Labour-based methods and technologies for employment-intensive construction works

A cidb guide to best practice

Best Practice Guideline – Part 4-7

Water-bound Macadam
Confronting joblessness

This set of best practice guidelines for labour-based construction represents a significant investment of leadership by the South African Construction Industry “to spearhead job creation and skills development so that our growing economy is increasingly accessible to all citizens” (Minister Stella Sigcau, SA Construction Industry – Status Report 2004).

In finalising this set as a tool for designers and practitioners, the Construction Industry Development Board (cidb) has assembled the knowledge and experience given freely by industry through a consultative process that commenced in 1996.

Taking forward this process, the cidb has published these guidelines in fulfilment of its mandate to “establish and promote best practice...and the improved performance of... participants in the construction delivery process”.

“We have made the firm commitment to confront the challenges of poverty and joblessness. We have made the solemn pledge that we will do everything possible to achieve the goal of a better life for all our people.”
President Thabo Mbeki, 18 May 2004 – launch of the Expanded Public Works Programme.

Labour-based methods and technologies for employment-intensive construction works

In this set: (colour coded)

Part 1
An overview of labour-based technologies and methods in employment-intensive works

Part 2
Labour-based construction methods
2.1 Labour-based construction methods for earthworks

Part 3
Labour-based methods for materials manufacture
3.1 Precast concrete products, bricks and block making
3.2 The BESA building system

Part 4
Labour-based construction technologies
4.1 Labour-based open channel flow technology
4.2 Rubble masonry dam construction technology
4.3 Rubble masonry concrete arch bridge construction technology
4.4 Foamed bitumen gravel
4.5 Cast in situ block pavement
4.6 Emulsion-treated gravel
4.7 Water-bound Macadam
4.8 Slurrybound and composite Macadam construction
4.9 Labour-based construction methods for unsealed roads

These best practice guidelines are supported by the Expanded Public Works Programme (EPWP), which directs a significant and increasing proportion of South Africa’s public investment towards a labour-intensive programme of construction, drawing the unemployed into productive work and providing access to skills development.

The guidelines draw on international experience and are endorsed by Engineers Against Poverty (EAP), an international development NGO established by leading UK engineering institutions. EAP is working to ensure that the engineering industry remains at the forefront of efforts to reduce and eventually eliminate global poverty.
Overview of best practice labour-based guidelines

1. Introduction

2. Materials and specifications

3. Practical aspects

4. Structural design

5. Plant and equipment

6. Construction

7. Quality control

8. Specialist literature

Acknowledgements

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Best Practice Guideline – Part 4-7

Water-bound Macadam

Contents

- Overview of best practice labour-based guidelines: 2
- 1. Introduction: 3
- 2. Materials and specifications: 6
- 3. Practical aspects: 9
- 4. Structural design: 13
- 5. Plant and equipment: 13
- 6. Construction: 14
- 7. Quality control: 19
- 8. Specialist literature: 20
- Acknowledgements: 25

cidb is a public entity established in terms of the CIDB Act, 2000 to provide strategic direction for sustainable growth, reform and improvement of the construction sector and its enhanced role in the country’s economy. In pursuit of this aim cidb partners with stakeholders and regulates the construction industry around a common development agenda underpinned by best practice procurement and project processes.

ISBN: 0-621-35565-8 Printed March, 2005

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Overview of the best practice labour-based guidelines

The South African White Paper Creating an Enabling Environment for Reconstruction, Growth and Development in the Construction Industry (1999) expresses a vision for public-sector delivery aimed at optimising employment opportunities through labour-intensive construction. This can be realised in the delivery of infrastructure through the adoption, where technically and economically feasible, of:

- labour-based methods of construction and manufacture where labour, utilising hand tools and light equipment, is preferred to the use of heavy equipment for specific activities; and
- labour-based technologies where there is a shift in balance between labour and equipment in the way the work is specified and executed for selected works components.

Appropriate specifications and labour-based technologies are required to optimise employment opportunities generated per unit of expenditure. The absence of adequate design information on labour-based technologies frequently limits the choices available in project design. As a result labour-based technologies are often approached circumspectly and conservatively.

These best practice guidelines present current state-of-the-art practices in a wide range of labour-based construction methods, manufacturing methods and technologies which have been successfully utilised in South Africa in recent years. They are intended to provide sufficient technical information on such methods and technologies to enable those responsible for the design of projects to make confident and informed choices on their use in projects.

The cidb best practice guidelines establish desirable and appropriate standards, processes, procedures and methods relating to the implementation of employment-intensive works using:

- labour-based construction methods for earthworks;
- labour-based methods for materials manufacture; and
- labour-based construction technologies.

Following a process of peer review and public comment cidb has published the guidelines in Government Gazette No 27352 on 11 March 2005.

The guidelines can be downloaded from the cidb website www.cidb.org.za free of charge and can be obtained in hard-copy from cidb or the South African Institution of Civil Engineering (SAICE), website www.civils.org.za, at the cost of printing and postage.
1.1 Background

Macadam-type pavement layers have been used successfully in South Africa for many decades. Macadam-type pavement layers traditionally refer to a layer of almost single-sized stone (usually 53mm nominal size for recent projects) in which the voids are filled with a dry, cohesionless fine aggregate filler. With the growing need for superior performance, a variety of modifications have been introduced, which include filling the voids with bitumen, slurry, etc.

A macadam layer essentially consists of a stone skeleton of which the voids are filled with another material. The stone skeleton, because of its single size, has large amounts of voids but has a high shear strength. If confined properly, a crucial requirement for macadam base courses, the stone skeleton forms the ‘backbone’ of the macadam and is largely responsible for the strength of the constructed layer. The material used to fill the voids provides lateral stability to the stone skeleton but adds little bearing capacity. This structure also gives water-bound macadam its good resistance to water as it drains well and the stone skeleton is less susceptible to the water present in the layer.

A water-bound macadam (WM) refers to a method of construction whereby water is used to force fine material into the voids during compaction. With proper construction control, and a phased construction procedure, the water-bound macadam offers a suitable labour intensive method for road construction.

