surface roughness coefficient
R = average roundness
A = average angularity.

The selection of the most appropriate particle-size distribution is dependent on how the aggregate packs together. Particle shape and texture have a significant influence on packing. The porosity, or voids content, of the compacted material is also dependent on the particle strength and the amount of degradation that occurs during compaction.

Degradation, particularly as influenced by the petrographic characteristics referred to in Section 3.3.3, has been studied by many researchers. Lees and Zakaria (1987) defined degradation as "the reduction in the size of particles which occurs during the process of laying and compaction and as a consequence of traffic action in association with weathering processes during the pavement life". These authors noted that degradation changes were frequently found to be detrimental to pavement performance but sometimes the opposite effect was also evident.

The consensus of opinion obtained from the literature is that densely packed, well graded aggregates (having Talbot "n" value of 0.40 - 0.50), consisting of sound crushed rock with no more than 5% passing the 75 micron sieve, in good environmental conditions for a pavement, provide excellent performance under heavy traffic loading. Aggregates of a lower standard, placed in the same environment, could still provide satisfactory pavement but only for roads with lighter traffic loading. Aggregate crushed from exceptionally hard rock may, because of the difficulty in producing fines, result in a pavement with high voids (>20%). Special crushing procedures may be necessary to produce a dense graded material.

3.3.5 Density

The importance of compacting a basecourse aggregate to a high density was recognised by most road authorities as essential for good pavement performance. Some authorities have suspected shear failure in a basecourse is the result of positive pore pressures developing under traffic loading, and have deliberately specified gradings which will give high voids after compaction. Positive pore pressures may also develop in a dense undrained pavement when saturation has occurred, e.g. during construction or when water is allowed free access to the pavement after construction.

Generally the objective of compaction, which is to achieve "maximum density", was controlled by the grading, the water content of the aggregate, and the energy level applied. Research has attempted to refine the methods of applying energy to aggregates. Impact, static loading, vibration and shear, or combinations of one or more of these processes, have been investigated to improve compaction.

Laboratory compaction of aggregates is an extension of a standard geotechnical test procedure. Various impact methods are available to compact aggregates in a laboratory: differentiation between these methods can be achieved by defining the compacting hammer mass (number of blows) and the layer thickness of the aggregate being compacted. The use of terms such as "standard", "modified" or "heavy" compaction is common. The physical restraint of the size of the test mould used for these tests requires larger sized particles (usually greater than 20 mm) to be removed before the sample is tested.

Martin and Toan (1971) drew attention to the changes in grading produced by impact and static loading methods of compaction. They developed a technique to minimise these effects using a kneading compactor and a large diameter mould. Maurice (1977) and Peploe (1991) used vibrating compactions and, in the process of strength testing, observed that gyratory shear produced higher densities. The maximum size of particle (less than 20mm) allowed in the test sample was again restricted by the physical size of the apparatus.

Translation of the results of the laboratory density test to the control of field compaction presents no real problem, but the relevance of the results has generally been questioned. During the compaction process, particle degradation is likely to occur until a dense grading is achieved. Bartley (1980) considered that inter-particle movement of the coarser fraction of a basecourse results in a change in grading caused by particle breakage and abrasion. He postulated that the in-service condition of a basecourse approximates to a grading close to the Talbot "n" value of 0.4.

Other properties may influence the performance of "ideal" gradings. For example, the shape of particles may assist or hinder particle packing, or the fines (less than 425 microns) may show plasticity and affect stability of the wet aggregate. Only a small quantity of plastic fines may be needed to significantly reduce the strength of a well compacted basecourse under adverse environmental conditions, for example a high water content.

Factors affecting the density obtained by compaction of crushed stone were given by van der Merwe (1984). These include moisture, grading, particle shape, particle strength, plasticity and the method of compaction. He also noted that density influenced the performance of an aggregate by affecting the permeability and the elastic parameter, shear strength and deformation.

Testing for density in the laboratory is frequently specified as a means of control for field compaction. Barksdale (1989) reviewed the requirements of eight US land transportation organisations, all of them specifying field compaction in terms of a laboratory standard, such as modified Proctor density. Dawson (1989) has made several objections to the use of a relationship between field and laboratory compaction as a field control technique. They are:

- If more than 100% maximum density is required, then there is every possibility that the optimum water content should be lowered.
- Laboratory compaction (hammer or vibrating) cannot be related to the use of a roller on a pavement in a straightforward manner.

- Laboratory compaction equipment is too small to avoid edge effects. The removal of a coarse fraction (i.e. greater than 19 mm) means that the sample is no longer representative, although the edge effects of the mould may be alleviated.
- Omitting coarse material may remove the most significant fraction of a basecourse.

Dawson questioned whether the laboratory determination of density was relevant and whether the moisture content could be controlled effectively on site.

An interesting development in France was outlined by Quibel (1989) relating to the compaction of unbound aggregate. Materials were classified in three categories of "difficulty of compaction" based on the crushing index, particle shape, grading and mineralogical nature:

- D_1: easy to compact
- D_2: middle difficulty of compaction
- D_3: difficult to compact (i.e. fully crushed material)

Compacting equipment was tested by the French roading organisations for real performance in relation to the above categories. This is somewhat similar to the certification of bitumen spraying equipment in New Zealand and Australia. Research on the efficiency of compactors (pneumatic as well as vibratory) and the methods of classifying the "difficulty of compaction" by laboratory testing is being continued. The latter includes factors such as the percentage of fines, particle strength, particle shape, water content, and the effect that these have on laboratory compaction and fill compaction. A special roller called a "compactabilimètre" (10 kg/cm with 1 mm amplitude) has been developed by its French researcher to make characterisation of compactability both easier and cheaper. The development of a data bank for recording density as a function of layer depth, number of passes and compactor characteristics is being developed. The research work has a very positive and practical approach to sensible compaction control.

3.3.6 Strength Characterisation

National and international research into pavement design, particularly in the last 10 years, has attempted to develop a rational method based on the analysis of load-induced stresses and strains in the layers comprising the pavement structure.

The widespread use of thick bitumen-bound layers used in the Northern Hemisphere has focused attention on the mechanistic characterisation of these relatively stiff layers. In New Zealand such pavements are only found in the more heavily trafficked arterial roads of major metropolitan areas. Low trafficked pavements, even those in metropolitan areas, and rural highways are more normally constructed of layers of unbound granular basecourse surfaced with a thin chip-covered bitumen membrane.

However Elliott and Laurdeonathan (1989) infer that a significant weakness in the mechanistic approach is its inability to realistically model the behaviour of an unbound granular base layer. As a result, the design of pavements in New Zealand, with comparatively thick layers of basecourse and thin bitumen surfacings, tends to follow the semi-empirical methods fashionable elsewhere.

The Clegg Hammer, developed in Australia, measures the stiffness characteristics of pavement materials under the impact of a falling weight. A relationship established between CBR (California Bearing Ratio) and the Clegg Impact Value (CIV) by Clegg (1985) is:

$$CBR = 0.07 \times (CIV)^2$$

The relationship was empirically deduced but in general has been accepted by pavement workers although slightly varying results have been obtained, depending on the type of materials for which the apparatus was used.

Sweere and Galjaard (1989) investigated in situ the stiffness of granular basecourse by means of both static and dynamic plate-bearing tests and the Clegg Impact Test (CIT). Their findings were that:

- CIT worked remarkably well,
- Stiffening of granular basecourse with time was reflected in test results,
- Repeatability of the test method was good,
- CIT shows great potential as a quick means of proof testing granular layers.

The CIT was used by Wallace (1984) in an attempt to relate CIV and density measured by the sand and nuclear density methods. Although he accepted that the equipment proved to be a "convenient panacea for the compulsive tester", the results of CIV/sand density or CIV/nuclear density were not encouraging.

Monk (1990) established that the CIT was a convenient tool for determining the number of roller passes required for compaction of basecourse, and that density values and CIV followed a similar pattern. A specification was recommended for determining the end point of compaction and, although Monk does not define what property is measured, he infers that the CIV relates to the hardening of an unbound pavement.

Research in USA by Garrick and Scholer (1985) confirmed that the CIV was a measure related to the strength of a basecourse. A minimum value of 40 was considered satisfactory for a pavement to perform adequately during the spring thaw.

A similar but more sophisticated device than the Clegg Hammer is the "Variable Impact Swinging Hammer Test Apparatus" or ODIN, described by Boyce et al. (1989) and developed by Loughborough University/Geotechniques Ltd. The ODIN has a variable hammer size, weight and fall. The results indicate that quasi-elastic behaviour occurs followed by plastic deformation and failure at higher stress. It is apparent therefore that the equipment will be used for proof testing of compacted materials. This work implies that the results of impact testing of granular materials are related to strength characteristics and not to density. The potential of the Clegg Hammer and/or ODIN for compaction control by measuring strength is encouraging.

The cyclic triaxial test has been accepted in both research and practical engineering as an appropriate tool to measure the shear strength and resilient modulus parameters used in pavement design. Martin and Toan (1971) developed a large triaxial test facility specifically

Erratum: Equation corrected and page substituted July 1994 for testing 40 mm basecourse aggregates for which they prepared a 250 mm diam. x 625 mm long sample using a kneading compactor.

Thom and Brown (1989) used a triaxial cell to assess the elastic stiffness, shear strength and deformation characteristics of unbound aggregates. Physical tests, in which particle shape, surface roughness (rugosity) and surface friction (mineral texture) were measured, showed relationships to shear strength, permanent deformation and stiffness respectively. However, a wide range in particle-size distribution of the aggregates used in their studies may well have been responsible for some of the correlations.

Some researchers considered the simple shear box more closely simulated pavement strain conditions than the triaxial test. Maurice (1977) developed a reciprocating shear compactor to investigate aggregate under repeated loading that tested a smaller more easily prepared sample (250 x 250 x 100 mm) than the Martin and Toan (1971) triaxial sample.

Lee (1979) and Peploe (1991) continued the work with the shear box, although the apparatus does not have universal approval. Peploe states that "the ability of the simple shear apparatus to produce a rotation of the principal stress axes is an attribute which has been recognised by many authors". This feature was considered to be most important in modelling unbound aggregate pavement layers. The research confirmed shear strain as a primary factor in compaction and that an energy barrier has to be overcome to carry out the test. Peploe states that "no permanent densification of a granular base will occur if the shear strains imposed on it during its service life are less than those applied during construction". If the energy barrier was exceeded in service however, then further permanent deformation would occur. The results also showed that high density promoted a high degree of stability but the frictional characteristics of the aggregate particles were also important.

A number of researchers drew attention to the fact that many aggregates have an affinity to water. Woodside and Woodward (1989) emphasised the importance of absorption and porosity and noted that the wet 10% Fines Test, used by several roading authorities in the UK, indicated that particle degradation is increased and inter-particle friction is reduced when an aggregate has a marked affinity for water.

It is surprising that few researchers have failed to recognise the importance that particle-size distribution has in relationship to the density, stability and permeability of an aggregate layer. Admittedly many of the overseas workers were testing aggregates primarily intended to have a drainage function, i.e. a sub-base layer under a stiff bound basecourse layer. Peploe's (1991) shear box testing was carried out using aggregates that had an over-abundance of fines. Such aggregates would have reduced particle-to-particle friction and probably could not be compacted to a high density. As a result, the relevance of these tests to roading aggregates would be limited.

Hence many of the results discussed related to aggregates selected for the convenience of laboratory preparation and which normally had a high porosity, a characteristic not usually found in a mature New Zealand highway pavement.

3.3.7 Permeability

Roading aggregate, in its compacted state, may be required to act as a load-bearing layer or as a drainage layer. Combining these two requirements is somewhat opposed as an aggregate may suffer loss of strength when close to saturation, as in a drainage situation. Stiffness and resistance to deformation under load requires a dense basecourse (compaction and dense grading) whereas high permeability requires a high voids content (low compaction and open grading). In general, there is a reticence to specify permeability in a drainage course because of the difficulties of measuring it in the field and in the nomination of a value which is meaningful.

Jones and Jones (1989b) conducted a survey of current British practice and found that specifications for the permeability of basecourse were not widely used and most engineers accepted the concept of Cedergren (1974) and Moulton (1980) that values could be predicted from particle-size distribution curves.

Basecourse aggregates may have maximum size particles of 40 to 75 mm. However the values presented by many researchers, based on the results of laboratory tests on samples with a smaller maximum size, require adjustment. Permeability is dependent on the horizontal and vertical boundary conditions of the pavement layer as well as on the particle-size distribution of the aggregate within the pavement. Thus the effectiveness of a basecourse layer as a drainage course can be materially affected by:

- Uniformity of the layer (e.g. thickness, cross fall, segregation),
- Upper and lower vertical boundaries (e.g. of seal, sub-base, subgrade),
- Intermediate boundaries at layer interfaces (e.g. of films of fines caused by construction traffic),
- Lateral boundary conditions (e.g. of road shoulder, kerb),
- Deformation of the layer (e.g. rutting),
- Position of the ground water level in relation to the basecourse (e.g. suction pressures normally exist in a pavement, provided surface water can be eliminated).

Tests have been devised to measure permeability but normal laboratory permeameters are frequently unsuitable for basecourse aggregates which may have maximum particle sizes in the order of 40 mm. The edge effects of the walls of the equipment have also been recognised by most researchers.

Jones and Jones (1989a) outline a test procedure for the measurement of horizontal permeability in which the results of tests undertaken on basecourse made from crushed dolomite, sandy gravel and crushed granite, were all greater that 10^{-3} m/s with some values in excess of 10^{-1} m/s for the coarse graded aggregates. The aggregates used had densities and gradings resembling the upper, middle and bottom ranges of TNZ M/4 (1985) specification requirements in the finished pavement. Jones and Jones considered that their test procedure was suitable for incorporation into future International Standards.

