recycling of road pavement materials in the Netherlands

by

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(road engineering division of the rijkswaterstaat, delft)

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Introduction

This report deals with the Rijkswaterstaat's work on the recycling of road pavement materials in the Netherlands.

We, the authors, were involved in some of this work, the rest of it – and some of the report – having been done by our colleagues and assistants. We also received help from the regional directorates of the Rijkswaterstaat and from the Dutch road-building contractors who carried out the practical work. We therefore take this opportunity to thank all those who helped us with the investigations and field tests, as well as with the drafting of this report.

The laboratory investigations and the field tests were done in the period 1973-84. The Dutch developments are reported here in the context of similar work done in other countries. As far as possible, the developments achieved by other road authorities in the Netherlands are also included in this account. The report reflects the state of affairs as at October 1983, as far as it is known to us.
1 Historical and background

The re-use of materials is not new in itself: beating of swords into ploughshares is both very old and quite topical. Waste paper and scrap metal have long been collected, but their value shows strong fluctuations.

In the building trade waste material was first used in the Netherlands in the 1920's, when rubble and slag were incorporated in single-sized concrete for building houses, although only on a rather small scale. Some of the houses built in this way are still standing and are in a good condition. After World War II, rubble was used both as a base-course material and as a component of concrete and asphalt. In the early 1950's, when building materials were in scarce supply, asphalt broken out of the pavement was heated, mixed with a rejuvenating agent, and re-used. This was done with little resources and on a small scale, but the results were satisfactory in every respect. The use of blast-furnace slag in cement has been a more continuous development, and the resulting cement since long has a market share of about 50% in this country. This is an example of using a waste material to make a product that has its own special characteristics and hence its own field of application.

The first oil crisis in 1973 triggered off large-scale investigations, mainly in the United States and Japan, into the recycling of old road-paving materials – both concrete and asphalt. The main reason for this was the steep rise in the price of the raw materials, especially bitumen (a petroleum product), and in the cost of energy. This period also saw the beginning of similar developments in the Netherlands, but we also had two other reasons.

The first is connected with the problem of quarried mineral building materials, a large part of which, including sand and gravel, is obtained in the Netherlands (see Section 3 for the quantities). However, there are increasing objections to quarrying, on the grounds that it disturbs the landscape and the biological equilibrium, even though a quarrying licence is already granted only on the condition the scars to the landscape are remedied afterwards. For advice on policy, the Minister of Transport and Public Works set up a National Committee on the Coordination of Policy on Excavations and other Ground Disturbances in 1976 from representatives of central and local government, who grant the quarrying licences. This Committee issued an interim report on gravel, clay, and sand for building and the production of concrete [1], recommending that the existing production level should be maintained in the
short term (taking the changes in the demand into account), but that in the longer term an attempt should be made to reduce the demand, e.g. by increasing imports, extracting materials from the sea, and using alternative materials, which includes the recycling of old materials. The short-term policy was later elaborated by three Inter-Province Study Groups, which issued their report in 1980 [2]. The long-term policy is being formulated by the Inter-Departmental Committee on Excavations and other Ground Disturbances, which also deals with the use of alternative materials [3, 59].

The second reason is connected with the problem of waste disposal in the Netherlands. The fact is that recycling of old materials is also of interest because it helps to solve this problem. Dumping, landfills, and incineration are being increasingly attacked on environmental grounds for taking up too much space and possibly polluting the air, the soil, and the surface waters. The Dutch Waste Disposal Act [4] came into effect on 1 October 1979 as part of the environmental regulations. This Act deals with household refuse, scrap cars, and other types of waste, including construction and demolition waste. The Act has two aims: to ensure an efficient removal and processing of waste materials, and to promote their re-use or limit their formation. The implementation of this Act, including the granting of licences for waste processing installations, is in the hands of the eleven Dutch Provinces. They must draw up plans for the removal and processing of certain types of waste materials, such as construction and demolition waste. Most of the Provinces have in fact already done this for the first 5 years.

A future Act on soil protection will clarify which forms of waste recycling are environmentally acceptable. It will list both the materials that must not be disposed of in or under the ground and the materials that can be so disposed under certain conditions, which will also be specified. It will also stipulate the maximum emission levels for environmentally harmful materials both for the ground and the surface waters. Finally, the Act will lay down what to do when recycled waste materials once more come to the end of their useful life.

The provisional ‘Indicative Multi-Year Programme for the Soil’, issued in September 1983, gives a ‘black list’ and a ‘grey list’ of substances. The former contains substances for which the permitted emission level is zero, which means that the amounts of these substances already present in the different types of ground or soil must not be increased. The grey list contains substances that can be placed on or introduced into the ground only under special conditions. Further stipulations and the definition of restricted and unrestricted use are being worked out at present.

An exhaustive study into the market for construction and demolition waste has revealed good prospects for its re-use, especially in the field of road-building [5].
2 Conditions for recycling

It depends on many factors whether a recycling operation is feasible. The following conditions have been listed by the Working Party on Alternative Materials of the Inter-Departmental Committee on Excavations and other Ground Disturbances [3]:

1 The material must meet the functional requirements [8].
2 The material or the product incorporating it must not have a shorter service life than new or conventional material, and its maintenance and related costs must not exceed those of the latter either.
3 The material must be used where the utilization of its value is highest ('value-restoring re-use').
4 The energy considerations are decisive for its use and marketing.
5 Its continued supply and quality must be ensured.
6 It must 'sell itself', i.e. it can get a grant only to help with its launch.
7 Its market price must not be higher than that of new or conventional material.
8 Investments for it must be profitable, also in the long term, taking into account the existing plants and expertise and the foreign competition. Its use must not mean a loss of capital for either the government or the industry.
9 Its use must not endanger public health or the quality of the environment.
10 The social consequences of its use (e.g. jobs and the spending of public money) must be taken into account.

On this basis, how are we to recycle old road pavements, and what are the limitations? The answer to the first question depends on the properties of the old pavement materials and on the ways of their removal, treatment, and storage. Since pavement material is generally uncontaminated, its treatment need only involve crushing and screening to the right size [7] (see later). In the case of removal and storage, the ideal separation of the different types must be weighed up against the cost of this operation (see Section 4).

The relevant chemical, physical, and mechanical properties of old pavement materials are determined in the laboratory in ‘preliminary tests’, but the results must not be simply matched up against the existing specifications, which are based on years of experience with new natural materials; in some cases it may prove necessary to introduce new or supplementary requirements and specifications. However, this cannot be done until promising laboratory results have been obtained, followed by
field tests. The construction of test sections with the recycled material in such field tests will reveal its workability and durability under the prevailing climatic and traffic conditions. Results of this type are discussed in Section 5-15. In many cases the work is still in progress. Furthermore, although we can naturally profit by foreign experience, the conclusions must generally be verified under Dutch conditions, because of international differences in the processes of preparation and laying, the types of aggregates and other additives, and the climatic conditions.

The important aspects of field testing are as follows. There are great differences between old and new materials in their properties, and often also in the way they are prepared and applied. In fact, these differences are generally so great that it is not sufficient to test the recycled material only by the existing quality criteria. As mentioned above, we must first obtain some idea about the properties of the materials and their mixtures from laboratory tests. If there is a specially developed plant for preparing and processing the mix, it must also be subjected to tests with a view to optimizing its use. The field tests must tell us how well this plant works and how the materials and mixes behave during and after laying. It is generally advisable to construct also a reference test section with comparable design parameters, such as bearing capacity and service life, but with new materials instead of recycled ones. Both road sections should be at least 200-300 m long in order to be able to ignore any initial problems occurring during production and construction. The two sections should be constructed soon after each other. They must also be near each other, so that they are exposed to the same weather and traffic. The results must satisfy some preset criteria not only in a relative but also in an absolute sense. Finally, it is essential to plan the subsequent tests for monitoring the performance of the test sections and to draw up reports.

Recycled pavements are still associated with a low quality and a variable performance, but – as will be shown below – the former is far from being always true and the latter can be avoided mainly by careful removal and storage of the old paving materials (see Section 4).

We have emphasized here the economic aspect, because it determines whether recycling will be done at all. On the one hand, we save materials and often also energy and transport costs, while on the other hand there are some new cost items connected with the methods used (selective removal, special equipment for mixing and laying), with greater wear and tear (caused e.g. by the use of angular instead of rounded particles), and with the additional storage area needed for the materials removed from the road. However, recycling causes an overall reduction in the space requirement, e.g. because there is less waste material to discard. The authorities can influence the economics of recycling via the tipping charges and facilities.