1.2 Origins of macadam construction (Hefer, 1997)

The origins of macadam-type pavement construction can be traced back to a period between 1750 and 1830 during which two Scottish engineers, Thomas Telford and John Louden McAdam were active in developing and promoting their respective road-building techniques in England. Telford used fairly large stones (75 mm long, 125 mm wide and 325 mm high) to build a foundation layer on a level roadbed. The heights of these large stones decreased from the centre-line to the edge of the roadway to create a slight camber. Smaller stones were driven into the open voids on the surface of this layer and any projecting points were broken off. A 100 – 200 mm thick layer of small broken stone was then placed on top of the foundation layer. McAdam simply used layers of broken stones, none of whose dimensions exceeded 25 mm and these layers were placed directly on the roadbed. The broken stone was angular and consolidated under traffic. McAdam recommended that the road be raised above the surrounding ground to improve drainage. A layer of small broken stones, spread on the surface of the road, was used by both road-builders. These stones were broken down further and compacted by traffic to produce a solid, smooth riding surface. Figure 1 illustrates the difference between the approaches used by Telford and McAdam.

Neither Telford nor McAdam used any fine filler in the voids of the stone layer and it is not clear when this practice originated. Macadam construction was boosted by the invention of the stone crusher and steamroller in the 1860s but, in essence, the process remained labour-intensive.

Increased motorised-vehicle traffic at the turn of the century created dust and surface disintegration problems because of higher vehicle speeds and increased
friction between tyre and pavement. This led to the development of tar penetration macadams.

1.3 The history of macadam pavements in South Africa

Macadam pavement construction went through various phases in South Africa. Several provincial road authorities and major municipalities constructed macadam pavements until the 1960s and even as late as the 1970s. Thereafter the use of water-bound macadam declined in favour of materials which were more easily placed by machine.

However, the use of water-bound macadam did not only decline in South Africa, but did so all over the world. In the developed world where wages increased dramatically, the use of water-bound macadam has practically disappeared. But even in other developing countries, the mechanisation trend has also lead to much reduced use of this technique.

The good in-service record of macadam pavements in the former Transvaal (Burrow, 1975) and in the wet climate of Natal caused the interest in this type of construction to be retained and gave rise to several attempts during the 1980s to mechanise the construction of macadam layers. These attempts varied from using motorised graders to spread and level the coarse aggregate and sand spreaders and mechanical brooms to spread and cause the fine aggregate filler to penetrate (Horak, 1983), to laying the coarse aggregate with modified pavers (Roux and Otte, 1993, McCall et al, 1990).

A new generation of macadam-type materials evolved in South Africa during the late 1980s and 1990s. The process started with the development of partially penetrated macadams (Roux and Otte, 1993) in Natal. The need for job creation and empowerment through labour-intensive road construction projects and contractor development led to the construction of slurry-bound and composite macadams that were used on several pilot projects by the Greater Johannesburg Metropolitan Council (Horak et al, 1995). A distinction is therefore made between the macadam material types outlined in 1.4 and 1.5.

1.4 Conventional types of macadam

Dry-bound macadam (DM): The voids in a layer of almost single-sized stone (usually 53 mm nominal size for recent projects) are filled with a dry, cohesionless fine aggregate filler. The voids are filled with filler through the use of compaction equipment only, and no water is used (see Figure 2).

Water-bound macadam (WM): Two water-bound processes have been identified in literature. It seems that the term ‘water-bound’ is generally used to describe a dry-bound macadam which has been ‘slushed’ after all the voids have been filled with dry filler. The slushing process consists of saturating the macadam layer (coarse and fine aggregate) by

<table>
<thead>
<tr>
<th>Why mechanisation gained favour</th>
</tr>
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<tbody>
<tr>
<td>Mechanised construction of pavement layers using continuously graded crushed stone gained favour for a number of reasons listed by Horak (1983), and influenced by the following:</td>
</tr>
<tr>
<td>• a trend to emulate the mechanisation of the industry in Europe and the USA where labour was scarce. In part this was prompted by the belief that progress resulted from mechanisation. This in turn led to policies and regulations designed to foster mechanisation;</td>
</tr>
<tr>
<td>• the large tax incentives that were allowed in respect of the purchase of new plant (Cohen, 1989; Lansdown, 1988);</td>
</tr>
<tr>
<td>• the introduction of a wage determination for the construction industry, which caused a substantial increase in the cost of labour;</td>
</tr>
<tr>
<td>• the difficulty which was experienced in mechanisation of the water-bound macadam process (Horak, 1983:10s); and</td>
</tr>
<tr>
<td>• government policy which actively discouraged the use of labour in urban South Africa.</td>
</tr>
</tbody>
</table>

Figure 2: Dry and water-bound macadam
spraying it with water, after which a number of passes are made with a steel drum roller, forcing the excess fines to the surface of the layer, from which they are then swept away (see Figure 2).

A completely wet process has been used in KwaZulu-Natal in cases where the climate did not allow the fine filler to dry out sufficiently to flow into the voids of the macadam layer (Roux and Otte, 1993; McCall et al, 1990). The fines were spread using a chip spreader and washed into the coarse aggregate layer with water-jets from a spray-bar.

**Penetration macadam (PM):** Fine aggregate is not used to fill the voids between the coarse aggregate of a penetration macadam layer. Hot tar is poured over the coarse aggregate layer and flows into the voids, coating the large aggregate in the process. The voids are, however, not filled completely by the tar (see Figure 3).

### 1.5 New generation macadam

**Partially penetrated macadam (PPM):** A dry- or water-bound macadam layer is constructed in the usual way but, instead of the excess fines being swept off the surface of the layer, some of the filler in the open voids at the top of the layer is also swept away. A very rough surface, with the coarse aggregate projecting from the layer, is obtained. Slurry is then applied with a slurry-box to fill these open voids on the surface of the layer. Slurry penetration is normally relatively shallow for this type of macadam (see Figure 4).