The field measurement of basecourse permeability has been based on procedures normally associated with infiltration tests for soakage and seepage characteristics of soils. Infiltration tests on pavements and in situ permeability tests are difficult to undertake as the volumes of moisture movement are usually very small and hence difficult to measure. The objective of a field test is ultimately to achieve a condition of steady state flow.

Moulton and Seals (1979) developed a method for testing compacted basecourse samples in situ using conductivity measurements. A "salt-slug" was introduced into the permeameter system once steady state flow conditions had been established, and the time taken to move a set distance was measured. Permeability values for basecourse aggregate using this technique were found to be in the order of 10^{-4} m/s or more, provided the saturated steady state flow could be maintained during the test.

Rutter (1986), who tested the Moulton and Seals equipment in New Zealand, recognised that several variables influence the permeability of a basecourse. The particle-size distribution, porosity, composition, fabric, and degree of saturation all influenced the results measured with the field apparatus. She also found that screening of the sensing probes can occur when basecourse has a maximum particle-size of 40 mm. The apparatus was shown to be very satisfactory for aggregates with permeabilities of 10^{-2} to 10^{-5} m/s but was unreliable outside this range. However the measurement times used in the tests were very short for high permeability materials and may well be inaccurate. For low permeability materials, appropriate flow conditions may not be possible to establish within a reasonable time and also piping, i.e. short circuiting, may occur. The values obtained by Rutter were in the order of 10^{-3} to 10^{-4} m/s for newly constructed pavements but of the order of 10^{-6} m/s for densely graded pavements which have been subjected to traffic for some years.

A variation of the Moulton and Seals equipment was made by Floss and Berner (1989). The equipment was designed to measure two parameters, the horizontal and the vertical coefficient of permeability, both in the laboratory and in the field. The research showed that on three soil (basecourse) types the horizontal permeabilities in the laboratory and in situ were in the order of 5×10^{-5} m/s and 5×10^{-6} m/s respectively. The vertical coefficients were in the order of 10^{-6} m/s and 5×10^{-7} m/s respectively.

Drainage courses, which had quite similar grading specifications to those of TNZ M/4, were investigated by Roy and Sayers (1989). The aggregate under study was specifically designed to provide a drainage course below a concrete pavement. Testing of its permeability was based on Moulton and Seals procedures and coefficients of permeability greater than 2×10^{-3} m/s were recorded for basecourse which had been in service for two years. These results confirmed that the design criteria based on the relationships between grading curves and permeability proposed by Cedergren (1974) were valid.

The survey undertaken by Jones and Jones (1989b) showed that, although the concept of permeability was well established, its application to pavement design and materials was infrequently used. In New Zealand, aggregates for drainage purposes are normally specified in terms of particle-size distribution. They are often placed using light compaction and generally function satisfactorily. However, in most countries, the knowledge of water movement in pavement layers was confused, particularly when the aggregate was also used as a structural component. It would appear from the work of Rutter (1986) that basecourse of TNZ M/4 quality, when compacted and trafficked, has a coefficient of permeability much lower (less than 10^{-5}) than that suggested by Cedergren (1974) or that obtained from conventional laboratory testing.

Although a coefficient of permeability of 10^{-3} m/s or 10^{-2} m/s was considered desirable for good pavement drainage by most roading authorities, an aggregate with these values was not regarded as free draining. The presence of an impermeable subgrade, which is characteristic throughout most of New Zealand, may impose a boundary condition negating vertical flow and transferring the movement of water along the horizontal direction.

Designers need to recognise the effects of construction (such as degradation, segregation, contamination, variability in aggregate source) on permeability. Aggregate designed to be open graded will densify when placed in a repetitively high stress situation, and may also degrade. The development of a skin of very fine material on the surface of a layer caused by excessive compaction during construction, may act as a barrier to vertical drainage. In service an aggregate layer may change from a highly permeable to a virtually impermeable condition.

3.4 Performance Monitoring

3.4.1 Introduction

The performance of aggregates can not be readily related to current design procedures. The pavement environment, which is a diverse arrangement involving temperature, moisture and traffic loading, cannot be reproduced in the laboratory. Models have been designed to replicate as many of the conditions found in the field as possible but in many instances the results of such work were found to be inaccurate purely because the real life situation could not be accurately modelled.

It has also been found that full scale pavement trials often generate a mass of data, little of which can be directly related to changes within the pavement. Although data covering temperature, pavement deflection, surface shape and roughness were relatively easy to collect, they were seldom correlated with pavement performance.

3.4.2 Highway Pavements

Experience has been gained by many practitioners over the years by simply observing, and in some cases recording the performance of the road pavements in their area. For example Batten (1967) recorded observations of the performance of two pavements and compared them to the properties of the aggregates measured in the stockpile immediately prior to construction.

The modern practice of maintaining a computer-based pavement inventory, such as the RAMM (Road Assessment and Maintenance Management) system, preferably complemented by CONMAN (Contract Management Scheme Package), now provides the historical record that is essential to monitoring such activities but was often missing in the past.

The disadvantages of monitoring the long-term performance of pavement sections using only RAMM include:

- Often little, if any, written record of start data, e.g. type of aggregate used, particle-size analysis, subgrade properties,
- Little or no traffic loading data,
- Inability to regularly monitor the condition of the pavement materials, e.g. water content,
- No maintenance costs data,
- All maintenance data is not always recorded.

3.4.3 Experimental Pavement Test Sections

Full-scale test pavements, constructed with different types of aggregate, have been used extensively in New Zealand to overcome the problems outlined in Section 3.4.2.

Cato (1985) and Tonkin and Taylor (1981, 1983) report the performance of a series of test sections constructed, with funding from the National Roads Board (now Transit New Zealand), using a variety of aggregates and subjected to loads of more than 10 million equivalent 80 kN axles over periods of up to 15 years. Some of these pavements still exist, virtually as in their original condition, more than 20 years after construction.

Other test pavements have been deliberately constructed using materials which did not meet Transit New Zealand specifications to document their performances. These include:

- Goat Valley Reconstruction, Wanganui (Shellrock) - Baines and Smith (1986), Smith (1990),
- Pipiwai Road, Whangarei (Tangihua Basalt) - Brenan (unpublished report, 1984),
- SH 38 Rerewhakaaitu (greywacke, rhyolite, cement-treated pumice) - Irvine (1982),
- Airport Road, Alexandra (Terrace gravel) - Watts (1990),
- Hobsonville Road, Waitakere (Waitakere Andesite) - Fraser & Cornwell (1989),

Monitoring these pavements was generally limited to deflection surveys although in more recent years roughness measurements were added. All, except the Pipiwai Road series and part of the Hobsonville Road, remain in very good condition (as at 1993). The establishment of these research projects has provided the record of start data and performance that was often unavailable in earlier projects. Such projects have, in most cases, confirmed the experience of local practitioners, i.e. that the aggregates were suitable for high traffic loads, and have enabled others to use local aggregates with greater confidence.

The major disadvantage of this type of research was the natural variation of the environment and an inability to monitor the effect of environment on the pavement, and the lack of a continuous record of performance. It was often impossible to keep the project under proper control throughout the extended time span involved, and the record of pavement performance suffered as a consequence.

3.4.4 Accelerated Trafficking Tests

Many of the problems encountered in monitoring the performance of full-scale pavement test sections can be overcome using the accelerated trafficking approach. In this situation the work is usually under the control of a professional engineer experienced in research, and consequently the quality and extent of records is now much improved.

The performance of pavements of various types has been studied in New Zealand using the accelerated testing facility at the University of Canterbury. This facility, now called CAPTIF and originally designed by Paterson (1972), comprised an outdoor circular test track with a mean diameter of 18.3 m trafficked by two vehicles, each loaded to 40kN. Attached to opposite ends of a steel beam which pivoted about a central point, one of the vehicles was driven by an electric motor and the wheels of the other were free to rotate. The operating speed, 18.7 kph, could not be varied.

The equipment was modified by Seddon to research unbound and stabilised pavements (Seddon 1979; Seddon and Bhindi 1983). It was relocated inside a covered area and techniques were developed to construct artificial subgrades, to measure pavement deformation at various levels, to replicate local rainfall conditions, and to monitor changes in surface shape.

In 1984 the National Roads Board (now Transit New Zealand), in conjunction with the University of Canterbury, commissioned the design and manufacture of a replacement test facility. The design was to provide:

- A test track of a similar size to the original Paterson design,
- A more robust mechanical system, plus
- Ability to control the pavement environment.

The new indoor facility comprised a concrete tank set in the ground within which the pavement could be constructed. Two vehicles, each attached to opposite ends of a beam pivoted from a central anchor point, are driven by hydraulic motors. A computer is used to control the speed, which can be varied up to a maximum of 50 kph, the radial position of the vehicles, and the number of revolutions for each test run. The tank is fitted with plumbing that enables the water content of the subgrade to be varied.

The facility was commissioned in December 1986 and has been used at the University of Canterbury by Pidwerbesky (1989) for a variety of research projects funded by Transit New Zealand. He has progressively developed the monitoring equipment including a system to record the strain within the pavement as well as improving pore water pressure, surface profile and surface deflection measurement systems. Recent research has been focused on the interaction between the loaded vehicle and the pavement.

The disadvantage of this accelerated testing facility is the inability to replicate the real-life situation, particularly with respect to weak subgrades and water changes within the pavement layers. The equipment that enables variation in the moisture content of the subgrade could not be commissioned because the permeability of the subgrade soil was too low. However, research into the subgrade problem is being undertaken by Transit New Zealand in association with Pidwerbesky and that into water movement and control may follow.

3.5 Selection of Aggregates for Unbound Pavements

3.5.1 Selection by Experience

The most commonly used technique for the selection of an aggregate to be used in a pavement is precedence, either that based on the experience of the designer or that of someone in authority. In New Zealand this has tended to favour materials that have readily met the requirements of TNZ M/4 specification, at the expense of lower quality materials. Few practitioners have the ability to correctly engineer the use of material of lower or perhaps of suspect quality, so consequently high quality material may have been used in a wasteful manner.

A great deal of research work has been carried out throughout the world on the topic of aggregates for use in pavements, and results of some of the most recent work have been mentioned in preceding sections. However, the progress made has been relatively slow in terms of the money and effort involved.

The research carried out in New Zealand over the past 25 years has more than kept pace with that in Australia, the United States, the United Kingdom and Europe. However, it is apparent that the unbound granular aggregate pavement with a thin surface seal, used almost exclusively in New Zealand, is not a major topic of research overseas. As a consequence the results of overseas research or the use of overseas experience should not be adopted for use on our roads without a great deal of evaluation.

Van Barneveld et al. (1984) provide a good description of the research work carried out in New Zealand up to 1984. Similar studies were continued particularly with respect to aggregates of lesser quality, the most recent being reported by Bartley and Cornwell (1991b). Both these reports cite the Aggregate Selection Chart, used by Bartley (1971) or modifications to it, as a useful empirical guide to follow. The chart, based on the results of laboratory and field tests as well as on experience, indicates the areas of use for a wide variety of materials.

3.5.2 Selection by Theoretical Approach

The use of deep lift asphaltic pavements for many of the heavily loaded highways in the major industrialised countries of the world and the development of theories based on the fatigue concept, has encouraged New Zealand road authorities to adopt a similar approach for the design of their pavements. The results of the AASHO Road Test carried out in the 1950s (AASHO 1962) and the theories that were developed from it have been accepted as still relevant today.

Design charts in State Highway Pavement Design and Rehabilitation Manual (Transit New Zealand 1989) postulate that a pavement constructed in accordance with the design theory will fail after it has been subjected to a specified number of repetitions of a standard wheel load.

However, few of the modes of distress described in that document (e.g. failure of surfacing, shallow shear within the pavement layer, densification with loss of surface shape), are related to the fatigue theory and then only by analogy.

On the other hand, current work on shakedown analysis by Sharpe (1985), Raad et al. (1989) and in New Zealand by Collins et al. (1986, 1992), has led to a much clearer appreciation of how aggregates perform in a pavement. This theory, which also has application in structural and mechanical engineering, acknowledges that particles under the influence of cycles of stress will be rearranged until a dense stable condition becomes established. This state will be maintained indefinitely provided that the level of stress (shakedown limit) is not exceeded and the properties of the material remain unchanged.

This theory, when applied to a road, effectively means that a granular layer compacted with a roller will reach a density which cannot be increased further by that particular roller, i.e. it will have reached the plateau level described in TNZ B/2 (1987) specification. It is possible for the basecourse in a pavement to densify when opened to traffic and to show some deterioration over a period of time.

However, it will eventually reach a stable condition after which the pavement will continue to provide a constant level of service provided the stress level and other environmental factors remain the same. Excessive surface deformation manifested as rutting may cause the bituminous membrane to rupture.

The properties of an aggregate which could be used in association with the shakedown theory is described by Peploe (1991). The shear box used by Peploe could be developed to provide the facility to establish the shear modulus and the shakedown limit stress for virtually every aggregate available for use in New Zealand. It should also be possible to determine these properties for a subgrade soil using the dynamic triaxial test, a technique that is already well established. This information could be used to design a pavement that would, in theory, last almost indefinitely.

One of the most satisfactory aspects of the shakedown theory relates to the elastic response of the material once it has been rearranged in a dense stable state. As a consequence the stress level and the deformation of the pavement under load can be estimated relatively easily. Monitoring the performance of a pavement in terms of surface deflection would then have direct relevance to the design theory.

To get the maximum benefit in terms of this design theory, a highway pavement will need to be constructed to the most stable condition possible. The aggregate used will have to satisfy a dense grading within tighter limits than those currently used (i.e. TNZ M/4(1985)), and it will have to be compacted to a dense condition, probably in excess of 85% solid density.

It would also be practical to design the lightly loaded pavement so that it can be built from materials of lower quality than those currently specified.

3.6 Conclusions

The review of international and national literature for this project has highlighted the difference in emphasis in the research carried out in New Zealand with that in major western countries of the world. In the United States, the United Kingdom and most of Europe, bitumen-bound or cement-bound material is used as the main structural layer in the pavement, with unbound aggregate most likely used in a sub-base layer that is designed primarily as a drainage layer.