Finally, the recycling of old pavements can be greatly promoted by two factors: the
laying-down of requirements and specifications that can also be used by those who risk contractual specifications and the dissemination of knowledge gained in the investigations concerning pavement recycling. The present report is intended to do both.
3 Supply and demand of road-building materials

The amounts of various road-building materials used in the Netherlands in 1980 are shown in the following table [9].

Table 3.1 Amounts of road-building materials used

<table>
<thead>
<tr>
<th>Material</th>
<th>Amount used in 1980, in Mt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand for industrial use</td>
<td>3.5</td>
</tr>
<tr>
<td>Gravel and chippings</td>
<td>3.5</td>
</tr>
<tr>
<td>Cement</td>
<td>0.1</td>
</tr>
<tr>
<td>Filler</td>
<td>0.5</td>
</tr>
<tr>
<td>Bitumen</td>
<td>0.5</td>
</tr>
<tr>
<td>Natural base-course and sub-base materials (e.g. lava and silex)</td>
<td>1.1</td>
</tr>
<tr>
<td>Slag (base-course and sub-base material)</td>
<td>2.2</td>
</tr>
<tr>
<td>Fill sand</td>
<td>30</td>
</tr>
</tbody>
</table>

These quantities are decreasing. Thus, the amount of hot-mix asphalt made was about 8 M t in 1980 but only about 5.5 M t in 1982, and a further drop cannot be ruled out. This is due to two reasons: the recession and the fact that in many respects the road network or infrastructure is now nearly complete in the Netherlands. The result is a great decrease especially in the annual volume of new roads built. The 1977 Traffic and Transport Plans [10] still envisaged the building of some new roads, but these have since been cancelled, whilst some other projects have been postponed. However, there are good reasons for regarding an annual production of about 5 M t of asphalt as a minimum, especially because much is needed for repairs, which are essential for road safety.

The amounts of various waste materials produced in 1980 are given in the table 3.2 [9].

The amounts of some of these, and especially construction and demolition waste and carbonaceous residues, are steadily increasing.

Breaking up old road pavements produces annually about 1.3 M t of material. Although this is not much in comparison with the total waste production of 54.1 M t, it is still very important for recycling because of its nature. About half of it (0.6 M t
Table 3.2 Amounts of waste materials produced

<table>
<thead>
<tr>
<th>Material</th>
<th>Amount produced in 1980, in Mt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dredge spoil (dry-matter content 40%o)</td>
<td>28.0</td>
</tr>
<tr>
<td>Sewage plant treatment sludge (dry-matter content 4%o)</td>
<td>5.2</td>
</tr>
<tr>
<td>Construction and demolition waste, including: masonry waste</td>
<td>6.5</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>concrete waste</td>
</tr>
<tr>
<td></td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>asphalt waste</td>
</tr>
<tr>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Household and industrial refuse via the Cleansing Services, including</td>
<td>0.7</td>
</tr>
<tr>
<td>incineration residues (mainly slag)</td>
<td></td>
</tr>
<tr>
<td>Agricultural waste</td>
<td>1.0</td>
</tr>
<tr>
<td>Carbonaceous residues (mainly fly-ash)</td>
<td>0.6</td>
</tr>
<tr>
<td>Scrap cars</td>
<td>0.5</td>
</tr>
<tr>
<td>Calcium sulphate waste</td>
<td>2.5</td>
</tr>
<tr>
<td>Chemical waste</td>
<td>1.0</td>
</tr>
<tr>
<td>Blast-furnace slag</td>
<td>1.4</td>
</tr>
<tr>
<td>Phosphate slag</td>
<td>0.7</td>
</tr>
<tr>
<td>Steel slag</td>
<td>0.9</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>54.1</strong></td>
</tr>
</tbody>
</table>

per year) is made up of bituminous material and the rest of concrete, slag, clinker bricks, and sand. About half of the material is broken up in projects of the central government. Contractual specifications show where asphalt pavement was broken up in 1977-80 and in what quantities. According to these data, about half was obtained in the west of the country; the greater part of the material was removed in small batches of less than 5000 t [11]; (see also table 3.3).

Despite the declining trend, the demand for road-building materials still cannot be fully satisfied, even if all the material broken up is re-used.

Table 3.3 Numbers of Rijkswaterstaat projects in 1977 and 1978, classified by the amount of old asphalt removed from the pavement

<table>
<thead>
<tr>
<th>Amount, t</th>
<th>Number of projects in 1977</th>
<th>Number of projects in 1978</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 1000</td>
<td>46</td>
<td>34</td>
</tr>
<tr>
<td>1000-5000</td>
<td>19</td>
<td>32</td>
</tr>
<tr>
<td>5000-10,000</td>
<td>9</td>
<td>4</td>
</tr>
<tr>
<td>10,000-20,000</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>20,000-30,000</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>&gt; 30,000</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

14
4 Breaking up and stockpiling old road pavements

4.1 Assessment of the types and amounts of materials removed

As we have seen, it is important to be selective in the removal of pavements, to be able to recycle them for a high-grade use without incurring high laying costs. The economically best situation must be found for this purpose.

We must always understand the old construction before removing the pavement, and can sometimes gain enough information from the contractual specifications used for the building or the maintenance of the road in question. However, if this information is not enough, or if it is not sufficiently reliable, core samples must be drilled out of the road to assess the type and amount of materials that will be removed. We distinguish here between the following groups of materials [12]:

a  hot-mix asphalt (including bituminous surface dressings),
b  sand asphalt,
c  mastic asphalt, cold asphalt, bituminous wearing course and special asphalt mixes,
d  sand cement (cement-bound sand),
e  plain concrete, concrete slabs, and lean concrete,
f  reinforced concrete,
g  stones and clinker bricks,
h  sand.

If any of these is present in an amount of less than 5 wt-%*, it is not considered separately. Otherwise, no group should contain more than 5% of the other types taken together, unless this is known to be immaterial for re-use. The recycled materials in group c can be put only to low-grade use (base-courses or sub-bases). The same holds for hot-mix asphalt that has not been separated into its constituents to comply with the above scheme. This means in practice that the removal of very thin layers is very costly.

If hot recycling of old asphalt is a possibility, then it is advisable to take some core samples before the pavement is removed, to determine its binder content and the penetration value of the binder as mean values for the whole road section. If large variations are expected, for instance on the basis of the contractual specifications,

* Unless mentioned to the contrary, all percentages used in the report are percentages by weight.
then the above values should be determined for each layer of the pavement or for each stretch of the road. For use as hot-mix asphalt, the material in group a is conveniently subdivided into type a1 with a penetration greater than 50, and type a2 with a penetration less than 50.

If the binder cannot be examined before the pavement is broken up, this is done on the site afterwards, provided that the removed asphalt material is kept long enough in separate batches differing in composition.

Materials like asphalt, asphalt made with crushed stone, and concrete are also obtained when dams, dikes, and other hydraulic engineering constructions are demolished, but little is yet known about their recycling potential, and therefore they will not be considered here.

4.2 Pavement removal

The materials in groups a, b, and c must always be removed separately. If a different composition or the amount involved makes it necessary, bituminous surface dressing can be removed in advance by milling, separated from the other materials in group a, and combined with the material in group b.

The materials in groups d, e, and f can be broken out of the road together if they are then crushed and screened into fractions. However, not all crushers can deal with reinforced concrete, so the latter may have to be removed separately.

The materials in groups g and h must generally be removed separately. For re-use as unbound base-courses or sub-bases, the materials of groups d-g can be removed together.

It depends on the envisaged re-use whether sand (group h) is to be removed separately or with other materials. If the re-use consists of the cold laying of asphalt, sand can be present in an amount of 10-15%, and this is even desirable, provided the sand does not have a very fine particle size (see Section 9). Sand can also be present in the materials bonded with cement if the required grading can be obtained for further processing, if necessary by screening.

Old pavements can be removed for example by planing, ripping, cutting and milling. The use of a cutting tool or a milling tool permits a more selective removal than a falling weight.