**Slurry-bound macadam (SM):** As in the case of penetration macadam, no fines are used to fill the voids of slurry-bound macadam. A slurry, produced from crusher sand (or a mixture of crusher sand and natural sand) and emulsion, is forced into the voids between the coarse aggregate of this type of macadam layer. (see Figure 5).

The slurry therefore performs the function of the tar in a penetration macadam. All the voids are filled with slurry in the case of a slurry-bound macadam, in contrast to the partial filling of the voids in a penetration macadam layer.

**Composite macadam (CM):** Composite macadam consists of a lower portion of dry- or water-bound macadam (usually of a nominal 53 mm stone size) and of a top portion consisting of a slurry-bound macadam (usually of a nominal 26 or 37 mm stone size) (see Figure 6).
2. Materials and specifications

2.1 Aggregate specification

The material specifications for the coarse aggregate used for water-bound macadam construction consist of grading and durability requirements. Table 1 and Figures 7 and 8 provide specifications for the grading of the coarse and fine aggregate used for water-bound macadam construction. Table 2 provides the specification for the durability and shape of the coarse aggregate and for the Atterberg limits of the fine aggregate according to TRH14.

The grading envelopes in Figures 7(a) and 8(a) are from TRH14. The grading envelopes in Figures 7(b) and 8(b) are additional to the TRH14 criteria and allow for the use of a wider selection of material in water-bound macadam construction.

The grading envelopes for the coarse aggregate have the common characteristic of an almost single particle size distribution. The Cape Town municipality grading envelope for the fine aggregate also shows a tendency towards a more single-sized particle size distribution. The TRH14 grading envelope for the fine aggregate clearly requires a continuously graded material. The Cape Town municipality criteria are incorporated in this document to allow for the use of natural sand as a fine aggregate for water-bound macadam. A crusher sand grading would be more typical of the TRH14 grading requirement.

2.2 Rock types suitable for producing coarse aggregate

The coarse aggregate for a water-bound macadam material should be obtained from the crushing of unweathered, hard rock. There are, however, certain rock types that are likely to be more suitable for use in a water-bound macadam material.

**Basic crystalline rocks**
- Andesite
- Basalt
- Diabase/dolerite
- Diorite
- Gabbro/norite

**Acid crystalline rocks**
- Granite
- Rhyolite

**High silica rocks**
- Quartzite

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### Table 1: Grading requirements for the coarse and fine fractions of a water-bound macadam material (CSRA, 1985)

<table>
<thead>
<tr>
<th>Sieve size (mm)</th>
<th>Coarse aggregate</th>
<th>Fine aggregate</th>
</tr>
</thead>
<tbody>
<tr>
<td>75.0</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>53.0</td>
<td>85 – 100</td>
<td>85 – 100</td>
</tr>
<tr>
<td>37.5</td>
<td>35 – 70</td>
<td>0 – 30</td>
</tr>
<tr>
<td>26.5</td>
<td>0 – 15</td>
<td>0 – 5</td>
</tr>
<tr>
<td>19.0</td>
<td>0 – 5</td>
<td>–</td>
</tr>
</tbody>
</table>

- **Notes:**
  - The wet 10% FACT should be 75% of the dry value.
  - Minimum dry 10% FACT for tillite should be 200 kN and the wet value 70% of the dry value.

### Table 2: Durability, shape and Atterberg limits specification for water-bound macadam base layers (CSRA, 1985)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crushing strength: Minimum dry 10 % FACT (kN)*</td>
<td>110**</td>
</tr>
<tr>
<td>Maximum ACV (%)</td>
<td>29</td>
</tr>
<tr>
<td>Maximum weighted average Flakiness Index (%) determined on the -26,5 mm; +19,0 mm and -19,0 mm; +13,2 mm fractions</td>
<td>35</td>
</tr>
<tr>
<td>Atterberg limits: maximum Liquid Limit (LL)</td>
<td>25</td>
</tr>
<tr>
<td>maximum Plasticity Index (PI)</td>
<td>6</td>
</tr>
<tr>
<td>maximum Linear Shrinkage, % (LS)</td>
<td>3</td>
</tr>
</tbody>
</table>

Notes: *
- The wet 10% FACT should be 75% of the dry value.
- Minimum dry 10% FACT for tillite should be 200 kN and the wet value 70% of the dry value.

---

### Figure 7: Grading requirement for the coarse aggregate

(a) TRH14 grading specification (CSRA, 1985) for 53 mm nominal size coarse aggregate

(b) Indian grading specification (Horak, 1983) for 63.5 mm nominal size coarse aggregate
Arenaceous rocks
• Quartzitic sandstone

Argillaceous rocks
Only sufficiently ‘baked’ argillaceous rocks, such as Malmesbury shale, will probably be suitable (‘Malmesbury Shale’ is in fact a misnomer, as this rock is actually hornfels and neither shale nor mudstone). In general, rocks from this group are not strong enough for use in base layers and are seldom crushed commercially.

Carbonate rocks
• Dolomite

Diamictites
• Tillite

Granite and quartzite, especially if they come from mine dump-rock, could contain excessive quantities of sulphide minerals. These minerals have a distinctive shiny appearance and colour, such as iron pyrite, which is gold-coloured; marcasite, which is silver-coloured and copper pyrite, which has an iridescent gold, red and green colour. These minerals decompose easily in the presence of water and air to form mainly sulphuric acid. The acid products are not stable and change into sulphate salts which may cause blistering of the surfacing. If a relatively pervious water-bound macadam is built with clearly visible quantities of these minerals present in the coarse aggregate, it is recommended that expert opinion be obtained, should the use of this material be contemplated.

Although tillites have performed well in water-bound macadam base layers under Heavy Vehicle Simulator (HVS) testing in KwaZulu-Natal (Roux and Otte, 1993; Wright and Hess, 1988), the strength requirement for the use of this material in base layers is increased to a minimum dry 10 per cent FACT of 200 kN, the wet 10% FACT being 70% of the dry value (CSRA, 1985).