In New Zealand the main structural layer in the pavement comprises unbound granular aggregate and, as a consequence, research effort in New Zealand has been mainly focused on the stability of aggregates, such as stability under a relatively high, concentrated, repetitive load regime. In contrast, international research of these materials appears to be more concerned with the stability of more open graded material under a relatively low, well distributed and constant load.

It is generally accepted that the geological characteristics of a rock (fabric, composition, degree of alteration, durability, etc.) have a significant influence on the production, and performance characteristics of a basecourse in a pavement. The review has indicated that little if any change worldwide has occurred over the last ten years in the manner in which such properties can be assessed.

Resource management has developed worldwide in such a way that greater emphasis is now placed on the utilisation of industrial waste products in road construction, and the re-use of roading materials. Such use of industrial waste material has to be evaluated in terms of the risk of the release of toxic material during construction or at some time in the future. Also restrictions on the establishment and operation of quarries are forcing up the cost of aggregate production.

The results of a petrographic analysis provides a good guide to the long-term durability of an aggregate. However, mechanical tests may still be required to quantify the extent of its potential breakdown. Further work is required in New Zealand to establish relationships between durability and such properties as the Clay Index, porosity, and absorption, and could be carried out as an on-going exercise.

A variety of mechanical tests of the durability of aggregate have been developed throughout the world. Many relate to problems encountered within a specific geographic area and have been named accordingly, e.g. California Durability Test. The results of some apparently standard tests may be misleading because modifications may have been made to the test method to cover local aggregate types or local environmental circumstances. Some test methods impose much greater stress on the rock samples than would actually be experienced in the road and, therefore, the significance of the results of such tests needs to be evaluated in terms of the pavement environment and the expected life of the pavement.

The density of an aggregate layer and hence its stability under traffic may be influenced by the shape of particles and the distribution of the various sizes. Shape can range from smooth rounded uncrushed river gravel to angular crushed quarried rock, and from cubic to flaky.

A complete range of particles could be expected to be represented within a basecourse although there could be an over-abundance or a deficiency of some of the smaller sizes. The distribution of particles can be most simply represented by the slope of the grading curve when plotted to a log-log scale.

Uncrushed river gravel, deficient in fines, may be difficult to compact and may be potentially unstable. However, it could be readily compacted to a dense stable condition if sufficient fines were added to fill all the voids. Crushed rock has similar properties although the angularity of the particles may ensure that even an open graded aggregate would be comparatively stable.

Changes to the grading may occur during the process of compaction of the aggregate and at any later stage. Such degradation is primarily a function of the grading prior to compaction, but may also be influenced by the hardness of the rock and the type of compaction equipment used. Open graded materials have a greater potential to degrade than the dense graded variety. Plastic fines may be generated during the process of degradation, and may reduce the stability of the aggregate.

The universal agreement is that stability is a function of density. The most dense layers suffer the least deformation under load and are the least likely to undergo shear failure. The process of compaction involves the rearrangement of particles until they reach a condition of maximum density in terms of the compactive energy applied. This process, which may also involve degradation, can be accelerated by adding excess water causing saturation of the material.

Further compaction can occur when the level of compactive effort is increased or the type of effort is changed, e.g. from a static to a vibrating roller.

The level of density is often referred to in terms of a standard laboratory test, e.g. 90% Standard Compaction. There is little justification for this approach and it is preferable to measure the compaction as a proportion of the solid density of the rock constituents, i.e. percentage total voids.

Considerable progress has been made in the last ten years in laboratory modelling of unbound granular pavements. The development of the large triaxial cell and the shear-box equipment has enabled researchers to gain a much clearer understanding of the mechanisms involved in the transfer of load and the factors which control stability.

The development of the shakedown theory is, in the authors' view, possibly the most exciting development in the field of unbound granular pavements as it provides a more realistic model of pavement performance than the fatigue theory. This theory and the concurrent development of the shear-box may provide, in the near future, the basis of a rational method of pavement design and construction control.

4. AGGREGATES FOR ROAD PAVEMENTS

This section is to assist those workers engaged in the design, construction and maintenance of unbound granular pavements. It is not relevant to those dealing with the heavily stabilised pavements, e.g. thick asphaltic concrete or lean mix concrete, used on some of the main highway systems of the major industrialised countries of the world.

However, it does apply to modified aggregates where a small quantity of chemical is added to correct or control a particular weakness in any aggregate, e.g. the addition of lime or cement to control plasticity.

4.1 Introduction

Most roads in New Zealand comprise layers of compacted aggregate, constructed on a natural soil subgrade and sealed with a one or two coat chipseal or a thin asphaltic layer.

The various elements which make up the environment in which a pavement exists are important to recognise. These include:

- The foundation soil - type, strength, compressibility
- Drainage patterns - position of the water table relative to subgrade
- Topography - effect on surface drainage
- Rainfall - frequency, duration, quantity that could enter pavement
- Temperature - effect on the stability of the seal coat, moisture movement and weathering
- Land use - effect on moisture movement
- Adjacent vegetation - effect on moisture movement
- Traffic - loading, size and frequency
- Surface seal - effect on underlying layers

The pavement could be quite stable under one set of environmental conditions but any change, e.g. inundation during a flood, could have a disastrous effect.

The important factors concerning the aggregate layers are:

- Water - amount of rainfall, condition of surface seal, drainage
- Load - size and number of repetitions, tyre pressure
- Foundation - characteristics of underlying layers
- Confinement - support from adjacent ground

4.2 Function of Structural Layers in a Pavement

In New Zealand roading terminology, a pavement comprises:

- Surface seal
- Basecourse
- Sub-base
- Subgrade

Basecourse, sub-base and subgrade are described as the "structural" layers because a load applied to the surface is distributed through the layers of aggregate to the foundation soil.

The process of load transfer is by inter-particle contact, either by point contact or by inter-granular friction, and is accompanied by elastic (i.e. recoverable) or plastic (non-recoverable) deformation of the layers.

The pavement is designed to spread the load so that the stress on each layer and on the foundation is at a level which can be sustained without significant distortion. "Distortion" includes elastic strain (as measured by the Benkelman Beam) and plastic strain such as that associated with the formation of ruts or heaves.

The aggregate used in a pavement layer must be compatible with the layers above and below it. This primarily concerns the grading of aggregate in the layers. For instance, migration of particles could occur from a dense graded aggregate layer to an open graded layer below.

The performance of a pavement layer depends to a significant degree on the characteristics of the materials in the subgrade. For example, excessive deformation of a subgrade soil will result in relatively large inter-particle movements in the overlying aggregate courses.

Such movement will result in shearing of even good quality aggregate, will tend to smooth the areas of contact of the aggregate particles, and will produce fines which could move into the voids and reduce the permeability. The fines could also be plastic.

Conversely, on a strong unyielding subgrade, an aggregate of relatively poor quality can perform quite satisfactorily.

The thickness and stiffness of the seal coat determines the stress carried by the aggregate. If, for example, the effective angle of the load spread through the seal is 45°, the stress will decrease with the square of the thickness. The reduction in stress that can occur through a thick asphaltic concrete layer will therefore be large, while a one coat chipseal will have negligible effect on the level of stress in the basecourse layer.

4.3 Characteristics of Aggregates

4.3.1 Definition

An aggregate used for roading is defined as "an assemblage of particles of soil and/or rock (natural or processed) which possess, when massed in layers within the pavement, stability and load-spreading ability".

It is common, however, to use the term "aggregate" to mean the loose material (as stockpiled in the quarry) as well as that compacted in a layer.

Aggregates can be made from crushed rock, naturally occurring river gravels, blast furnace slag or other manufactured material. They may comprise very fine material, e.g. sand, or very large material, e.g. "run of pit gravel".

4.3.2 Grading

The "particle-size distribution", or more commonly the "grading", is the proportion by weight of the different particle sizes in an aggregate. It is usually measured in a laboratory by sieving a representative sample of the material. The weight of the particles passing a particular sieve is expressed as a percentage of the total weight of the sample; when plotted on a graph it forms a "grading curve".

Materials can be "uniformly graded", "gap graded" or "continuously graded".
Uniformly graded materials contain particles predominantly of one size, e.g. dune sand. The grading curve will be a vertical or nearly vertical line.
Gap graded materials do not contain all sizes so that the grading curve has one or more nearly horizontal sections. Gap gradings are used in the manufacture of concrete and sometimes in asphaltic concrete.
Continuously graded aggregates have particles in all size ranges (below the maximum size) and the gradation change generally follows a continuous, regular pattern.
Dense graded (well graded) aggregates contain particles in all size ranges (below the maximum size), so that all particles pack tightly together after compaction to give few voids. Ideally the grading curve is a straight line on log-log paper.
Open graded aggregates contain a range of particles (below the maximum size), but are deficient in fines so that after compaction have many voids.

Traditionally, particle-size analyses are plotted on semi-log paper, with the particle-size range to a logarithmic scale (Figure 1). A more meaningful practice is to plot both axes to a log scale (Figure 2). The grading curve for a well graded aggregate will then plot as a straight line. The slope of that line equals the integer "n" in $P = 100(d/D)^n$, where P is the percentage finer than particle size, d is the particle size, and D is the maximum particle size.

The value of "n" and the maximum size of particles (usually 40 mm for basecourse) can be used to describe the aggregate.
Open graded aggregates are those with an "n" value much greater than 0.6.
Dense graded aggregates are those with a value of "n" less than 0.45.
The **maximum density** of spherical aggregates occurs, theoretically, when n = 0.5.

Figure 1. Common form for plotting the results of particle-size analysis (semi-log plot).

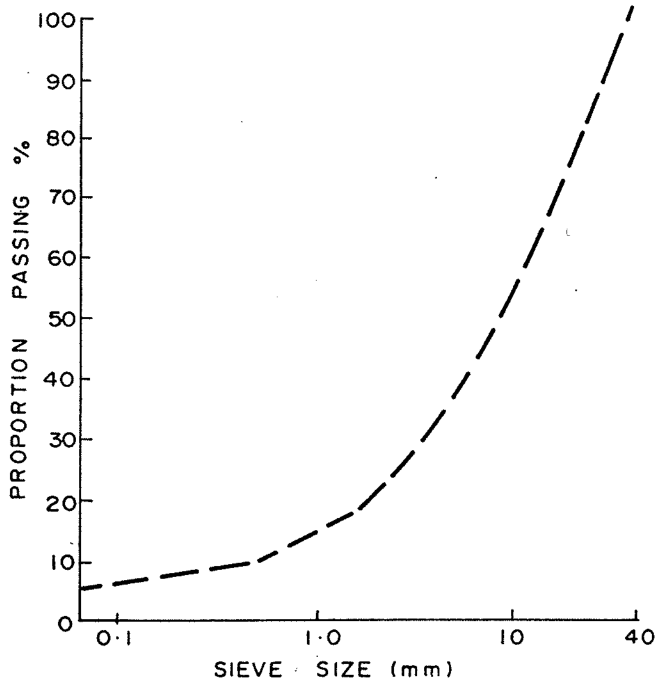
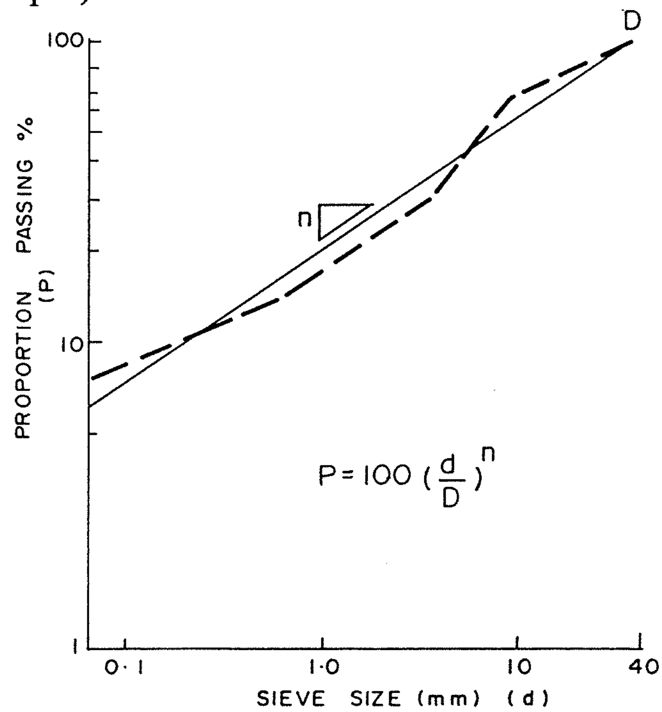


Figure 2. Preferable form for plotting the results of particle-size analysis (log-log plot).



A compacted layer of an open graded aggregate (Figure 3a) has large particles in close contact with a small quantity of fine material in the voids.

A similar compacted layer of dense graded material (Figure 3b) will have the large particles in close contact, with all voids filled with smaller sized material. For any aggregate, the optimum value of "n" for maximum density depends on the particle shape and texture.

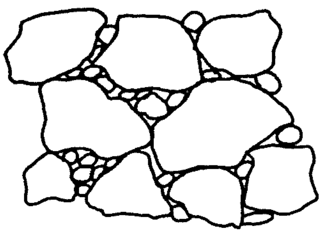


Figure 3a. Open graded aggregate (n>0.6).

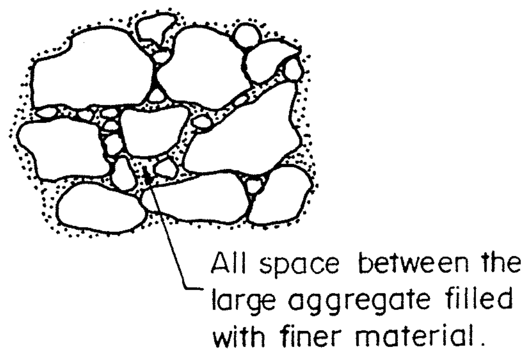


Figure 3b. Dense graded aggregate (n<0.45).