The type of re-use mostly determines the size of the slabs, lumps, or blocks in which
the paving is removed. If the material is to be broken up later in a crusher, the slabs should not be larger than $1.0 \times 0.7 \times 0.4$ m. Since some jaw crushers can take larger pieces, it is advisable to find out in advance what sort of crusher will be used. If the comminution is done by steaming, the lumps should be smaller, namely $0.4 \times 0.4 \times 0.4$ m at the most (see Section 6).

If hot milling is used, it should preferably be followed immediately by actual re-use. If this cannot be done, extensive congealment (caking) occurs, so that the material needs a primary comminution before a crusher can be used upon it.

4.3 Stockpiling old paving materials

The materials removed selectively must also be stockpiled separately in the storage or collection area. It is important to record the details of each load as it arrives, making a note of the type and amount of material, the place of origin, and any undesirable or unidentified contaminations. In this latter case the batch must be kept separately while awaiting the results of identification tests.

Asphalt should not be piled higher than 3 m, in order to prevent caking, which occurs mostly under the influence of the generated heat. Asphalt destined for hot regeneration without previous comminution by steaming should be covered up, e.g. with a layer of sand, or kept under a roof to restrict the penetration of water.

The storage area or collection point should not be open to the public, to prevent any unauthorized dumping of other types of waste.

4.4 Processing of the old material

The contractual specifications should stipulate the envisaged use of the old pavement materials to be removed from the road. It must therefore be first ascertained whether the materials are to be used within the same project or in later ones, and whether they can be used by other clients or authorities in the same area. The authorities commissioning the work must therefore regularly estimate the amount and type of paving materials to be removed and inform one another about them. However, the establishment of this system still has a long way to go in the Netherlands.

Materials without any potential use in the near future, and materials obtained in small isolated batches can be temporarily stored on premises where rubble is processed. The number of such premises has recently risen greatly in the Netherlands, reaching about 30, scattered throughout the country, in 1982. These gener-
ally keep modest stocks of crushed asphalt rubble and various size fractions of old concrete and masonry rubble.

The pretreatment of old road paving materials consists of crushing and screening. The old material is generally comminuted in two steps: first in a jaw crusher or cone crusher (primary breaking), and then in a second jaw or cone crusher or an impact breaker (secondary breaking). Jaw crushers usually give a coarser product than impact breakers. When the old material is to be used as an aggregate-type addition, jaw crushers give coarse particles of reasonably cubic shape. Impact breakers are particularly suitable for making 0-40 or 0-60 mm base-course and sub-base materials with the required grading and a satisfactorily cubic shape. Impact breakers are more suitable than other crushers for comminuting bituminous materials, because the clogging-up of the apparatus by coalescence of the material is less likely to occur in them even in the summer.

Crushing is followed by screening to the required particle-size fractions as the second stage of pretreatment of the old paving material.
5 Asphalt recycling – general considerations and foreign experience

5.1 Introduction

The principal difference between old and new asphalt is that bitumen – its binder – changes because its most volatile components evaporate and because of oxidation and polymerization. It then partly or entirely loses its original viscoelastic properties, i.e. it suffers ageing. Although these processes are in principle irreversible, the original viscoelastic state of asphalt can be restored by the addition of either new bitumen with a higher penetration value or a rejuvenating agent. The latter is prepared chemically from petroleum and must comply with precise specifications as regards viscosity and composition [20].

The old asphalt is generally heated with or without new mineral aggregates and the mix is laid hot. For hot processing, the materials are either mixed on the site (in-place mixing) or in a central mixing plant somewhere else (in-plant mixing).

The alternative is cold regeneration. In this case the old asphalt is generally comminuted in a crusher and used not for a new wearing surface but as an underlying base-course or sub-base, with or without added new mineral materials or a binder.

5.2 Hot in-plant regeneration

This can be done with hot-milled or cold-milled material or with old material that has been comminuted in a crusher to the required grading (e.g. 0-40 mm), and which is called crushed asphalt. Milling and breaking out have the advantage that, when the old asphalt contains rounded aggregates such as gravel, the amount of old material in the mix can be considerably increased, which raises the stability of the mixture. The disadvantage of these methods of removal is that they generate too much fine material, which can cause an undesirably high degree of void filling in the regenerated mix.

There is also a thermal comminution of the old asphalt with the aid of steam, in which the material is treated for some time with steam at atmospheric pressure; the material softens at 85-90°C sufficiently well to permit disintegration (see Section 6). The moisture must of course be subsequently evaporated. As far as we know, this method is used only in the Netherlands and – on a limited scale – in Japan.
During the subsequent processing of the comminuted old asphalt the main concern is to prevent undue oxidation of the old bitumen, for instance by direct contact with the hot gases or with the heater itself. This must be prevented, because it makes the material much less useful and produces 'blue smoke', a serious environmental hazard. Two ways have been found to restrict this bitumen oxidation, represented by modified batch mixers and modified drum mixers [13, 14], which will be discussed below in turn.

Batch mixers are generally used in the Maplewood-Minnesota process (see Fig. 5.1). Here the old asphalt is introduced into the mixer in an amount of 20-50% and mixed with new aggregate superheated for example to 260-270°C. When the heat transfer has been largely completed, fresh bitumen is added in a calculated quantity. The residence time in the mixer is 10-30 sec longer than in the preparation of new asphalt. The modification to the usual batch mixer consists in the incorporation of a means for proportioning and introducing old asphalt in such a way that it does not deposit and build up on the walls.

![Diagram of the Minnesota process](image)

Figure 5.1 Partial regeneration of asphalt by the Minnesota process, involving the use of a batch mixer.

The ratio between old and new asphalt mainly depends here on the maximum permitted mixer temperature, the moisture content of the components and the end product, and the required laying temperature. Under the Dutch conditions, the maximum amount of old asphalt on this basis is 20-30%. This method has been used in the USA, Canada, and Japan to regenerate millions of tons of asphalt, and the Dutch experience is described in Section 7. The mix design will of course depend on the properties and composition of the old asphalt. The resulting mix must conform to the same specifications as the new paving material and is laid in the same way. No difference has so far been found between them as regards durability.
Among drum mixers representing the second solution, the heating-tube system developed by the RMI company (see Fig. 5.2) was one of the first. Crushed old asphalt is fed here into a drum with or without new aggregate and is heated with a large number of closed tubes carrying hot gases. There is a batch mixer at the end of the drum where fresh bitumen or a rejuvenating agent is introduced. However, clogging occurs because the old asphalt deposits on the tubes and builds up on them, and for this reason the system is no longer used in the USA. Deposition was also observed in the pilot plant used in the Dutch experiments.

![Diagram of asphalt regeneration by the RMI process.](attachment:image)

Figure 5.2 Regeneration of asphalt by the RMI process.

Owing to this shortcoming, some improved methods were developed in the second half of the 1970's. One of these, shown in Fig. 5.3, makes use of a drum mixer with a heat dispersion shield or a flame diffusion system, called the Boeing Pyrocone System. Hot gases are introduced into the mixer from the screened burner via a set of slots. Old asphalt and new aggregate are charged in at one end of the drum, and fresh bitumen at the other. The maximum amount of old asphalt used is 50%.

Another method, called the Iowa Manufacturing System, uses two drums (see Fig. 5.4). The new aggregate is heated directly in the first drum, and crushed old asphalt is charged into the second drum, where it is heated by hot gases and by the new material. Old asphalt can be used here in an amount of up to 60-70%.
Figure 5.3 Regeneration of asphalt by the Boeing Pyrocone process involving the use of a drum mixer.

Figure 5.4 Regeneration of asphalt by the Iowa Manufacturing process involving the use of drum mixers.

A drum mixer with separate inlets has been developed for instance by CMI, Barber Greene and Standard Havens (see Fig. 5.5.). The new aggregate is fed in near the flame, and the crushed old asphalt is fed in roughly into the middle of the drum; it is then heated by hot gases and by the new aggregate. Direct contact between the old asphalt and the heater is prevented by a ‘curtain’ of falling and tumbling new aggregate and – in some cases – also by a heat shield with air cooling. In this method up to 70% of old asphalt can be used. The drum is longer (1-1.5 m) than a drum mixer for new asphalt, in order to obtain the correct final temperature and moisture content.