2.3 Material suitable for use as fine aggregate
There are basically two sources of the fine aggregate for water-bound macadam. The first option, which seems to be recommended in most of the literature, is to obtain the fines from the crushing of the same parent material used for producing the coarse aggregate. In this case, a continuous particle size distribution is obtained and the TRH14 grading curve envelope for the fine aggregate shown in Figure 8 (a) will apply.

There are, however, also a number of sources of natural fine sands which may be used for water-bound macadam construction. These sands should be screened for PI and salt content before they are used in water-bound macadam construction. The particle size distribution of these and other natural sands will tend towards an almost single-size distribution and the Cape Town municipality grading envelope (Horak, 1983) for fine aggregate shown in Figure 8(b) will apply.

A blend of crusher dust and natural sand may also be used to achieve the required particle size distribution for the fine aggregate.
2.4 Relaxation of the TRH14 material specifications

The relaxation of the TRH14 material specifications may be viewed in terms of deviations from the grading requirements for the coarse and fine aggregates and/or deviations from the strength and plasticity requirements for the coarse and fine aggregates respectively. Such relaxations should only be considered for low volume roads. Expert opinion should be consulted whenever the use of marginal materials is considered.

In terms of deviations from the grading requirements for the coarse aggregate, the grading envelopes specified by most institutions seem to agree to a great extent. The impetus for deviating from this basic grading specification seems to be small, as the coarse aggregate is basically a manufactured material whose particle size distribution can be controlled. The grading specifications for the fine aggregate seem to have been adapted by local road authorities to suit the natural sands available in specific areas. In view of the previous comment on the relatively small effect that the grading of the fine aggregate has on the behaviour of the water-bound macadam under repeated loading, a deviation from the grading requirement for the fine aggregate does not seem critical. Adjustment of the grading envelope for the fine aggregate, such as the example shown in Figure 8, to suit locally available sands may therefore be allowed, with due consideration being given to the effect that this may have on the permeability of the composite material.

Although it has been suggested that the strength requirement for the large aggregate may be too stringent (Roux and Otte, 1993), Horak (1983) reported a change in the grading of the coarse aggregate under HVS testing and Philips (1994) reported that fracturing of the coarse aggregate occurred under vibratory compaction. It is therefore recommended that the TRH14 strength requirements for the coarse aggregate be adhered to.

Hefer (1997) investigated the performance of seven water-bound macadam pavements in the Johannesburg area, all of which performed well. Of these, the fine aggregate in five of the water-bound macadam base layers had PI values in excess of the specified value of 6, with values as high as 9 and 11 in some cases. Horak (1983) recommended a range of values for the PI of the fine aggregate between 4 and 9, the intention being that the higher PI material should be used to reduce the water permeability of the top portion of the water-bound macadam base layer.
3.1 The use of water-bound macadam in wet areas

Water-bound macadam is one of the preferred base layer types in the wet climate of the eastern part of South Africa. HVS test results (Roux and Otte, 1989) and recent laboratory test results (Theyse, 1999) indicate that water-bound macadam loses static shear strength and deforms to a significantly greater extent at high saturation levels than at low saturation levels. It is therefore desirable to keep the saturation level of even a water-bound macadam base layer as low as possible in order to ensure best performance.

Although this has not been confirmed by experimental results, the permeability of water-bound macadam should presumably be a function of the particle size distribution of the fine aggregate. A water-bound macadam layer with a continuously graded fine aggregate such as crusher sand should have a lower permeability than a water-bound macadam layer with an almost single-sized fine aggregate filler. It is therefore recommended that a continuously graded fine aggregate should be used as far as possible to prevent water from entering the base layer. If, on the other hand, it is foreseen that, despite all precautions, the water-bound macadam layer will have to perform some drainage function, the permeability of the water-bound macadam should be sufficient to allow the water to drain away, but not high enough to cause the transportation of the fines from the layer. A natural sand filler is the appropriate choice in this case.

Complete saturation of the layer with the associated high pore-pressure under traffic loading should be avoided at all cost. Side-drains provided for draining away construction water should be able to accommodate the in-service drainage of the layer but these must be maintained properly.

TRH15 (CSRA, 1984) should be consulted for general subsurface drainage aspects in addition to the water-bound macadam specific drainage systems discussed in this document. Figure 9 shows the detail of a side-drain design (McCall et al,1990) that is incorporated in the concrete edge-restraint of a water-bound macadam base layer. A 50 mm slotted pipe wrapped in geotextile is laid on the completed subbase parallel to the front face of the edge-restraint. The geotextile is wrapped around the slotted pipe from the front face of the edge-restraint over and then under the pipe and the geotextile overlap is laid flat on the subbase. The shuttering for the concrete edge-restraint is then placed in position and the pipe and geotextile are fixed to the shutters. Care should be taken not to contaminate the geotextile overlap which is lying on the sub-base outside the shutters when pouring the concrete edge-restraint. The drainage of the water-bound macadam layer will be through this portion of the geotextile. The geotextile overlap is lifted and glued onto the front face of the concrete edge-restraint after removal of the shutters. Extreme care should be exercised in the construction of the edge-restraint drain, as McCall reported problems with the contamination and tearing of the geotextile, the blocking of the slots in the pipe by concrete fines and the separation of the pipe from the front face of the edge-restraint. Modifications to make the system more robust should be considered.

Figure 9: Concrete edge-restraint and side-drain detail

Figure 10: Transverse, no-fines concrete subbase drain
Figure 10 shows a section through a sub-base drain for a water-bound macadam base layer consisting of a transverse no-fines concrete strip, wrapped in filter fabric. The sub-base drain is easier to construct and more robust than the edge-restraint drain. This type of no-fines concrete drain should not be used in the base layer, as crushing of the concrete will occur during compaction of the water-bound macadam base layer.

