CHAPTER 9

# PAVEMENT

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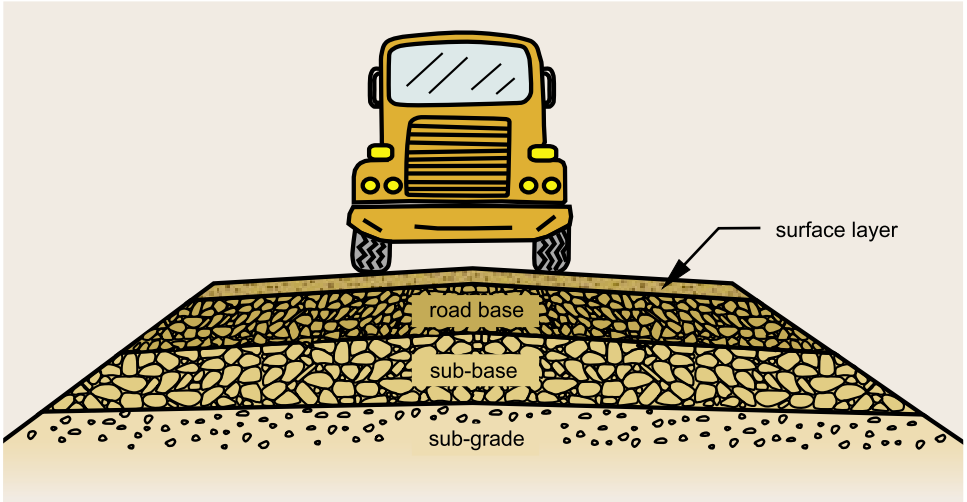
## 9.1 Function and Composition of Road Pavements

Roads are built up in several layers, consisting of sub-grade, sub-base, base and surface layer. These layers together constitute the pavement. Pavements made from good quality building materials spread the forces caused by the traffic so that the loads exerted on to the road foundation is protected from overloading and deformation.

Different levels of traffic require specific appropriate designs. The pavement can be constructed from a wide variety of materials and mixtures of materials consisting of gravel, stone, bitumen, concrete or improved soils. The choice of materials and thickness of the pavement layers are determined by the expected traffic density. Factors, such




as available budgets, the location of the road and the availability of suitable local materials are key parameters, which also need careful consideration during the design stage.

The surface layer seals the pavement and prevents surface water from penetrating and weakening the base and sub-grade. The most common surface for rural roads is constructed from natural gravels. Bituminous and concrete surfaces provide more impermeable seals and are more resistant to the abrasive forces caused by the combined effects of weather and traffic.

The road base (also referred to as the base course) is the main layer in terms of providing additional strength and load bearing capacity to the road. Commonly, this layer consist of crushed and graded materials or selected soils from natural sources which conform to certain characteristics known to improve the quality of the road.

The sub-base is an additional strengthening layer with a similar purpose as the road base. As the road base takes care of the initial load dissipation, the sub-base will have less stringent quality requirements as compared to the road base. The sub-base may also act as a separating layer between the road base materials and the sub-grade.

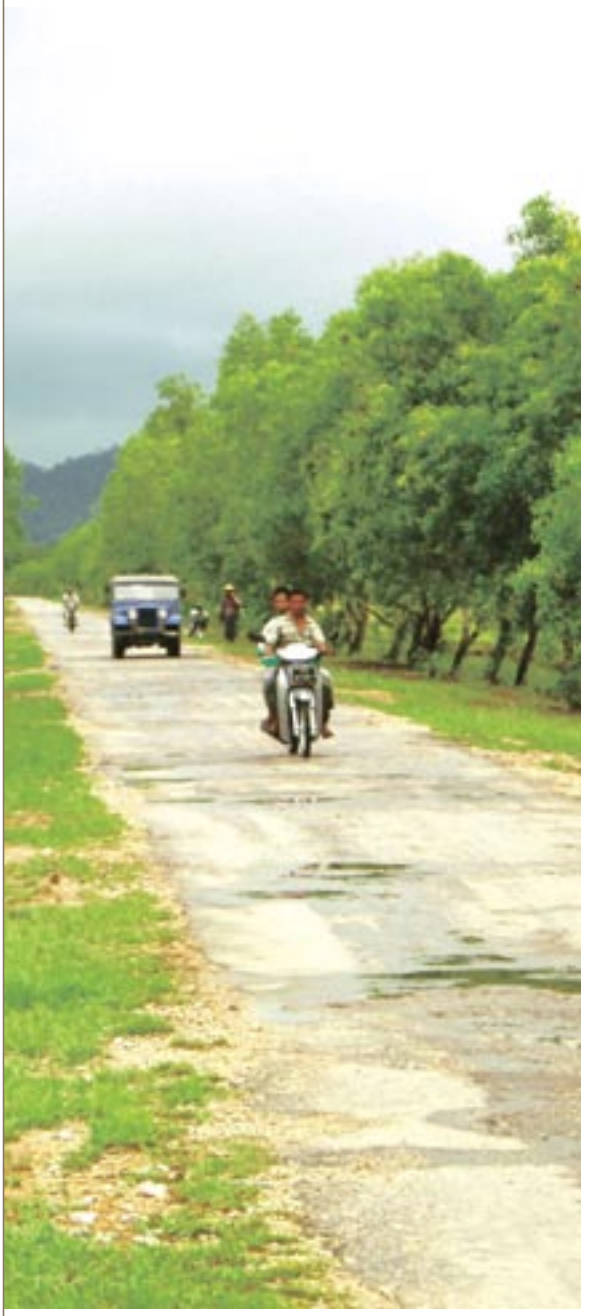
The natural soil on which the road is constructed is referred to as the sub-grade. The sub-grade consists of undisturbed soils or it may be a road fill with soils imported from elsewhere along the road line.

Rural roads built for low traffic loads or on very good soils do not need all these layers. In some cases, it is adequate to provide a good surface layer. In other cases, natural soils may be strong enough to carry the expected traffic.

A major part of road design consists of deciding on the composition of each of the layers forming part of the road pavement. Like any engineered structure, the design depends on the type of usage to which the road is exposed. The traffic exerts pressure

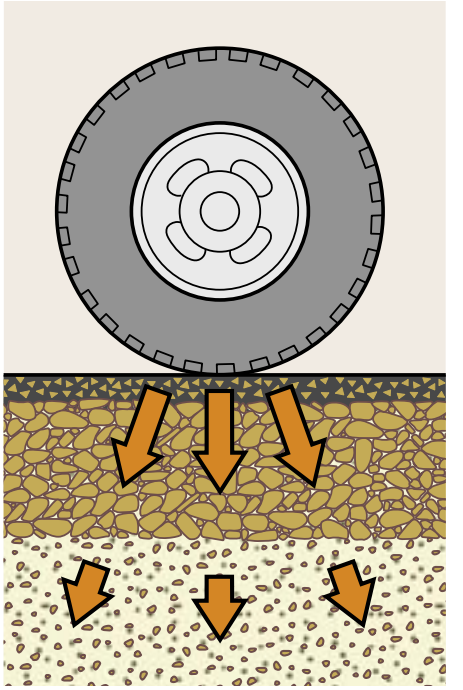
on the road body and its foundation, as well as causing abrasive wear to its surface.

The loads caused by the traffic need to be transferred from the surface down into the foundation, i.e. to the sub-grade without causing any damage to the road. An important factor in terms of determining the appropriate pavement design is therefore the quality of the foundation.



When the road is located on strong sub-grades, the need for strengthening layers is reduced. Roads located in areas with poor soils need a stronger base, distributing the forces more widely onto the foundation. Equally, roads with high traffic levels will need more durable surface treatments.

National design standards provide guidance on appropriate design solutions, depending on the function of the road (primary, secondary, tertiary, feeder or village road) and the amount of traffic. These guidelines normally contain several alternative solutions, thereby allowing the final design for a specific project to make best use of the locally available sources of materials.





## 9.2 Pavement Design

### Design Methods

Pavement design is essentially an empirical science, relying on what actually works in practice. With the diversity of soils and variations in local conditions, pavement design relies to a large extent on solutions which in the past have proved to be effective under certain specific conditions, i.e. weather, traffic levels, soil conditions, etc.

Road building materials are not manufactured products, produced under strict quality control systems. Instead, the soils and aggregates used for road construction consist of materials with certain minimum performance features. Through trial and error, experience has shown that these materials can perform well under certain conditions when improved or combined with other building materials. On this basis, road agencies have developed a series of design alternatives to cater for the various scenarios in which roads are expected to perform.

While the essential building blocks consist of local soils, crushed rock, bitumen and cement, design standards vary a great deal from one country to another. Despite this, the basic principles of providing a surface and base layer and using the quality of the underlying in-situ soils as a major dimensioning factor for the base course(s) is applied everywhere. In-situ soils are often evaluated using the California Bearing Ratio, CBR, as an indicator of its appropriateness and quality (ref. Chapter 10 Soil Mechanics).

The main differences in design standards are related to the variations in access to appropriate building materials. The prevalent geological features determine the availability of good soil materials and aggregate and these vary significantly from one region to another. Road construction requires substantial volumes of materials so reducing the transport distances has a major impact on the final cost of the works. Therefore, design methods are developed with the objective

of relying to the extent possible on locally available resources.

The main determining factors when designing a road pavement are as follows:

- quality of sub-grade soils,
- distance to appropriate building materials – and their resulting costs,
- amount and type of traffic (heavy or light),
- traffic projections,
- weather conditions,
- maintenance demand.

Based on research carried out by institutions such as TRL and AASHTO, road works agencies in most countries have managed to establish sound designs and work methods, which also address the specific needs relating to rural access. The performance of these roads has certainly confirmed that with regular preventive maintenance, they perform well, providing all-weather access into the rural areas.

### Traffic Predictions

The most central issue when deciding on the final design of a road is the anticipated traffic expected once the road works have been completed. For existing roads, the traffic volumes can easily be measured by carrying out traffic counts. On the basis of these counts the observed traffic can be categorised into light and heavy vehicles and provide a good indicator for the physical requirements of the pavement.

When building new roads, it is more difficult to predict the amount of traffic

expected to travel on the road once it has been completed. Often, new roads are constructed following the alignment of tracks and trails, which in the past allowed for some limited traffic during the dry season. An equally common scenario is the re-construction of a road which has fallen into disrepair due to the absence of regular maintenance. In both these cases, it is important to note that the amount of traffic on such "roads" is limited due to its poor quality, and during the rainy season, due to its inaccessibility. When these tracks are upgraded to full all-weather roads, there may be a substantial increase in traffic.

Trying to predict the amount of traffic upon completion of the road construction works is important since the chosen design parameters for the road improvement works need to cater for the resulting levels of traffic. The expected increase in traffic is also a common determining factor when studying the feasibility of the road improvement works.

When building a new road, the traffic

prediction is often based on comparisons to other roads in the area, serving a similar amount of people and villages. This type of approximations is normally sufficient in order to determine the key design parameters of the road such as carriageway width and pavement structure.

There are however many cases in which the traffic levels rise higher than originally expected, and when they do, the road authorities need to deal with this in a realistic manner. Road designs are ideally based on finding the right technical solution for a certain level of traffic, which keeps the combined costs of construction and maintenance works at its lowest. When a road is under-designed for the current levels of traffic, this causes an additional maintenance burden. It is therefore important to select designs, which can be improved upon when the traffic eventually increases to a level beyond the original projections. Additional strengthening layers and stronger surface material can be added to the road when the traffic increases through a process of stage construction.

The most common scenario in road construction works is to upgrade the quality of a road in order to enable it to more effectively cater for the existing or increased levels of traffic. Very often, the decision to build or improve a road has been triggered by the fact that the condition of the existing road has deteriorated to such an extent that there is a need for a major improvement. This work will commonly include an improvement of the road design to cater for the current levels of traffic.

There are a number of methods and formulas in use for the prediction of future traffic volumes, and often the national road design manuals provide a preferred procedure. It should be noted, however, that these models have been designed to deal with highway traffic and does not cater for the particular features and mechanisms relating to rural transport.

Most models used for traffic prediction have been developed for the use on highways, providing a prognosis of what the traffic will look like 10 to 20 years into the future. On this basis, appropriate road designs are selected which matches the expected traffic. With rural roads, however, the main increase in traffic actually takes place at the stage when the road construction works have been completed.

It is important to bear in mind that

rural roads often provide the only access into the rural areas. Before building the road, the population was confined to very basic transport facilities, commonly limited to trails catering for pedestrian or animal drawn traffic or at best a track open for motorised traffic during the dry season. When an all-weather road is provided to these areas, the traffic patterns change dramatically, as the road allows full vehicular access throughout the year. For this reason, it is more important to provide some form of prognosis of expected traffic at the time of completion of works rather than 10 to 20 years after the rural road was built.

## Axle Loads

### Basic Principles

The bearing capacity of a road pavement is designed to withstand a certain amount of traffic over a defined period of time before it wears out. As the loads vary depending on the type and weight of the vehicles, traffic loads are converted into standard axle loads for pavement design purposes. Design standards will thus provide guidance on the type and thickness of pavement layers depending on the cumulative number of standard axle loads over the design life of the road.

Like any other civil engineering structures, roads and bridges are designed to carry certain maximum loads. Each country has established legal limits to the axle loads allowed on to the public road network. National design standards apply this maximum as a basis for calculating the required strength of bridges and pavements. When exceeding these maximum axle loads, the traffic will incur extensive damage to the road and its structures and shorten the life expectancy of the road.

| Axle load limits | |
|---|---|
| Country | tonnes |
| Cambodia | 10 |
| Ghana | 11.5 |
| India | 10.2 |
| Indonesia | 10 |
| Kenya | 10 |
| Laos | 9.1 |
| Philippines | 13.5 |
| Thailand | 8.2 |
| Tanzania | 7 |
| Zambia | 10 |

The damaging effect of traffic loads was established by AASHTO through a series of field trials in the 1950s. The conclusion of the trials was that the amount of damage caused by a certain traffic load is governed by the "Fourth Power Law". This implies that an increase in axle load from say 8 to 16 tonnes will result in damages to the road increasing by a factor of 16 (and not by a factor of 2). As a result of this relation between axle loads and potential damage to a road, it is important to differentiate between light and heavy traffic - heavy traffic mainly consisting of trucks. As the AASHTO road test proved, it is the heavy traffic that has an impact in terms of wear and tear of the road. Passenger cars, motorbikes, single axle tractors and similar traffic have very limited impact on the bearing capacity of the road.

This implies that:

(i) when designing road pavements, it is important to identify the amount of heavy traffic, for the purpose of determining the correct load bearing capacity for a road. This would normally require traffic surveys;

(ii) Other traffic does matter, in terms of establishing travel patterns and on this basis making priorities between road projects. However, the light traffic does not have any significant impact on the deterioration of the pavement;

(iii) In regards to (i), it is important to acknowledge the severe damage heavy vehicles can cause to the roads. Therefore, it is important to look out for commercial activities, involving a substantial amount of heavy traffic, such as logging activities, commercial quarries and its related transport services.

Most design standards use the frequency of vehicles with the maximum load as a key input for the choice of type and thickness of pavements. As the actual traffic consists of vehicles of varying size and weight, the number of vehicles observed during traffic surveys is categorised according to axle loads and resulting wear on the road. To establish the combined effect of all types of traffic, design standards apply equivalence factors to the vehicles lighter than the maximum axle loads. These factors relate to the damage caused by a certain load as compared to the maximum axle load following the principles of the "fourth power law".

**Challenges**

The growth in the movement of freight by road, and the production of a new generation of larger and more powerful commercial vehicles, has lead

to increased pressure from transport operators to increase maximum axle loads permitted on public roads. In general, the larger the vehicle and the heavier the axle load, the cheaper is the specific transport cost.

Despite the fact that some governments have increased the legal axle load limits, there is limited evidence that such measures have had any impact on the practice of exceeding the legal limits. In many developing countries vehicles are often loaded far above the legal load limits. Axle load surveys commonly show that up to 70 percent of commercial vehicles are overloaded.

This aspect is to a certain extent taken into consideration when engineers carry out their pavement designs. With the multitude of uncertainties relating to the construction works, such as varying quality of materials and workmanship, certain safety margins will always be incorporated into the designs. Considering the fact that overloading is becoming a more common feature, there is a tendency of the engineers to ensure that the safety margins built into the designs are on the high side. This practice does not provide an adequate solution, as the extent of overloading is so excessive that only proper enforcement of legal limits will in effect protect the road pavements.

**Restricting Heavy Traffic**

Discussions regarding axle load limitations are not only confined to the highway network. Rural roads, when they form part of the public road network need to cater for axle loads for which the rest of the national road network is designed. The issues relating to overloading is equally relevant to the safekeeping of rural roads.

Since rural roads are designed for lower traffic intensity, the damaging effect of overloading can be more immediate. Highways are designed for larger volumes of traffic and such pavements are normally able to resist overloading longer than rural roads. There are enough examples of logging trucks or transport to and from quarries where heavy vehicles have caused major damages to rural roads in a short period of time.

Overloading not only causes premature failure of road pavements. It can also cause major damage to road structures such as culverts, bridges and retaining walls. For rural communities relying on a single access road such damages have major implications for economic and social activities relying on these transport facilities. With limited resources for repair works it may take months or years before the transport link can be re-established.

The discussion on limiting heavy traffic is therefore common when local roads are improved. Local residents are keen to protect their newly acquired road from the misuse and damage caused by heavy traffic. A common solution is to erect barriers to restrict large vehicles from entering the road, however, the success of these measures are still dependent on the extent to which authorities are prepared to enforce the axle load regulations.

The issue of adhering to axle load limitations is also a responsibility shared by any project manager of ongoing road construction works. The works often involve the import of considerable amounts of soil materials in the form of gravel material or aggregate. The trucks supplying this material frequently use the public road network to reach the work site. If axle load limitations are not observed, this can easily lead to significant damage to the roads between the quarries and the work site. To avoid this, clauses are included in the contracts limiting the quantities of material in each truck delivery, and also charging the contractor with the responsibility to repair any damages caused during the material delivery.

**Stage Construction**

Design and construction of a road in stages is a common strategy used by most highway agencies. Investments are often carried out with a 30 – 40 year horizon, however it is seldom the case that the initial design and construction survive this length of time without any additional interventions. As most road works agencies cannot afford the luxury of over-designing its construction projects, the goal of any design works is to meet the future capacity requirements based on traffic projections. The resulting approach is therefore often a conservative estimate of future needs combined with the provision of a second stage improvement intervention at a later stage if traffic numbers increase beyond the initial projections.

Designing for the next 30 to 40 years is a viable approach in countries where adequate financing is available at the time of interventions, when sufficient capacity exists to carry out proper need assessments and match it with adequate technical designs, and when the road network is managed properly with an effective maintenance programme.

In such a scenario, it is often also the case that the full extent of the road

network is already established. In several developing countries, this is not the case as there are still severe limitations to year round access to a significant portion of the rural population. As a result, a major task of government agencies is still to develop a transport network providing the first basic all-weather access to rural communities. Obviously, when building new roads, there are more uncertainties when attempting to predict future traffic volumes.

Providing this first basic access to all rural communities also require sizeable investments. Equally, large-scale road construction programmes involve significant challenges in relation to core issues such as finance, managerial and technical capacity and providing maintenance to the new roads. A common approach in large scale programmes has therefore been to address the task at hand in stages, in which the initial stage involves providing the first basic all-year access using a standardised approach to design and implementation. Once that core road network has been established, it is then possible to fine tune technology and designs with more optimal solutions addressing the actual development of traffic, its type and frequency.

A common approach following this strategy has been to provide access through the construction of basic gravel roads and low-cost structures with the initial objective to enable basic services to be provided to the rural communities. At a later stage, when the new traffic and transport patterns have been established, the same roads are upgraded in order to meet higher performance requirements with attempts to reduce combined life cycle costs, adding in essential factors such as vehicle operating costs and maintenance.

## 9.3 Pavement Types

Road pavements come in a multitude of configurations and variations. For the purpose of rural road construction, it is sufficient to look at some of the commonly applied solutions used to provide the basic all-weather access roads in the rural areas. Rural roads can be categorised according to the main building materials used in the pavement:

- earth,
- gravel or aggregate,
- bituminous mixes,
- concrete, and
- stone or brick.

Earth and gravel roads are often referred to as roads with an un-bound surface as opposed to bound surface treatments, which include bitumen or cement as a binder mixed into to the aggregate used in the pavement.

Earth and gravel surfaces are appropriate for roads with limited traffic. The quality of earth roads varies significantly, depending on how suitable the local soils are as road building materials. With very sparse traffic, it may be difficult to justify anything else, even when only poor soils are available. On the other hand, when local soils consists of well-graded materials, earth roads will perform well for the average traffic expected on rural roads.

Gravel and crushed aggregate is not only used for surface layers, but also as base course layers. The most common approach is the use of well-graded materials, however, the practice of water-

bound macadam and other solutions relying on coarse aggregate as a road base is still in practice in several countries.

For roads with high traffic volumes, the use of bitumen binder is applied to both base and surface layers. Concrete, stone or bricks are predominantly used for surfacing works. Due to its higher costs, such materials are mainly used for surfacing of roads within villages and towns or semi-urban areas. Although this type of pavement is very durable, the main reason for its use is more related to environmental concerns.

All of these building practices lend themselves to labour-based construction methods in various degrees of intensity. This chapter will discuss each, but with particular emphasis to gravel roads because a majority of rural roads are constructed using this material configuration.

Notwithstanding the choice of building materials, all roads need some form of maintenance, both on a recurrent basis and periodically. A well-designed and well-built road requires less maintenance, however, there will always be a need for some form of maintenance inputs. Contrary to popular belief, it is not possible to design and build maintenance free roads.

## 9.4 Earth Roads

### General Description

The term earth road is often used for any road without a bound surface layer, i.e. a road without a bituminous or cement based surface treatment. Often, gravel surfaced roads are incorrectly referred to as earth roads. In its correct sense, earth roads are roads constructed from the soils adjacent to the road without setting any specific demands to the performance of the soils used. In this context, it is also useful to distinguish the earth road from tracks and trails, the main difference being that properly designed earth roads have many of the same engineering features as other roads, including a proper alignment and a road carriageway allowing all forms of traffic to pass. Proper design of earth roads also includes a comprehensive drainage system. In comparison, tracks and trails are mainly intended for non-motorised traffic or smaller vehicles, often with more limitations on when they are accessible.

Earth roads can be a feasible means of providing basic access to areas where very limited traffic is expected. Earth roads are commonly built to provide the final connection between villages and district or feeder roads. Due to their limited traffic as well as short distances, the demand for keeping them open throughout the year and in all types of weather is not as critical as for roads catering for more frequent and diverse forms of traffic.

Earth roads also provide a common solution to access needs to private properties, farms, plantations and estates. They serve as temporary access on civil works projects and when traffic needs to be temporarily redirected away from construction sites. Food for work and other employment generation programmes often prefer building earth roads since a high proportion of the funds can be used for labour wages instead of equipment and materials. In many areas, earth roads are the first rudimentary access provided to rural communities. As a result, earth roads often constitute a significant portion of the road network.

When the anticipated traffic is light, an earth surface properly shaped, compacted and maintained can provide an adequate solution which is cost effective and surprisingly durable. The cost of surfacing works, sometimes in excess of 50% of total construction cost, may not always be justified. As a result of the cost savings, available funds can be used to provide similar access to other areas where traffic is also expected to be limited.

### Design

Local traffic in rural areas predominantly consists of non-motorised traffic or light intermediate means of transport such as bicycles, motorcycles, animal drawn carts and two-wheel tractors. Obviously, this type of traffic set different performance requirements for the road as compared to heavy and frequent commercial traffic. With the light traffic loads often experienced in rural areas there may not be a need for installing costly pavements and surface treatments.

As with any engineered road, a key

feature when designing an earth road is to manage surface water with the aim of keeping the road as dry as possible. As earth road construction relies on the soils found along the road alignment, the need for draining away surface water before it weakens the road is even more important. Well-graded granular soils provide good resistance to the combined effects of rain and traffic. If the soils mainly consist of clayey materials, the earth road may deteriorate quickly if water is not drained away from its surface. Therefore, proper location of the road alignment, adequate drainage measures and attention to construction details are equally important for earth roads.