Finally, there is also a tandem drum system developed e.g. by Barber Greene (see Fig. 5.6). The operation of this is similar to that of the Iowa Manufacturing System, and it permits the use of crushed old asphalt in amounts of up to 80%.
These drum mixers are becoming very popular in the USA, and have also been tried on a smaller scale in some European countries, such as France, Italy, and Finland. In the first test in the Netherlands, carried out in 1982, a drum mixer with separate inlets was used to make regenerated asphalt from a mixture containing 50% of old asphalt coming from surfacings and binder courses. The regenerated asphalt met all the requirements and was used for the same layers from which the material had come. However, further investigations must be done, especially on the mechanical properties and the long-term durability.

In some German tests with a drum mixer, 65% of old asphalt removed by milling and 35% of new aggregate were introduced into the drum through a set of blades and
allowed to fall past the flame [15, 60]. Fresh bitumen was introduced into a falling
curtain of material in the middle of the drum. The new coarse aggregate also acted as
a filter for the exhaust gases.

In comparison with the production of new asphalt, the hot regeneration of asphalt
saves a great deal of energy, mainly by saving bitumen, which requires a large
amount of energy to make in the first place and therefore has a high energy content.
This energy saving (in the form of materials, preparation, laying and transport)
amounts to 20-70%, again in comparison with new asphalt; the exact figure depends
on the local conditions, the amount of old asphalt incorporated, and the type of the
process used. Considerable cost reductions have been achieved in the USA and
Japan, amounting to 20-30% in comparison with new materials. The corresponding
figure in Europe is lower (10-20%), mainly because of the smaller scale of applica­
tion here and because these have mostly been limited to base-courses and sub-bases.

Since these regenerated pavements are fairly new, their long-term performance is
still uncertain. However, some specifications have already been drawn up for the end
product in the USA, and in some of its states also for the process itself [16, 17]. It
should be emphasized, however, that we do not have enough data e.g. for the effect
of the rejuvenating agent on the road’s durability. On the other hand, basic research
on the properties of bitumen shows that rejuvenating agents can reduce the suscepti­
bility of bitumen to ageing [13].

5.3 Hot in-place regeneration (‘surface regeneration’)

The term ‘surface regeneration’ covers all the methods in which the asphalt pave­
ment is heated to a depth of a few centimetres and then laid again on site. We
distinguish between reshaping, regripping, repaving, and remixing.

If the treatment of the surface is restricted to heating (with infrared radiators),
rooting, re-spreading, and compaction without the addition of any new material, the
process is called reshaping and can be used for instance to improve the evenness of
the road. If the heated and rooted layer is sprayed with optionally precoated
chippings to improve the skid resistance of the surface, we speak of regripping. This
method can also be used when both the skid resistance and the evenness are to be
improved. In the case of repaving, the surface is heated and rooted, and a layer of a
new material, only a few centimetres thick, is laid on top. This method can be used
either across the entire width of the road or for example for filling up ruts. In
remixing, the fourth method of in-place surface regeneration, the top layer of the
pavement is heated, rooted, and taken up into a machine where it is mixed with new
mineral aggregate and possibly a binder or a rejuvenating agent, after which it is
immediately re-laid.
In all four of these methods the depth of the treatment depends on the range of the infrared radiators, which is at the most 40 mm, and the whole underlying structure of the road must be in a good condition, so that it needs no repair. In the case of reshaping, regripping and repaving, furthermore, the old wearing course must be suitable for re-use, particularly as regards its mechanical properties. Surface regeneration can be considered particularly for asphalt pavements whose wearing course shows ravelling, cracking, or insufficient skid resistance.

The temperature must be carefully controlled in repaving. Only if the temperature is high enough will a sufficiently strong bond form between the old and the new material to be able to speak of a single layer. It also applies to all four methods, on the other hand, that the temperature must not exceed a certain value, to prevent ageing of the bitumen.

Some very good results have been obtained with surface regeneration in the USA, France, Italy, Belgium and West Germany [18, 19]. However, the process is complicated, and the manner of its performance is therefore critical. Again, the durability of the resulting regenerated pavements is not known yet sufficiently well except in the case of repaving. The Dutch experience is described in Section 10.

Owing to the saving on new materials, the energy balance is better here than in overlaying, despite the fact that heating of the pavement requires considerable energy, particularly in cold weather. It should be added, however, that the total cost sometimes is still rather high [18].

Finally, in a method that is still in the experimental stage [18] in the USA, the pavement is subjected to hot milling and treatment with a rejuvenating agent in situ, on the assumption that this agent fully penetrates the layer in a few weeks and restores the binder properties. However, little is yet known about the long-term performance of the resulting road pavement.

5.4 Cold recycling

'Cold recycling' is the collective name for all the methods in which old asphalt is comminuted and possibly mixed with new material either in-place or in-plant without heating, being thus made suitable for re-use.

The old asphalt is milled or broken out of the road and the pieces are further comminuted in a crusher. This may be followed by the addition of sand, bitumen emulsion, rejuvenating agent, lime, cement, or a combination of these either in-place or in a plant situated elsewhere. The resulting asphalt mix is then used for
base-courses and sub-base layers. In these methods the residual value of old bitumen is utilized only partly or not at all. In other words, cold recycling is not as value-restoring as hot regeneration.

In-place methods tend to give a material with a lower quality than in-plant methods, mainly because of its poorer homogeneity. They are therefore used in the USA and Japan only for lightly trafficked roads. However, the advantage of in-place recycling is that it involves lower transport costs.

When only a rejuvenating agent is added, e.g. in the form of an emulsion, to milled or broken-up old asphalt that is then re-compacted, it must be borne in mind that it takes the rejuvenating agent several weeks to penetrate into the old binder, and if traffic is allowed on the road too soon, serious rutting will occur [18].

When nothing is added to the removed old asphalt, i.e. when it is intended for re-use as a mineral base-course or sub-base material, a building material is obtained that exhibits a great deal of creep under a heavy load [21]. The addition of sand helps, but the mixture is still only suitable for lightly trafficked roads.

The addition of a binder results in a considerably improved mechanical performance. The binder used in the USA and in Canada is mostly a bitumen emulsion [18, 22]. The reports on these methods generally deal with the design and execution, and little is known about the durability of the resulting roads. The Dutch experience is discussed in Sections 8 and 9. Although from a technical point of view cold recycling is less value-restoring than hot regeneration, it saves much more cost and energy in Japan and the USA than does hot regeneration, mainly because the preparation of the material for re-use needs no special equipment. In the USA the cost of cold recycling is 35-50% of the cost of the removal of the old pavement by milling and the application of new material or overlaying. The energy cost is only about 20% of that incurred when new material is used with the same dimensions [18].
6 Hot regeneration of warm asphalt by the Renofalt process

6.1 Introduction

The Rijkswaterstaat approached the following contractors in 1974:
- Koninklijke Wegenbouw Stevin B.V.,
- Wegenbouwmaatschappij J. Heijmans B.V.,
- B.V. Aannemingsbedrijf NBM,
- Hollandsche Wegenbouw Zanen B.V., and
- Mourik Groot Ammers B.V.,

which later formed the ‘Combinatie Renofalt’, to develop and use a highly value-restoring method for regenerating old asphalt.

The first few years of this joint venture were spent studying the literature and doing laboratory investigations. Later a pilot plant was built, and the method developed was used on test sections along highways 21 and 19. This stage came to an end in 1977.

Renofalt chose the American RMI process, which had proved to be 10-15% cheaper than new asphalt in the USA. In this method the asphalt broken out of the road is crushed to a 0-40 mm grading, heated in a drum fitted with fire tubes, and then mixed with a rejuvenating agent. Gerardu and Jonker [23] have found that the regenerated mix is at least as good as new gravel asphaltic concrete (on the basis of e.g. its mechanical properties.) The regenerated material is laid in the same way as new asphalt.

However, the tests were not free of problems, because the asphalt stuck to the fire tubes in the pilot plant. In fact, the use of the RMI process was in the meantime stopped in the USA because of the same problem occurring there in a large-scale plant. This deposition or material build-up occurs when fairly plastic asphalt at about 80-100 °C comes into contact with the hot fire tubes, leading to excessive oxidation of the bitumen (coking). This causes clogging between the fire tubes, with consequent loss of production, and the dislodged lumps degrade the quality of the end product.

Three years after being constructed the test section in the USA showed rutting, ‘sweating’ of the asphalt, and in places more ravelling than new asphalt [24, 25]. The
regenerating process and the change in the mix design have been cited as possible causes for these phenomena.