The side-drain and concrete edge-restraint shown in Figure 9 has been used successfully in KwaZulu-Natal (VKE, 1987) with a slight modification. The drainage pipe was moved to the bottom centre part of the concrete edge-restraint and no-fines concrete was used for the edge-restraint. As the drainage pipe and geotextile did not become clogged with concrete fines, this system performed exceptionally well, allowing all the construction water to drain away under saturated conditions. The only problem with this design was that the no-fines concrete did not bond well to the cemented sub-base and that the edge-restraints moved laterally during placement of the base layer. It is suggested that metal spikes be driven into the sub-base and that the no-fines concrete be poured around the protruding spikes. The suggested modified design is shown in Figure 11. Although this design performed reasonably well during construction, there is concern that the no-fines concrete will be crushed if it is exposed to traffic loading. Figure 12 shows another alternative for the design of the edge-restraint drain normally used with block paving (Visser, personal communication).

3.2 Field density specification, compaction and quality control

The purpose of setting a certain minimum level for the density of a pavement layer is to ensure that an adequate bearing strength is achieved. Although bearing strength is the desired parameter, density is a convenient parameter to measure under field conditions and in the laboratory and the relationship between bearing strength and density can easily be confirmed from laboratory test results. The field density specifications for water-bound macadam are based on the apparent density of the coarse and fine aggregate combined. TRH14 (CSRA 1985) makes provision for two water-bound macadam classes whose density requirements are:

- **WM1**: 88 – 90% of apparent density
- **WM2**: 86 – 88% of apparent density

Potgieter, Hattingh and Schultz (1997) described the four stages of water-bound macadam compaction summarised in the list below and described how these levels of densification could be achieved.

**Loose**: Loose material after placement.

**Orientated**: The orientation of the large aggregate is adjusted to achieve an optimum packing pattern of the coarse and fine aggregates. This level may be achieved with light rollers.
Interlocked: The large aggregate is locked into an optimum packing pattern. According to Potgieter, Hattingh and Schultz, this is the highest level of densification that can be achieved during construction by using heavy (12 tonne) rollers.

Densified: The air voids in the layer are minimised through the optimum packing pattern of the coarse and fine aggregates. According to Potgieter, Hattingh and Schultz, this condition will be achieved for water-bound macadam under traffic loading.

It has often been said that the large aggregate provides the bearing strength of water-bound macadam and that the fine aggregate provides stability to the material. The bearing strength is achieved through the normal forces acting at the contact points between the large aggregate particles. Maximisation of the number of contact points by achieving an optimal packing pattern of the coarse aggregate in an interlocked state will therefore result in maximisation of the bearing strength. This optimal packing pattern with its associated maximum number of contact points and normal contact forces is, however, only maintained through the frictional forces at the contact points and the stabilising effect of the fine aggregate. It is therefore essential to the performance of the water-bound macadam that an interlocked condition be achieved with a dense filling of the voids with the fine aggregate. The current general consensus (Visser and Hattingh, 1999) is that only the use of conventional heavy compaction equipment (12-tonne flat wheel roller) will ensure the desired interlocked and stable condition of water-bound macadam.

The use of these heavy rollers also enables the slushing of the water-bound macadam layer to remove excess fines from the layer. The slushing process is similar to the slushing process for a G1 crushed stone base layer and will be discussed under the construction section of this document.

Horak (1982) investigated the effect of slushing on the density of water-bound macadam at one HVS test site. The maximum density achieved by rolling alone was 86.5% of apparent density, while the density increased to 88.6% after slushing and to 89.5% after trafficking. These results seem to confirm the hypothesis by Potgieter, Hattingh and Schultz and emphasise the need to achieve the maximum possible density of the water-bound macadam layer during construction before the road is opened to traffic. It is therefore recommended that, except in areas with water shortages, water-bound macadam should be slushed to achieve the highest possible density during construction so as to avoid post-construction compaction and deformation of the material.

The construction quality of nine roads with labour-intensively constructed water-bound macadam base layers was evaluated for the Central Witwatersrand Regional Services Council in 1994 (van Huyssteen, 1994). Only one of the 10 density samples taken from these roads complied with the density specification of 88% of apparent density for a WM1 material and one sample met the density specification of 86% of apparent density for a WM2 material. It is not stated what compaction equipment was used on these base layers, but the field density of the water-bound macadam clearly did not meet the specifications and Van Huyssteen concluded that inadequate inclusion of fines in the large aggregate skeleton was the cause of the low field density. A localised failure occurred on one of these roads. The fines settled to the bottom of the water-bound macadam layer under the vibratory action of traffic. The asphalt surfacing had a cobblestone appearance (seemingly spanning from one large stone to the next) and a dense crack pattern. This same type of localised failure has been noted on several

Density is crucial

The density of water-bound macadam is the single most important factor governing the performance of the material. There can therefore be no compromise on the density specification for water-bound macadam and the use of conventional, heavy compaction equipment is imperative.
recently constructed water-bound macadam base layers in the Gauteng Province (Sadzik, personal communication).

3.3 Selection of a surfacing type

The selection of a surfacing type for water-bound macadam is largely dictated by the riding quality of water-bound macadam rather than by structural requirements. From previous studies the following riding qualities are typical:

- Water-bound and slurry penetration macadam: 1.5 - 2.0 PSI
- Asphalt wearing course on a slurry penetration layer: 3.0 - 3.5 PSI
- Asphalt wearing course on an asphalt levelling course: 3.5 - 4.0 PSI.

According to the constructed riding quality requirement from TRH4, a water-bound and slurry penetration macadam with a single or double seal will therefore not even satisfy the riding quality requirement for a Category D road in a rural environment. Single or double seal surface treatments are therefore not recommended for water-bound macadam pavements.

Slurry penetration macadam has been applied successfully as a stage construction option to accommodate construction traffic without disturbing the base layer (Roux and Otte, 1993). An asphalt wearing course on a slurry penetration macadam may be applied to category D, C and less important category B roads. Important category B roads and category A roads require both asphalt levelling and wearing courses.