Earth roads are commonly built as the first step of a stage construction process. In areas with no road access at all, it should be acknowledged that the provision of an earth road can be a significant access improvement for local communities. In combination with the installation of permanent river crossings, this solution may be sufficient to cater for the transport needs. Once the traffic increases and more maintenance is required, it may be necessary to improve the road surface and its base course.

Future traffic levels in rural areas can be particularly difficult to predict. Deferring the upgrade of the road to full all-weather standards for one or two years therefore allows the road authorities to take a "wait and see approach" in relation to assessing the need for a higher standard road.

### Suitable Soils

As earth roads are built relying on the soils along the road line, it is useful to assess the performance and features of local soils. The properties of the soils have an important bearing on how the road surface performs when subjected to traffic and weather, and the amount of maintenance and repairs required to keep the road open most of the year.

In some areas, local soils consist of a good mix of fine and granular materials, providing a strong base and surface for the road. In such conditions, one can consider relying solely on the local materials also when traffic levels increase.

Good building materials consist of a mixture of clay, sand and stone. Cohesion is secured through a certain clay component in the soils, providing the binding effect to avoid ravelling and corrugation of the surface. Then again, the clay content needs to be below a certain level to limit the overall plasticity of the soils, thereby avoiding that the road surface becomes soft or excessively slippery when wet. A good amount of larger particles acts as a skeleton for the finer particles and improves the strength of the road.

A graded material is always preferred

as it provides both strength through its larger particles and cohesion from its fines. Soils with a good distribution of particle sizes also packs well, with good interlocking between the particles. This type of materials provides good resistance to erosion and has sufficient strength to carry the traffic.

Pure clay or silt, clay and silt mixes, organic soils or pure sand are generally unsuitable road building materials due to their poor performance when wet. Maintaining a good camber on the surface thereby facilitating the rapid removal of water can to a certain extent mitigate this problem. Soils with high clay contents provide a firm and solid surface when dry, so in dry and arid areas these soils can provide a good solution. Poorly graded silts and sands perform poorly when dry due to their lack of cohesion.

Sand/clay mixtures provide reasonable surfaces, although the strength and durability are less than a mixture in which stone or gravel is present. Preferably, the clay content should not exceed 25 percent.

## Maintenance

Like all roads, earth roads are subject to wear and tear and require timely and well-targeted maintenance. Similar to all other roads the most important part of maintenance is to keep the drainage system in good order. When relying on inferior local materials, the road surface will eventually become rutted and require frequent reshaping. Similar to other types of roads, this maintenance can be carried out relying mainly on locally available resources such as local labour and hand tools.

Combined with the fact that these roads often cater for a limited amount of people such as a rural village, a group of farms or a plantation, the operation and maintenance can be organised through and by the local users. As the road has been built using local materials there is no reliance on outside inputs expect for the occasional technical advice and purchase of basic hand tools.

## 9.5 Gravel Roads

In any public road network, the majority of roads consist of the numerous arteries connecting villages and settlements to the main trunk roads and highways. While highways provide the mobility between the various parts of the country, the local roads provide essential access to and from the rural communities. Local roads typically carry relatively small volumes of traffic, however, they play an essential role for the local population they serve, as they are often the only transport link to their communities. In order to secure all weather access to these areas, there is a need for an extensive network of rural roads.

Gravel roads often constitute the majority of the public road network in developing countries. The reason for this is obvious. This type of roads is inexpensive to build and is well suited for the purpose of providing basic all-weather access. Since the materials used to build gravel roads are found locally, it is also possible to use construction methods relying on manual labour supported with some equipment. For this reason, they can be constructed and maintained relying on the skills and capacity of the local construction industry.

An important feature of these roads is that the gravel layer fulfils two purposes. First of all, a well-compacted gravel surface with a good camber or cross slope prevents water from penetrating into the road body and thereby avoids surface water from compromising its bearing capacity. For the average road user, the gravel surface is only regarded as the running surface, and its effectiveness is only judged on

the basis of its smoothness. However, the gravel surface layer also functions as the base course for the road, providing the strength, which allows heavy traffic to pass during both dry and wet weather without causing any damage.

With its dual function, having to meet the combined requirements of a surface layer and providing the bearing strength of the road, it is important that the gravel layer is constructed in a manner which allows it to perform according to these expectations. Like any other type of road, the construction of a quality gravel road requires sound engineering and vocational skills to secure the desired outputs.

Although the construction of gravel roads is a common solution for providing all-weather access into the rural areas, it is also important to acknowledge its limitations. As for any road design, it has been developed for a certain traffic pattern, essentially catering for limited volumes of traffic. Equally, these roads have specific maintenance requirements different from other surface types and designs.

With this in mind, a gravel road is often the most appropriate solution when installing the first all-weather connection to rural communities. When traffic levels increase, the gravel road can be used as the first building step and later upgraded to a higher technical standard.

### Composition of Gravel

The most suitable material consists of a mixture of stone, sand and clay. A good gravel surface should contain 35-65% stone for strength, 20-40% sand to fill the gaps between the stone and 10-25% clay. The stone particles will lock together and form a strong skeleton, which transfers the traffic load to the sub-grade. The clay acts as a binder keeping the sand and stone particles in place. In the wet season or in predominantly wet areas, the presence of too much clayey material is a disadvantage because it softens with water, resulting in wheel ruts or producing a slippery surface. The wetter the area, the more important it is that the stone/sand proportion of the mixture is high and well graded. In a dry climate, a higher proportion of clay is acceptable.

### Gravel Quality

Although the process is called "gravelling", various materials can be used, such as laterite, limestone and gravel. Suitable surface layers can also be constructed from materials such as coral stone and crushed stone. Some materials such as coral and limestone have the tendency to harden when they are exposed to air, water and compaction, while other types of rock may decompose under the combined action of weather and traffic.

The quality of gravel needs to be determined well in advance of commencing surfacing works. This enables the project to prepare and negotiate gravel sub-contracts with local contractors well in advance and allows project management to schedule the gravel works to the optimal period of the year (dry season).

Information about soil characteristics is useful for selecting optimal alignments and quarries and to facilitate design and work specifications. Usually, samples are sent to a soil laboratory to ensure that the selected material can be used. It must be recognised, however, that in many places good laboratory facilities are scarce and tend to be located far away from the project sites. In addition, laboratory tests can be expensive and time consuming for rural road works, often situated in remote locations.

Engineers and technicians are therefore often forced to carry out simple field tests. When combined with laboratory tests taken on similar samples for other projects and with good knowledge of how similar materials have performed, these field tests can provide a good first indicator of where decent materials can be sourced. The field tests are also important as they act as the initial screening of candidate soils which the surveyors believe may pass more comprehensive laboratory tests.

Throughout the use of a specific gravel quarry, the project management needs to monitor any change in the quality of the gravel. If the gravel changes its composition, arrangements need to be made to sample and test the gravel. If the results of the laboratory test show major discrepancies in the properties of the gravel, no longer conforming to the specified requirements, the project may have to abandon the quarry and locate an alternative source.

### Sources of Gravel

The first step is to identify suitable quarry sites. There are several ways of locating quarries, ideally taking place at the time of the initial surveying works. Technical agencies and public works departments keep details of

quarry locations and material quality. This is usually the principal source of information. Local administrators, contractors, farmers, merchants and others can also be consulted. In most cases, there is some history of gravel use in the area. To reduce transport costs, it is worthwhile examining suitable material at locations as close as possible to the road worksite. In some areas, gravel is available along the road alignment. Even if these sources are limited, they may be a significant contributor to limiting the costs of the gravel surfacing works.

If there is no previous quarry in the immediate area or known sources have already been depleted, it is necessary to carry out a more comprehensive survey for appropriate sources. Local people might be able to help. One option may be to leave a sample of good gravel (from some other quarry) with local officials and spread the word that a reward will be given to the individual who can find similar quality gravel.

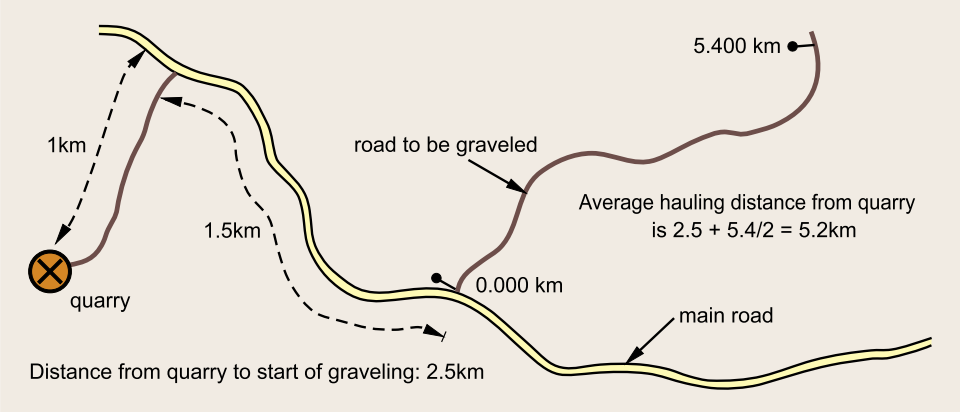
The first place to look for gravel is along the road alignment. Take careful note of material excavated during earlier construction works seeking indications as to the presence of gravel immediately adjacent to the road.

### Quarry Selection

The main criteria for selecting a quarry are quality of the gravel, access to the quarry and the hauling distance. Much depends on which materials are available in close proximity to the roadwork sites. Suitable surface layers have been made of materials ranging from coral to crushed stone. However, great care should be taken when a particular material is selected as its performance may change as a result of the combined effects of weather and traffic.

If there is no experience with a particular material and the stone fraction is easy to crush with a small hammer, the material should be subjected to proper tests to determine its suitability.

The haulage of materials is a major cost item for the project so suitable sources of gravel need to be identified during the planning stage. If the nearest quarry is very distant, it may be cheaper to use crushed rock instead of hauling gravel



over a long distance. Equally, there will be a demand for materials for future maintenance. With long haul distances, it may therefore be more feasible to install a more durable pavement, which does not require frequent replenishment of surface material.

The quarry must contain a reasonable quantity of gravel. Quarries in low places should be avoided or drained before commencing excavation, as they may flood and become unworkable during rains.

The following aspects need to be considered when selecting a quarry:

- The quarry should contain sufficient gravel of adequate quality.
- The depth of topsoil, preferably not exceeding 30 centimetres. Removal of topsoil is expensive and time consuming.
- The quarry should be as close as possible to the work site.
- There should be good access from existing roads to the quarry, as opening new access roads to the quarry will increase costs.
- The quarry should avoid farmlands or land already in use for other purposes.
- Land ownership and compensation issues, quarry concession rights and royalty fees need to be arranged at an early stage.

The location of adequate gravel quarries is an integral part of the design work. Having located the quarry sites, it is possible to calculate the average transport distances. This forms the basis for estimating realistic unit prices for the supply of gravel material. The quarry location and hauling distance is key information included in the bid documents when engaging contractors to deliver gravel. Although the client may indicate the appropriate sources of gravel, it is still necessary to control the quality of the material during works implementation.

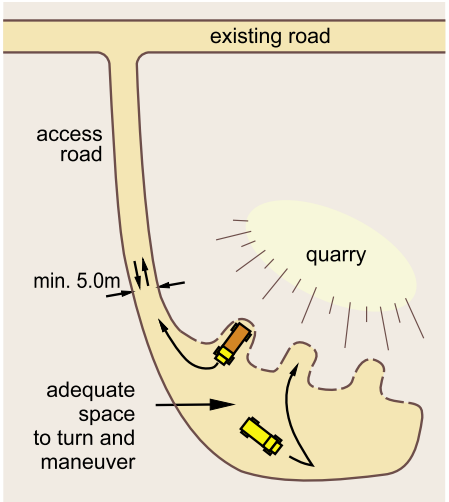
Quarries are commonly opened up to serve several civil works projects. Therefore, quarry selection is often a matter of choosing an existing quarry where the quality of materials has already been determined. Existing quarries have established access roads, and their use will normally not require any major preparation works. Equally, any land and concession rights have already been arranged.

Some quarries are privately owned, operated by local businesses or contractors. In addition to the cost of extracting and transporting the materials, such quarries may charge a levy specifically for the materials, which needs to be included in the estimates. Equally, the government may demand royalty fees for the use of a quarry.

In remote areas, there is usually less knowledge available relating to suitable gravel and aggregate sources. Equally, there may not be any quarries already in operation. In such circumstances, it is important that surveys of possible material sources are carried out during the early stages of project preparations.

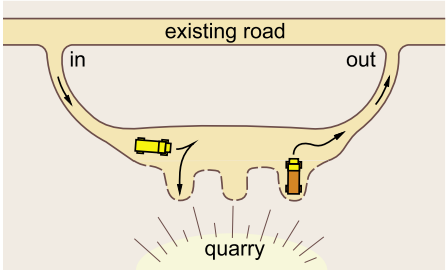
## Quarry Access

The efficiency of the gravel supply is very much dependent on the quality of the roads on which the gravel is transported. This also includes the access road from existing roads to the quarry site. The access roads need to be improved to a level, allowing vehicles to pass throughout the period during which gravel works take place. This implies that it may be necessary to build and maintain a temporary access road, allowing heavy traffic to and from the quarry to operate also during rainfall.




The quarry should be operated in such a way that the transport vehicles can enter and leave without being in each other's way. Waiting time reduces the performance of equipment and labour and eventually leads to increased construction costs.

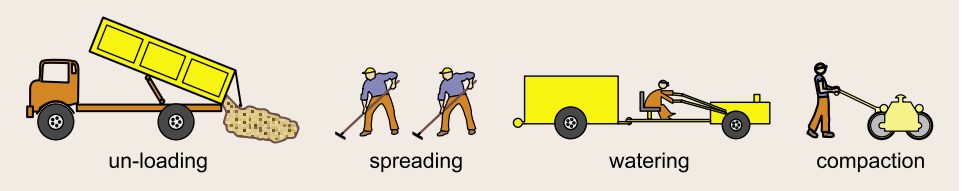
When the quarry is located at some distance from existing roads, the access road needs to be designed so that trucks or other vehicles are able to meet and pass each other while travelling on the access road. This can either be organised by building the access road wide enough for two vehicles to pass each other, or by installing meeting points at regular intervals along the road.




If the quarry is located close to an existing road, the transport can be organised with separate entry and exit routes. The advantage of the ring road arrangement is that it allows the vehicles to enter and leave the quarry and to manoeuvre with a minimum of interference. These access roads only require a width sufficient for one vehicle to operate. This arrangement also reduces the amount of space required for turning and manoeuvring at the loading points.

## Work Procedures

The graveling operation consists of three major components, (i) quarrying works, (ii) transport of materials, and (iii) the surfacing works at the roadwork site. Each of these components needs to be carefully planned, thereby ensuring that they are properly fine-tuned to work efficiently together. A major objective during the planning of this type of works is therefore to ensure that the production rates in each of the main group of activities are at sufficient levels thereby avoiding that any activity causes delays to the other works.




The gravel surfacing activities can be divided into two distinct groups depending on the location. The quarry works includes excavation works, stockpiling materials and loading. In addition, there are several activities relating to the overall operation of the quarry, such as maintaining access roads, removing topsoil and other unsuitable materials, and eventually restoring the quarry or sections of it to its original condition.

At the other end of the chain of activities, where the gravel material is delivered, there needs to an effective organisation which ensures that unloading, spreading, watering and compaction are carried out to the expected rate of progress.

Before carrying out any gravelling works, it is necessary to first check that the earthworks have been properly carried out to exact levels and required standards. Equally, all levels need to be checked and the camber investigated to ensure that it has not been damaged.

Careful planning and preparation is required in order to secure the necessary progress under each work activity. The gravel works rely on a combination of inputs including equipment, tools and labour. To avoid any idle time on any of the resource inputs, it is essential that this operation is properly planned. This plan should contain details on inputs (number of workers and equipment), productivities, outputs and timing of the work.

## Work Plan

The selection of transport equipment is determined on the basis of the amount of gravel required and the distance to the gravel source. With gravel readily available along the road line, both excavation and transport can be organised using manual labour. However, this is not often the case as good quality gravel is only found at certain locations, which may be at a considerable distance from the road site.

With longer haulage distances between the quarry and the work site, it is necessary to bring in mechanised equipment for transport. It is also necessary to increase the number of transport vehicles.

Similarly, when there is a need for large quantities of gravel, it may be more feasible to rely on equipment rather than manual labour for excavation and loading. In any case, the excavation and loading activities need to be carefully coordinated with the capacity of the transport equipment to reduce the idle time of the vehicles to a minimum. At the road site, sufficient resources such as labour and equipment need to be mobilised for spreading and

compaction, thereby keeping pace with the supply of materials.

The pace at which the gravel works can take place is mainly determined by the number of transport vehicles allocated to this operation and the turn around time of the vehicles. Good quality access roads are therefore essential in order to reduce the hauling time.

The number of vehicles and how fast they deliver their loads and return to the quarry determines the required production rate in the quarry. Transport equipment is the major cost component of the graveling operation, so it is essential that work in the quarry is organised efficiently to minimise the idle time on the transport vehicles.

## Excavation and Loading

Unless the soils are very loose and easy to excavate, it is common practice to carry out the excavation works in advance of the loading and transport of the materials. The loading place for the vehicles needs to be excavated at a gradient thereby ensuring that it is well drained and remains dry after rains.

Excavating and loading gravel can be carried out using a large variety of work methods and equipment. In all cases, it is important to organise the works in an orderly fashion in which equipment and labour have ample space to operate without being in conflict with each other.

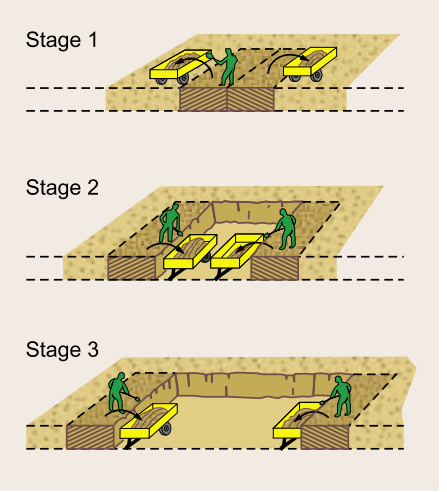
The excavation can be carried out with a front-wheel loader, an excavator or using hand tools such as pickaxes, crowbars, hoes and shovels.

If natural gravel is not available, it may be necessary to obtain materials from solid rock. The source would then either be loose rock and boulders or from drilling and blasting. Quarried rock produces a stronger aggregate as only the top surface layer has been exposed to the natural elements and has become weathered. Crushing rock can be done either with a (mobile) rock crusher or by hand. Crushed rock is an excellent road building material, however, it is more expensive than natural gravels.

Areas where gravel is quarried are covered by topsoil of varying thickness. This overburden needs to be removed in order to access the gravel material. The

overburden should be stockpiled away from the gravel source at a safe location and ready for use when restoring the quarry to an environmentally suitable standard after the gravel has been exhausted in a particular section of the quarry.

Any oversized material, which is hard and cannot be broken down, should be removed from the excavated gravel before loading. The oversized material should be stockpiled in a safe place in the quarry area out of the way of equipment and labour.




When loading materials manually into trailers or trucks, work should be organised in such a way that the loading height is kept at a minimum. This is most important when the loading height is 1.5 m or more. The loading heights can be reduced by arranging loading bays and directing the trucks and trailers to the lowest spot of the loading area.

If trailers are fitted with tailgates, they should be kept closed in order to simplify the loading. The trailers should be loaded to the rim of the trailer sides. There should be enough space for the workers when loading. On flat ground 1.5 – 2 m is required between the trailer and the loader.

Shovels are the most efficient tools when loading soil and gravel by hand.

Head baskets or stretchers can be used when stockpiling materials. Head baskets and hoes are particularly effective when loading coarse material into trailers or lorries.

### Hauling Gravel

Gravel transport can be organised in many ways, depending on the distance from the gravel source to the road site and the type of equipment available to the project. When gravel is readily available in the vicinity of the work site, it can be transported using wheelbarrows. However, once the distance exceeds 150 metres, it is recommended to consider other means of transport. If the quantities required are limited, it may be feasible to rent some form of transport available in the local communities, such as animal drawn carts or tractors with trailers.

| Distance | Transport Mode |
|---|---|
| 10 - 150m | wheelbarrows |
| 150 – 2000m | animal carts |
| 500 m – 8 km | tractors and trailers |
| 1 km - | trucks |

Tractors towing trailers can be an economic mode of transport when the hauling distance does not exceed 8km. The trailers are more suited to manual loading than lorries, which have a taller loading height. Several trailers can be used for one tractor so that while one is loaded, the other transports material to the site. On the other hand, trucks are better suited for longer haul distances. River-based transport is sometimes used when distances are exceptionally long.

When relying on trucks to deliver gravel, active measures are required to limit the loads carried by each truck. When the transport involves travelling on public roads, the trucks are obliged to observe the axle load limitations set by the road authorities.

With very short hauling distances (less than 150m), it is possible to carry out all gravel surfacing activities with labour. Hauling materials can then be done effectively using head baskets, stretchers or wheelbarrows.

## Unloading

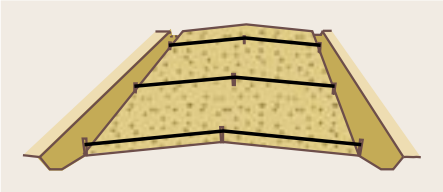
Unloading should be organized in such a way that waiting time for the vehicles is minimized. There must be sufficient turning and meeting places available along the road.

There are two ways to organize off-loading of gravel, either towards or away from the quarry. Gravelling towards the quarry can be organised in such a way that the vehicles have very short waiting times for un-loading, reducing congestion when several vehicles arrive at the same time. The emptied equipment can immediately return to the quarry without delay. However, this method requires the trucks to drive over the road sections still not gravelled, which may cause damage to the road surface, especially during rainy periods. It may even become impossible to continue the works, as the soils may become too slippery and muddy.

Gravelling away from the quarry implies that the trucks will pass over the newly surfaced road sections. This arrangement has the advantage that the vehicles frequently pass over the newly levelled gravel and thereby provide some compaction to the gravel surface. However, this method also has some disadvantages. It requires that the delivered material is levelled before the next vehicle can dump its gravel and may therefore delay the un-loading. Finally, the transport vehicles may cause ruts and deformations to the newly laid gravel surface. To avoid this, the vehicles should be directed to drive in such a way that the whole road width is compacted and ruts are not created.

Before unloading it is useful to once again check the levels and quality of the surface on which the gravel is placed. Since the completion of the sub-grade or base course, the surface may have

been damaged from traffic and weather. If any repairs are required, these should be carried out before the gravel is added to the road.



Drivers should be instructed to dump the entire load within an area clearly marked with pegs and string lines, thereby ensuring that the final thickness is according to the drawings. To make spreading easier, instruct the drivers to move slowly forward while dumping, so that the gravel is evenly distributed along the length of the rectangular area.

The area set out for each load of gravel depends on (i) the dimensions of the gravel surface and (ii) the average load carried by each of the trucks or trailers. The site supervisor is responsible for calculating the area in order to ensure the correct distribution and thickness of gravel.

**Example:**

With a carriageway width of 5.5 m and a desired gravel thickness of 20cm, then one linear metre of the road will need a gravel volume as follows:

0.2m x (5.5m - 0.2m) x 1m = 1.06m$^3$

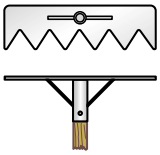
If the average load of a truck is 10m$^3$, this load covers a road section with the following length:

10m$^3$ / 1.06m$^3$ per m = 9.43m

To avoid excessive moisture contents during spreading and compaction, it is recommended to carry out the delivery of gravel during dry weather. The project management needs to monitor the quality of the supplied gravel. Any substandard material should be rejected and immediately removed from the site.

## Spreading

Spreading is effectively done manually, using common hand tools such as rakes, shovels and hoes. Take care to spread immediately before compaction to make use of the natural moisture content in the materials. If the gravel is left on the road for some days before spreading and compaction takes place, it will dry out and then requires more water when compacted.