The aim in the Netherlands was to solve the problem of deposition while maximizing the proportion of old asphalt in hot regeneration, to make it possible to remove all the old road pavement in large-scale reconstruction projects and re-use as much of it as possible in the same project or in subsequent projects. However, the RMI process was abandoned because the problem of material build-up could not be solved in a technically and economically acceptable manner.

Visiting the USA and Japan [108], Renofalt experts concluded that deposition was mainly caused by fine material at low moisture contents. This led to the idea of using steam for the thermal comminution of the old-asphalt lumps, a method used in a simple form already in the 1950’s. In this case, the plastic range of asphalt is traversed while the material still contains enough moisture to prevent deposition, after which further heating ensures that the moisture content is reduced to below the permitted maximum for the end product. This further heating must likewise be carried out without appreciable oxidation of the old bitumen, and so without the formation of the polluting blue smoke.

Renofalt had so much faith in this modified process that they built a full-scale plant with a capacity of about 100 t/h without first trying it out in a pilot plant; this was partly done to circumvent any scaling-up problems. Another advantage was that much of the laboratory and field-test results could be directly utilized, though more research was needed e.g. on the following points:

- recovery of the old bitumen,
- determination of the properties of the old bitumen,
- Marshall tests in suitably modified form,
- amount of rejuvenating agent to be used,
- amount of sand to be added in the case of asphalt with a high bitumen content.

The Marshall tests had to cause as little oxidation of the old bitumen as possible, similarly to the regeneration process itself. The results obtained in all these investigations were used to establish the specifications for the material mixed in the asphalt plant and for the re-laid pavement, as well as to establish a procedure for preliminary tests and production control. These aspects will be discussed in detail in the following sections.

This, then, is how the Renofalt plant came about. We also examined for what type of projects the Renofalt process could be used. After much discussion, for instance about several points on the technique of application, the choice fell on recon-
struction of part of highway 16 between Rotterdam and Dordrecht. This project was scheduled to last about three years and was to involve the removal of about 300,000 t of asphalt and its re-use as bituminous base instead of new asphalt made with gravel. In December 1979 the Minister for Transport and Public Works approved the hot regeneration of asphalt by the Renofalt process for use in this project.

Part of the asphalt to be regenerated had already been broken out of the road and was being stockpiled in a central depot at Ridderkerk in the Province of Zuid-Holland. The rest was to be broken out of the road later. Specifications had to be drawn up for characterizing the important properties of both these batches of asphalt. Experience had shown that some selectivity in the breaking-out and storage of the old material was desirable for efficient recycling. The techniques to be used for these operations were also finalized in the meantime (see Section 4).

6.2 The Renofalt plant

As mentioned before, the pilot-plant scale was omitted and a large-scale plant with a capacity of 100-120 t/h was constructed straightaway. This called for optimization tests with the finished plant in order to check the calculations and the operating conditions. However, before discussing this work we shall first describe the process itself.

6.2.1 The Renofalt process

The flow diagram for the process is shown in Fig. 6.1. The old pavement is first broken out of the road in the form of large lumps, which are loaded onto trucks with the aid of a loading shovel and transported to an asphalt depot next to the processing plant.

Fig. 6.2 shows the Renofalt plant. For satisfactory operation of the steaming compartments these lumps should not be larger than 40 × 40 × 40 cm. If necessary, the lumps are passed through a crushing and screening, where the larger lumps are broken up and the contaminants entrained during the breaking-out process (mainly sand from under the pavement) are screened out.

The first step in the actual Renofalt process is comminution of the large pieces by thermal treatment in five steaming compartments. When steam at atmospheric pressure is passed into these compartments, the high temperature and the moisture penetration cause the lumps of asphalt to disintegrate into a coarse granular material. This method scores over crushing, because the material is not shattered and so
Figure 6.1  Flow diagram of the Renofalt process.
no dust is formed as a filler. On the other hand, it lacks the broken-up mineral, which is formed when asphalt made with gravel is crushed and which has a favourable effect.

The steamed material is passed through a 40-mm screen to remove any impurities (e.g. concrete and clinker) and lumps of asphalt that have been insufficiently heated and are therefore still too large. It may be necessary to add some sand to the steamed asphalt, because test sections indicate that this is needed if we are to ensure a sufficiently high resistance to deformation even in the case of old asphalt with a high bitumen content.

The steamed asphalt and any sand that may have been added to it are introduced into a drying and heating drum specially developed for this purpose. Here the asphalt is heated to the mixing temperature without appreciable further oxidation of the bitumen. This is achieved by combined direct and indirect heating (see Fig. 6.3), in which the hot gases coming from the indirectly heating hot gas oven first are passed into the space between the double walls of the drum. Heat is transferred to the asphalt indirectly through the inner drum and blades fitted on the wall. The gases leave at the end of the drum at a much lower temperature, and are reheated with a second burner (directly heating hot gas oven) and returned into the drum. The remaining heat transfer comes about by direct contact between the heating gases and the asphalt.

Figure 6.3 Heating system used in the Renofalt plant.
The temperature of the heating gases is regulated by admixing some cold gas. For the sake of energy economy, this cooling gas is obtained from partial recycling of the gases leaving the drum.

The asphalt thus brought to the mixing temperature gathers in the collecting section at the end of the drum, from where a bucket elevator takes it up in batches to an intermediate buffer storage tank (see Fig. 6.1). From here it is released, also in batches, into a weighing hopper and then into a mixer. The asphalt is mixed here with the required amount of a rejuvenating agent to restore the desired binder (bitumen) characteristics. The addition of new bitumen has been considered, but so far found to be unnecessary.

Figure 6.4  Renofalt plant with the drying and heating drum.

Another bucket elevator takes the mixed regenerated material up to a silo, shown in Fig. 6.4, from where it is transported in trucks to the road where it is to be laid. The material is laid in the same way as new asphalt.
6.2.2 Optimization of the operation

As mentioned before, the three steps involved, namely steaming, drying-cum-heating, and mixing, had to be optimized by carrying out a systematic optimizing programme, outlined below for each stage in turn.

a STEAMING
Tests were done with asphalt lumps measuring between 20 x 20 x 20 and 40 x 40 x 40 cm, the latter being the maximum size for satisfactory operation of the steaming compartments. The tests showed that a 20-min steaming per compartment was sufficient to obtain the required comminution. The asphalt reaches a temperature of about 90°C, and the moisture content after the steaming is 2-4%. One must not include too much fines (sand), because they considerably raise the moisture content of the steamed material. A longer steaming time has a negligible additional effect on the final moisture content of the asphalt.

By varying the location of the steam inlet into the steaming compartments, we found that entry at the bottom of the compartments was most effective. Between leaving the steam compartments and entering the heating drum, the asphalt cools by about 10-15°C, mainly because of the evaporation of about 0.5% of moisture.

b DRYING AND HEATING
In the tests the heating gases had an initial temperature of 800 and 400°C in the case of indirect and direct heating, respectively. At these temperatures, to be regarded as maximum values, the plant was running at a capacity of about 110 t/h. The final temperature of the asphalt was on average about 170°C and the residual moisture content was invariably below 0.1%. The additional oxidation of the binder was negligible. Six tests were carried out on the recovery of bitumen from the asphalt before and after heating in the drum, and the results indicated no reduction in the penetration value of the bitumen, and a rise of only about 0.5°C in its softening point.

c MIXING
The total time of 1 min selected for the mixing cycle gave a net mixing time of 35-40 sec, this being the time between the introduction of the rejuvenator into the mixer and discharge of the asphalt from it. Samples of the finished product taken from different places in the bucket elevator indicated a good homogeneity in terms of both mixing and coating of the particles with the binder.

6.3 Technological considerations

The materials and methods to be used in the production of an asphalt mix in any
particular project in the Netherlands are usually known in advance. When they are not, the road-building authorities and the contractor – even before doing any tests – must establish which method is likely to lead to the required results. This is designed to minimize the risk to both parties and was in fact done in the present case as well. The results of the tests that followed were used to lay down guidelines for the recycling of asphalt. The main aim here is twofold: to follow the existing specifications as far as possible and to establish the practical performance of the recycled pavement. Conventional methods and materials have been used for many years, and the long-term performance of road pavements obtained with them is also well known. If the methods and materials used in the production of recycled road pavements do not differ much from those involved in the production of new pavements then previous knowledge can be used, and it is sufficient to investigate only a few quality parameters, which furthermore can almost always be done by the conventional tests prescribed in the existing specifications.