The movement of water within a layer of aggregate will be controlled by the porosity of the layer (i.e. the ratio of the total void space to the total volume) and the porosity of underlying layers. The main factors controlling porosity are the grading, particularly of the very fine fraction (passing a 75 micron sieve), and the closeness of packing after compaction.

A load applied to a layer is transmitted through the aggregate by point to point contact and inter-particle friction (Figure 4). An individual particle is subjected to forces tending to crush or shear it.

The shear strength is a function of the level of support provided by adjacent particles. The more support provided to each particle, the higher the shear strength and the less particle breakdown.

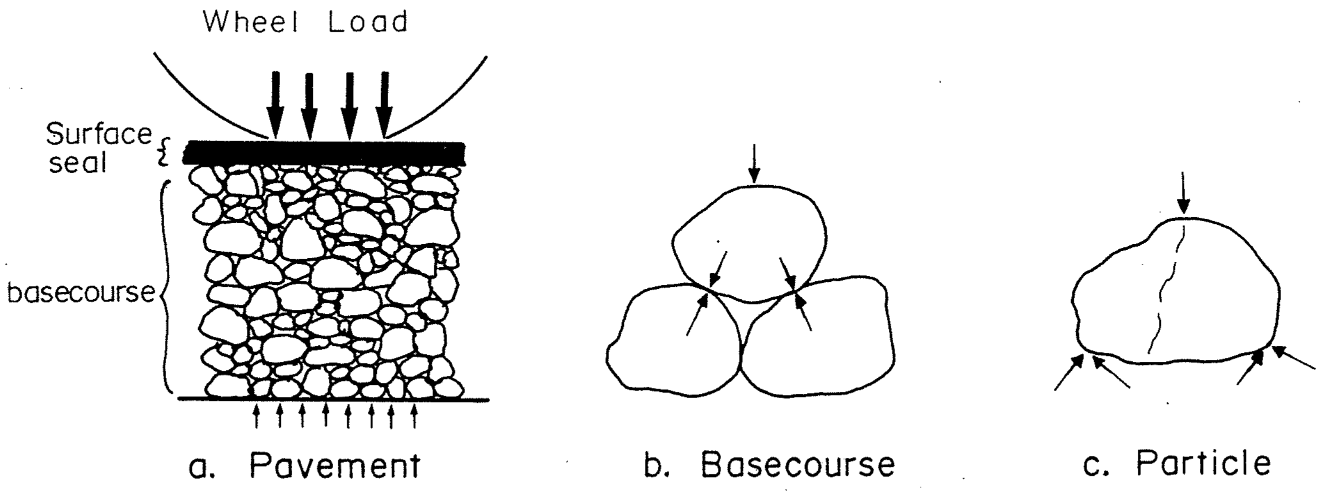


Figure 4. Transfer of load between the particles of a layer of aggregate.

Hence, dense aggregates are less prone to degradation while open graded aggregates degrade to a degree dependent upon the strength of the constituent material. Hard rocks tend to be deficient in fines and may tend to degrade and densify with time. Weaker rocks crush more readily to produce dense gradings and may form layers with relatively high levels of stability.

4.3.3 Density

The density of an aggregate is determined to some extent by the shape of the particles. Natural river gravels have rounded shapes. Rounded material tends to be more workable and should compact readily to a dense arrangement provided it has a suitable grading. If it is deficient in fines, it will be difficult to compact.

Crushed river gravel contains a mixture of angular and rounded particles.

Crushed quarried rock is angular and more difficult to work, but may compact to a stable arrangement relatively easily. Hard rocks, e.g. greywackes, tend to produce aggregates that are deficient in fines and the compaction process may involve the breakdown of particles to form a dense, stable grading.

4.3.4 Plasticity

The fine material in a basecourse (i.e. less than 425 microns) will either be non-plastic or have a level of plasticity that is determined by the mineral constituents of the parent rock.

Plastic fines often have the potential to absorb and hold water because of their mineral composition and size. Moist plastic fines will provide lubrication to the faces of the larger particles, thereby reducing inter-particle friction and the strength of the aggregate mass.

However, if the moisture is removed, the lubricating effect may be completely eliminated and thus the shear strength of an aggregate layer can be substantially increased. The lubricating effect of the fines is transformed into increasingly strong cohesion as drying out occurs.

Research has shown that an aggregate is stable when the proportion of material passing the 425 micron sieve is less than 10% or when the moisture content of that material is below the Plastic Limit.

4.3.5 Stability

Roading materials are required to retain their stability throughout the life of the pavement. The particles of aggregate must neither disintegrate or suffer significant wear under load, nor should they be adversely affected by temperature or moisture changes. Aggregates which contain highly plastic minerals may lose their stability under adverse moisture and load conditions.

Aggregates should therefore be evaluated according to the likely products of weathering. Those which could release highly plastic minerals may be used in the low stress situation, e.g. as sub-base.

Alternatively, if special measures are taken to keep the water content at a low level, to limit the quantity of plastic fines, or to neutralise plasticity by treatment with lime the material should be satisfactory as a basecourse.

4.3.6 Clay Index Test

The "Clay Index Test", developed by Sameshima and Black (1979), can be used to rate the potential performance of an aggregate in terms of the quantity of swelling clays (montmorillonites, chlorites and various interlayered clays) present in the fines.

The index scale is from a value of 1 which correlates with a "sound" aggregate, to 5 or greater which indicates "unsound" aggregate. Examples of the clay index of some New Zealand aggregates from the Auckland area are:

Aggregate	Clay Index	Plasticity Index
Mt Wellington basalt	1	0
Drury greywacke	3-5	5-20
Hallewell's greywacke	9	12
Maramarua greywacke	3-7	8-24
Whangarei greywacke	4	14
Waitakere andesite	5-11	6-17
Wainui conglomerate	4	-

Note: The Clay Index and the Plasticity Index listed were measured on material passing the 75 micron sieve. The standard Atterburg Limit test, used to determine Plasticity Index in aggregate specifications, prescribes the use of material passing the 425 micron sieve. Therefore, the Plasticity Index values listed cannot be compared with results obtained using this standard test.

4.4 Factors Influencing Performance of Basecourse

4.4.1 Introduction

A well constructed unbound granular pavement will have the following characteristics at the completion of compaction:

- Uniform compaction to the highest level of density attainable with the type of compaction equipment used
- Relatively smooth surface
- Water content close to saturation

The process of compaction involves the re-arrangement and possibly the breakdown of aggregate particles until no further reduction in volume can be achieved. When the pavement is opened to traffic, repeated stressing of the basecourse layers, particularly by heavy trucks, will inevitably cause some reduction in volume. This may show as depressions in the wheel tracks, commonly called "ruts".

The changes that occur during compaction and of subsequent trafficking can be explained by the theory of "Shakedown". This theory predicts that particles within a mass subjected to cycles of uniform stress will be re-arranged, i.e. they will suffer plastic strain, until a dense stable condition is established. This condition will be maintained indefinitely, i.e. the mass will respond elastically, provided that the level of stress is not increased and the properties of the mass of particles are not changed. This level of stress is termed the "shakedown limit".

Shakedown theory, which has only recently been applied to layered systems, is significant for a number of reasons: it provides a rational method of pavement design; it can be used to explain all known modes of pavement deformation; and it explains why a pavement which has been stable for many years may suddenly develop areas of failure.

4.4.2 Load
An increase in the magnitude of the wheel load applied to the pavement beyond the shakedown limit will cause an increase in the plastic strain, i.e. an increase in the depth of the ruts. Hence the passage of one heavily overloaded truck could cause major deformation of a previously sound pavement.

4.4.3 Water Content
An increase in the water content in any of the pavement layers (including the subgrade), could cause a reduction in the shakedown limit stress and result in an increase in the deformation of the pavement. Conversely, a decrease in the water content could result in an increase in the limit stress. The pavement could then carry larger wheel loads without permanent deformation.

4.4.4 Confinement
The shear strength of a pavement layer depends on the development of adequate restraint against horizontal movement. This is usually provided by a shoulder or kerb line of a road. Shear failure will occur in the granular layers or the subgrade if the restraint is not adequate.

4.4.5 Aggregate Properties
The properties of some aggregates could change during the life of the pavement. Seasonal cycles of wetting and drying accompanied by cycles of stress could cause degradation of particles and the release of deleterious minerals, e.g. swelling clays. Such changes may be accompanied by a decrease in the limit stress and give rise to increased deformation of the pavement.

A wide range of physical tests are available which provide a measure of the potential weathering of an aggregate, e.g. weathering quality index (SANZ 1991b), 10% fines test, etc. While many of these tests may go some way towards representing conditions in a stockpile, they subject the aggregate to more severe levels of stress than it would experience in the pavement. However, the results can be used to rank aggregates in terms of weathering potential.

4.4.6 Subgrade Properties
The subgrade soil also has a shakedown limit. A soil which is free to drain will densify under the applied cycles of uniform stress until a stable condition is established. Any subsequent increase in the levels of stress or water content could result in increased plastic deformation of the subgrade and hence in the pavement as a whole.

4.4.7 Surface Seal
The seal on the surface of a pavement prevents removal of the granular material by traffic and also resists movement of water either into or out of the pavement. Preservation of the surface is absolutely essential to continued sound performance of the whole pavement.

4.5 Selection of Pavement Aggregates

4.5.1 Introduction

The selection of an aggregate has been a difficult task mainly because the properties used in design, e.g. modulus, shear strength, etc., could not be readily measured. It was also difficult to relate the measurable properties, e.g. particle-size distribution, plasticity, etc., to criteria assumed in pavement design.

The Aggregate Selection Chart was introduced by Bartley in 1980 to provide a guide to the selection of an aggregate for a particular purpose. The chart, based on the measured properties and estimated performance of a range of aggregates used in New Zealand, has been modified by a number of authors since it was originally published. It has been revised further for this report (Figure 5).

The original chart indicated a possible service life in terms of Equivalent Design Axles (EDA). However, the shakedown theory predicts that an aggregate will achieve a stable elastic condition in terms of a design wheel load after which it will suffer little further permanent deformation. The fatigue concept, incorporated in the earlier editions of the selection charts, is therefore inappropriate and has been abandoned.

It is expected that in the future it will be possible to establish the shakedown limit stress and shear modulus values for a large number of the roading aggregates used in New Zealand. This information could then be used, in conjunction with existing design programmes, to design pavements and to select aggregates. It will also be possible to define more precisely the requirements for the manufacture of aggregates and construction of pavements.

Documents relating to aggregate supply and construction may use a range of engineering or trade terms to describe unbound granular aggregate. Many of the terms are used as a matter of convenience rather than to imply a particular function. Subgrade improvement drainage course, transition aggregate and sub-base are terms frequently used to describe the layer between the subgrade and the basecourse. It is also true that a pavement layer may often perform a different function to that envisaged by the designer.

4.5.2 Sub-base Aggregate

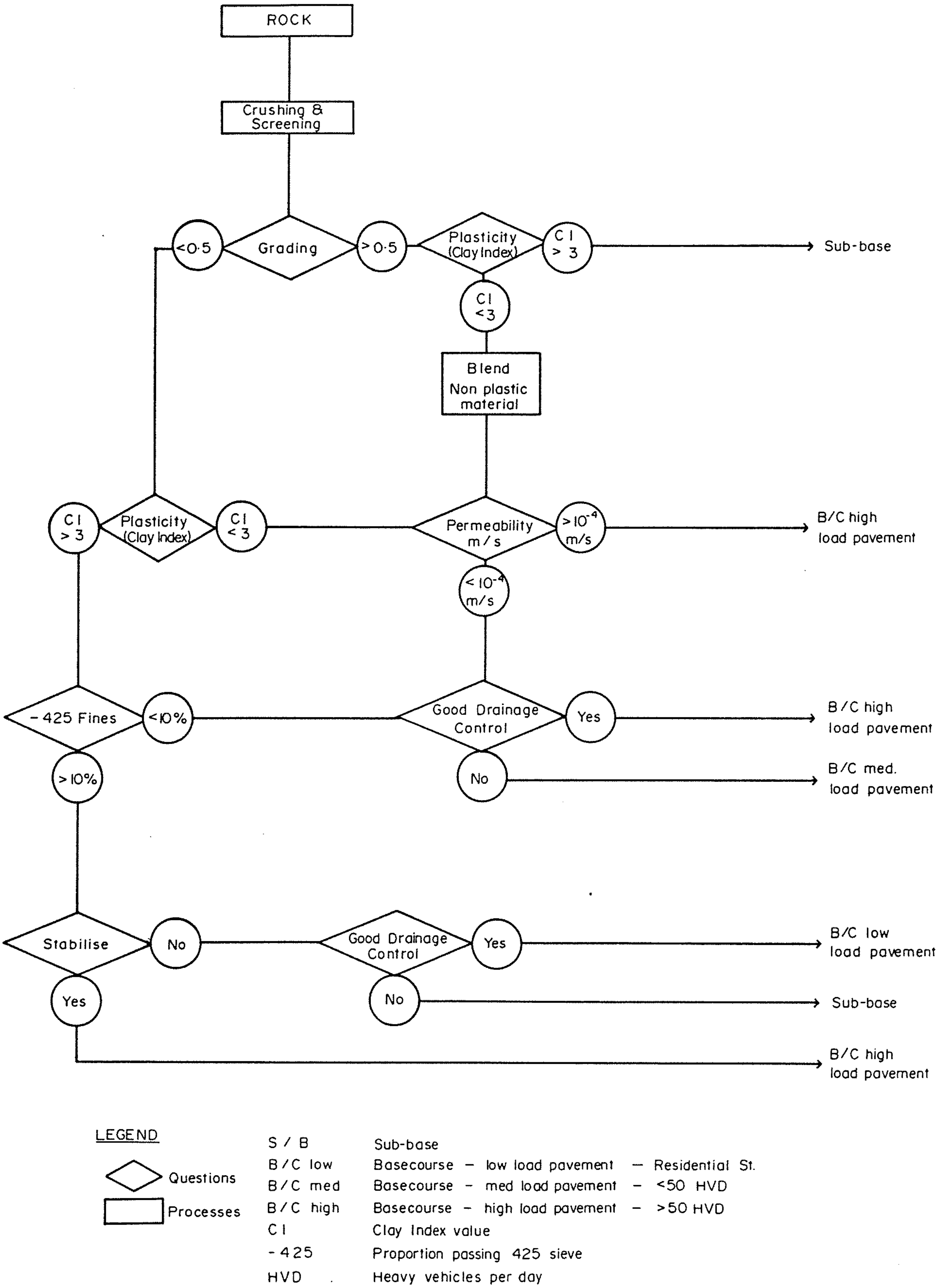
A sub-base layer is often required to perform three functions: to carry construction traffic; to distribute the load from the basecourse layer on to the subgrade; and to provide drainage.