Spreading is best carried out from the centre line towards the shoulders, levelling one side of the centre line at the time. Any oversize pieces of rock should be removed or crushed using a sledgehammer. Like all pavement layers, the levels of the gravel surface are set out using profile boards. When the levelling is carried out by manual labour, it is useful to indicate the final levels using pegs and string.

## Compaction and Watering

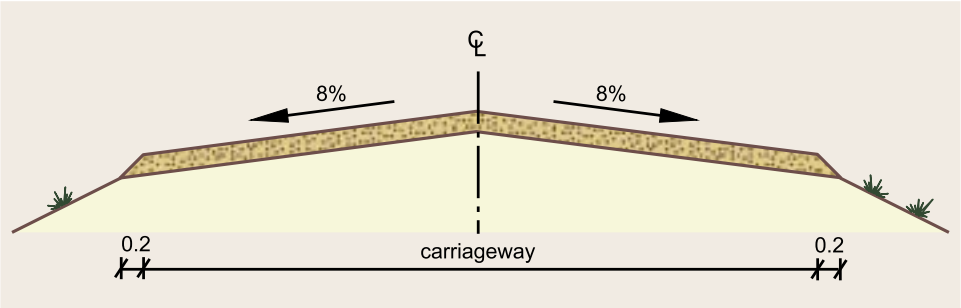
Once the surface material has been spread to the correct thickness and levels, compaction works can commence. Make sure that there is sufficient supply of water so optimal moisture content can be maintained in the gravel during compaction. If the gravel is spread immediately after excavation, it will have a natural moisture content very close to the optimal, thereby reducing the demand for watering. Regular density testing should be organised to ensure that the compaction has been carried out to the prescribed levels.

Gravel compaction is best carried out using steel drum rollers. Any roller with a minimum weight of one tonne, preferably with a vibrating mechanism, will be effective as long as the material is spread in layers not exceeding a thickness of 15cm. When the surface is designed with a camber, the compaction should start at the shoulders. Compaction should always begin at the lowest point of the cross-section, ending up with the last passes at the highest point of the road, i.e. the crown.

When the gravel has been spread and compacted, profile boards are erected along the centre line and the road shoulders. Using a traveller, it is then possible to control that the road surface is smooth, to the desired levels, and that the required camber or cross slope has been achieved throughout the road line.

## Stockpiling

During the gravelling operation, it is useful to stockpile gravel at regular intervals along the road for future routine maintenance works. This gravel is used later for repairing damages to the road surface, i.e. pothole patching, filling of ruts, etc. Ideally, a load of 10m³ of gravel should be placed along the roadside at 500m intervals. The gravel deposits should be placed at locations where they do not conflict with the road drainage system.




## Standard Designs

The thickness of the gravel surface depends on the quality of available gravel material, the strength of the sub-grade and the expected traffic load. With average quality gravel, it is common practice to apply a layer of 10-20cm. The gravel can be applied to the entire road surface or limited to the middle section where most of the traffic travels.

Leaving the road surface with shoulders without a gravel layer will obviously reduce costs, however, it also leaves the shoulders more prone to erosion. A well-compacted gravel surface not only protects the road from damage caused by traffic. If the gravel layer is extended to the shoulders, it also protects the edges of the road from erosion caused by rainwater. Particularly in areas with predominantly non-cohesive soils, it is recommended to cover the entire road surface with gravel in order to protect the shoulders and the sub-grade from erosion as shown above.

The road camber is established before the gravel surface is installed. For gravel surfaces it is recommended to use a higher gradient than the normal practice for bituminous surface treatments, applying a camber between 6 and 8 percent.

## Measurement and Payment

The estimated quantity of gravel is entered into the Bill of Quantities. Unit rates for gravel supply usually cover all costs relating to this operation, including activities such as quarry preparation, excavation of material, haulage and un-loading, maintaining access roads and reinstating the quarry upon completion of works.

The total volume should be based on the theoretical volume of material to be provided to the road, i.e. based on the compacted layer thickness, width and length of road.

The quantity for which payment is made is based on the amount delivered after controlling the completed thickness of the spread and compacted gravel. In addition, the project management usually monitors the amount of gravel delivered by counting the amount of truckloads (or trailer loads) arriving on site as a precautionary measure to ensure that the prescribed thickness of gravel is provided. On this basis, it is also possible to carry out intermittent payments.

## Estimating Transport Rates

With the locations of quarries identified and having selected the appropriate equipment for excavation and transport,

it is possible to estimate production rates for the gravel surfacing works. The key factors for determining the production rate are the capacity (speed and size) of the transport vehicles and the time it takes to load each vehicle, transport the materials to the work site, un-load and return to the quarry. This total turn-around time depends on how the individual activities relating to the material supply is organised.

The travel time between the quarry and work site is the major determining factor for the turn-around time for the transport vehicles. The time spent on travel to and from the quarry depends on (i) the hauling distance, (ii) the quality of the road and (iii) the type of transport vehicles used. The hauling distance varies depending on whether gravel is being supplied at the start of the road or the opposite end of the works project. In order to determine the appropriate number and type of vehicles required, it is useful to start by estimating the transport needs based on the average hauling distance, i.e. the distance from the quarry to the middle of the road worksite. Good quality roads have a significant impact on the time required to travel from the quarry to the work site. With access roads in good condition, the travel time can be reduced to a quarter of what is required on bad roads. Finally, the type, size and quality of the transport vehicles also have an impact on the travel time. Tractors and trailers travel at speeds significantly slower than well-conditioned tipper trucks. For this reason, trucks are the preferred mode of transport for long hauling distances.

Loading is the second most time consuming activity relating to supply of materials. In order to reduce the time the vehicles stand idle, the loading needs to be organised as effectively as possible. For this reason the quarry

**Example:**

The calculations below describe how to estimate the required amount of trucks required for the daily supply of 150 cubic metres of gravel with an average hauling distance of 20km.

The following estimates are made for travel speeds, loading, un-loading and manoeuvring:

| Travel speeds | good road | | bad road | |
|---|---|---|---|---|
| | with gravel | empty | with gravel | empty |
| | 40 km/h | 60 km/h | 10 km/h | 20 km/h |
| Loading | 7 minutes[1] | | Unloading: | 5 min.[2] |
| Manoeuvring | at the quarry: | 3 min. | at the worksite: | 10 min. |

Remarks: 1: Loading carried out by front wheel loader 2: Assuming self tipping trucks

Travel time from the quarry on a good road can be calculated as:

20km/40 km/h x 60 = 30 minutes.

The return trip with an empty truck travelling from site to the quarry is:

20/60 x 60 = 20 minutes.

With time for loading and manoeuvring, the total turn-around time is:

30+20+7+5+3+10=75 minutes.

Assuming that the trucks are available for transport during an entire 8 hour workday, each truck is able to deliver 8 x 60 min / 75 = 6.4 loads per day. As the trucks will not perform a fraction of a delivery, this needs to be rounded off to 6 trips per day, leaving the remaining time for travel to the campsite and vehicle maintenance.

A truck with a capacity of 10 $m^3$, providing 6 loads per day can provide 60 $m^3$ per day. To reach a planned output of 150 $m^3$ per day requires a fleet of 3 trucks.

In comparison, the travel time on a bad road would be 20/10 x 60 = 120 minutes with gravel and 20/20 x 60 = 60 minutes on an empty return.

The total turn-around time is then 120+60+7+5+3+10 = 205 minutes, allowing for only 2 trips per day. To reach the daily output of 150 $m^3$ per day would then require a fleet of 8 trucks.

works are often split into two separate activities by excavating and stockpiling the materials in advance before loading takes place.

Although unloading is faster using self-tipping mechanisms, the practice of manual unloading from a flatbed truck or trailer has a lesser impact on the total turn-around time for the vehicles.

In addition, the vehicles spend some time on manoeuvring into the correct loading points in the quarry. When there are several vehicles in use, they also spend some time waiting for each other. Equally, the vehicles may have to spend some time to turn around and reverse into position before the unloading can take place at the worksite.

| Hauling distance (km) | Turn-around time (minutes) | | No. of trips per truck per day | | Recommended number of trucks | |
|---|---|---|---|---|---|---|
| | good road | bad road | good road | bad road | good road | bad road |
| 5 | 38 | 70 | 12 | 6 | 2 | 3 |
| 10 | 50 | 115 | 9 | 4 | 2 | 4 |
| 20 | 75 | 205 | 6 | 2 | 3 | 8 |
| 30 | 100 | 295 | 4 | 1 | 4 | 10[1] |
| 40 | 125 | 385 | 3 | 1 | 5 | 15 |
| 50 | 150 | 475 | 3 | 1 | 5 | 15 |
| 60 | 175 | 565 | 2 | 1[1] | 8 | 15[1] |

1: Requires more than 8 hours of operation of the vehicles

Finally, the rate of supply of materials depends on the carrying capacity of each of the vehicles. Tractor drawn trailers have a smaller capacity than tipper trucks. With long hauling distances, the transport supplier may also decide to add trailers to the trucks in order to increase the volume being transported in each trip.

Using the average delivery times from the previous example, the table above provides some estimates of average capacity for the provision of gravel using tipper trucks. From the calculations presented in this table, it is clear that the quality of roads between the worksite and the quarry has a significant impact on the performance of the transport equipment.

The table above also provides good estimates on the minimum amount of equipment required in order to provide a reasonable production rate at site. Once works commence, it is important that these estimates are confirmed by observing the actual performance. As it is difficult to predict the exact time required for each of the sub-activities involved, it is useful to follow up the estimates with time studies once the work is ongoing.

The above calculations are based on the assumption that the vehicles are maintained in good order and that they are available for the estimated period of time during each workday. If repair work is required during normal working hours, the capacity of the transport equipment will be reduced. For this reason it is always useful to include some backup vehicles in order to ensure that the planned production targets are reached.

### Balancing Haulage Equipment with Other Inputs

Contractors normally allocate a fixed number of vehicles to the surfacing works. This results in a high rate of supply when the haul distance is short and a less frequent supply when the hauling distance increases. These variations need to be taken into consideration when planning the inputs for the related activities such as the excavation works in the quarry and the spreading and compaction of the material delivered on site.

## 9.6 Soil Mixing

Good road building materials can be difficult to find in some places. Due to the prevalent geological features, such as in flood plains the soils may consist of only clay, silt and fine sand – which are inappropriate for road building purposes.

Rather than importing materials from far away, it may be more feasible to improve the properties of the local soils by mixing it with other soils containing the missing fractions. Sandy soils can be mixed with clay, and clayey soils with sand and gravel. This form of mechanical stabilization works best when the soil contains the right quantities or hard, well-graded coarse particles, only having to add a binder of cohesive materials.

Four factors contribute to the strength and stability of soils:

- The hardness and shape of the coarse particles. Angular shape as opposed to rounded material is preferable, because such particles interlock better. The friction between angular particles is also higher than within rounded material.
- By ensuring the right proportions of coarse, medium and fine material, the space between the particles can be reduced, resulting in soils with a higher density and improved bearing capacity.
- The clay fraction should be about 10 to 25 percent. The stone and sand particles will then be bound together by the cohesive qualities of the clay.

- The large particles within the soil form a strong skeleton. When loads are applied to the soil, the friction between these particles contributes to its stability.

A common solution in areas with predominantly fine soils is to rely on river gravel to obtain a building material with sufficient coarse particles. Although river gravel consists of rounded material usually with very limited cohesive features, it can be sorted and mixed with other soils to achieve the desired grading.

The rounded shape of river gravel can be improved by running the material through a crusher, thereby obtaining a more angular material with improved interlocking features. With an improved shape of the particles, it can then be sorted and mixed according to the prescribed grading curves.

The easiest method of mixing materials is by carrying it out when laying the pavement layer. First the base material is spread, onto which the missing fractions are added. The materials are then thoroughly tilled to create a homogeneous mixture. Mixing can be carried out using a grader or by tractor drawn ploughs and tillers. If required, additional water is sprinkled to bring the mass to the required moisture content, however the addition of water should take place after the materials has been properly mixed.

The mix is then shaped to the proper profile and width. Rolling is done in the same manner as for graded material, making sure that it is compacted at its optimal moisture content.

## 9.7 Chemically Stabilised Soils

### General

Various methods have been developed to improve the quality of soils. The most common method is by mixing soils or aggregate with bitumen, however, there are a number of other materials such as chlorides, molasses, lime and cement which can improve the quality of soils for road building purposes. When referring to chemical stabilisation of soils, the most common methods are the use of lime or cement to improve the soil properties.

The soil becomes stabilized because the cement or lime reacts chemically with the soil particles and bind them together. This process can be achieved in both clayey and granular soils, however, organic soils cannot be stabilized in these ways because they contain (acid) components which prevents the chemical reaction.

Materials with low plasticity, i.e. granular materials, are best treated with cement. Lime stabilisation is more appropriate for soils with high clay contents.

The use of chemicals to improve local soils is costly, and should only be considered when the cost of obtaining good quality natural or processed materials, such as crushed rock, exceeds the cost of using a local soils modified with chemicals.

### Construction Procedures

The process of chemical stabilisation involves a series of works activities consisting of the addition of the stabiliser to the soil, mixing with sufficient water, compaction and finally proper curing to secure the expected strength improvements. For proper mixing to take place, it is important that any lumps are broken up into fine particles.

Most of this process can be carried out using labour-based work methods. Light agricultural equipment can be used for the mixing operation. As the soils are sourced locally, their excavation and delivery can be carried out relying on manual labour. Levelling and compaction works would follow similar work methods as applied when using natural soils without chemical additives.

Before the stabiliser is added, the layer is first shaped to the correct levels. As for any road fill, the thickness of the layer should not be greater than 20 cm. Depending on the amount of stabiliser prescribed, it is distributed at appropriate intervals and raked across the surface. The stabiliser is then spread and mixed through the layer. The mixing needs to distribute the stabiliser evenly, as well as breaking down any lumps in the soil, allowing the chemicals to mix uniformly with the soil particles. Sufficient water is finally added to the mix.

Compaction needs to take place immediately after mixing the materials, in order to secure the intended strength improvement from the additives. Knowing the capacity of the compaction equipment, the works should be planned so that each treated road section can be completed within two hours.

The final step is the curing process. Similar to concrete structures, the strength of the material rapidly develops during the days following construction. By applying adequate amounts of water to the surface, during the ensuing week, the curing can take place and produce the expected strength improvements to the soils.

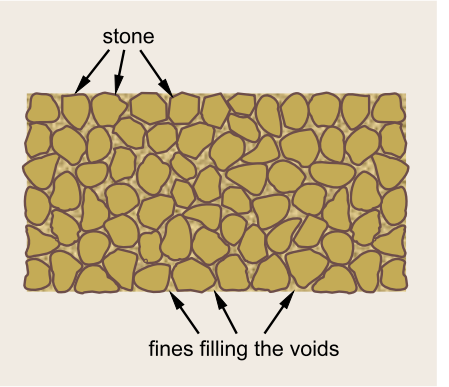
The concentration of stabiliser is expressed as a percentage by weight of the dry soil. The amount to be used for stabilization relies on a number of factors, including the soil type, design requirements and economics of construction. In general, the proportion of lime or cement for effective stabilization ranges from 3 to 8 percent. Amounts smaller than 2 percent are not recommended as such limited amounts are difficult to distribute evenly in the soils.

The volume per square metre can be calculated on the basis of the thickness of the layer to be stabilised. For example, a 20 cm layer is equivalent to a volume of 0.2 x 1.0 x 1.0 = 0.2m³ per square metre. If the density of the soil is 1,000 kg/m³, the weight of the layer per square metre is 200 kg. With a cement proportion of 5 percent, this means that 10 kg is required for each square metre (a 50kg bag would cover 5 square metres).

Even when stored properly in a dry environment, the quality of cement and lime deteriorates quickly over time. For this reason, the delivery of the stabiliser should be organised as close as possible to the time when the works are carried out. Any lime older than 6 months should be discarded.

## 9.8 Macadam Type Pavements

In a number of countries, the use of Macadam type pavements layers are still regarded as an effective method of securing a good bearing capacity in the road base. It is commonly used for secondary and tertiary roads carrying moderate volumes of traffic.




The origins of this construction method dates back to the 17th century when John Louden McAdam and his contemporaries introduced road pavement designs consisting of selected course aggregate.

The main content of a Macadam type pavement layer consists of almost single size coarse aggregate, usually from quarried stone. The voids in the coarse aggregate are filled with finer materials to increase its density and stability. These fines consist of uniformly graded non-cohesive soils such as silt and fine sand. The coarse stone provides a strong skeleton, and is the main contributor of the strength of the pavement layer. A good quality angular rock, compacted to a level in which it interlocks properly provides a layer with high shear strength.

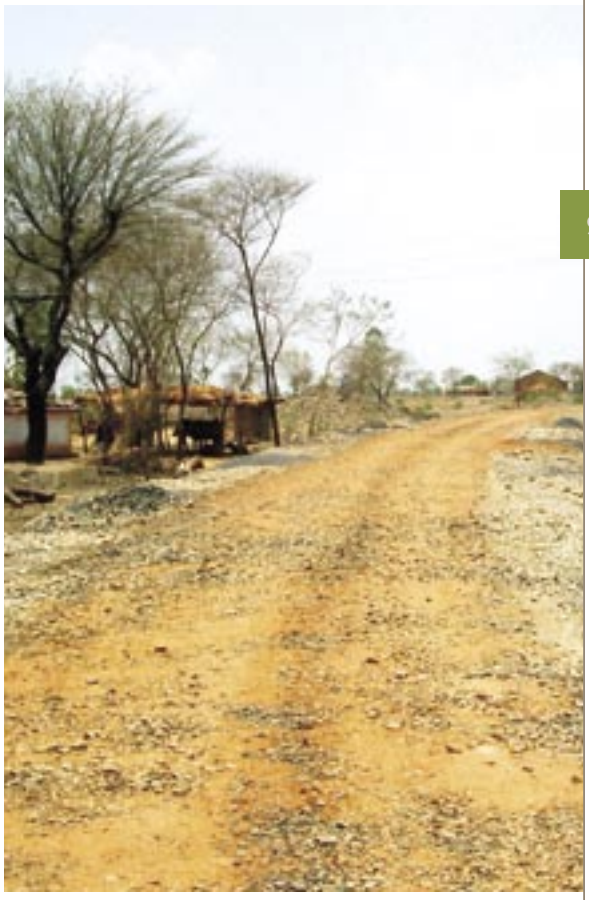
The filler material is added to the layer after the coarse stone has been spread and compacted. The fines are then distributed on top of the coarse aggregate, which is then inserted into the voids between the large stone, using plate compactors or vibrating rollers. The vibration facilitates the movement of the fine materials into the voids.

In dry and arid areas, this process is carried out without the use of any water – and referred to as dry-bound macadam. A wet-bound or water bound macadam uses a similar construction method, the only difference being that in the wet-bound process water is used as a lubricant facilitating the movement of fines into the voids of the coarse aggregate.

As both the coarse and fine aggregate consists of non-cohesive materials, the water drains away after the filler has been added, leaving behind a strong and stable pavement layer. This choice of materials provides the road with a solid base layer, which has a good resistance to water due to its low content of cohesive soils. As it drains well, this pavement provides an effective construction method in wet and humid areas because of its good ability to deal with water.

There are also a number of macadam type layers in which bituminous materials are used to fill or partly fill the voids between coarse stone. The most common design in this respect is penetration macadam, in which the fine material is replaced with bitumen.

This approach can also be applied in combination with the use of fines such as in partially penetrated macadam, where the use of bitumen as a binder is confined to the surface.



### Aggregate

The quality of the coarse aggregate is the key component in macadam pavements. The most common dimensions for this material ranges from 40 to 60mm. The preferred material is crushed or broken stone, however, crushed slag or over burnt brick aggregate has also been used as an effective substitute. Angular stone as opposed to rounded stone is preferable as it provides better interlock and a denser structure.

The material used to fill the voids in the coarse aggregate consists of fine sand

with a particle size ranging from 0.1 to 2 mm. The normal source of the fine material is from the crushing process when producing the coarse aggregate. It is also possible to use natural sources of fine sand for this purpose.

### Construction Method

The construction process can be divided into two stages, consisting of (i) laying the coarse aggregate and (ii) filling the voids with fine aggregate. The bearing strength of a macadam layer is achieved from the coarse aggregate. With sufficient compaction, the stones interlock properly and thereby form a strong skeleton. Achieving a high density is therefore the most important factor in order to secure the required strength of the layer. A good indicator of the degree of compaction can be obtained from measuring the reduction of thickness when the loose gravel is compacted. A good result is achieved when the layer thickness can be reduced by 30 percent. To secure a uniform degree of compaction throughout the layer, the maximum thickness should be limited to twice the size of the material.

The materials in a macadam layer can be spread using manual labour and hand tools. In order to secure a level surface, it is essential that the coarse aggregate is spread to the correct levels before compaction works commence. Setting out this work can be done using the same method as when producing the final surface levels for the earthworks operation. The use of profile boards and a line level, and marking the levels with pegs and string provides sufficient accuracy.

After the coarse aggregate has been thoroughly keyed and set, a fine material is applied in successive layers over the coarse aggregate to fill the voids. By applying vibratory compaction the fines will filter down into the voids between the coarse stone. Dry rolling and sweeping is continued until no more material can be forced into the voids of the aggregate.

The construction method discussed above describes the process of building dry bound macadam. When applying the wet-bound method, the process is extended by spraying water onto the surface in order to add more filler material. The water then acts as a lubricant, facilitating the entry of fine material into the aggregate. Where necessary, additional filler is applied until the coarse aggregate is fully saturated with fine material.

As described later in this chapter, there are also a number of bitumen stabilised macadam pavements, essentially using the same coarse building materials as the main ingredient.

## 9.9 Bituminous Pavements

Bituminous pavements are manufactured using a wide variety of methods and materials. Some are ready-made mixes manufactured in large industrial mixing plants and others are produced by mixing the ingredients on site. Their common feature is that they all contain natural soils or crushed aggregate mixed with different formulae of bitumen.

Flexible pavements for high volume roads, such as national highways, commonly consist of several layers of bitumen stabilised pavements. For rural roads, where traffic loads are much less, the thickness of the bituminous pavement is significantly reduced. Often, only a thin surface layer is laid over a base course consisting of natural gravels or crushed and screened stone aggregate.

Most bituminous surface seals consist of a coat of bitumen in which stone aggregate, gravel or sand has been embedded. The main function of this surface layer is to provide resistance to the abrasive wear of the traffic and stop water from penetrating into the road pavement, while the base course underneath provides the necessary load bearing strength of the road.

Some bituminous pavements however, such as penetration macadam and some hot mix asphalts, can perform both as surface treatments and also contribute to the load bearing capacity of the road.

### Bitumen

Bitumen[1] is widely used in the construction industry due to its waterproofing and adhesive properties and commonly used in road pavements as a bonding and sealing agent. Historically, it was obtained from asphalt lakes from which natural deposits of bitumen were extracted. Today, most bitumen is obtained from crude oil, essentially being the leftover, heavy, semi-solid fractions from the distillation process. At room temperature, it varies in texture from solid to a sticky liquid. When heated it melts and turns into a low-viscosity fluid.

Bitumen needs to meet specific performance requirements first in relation to when it is applied to a road surface and secondly once traffic is allowed onto the road after completion of works. During construction the

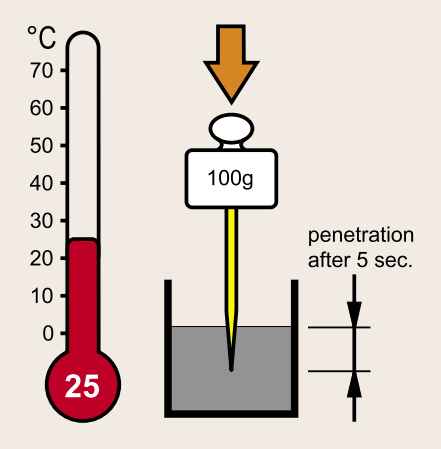
1: In Europe, bitumen is the commonly used term for the heavy fractions in crude oil, while it is referred to as asphalts in the United States (and American literature). In the European sense, asphalt usually refers to asphalt concrete which is a mix of bitumen and aggregate used as a road surfacing material.

bitumen needs to be soft enough to (i) mix with the selected aggregate and (ii) adequately viscous to spread on a road surface. Once it has been applied, the performance requirements change to a rather opposite feature in which the objective is to produce a hard and durable surface which resists the effects of adverse weather conditions and traffic.