Although the riding quality of a water-bound or slurry penetration macadam with a single or double seal may be sufficient for application on streets in urban areas, an asphalt surfacing is still recommended. The turning, breaking and accelerating motion of traffic in the urban environment may damage surface treatments and expose the water-bound macadam to the scouring effects of stormwater run-off. The placement of water-bound macadam with a paver does not have a significantly beneficial effect on the riding quality of the material, an acceptable riding quality only being achieved when a correction layer (hot-mix asphalt or penetration slurry) and a wearing course layer are applied.
The purpose of structural pavement design is to make an unbiased estimate of the bearing capacity of layered pavement systems of different types. If the bearing capacity of a specific design is under- or overestimated in relation to the bearing capacity of alternative designs, the particular design will respectively be unfairly penalised or promoted during the economic analysis. A structural design method that will assess the bearing capacity of different pavement types according to the same set of rules is therefore required. A mechanistic-empirical design method has the potential to do this. SANRA (2000) presents a mechanistic-empirical design model for water-bound macadam material based on Heavy Vehicle Simulator (HVS) and laboratory test results. This design model was used for the design of the structural pavement layers shown in the pavement design catalogue in Figure 13.

The catalogue indicates the minimum material quality and layer thickness requirement for each combination of road category and design bearing capacity. Construction tolerances should be added to these minimum requirements to ensure that the constructed layers are never thinner than the minimum requirement given in the catalogue. The catalogue also allows the use of double and Cape Seals for combinations of low design-bearing capacity and for less important road categories. This reflects the minimum requirement from a structural design viewpoint. A hot-mix asphalt surfacing may be required from functional considerations and the reader is referred to the previous section of this document for selection of an appropriate surfacing.

**Figure 13: Structural design catalogue for waterbound macadam bases**

<table>
<thead>
<tr>
<th>ROAD CATEGORY</th>
<th>PAVEMENT CLASS AND DESIGN BEARING CAPACITY (80 KN AXLES/LANE)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ES0.003 ESO.01 ESO.003 ESO.01 ESO.003 ES1 ES3 ES10 ES30 ES100</td>
</tr>
<tr>
<td></td>
<td>0.1-0.3x10^6 0.3-1.0x10^6 1.0-3.0x10^6 3.0-10x10^6 0.1-0.3x10^6 0.3-1.0x10^6 1.0-3.0x10^6 3.0-10x10^6 10-130x10^6</td>
</tr>
<tr>
<td>A: Major interurban freeways and roads. (95% approximate design reliability)</td>
<td>30A 125 150C3 30A 125 150C3 30A 125 150C3</td>
</tr>
<tr>
<td>B: Interurban collectors and major rural roads. (90% approximate design reliability)</td>
<td>30A 125 150C4 30A 125 150C4 30A 125 150C4</td>
</tr>
<tr>
<td>C: Lightly trafficked rural roads and strategic roads. design reliability)</td>
<td>30A 125 150C6 30A 125 150C6 30A 125 150C6</td>
</tr>
<tr>
<td>D: Light pavement structures, rural access roads. (50% approximate design reliability)</td>
<td>30A 125 150G7 30A 125 150G7 30A 125 150G7</td>
</tr>
</tbody>
</table>

Symbol A denotes AG, AC, or AS. AO, AP may be recommended as a surfacing measure for improved skid resistance when wet or to reduce water spray. S denotes Double Surface Treatment (seal or combinations of seal and slurry). S1 denotes Single Surface Treatment. * If seal is used, increase C4 and G5 subbase thickness to 200 mm.

Most likely combinations of road category and design bearing capacity.

The catalogue indicates the minimum material quality and layer thickness requirement for each combination of road category and design bearing capacity. Construction tolerances should be added to these minimum requirements to ensure that the constructed layers are never thinner than the minimum requirement given in the catalogue. The catalogue also allows the use of double and Cape Seals for combinations of low design-bearing capacity and for less important road categories. This reflects the minimum requirement from a structural design viewpoint. A hot-mix asphalt surfacing may be required from functional considerations and the reader is referred to the previous section of this document for selection of an appropriate surfacing.
Designs were developed for two design cases. The first case consists of a WM2 water-bound macadam base layer constructed on a granular sub-base or relatively thin or weak cement-treated sub-base. The base layer is at 84% of apparent density because of the relatively weak compaction anvil provided by the sub-base. The second case consists of a WM1 water-bound macadam base layer constructed on a sufficiently strong compaction anvil consisting of at least 125mm of cement-treated material and the base density is 88% of apparent density.

5. Plant and equipment

The following plant and equipment is required:
• 12 ton steel wheel roller compactor: for compacting aggregate and working fines into voids,
• Steel shuttering: for edge-restraint and thickness control during construction,
• Steel rakes and shovels and wheelbarrows: for transporting, levelling and placing aggregate,
• Screeds which are used between the top of the steel shuttering and the top of the side drain or the top of the inside edge of the concrete gutter to obtain the pre-compaction level,
• Steel gauges which are placed on top of the steel shuttering and edge of concrete to obtain the uniform loose level before compaction and to ensure that the correct final compacted level is obtained,
• Water tank and heavy duty hose and fittings for the supply of water and slushing of fines.

6. Construction

6.1 Loss of previous generation skills

The success of early water-bound macadam construction in South Africa depended largely on the skills of the road-builders of the time. Meticulous attention was paid to the detail of each step of the construction process. With time and as a result of the increasing use of continuously graded crushed stone for base layer construction, these skills were lost to the road-building industry. The interest in water-bound macadam construction was revived when job-creation became a national priority because water-bound macadam construction is well suited to labour-intensive methods. By this time, however, the earlier skill of water-bound macadam construction had faded and with new, inexperienced emerging contractors entering the road-building industry, the risk associated with water-bound macadam construction increased. It is therefore strongly recommended that the construction process for water-bound macadam construction be broken down into as many steps as possible, with the contractor and consultant paying the greatest attention to every detail of each step. As many checks as possible should also be built into the process to enable the quality of the product to be monitored continuously. It is not possible to go through the steps of water-bound macadam construction carelessly and still achieve a high quality product.