If, on the other hand, entirely new materials and/or methods of preparation are used, it is necessary both to determine the directly measurable characteristics of the material by the usual tests and to find out its long-term performance. Strictly speaking, the latter can be done only by constructing test sections on a road, but if the expected service life of the resulting pavement is for example ten years, then that is how long we have to wait before we know the results. This is hardly acceptable in the present case, since both the authorities and the contractors want to speed up the recycling of asphalt.

It was therefore decided to choose a minimum set of necessary tests. The aim was to make the regenerated asphalt structurally the same as the reference mix, i.e. to give it equivalent properties and use it in an equivalent thickness. In view of the field of application envisaged so far, the reference material was mainly gravel asphaltic concrete. Constructing both a test section with the regenerated material and a test section with the reference material enabled us to compare the performance of the two as a function of time under identical traffic conditions.

These considerations were utilized for drafting some standards and specifications [26, 27], the most important parameters involved in these being as follows:
- Marshall properties of the mix, to be determined in preliminary tests and in production control,
- proportioning and mixing of the materials in the plant, together with the mix composition,
- resistance to deformation in the wheel tracking apparatus,
- creep properties, determined with a creep tester,
- fatigue properties, determined by a three-point bending at a constant deflection amplitude.
The ‘Renofalt Specifications’ will be discussed below in the context of the Requirements for Road-Building Materials [35] and the Specifications for Constructing and Testing Road Pavements [36], both issued in 1978. The Renofalt Specifications partly supplement and partly supersede these documents.

6.4 Preliminary investigations of test sections

a PROCEDURE
The procedure involved here comprised the following steps:

– Sampling: The sample consisted of relatively large lumps of asphalt with different compositions. The sample was first comminuted and then homogenized. For this purpose the whole sample was heated to 90°C in an oven and then crumbled into pieces of at most 4 cm without any crushing. After cooling, the whole sample was homogenized.

– Determination of the composition of the old asphalt (extraction and sieve analysis).

– Recovery of the bitumen from the old asphalt and determination of its properties such as penetration value, softening point ring-and-ball, and penetration index.

– Determination of the required amount of rejuvenating agent: If the penetration value of the mixture of bitumen and rejuvenator is plotted on a logarithmic scale against the amount of rejuvenator on a linear scale, a straight line is obtained, as shown in Fig. 6.5. This graph was recorded for a series of mixtures of 20-30 bitumen and various amounts of the rejuvenating agent.

– Preliminary Marshall tests on a mixture of old asphalt and the amount of rejuvenator chosen on the basis of the tests on the binder. Mixtures with 0.1% more rejuvenator and with 0.1% less (calculated on 100% of old asphalt) were also tested. The mechanical properties and the void content of the regenerated asphalt must meet the existing requirements. As regards the degree of void filling (i.e. the percentage of void filled by the binder) a maximum of 75% was for the time being taken as a requirement.

b STOCKPILING AND ASSESSMENT OF THE BROKEN UP ASPHALT
An asphalt depot was set up in 1979 for collecting all the old asphalt removed in road-works in the area; it contained about 80,000 t in 1980. The asphalt had not been taken up selectively, and was contaminated with sand, concrete and clinker, so that a proper stocktaking was impossible. It was decided to measure out a batch for each week’s production, assess it visually, and carry out the Marshall tests on it. About 4000 t were needed for the test sections (about one week’s production), this quantity being freed from contaminants and stored separately.
After the visual assessment of the batch destined for the test sections, four samples were taken and subjected separately to thermal comminution with steam and then to homogenization. A portion was withdrawn from each of these four samples, and the four portions were combined to form a fifth, mixed sample. The preliminary tests were carried out on these samples. The results of the Marshall tests met the requirements. For the test section on highway 16, the rejuvenator was added in an amount of 0.3% on the basis of the preliminary tests and the production-control tests done with a quantity of 500 t in an exploratory field trial.

![Graph](image)

Figure 6.5 Penetration (pen) value of the binder rejuvenating mixture as a function of the amount (b) of the rejuvenator used.

### 6.5 Investigation of the production and construction of a test section with regenerated asphalt

The test section was constructed on the westernmost lane of highway 16 in September 1980, using about 3400 t of asphalt. Four layers of regenerated asphalt, each with a thickness of 6 cm, were laid on one another directly on a sand sub-base. The asphalt made by the Renofalt process was laid in almost the same way as conventio-
nal gravel asphaltic concrete. The preparation of the asphalt was closely monitored with the aid of very rigorous production control measures.

a **OLD ASPHALT BEFORE REGENERATION**
Six or seven samples were taken from the old asphalt every day after steaming but before heating for regeneration. The samples were tested for composition and for the properties of their bitumen.

b **REGENERATED ASPHALT**
Six or seven random samples were taken daily from the same places in the elevator bucket downstream of the mixer. The samples were first used for Marshall tests, after which the tablets were checked for their composition, and the properties of the recovered binder were determined. Both the bitumen content and the penetration value of the binder showed a greater scatter than before the regeneration, possibly because of an uneven distribution of the rejuvenator in the asphalt.

c **MOISTURE CONTENT OF THE ASPHALT AFTER MIXING**
A sample was taken daily from the finished product and tested for the moisture content, which was invariably below 0.1%.

d **DRILLED CORE SAMPLES**
These were taken from the laid asphalt daily, sawn into the various layers, and each of these was tested for composition, the characteristics of the binder, and the degree of compaction.

### 6.6 Results of the laboratory tests

Samples were taken from the test section constructed with the regenerated asphalt to test them for deformation and fatigue properties in the laboratory. For this, 3 sampling points were chosen on the test section at random and samples were taken in the form of both plates and drilled cores at each point. The resulting specimens were allocated uniformly to the various tests. The investigations were done on the material taken from the third asphalt layer from the bottom.

In addition, rutting and creep tests were done on samples taken from the fourth layer of the construction at one point. The absolute values of the test results were compared with the standards stipulated for roads carrying traffic of category No. 4* [27]. These standards for resistance to deformation are based on wheel tracking and

* Average daily number of motor vehicles \( \geq 20,000 \) (two lanes) or \( \geq 50,000 \) (four or more lanes)
creep tests on gravel asphalt mixes with various compositions, the samples having come from some rarely used parts of existing road pavements. The standard for fatigue strength had been taken from the Shell Pavement Design Manual (for all these standards, see [31]). Asphalt made with gravel and taken from an earlier reference section was tested for creep and fatigue properties in the same way as the regenerated asphalt.

6.6.1 Results of the investigations on a test section made with regenerated asphalt

a. WHEEL TRACKING
This was done in an apparatus developed by the Road Engineering Division. The initial contact pressure between the wheel and the asphalt surface was 0.5 MN/m², and the initial sample temperature was 40°C [28]. The requirement is that the mean relative permanent deformation of the tested samples for each test section should not exceed 4% after 100,000 wheel passes ($\varepsilon_{w(N = 10^5)} \leq 4.5\%$).

Fig. 6.6 shows the mean permanent deformation as a function of the number of wheel passes for the three sampling points on the test section made with regenerated asphalt. The mean resistance to deformation observed compiled with the requirement, with a value of $\varepsilon_{w(N = 10^5)} = 4.2\%$.

Figure 6.6  Permanent deformation $\varepsilon_{w} (%)$ as a function of the number of wheel passes (N) in the case of the test section constructed with regenerated asphalt on highway 16.
The bitumen content was found to be high (5.7 and 5.6%) at two out of the three sampling points. It turned out that the material in layer 3 in both cases came from the batch made in the same hour. The bitumen content was lower (4.5%) at the third sampling point. For this point, the mean resistance to deformation amply satisfied the requirement, the figure being $\varepsilon_{w(N = 10^5)} = 3.5\%$.

It was therefore decided to carry out another set of wheel tracking and creep tests. The production control data were first used to determine for which part of the material present in the regenerated test section a bitumen content of less than 5.0% could be expected. The choice finally fell on the fourth layer at sampling point 3, where the mean bitumen content was 4.9%. The mean resistance to deformation, determined in this additional test, only just satisfied the requirement, with a value of $\varepsilon_{w(N = 10^5)} = 4.5\%$.

b) CREEP TEST
This was done with the samples kept at 25 and 40°C [32]; the load was 0.1 MN/m$^2$, and both the time under load and the time of recovery were 60 min. Since the height of the samples (the layer thickness) was smaller than the required value (minimum 100 mm), two samples were placed on top of each other and tested in this position.