### Penetration Grades

At room temperature, bitumen ranges from semi-fluid to solid, so it is normally heated to 150 to 180 degrees Celsius before being spread on a surface or mixed with aggregate. The penetration grade of bitumen describes its viscosity or its stiffness. It is measured in a standardized test in which a fine needle is used to determine the softness of the bitumen. The numeric identifier refers to the depth of penetration in 1/10ths of a millimetre by the needle with a 100g load applied during 5 seconds at 25 degrees Celsius. Penetration grades varies from 50 to 300, 50 obviously being the hardest grade.

Different grades of bitumen are applied




to pavements using a variety of work methods and recipes, depending on the prevalent weather conditions, expected traffic loads and type of aggregate being used. In general, harder penetration grades are used in warm climates and softer grades in cold environments. Open graded aggregate require higher viscosity binders, while more dense and graded material will need a less viscous binder.

Working with these materials at high temperatures involves certain safety risks. It also requires specialised and costly equipment which may not be readily available. Alternatively, the bitumen can be mixed with solvents or emulsified in order to make it workable at normal temperatures.

### Cutback Bitumen

Instead of heating the bitumen to reduce its viscosity, penetration grade bitumen can be mixed with a volatile solvent to produce a binder workable at or near room temperature. Depending on the choice of solvents and the rate at which they evaporate, cutbacks are classified as rapid, medium or slow curing (RC, MC or SC). The cutbacks are produced by adding solvents such as naphtha (RC), kerosene (MC) or diesel (SC), which eventually evaporates,

leaving behind a stiff binder. The code relates to the rate of curing, followed by a number describing the viscosity of the binder. The viscosity is determined using an instrument that measure the time it takes for a fixed amount of binder to pass through a standard size orifice (ranging from 15 to 3000, the lowest being the most fluid i.e. less viscous binder).

As all the solvents are flammable, the use of cutbacks requires stringent safety measures to ensure safe handling during storage and application. Due to the type of cutter, the rapid curing cutbacks are more flammable. The solvents eventually evaporate and are also a source of air pollution. For these reasons they are becoming less attractive. Due to the environmental effects, the use of cutbacks may be restricted and in some places only allowed for patching works.

### Bitumen Emulsions

The alternative to cutbacks is the use of bitumen emulsions, in which the solvent is replaced with water. The essential ingredients in emulsions are bitumen, water and an emulsifying agent. In most emulsions, the bitumen is dispersed in the water which, with the help of the emulsifier, produces a binder with a workable viscosity.[2] After it has been applied to a road surface or mixed with aggregate the water evaporates, leaving behind a film of bitumen at its original viscosity.

#### Specific Features of Emulsions:

- Although emulsions can be used in damp conditions, they should not be used when it rains. They can however be used with wet aggregate;
- As emulsions can be used at ambient temperatures, the need for heating and the risk of over-heating the bitumen is taken out of the equation;
- As they are not heated, it avoids a number of environmental and safety hazards;
- Being applied cold also simplifies transport, storage and usage, with less dependence on sophisticated construction equipment;
- Emulsions also provide improved adhesion to aggregate compared to cutbacks and hot mixes;
- Emulsions tend to be more expensive than cutbacks due the extra amount required to compensate for its water content. It is only the bitumen that provides the binding effect. Using a K1-60 emulsion, a spray rate of 1.7 litres per square metre will only leave behind 1.02 litres of bitumen.

Since emulsions do not require any heating before they are used, they are safer and easier to work with and have less detrimental effect on the environment. As no heating is necessary, they also require less sophisticated equipment when transported and distributed. With water being a significant ingredient in emulsions, they are also less sensitive to humidity.

2: There is also an inverted emulsion in which the water is suspended in bitumen which is commonly used as a primer. Invert emulsion binders normally contain 80 percent bitumen

An emulsion is said to start breaking when the suspended bitumen starts to coagulate. The breaking process can be observed when the colour of the binder changes from brown to black. Eventually, the water evaporates and the bitumen sets, producing a stiff binder.

As emulsions are produced by mixing bitumen and water, these binders do not emit any gases when curing. For this reason emulsions are often preferred to cutback binders as they provide a more environmentally friendly alternative.

Bitumen emulsions are classified according to how rapid they break. There needs to be sufficient time for the spreading of both the binder and the aggregate. Once the aggregate has been mixed with the binder, it is on the other hand desirable to have a rapid breaking process thereby allowing the road to be opened for traffic as soon as possible. As the breaking process is facilitated by the contact with aggregate particles, rapid acting emulsions are commonly used for surface dressings, tack coats, patching and sub-base sealing.

There are two basic types of emulsion, cationic and anionic, referring to the chemical features of the emulsifying process. Cationic emulsions are the most common as they are applicable with a larger variety of rock types, and are available in a variety of types with varying breaking time. Cationic emulsions have a positive charge, which fits well with most aggregates - a majority consisting of negatively charged minerals. The anionic version is normally a slower setting mix, often preferred in slurry seal works. Due to their opposite ionisation features, cationic and anionic emulsions are never be used in combination as this will produce an instant breaking process.

Emulsions are produced by specialist manufacturers, and are sold in bulk or in drums of 200 litres. The most common mixtures contain 60 to 70 percent bitumen. Emulsions have a limited shelf life, after which they start to separate. For this reason, it is important to check its production date and avoid storage longer than 3 months. Drums should be stored lying down so that they can easily be turned to delay the separation process.

### Hot Mixed Asphalt

Hot mixed asphalt is produced by heating both aggregate and bitumen to 170 °C and placing it before it cools and stiffens. Although more demanding in terms of equipment and skills requirements, hot mixed asphalt is in general superior to the cold mixed solutions.

As the hot mix produces a more durable surface, it is often applied on roads with high traffic volumes. High quality hot mixes are produced in large mixing plants from which it is transported to site while still warm. As the mix is only workable while its warm, it is essential that transport, placing and compaction is carried out before the asphalt looses its temperature.

As compared to cold mixes in which solvents need to dissipate in order for

the curing to complete, hot mixes cures immediately on cooling. Due to its intensive demand for heavy equipment, it is often not feasible to use hot mixed asphalt for smaller works. The exception is however when the equipment has already been mobilised for some large-scale works and at the same time can be used for smaller projects in its close vicinity.

Hot mixes can also be assembled on site however the quality control is normally not as good as when hot asphalt is mixed in a plant.

### Spray Rates

Bitumen is applied according to clearly specified recipes, depending on the surface on which it is used and the type of aggregate with which it is mixed. Most recipes refer to spread rates in litres per square metre. The density of bitumen is approximately 1 tonne per cubic metre or 1 kg per litre. With a spray rate of one litre per square metre the layer thickness of the bitumen would then be 1 millimetre.

The ideal rate of application is to apply just enough to secure (i) proper adhesion to the underlying layer, (ii) sufficient bonding between the aggregate particles and (iii) achieve the desired sealing effect. As the strength of the pavement is essentially carried by the aggregate, any excessive use of binder will not contribute to the quality of the pavement. Too little binder will lead to aggregate being chipped away when subjected to heavy traffic. Too much binder causes bleeding of the surface which in turn may result in the binder being picked up by the traffic. This may cause additional damage to the road surface. Low viscosity binders may also start ponding or running off the road – in particular on sections with steep road gradients.

Whether the spreading is carried out using equipment or by hand, the equipment and spread method first need to be calibrated to ensure that the correct amount is applied. When using manual labour, this is simply done by calculating the area to be covered by the contents of one spray can. Hand sprayers are checked by measuring the

time it takes to fill a container with a known volume. When using a tank and a spray bar, it is important to carry out a "dry run" to check that the spray bar releases the correct amount of bitumen.

## Bitumen Bound Pavements

### Surface Treatments

There are a wide variety of bituminous surface treatments. The appropriate choice is essentially dictated by the availability of aggregate and the different forms of bitumen. The table below briefly summarises the most commonly used alternatives.

## Prime Coats

A prime coat is a layer of bitumen applied as a glue to ensure good adhesion to an existing pavement layer or as a means of preparing the surface of an unbound layer. Prime coats are commonly applied at a rate of 1 litre of bitumen per square metre.

Primers are essentially used to make sure that there is good adhesion between the surface treatment and the existing surface or base course. The primer fills the voids of the surface on which the surfacing material is placed. It also binds any loose fine particles and penetrates into the road base materials thereby improving the adhesion between the layers.

Primers with low viscosity are used for dense surfaces such as already existing bitumen or cement-stabilised surfaces. Higher viscosity binders are necessary when priming an unbound coarse surface. A primer also provides temporary protection of an unbound surface from traffic wear until the surface has received its final treatment.

| | |
|---|---|
| Surface Dressing | Surface dressings consist of one or two layers of single size aggregate and a bitumen binder. If a second layer is applied, the size of the aggregate is usually reduced to half of the size used in the first layer. When applied to a gravel surface, it will first need a primer. |
| Otta Seal | This seal is also produced from bitumen and aggregate spread in layers. However it allows for the use of graded material such as natural gravel or crushed rock. Due to the use of a graded material, it requires an increased use of binder. On the other hand it does not require a primer and produces a more durable seal than the conventional surface dressing. Single Otta seals are effective for traffic levels up to 500 vpd. |
| Sand Seal | Sand seals consist of a soft bituminous binder and graded sand. They are generally used in areas where the only available aggregate is natural sands. They provide a light wearing course suitable for low traffic roads less than 100 vpd. The sand seal should be placed on a primed base course. They are also used as a final layer on top of other seals. |
| Slurry Seal | Slurry seals consist of a mixture of fine aggregate, cement and bitumen emulsion and water. The ingredients are mixed in a concrete mixer and preferably laid in two layers, each 5 to 10 cm thick. |
| Penetration Macadam | Penetration macadam is also used as a base course. When applied as a surface layer, it is normally constructed using a layer of coarse aggregate followed by a less coarse aggregate which is then penetrated with a binder. It produces a very sound surface, although with somewhat higher roughness than the above alternatives. |
| Pre mix | This material, consisting of a slow breaking bitumen emulsion and natural gravel is mixed in a concrete mixer and spread while the emulsion is still in an unbroken state. |
| Hot mix | Hot mixes are generally produced in large scale mixing plants, where heated bitumen and graded aggregate is mixed together. In some countries hot mixes are also produced on site in smaller quantities. The advantage of using mixing plants is that the quality of all ingredients as well as the mixing conditions can be closely monitored and controlled. The mix needs to be transported and placed before it cools down. |

## 9.10 Surface Dressing

Surface dressings are a widely used road surface treatment. They essentially consist of a thin coat of bitumen on which a layer of single size aggregate stone is spread. The stone layer is evenly laid with a thickness equivalent to the size of the chippings. As this surfacing method require screened materials, usually made from crushed rock it is relatively expensive unless the source of aggregate is located close to the roadwork site.

Like any other road surface treatment, the main purpose of this dressing is to provide the road with a watertight seal, which is also strong enough to resist the abrasive wear caused by the traffic. It is important to note that the surface dressing is a seal and does not have any significant impact on the bearing capacity of the road.

Surface dressings are applied either as single or double seals. The single seal is appropriate for low-volume roads up to 100 vehicles per day, while the

double treatment is used for medium and heavy traffic and for road sections where the surface abrasion is higher, such as in steep sections. It is generally recommended that double surface treatments are used on non-bituminous pavement layers. The double seal is commonly referred by its acronym DBST – Double Bituminous Surface Treatment.

The existing base should be in good condition before laying the dressing. If the existing surface is uneven, these defects eventually reappear in the completed surface treatment.

The surface dressing is built up in layers, normally starting with a primer, thereby ensuring a good adhesion to the underlying surface. The primer is normally left on the road for 24 hours before spreading the binder (tack coat) into which the aggregate is immediately spread. Both spreading of bitumen and aggregate can be carried out either by labour or by machines. In both cases the rate of spread should be controlled by using calculated quantities over measured areas.

As soon as the aggregate has been evenly distributed, the surface is gently compacted, preferably with a rubber-wheeled roller to ensure that the stone is properly lodged into the binder. Any excess aggregate should be brushed off and collected.

### Chip Spreaders

Although spreading of aggregate can be carried out manually, large surfaces are obviously more effectively surfaced using mechanised equipment. Chip spreaders for surface treatments come in different sizes and sophistication. The most simple and inexpensive versions are attached to the tailgate of the tipper truck. The truck reverses while discharging the aggregate, which is controlled by an operator walking next to the spreader. The rate of chippings discharged essentially depends on the speed of the truck. The quality of the spreading is very much determined by the skill of the driver. Larger and more sophisticated spreaders have metering devices and more advanced feeding mechanisms to ensure an even distribution of the stone.

The binder can be hot bitumen, a cutback or an emulsion, commonly with a 80/100 penetration grade bitumen base. If the binder is spread manually, it is preferable to use an emulsion as it avoids the safety hazards of hot bitumen. The bitumen should not be applied if the surface is damp or moist and certainly not during rainy weather.

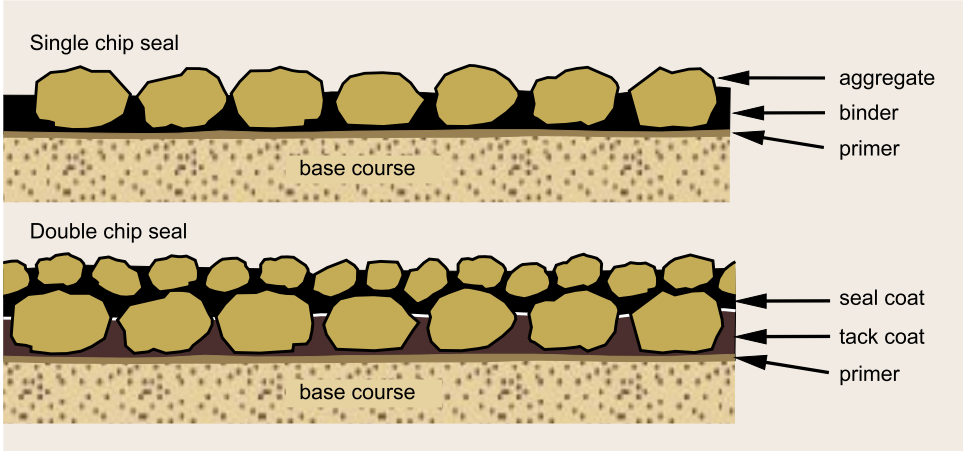
The size of the stone chippings for a single seal is normally in the range of 10 to 14 mm. The aggregate is spread at a rate that ensures that the entire surface is covered after rolling. The exact rate of spread depends on the size and shape of the chippings and needs to be closely monitored on site.

The stone should be clean and dust free in order to adhere properly to the binder. Angular shaped chippings are preferred, however, more rounded material from river gravel can be successfully applied as well.

For a double seal, it is common to use a large size stone in the first layer and thereafter roughly half the size in the

second layer of chippings. This provides the best interlock between the stones in the two layers. The size of the chippings in the first layer is chosen on the basis of hardness of the layer to be sealed. A soft surface will allow for larger chippings to be used as the stone can penetrate into the underlying surface under heavy traffic. Traffic should be allowed to run on the new surface for at least two to three weeks before a second layer is applied.

In a successful surface dressing, a quarter of the stone should protrude



above the binder. If more than half of its size is above the bitumen, there is a risk of the traffic breaking loose the aggregate. With too much bitumen, the surface will bleed and become unstable. Also it will loose the surface texture, which ensures good skid resistance. Excess binder on the road surface may also stick to the tyres of vehicles and cause additional damage to the road surface.

### Slurry Seals

This seal consists of a mixture of fine aggregate, cement, bitumen emulsion and water. It can be mixed in a concrete mixer, producing a thick consistency, which is spread at a 5 to 10 mm thickness. It is normally used in combination with a single surface dressing (Cape Seal), applied as the top layer to produce a less rough surface texture. It is however more expensive than a conventional DBST and requires close quality control.

Although it works best on top of an existing bituminous surface or base course of crushed rock, it can be used on its own on low-volume roads. If it is used as the first surface treatment it should be applied in two layers, on top of a primed surface.

### Sand Seals

In areas with poor availability of quality aggregate, the use of bitumen stabilised sand seals may be the only alternative. Sand seals are less durable than surface dressings and therefore only feasible for roads with low to medium volumes of traffic.

Similar to chip seals, the sand seal requires a primed surface. Equally, a double sand seal will provide a more durable surface layer. After laying the surface, it is useful to brush loose sand back into the wheel paths during the next one to two weeks.

The best result is achieved with coarse angular sands with less than 10 – 15 percent fines. The binder can be a viscous cutback or emulsion. The best result is obtained from using penetration grade bitumen, however, this will require heating both the sand and the binder.

## 9.11 Otta Seals

Originally designed as a measure to reduce surface maintenance of gravel roads, this surface treatment provides a cost-effective alternative to more conventional surface treatments.[3] The Otta Seal consists of spreading a graded material on a thick film of soft binder which is rolled until the binder has worked itself up through the aggregate. The strength of this pavement results from a combination of good mechanical interlocking due to the mixture of different aggregate particle sizes and the bitumen binder. Due to the use of a thick coat of soft binder, there is no need for priming the surface before spreading the aggregate.

What is attractive with the Otta Seal is that it allows for a multitude of soil types to be used as aggregate ranging from natural gravels, river gravel to crusher gravel. In places where processed aggregate are expensive, this seal can provide a cost-effective and durable surface treatment because it allows for a wide variety of sources of material to be used. Its successful performance

3: Essentially a bitumen gravel mix, the name originates from where the original trials and development of this surface type was carried out by the Norwegian Road Administration.

depends on the distribution of binder in the aggregate, achieved by extensive rolling and traffic.

Due to the use of graded material, the completed surface layer has a consistence similar to a hot mixed asphalt concrete. As it relies on a lower viscosity bitumen binder, the seal is more flexible than other seals. With its graded aggregate, providing good interlock between the aggregate particles, it produces a dense and lasting surface pavement.

## Configurations

The Otta Seal can be applied as a single or double layer, and in combination with a sand cover seal. Single layers with or without sand seals are suitable for traffic volumes lower than 500 vehicles per day. With an average annual daily traffic exceeding 500 vpd, the double configuration can be used.

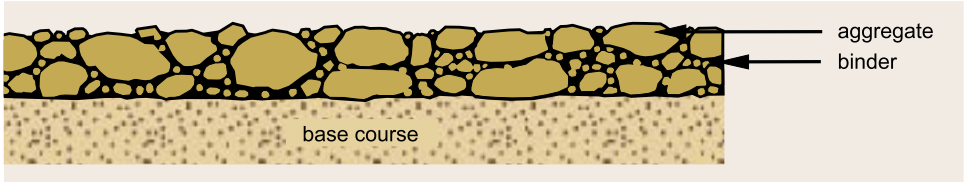
Once the aggregate has been spread, the surface is compacted using a pneumatic roller, thereby kneading the material into the bitumen. The mixing of bitumen and aggregate continues when traffic is allowed onto the surface. Any bleeding of the surface due to excess bitumen is blinded with fine aggregate or sand. With further rolling of the surface and traffic, the fines mix with the graded materials and work into any remaining voids in the graded material.

## Construction Procedures

An essential part of the construction of the Otta Seal is the extensive rolling required. On the day of construction, a minimum of 15 passes with a 12 tonne pneumatic roller is required for the entire surfaced area. For each of the next two days, a similar amount of rolling should be carried out. After the first day of pneumatic rolling, it is useful to apply one pass with a steel roller thereby improving the embedding of larger aggregate. In practice this entails that two pneumatic rollers are available for the full period until rolling has been completed. Traffic should be allowed onto the surface immediately after the initial rolling, as this contributes to the kneading process.

During the first two to three weeks after construction, any aggregate dislodged by traffic is brushed back into the wheel tracks, thereby allowing for a maximum amount of aggregate embedded into the binder. Any bleeding and fatty spots are blinded off with aggregate and preferably rolled into the surface. A work team for blinding may be required during a period of 4 to 8 weeks.

A second layer or a cover seal should only be applied after a minimum period of 8 to 12 weeks, thereby allowing traffic to provide adequate compaction to the initial layer.



## Material Requirements

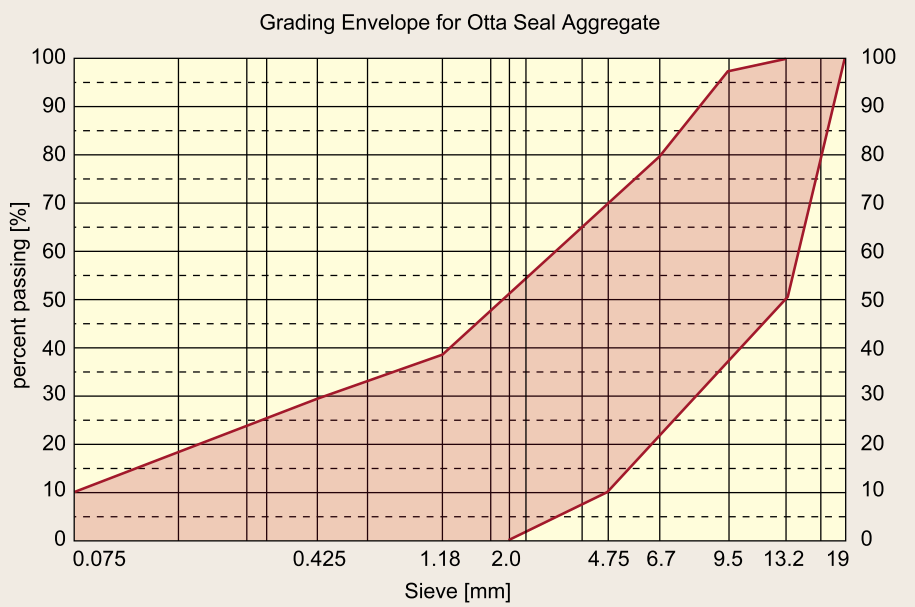
The binder used for Otta Seals needs to be soft enough to (i) coat all the fines in the aggregate and (ii) move up through the aggregate voids when kneaded by rolling and traffic. Furthermore it needs to remain soft for a sufficiently long duration for the entire mixing and kneading process to take place. Finally, it needs a consistency allowing it to be sprayed as one layer.

As with any other bituminous seal, the binder needs to be viscous enough to provide sufficient stability after the initial laying and curing and sufficiently durable to cater for the expected traffic loads.

To meet these functional criteria it is important to choose a binder soft enough to move up through the aggregate when subjected to compaction by rollers and traffic, thereby coating all the aggregate.

On the other hand, the binder must be viscous enough to allow it to be spread in one operation. The most common binder is a cutback bitumen in the MC3000 to MC800 range. The hardest type of bitumen used is the 150/200 penetration grade. Nowadays, also bitumen emulsions are used for Otta seals.

The quality of the seal is very much dependent on the grading of the aggregate. A dense grading, i.e. well-graded aggregate, will stand up to an AADT well over 1000 vpd. Medium and open gradings, containing less fine material, should only be allowed for more limited traffic volumes. Equally, the grading determines the exact binder spray rate, ranging from 1.5 to 2.0 litres per square metre, with the dense grading demanding a slightly higher rate.



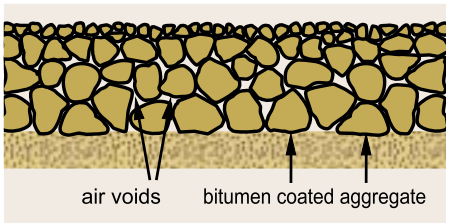

Source: Norwegian Public Roads Administration

## Penetration Macadam

Penetration macadam is a widely used pavement due to its particular strength features. It is used as a surface treatment as well as a measure to strengthen the bearing capacity of a road. As opposed to most other surface treatments penetration macadam also contributes to the overall load capacity of the pavement.