The construction of water-bound macadam may be divided into two components, namely the placement of the large aggregate, and the filling of the voids in
the large aggregate skeleton with a fine filler. Manual labour may be used to varying extents in each of these components but the principles of construction should remain the same for labour-intensive or plant-intensive construction. The following steps in the construction process will be discussed individually:

- Sub-base and edge-restraint preparation,
- Placement of the large aggregate,
- Filling of the voids in the coarse aggregate skeleton with a fine filler.

6.2 Sub-base and edge-restraint preparation

The catalogue of pavement designs in Figure 13 indicates that both unbound natural gravel or lightly cemented natural gravel sub-base layers may be used for pavements with water-bound macadam base layers. The use of lightly cemented sub-base layers is, however, strongly recommended if the wet method of construction is used and should be considered if the slushing process is to be used.

Permanent and temporary edge-restraints serve a dual purpose during water-bound macadam construction. Firstly, they act as an edge-restraint to box-in the large aggregate during the construction process and secondly, they are used without exception to provide a reference for the control of the levels on the water-bound macadam base layer. The option to construct a permanent concrete edge-restraint incorporating a side drain seems to be preferred in the wetter, eastern coastal areas of South Africa (VKE, 1987, McCall et al, 1990). These edge-restraints provide confinement of the water-bound macadam layer and the side drains drain away excess water during construction and the service life of the pavement. The use of temporary steel shutters in combination with gravel shoulders seems to be preferred in the dryer parts of the country to provide the edge-restraint for the water-bound macadam base layer.

If concrete edge-restraints are used, the line and level of the shutters on the front face of the edge-restraint are surveyed at 20 m intervals on straights and 10 m on curves (McCall et al, 1990). String lines and dipsticks are then used from the top of the completed concrete edge-restraints for level control on the water-bound macadam base. The problem with string lines is that they sag towards the centre-line of a wide carriageway. Modern laser levels should not suffer from this problem.

If temporary steel shutters are used on the centre-line and at the edges of a carriageway, the coarse aggregate for the water-bound macadam may be levelled against a screed rail placed on spacers on top of the steel shutters. The problem with this method is that, because of the fixed height of the shutters, any undulation at the top of the sub-base is reflected to the top of the base layer. It is therefore recommended that the steel shutters should only be used as an initial thickness guide and should be removed before any compaction is applied to the coarse aggregate layer. Final level control should then be done by string line and dip stick from levelled survey pegs. If temporary steel or wooden edge-restraints are used during the construction, care should be taken that the shoulders are constructed and compacted properly so that they can provide the confinement that is essential to the long term performance of the water-bound macadam layer.

Edge-restraints, either permanent or temporary, are the first step in the process of level control of the water-bound macadam base layer and should receive attention accordingly.
6.3 The placement of the coarse aggregate

The placement of the coarse aggregate may be done from stockpiles by hand labour using coal forks (Horak, 1983) (see Figures 14 and 15), with a heavy grader (VKE, 1987) if the coarse aggregate is dumped on the sub-base or by mechanical paver (McCall et al, 1990). The use of a mechanical paver in the case study reported by McCall resulted in slightly better riding qualities on the surfaced road than the labour-intensive and plant-intensive methods.

Several authors (Horak, 1983; VKE, 1987; McCall, 1990 and VKE & McCutcheon and Associates, 1999) agree that about 33% reduction in the thickness of the loose, coarse aggregate should be allowed for during compaction. Spacers of the required height are therefore placed on the edge-restraints and the coarse aggregate is spread to the top of the spacers by the preferred method. Before any compaction is done on the coarse aggregate layer, a level surface finish should be obtained. This is done by filling in lean spots by hand labour and by removing excess material from high spots. An uneven surface of the loose coarse aggregate layer before compaction will result in an uneven surface after compaction.

If the coarse aggregate stockpile is dumped directly onto the sub-base, on delivery, it is desirable to move the entire stockpile during spreading, as otherwise the partial compaction at the bottom of the stockpile heap will lead to greater undulations of the final surface. Also there may be some fines within the coarse material that will fall to the bottom of the heap and interfere with the bedding of the coarse aggregate onto the sub-base.

One of the aspects of early water-bound macadam construction which was highlighted by Horak (1983) was that the maximum layer thickness constructed in one lift should not exceed twice the size of the coarse aggregate. This was done to assist in the proper penetration of the layer with the fine aggregate.

Once a level surface is achieved on the loose, coarse aggregate layer, the spacers are removed from the concrete edge-restraints or the temporary shutters are removed totally. The furrows left by the temporary shutters are then filled with loose aggregate. The coarse aggregate layer is now ready for compaction. Horak (1983) often referred to the use of 12 ton, 3-wheel rollers for the compaction of the coarse aggregate layer. Other sources (VKE, 1987 and McCall et al, 1990) mention the use of 8 ton tandem rollers and McCall specifically mentioned the breaking of an unweathered dolerite coarse aggregate with an Aggregate

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Figure 14: Spreading of the coarse aggregate between temporary edge restraints
Crushing Value (ACV) of 14.4% under a 12 ton, 3-wheel roller. Phillips (1994) also reported the crushing of the coarse aggregate under a vibratory roller. Ideally, trial sections should be constructed to determine the degradation of the coarse aggregate under 12 ton or vibratory compaction. If degradation of the coarse aggregate proves to be a problem, 8 ton tandem rollers should be used.

Rolling should always be towards the higher side: if cambered, rolling starts at the sides and progresses towards the centre; if super-elevated, it starts at the low side and progresses upwards. If gravel shoulders are used, the drum of the roller should overlap onto the shoulder to ensure proper confinement. After the initial compaction passes the surface of the layer is again rectified by hand. Rolling is continued until no movement of the coarse aggregate is visible under the rollers and the coarse aggregate is keyed in. The stone layer is then ‘locked up’. It should be noted that if lock-up is not achieved and the fines are spread and slushed, the shape and level of the base will be distorted by each subsequent operation. Lock-up ensures higher stability of the coarse aggregate and less distortion of the final surface.