![Figure 6.7 Relationship between the stiffness modulus of the mix (Sm) and that of the bitumen (Sbit) in the case of the test section constructed with regenerated asphalt on highway 16 at three different sampling points ('Loc.').](image-url)
The standard requirement here was that the mean stiffness modulus $S_{\text{mix}}$ for a test section at 40°C and with a load time of 60 min should not be less than 8 MN/m$^2$ ($S_{\text{mix}} \geq 7.5$ MN/m$^2$).

Fig. 6.7 shows the mean stiffness modulus $S_{\text{mix}}$ for the test section constructed with regenerated asphalt as a function of the stiffness modulus of the bitumen $S_{\text{bit}}$ at different temperatures and for different sampling points. The mean value obtained for the mix at 40°C after 60-min, 7.4 MN/m$^2$, did not meet the requirement. This was attributed to the bitumen content, which was checked (see the previous Section), and an additional creep test was carried out. This indicated that the mean stiffness modulus at 40°C after a load time of 60 min did satisfy the requirement, with a value of $S_{\text{mix}} = 16.9$ MN/m$^2$.

C FATIGUE TEST
This was done in a three-point bending apparatus at a frequency of 40 Hz, three deflection values (with a constant amplitude), and a temperature of 5 or 20°C. The dynamic stiffness modulus was measured at the same time. The requirement was that the fatigue properties should be similar to those of an $F_1$ mix and considerably better than those of an $F_2$ mix (for the identity of these mixes see [33]). Fig. 6.8 shows some of the results; the difference between the values obtained at 5 and at 20°C is small.
The mean value of the dynamic stiffness modulus obtained for the three levels of applied strain was $7.1 \times 10^9 \text{ N/m}^2$ at 20 °C and $15.9 \times 10^9 \text{ N/m}^2$ at 5°C for the regenerated asphalt.

The fatigue properties of the regenerated asphalt complied with the requirements: at a short design service life with fewer than $10^5$ strain repetitions ($N_{\text{fat}} < 10^5$) the regenerated asphalt was as good as or even somewhat better than the $F_1$ mix, and definitely better than the $F_2$ mix. At a longer design service life ($N_{\text{fat}} > 10^5$), the regenerated asphalt was comparable to or somewhat less good than the $F_1$ mix but definitely better than the $F_2$ mix as regards the fatigue characteristics.

The composition of the test plates of regenerated asphalt used in the fatigue tests lay within the range of scatter found when determining the composition in the deformation tests.

6.6.2 Test results for the reference section made with a new asphalt mix

The stretch of road finally chosen as the reference section had a surfacing made of 0-16 mm dense asphalt of type C for traffic of category No. 4. Underneath it there were four layers of asphalt made with 57% of gravel for traffic of category No. 4, lying directly on a sand sub-base. The nominal thicknesses of the five asphalt layers going upwards were 8, 5, 5, 6, and 4 cm. The reference section was opened to the traffic at the same time as the other test section.

a Creep Test
A creep test was done on samples of the gravel asphalt taken from the third layer, using the test procedure described in Section 6.6.1. Fig. 6.9 shows the mean value of $S_{\text{mix}}$ as a function of $S_{\text{bit}}$. The mean stiffness modulus at 40°C after a load time of 60 min was 14.4 MN/m². Taking into account the scatter of the results, the rigidity of the new asphalt was significantly higher than that of the regenerated asphalt. The stiffness modulus at 25°C after a load time of 60 min was also significantly higher than that of the regenerated asphalt.

b Fatigue Test
Samples taken from the top asphalt layer made with gravel were tested for fatigue properties and dynamic stiffness modulus under the same conditions as those described in Section 6.6.1, except that the values of the applied strain were different. Fig. 6.10 shows some of the results of the fatigue test. At 20 °C the line for the new asphalt made with gravel lies significantly lower than that for the regenerated asphalt (number of strain repetitions lower by a factor of 6-7). At 5 °C, the difference was smaller (about twofold), but still invariably significant.
Figure 6.9  Relationship between the stiffness modulus of the mix (Sm) and that of the bitumen (Sbit) in the case of the reference section on highway 16.

Figure 6.10  Fatigue curves for the new asphalt in the reference section on highway 16.
The mean dynamic stiffness modulus at the three preset applied strain levels for the new asphalt made with gravel was $8.2 \times 10^9$ N/m$^2$ at 20 °C and $17.8 \times 10^9$ N/m$^2$, i.e. about twice as high, at 5 °C. Within the range of applied strains involved here, the values of the dynamic stiffness modulus for the new gravel asphalt agreed with those for the regenerated asphalt at both temperatures.

6.7 Additional tests prompted by the investigations of the test sections

Although the above results showed that the Renofalt asphalt largely met the requirements, it was found necessary to modify the method in a few points. A number of technical improvements were made to the Renofalt plant; thus, the steaming compartments were insulated, and the rejuvenating agent was proportioned. Modifications were also needed in the preliminary test procedure, and it was necessary to ensure a sufficient deformation resistance for traffic of category No. 4, as far as possible irrespective of the supply and quality of the old asphalt.

As it proved difficult to obtain representative samples of about 50-100 kg of large lumps of old asphalt from the asphalt depot, it was decided to do the preliminary tests (for choosing the type and the amounts of additions) instead on thermally comminuted asphalt, i.e. on material that had been subjected to steaming in the steaming compartments. As mentioned before, the steamed asphalt was sampled on the conveyor belt feeding the heating drum. Owing to homogenization on leaving the last steaming compartment and to the subsequent screening stage, this material had a very uniform composition.

To ensure a sufficiently high deformation resistance for traffic of category No. 4, the preliminary requirement of a maximum permissible degree of filling of 75% was accepted as a definite requirement for the regenerated asphalt obtained by the Renofalt process, on the basis of the results for the test section. This means that the old asphalt, which consisted to a large extent of overlays with a relatively high bitumen content, had to be made leaner. This is best done by adding to it fine sand, as emerged from previous investigations. However, the amount of this sand addition had to be determined for different compositions, and particularly different bitumen contents, of the old asphalt. This was done by Marshal tests in conjunction with the assessment of the modified preliminary test procedure, in which the old asphalt was sampled after steaming.

The starting material was old asphalt containing 4.6, 5.3 and 5.8% of bitumen, to which sand was added in amounts of 0-10%. If we take a maximum permissible degree of filling of 75% for the regenerated asphalt, and if we keep the other required aspects of the composition and the Marshall characteristics constant, the
relationship between the bitumen content and the amount of sand added is as shown in Table 6.1, these figures having been adopted for production control.

Table 6.1 Amount of sand addition needed in the case of different bitumen contents of the old asphalt (regeneration for traffic of category No. 4)

<table>
<thead>
<tr>
<th>Bitumen content of steamed asphalt, % (on 100% of aggregates)</th>
<th>Amount of sand added, % on the steamed asphalt</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.0-4.7</td>
<td>0</td>
</tr>
<tr>
<td>4.7-5.5</td>
<td>5</td>
</tr>
<tr>
<td>5.5-6.0</td>
<td>10</td>
</tr>
</tbody>
</table>

6.8 Production control chosen for the project

On the basis of the results obtained for the test sections and the results of the additional tests, it was decided to continue the regeneration of asphalt by the Renofalt process, provided that:

- the modified preliminary test procedure proved satisfactory in practice,
- the proportioning of the rejuvenating agent gave good practical results, and
- suitable means were introduced for adding sand to the mix.

It was also agreed to stop the operation after a fairly short time and to evaluate the product by comparing it with the requirements (evaluation period). The specifications for the production and laying of regenerated Renofalt asphalt contained separate stipulations, whereby the contractor had to perform the production control.

Since the preliminary tests and the production control of the regenerated asphalt are very different from those involved in the case of conventional warm asphalt, these aspects will be discussed separately below.