In its broad sense penetration macadam is a general reference to the use of screened coarse materials to which a bitumen binder is added to increase its cohesion and water impermeability. It can be used as a base course as well as surface layer. The most common method of producing penetration macadam is by first placing a layer of coarse aggregate, followed by one or two layers of successively smaller stone. The smaller stone will fill the voids in the largest aggregate and provide improved interlocking.

The surface is then rolled with a relatively heavy roller to ensure that the rock is properly settled and forms good interlocking bonds. Finally the stone is covered with a bitumen binder, which penetrates through the remaining voids and coats the aggregate. Alternatively, the bitumen is applied between the spreading of the different layers of aggregate.




As opposed to water- or dry-bound macadam, fines are not used to fill the voids in the aggregate in penetration macadam.

The cost of this pavement is relatively high, due the use of crushed and screened aggregate and a high binder content - commonly applied at a rate of 5 – 7 l/m². On the other hand it produces a durable pavement suitable for road sections subject to extensive wear.

In a number of countries, the construction of penetration macadam is still carried out by labour-based work methods – including the production of stone aggregate.

Penetration macadam has a rough surface texture. Although this provides good friction for the traffic, it also causes considerable vibration and noise. After the binder has been applied it is common practice to blind the surface

with crusher dust or sand. Alternatively, the surface can be treated with an additional smoother seal.

There exists a multitude of variations on the penetration macadam. In a partially penetrated macadam, the fines in the voids on the surface of a dry or wet bound macadam are brushed away and filled with slurry. This construction method reduces the usage of binder and also produces a smoother running surface.

In slurry-bound macadam, all voids are filled with slurry instead of fines. Finally, the above solutions can be merged into a composite macadam, consisting of a lower portion in which the voids between the large aggregate are filled with fine granular material and the top layer consisting of a bitumen-bound macadam.

### Macadam Pavements

John Macadam devised some of the fundamental principles of modern road construction and on that basis developed a road design still in use today. When building a road, he emphasised that (i) with proper drainage the sub-grade is able to carry the loads incurred by the traffic, and (ii) broken angular stone can form a sufficiently solid riding surface. The design he developed was to first shape the sub-grade with a camber. On top of this he prescribed two 10 cm layers of 76mm broken stone and a finishing layer of 25 mm stone rammed into the interstices between the stone in the layer beneath.

These roads provided sufficient strength for the slow moving horse and carriage, however with the introduction of faster motorised vehicles, the traffic caused the surface stone to loosen. To reduce this problem, hot bitumen or tar was poured on the surface penetrating into the open structure of the pavement and improving the cohesion of the pavement including its surface. This solution was referred to bitumen or tar bound macadam (tarmac), penetration macadam or "penny mac".

## 9.12 Stone Pavements

The use of stone pavements is an old building practice and its use has been found in a number of ancient civilizations including the Romans, Khmers, Egyptians and Byzantine. They are commonly used for their decorative features but are also chosen for their good abrasive resistance to high volumes of traffic.

Although they are more common in urban areas, stone pavements provide feasible solutions to sections of rural roads on which heavy wear is expected, such as on sections with steep longitudinal gradients. They may also provide appropriate surface treatments for road sections through rural villages and communities as well as market places, loading areas, bus stations, etc.

Stone pavements can be produced using the natural shape of the stone and assembling it by hand in its tightest possible positions thereby minimising the size of the joints. Alternatively, the stone can be cut into cubic or rectangular shapes in order to ensure that they are assembled in a tight pattern.

When laying a stone pavement each individual stone is placed manually at the correct position and level using pegs and string line. The work is therefore a labour-intensive activity, requiring limited use of equipment. The main cost of the pavement is related to the supply of quality stone and the labour required to assemble the stone.

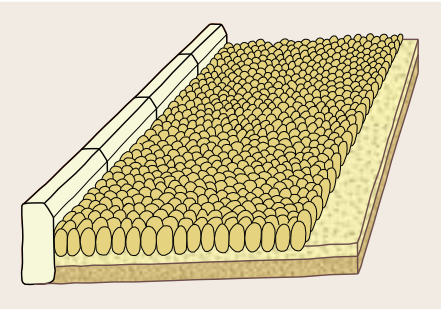
Stone pavements are normally set in a cushion of sand. The sand accommodates any irregularities in the shape of the stone allowing the stone to be assembled with a smooth and level riding surface. The sand should be free of fine material thereby also acting as a drainage cushion for any water entering between the rock. The joints between the rock are filled with fine sand.

The joints will collect finer material and eventually become waterproof. In urban areas, it is common practice to grout the joints of stone paved streets with mortar or bitumen, producing a fully watertight surface.

Unlike other pavements, stone pavements need well-designed edge restraints. This is secured through the use of a larger curbstone that retains the adjacent stone or block pavement in the tight pattern to which it was originally constructed. In urban areas, the curbstone also functions as a means to elevate the sidewalk. Curbstones are either made from dressed stone or concrete.

### Cobblestone

Cobble stone pavements consist of small boulders placed side by side on a bed of sand. The word cobble is a geological term referring to rock with a size ranging from 2 to 10 inches in diameter. Although cobblestone is often confused with dressed stone with a square surface, the origin of this pavement relied on stone in its natural shape and size.



This pavement, usually relying on river stone, was commonly used in the past as street pavement in European cities. Although is provides a durable road surface, its disadvantage is its rough surface texture which results in increased traffic noise and vibrations. Although, this road surface is mainly used in historic areas, it can also be a feasible building material for village streets, market places, and rural road sections with steep gradients – when angular shaped rock is not available.

Like other stone pavements, the stone is set in a cushion of sand. The preferred size of the cobblestone should have a longest diameter of 15 to 25cm with the smallest diameter normally not less than 5 to 10cm. The stone is laid with the longest diameter in a vertical position with each stone placed tightly next to each other. The stone can be arranged in patterns or at random.

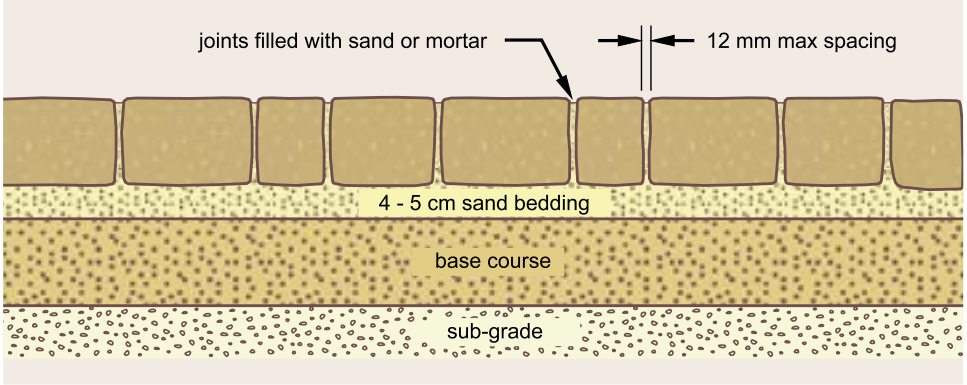
The joints are normally filled with sand. The final surface is compacted with a plate compactor or a small roller. For streets in urban areas, it is common practice to set the stone in a bedding of concrete.

### Dressed Stone

Dressed stone pavements provide a smoother riding surface than when using cobblestone. When using good quality stone, this design produces the most durable road surfaces of all. Once again, it is mainly used in urban areas where high traffic volumes are expected.

In recent years, this surface pavement has received an increased interest not only due to its decorative features but also due to its high durability. When properly laid on a solid foundation, this surface is known to last for more than 30 years without the need for any significant maintenance. This feature is important for a number of key thoroughfare roads in urban areas which when closed for repairs and maintenance causes major traffic congestions.

As this surface option is often applied to roads and streets with high traffic volumes, there is also a need to provide a solid foundation in order to secure the desired lifetime of the entire road (and not only its surface). For this reason, the stone is regarded as merely replacing a conventional surface treatment and is therefore placed on a sand cushion on



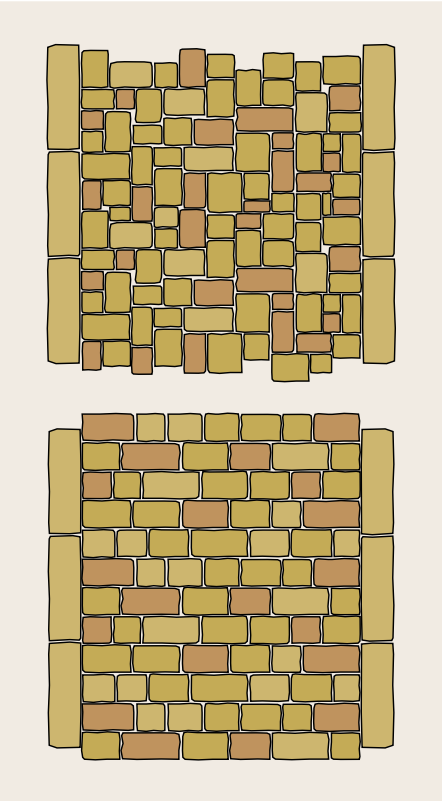

top of an adequately dimensioned base course.

Even when this pavement is used on low volume roads it is important to provide an appropriate base course on which this surface is installed. In this respect, it is important to remember that this is not a watertight surface as the joints allow water to enter into the road body. For this reason, it is important that the sand bedding is constructed with a camber so that water drains off to the shoulders, and that the base course consists of materials impervious to water.

Dressed stone has a rectangular shape, commonly with a length of 14 to 30cm and a width and depth of 14 to 20 cm. The cubical shaped stone, often used to produce intricate patterns, are slightly smaller with a length and width of 8 to 10 cm. Curbstones have a larger cross-section thereby being heavy enough to retain the stone pavement.

The preferred rock for dressed stone pavements is one with a high abrasive resistance and which is easy to cut. Although these may seem conflicting characteristics, some rock such as granite easily splits in three perpendicular planes, thereby facilitating the efforts of dressing the stone. Hard sandstone and basalt are also used for pavements, as they are softer and therefore easier to shape.

The stone used for the surfacing works needs to conform to quality norms



relating to durability and shape. Each stone should be inspected for any crack before placed. An even shape and surface secures a smooth siding surface and allows for tight joints between the placed stone. For this reason, it is good practice to allow for some final adjustments to the shape of the dressed stone after it has been delivered to the work site.

Dressed stone is shaped using traditional work methods such as splitting with plugs and feathers, and securing the final shape through chiselling. Stone can also be cut or sawed, however, this method is far more costly and mainly used when the stone is used for building construction. Although large boulders can be used, the most common source of stone is from quarries. Quarried rock is stronger than weathered surface rock, because better quality rock can be mined from below the surface.

Stone with uniform width is laid in rows perpendicular to the road centre line with a staggered joint pattern. Alternatively, the pavement can be laid using stone with varying length and width, producing a random pattern. If all the dressed stone is of uniform and square size, it can be arranged in various decorative patterns.



## 9.13 Concrete Surfaces

Concrete pavements are commonly used in a number of countries, in particular for roads with high traffic densities. Concrete pavements are referred to as a rigid pavement as the slab acts as a bridge over any irregularities in strength in the layer beneath. They are built either with or without reinforcement. In some countries, the use of bamboo instead of steel to reinforce the concrete has provided successful results, however the durability of this technical design is still uncertain, as it has mainly been applied to low volume roads.

Concrete pavements provide both strength and a durable surface that can cater for high frequencies of traffic. Concrete pavements are commonly found on motorways and streets, which are frequented by heavy loads and high traffic numbers. Concrete pavements are used for both surface layers as well as base courses. Despite the durability of this building material, its high costs should be observed. Being one of the more expensive solutions, it is still surprising to see how widespread its use is. The use of concrete pavements is often advocated for several reasons:

(i) Bitumen has to be imported while cement is manufactured locally and is readily available. The use of cement in preference to bitumen can place less demand on foreign currency resources;
(ii) Bitumen has to be heated and

laid with specialized equipment while concrete can be mixed and placed using simple work methods and manual labour;

(iii) Due to the continuous problem of poor supply of maintenance, the construction of concrete pavements is often favoured, as it requires less surface maintenance.

The use of some bituminous materials creates a need for specialist equipment and skills, which have little application outside the field of road construction and therefore these specialist resources are limited and often only found in government organizations or among large contractors. The use of concrete requires simple equipment and skills more readily available among small contractors. Because of the widespread use of concrete in other sectors there is often readily available equipment and technical skills necessary for this type of pavement works.

Concrete pavements are cast on site using standard construction practices similar to building any concrete platform. This includes erecting the necessary form-work, laying and fixing the reinforcement steel, mixing the concrete and finally making sure that the surface is cured sufficiently before traffic is allowed access.

The concrete pavement requires a sound well drained foundation on which it is placed. Once cured the concrete pavement is a stiff structure, relying on a sound foundation on to which traffic loads are transferred without incurring excessive stress forces in the concrete.

When pouring the concrete, it is important to ensure that moisture from the concrete does not disappear into the underlying layer. This can be avoided by soaking the surface of the base coarse immediately before pouring the concrete or by inserting a plastic membrane.

Concrete pavements are normally constructed with regular expansion joints at intervals of three to four metres along the road. Normally joints are also inserted along the road centre line. It is common practice to build one side of the road at the time, allowing traffic to pass on the other side during the construction and curing period.

Due to its high costs, concrete pavements

are seldom an economically viable solution for rural roads, the exception being certain road sections with steep gradients or where other social and aesthetic concerns are more important, i.e. market places, loading and unloading areas. Due to its good resistance to water, concrete pavements are also used for drift crossings and other road sections on which extensive amounts of water are expected.

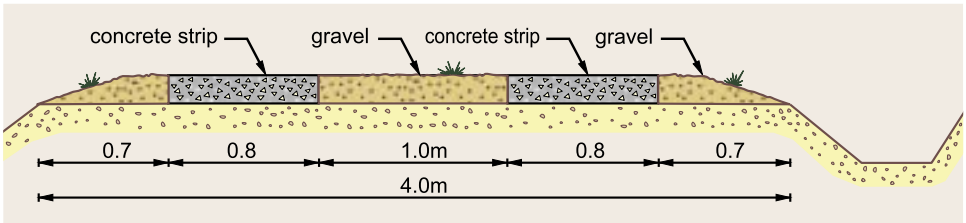
### Block Pavements

A variation to the standard concrete pavement is the use of block pavement or strips of concrete. Block or strip pavements are successfully used for low volume roads on which limited traffic is expected. Once again it provides a durable surface, which can last for a very long time with limited need for maintenance.

For roads with limited traffic the block pavement can be placed directly on a levelled sub-grade. However, if any significant amount of traffic is expected the concrete strips needs to be placed on a high quality sub-base, in order to secure a sufficiently stable foundation.

Concrete strip pavements are mainly used for roads with limited traffic, such as short village access roads. With limited traffic, the gravel surface between the strips is eventually covered by vegetation, thereby providing a clean and dust free road surface.

Although the gravel material between the concrete caters for the normal traffic loads, it will quickly wear off and result in a lower surface level between and outside the concrete strips. This makes it more difficult for vehicles to navigate on and off the pavement when two vehicles meet. For this reason, this design is normally only used where the traffic is limited.



CHAPTER 10

# SOIL MECHANICS

# Soil Mechanics

## 10.1 Introduction

Soils are the primary building material in road works projects. However, before they are used for this purpose, they need to fulfil certain quality requirements. Soils come in a variety of forms and with very different characteristics. Some are suitable for road construction while other materials may be inappropriate. Finally, some

soils, despite their shortcomings can still be used for certain purposes, and if their characteristics are well known, can be improved to meet the performance requirements as a road building material.

Design drawings and technical specifications prescribe the required quality and performance features of soils when used as building materials. These specifications also prescribe how the soils need to be treated in order to perform effectively as a building material (i.e. compaction, moisture content, mixing with stabilizers, etc.). Finally, the specifications provide instructions on how to test and verify the quality and performance of the soils used in the construction process.

Building and maintaining roads at the established performance standards set by the road authorities allows for a wealth of alternative construction methods and as part of this, a multitude of choices of appropriate building materials. The reason for this is to allow the designer to rely to the extent possible on locally available materials to construct the road, with the main emphasis on use of the soils available in the vicinity of the road alignment.

In order to effectively use local materials, it is necessary to understand the basic mechanics of soils and which features are important when used as road building materials. With this knowledge, it is possible to identify appropriate soils and perform the appropriate tests to verify that they conform to prescribed standards.

Identification and testing of soils are done at various stages of the construction process. Simple tests are required when carrying out the initial field surveys to obtain a general impression of prevalent soil conditions and to locate possible sources of good building materials. More advanced tests, providing exact and quantifiable results, are required before the materials are used in the construction works. Finally, it is necessary to test and verify that the materials actually perform according to specifications, once they have been utilized in the construction works. For each of these stages, appropriate test methods have been established in order to monitor the key performance features of the soils.

Rural road works often rely entirely on the use of locally available building materials. Sub-grades are made from existing materials in close vicinity to the road, and surfacing materials are quarried from local borrow pits within reasonable distance from the road. Good knowledge of the local materials and how they best perform can contribute to a cost effective and high quality road works programme.

## 10.2 Definitions

Soils are commonly classified on the basis of how they have been created and based on which minerals they contain. For the purpose of civil works it is more important to establish their composition and the engineering properties of each of the ingredients. In this respect, soils are classified according to the size and shape of the individual particles, which

make up the soil. For road building purposes it is the four fundamental groups consisting of clay, silt, sand and gravel that are commonly referred to. Although various organisations have assigned slightly different sizes to each of these groups, they are essentially grouped according to their main physical properties.

Gravel is a term commonly used for a variety of soils, however in soil mechanics, it refers to soils or soil fractions with a certain grain size. In this context it refers to the larger particles of a soil, with a diameter of 2 to 60 mm.

Sand consists of smaller rock or mineral fragments. Particles classified as sand have a diameter of 0.06 to 2mm. Both gravel and sand particles are visible to the human eye.

Silts consist of very small particles (0.002 – 0.06 mm), appearing soft and floury when dry. Silt particles are too small to be seen without a microscope. Lumps of silt will crumble easily when dry.

Clay consists of the finest particles found in soils (< 0.002 mm). It has a very fine texture, which forms hard lumps or clods when dried. When moist, it is sticky and soft.

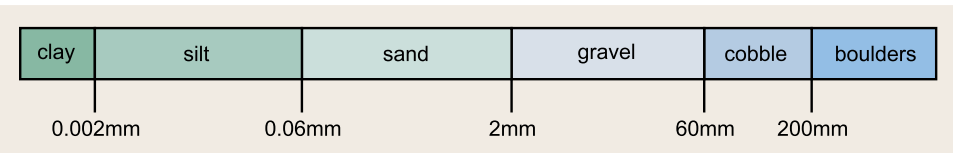
Organic soils have a distinctive odour produced by rotting organic matter such as decayed roots, leaves, grass and other fibrous vegetable matter. They are generally dark brown, dark grey or black. The identification of an organic soil can normally be done by the organic odour of fresh samples. If the sample is dry, moistening and warming it will bring out the odour more distinctively.

## Cohesive and Granular Soils

When it comes to engineering properties, soils are commonly classified into two distinct groups: cohesive or non-cohesive. The cohesive features are caused by the smallest particles in the soil, the clay fraction. When dry, cohesive soils become very hard. When wet, they become plastic and can be moulded.

Granular soils consist of silt, sand and gravel and are non-cohesive. These soils display very different features when applying pressure and water. Due to their non-cohesive features, they cannot be moulded and will easily crumble both when wet and dry.

Granular soils are easily identified through a sieve test since most of the grain particles are large enough to be retained on the sieves. Smaller particles such as clay and silt cannot be distinguished from each other using a sieve analysis. Since silt is noticeably less cohesive than clay, the soil analysis instead distinguishes between these two fractions based on their plastic features.



| | Granular Soils | Cohesive Soils |
|---|---|---|
| Appearance | The grains can be seen or felt. The soil feels gritty when rubbed between fingers. | Feels smooth and greasy when moist. Has a flowery texture when dry. Grains cannot be seen by the naked eye. |
| Water movement | Easy to mix with water. Excess water easily drains out of the soil. | These materials do not easily absorb water. Excessive amounts of water will turn the material liquid. |
| When moist | Very limited plasticity and crumbles easily. | Shows plastic features i.e. it can be rolled into threads and easily moulded. |
| When dry | Limited or no cohesion at all and will easily crumble. | Becomes very hard when dry. |

The wide range of soil types available as road construction materials makes it necessary for engineers to identify and classify the different soils. There are a number of classification systems, some relating to the specifics of local geological features. The table below describes a commonly used classification adopted by the American Society for Testing and Materials (ASTM).

Each of these soil fractions has very distinct physical properties. In most cases, natural soils consist of a mixture of large and small particles. This mixture and the proportion of each fraction determine how appropriate the soils are for road building purposes. The larger soil particles provide strength to a soil, thus providing high bearing capacities, while finer soils provide the adhesive properties needed to contain the soils and make them withstand the abrasive and erosive forces caused by water and heavy traffic.

## Soil Properties

Soil mechanics is the science of how soil behaves and explains how soils with certain features can be used as building materials. This also includes how soils can be improved to become suitable for various construction purposes as building blocks in the base course, surface layers, foundations, etc. For this purpose soils are characterized by a description of their physical properties:

(a) **Permeability** is the ease with which water can pass through the soil. Soil texture, grading and the degree of compaction determine the permeability. Course grained soils are more permeable than fine-grained soils, due to the larger voids between the particles;

(b) **Cohesion** relates to the ability of the material to stick together. Clay provides good cohesion and can act as a binding agent between larger particles such as sand and gravel;

(c) **Plasticity** refers to a soil's compressibility and the degree to which it can be moulded into different shapes. More scientifically, it is defined as the range of water contents within which a soil exhibits a plastic behaviour;

(d) **Compressibility** is the extent to which the volume of the soil

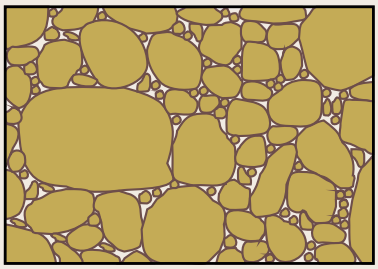
can be reduced when a force is applied to it. Soils with high compressibility have particles that easily reorient themselves to reduce the space of air and water voids.

(e) **Grading** defines the proportions of different grain sizes. Natural soils occur as a combination of soil types with different particle sizes and shapes. A mixture of these soil grades will carry the combined features of each of the soil types, depending on the proportion of each. In order to determine the exact performance of the soil, it is often useful to examine the composition of the soil.

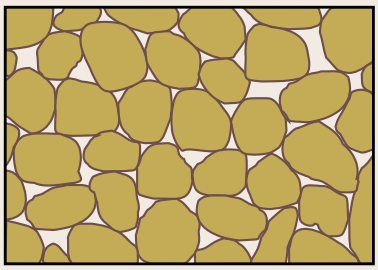
A well-graded material consists of a wide range of particle sizes with an even distribution of all sizes. A poorly graded soil consists of material with too much of some sizes and too little of others. Well-graded materials are stronger and

| Unified Soil Classification System | | | | |
|---|---|---|---|---|
| Major Divisions | | | Symbol | Typical Names |
| Coarse-Grained Soils More than 50% retained on 0.075mm sieve | Gravels 50% or more of course fraction retained on 4.75mm sieve | Clea Gravels | GW | Well-graded gravels and gravel-sand mixtures, little or no fines |
| | | | GP | Poorly graded gravels and gravel-sand mixtures |
| | | Gravels with Fines | GM | Silty gravels, gravel-sand-silt mixtures |
| | | | GC | Clayey gravels, gravel-sand-clay mixtures |
| | Sands 50% or more of course fraction passes 4.75mm sieve | Clean Sands | SW | Well-graded sands and gravely sands, little or no fines |
| | | | SP | Poorly graded sands and gravely sands, little or no fines |
| | | Sands with Fines | SM | Silty sands, sand-silt mixtures |
| | | | SC | Clayey sands, sand-clay mixtures |
| Fine-Grained Soils More than 50% passes 0.075mm sieve | Silt and Clays Liquid Limit 50% or less | | ML | Inorganic silts, very fine sands, rock flour, silty or clayey fine sands |
| | | | CL | Inorganic clays of low to medium plasticity, gravely/sandy/silty/lean clays |
| | | | OL | Organic silts and organic silty clays of low plasticity |
| | Silt and Clays Liquid Limit greater than 50% | | MH | Inorganic silts, micaceous or diatomaceous fine sands or silts, elastic sits |
| | | | CH | Inorganic clays of high plasticity, fat clays |
| | | | OH | Organic clays of medium to high plasticity |
| Highly Organic Soils | | | PT | Peat, mulch and other highly organic soils |

Prefix: G = Gravel, S = Sand, M = Silt, C = Clay, O = Organic
Suffix: W = Well-graded, P = Poorly Graded, M = Silty, L = Clay, LL < 50%, H = Clay, LL > 50%



well graded



poorly graded

compact better than poorly graded materials. Angular shaped particles are preferable, because they will lock together better than round particles.