The granular sub-base material should therefore have:

- Adequate stability under high axle loads,
- Sufficient stiffness to distribute the load within the pavement,
- Relatively high permeability.

However, the last property may be incompatible with the first two. For example, an aggregate with a high permeability will have an open grading and a relatively low shakedown stress level. As it will tend to densify under heavy wheel loads the use of such a drainage layer by construction traffic should be avoided.

Figure 5. Aggregate selection chart.



Materials required to have high permeability may be manufactured from hard durable crushed rock to a relatively open grading, i.e. n > 0.6. During the process of compaction some degradation may occur but it will be relatively minor provided the rock is strong. Crushed greywacke gravel with 70-80% broken faces should be suitable.

Soft rocks, particularly partially weathered material, are not suitable because they will degrade during compaction.

The compatibility of a drainage layer with a subgrade soil can be evaluated in terms of filter criteria found in most geotechnical texts. Alternatively, a filter fabric (geotextile) can be used where the cost of locating compatible material is high.

4.5.3 Low Load Pavement

The magnitude of the load should be evaluated in relation to the number of heavy vehicles which could be expected to use the pavement within its economic life. Most residential streets carry few heavily loaded vehicles.

For instance the greatest loading a new residential street receives occurs in its early years when trucks deliver building materials to new house sites. Thereafter the only significant load would be an occasional moving van and the rubbish truck once a week.

Such pavements could be built from relatively low quality material not only because the number of heavily loaded vehicles will be small but also because local authorities require good subgrade/drainage to be provided. Some pavement deformation may occur but it will be relatively minor since the number of heavy vehicles will be small.

4.5.4 Medium Load Pavement

The medium load classification is slightly more difficult to define. However, it is suggested that a maximum number of 50 heavy vehicles per day (HVD) should be catered for. The aggregate defined by the criteria given in the Aggregate Selection Chart (Figure 5), should provide a more than adequate pavement for roads that carry less than 50 HVD.

4.5.5 High Load Pavement

The high load classification applies to all pavements which carry in excess of 50 HVD.

4.5.6 Control of Water

Control of water is absolutely essential in the construction and operation of a road pavement. Enough water to saturate the aggregate is required for the efficient compaction of the sub-base and basecourse layers. However, once compaction of the basecourse has been completed it is necessary to remove as much water from the pavement as possible before the seal coat is applied.

Drainage of the aggregate layers by gravity and natural drying of the surface by the sun and wind is the only practical method of lowering the water content. Significant pore water suction pressures which effectively increase the shear strength of the aggregate can be established by this means.

4.6 Aggregate Production

4.6.1 General

New Zealand is well endowed with a wide variety of materials from which aggregate are manufactured (river gravels, glacial moraine deposits, volcanic ejecta and hard igneous and sedimentary rocks). It appears that there is an infinite source of raw material for aggregate production. However, rock reserves have a finite life because of requirements imposed by land ownership, environmental considerations and physical restrictions on the size and quality of the deposit.

The quarry industry, classified as a heavy industry, has a high level of capital investment and high running costs. Over recent years, public resistance has been growing against the mining and treatment of minerals by open-pit methods. Under the recently approved Resources Management Act (1991), the establishment of a new quarrying site involves a complete review of the potential impact on the environment. Many operating quarries are now located in metropolitan areas without buffer zones to separate them from residential areas. They face restrictions governing the period of operation, blasting, dust emission and stream pollution.

Aggregate for road base construction is a relatively low cost, high bulk commodity. However, it becomes a high value material because of the cost of transport to, and compaction at, the construction site. It is, therefore, desirable to position quarries as close as possible to the major demand centres so that transport costs can be minimised. This implies that production sites will be located close to metropolitan and industrial centres - a concept that is not readily accepted by the local population.

The cost of producing an aggregate not only involves the crushing and screening of rock but also the provision and maintenance of access, the removal of overburden and the construction of anti-pollution measures to protect streams and the atmosphere.

The final cost for the owner is the requirement to landscape and reinstate the quarry site on the cessation of activities.

4.6.2 Quality of Aggregate Resource

The establishment of a viable quarry operation has to be based on four principal criteria:

- The size of the rock or gravel resource must be adequate for the term of the investment,
- The quality of the rock must be appropriate in terms of the range of product to be manufactured,
- A market of adequate size must exist within an economic distance,
- The cost of production must be within the market range.

In New Zealand, a large part of the output will be used in ready mixed concrete, concrete products and drainage work as well as in road building. Roading aggregate may be used in bound pavement construction in addition to that used in an unbound state.

A quarry operation close to a metropolitan area may be expected to provide a much wider range of products than a quarry located in a rural locality where 90% of the output may be associated with road construction.

4.6.2.1 Locating resources

Geological exploration and sampling of the deposit for petrographic analysis, mechanical and chemical testing, by subsurface drilling and/or test pits are essential when new quarries are established or old ones extended. The range of quality of all parts of the deposit must be known so that the economic development of the site can be planned. Aspects that will be investigated will normally include:

- Petrographic analysis - extent of weathering or secondary mineralisation,
- Hardness - influence on fracture and shape of particles,
- Abrasion - influence on equipment wear,
- Soundness - durability of product,
- Secondary minerals - influence on plasticity,
- Alkali content - influence in concrete manufacture,
- Sulphide content - influence on environment.

In the preliminary stage of establishing a quarry, the basic aspects of the quarry operation are considered. These include the orientation of the strata, the degree of weathering, alteration and fracture of joint systems. Benching development, road, plant layout and stockpile areas need planning to cope with the range and quantity of product being produced.

The design of the plant will be largely dependent on the range of aggregate to be produced. For road aggregate manufacture, a simple two-stage (Figure 6) or a more complicated three-stage crusher system (Figure 7) are common. These include the provision for recirculation of the crushed oversize material. More sophisticated plant is required for graded aggregate production which may involve blending of sizes for concrete or asphaltic paving mixtures.

4.6.2.2 Cleaning

Removal of material likely to contaminate the crushed aggregate, such as overburden or clay from joints, is normally carried out by "grizzly" bars before, or coarse screens after, breakdown crushing.

The dirt-free rock is then processed through at least two crushers with vibratory screens and recirculation belts to produce a product which is generally referred to as "crusher run" basecourse.

It is unusual for sized aggregates to be recombined or for aggregates from two or more crusher systems to be recombined into basecourse.

Historically, aggregate for unsealed roads required a proportion of binder as well as crushed rock. It was produced from what is now regarded as a second grade rock at a low cost. The expectation by today's customers that the basecourse should still be a low cost material is apparent but the quality requirements have changed dramatically.

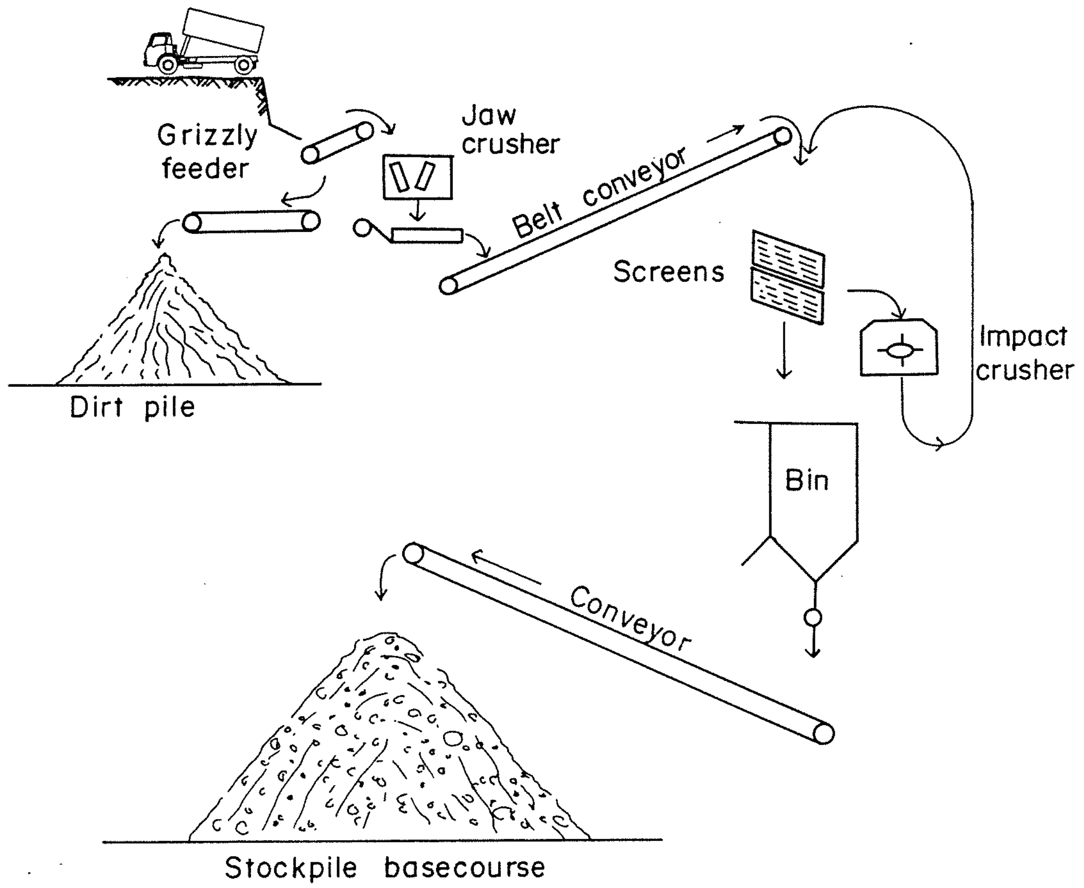


Figure 6. Simple two-stage crusher system for basecourse production.

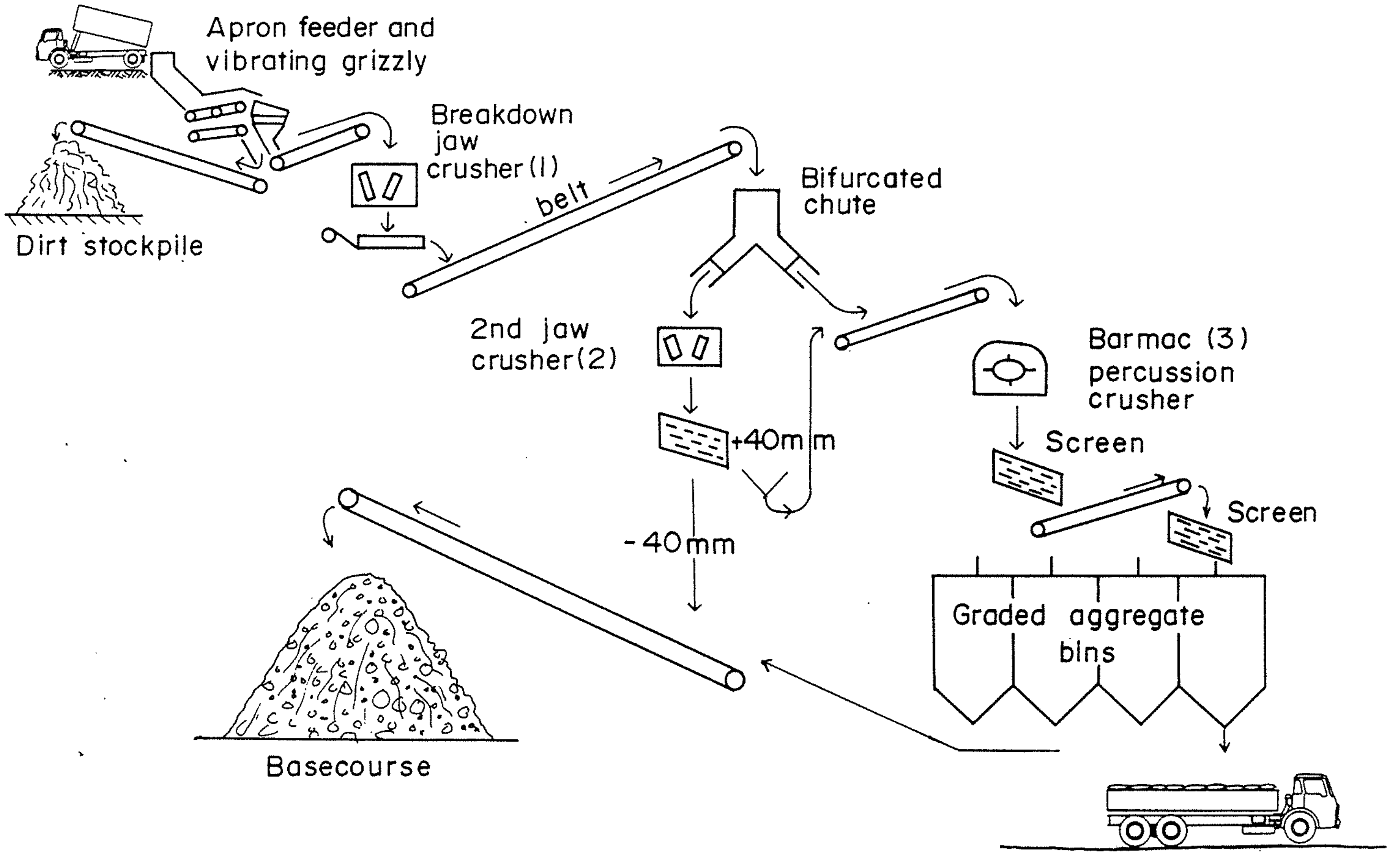


Figure 7. Three-stage crusher system with provision for mixing from graded bins.