6.4 Filling of the voids in the coarse aggregate with fine aggregate

The fine aggregate is spread on the keyed-in coarse aggregate layer by hand using shovels or by mechanical chip-spreader (see Figure 16). The thickness of the loose filler placed in one application should not exceed 25mm and should be evenly distributed. If the material is slightly moist, it should be left to dry before vibratory compaction is applied to enable the fine aggregate to filter down into the coarse aggregate layer. The process of successive applications of fine aggregate and vibratory compaction is continued until the layer is choked with fine aggregate. If the dry process is selected, the construction process stops at this point. The dry method is appropriate for arid areas where very little water is available for construction. In this case, water-bound macadam construction should compare favourably with the construction of a continuously graded material which will require compaction water.

If slushing is selected, the choked layer is watered and compaction should then resume, working from the highest to the lowest point. Drainage outlets should be inspected to ensure that the construction water drains freely from the layer. The excess fines should be slushed from the layer and broomed to the side of the layer (see Figure 17). After completion of the slushing process, the layer should be left to dry and then broomed again.

McCall et al (1990) mentioned the use of a 24 ton pneumatic roller for the slushing process and VKE (1987) indicated that the use of a 24 ton pneumatic roller had no significant effect on the slushing process. Density results (Horak, 1982) from water-bound macadam base layers seem to indicate that a density of 84% to 86% of apparent density may be
achieved with vibratory compaction using the dry method and that a density up to 88% may be achieved if the layer is slushed and that this will be further increased by trafficking to between 88% and 90% of apparent density. This seems to correspond well with Potgieter, Hattingh and Schultz’s theory of orientation, interlock and densification.

After the fine aggregate is applied to fill the voids, the layer is then ready to be primed. A blanket of loose filler may be left on top of the layer to prevent kick-out of the coarse aggregate under construction traffic but all loose material must be broomed off before the prime is applied. In general it is not recommended that traffic is allowed on the water-bound macadam layer before the surfacing layer is applied. This can be costly and difficult under some circumstances. If it is foreseen that it will be difficult to prevent traffic (including construction traffic) using the road, the possibility of applying a slurry layer across the water-bound macadam should be considered. This is also costly but will be cheaper than having to do major reconstruction of the water-bound macadam layer. McCall et al (1990) reported on the use of a slurry penetration layer in the top portion of a water-bound macadam base layer that was opened to construction traffic within four hours of construction with no damage to the base layer.

To summarise, the following list of important aspects which should be monitored closely during the construction process, is provided:

- The edge-restraints, either permanent or temporary, form the first step in the process of level control of the water-bound macadam base layer and should receive attention accordingly,
- The maximum layer thickness constructed in one lift should not exceed twice the size of the coarse aggregate,
- If the surface of the loose coarse aggregate layer is uneven before compaction, this will result in an uneven surface after compaction,
• After the initial compaction passes, the surface of the coarse aggregate layer is again rectified by hand,
• Rolling is continued until no movement of the coarse aggregate is visible under the rollers and the coarse aggregate is keyed-in.
• The thickness of the loose filler placed in one application should not exceed 25 mm and should be evenly distributed,
• If a slushing process is used, compaction should start from the highest point, working to the lowest point,
• If a slushing or completely wet process is used, drainage outlets should be inspected to ensure that the construction water drains freely from the base layer,
• The layer must dry out completely before it is sealed,
• A layer of loose filler material or a slurry penetration layer may be used if the newly constructed water-bound macadam layer has to be opened to construction traffic,
• All loose material must be broomed off before a prime is applied.

7. Quality control

The density of the layer can be checked against the following requirements from TRH 14:
• WM1 88-90% of apparent density
• WM2 86-88% of apparent density

Sand replacement tests or nuclear density measurements can be used to determine density. However, as these tests can only be performed after the fine aggregate has been placed and the base slushed, it may be very difficult to improve the density if the coarse aggregate was not compacted properly. If additional slushing does not bring the density up to specification, then the layer will have to be scrapped and new material brought in. It is generally very costly to separate the coarse and fine materials for re-use. It is therefore important that measures are in place to ensure that the coarse aggregate is sufficiently compacted before the fine materials are placed. One important means of doing this is using levels to ensure that the 33% reduction in thickness of the loose layer was achieved.

All the geometric requirements of the specification must be checked and met: level, layer thickness, and eveness (with straight-edge tests). The cleanliness of the mosaic must also be checked carefully. Poor brooming will leave fines on the stone surface, which will lead to delamination of the surfacing.
8. Specialist literature


This guide to best practice would not have been possible without the contribution of all sectors of SA Construction and its stakeholders, a contribution of time and leadership made in the interests of a better industry.

It is impossible to list all those who have made an input to this product since the 1996 initiative between the Minister of Public Works and Captains of Industry. The "Captains’ Initiative" kick-started a number of key interventions towards a transforming industry including a focus on labour-based construction.

Initial conceptual work was taken forward by the Inter-ministerial Task on Construction Industry Development, which established a focus group under the leadership of Graham Power. The Focus Group built on the experience of pilot public works projects to develop a preliminary set of guidelines.

Building on the work of the Task Team, the cidb has expanded the application of technologies and methods to increase the employment generated per unit of expenditure. A focus group of industry specialists and stakeholders has further reviewed and refined these guidelines, which are now recommended by the Expanded Public Works Programme in the delivery of national, provincial and municipal infrastructure.

cidb wishes to thank the many individuals whose passion, commitment and knowledge has enabled the development of this publication as a common resource in the fight against poverty and joblessness, both in South Africa and globally.

A special thanks is due to Ron Watermeyer (past President of the SA Institution of Civil Engineers) whose involvement has ensured a continuity of focus throughout the process.
“Like slavery and apartheid, poverty is not natural. It is man made and it can be overcome and eradicated by the actions of human beings.”

Nelson Mandela, 2005 – Global Campaign for Action against Poverty