For most building purposes, it is preferred to use graded materials with an appropriate mixture of small, medium and large size soil particles. When properly compacted, this type of soil provides a dense and impermeable pavement layer. However, poorly graded granular material can in certain circumstances be of use due to its good drainage properties. In other words, soils with different features may serve different purposes and functions in a civil works project.

## 10.3 Distinguishing Soils

It is possible to say a lot about a soil by only looking at it, touching it and smelling it. Soil consists mainly of mineral matter formed by the disintegration of rock, by the action of water, frost, temperature, pressure or by plant or animal life. Based on the individual grain size of soil particles, soils have been classified as gravel, sand, silt and clay. Before any proper tests are carried out, the following preliminary identification can be done at the source where the material is located.

### Grain Size

It is easy to establish whether the soil consists of coarse or fine material. Coarse material such as stone and sand is detectable by just looking at the size of the particles. Sand also feels gritty when rubbed between two fingers. By squeezing larger particles between your fingers, it is possible to establish whether these are solid particles or lumps of finer materials.

### Organic Materials

Organic materials are most likely to be found in the layers closest to the surface. The thickness of the top layer varies, but in most cases the organic material is found in the top 20 to 30 centimetres. Large pieces of organic material such as dead roots and leaves are easy to detect, however, if it is sufficiently decomposed it may be of finer texture. When the soil smells earthy or of plants, it is likely to contain a considerable amount of organic materials.

### Silt/Clay or Sand/Gravel

Dry soils which contain a large portion

of sand and gravel feel course and gritty, while dry clay feels hard and smooth. Water added to clean sand and gravels sinks in immediately without making any mud.

Dry silt feels floury and disintegrates into a fine powder when rubbed between two fingers. When wet, sand and gravel do not stick to the fingers, while wet clays and silts feel sticky and will stain the fingers. While silt is easily removed, clays leave a crusty dry residue, which is harder to remove from the fingers.

Sand and gravel with little clay may still soil the hand when kneading a moist sample, however it will not contain enough clay to allow a lump or ball to be formed. With higher clay contents, a ball can easily be shaped in your hand and also stands up to some pressure when pinching it. With lower clay contents, the ball crumbles more easily (ref. definition of plasticity).

The size of particles determines to a large extent the properties of a particular soil (in addition to water and air contents). As most soils consist of a mixture of particles of varying sizes, the proportion of stone, sand, silt and clay in a soil therefore determines to a great extent its properties and behaviour when exposed to water and pressure (i.e. compaction or traffic). The following table describes some of the key features of the various soil fractions.

| Type and effect in soil mixtures | Shape | Cohesion | Plasticity | Permeability | Compres-sibility | Volume change |
|---|---|---|---|---|---|---|
| Stone contributes to stability and strength | Various | None | None | High | Little | None |
| Sand provides strength and stability | Angular or rounded | Apparent when damp | None | High to medium | Slight | Slight |
| Silt contributes to instability, especially when vibrated or wet | Angular or rounded | Very little | Slight to medium | Medium to low | Slight | Medium |
| Clay provides strength by cohesion, but is unstable due to its plastic features | Plates and sometimes rods | High | High | Low | High | Consi-derable |

## 10.4 Simple Field Tests

Many, if not most soils are mixtures of gravel/sand/clay or silt/sand/clay. Before using them for road building purposes, it is necessary to establish their exact performance characteristics, i.e. their strength and resistance to the wear and tear caused by traffic and weather – and the combination of the two.

Soil testing is therefore an essential element in the process of selecting the right quality building materials. Before the soils can be used, they need to satisfy certain minimum performance requirements. When soils are used in fills and as part of the road pavement, they are subjected to various treatments to improve their performance, such as compaction, mixing of soils, use of bitumen or other chemicals. In order to prescribe the optimal approach and work methods to secure the desired performance of these building materials, the exact type and characteristics of the soils need to be established.

Material testing is also a crucial quality control after works have been completed to ensure that prescribed quality standards are achieved, and that the road or a specific component of it meets intended performance requirements.

Before carrying out a comprehensive laboratory analysis of a large number of soil samples, it is useful to first identify soils likely to meet the prescribed specifications. Using simple field tests it is possible to determine the main properties of the soils and thus obtain a rough picture of the quality of available materials in the vicinity of the road. By applying these field tests it is also possible to screen out unsuitable soils. Laboratory test are time consuming and expensive. By applying some simple tests in the field, the chances are better in terms of selecting material sources which eventually meet the specifications when the full and proper laboratory tests are carried out.

Field tests provide an initial indication of the properties to be expected from a particular soil. Laboratory tests are still necessary to determine the detailed soil classification and its exact properties. The following tests provide simple methods to determine the proportions of gravel, sand and fine particles in a soil sample.

### Touch and Feel

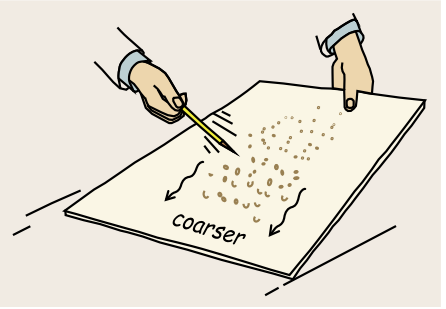
A lot can be said about a soil just by visual inspection, taking a sample and moulding it in the hand. Larger particles are clearly visible and smaller sand particles can easily be detected by touch and by rubbing the soil between two fingers. A gritty feel of the sample indicates the presence of sand and gravel. Fine sand does not stain the fingers, as opposed to soils with a certain clay content which leaves a stain.

If, after drying, the sample retains its shape, it can be assumed that the soil contains a significant amount of clay.

A flat thick piece can also be made from a moist sample. By trying to penetrate it with a pencil will indicate the contents of clay. If the pencil penetrates easily, the material contains too much binder or clayey material. If it is difficult to penetrate, there is a good mixture of fine and course materials that interlock well.

### Vibration Test

The test consists of first placing a dry sample on a board or a piece of cardboard. When lifting the board at the end and tapping it slightly, the particles separate since the difference in weight causes the finer ones to stay high and the coarser ones to move downward.




If there are a lot of different fractions between the largest and the smallest, the sample is well graded. If only a few sizes can be seen, the sample is single-sized or poorly graded.

Single-sized materials do not compact well, because there are no suitably small-sized particles to fill the empty voids between the bigger particles to produce a good mechanical interlock.

### Settling Test

The settling test provides a simple method to determine the proportions of the various soil fractions. A sample is placed in a glass jar with straight sides. Approximately half the jar is filled with a sample of the soil. Add water until the jar is three-quarters full. Adding some salt to the water speeds up the settling of the finer material. Shake the jar, and then let it settle.

The gravel and coarse sand fractions will settle immediately. The finer sand settles more slowly, taking approximately half a minute. The silt fractions will remain in suspension for as much as an hour before settling, while the clay fraction remains in suspension for a longer time. The approximate quantities of each size can be seen as layers in the sample.

### Cohesion Test

To determine whether a soil contains a high quantity of silts or clays, a handful of moistened soil is moulded into a ball. When silts or clays are present, the ball stays together and your hands are stained. If the sample contains only fine sand, the ball will stick together but crumbles easily when applying pressure.


If the sample contains only coarse sand and gravel, the material cannot be moulded at all.

## Silt or Clay

The above tests show how to determine the proportions of coarse and fine particles and define whether silt or clay is present. For road building purposes it is important to have a well-graded material, with a large portion consisting of gravel and sand. In addition, the soil should contain some clayey materials in order to bind the particles together. As seen in the cohesion test, the clay acts as a binding agent between larger particles.

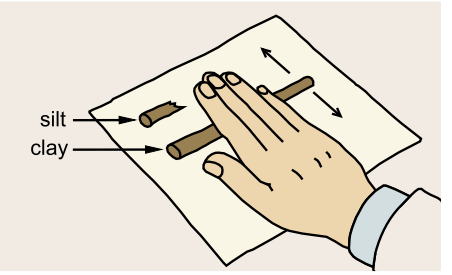
Silt and clay have very different features, however both fractions are too small to see with the naked eye. The clay content in a soil acts as a binder, as opposed to silt, which has very little cohesive features. Silt becomes powdery when dry and does very little to keep larger particles together.

In order to test the soils for clay or silt, it is useful to separate the fine particles from the larger fractions. This can be done using a sieve and discarding the larger particles. Another alternative is to take the sample jar from the settling test and let it dry in the sun until almost all the water has evaporated. With a spoon, it is then possible to remove the fines from the top of the sample.

The following tests are designed to define the clay and silt proportions within the fine fractions of soils.

## Moulding Test

When moistened, soils with high clay contents can be moulded into a thread. Moist silt, however, will crumble or form short threads. The moulding test is also used to measure the plasticity of a soil sample. By varying the amount of water in the sample and observing its behaviour when being moulded into a thread determines the plastic limit of the material. A plasticity index can be

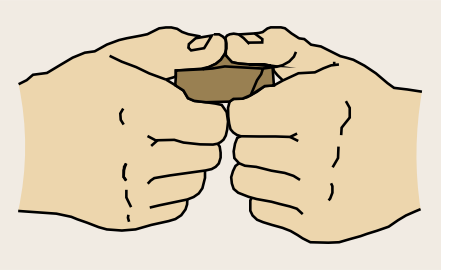



established by measuring the lowest and highest moisture content within which the soil sample can be moulded.

High plasticity indexes indicate a rich clay content, while lower plasticity indexes would indicate contents of other soil fractions such as silt and fine sands instead of clay.

### Dry Strength Test

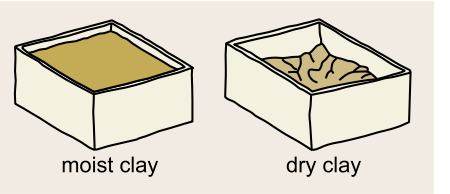
In this test a sample is taken, which has been properly dried. An attempt is then made to break it using the thumb and forefinger of both hands. If it is possible to break it, an attempt should be made to crumble the sample between two fingers.



If the sample can hardly be broken and cannot be powdered by finger pressure, it will consist of a highly plastic soil. If the sample can be broken and powders more easily, the material is less plastic. Soils with no plasticity have very little dry strength and crumble easily when picked up and applying the slightest pressure.

### Shrinkage Test

A matchbox is filled with a well moistened sample of fines and allowed to dry out. If there is a high clay content in the soil, the sample will crack and shrink when it dries. Silt will not shrink, but tends to crumble after it has dried.




### Bite and Grit Test

This is a quick and useful method to determine whether a soil consisting of fine material is made up of sand, silt or clay. It essentially consists of taking a pinch of the material in your mouth and grinding it between your teeth to determine the size of the soil particles. The largest particles, also visible to the eye, are the sand particles. The silt grains are much smaller, so they do not feel nearly so harsh between your teeth. They are not particularly gritty although their presence can still be detected. Clay is not gritty at all, but feels smooth and powdery like flour between the teeth.

Most soils are mixtures of various soil types. This means that the result of the tests described above can only provide rough indications about what can be expected from these soils. Laboratory tests are necessary in order to establish the exact composition and properties of the soil.

## 10.5 Soil Sampling

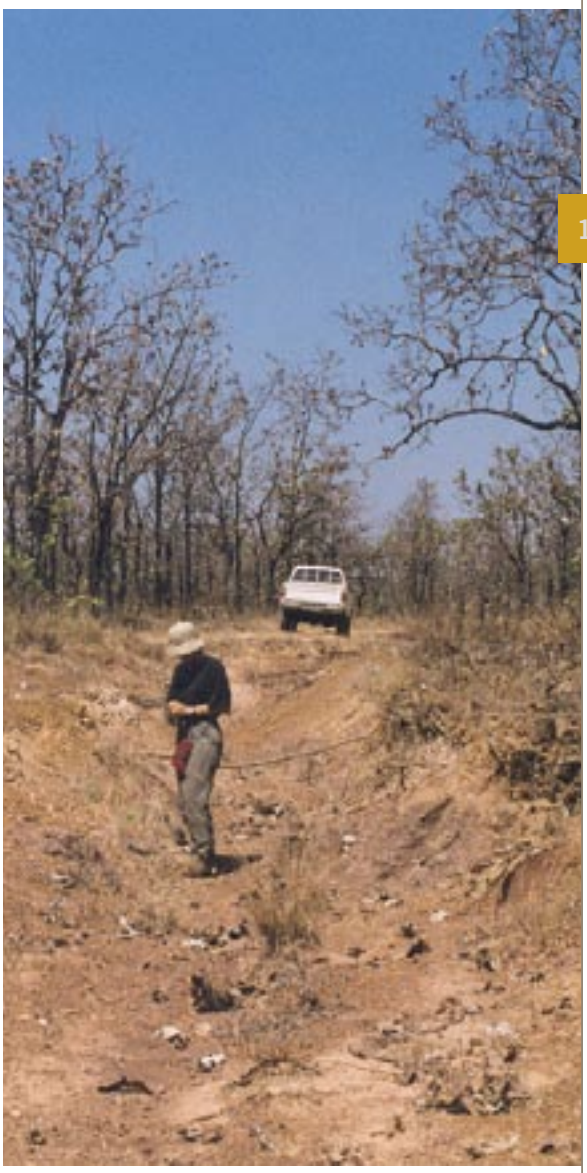
### Soils as Road Construction Material

Soils form an integral part of the road structure as it provides support to its foundation, as well as being used as a building material when constructing the base course and other pavement layers. Soils are also used for building fills and embankments. The fills need to provide a uniform and stable foundation on which the road pavement is placed. The sub-grade must provide adequate support to the pavement also in adverse climatic and loading conditions.

Soil is also used as an ingredient in engineered pavement layers such as water-bound macadam, various types of surface treatments and, last but not least, in gravel surfaces. Soil is therefore considered as one of the principal road building materials. The foundation of structures, such as embankments, culverts, bridges and retaining walls, rests on soils and their stability depends on the soil strength.

Different types of soils behave differently when exposed to water. Some soils are highly permeable and easily absorb water. Some soils are easily eroded when exposed to surface water. These features are important to consider when designing the drainage system. Equally, the stability of side slopes and cuts are dependent on the cohesiveness and permeability of the soils.

Knowledge of soil properties is therefore essential for the selection of appropriate materials for fills, pavement layers, drainage designs and foundations for structures.



Some soils are not suitable for road construction. Before building a road it is therefore important to find out what kind of soils are available along the planned alignment. In most cases local soils will provide the qualities required, however, marshy areas, steep slopes with unstable soils and rocky terrain are best avoided if possible.

If the road cannot be realigned, it may be possible to improve or stabilise the soil. This can be achieved by mixing the poor soils with a stronger type of soil or materials with a complementary soil gradation (see Chapter 9). Chemicals such as cement or lime can also be used to improve soil properties. Some soils may be adequate if a protective surface layer is provided. If none of these remedies are feasible, the final solution may be to remove the unsuitable soil and replace it with imported materials. A good knowledge of soil mechanics will assist in judging what to do in different circumstances.

### Material Survey

Material surveys form an integral part of the design and planning of rural road works. Accurate information needs be gathered about the suitable sources of all relevant and naturally occurring materials (i.e. stone, gravel, sand, etc.). The strength and physical characteristics of the soils are evaluated based on the result of field tests as well as tests carried out in a laboratory. Information relating to good soil sources may be available in the form of quarry charts and experience from previous civil works in the area. In other cases, it may be necessary to conduct fresh surveys to identify appropriate sources of material.

Knowledge about the availability and cost of imported materials is necessary for preparing reliable cost estimates and choosing the most appropriate technical designs. The use of local materials reduces transportation and generally leads to lower costs. Besides the use of crushed stone, locally available soft aggregates such as gravel and laterite are commonly used for rural road works. Where the local materials are inferior, materials need to be imported. It is then essential that the selected technical solutions consist of importing materials from sources that are still within a reasonable distance from the work site.

The material survey also needs to cover the demand for aggregate for other purposes such as mortar and concrete

for structural works, as well as bitumen based surface pavements.

Along the road alignment, surveys are carried out to assess the quality of the soils which can provide a good foundation for the road, and to which extent the soils in the vicinity of the road are appropriate as fill material.

The frequency of soil sampling is very much dependent on how strict the performance requirements are for the sub-grade and fill materials. Equally, in areas where the soils properties seems to be uniform, the frequency of testing can be reduced to selecting some few representative samples. Instead, it is more important to look out for any changes in the soil properties along the road line and establish the border points where different types of soils appear.

During the road alignment survey, it is also important to look closely for problem areas such as marshy and water logged areas or rocky terrain. Some areas contain soils that cannot be used as road building materials and will not provide sufficiently strong foundations for the road and its structures. Rather than replacing these local materials with imported soils, it may be more feasible to realign the road to areas with better soil conditions.

When material sources such as gravel quarries and borrow pits have been identified, representative samples are taken for laboratory testing. When selecting the material sources it is also important to make an assessment of the quantities of appropriate material available. Soils with acceptable quality are often found in layers. When surveying the material sources, it is important to establish the exact depth and borders within which the material has an acceptable quality. These borders should be confirmed by testing samples from various locations in the quarry.

Finally, after a quarry has been opened and materials are supplied to the work site, quality tests are once again carried out as a final check to confirm that the road is being built using proper materials.

The samples collected are commonly evaluated for:

- particle size applying a sieve analysis,
- liquid limit and plastic limit,
- maximum dry density and optimum moisture content, and
- bearing strength.

## 10.6 Laboratory Testing

Although a good deal of information can be obtained through simple field testing methods, it is the tests carried out in a laboratory, using standardised equipment and procedures which confirm the quality and the appropriateness of a soil as a potential road building material. For this reason, laboratory testing of materials is also included in the preparatory stage as part of the design and planning activities. During works implementation, laboratory testing forms part of the quality assurance measures. The type and frequency of tests are normally prescribed in the works specifications.

Some countries have chosen to develop their own test procedures, while most refer to industry standards developed by institutions such as the American Society for Testing and Materials, ASTM and the British Standards Institution.

### Sieve Analysis

The larger particles are the main structural members of the pavement; however, if the soil only consists of large particles there will be a considerable amount of unfilled voids between the particles. The fewer voids the mixture has, the more dense the pavement and, therefore, the more durable it is. Ideal density is obtained by filling the voids between the largest particles with smaller particles and so on, right down through the whole range of sizes from coarsest to finest.

The particle size distribution is by far the simplest way of broadly classifying a soil in terms of it being granular, medium grained or fine grained. By passing a sample through a number of sieves with different size mesh, it is possible to separate the particles according to their size. By weighing the remaining material on each sieve, the exact distribution of sand, gravel and fine materials is established.

The sieves are fitted with wire screen with uniform, specified openings. A sieve analysis is performed by shaking the soil through a stack of standard sieves with varying mesh size. The sieves

used for the analysis are defined through the standardised test procedures that form part of the work specifications.

The number of sieves and mesh size used for this test varies, depending on the purpose of the soil test, i.e. what the material is intended for. For rural road works, the main concern is to establish a rough picture of the grading, determining whether there is a good distribution of sand and gravel and the amount of fines. The exact sieve sizes need to match the ones mentioned in the soil specifications.

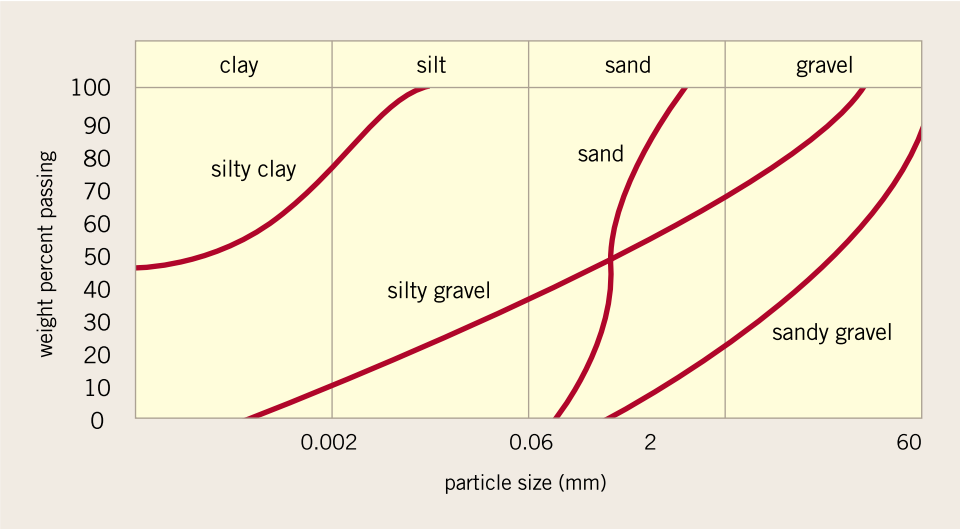
The material needs to be properly dried before it is sieved and any lumps should be carefully crushed without breaking the individual particles. While a mechanical shaker is generally used in well-equipped laboratories, manual shaking of sieves is considered sufficient if carried out for a period not less than three minutes.

Once the soil is separated into different sizes, the remains in each of the sieves are weighed and plotted into a graph. Graphs depicting the soil distribution are commonly presented in a logarithmic diagram in which the fractions from the individual sieves are presented as a weight percentage.

| Gravel Specifications | | | |
|---|---|---|---|
| Sieve size [mm] | Percentage passing | | |
| | Nominal maximum size | | |
| | 37.5mm | 19mm | 9.5mm |
| 37.5 | 100 | - | - |
| 19 | 80-100 | 100 | - |
| 9.5 | 55-80 | 80-100 | 100 |
| 4.75 | 40-60 | 60-85 | 80-100 |
| 2.36 | 30-50 | 45-70 | 50-80 |
| 0.425 | 15-30 | 25-45 | 25-45 |
| 0.075 | 5-15 | 10-25 | 10-25 |

Source: Transport and Road Research Laboratory

Soil curves provide good graphical images of the soil particle distribution. It enables engineers to quickly classify the soil and make a preliminary assessment of its suitability as a building material. The soil distribution curves also clearly shows whether a material is well graded or not. Steep curves



present soils with limited particle size distribution, in other words, most of the soil particles are of similar size. On the other hand, soils with a less steep gradient contain a larger variety of particle sizes and represent a well-graded material.

Specifications for pavements such as the base course and gravel surface layer will prescribe materials with a certain percentage of fractions left on each of these sieves. Alternatively, the specifications prescribe a coefficient describing the gradient of the soil curve from the sieve analysis.

Gravel used for surfacing works is prescribed with a higher content of fines than is accepted for gravel used as a base course. The reason for this is that good surface gravel needs a certain amount of plastic material, acting as a binder in the predominantly granular material.

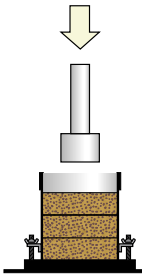
## Compaction and Density Tests

Compaction is applied to road building materials in order to increase density and thereby improve essential engineering properties such as strength and permeability. Higher densities are achieved when the soil particles are packed closer together. Compaction is carried out by rolling or tamping the soils, using various types of construction tools and equipment. The degree of compaction needs to be specified and is often compared to the degree of compaction which can be achieved on the same soils using standardised test methods in a laboratory.

In the laboratory, compaction is carried out by placing the soil into a standard size cylinder and dropping a standardized weight onto the soil from a known height for a specified number of times. The amount of tamping of the soil sample is referred to as the compactive effort.