4.6.2.3 Storage

Basecourse aggregate is used in large volumes, for example the construction of a suburban street may well require 150 m^3 of basecourse for every 100 m of roadway. Storage of large quantities are therefore required as a normal crushing plant could not meet the demand direct from crushing during the main summer construction season. Stockpiling aggregate becomes a fundamental necessity in a quarry for two important reasons:

- To assemble the required quantity of aggregate for a particular project, and
- To even out production variability.

4.6.2.4 Stockpile construction

The method of constructing stockpiles (Figure 8), whether at the quarry or close to the construction site, demands planning and control. Haphazard dumping of aggregate leads to massive segregation of material which can only be corrected by complete remixing procedures. These add significantly to the cost of the material.

Stockpiles should be constructed by reversed layering (Figure 8a) and then kept in a damp condition. The equipment used to load trucks should have enough reach to cut a swathe through the stockpile from base to top without causing the face to collapse (Figure 8b). The use of large dump trucks (Figure 8c) or of end dumping (Figure 8d) create segregation of material which cannot be overcome unless the stockpile is completely remixed.

4.6.2.5 Specifications

It is the responsibility of quarry management to ensure that the resource, whether gravel from a pit or rock from a quarry, is capable of being mined, processed and stored so that the product will meet the required specifications. Improved techniques in road building and in the construction of concrete structures has placed greater demands for higher strength, better shape, greater cleanness and an overall tighter manufacturing control of aggregate production.

The quarrying and crushing processes culminate when a saleable aggregate is produced. Management, through the processes of quality control, should then be able to give an assurance that the product meets the specified requirements.

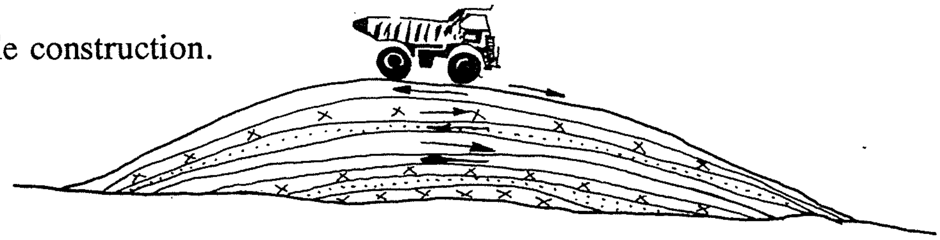
4.6.3 Process Control

4.6.3.1 Selection

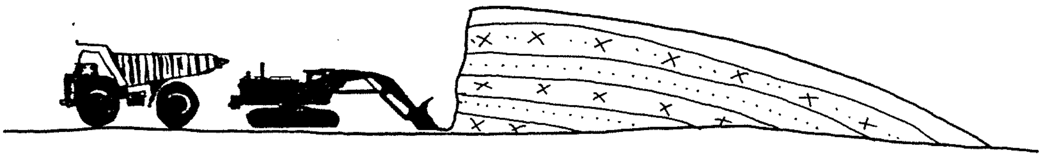
Control of the aggregate production process is the art of quarry management and is largely a combination of experience and technical knowledge. Skill is required in selecting rock to be quarried, operating the crushing and screening plant, and in storing and dispatching the product. Physical tests, such as particle-size analysis, are required to confirm that the product meets specified requirements but otherwise they play a minor role in process control.

The quality of the aggregate produced depends on control at the quarry face where significant variations in layering, jointing, and weathering may occur. The inadvertent inclusion of overburden, weathered rock or joint fillings within the processed material will have a detrimental effect on quality of the product.

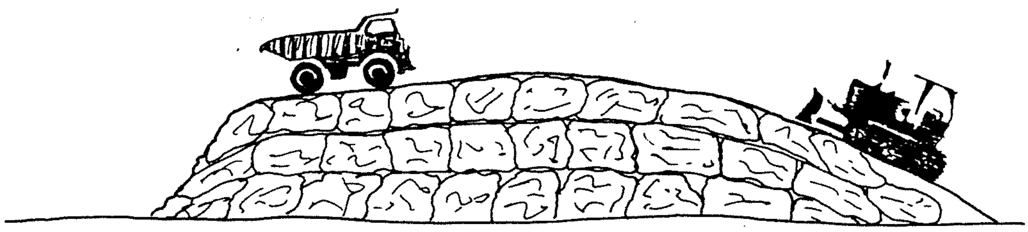
Figure 8. Stockpile construction.



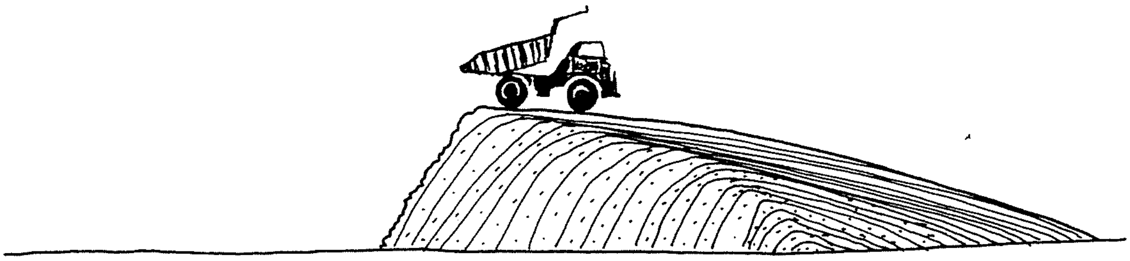
a. Stockpile layered from alternate directions



b. Loading from layered stockpile



c. Stockpile semi-layered by large dumpers
(not recommended)



d. Stockpile built by end tipping
(not recommended)

4.6.3.2 Production

Primary stages of production involve blasting and removal of material from the quarry face, scalping, and primary crushing to obtain a manageable product for secondary treatment. Competent visual inspection of the face is required so that the most suitable material can be selected for processing.

Particle shape is determined largely in the final stages of crushing and may be dependent on the type of crusher, the reduction ratio, the rate of feed and load on the crusher. It is difficult to change the shape without changing the reduction ratio of the crusher and thereby reducing the production rate of the plant.

4.6.3.3 Control of particle-size distribution

Control of particle-size distribution is a normal requirement for most aggregate specifications. Separation of particles by screening at the plant depends on the smallest particles working their way to the bottom of the bed of material and through the screen. Particles smaller in size than the screen aperture drop through while the coarser material moves along the screen. The rate of aggregate flow and the amplitude of vibration of the screen control the efficiency of screening.

Crusher run (all-in) material has a wide and inconsistent variation in sizes. A screened aggregate will have a relatively consistent grading provided the feed to the crusher is uniform in quality and the difference in the aperture size of each successive screen is relatively small.

Aggregate manufactured for Portland and asphaltic concrete are normally blended from graded aggregates, but it is not a generally accepted practice to employ blending techniques in the production of basecourse. However, as basecourse is the major structural component of most New Zealand pavements, blending techniques may be essential to provide an aggregate which will satisfy pavement design criteria. The need for blending graded aggregates increases as the crushing resistance value of the rock increases.

Deficiencies in particle-size distribution are more economically corrected in the quarry or pit using crushing equipment and blending techniques rather than with compacting equipment at the road construction site.

As the parameters used in pavement design for heavy traffic loads demand that basecourse in the completed pavement be a premium product, producing a premium quality basecourse, particularly from hard rock types, will require screening and blending. Obviously the cost will reflect the more complex processing.

The geological origins of the rock pre-determine many of the characteristics of an aggregate. For instance greywacke rocks in the Auckland area have greater strength and hardness than the local basalts. When processed using similar crusher systems, the particle shapes and the percentages of sand sizes produced from the two rock types will be quite different. To manufacture greywacke basecourse aggregate to the same grading as basalt would require an additional crushing unit to produce sufficient sand to make up grading deficiencies.

The quarry manager can control the amount of contamination, and the shape and grading of the aggregate within the plant but he has little control over other physical properties such as crushing resistance, skid resistance, water absorption and specific gravity.

4.6.3.4 Sampling and testing

Most of the larger quarries regularly sample and test the product for grading and cleanness. Test records should cross reference important aspects of production, e.g. changes of rock type in vertical and horizontal directions in the quarry, weather conditions, crusher settings, feed ratios, etc. A record of the significant features of the quarry operation, efficiency of screening and crushing, and methods of storage leads to consistency in the product - a vital factor in quality pavement construction.

4.6.4 Quality Control

4.6.4.1 Introduction

The customer has the right to know that the aggregate supplied meets the standard and quality specified. A producer who relies on the customer to ensure that the material complies with the specification is at risk when disputes arise concerning the quality and performance of the materials supplied.

4.6.4.2 Sampling

Samples of aggregate can be taken at a variety of stages during the production, from storage bins, conveyor belts and from the stockpile. Opportunity also exists for samples to be taken from delivery trucks, construction site stockpiles, and from the road bed before or after compaction.

Generally the producer is only interested in sampling before the product leaves the quarry gate. The customer on the other hand may wish to obtain samples from the construction site.

Where blending is required, sampling from conveyor belts and bins may be necessary. Access to sampling points whether in the plant or in the field is very important. Basecourse bulk samples are large and difficult to handle and samples are most easily obtained using quarry loaders from well mixed or layered stockpiles. It is also essential to maintain the stockpile in a moist condition so that particle segregation is kept to a minimum prior to sampling.

The point at which a sample is obtained for acceptance testing is of considerable importance. Sampling is best carried out from mini-stockpiles formed by dumping a randomly selected bucket load of aggregate on to a clean surface while trucks are being loaded. Sampling from trucks presents safety problems, and representative sampling of aggregate with particle size greater than 25 mm presents considerable difficulties in ensuring that the sample is representative. The use of sampling mats on the road surface over which a truck trails basecourse can provide a satisfactory "sub lot" provided the truck speed is controlled. Care is necessary to ensure an even flow of basecourse through the tail gate.

4.6.4.3 Acceptance Testing

Acceptance testing of roading aggregate has, historically and almost universally, been the responsibility of government or state roading authorities. Many quarries have relied on these organisations to provide testing services to assist production management. Quality assurance (QA) is however the responsibility of the producer.

Quarries which have established testing laboratories and can demonstrate the reliability of their QA programmes, should be "preferred" suppliers. Small on-site laboratories monitoring production on a day-to-day basis would provide management with information and test results in product control, quality control, process control and development.

The two most important parameters of road aggregate that should be measured are:

- Particle-size distribution or grading,
- Properties of the fines (less than 425 microns).

Other factors such as the crushing value and shape should remain relatively consistent and need only periodic checking.

Testing for grading and the quality of the fines can be time consuming, for example when following the New Zealand standard methods of tests using wet extraction. However, for day-to-day control, whether at the quarry or on the job, more rapid methods can provide valuable information on the product. Some of the more rapid techniques used in the United States allow for:

- Speed drying
- Gap sieving, using critical sieves only
- Coarse sieving
- Pyrometer method of fines removal
- Quick Sand Equivalent test
- On-line automatic sizing techniques

Testing work can be done more efficiently and economically by the producer (with limited verification testing by outside agencies) without losing product quality or production efficiency. However, the test method, irrespective of whether it is a national standard or an "in-house" method, relies solely on the authenticity of the sample. A test carried out on a sample which is not representative is of no value whatsoever.

4.6.4.4 Control Testing

Test procedures to be used for the control of aggregate quality are specified in national standards. Frequency of testing is generally the prerogative of the project specification writers and is not discussed in these notes. However, quarry management should establish an adequate test programme to allow for variability in the rock, methods of processing and volume of aggregate production. Tests for hardness and shape are normally undertaken at relatively infrequent intervals. To maintain consistency in production tests for grading and cleanliness or plasticity should be carried out frequently.

Some salient facts in relation to test results are:

- Grading variations in stockpiles do occur even though good control is exercised over stockpile building, sampling and testing
- Sampling errors are very real
- The reduction by quartering or splitting bulk samples can be a source of variation in itself
- Variations in results occur because of deficiencies in test methods

The above points indicate that testing for production control in quarries should be an ongoing commitment. The lack of reliability caused by occasional and haphazard testing must ultimately lead to conflict between the aggregate manufacturer and the customer.

4.7 Construction

4.7.1 Subgrade Preparation

The reaction of the subgrade has a major influence on the performance of the aggregate layers during and after construction. Before aggregate placement the subgrade should be consistent in both strength and shape. A firmer subgrade will mean that overall performance of pavement will be better and also that the aggregate layers will be easier to compact. However, in many parts of New Zealand, the subgrade-bearing values are low and it may well be necessary to provide a working platform on which to place and compact the basecourse layer.

In Britain, the working platform is referred to as a "capping layer" and is normally composed of a granular material and, although natural materials are acceptable, specifications often call for imported aggregate. In France, capping is treated as part of the earthworks and their specifications call only for a certain level of compaction. In New Zealand, allowances are often made for low bearing value in the subgrade by utilising one or more of the following procedures:

- Subgrade is dried and recompacted,
- Subgrade is stabilised with lime or sometimes cement,
- Subgrade is excavated and replaced with a higher quality material,
- Subgrade is replaced with a crushed rock sub-base,
- Filter fabric may be laid over a weak soil to prevent mixing of the subgrade and basecourse layers.

The capping layer must have properties that are compatible with the subgrade. A low strength subgrade can easily be distorted by heavy equipment such as stabilising units, rollers and earthmovers. The thickness of the capping, its use during construction and its influence on the long-term performance of the pavement as a whole needs to be carefully evaluated.