Highway authorities prescribe how this test is carried out, with detailed descriptions of the laboratory equipment and how the materials should be treated. Some countries have developed test methods appropriate for local soils, while most countries rely on internationally established test methods.

The most common procedure for analysing the behaviour of soils when compacted was developed by R.R. Proctor in 1933, and is commonly referred to as the standard proctor test. The test consists of compacting a soil sample by dropping a 2.5kg hammer with a 50mm diameter head from 300mm above the sample. The sample is compacted in layers, each receiving 25 blows.



In order to reflect current compactive efforts achieved on modern civil works sites, a modified proctor was introduced, which consists of the same test method, only increasing the compactive energy applied to the soil sample (more than four times increase in compactive effort).

The result achieved in the laboratory is then compared to the results of the compaction carried out on the work site. Work specifications normally

prescribe the degree of compaction as a certain percentage of the achieved density in the laboratory test, either using the standard or modified proctor test. Rural road works commonly prescribe the compaction works to achieve a minimum density of 95 percent Modified Proctor.

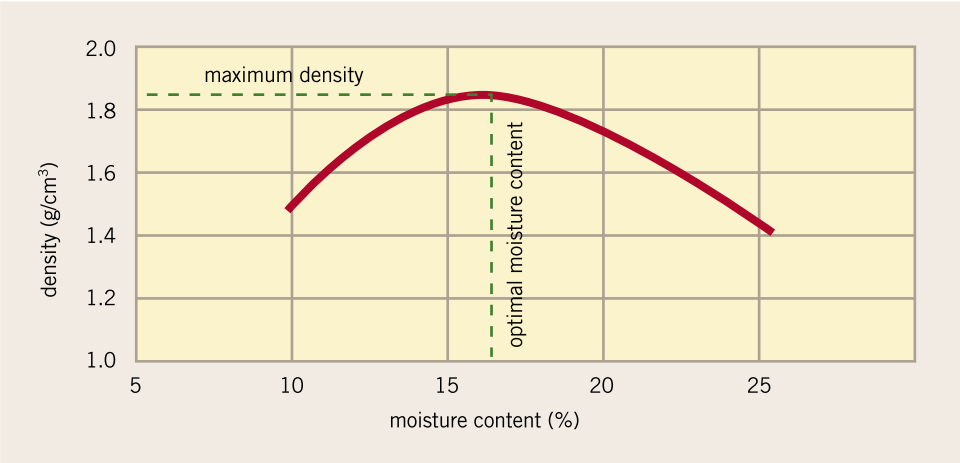
### Optimal Moisture Content

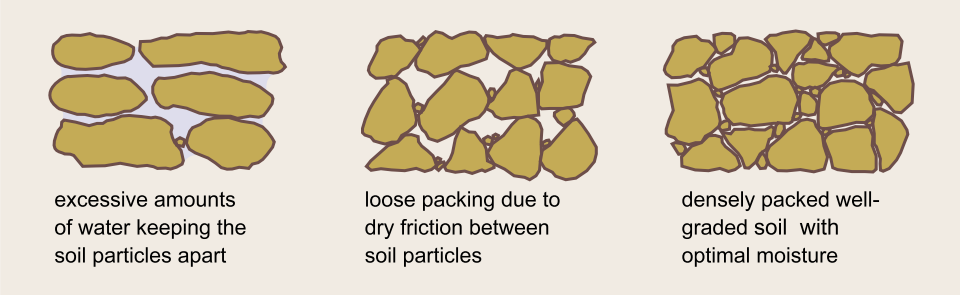
Having a certain amount of water in the soils improves the effect of compaction and increases the resulting density of the material. The highest density achieved is referred to as the maximum density. Once the maximum density is achieved any further increase of the moisture content in the soil will result in a lower density. This amount of moisture at which the soil achieves its highest density (and highest level of compaction) is referred to as the optimal moisture content (OMC).

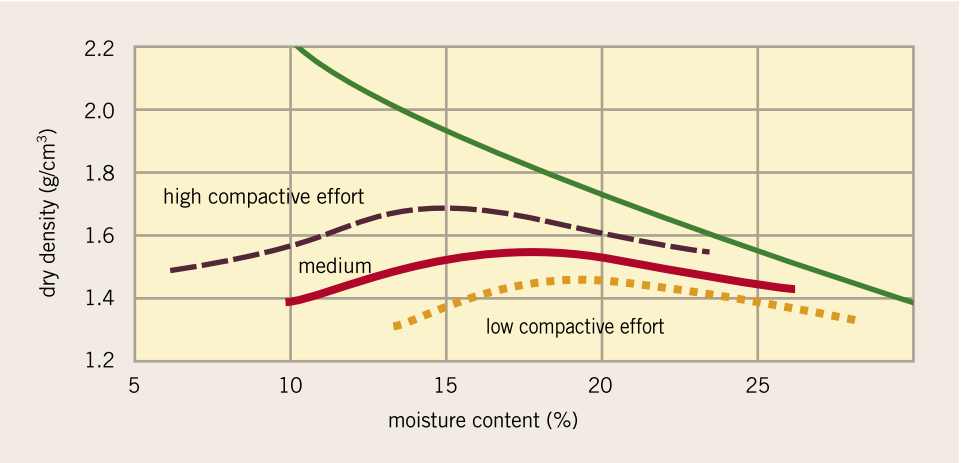
For a given compactive effort, the OMC is the water content at which the soil becomes sufficiently workable to cause the soil particles to become so closely packed that most of the air is expelled.

The explanation of this effect, is that the water coats the surface of the soil particles and serves as a lubricant, thereby reducing the friction between the soil grains and allowing the compactive forces to become more efficient in packing the soil grains together.

If the moisture content is not sufficient to provide the necessary lubrication, the resulting density will be lower because






the compacting force is not enough to overcome the friction between the soil particles. When the water content exceeds the optimal amount, the water will interfere with the packing of the soil particles and the resulting density is less than the optimal.

For road works, it is desirable to work the soils when they contain this optimal level of moisture, thereby ensuring that the best possible effect is achieved from the applied compaction, and thus reaching the targets set in work specifications. Control of moisture during compaction can be carried out visually by tightly squeezing a sample of the material in the hand. The material should be moist enough to stick together without any visible sign of water coming out of the sample. If the material disintegrates, it is probably too dry for compaction. If the soil sticks to the hand, it is too wet.

Each compactive effort for a given soil has its own optimal moisture content. When the amount of compaction is increased, the maximum density generally increases and the OMC will

decrease. In practical terms, this implies that there will be less demand for water, when applying higher compaction efforts.

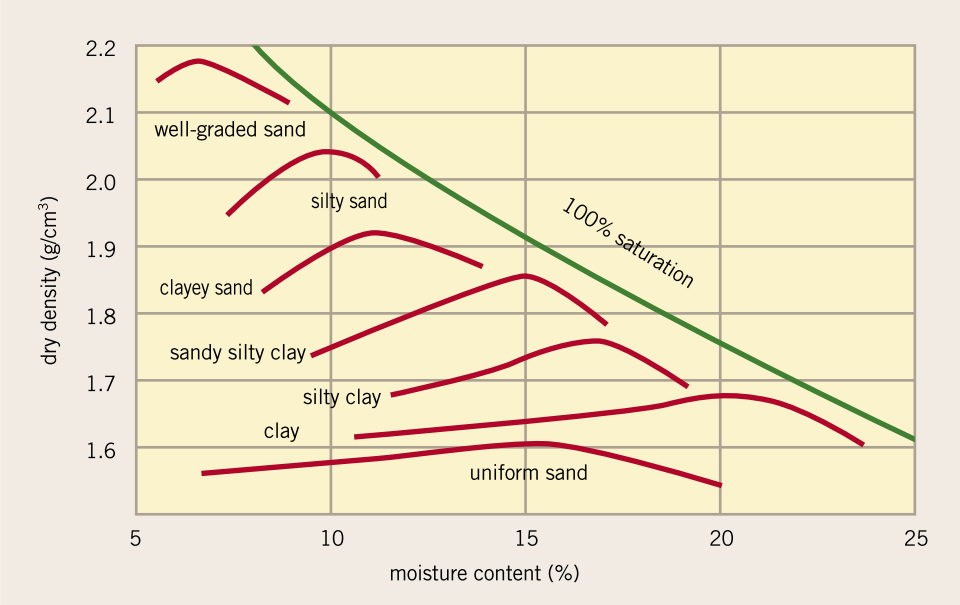
Well-graded granular soils normally give the highest densities, in the range of 1.8 to 2.2 g/cm³, as compared to clayey and silty soils, which are in the range of 1.4 to 1.8 g/cm³.

Depending on the soil type and its contents of clay, sand and gravel, the optimal moisture content will vary between 5 and 35 percent. Granular materials generally reach optimal moisture content at 5 to 15 percent water, as compared with clayey and silty soils, which have an OMC from 20 to 35 percent.

The maximum density does not imply that there are no remaining voids between the soil particles. It is simply the resulting density achieved when applying a certain amount of compaction. The point of 100 percent saturation is a theoretical limit, as there will always remain some air trapped inside the material.

What can also be noted is that different soils react differently to compaction when the moisture content is lower than the optimum. Well-graded granular materials react sharply to slight changes in moisture, resulting in significant changes in the achieved density. Clays or clayey soils may be compacted at a wider range of moisture contents and still achieve a result close to the maximum density. However, if soils with high clay contents are compacted at moisture contents higher than the OMC, there is a risk that the clay becomes plastic and unworkable.

To obtain the desired degree of compaction, it is often necessary to add water to the soils used for embankments, fills and gravel surfaces. As different soils require varying amounts of moisture,

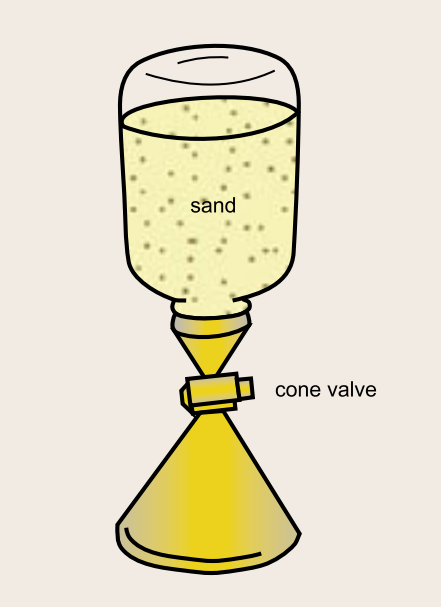


the watering process should be closely monitored by competent technical staff. When materials are stockpiled for a period of time before they are spread and compacted, there will be a demand for more water.

The most common watering method is by sprinkling the loose material after it has been spread before it is compacted. After the sprinkling has been carried out, it is important to allow sufficient time for the water to soak the material in a uniform manner. To reduce the amount of evaporation in hot and sunny environments, the watering activity can be carried out at the end of the workday, commencing compaction works the following day.

### Controlling Compaction Results

Through laboratory trials, it is possible to establish the optimal moisture content and maximum density for a given soil. On this basis, it is possible to establish clear compaction targets for the road works site. However, a control procedure must be in place to ascertain whether the compaction carried out on site actually produces the desired densities.



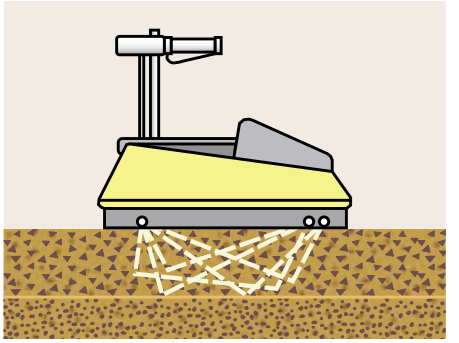

Density testing on site is commonly carried out using the sand displacement method or a nuclear moisture density meter. Today, some compaction equipment is fitted with density measuring gauges, monitoring the resulting density on a continuous basis.

### Sand Displacement Method

This test essentially consists of digging out a sample of the compacted material and using calibrated sand to determine the volume of the hole from which the sample was removed. The excavated sample is analysed to find its weight and moisture content, and with the volume established using the replacement sand, the density can easily be calculated.

### Nuclear Moisture Density Meter

This instrument contains sealed radioactive materials, which emits radiation which a detector in the meter can count when it is passed through the soil. This count can be translated to density. The moisture content is determined by measuring the hydrogen concentration in the soil. Counts or



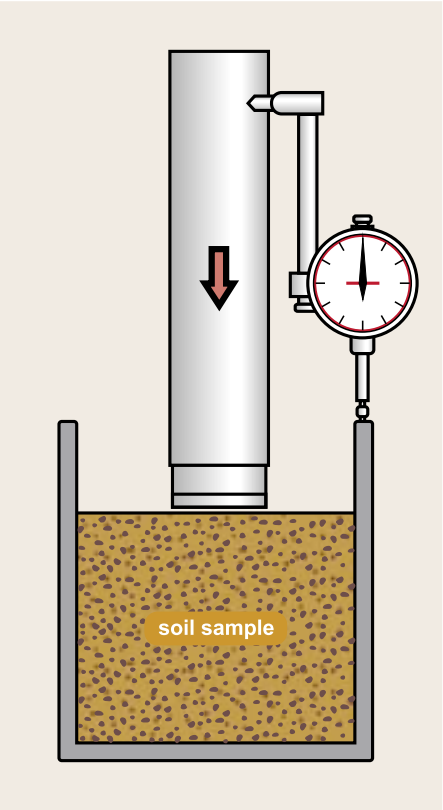
readings are obtained and used with a calibration chart to determine the wet density and moisture content.

### Material Strength

When assessing the strength of soils for road building purposes, it is important to consider the behaviour of the soil in the completed structure, especially at the time when the stability and the performance of the structure is most critical. This would in most cases be during the rainy season, when the road and its foundation are exposed to excessive amounts of rain and floodwater. During this period, the degree of water saturation in the soils is increased by water permeating into the road body. The designer must therefore not only consider the strength and compressibility of the soil during the ideal conditions when it was constructed, but also in a worst case scenario when it is exposed to traffic and adverse weather conditions.

### California Bearing Ratio

This test is widely used to measure the physical strength of soils. It was first developed by the California State Highways Department – hence the name. The test consists of forcing a standardised size metal cylinder into the soil sample and measuring the force required to achieve a specified rate of penetration. Before carrying out the CBR test, the soil samples are compacted to maximum density following a standardised procedure such as the Standard or Modified Proctor and soaked in water until they are fully saturated.




The CBR rating was initially developed for measuring the load-bearing capacity of soils used for road building purposes. Actually, what the test measures is the shear strength of the material when it is soaked with water. CBR tests are also carried out on sub-grade soils to establish their capacity to support the road body and its traffic. Together with traffic projections, it is then used as a basis for calculating the required pavement thickness.

The basic CBR test is carried out in a laboratory, however, appropriate field-testing equipment such as a dynamic cone penetrometer allows for measuring the shear strength in soils on site.

The actual CBR value is a percentage of a standard value obtained from

compacted crushed rock. High CBR values indicate good building materials. Well-graded granular soils have CBR values from 20 to 80 percent, while clayey soils and poorly graded fine sands will have lower values ranging from 2 to 10 percent. The minimum CBR requirements for gravel surface materials are commonly found between 15 and 20 percent, with the material compacted to 95 to 98 percent Modified Proctor.

## Strength and Shape of Gravel

The larger particles are the main contributors to the physical strength of a material. Tests have therefore been designed to evaluate how well the larger particles in a soil will stand up to the impacts and abrasion caused during the production, spreading and compaction and finally by the road traffic. These tests basically consist of various methods of breaking down the material in a controlled environment and measuring the extent to which the material has been destroyed.

The strength of a granular soil is also dependent on the shape of its particles. For most building purposes, soils with angular shaped grains are preferred to materials in which the grains have rounded or flaky shapes. Cubic angular-shaped particles with a rough surface texture are best as they provide good stiffness and strength by interlocking well with one another. Rounded particles do not interlock as well and will therefore not produce an equally stiff and cohesive pavement. Angular grains also pack more densely than round grains. Flaky materials run the risk of breaking when exposed to traffic loads.

Angular gravel can be obtained from natural sources or can be produced from crushed rock. Rounded materials are commonly found in rivers or river deposits.

## Plasticity Tests

**Liquid Limit**

The liquid limit is the level of water content in a soil at which stage it changes from a liquid to a plastic state. Equally, it can be defined as the moisture content at which a soil stops behaving as a plastic material and starts behaving as a liquid.

### Liquid Limit Test

The test is commonly carried out in a standard Casagrande Liquid Limit Device, in which a cup containing a grooved specimen is made to fall on a rubber plate. The number of blows to close the groove in the sample to a length of about 12.5 mm is determined for different moisture contents. The liquid limit is determined as the moisture content at which the soil will require 25 blows to close the groove. The liquid limit can also be established using a test method relying on a drop cone.

The liquid limit is one of many properties used to classify soils and determine its strength. Soils with a high liquid limit are able to absorb a high amount of water before they begin to behave as a liquid. Such features are commonly found in clayey soils. As compared to granular materials, clays have the capacity to hold a significant amount of water. Particularly in areas with heavy rainfalls, it is important to determine how soils behave when they are subjected to a wet environment.

**Plastic Limit**

The plastic limit is defined as the moisture content at which the soil no longer behaves as a plastic material, i.e. it starts to crumble when it is kneaded. To establish the plastic limit, the material is repeatedly kneaded and rolled into 3mm treads until it starts crumbling. At this stage, the moisture content of the sample is measured. The plastic limit is then simply the measured water content.

The liquid limit and plastic limit of a soil are also referred to as the Atterberg Limits after the scientist who developed the original concepts.

The plasticity index (PI) is the range of moisture content over which the soil has plastic properties. The PI is calculated as the difference between the liquid limit and the plastic limit. Soils with a high PI, in the range between 40 and 90, tend to be predominantly clay, while those with a lower PI contain more silt.

Work specifications normally set limitations to both the liquid limit as well as the plasticity index in soils used for road building purposes. It is desirable to secure materials with relatively low plasticity indexes, thereby avoiding soils which have plastic properties over a wide range of moisture contents. The adjacent table provides some recommendations on plasticity levels for gravel surface material.

| Climate | Liquid Limit not to exceed [%] | Plasticity Index range [%] |
|---|---|---|
| Moist tropical and wet tropical | 35 | 4 - 9 |
| Seasonal wet tropical | 45 | 6 - 20 |
| Arid and semi-arid | 55 | 15 - 30 |

Source: Transport and Road Research Laboratory

## 10.7 Applying Compaction to Various Soil Types

Compaction is one of the most critical components in the construction of roads, embankments and foundations. The durability and stability of a structure are dependent on the achievement of proper soil compaction. Structural failure of roads and the damage caused by foundation settlement can often be traced back to substandard compaction works.

Principal soil properties affected by compaction include settlement, shear strength and water permeability.

### Settlement

The main advantage of compaction of soils used in embankments and fills is that it reduces settlement caused by consolidation of the soil within the body of the embankment. Through proper compaction, it is possible to limit later consolidation and settlement of the soils in a fill. Although future settlements may not be entirely eradicated, the compaction may produce a uniform density of the soils and reduce this process to a minimum. Also it may result in future settlements being more uniform and thereby limit the damage caused by it.

The design drawings will prescribe the thickness of pavement layers after they have been compacted. In order to reach the required thickness, it is useful to know how much the volume of the loose soil will be reduced by compaction. This bulking factor is normally in the range between 25 and 35 percent, depending on the grading of the material and the amount of compaction provided.

### Shear Strength

Increasing the density a soil will usually result in higher shear strength, which is the determinant factor in relation to resisting the loads induced by the traffic travelling on the road. High shear strength is desirable as it allows the use of a thinner pavement structure over a compacted sub-grade or the use of steeper side slopes than would otherwise be possible.

### Water Permeability

When the soil particles are forced together by compaction, both the total volume of voids contained in the soil and the size of the individual void spaces are reduced. This change in voids has an obvious effect on the movement of water through the soil. One effect is to reduce the permeability, thus reducing the seepage of water into or through the soil. A firm road body which is well compacted will resist water from entering it during periods of rainy weather. Reduced permeability is also an essential property of a gravel surface.

### Compacting Soils

Proper compaction will substantially increase the load-bearing capacity of the soil and control other factors such as permeability, capillary action, shrinkage and swelling. How to effectively apply compaction depends on a number of factors, such as availability of equipment, size and type

of works, type of soils and availability of water. Certain aspects of compaction are directly linked to the characteristics and condition of the soils.

### Sand and Gravel

Free draining sand and gravels, containing very little fines are easily compacted, especially when they are saturated with water. Vibratory compaction using steel drum machines, combined with generous amounts of water, produce high densities after few passes, given that the layer thickness is appropriately adjusted to the size of the compactor. Any excess water will drain out of the layer during the compaction process.

If the sand or gravel contains more than 10 percent clay, the soil is no longer free draining and becomes more plastic when the water content is high. When compacting this type of soils, there will be an optimum moisture content at which maximum density can be obtained. It will then be more important to control the use of water during the compaction process. In wet conditions, these soils may need to dry out before they can be compacted.

### Silt

Silts, just like sand and gravel, are non-plastic soils, which are well compacted using steel drum vibratory rollers. Unlike gravels, these soils should be compacted at their optimum water content in order to achieve the best results. If too much water is present, silts tend to rapidly approach a fluid state making compaction impossible.

Silty soils with a certain clay content have characteristics more similar to clayey material. They will have considerable cohesion and plastic features similar to sands and gravels with significant clay content.

### Clay

Clay has plastic properties, which means it has very specific characteristics depending on its moisture content. The effect of compacting clayey soils is very much dependent on the amount of moisture in the soil. When dry, the clay is hard and firm and in the context of road building actually provides a strong and firm basis on which a road can be constructed. However, when applying compaction, the clay needs to contain a certain level of moisture in order to achieve the desired effect. Dry clay looses its cohesion and thereby compromises the result of compaction. The soil will simply crumble and turn to dust.

Due to its impermeable features, dry clay is difficult to mix with water. When water is added, it is often necessary to wait for a while for the water to soak into the material. By watering at the end of the day, the soils can be left to soak overnight. Alternatively, it is possible to turn the materials with a disc plough in order to facilitate the mixing of water into the materials.

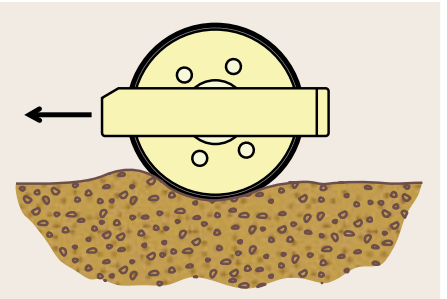
The characteristics of clay change radically when adding water. Clays should be compacted close to its optimum water content. Clay often has an OMC very close to its plastic limit so it is recommended to keep the water content on the low side of the OMC.

It is also important to bear in mind the poor permeability of clays. As opposed to sand and gravels, excess water in clays will not drain away. This implies that working with clayey soils is difficult during periods of excessive rainfall. Also, it is important to show some caution as regards to the amount of water added to the soils. In comparison, sand and gravel can be worked during rains as excess water easily drains away. Wet clayey soils need to be dried out before they can be used.

If too much water is added, clayey soils become elastic and tend to slide away from the roller drums. Excessively wet material should be removed from the road site and not used before the water content is reduced to a level where the materials can once again be compacted.

Even at optimum moisture content, clays require a higher compactive effort in order to reach the desired density levels. It is therefore important to (i) limit the thickness of the layers when spreading the material, (ii) closely monitor how compaction is actually carried out on site and (iii) carefully review the results.

Due to its cohesive features, a fill material rich in clay may contain large slabs, lumps or clods, which need to be broken up before compacting. These lumps can be broken manually, at the same time as the material is unloaded. Alternatively, a sheep foot roller can be used to break up the material.



## Rock Fills

Rock fills are more common in highway construction, however, in some cases they are used on rural roads in mountainous terrain. They are also commonly used for other civil works such as dams and foundations for various types of structures, including buildings. Due to the size of the rock, the fill is often spread in thicker layers than soils, using mechanized equipment for spreading. The heavy equipment used to unload and spread the material will provide some initial compaction during the spreading activity. To further compact such fills, it is necessary to use heavy compaction equipment.