4.7.2 Handling

The aggregate suppliers use much skill, ingenuity, time and capital investment in the manufacture of a product to comply with a specification. Constructors need to know how to take advantage of these efforts to minimise their costs in the road building process.

For example they should be aware that a well produced basecourse aggregate will have a grading which is ideal for compaction and that, if segregation occurs, extra cost will be necessary to restore it to a satisfactory condition. Care must therefore be taken when handling aggregates from bins to stockpile and from stockpile to the road, to minimise changes in grading.

Rock quality, weather and inconsistencies in the crushing plant will give rise to variations in the end product. These can be minimised by stockpiling the aggregate rather than having it delivered directly to the road bed from the crushing plant. Stockpile foundations need to be prepared to ensure that contamination from the underlying soil does not occur.

Some rock may commence to weather when quarried and aggregate may undergo significant change and degradation when left in a stockpile for long periods. Aggregates should at all times be maintained at about the optimum water content to minimise segregation during transport and laying processes.

Loading delivery trucks at the stockpile is the job of an experienced person who must ensure that the material does not segregate. In the event of segregation within the stockpile, mixing and/or the application of water may be required before loading onto the truck.

4.7.3 Laying

Care is required when handling aggregate during the laying and compaction processes so that grading and uniformity are preserved.

The constructor has to place the aggregate in one layer of uniform thickness and consistency and then compact it to develop a uniform level of load-carrying capacity.

Spreading is generally carried out directly from a truck by trailing onto the road. A grader is then used to spread the layer of aggregate to a uniform thickness. Laying through a paving machine has been tried on some larger projects, but it has not been adopted as common practice.

Paver laying when used for the construction of research test strips was found to be a practical and efficient means of laying aggregate. The method caused minimal disturbance to the aggregate and produced an even surface after laying so that no further shaping was required. Some segregation occurred on either side of the paver but this material was removed.

Spreading direct from the truck is a relatively uncontrolled operation which undoubtedly results in segregation. Substantial improvement in laying practice is needed and the use of a paving machine offers a number of advantages which should be evaluated for individual projects. Paving machines may not be suitable for small projects or where geometrics and alignment present difficulties in machine operation.

On most highway projects, provided a continuous supply of aggregate is assured, laying by pavers specifically adapted for the purpose should save construction cost. The grading and water content of the basecourse must be rigidly controlled and there are marked benefits if the maximum size of the aggregate is lowered from 40 mm to 25 mm.

4.7.4 Water Content

Water is essential as an aid to compaction. The tendency of a dry aggregate to segregate can be reduced by adding water at the time of processing. Maintaining the stockpile in a wet condition will ensure that the aggregate arrives on the construction site in a moist, well graded condition, ideal for compaction.

Optimum water content is frequently defined by the laboratory compaction of soils to achieve satisfactory compaction of aggregates. It is the water content at which maximum density occurs. A typical result of a compaction test in the laboratory carried out on a well-graded aggregate of maximum particle size of 40 mm is illustrated in Figure 9.

Two peaks occur in the graph. The first occurs when the aggregate is dry and the second when the aggregate is in its optimum moisture condition. Some researchers have queried whether basecourse aggregates with a particle size greater than 20 mm exhibit a clearly defined optimum moisture content in the same way as fine grained soils but, generally, the consensus is that water is a lubricant and as such assists in the compaction process.

The relatively large proportion of fine material in a basecourse will ensure that the material does have some of the characteristics of a fine grained soil.

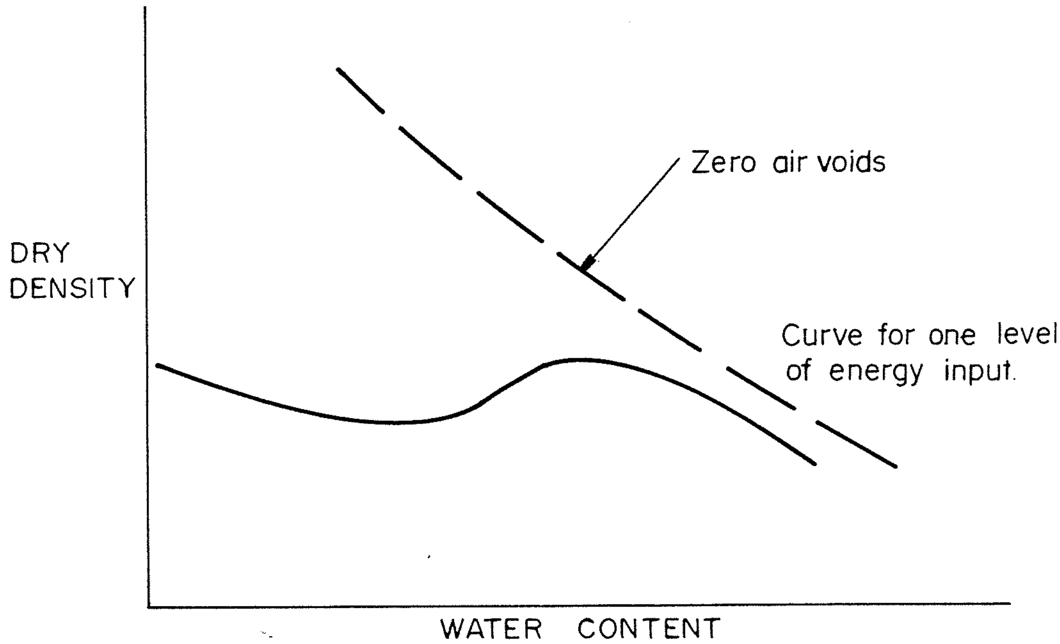


Figure 9. Typical compaction curve for basecourse.

4.7.5 Compaction Methods

Significant changes have occurred to the equipment used in compaction over the last 20 years. There has been a gradual shift from the heavy static steel drum rollers to a wide range of vibrating rollers with variable frequencies and amplitudes. Research involving field and laboratory measurements using different materials and a variety of compaction machines have enabled improvements in the methodology of road base construction.

4.7.5.1 Controlling compaction

Compaction has traditionally been controlled (and still is in many countries) using field density measurements which were then compared to maximum density measurements obtained in the laboratory. This method of control is satisfactory for fine grained soils but has little relevance to basecourse construction. Some disadvantages of the use of this concept include:

- Laboratory density is obtained in a mould using a pre-determined energy input (usually Standard or Modified Standard compaction test),
- Laboratory compaction does not consider what degree of compaction can be achieved in the field,
- The value of density measured in the field can show a wide variability but the coefficient of variability of the laboratory reference densities may not show a similar trend,
- The type of vibration test used in the laboratory does not model the type of vibrating rollers used in the field,
- Field density testing is often slow and the results may not be available soon enough to assist in construction control,
- Compaction of a basecourse is partly a function of subgrade strength over which the constructor has no control.

Some of these disadvantages can be overcome by the establishment of an on-site standard. There has been a tendency to construct test sections to establish criteria for field compaction control and the development of the concept of "plateau" density values.

Associated with this is the term "refusal" density which again is a debatable term in the field, and rather a meaningless term to the pavement designer. These terms are used to denote when no further increase in density can be attained.

A preferred method of density control uses the relationship between the maximum field density and the solid density. This is a more direct measure which also enables both porosity and percentage air voids to be calculated.

4.7.5.2 Compaction by rolling

Steel wheel rollers are usually adopted for the compaction of unbound aggregates because they provide a means to crush the aggregate, if required. Heavy static rollers are still favoured by some contractors, particularly if aggregates are hard (greywacke). Light vibratory rollers have been used to good effect by others and are particularly suitable for the softer, degradable aggregates (rhyolite rock types).

There is no reason why other types of compaction should not be used provided a sufficiently high level of energy and stress can be applied. However, the selection of construction equipment should be related to the strength of the subgrade. For example, heavy rollers are unsuitable when compacting granular materials on soft subgrades. Over-stressing the subgrade may lead to shape distortion by heaving and unevenness in the layer thickness.

It is important that the compactive effort is applied in a uniform manner over the full width of the pavement. In the initial stages, rolling should concentrate on the edges so that the centre material can be contained. Rolling should then move systematically across the layer with each backward and forward pass overlapping the previous one. Care is necessary to preserve the crossfall and shape of the pavement.

The number of passes of a roller may range from 10 to 40 before a "state of refusal" is reached. The number of passes is dependent on the aggregate strength and grading and the type of roller used. Figure 10 shows the results of a rolling experiment on a very hard crushed greywacke and a medium strength basalt aggregate. Refusal or plateau density was achieved for both aggregates but the percentage voids show remarkable differences. A much greater level of energy and stress would be required to reduce the voids within the greywacke aggregate.

The rolling process should be closely supervised to ensure that the roller gives adequate coverage of the whole pavement. The number of passes must also be adequate for the material and conditions existing on site. Normally rolling is continued until the density reaches a maximum value no less than 80% of the solid density, i.e. less than 20% air voids. (Note: the "solid density" is based on the "apparent specific gravity".) The efficiency of the compaction process and the level of compaction reached will depend on the aggregate water content, compactive effort, the type of rock and the grading of the aggregate.

4.7.5.3 Monitoring compaction

The level of compaction should be monitored as rolling continues. The **sand** or **seed replacement** or the **balloon densimeter** tests have been used in the past. These involve digging a hole in the aggregate layer, measuring the mass and volume of the material removed, and drying a sample to get the water content and hence the dry density of the aggregate. It is a tedious and expensive process.

The alternative is a **nuclear densimeter** which, when used in the back scatter mode, can measure the density and the water content by simply setting the source segment of the equipment on the surface of the layer being monitored. This is a relatively quick and reliable method of direct measurement of density. However, it may have to be calibrated in terms of the aggregate to get an accurate measure.

The **Clegg Hammer** is another device that can be used to indicate the end point in the compaction process. The apparatus is transportable, easy to use and provides information rapidly without needing to remove samples from the pavement.

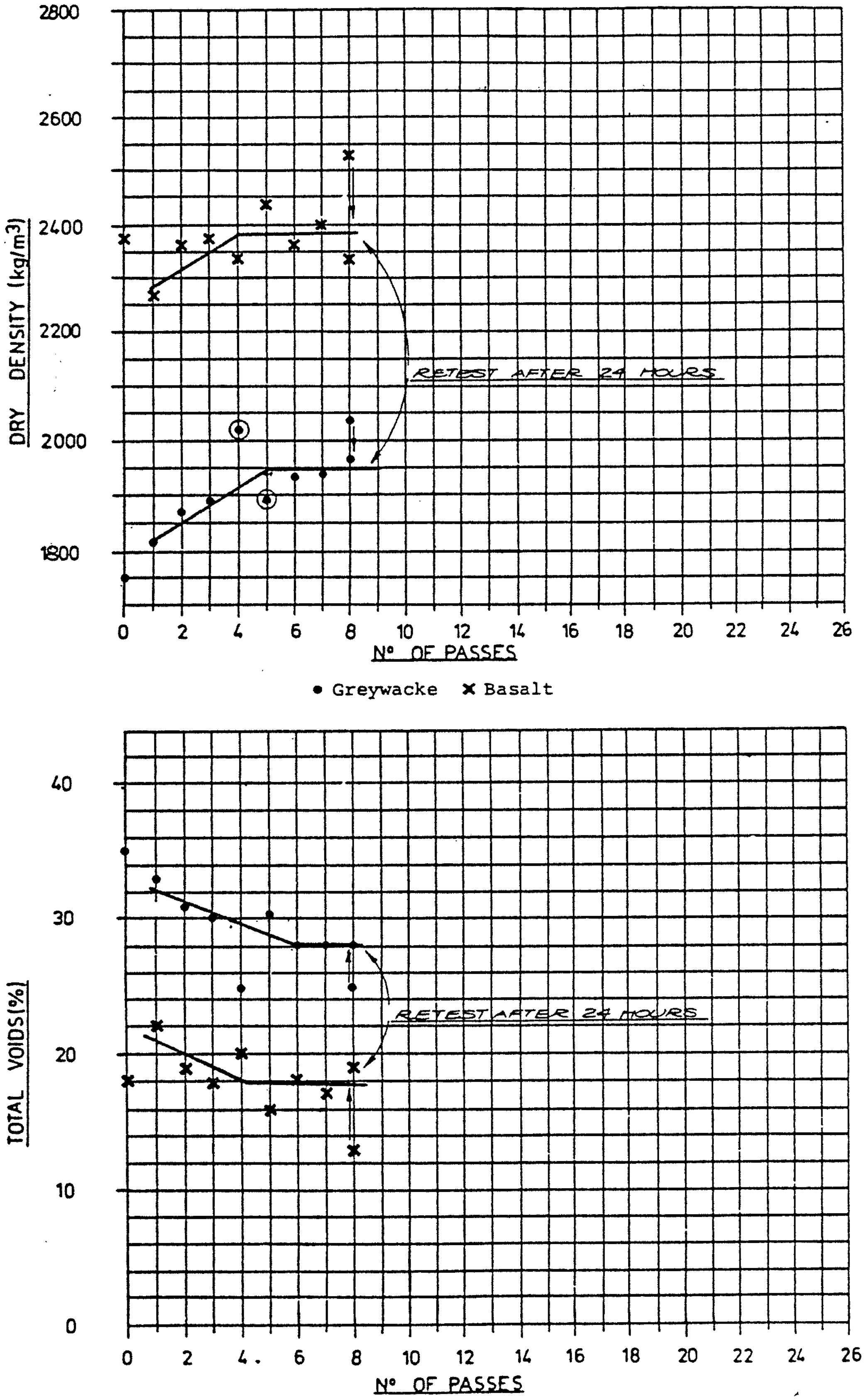


Figure 10. Compaction characteristics of basecourse using an Ingersoll Rand vibrating roller.