CHAPTER 11

# COMPACTION

# COMPACTION

## 11.1 Purpose

The purpose of compaction is to increase the quality of road building materials such as soils, gravel and aggregate. The effect of compaction is to reduce the volume of air in the material. By forcing the soil particles closer together, the density is increased and the soil becomes stronger. This enables the materials to carry heavier loads and increases their resistance to erosion. A dense material also absorbs less water and thereby improves the performance of the material. Equally, a densely compacted material resists any further decreases in its volume when exposed to heavy traffic loads.

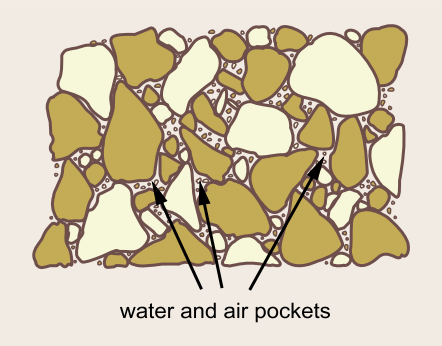
The effect of compaction is equally important for the road base as well as the surface layer. The increased strength of the base course allows for the passage of heavy loads without causing any deformation of the pavement. Compacting the base course and surface layers also reduces the amount of water penetrating the road body, which would compromise the strength of the road. A well-compacted surface layer resists the abrasive wear from traffic and prevents water from entering into the road body.

## 11.2 Fundamentals of Compaction

Good compaction is not difficult to achieve, however, it requires a good understanding of what is actually taking place when applying compaction to soils and surfacing materials. Good knowledge of the properties and performance of the materials, combined with the correct use of available equipment should result in reaching the prescribed quality levels.

The effect of compaction varies depending on the nature of the soil. Clayey materials behave different from sandy materials or gravel. It is likely that the materials on site are a combination of clay, sand and gravel, with the result that each project needs a careful analysis of the soils and on this basis prescribe the necessary compaction method.

Soils in their natural state consist of solid particles, water and air. Air does not contribute to the strength and stability of the soil - on the contrary, it reduces the stability of a soil.




A certain optimum quantity of water, usually between 8 to 20%, depending on the soil type, provides a lubricating effect between the soil particles and thereby facilitates the compaction. Having a certain amount of water in the soils during compaction has a significant effect in terms of achieving the required pavement strength and stability.

Clayey soils have the ability to contain more water than granular soils, and the optimal moisture content is higher in clays than in sands and gravels. The water lubricates the particles and allows them to settle in a dense mass.

If the soil contains too much moisture and is too wet, the soil particles are kept apart by the water. When the soil is too moist and attempts are made to compact it, it will not compress, but flow out sideways when pressure is applied. This can be clearly seen when trying to compact very wet soils.

## Optimal Moisture Content

Experience shows that if recently excavated soil is spread and compacted immediately, the natural moisture content is usually sufficient for achieving good compaction. Sometimes, however, the soil comes from a dry stockpile and then needs to be watered. Soils are often excavated and transported to their intended location and then left for a while before they are properly levelled and compacted. During this period, the materials lose their natural moisture. This water needs to be replaced in order to achieve optimal moisture content during compaction.

It is important to check this so-called "optimum moisture content", between too wet and too dry. Dry soils or very wet soils do not compact well. Clayey soils with high water contents shrink when they dry, so it is important that they are close to their optimal moisture contents during the construction period.

A simple way to check moisture content is to take a sample of the material and compact it in the hand. The sample is then squeezed into a ball. If the ball cannot be formed, the material is too dry. The correct level of moisture is reached when a ball can be formed and the material packs well together. When applying pressure, the ball should retain its shape. This test is particularly useful for gravel materials.

If the formed ball is flattened easily when applying pressure to it, the sample most probably has a too high moisture content. When the water oozes out of the sample when applying very light pressure it is obviously far too wet.

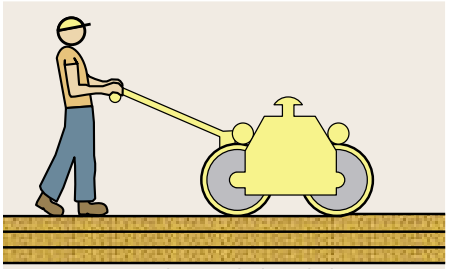
Unless the materials are compacted immediately after excavation, there is normally a need for watering the soils during compaction. For this reason, arrangements for supplying water to the construction site need to be considered at the time of planning the compaction activities. Hauling water often involves long and costly transport distances, so the option of using the natural moisture in the soils should be taken seriously.

During rainy periods excavated soils may contain too much water (soaked soils). In such cases the soil needs to be left to dry until the water content is reduced to the optimal levels for compaction.

### Compaction of Large Fills

Securing proper compaction of large fills such as embankments and fills are obviously more critical than for smaller works. In order to achieve a homogenous compaction of the materials, large fills are built up in layers, where each layer is compacted properly before the next is added. If any layer is not compacted to the prescribed quality levels, the material continues to settle after the road has been completed. If several of the layers have not been sufficiently compacted, the amount of settlement may accumulate, resulting in a very uneven road surface once traffic is allowed on the completed road.

Equally, it is important to pay close attention to compaction when roads are being widened by extending fills and embankments. On the existing road the degree of compaction is normally very high due to the traffic travelling on the



compaction carried out in layers

road since it was originally constructed. When extending a fill adjacent to an existing road it is therefore important that the extended section is thoroughly compacted in order to avoid a partial settlement of the road.

Road sections next to structures such as culverts and bridges also require careful attention when building up the fill. If these sections are not properly compacted, an uneven transition from the road fill to the structure will emerge soon after traffic commences.

Adequate compaction plays an important part in achieving the prescribed quality levels for the road works. Inadequate

compaction works have a direct impact on the final riding quality of the road. It will also increase the maintenance burden at an early stage, and warrants early repair works, which could have been avoided if proper attention was given to the compaction activities.

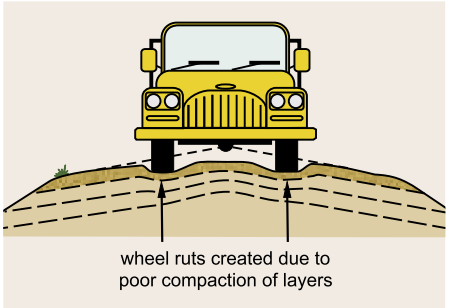
## Compaction Effort

Depending on the type of soils and materials, fills are compacted in layers not more than 15 cm loose thickness. In no circumstances should the layers be thicker. The most common cause of poor compaction is attempting to compact thick layers of material.

Each of the layers should be spread in an even and uniform manner to ensure that the final layer remains even and provides a smooth surface. Any adjustment layers due to unevenness in the original terrain should be placed at the bottom of the fill, and thereby provide a level base for the remaining layers to be constructed at equal thickness until the top of the road is reached.

The amount of compaction to be applied depends on the nature of soil and the available compaction equipment. Heavier vibrating rollers require less passes than lighter equipment. Trial compaction runs and analysing the impact on the soils are often required to establish the amount of compaction required to reach the prescribed quality levels. These trials need to be carried out using the specific types of equipment available to the work site, and the results vary depending on the soil type.

When compacting fills consisting of several layers, it is important to secure good compaction of every layer in the fill. Poor compaction in one layer affects the evenness of all the above lying layers once traffic starts on the completed road section. If the layers in




the sub-base are not well compacted, they will start settling due to the traffic, and eventually cause early wheel ruts and an uneven surface.

The combined effect of the early creation of wheel ruts and loosing the original camber slope reduces the rate at which water drains away from the road surface. Eventually, the effect of standing water in the road carriageway combined with traffic leads to an accelerated rate of deterioration of the road surface.

## Surface Evenness

A number of different methods can be applied to check the longitudinal evenness of the compacted surface. First of all, it is important that the levels are correctly set out when spreading the loose soils. This can be done by first setting out all levels using profile boards and transferring these levels to string lines indicating the top of the layers. Soils compact unevenly and the spread is looser further away from where it was unloaded. This becomes apparent during the initial passes of the compaction equipment. With profile boards and a traveller, or by maintaining the correct levels on the string lines, this unevenness is rectified by adding additional material to the low spots.

The evenness of smaller areas can also be controlled using a three-metre long straight edge. Work specifications often specify the tolerance levels for the top layer of the earthworks and the completed gravel surface. Recommended standards for surface evenness on gravel roads are given in the table below. If the surface evenness falls below these limits, the surface should be corrected before proceeding with the next layer.

| Warks Activity | Control distance or interval (m) | Longitudinal Profile: Maximum permissible undulation when tested with profile boards or using string lines (m) | Cross-section profiles: Maximum variation from specified levels (mm) |
|---|---|---|---|
| Levelling of existing ground | 20 | 30 | 15 |
| Layer of embankment | 20 | 20 | 15 |
| Camber (earth) | 5 | 15 | 10 |
| Gravel surface | 5 | 10 | 10 |

## 11.3 Compaction Methods

There are basically four methods of compaction:

- manually or mechanically operated tampers or rammers,
- deadweight rollers,
- vibrating compaction, or
- natural compaction.

### Hand Rammers

Hand rammers compact the soils by impact. Specially designed hand rammers can be used for this purpose.

Hand rammers are cheap to manufacture and can be made locally. A common design consists of a long wooden handle with a cast iron or concrete weight at the end. It is lifted and dropped on the surface repeatedly to produce compaction. Its weight is usually 6 to 8 kilograms.

Using hand rammers is expensive and difficult to apply evenly over large areas. A lot of manpower and direct supervision is needed to produce a steady output of reasonable quality. Hand rammers are most useful in small and confined areas such as around culverts, potholes and other places where it is impractical or difficult to access with larger equipment.

### Deadweight Rollers

There are several types of deadweight rollers, ranging from single or double steel drums, towed or self-propelled or with a load container to hold the deadweight. A major concern when choosing the appropriate type of compaction equipment is:

- its availability in the area close to the road works activities,
- how to deliver it to the construction site,
- how easy it is to operate and how easily it can be reversed, and
- its cost, reliability and access to repair facilities.

Large and heavy towed rollers have a good compaction capacity but may prove difficult to turn and operate in hilly or steep terrain. Most self-propelled rollers can be operated in both directions, however, they are more prone to breakdowns.

Some rollers can be ballasted with weights of one tonne or more, using water, sand or stone. When using this

type of roller, the first passes can be provided with a relatively light ballast in order to avoid traction problems. After the first few passes the ballast can be increased.

Commonly, deadweight rollers are former vibrating rollers with defunct vibration mechanisms. If these machines are large (heavy) enough, they may still prove effective in achieving the prescribed levels of compaction.

### Compaction by Vibration

The most common pieces of equipment are the plate compactors and vibrating rollers. The advantage of vibrating compaction equipment is that it is effective on most types of soils. The vibration reduces the friction between the soil particles during compaction, and thereby allowing the particles to move more easily into tighter interlocking positions. Compaction with vibration is more effective than without vibration.

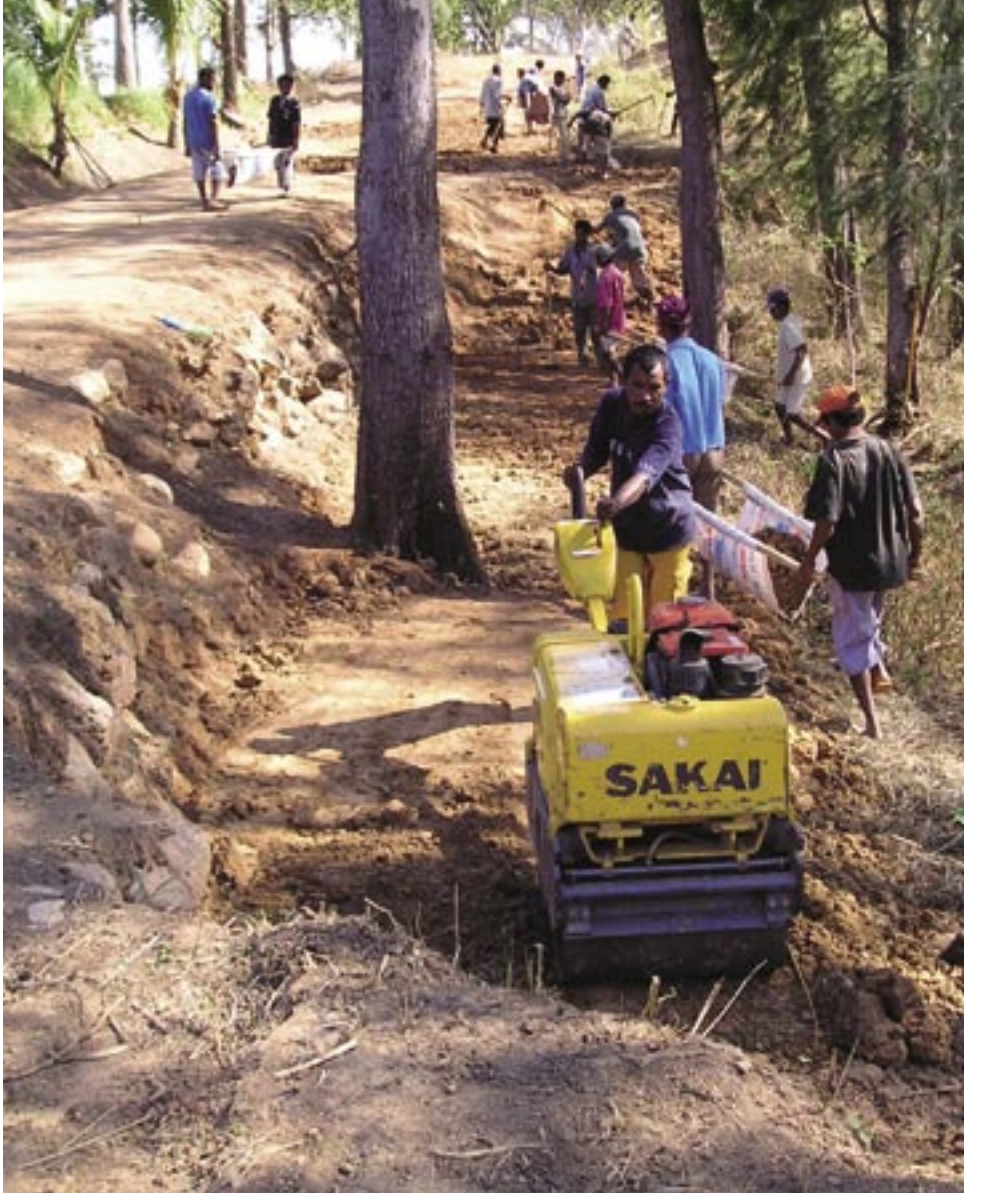
Plate compactors are used in confined spaces such as in trenches close to abutments and foundations and on road shoulders or edges of fills. They are easy to transport and are commonly used instead of hand rammers.

The vibration in rollers is produced using an eccentric weight rotating inside the drum. Vibrating rollers generally compact to a greater depth than a deadweight roller. The effect of the vibrating motion depends on the intensity of the vibrations and the type of material on which it is applied. As a general rule, a higher vibration frequency is preferred, as it increases the number of impacts over a fixed length of surface being rolled.

Vibrating equipment requires a lower moisture content as compared to compaction carried out using deadweight rollers. However, it is important to maintain an even speed to achieve even compaction. With deadweight rollers this is less important.

In loose soils, the first passes are often carried out without vibration to avoid that the roller sinks into the soil. The speed should be around 3 kilometres per hour, equivalent to a slow walking speed. The operators should be instructed to run the roller at a slow and constant speed. The speed of the rolling should not be increased in order to increase production. This only compromises the performance of the compaction works. If the capacity of the available rollers on site is insufficient, the only solution is to obtain additional compaction equipment.

Most rollers today are supplied with a vibration mechanism, although older versions may have lost this utility as a result of wear and tear. Rollers are manufactured in a wide variety of sizes and shapes, ranging from small

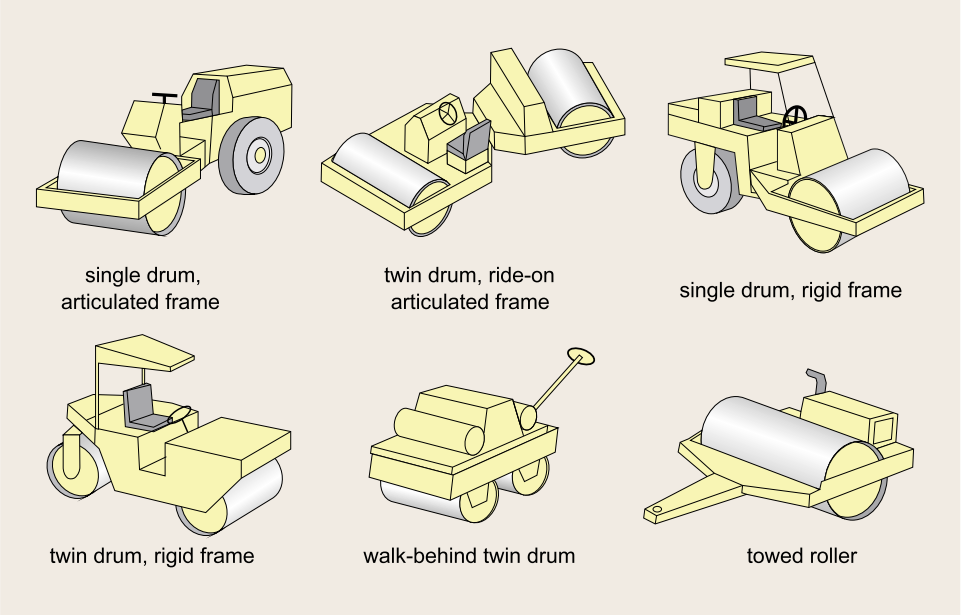



manually guided drum rollers to large self-propelled machines.

Smaller pedestrian versions are easy to transport, weighing from 600kg to 1.2 tonnes. These are common in rural road projects, spot improvement and maintenance works. These rollers are also useful for works involving the widening of roads as the small equipment can be manoeuvred into smaller surface areas.

Larger rollers are commonly found on highway projects and works requiring higher capacity in order to efficiently cover larger surfaces. For rural road works, the one tonne pedestrian rollers have proven to be very efficient during earthworks and gravel surfacing. However, for larger earthworks, such as large embankments, and gravel surfacing works, larger vibrating rollers are also very useful.

Rollers fitted with steel drums are the most common for compaction of soils and crushed aggregate. They are also used for certain bitumen based pavement layers, however, when compacting




surface treatments it is important to avoid crushing the aggregate.

For this reason, it is common practice to use pneumatic tire rollers for compacting certain types of bitumen-based pavements. Pneumatic rollers provide a different type of compaction, which can be described as a kneading action as opposed to the more direct, and to a certain extent, crushing effect of a steel drum roller.

### Natural Compaction

The simplest method of compaction is by leaving the soils to settle naturally for a period of time. The soil by its own weight, rainfall and people, animals and vehicles travelling on it will eventually consolidate enough to carry heavier traffic loads.

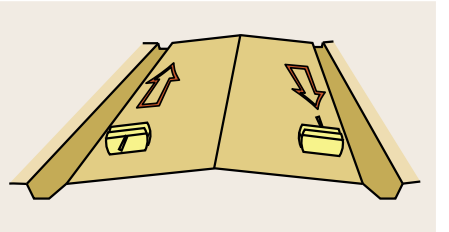
This so called `indirect compaction' method or natural consolidation is a slow process. It is normally only used on very low fills, and is most effective if the fill material is very moist and is allowed to dry out. Given sufficient time, it has been found that roads compacted by natural consolidation can achieve similar densities as roads compacted by equipment. The main disadvantage is that while the soil is not consolidated, it is prone to erode more easily. In most cases, it is necessary to leave the fill for a period six months to achieve an effective degree of compaction, and during this period carry out some reshaping due to the damage caused by the traffic.

## 11.4 Compaction Procedures

In order to achieve the high quality outputs relating to this activity, it is useful to assign and train specific workers to operate the compaction equipment. They will eventually build up the experience to efficiently operate in a manner producing uniform and good compaction results. Equally important is that they are trained in how to maintain and service the rollers.

The operation of mechanical compaction equipment as well as water bowsers requires some security measures on site. Manual labour needs to be directed away from the construction equipment to avoid accidents. The machine operators will be working in a very noisy environment, so it is important that they are equipped with adequate noise protection gear.

To produce a good quality road, it is essential that all soils are properly



compacted. Compaction should be carried out in straight lines parallel to the road line, starting at the shoulder of the road, gradually working towards the centre line. Compaction of the road shoulders should be done using hand rammers or plate compactors.

The camber of the road should always be maintained at the correct gradient for both the base layers as well as the surface layer.

After compaction, it is important to check that all levels are correct and that the surface is smooth and does not contain any uneven spots. An accurate and quick method of checking the levels is by using profile boards and a traveller.

It is important to ensure that there is a sufficient supply of water, in order to maintain optimal moisture content in the soils being compacted.

## 11.5 Quality Standards

Work specifications in civil works contracts specify how compaction should be carried out. This is either done by describing how a specific type of equipment should be used on various types of soils, or by specifying the end result in terms of the degree of soil compaction. In some cases, work specifications prescribe both the method and the end result.

When specifying the method of compaction, soils are divided into different classes, depending on their strength and other characteristics. For each of these soil classifications, the specifications will then prescribe the type and size of equipment, maximum layer thickness, number of passes and how the outer edges are treated.

When specifying the end result, the required level of compaction is normally prescribed relative to a laboratory compaction test. For example, compaction to 95% means that the dry density of samples taken in the field should be 95% of the dry density obtained in a specified laboratory compaction test. Alternatively, the percentage of air voids can be used as a reference to the degree of compaction.

Today, there are a number of methods to check the results of compaction – some

### Dynamic Cone Penetrometer

This testing equipment does not actually measure the degree of compaction. What it does is to measure the degree of penetration of a standard-shaped steel rod, which is pushed into the compacted soils using a mass of 8kg falling from a fixed height onto an anvil attached to the steel rod.

The resistance of the soil to the penetration is used as an indication of the degree of compaction. If a large number of blows are required for penetrating a short distance, the soils are considered well compacted. If the rod easily penetrates the soils, they are regarded as poorly compacted or unsuitable.

The advantages of this test method is that while giving a fair indication of compaction results, the testing equipment is simple, inexpensive and quick to operate. If this testing is compared with results of laboratory tests, it can be an effective way of carrying out simple testing in the field.


are applicable in the field and others require laboratory facilities. For rural road works, the cone penetrometer is commonly used to verify compaction results. The advantage of this test method is that it can check the degree of compaction through several layers.

Although the cone penetrometers provide easy and quick test results, it should be backed up with more accurate test methods such as a sand displacement test.

How to obtain a certain level of compaction depends on the type and size of the compaction equipment and the soil type. Equipment suppliers provide reliable information on how their equipment perform in various soil types and make recommendations on the type of equipment and how it is best used to achieve prescribed quality standards. Still, due to the complexity of soils and varying degrees of moisture, such guidelines need to be verified with field trials and testing. For each type of soil encountered, the engineer needs to prescribe the appropriate method and equipment for compaction and then monitor the result in order to make sure the prescribed quality levels are achieved.

A loaded vehicle can be used as a simple way of checking whether compaction has generally been carried out to acceptable standards, by driving over the compacted section a few times and see if it leaves any wheel-ruts in the pavement. If ruts are created then more compaction is needed.

Quality testing of completed earthworks is often included as a paid activity in civil works contracts. For this reason, the contractor would normally equip the construction site with field-testing equipment. Some contractors have their own laboratory facilities, while others rely on buying such services from larger contracting firms or government institutions.

Field supervisors need to be instructed on the time and intervals for quality testing of compaction works. Civil works contracts often specify (i) when tests should be carried out, and (ii) when clearances are required from the supervising engineer, before the ensuing works can commence. A common procedure is to not allow any gravel surfacing works to take place before the quality of the earthworks have been inspected and the results of the tests verify that quality standards have been attained.