The **Clegg Impact Value (CIV)** is a measure of strength rather than density, but indicates a plateau strength index in terms of the construction equipment used. It has the advantage of providing immediate answers so that a large part of a pavement can be assessed rapidly.

Other traditional, less sophisticated methods of assessing the end point of compaction exist. For instance, sometimes it is requested that a dense "mosaic" surface to the basecourse be produced before chipsealing. This will only be achieved after the rest of the layer has been well compacted. If static steel wheeled rollers are being used, the maximum density for a particular roller will have been achieved when it fails to leave a mark on the surface. Note that this indicates compaction to maximum density for a particular roller; it does not necessarily mean that the maximum density for the aggregate has been reached. However, it does provide another simple means of determining that compaction has been achieved.

4.7.5.4 Pavement uniformity

The process of compaction will invariably result in a greater density at the surface than that at the bottom of the layer. The resilience of the subgrade and sub-base, and the construction processes will influence the actual difference. Further, if the aggregate has not been carefully handled and placed, open graded areas will exist and additional compaction will be necessary to crush coarse material to produce the fines needed for a stable grading.

It should not be necessary to disturb the aggregate or manipulate it in any way once it has been placed. However, final trimming of the surface may be warranted to correct the shape. The application of a running course may assist final preparation of the pavement surface and provide a running surface for pavements being reconstructed while still in service.

4.7.6 The Art in Pavement Construction

As in most other engineering techniques, a certain amount of "art" is required to devise the most economical and effective pavement construction. All the theory at present available is based largely on experience and by no means should an engineer apply one particular method without a great deal of thought and consideration of all the options.

In particular, there is a degree of art in the utilisation of available resources. It is a simple matter to decide to use the best quality basecourse carted in from a reputable quarry and to ignore an alternative resource available right alongside the job. Again, the rejuvenation of an existing pavement using a stabiliser, say cement, may be a more satisfactory solution for a distressed pavement than an overlay. The actual computation necessary in road design is of a minor nature compared with the effort necessary to find the most economical materials to make the design work.

Road construction gangs often contain some very experienced practical roading people. They nearly always know how to use the materials and plant available to them to best effect and discussions with them will often save an engineer a great deal of research and time.

Competence in road construction depends on the development of the art. It is desirable to investigate fully and record all relevant data. Design, construction and subsequent performance all need to be monitored. A photographic record is one of the most effective methods of compiling a history of a road.

Regular deflection testing, surface inspection and deformation measurements are essential. The periodic analysis of the deflection test results for instance, will invariably prompt an investigation (perhaps only superficial) to sort out why certain changes have occurred. Back analysis will perhaps show up some aspect that has been overlooked in the original design or during construction.

It may seem that in New Zealand today the road network is complete and that there is no need for new roads. To a large extent this is true, at least for major roads. Instead, the emphasis has changed over the last two decades from construction of new roads to finding the best ways to maintain and develop the existing roads.

In spite of this change, selection and construction of unbound basecourse is, and will remain for the foreseeable future, an essential part of our road maintenance works whether it is for construction, slope correction, or merely digout reinstatement.

Understanding and applying both the science and the art of unbound basecourse selection will remain as a challenge for current and future roading engineers.

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GLOSSARY

Abrasion - Loss of material from one or both surfaces of aggregate which are in contact and undergoing relative motion.

Absorption - The process of water molecules penetrating the interior of an aggregate particle.

Adsorption - The condensation of water on the surface of an aggregate particle.

Aggregate - mineral material such as sand, gravel shell, slag, broken stone or combinations thereof.

Alteration - Change in the mineralogical composition of a rock as the result of action by hydrothermal solutions or mild metamorphism.

Atterberg Limits Test - The test method describes the measurement of the following:

(a) liquid limit and plastic limit which define the water content at the upper and lower boundaries of the plastic state respectively.

(b) Shrinkage limit - the water content below the plastic limit when no further shrinkage will take place.

(c) Plasticity index is the numerical difference between the liquid and plastic limits.

Basecourse - An unbound aggregate that can function as the major structural component of a pavement.

Bound Material - Aggregate with particles bound together by bitumen, cement, lime, flyash etc., which alter the strength and stability properties of the aggregate.

Bulk Density - The mass of material (including solid particles and any contained water) per unit volume including voids.

Capping Layer - A layer of material placed on the road bed to provide a working platform for construction equipment but not considered to be part of the pavement.

CBR - California Bearing Ratio.

Chip	-	Manufactured aggregate of single size range, used in sealing the surface of a pavement.
Chipseal	-	A thin layer of bitumen with adhering aggregate chippings which prevents ingress of water into the pavement.
CIT	-	Clegg Impact Tester.
CIV	-	Clegg Impact Value.
Clay Index	-	A measure (percent) of the expandable clay minerals in the minus 75μm fraction in an aggregate or in a crushed rock powder.
Coarse Aggregate	-	Aggregate with particle size greater than 5 mm.
Coefficient of Permeability	-	See Permeability.
Compaction	-	The process of packing mineral aggregate particles more closely together by mechanical means thus increasing the density.
Crushing Resistance	-	Resistance to breakdown or crushing of aggregate particles under load as determined by laboratory test.
Decomposition	-	The breakdown of minerals in rocks through the chemical processes related to weathering.
Deep Lift Asphalt	-	A thick layer of bituminous-bound aggregate used as the main structural component of the pavement. Normally placed by paving machine.
Degradation	-	The wear and breakdown of an aggregate under compaction equipment or while in service.
Dense Graded	-	An aggregate containing particles in all size ranges (below the maximum size), in which all particles can pack tightly together. Ideally, grading curve is a straight line on log-log paper. "n" value less than 0.45.
Densification	-	Reduction in voids and an increase in dry density of an aggregate.
Disintegration	-	Natural mechanical breakdown of a rock on weathering.
Dry Density	-	The mass of dry material, after drying to constant mass at 105°C, contained in a unit volume of undried material.

Durability	-	The ability of a material to continue to provide the service for which it was intended.
Elasticity	-	The property of a material such that deflections are linearly related to load and are recoverable.
Failure (pavement)	-	A pavement is considered to be in a failed condition when the surface has become distorted to the extent that it is no longer safe for vehicular use.
Fatigue (pavement)	-	The progressive deterioration of a pavement as a result of vehicular loading.
Fine Aggregate	-	Aggregate with particle size less than 5 mm.
Fines	-	Material finer than 425 micron sieve. (The term is used erroneously to designate material finer than 5 mm, 0.075 mm or even clay-size particles. The division on the 425 sieve used in this report is based on the material size required for the Atterberg Limits tests.)
Flexible Pavement	-	A pavement formed from layers of various types of material each of which has a relatively low modulus of elasticity, e.g. compacted crushed rock. The load from the vehicle is spread by interaction of the particles in each layer so that the stress is progressively reduced as the depth below the surface is increased.
Gap Graded	-	An aggregate with both fine and coarse material but without intermediate size fractions.
Hardness	-	The resistance of a rock to scratching or abrasion. Mineralogical hardness is found by comparison with an arbitrary reference scale, the Mohs' Scale of Hardness.
HVD	-	Heavy vehicles per day.
Maximum Dry Density	-	The dry density of a soil obtained using a specific compactive effort at the optimum water content.
Moisture Content	-	The term is sometimes used instead of water content. Not accepted New Zealand use.
Nuclear Density	-	In situ density of a soil or aggregate layer as determined by a nuclear surface moisture-density gauge (NZS 4407: Parts 4.2.1 and 4.2.2:1991).
ODIN	-	A variable Impact Swinging Hammer Test Apparatus.

Open Graded	-	An aggregate containing a range of particles (below the maximum size), but is deficient in fines so that after compaction it has many voids. Ideally, grading curve is a straight line. "n" value is much greater than 0.6.
Particle Density	-	See Solid density.
Particle Size	-	The effective diameter of the aggregate particle, i.e. minimum sieve opening that allows the particle to pass through.
Particle-size Distribution	-	The percentages of the various grain sizes present in an aggregate as determined by sieve analysis.
Pavement	-	The structural load-bearing component of a road which is supported by the subgrade.
Pavement Performance	-	The serviceability – age relationship of the pavement.
Pavement Serviceability	-	The measure of the pavement's ability to serve its function at any time.
Permeability	-	The property of an aggregate which permits water to pass through it when subjected to pressure. When the flow is laminar, $v = ki$ where v = discharge velocity of flow k = coefficient of permeability i = hydraulic gradient.
Petrography	-	The study and description of rocks.
Petrology	-	Study of rocks, especially their mineral composition, texture and origin.
Porosity	-	Ratio between volume of voids in a material and its total volume: $porosity\ (n) = \frac{e}{1 + e}$ where ***e*** is the void ratio.
Proctor Density	-	The dry density determined using a particular American laboratory compaction test devised by Mr R.R. Proctor.
PSD	-	Particle-Size Distribution.

PSSR	-	Peak Shear Stress Ratio $= \dfrac{\textit{peak shear stress at failure}}{\textit{normal stress}}$
Quality Control	-	The operational techniques and activities that are used to fulfill requirements for quality.
Quality Assurance	-	All those planned and systematic actions necessary to provide adequate confidence that a product or service will satisfy given requirements as to quality.
Quartering	-	The reduction in quantity of a large sample of aggregate by division.
Reduction Ratio	-	The process of secondary (or more) crushing to reduce the coarser size material by approximately half.
Relative Compaction	-	The percentage ratio of the dry density of an aggregate to the maximum dry density of the same soil as determined by a specified laboratory compaction test.
Riffling	-	Reduction in mass of a large quantity of aggregate by dividing into two halves by splitting through a riffle box. The process is repeated until a sample of the required size is obtained (see Quartering).
Rigid Pavement	-	A pavement which has a relatively stiff top layer, e.g. reinforced concrete. Most, if not all the load, is effectively carried by the stiff layer so that the stress on the lower layers is relatively small.
Road Base	-	Top of subgrade or pavement foundation.
Rock Quality	-	The condition of the rock mass as observed in the quarry face.
Roughness	-	Imperfections in the surface of a pavement, such as potholes, corrugations, loose stone, etc., which cause a vehicle to move vertically as it travels over the road.
Rugosity	-	Irregularity of surface, generally of a wrinkled form.
Run of Pit	-	Fresh won, unprocessed material from a gravel pit.
Sampling	-	The selection of a representative portion of an aggregate.

Sand Density	-	In situ density of a soil or aggregate layer as determined by the sand replacement method (NZS 4407:Part 4.1.1:1991).
Sand Equivalent	-	A measure of the relative amount of silt- and clay-size particles in an aggregate (less than 5 mm diameter) (NZS 4407:Part 3.6:1991).
Sand Circle	-	The sand circle test often used to determine the texture depth of chipseal.
	-	The diameter of the sand circle obtained from the test can be used to assess irregularities of any surface.
Scalping	-	A process in a quarry crushing plant where separation of two grades of rock takes place. Scalping by grizzly bars removes quarry waste and clay from quality rock.
Shakedown Theory	-	A theory used to explain the behaviour of an arrangement of particles under repetitive loading. A structure may exhibit progressive or increased accumulation of plastic strains under repeated loadings until a stable arrangement of particles is established. At this stage the structure has "shaken-down" and will exhibit elastic response to the load. If the magnitude of the load is increased, further plastic deformation will occur until a new shakedown state is established or the structure fails.
Shear Box	-	Equipment used to determine the shear strength. The sample box is split horizontally into two halves which, when moved relative to each other, cause the specimen to be sheared.
Shear Failure	-	A material is said to exhibit shear failure when the shear stress exceeds the available shear strength on a plane.
Shear Strength	-	The maximum shear stress that the aggregate mass can withstand under a specified set of loading conditions. It is controlled by: (a) normal pressure on the shear plane, (b) drainage conditions, (c) rate of strain. It is a function of the effective stress, cohesion and the angle of shearing resistance.

Solid Density - The mass of dry material after drying to constant mass at 105°C per unit volume of solids (including the volume of any closed pore inaccessible to water).

The solid density expressed in t/m^3 is numerically equal to the specific gravity.

Soundness - The ability of an aggregate to withstand mechanical breakdown under cyclic treatment of wetting, drying, freezing, thawing with or without chemicals.

Specific Gravity - See Solid density.

Sphericity - The ratio between the surface area of a sphere having the same volume as a particle and the surface area of that particle.

Splitting - See Riffling, Quartering.

Stabilisation - The process of incorporating additives to improve the stability of a layer of soil or aggregate.

Stability - The ability of a material to provide the service for which it was intended without permanent loss of shape.

Stiffness - The resistance of a material to permanent or recoverable deformation.

Strain - Change of shape as a result of an applied stress.

Stress - Force divided by the area over which it acts.

Sub-base - A lower structural layer of the pavement consisting of aggregate, stabilised aggregate or stabilised soil.

Subgrade - The upper layer of the pavement foundation, i.e. the top of a fill (imported material) or bottom of cut (in situ material).

Surface Seal - A thin layer of bitumen and aggregate which prevents ingress of water into the pavement.

Triaxial Cell - A pressure vessel used in testing soils and aggregates. The specimen is sealed in a rubber membrane, enclosed in the cell and subject to water pressure.

Triaxial Compression Machine - Laboratory equipment for testing cylindrical samples of soil which allows independent control of three principal stresses.

Unbound Material	-	Aggregate or soil which contains no additives.
Uniformly Graded	-	An aggregate having a limited particle-size distribution approaching a single size.
Void Ratio	-	Ratio between volume of voids and the volume of solids in a material.
Voids	-	Voids or spaces between particles of soil.
Water Content	-	The mass of water which can be removed from a soil by heating to 105°C expressed as a percentage of dry mass (NZS 4407:Part 3.1:1991).
Weathering	-	The change in rock resulting from exposure to the influences of the atmosphere.
Well Graded	-	An aggregate having a particle-size distribution extending over a wide range of particle sizes without excess or deficiency of any specific sizes within the range.
Workability	-	The comparative ease with which material can be placed and compacted.