6.8.1 Preliminary test procedure

This consists of a) assessment and sampling of the old asphalt, and b) establishment of the amounts of additions needed.

a ASSESSMENT AND SAMPLING

The old asphalt may still be intact on the road that is to be broken up or it may already be stockpiled at a tip or collection point. In the first case the assessment of the nature and amount of the material is based on data about the pavement con-
struction, supplemented if necessary by data obtained by testing cylindrical specimens drilled out of the pavement. If there are great differences in the layer thicknesses of the various types of asphalt along the road, the stretch to be broken up is divided into shorter sections, cylindrical specimens are drilled out from each section, and these are tested. For the Marshall tests the asphalt is homogenized by thermal comminution after heating it to about 90 °C in an oven. It is also possible to carry out the further testing after the old asphalt has been broken out of the road, possibly separated into different classes, and stored. In this case a batch of material is steamed in a steaming compartment, homogenized, and sampled. The additions can be chosen either for each class of material or for a mixture of different classes.

When the old asphalt is stockpiled without its composition and type being known, the additions have to be worked out for each expected weekly production by doing a visual assessment on it in advance, steaming a representative batch, taking samples from the thermally comminuted material, and testing them. However, if a preliminary test has already been done on the material, it is enough to do a visual assessment on the weekly production, provided the batches coming in week after week satisfy the requirements as regards their composition and the Marshall characteristics.

b WORKING OUT THE ADDITIONS
This was done as described for the preliminary investigations on the test sections, but if necessary the Marshall tests are also done on batches to which sand has been added.

6.8.2 Production control
This was mainly based on the Marshall characteristics, determined on material mixed in an asphalt plant. Four samples were taken five times a day from the amount produced during that day. The plant was run in such a way as to obtain the values shown in Table 6.2. The process was also controlled via the bitumen content of the

<table>
<thead>
<tr>
<th>Table 6.2</th>
<th>Criteria used when assessing the Marshall characteristics (five determinations per daily output)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$x_5$</td>
</tr>
<tr>
<td>Stability, N</td>
<td>$\geq 6000$</td>
</tr>
<tr>
<td>Quotient, N/mm</td>
<td>$\geq 3000$</td>
</tr>
<tr>
<td>Degree of filling, vol. %</td>
<td>-</td>
</tr>
</tbody>
</table>

$x_5$ = mean of 5 determinations
$s_5$ = standard deviation for the 5 determinations
$x_i$ = individual determinations
steamed material, which was determined five times a day, using a BIMO meter, a device that measures the slowing down of fast neutrons by hydrogen atoms in the bitumen. Apart from giving quick results, this method has the advantage that it is done on large samples, weighing about 9 kg, which minimizes the sampling error. The results obtained with the BIMO-meter have been described separately by Bolk [34]. As far as the addition of sand is concerned, the process was controlled in such a way as to obtain the values listed in Table 6.5. A visual assessment of the cylinders used in the Marshall tests already gives a good indication of the percentage of sand to be admixed.

Table 6.3  Statistical processing of the results of the preliminary tests. The samples were taken at a point between steaming and heating

<table>
<thead>
<tr>
<th>Composition,</th>
<th>n</th>
<th>x</th>
<th>s.d.</th>
<th>max.</th>
<th>min.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bitumen content</td>
<td>57</td>
<td>4.8</td>
<td>0.58</td>
<td>6.6</td>
<td>4.0</td>
</tr>
<tr>
<td>Aggregate of size &gt; 2 mm</td>
<td>57</td>
<td>55.5</td>
<td>4.81</td>
<td>65.5</td>
<td>43.8</td>
</tr>
<tr>
<td>Aggregate of size 2 mm – 63 μm</td>
<td>57</td>
<td>37.5</td>
<td>4.19</td>
<td>48.9</td>
<td>30.1</td>
</tr>
<tr>
<td>Aggregate of size &lt; 63 μm</td>
<td>57</td>
<td>7.0</td>
<td>1.22</td>
<td>9.2</td>
<td>3.7</td>
</tr>
<tr>
<td>Sand point in the triangular diagram:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 mm – 500 μm</td>
<td>57</td>
<td>20.9</td>
<td>2.13</td>
<td>26.7</td>
<td>16.7</td>
</tr>
<tr>
<td>500 μm – 180 μm</td>
<td>57</td>
<td>39.1</td>
<td>3.54</td>
<td>51.7</td>
<td>33.0</td>
</tr>
<tr>
<td>180 μm – 63 μm</td>
<td>57</td>
<td>40.0</td>
<td>4.65</td>
<td>45.2</td>
<td>26.3</td>
</tr>
</tbody>
</table>

Properties of the recovered bitumen

| Penetration (in 0.1-mm units)                    | 57 | 37   | 3.41 | 47   | 30   |
| Softening point °C (ring-and-ball method)       | 57 | 56.5 | 1.47 | 60.5 | 52.5 |
| Penetration index                                | 57 | -0.4 | 0.19 | -0.0 | -0.7 |

Note: In this table and thereafter n = number of samples, x = mean value, s.d. = standard deviation, max. = maximum and min. = minimum

Table 6.4  Statistical processing of the results of the Marshall tests done on the regenerated asphalt

<table>
<thead>
<tr>
<th></th>
<th>n</th>
<th>x</th>
<th>s.d.</th>
<th>max.</th>
<th>min.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bitumen content</td>
<td>256</td>
<td>4.8</td>
<td>0.27</td>
<td>5.9</td>
<td>4.0</td>
</tr>
<tr>
<td>Void content, vol. %</td>
<td>256</td>
<td>4.7</td>
<td>0.79</td>
<td>7.2</td>
<td>3.0</td>
</tr>
<tr>
<td>Degree of filling, vol. %</td>
<td>256</td>
<td>69.3</td>
<td>4.55</td>
<td>81</td>
<td>56</td>
</tr>
<tr>
<td>Stability, N</td>
<td>256</td>
<td>9720</td>
<td>1508</td>
<td>17630</td>
<td>6650</td>
</tr>
<tr>
<td>Flow, mm</td>
<td>256</td>
<td>2.3</td>
<td>0.34</td>
<td>3.9</td>
<td>1.7</td>
</tr>
<tr>
<td>Quotient, N/mm</td>
<td>256</td>
<td>4460</td>
<td>1055</td>
<td>8930</td>
<td>1970</td>
</tr>
</tbody>
</table>
Finally, the viscosity or penetration characteristics of the binder are also important parameters. Several investigations have shown that the bitumen from the steamed asphalt has a penetration (pen) of about 30-40 (in 0.1-mm units). Since the value for the bitumen from the regenerated asphalt should be 45-60 in 0.1-mm units, the difference calls for the addition of an average 0.3% (0.2-0.4%) of rejuvenating agent, calculated on the asphalt mix.

For monitoring the production a sample of steamed asphalt and a sample of material mixed in an asphalt plant were tested on each daily output for the properties of the bitumen in them and for their composition (grading and bitumen content).

Production officially was started in the second half of March 1981, and Tables 6.3-6.5 show the main data obtained for the production control during the first three months of production, during which time about 40,000 t of regenerated asphalt were made and applied.

Table 6.5  Statistical processing of the results of tests done on the core samples drilled out of the re-used asphalt

<table>
<thead>
<tr>
<th>Composition</th>
<th>n</th>
<th>x</th>
<th>s.d.</th>
<th>max.</th>
<th>min.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bitumen content</td>
<td>56</td>
<td>5.0</td>
<td>0.39</td>
<td>6.5</td>
<td>4.2</td>
</tr>
<tr>
<td>Aggregate of size &gt; 2 mm</td>
<td>56</td>
<td>54.2</td>
<td>2.70</td>
<td>62.6</td>
<td>49.6</td>
</tr>
<tr>
<td>Aggregate of size 2 mm - 63 μm</td>
<td>56</td>
<td>38.3</td>
<td>2.37</td>
<td>42.6</td>
<td>31.8</td>
</tr>
<tr>
<td>Aggregate of size &lt; 63 μm</td>
<td>56</td>
<td>7.5</td>
<td>0.83</td>
<td>9.4</td>
<td>5.7</td>
</tr>
<tr>
<td>Sand point in the triangular diagram:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 mm - 500 μm</td>
<td>56</td>
<td>20.3</td>
<td>1.59</td>
<td>25.0</td>
<td>16.9</td>
</tr>
<tr>
<td>500 μm - 180 μm</td>
<td>56</td>
<td>38.6</td>
<td>2.56</td>
<td>44.0</td>
<td>33.5</td>
</tr>
<tr>
<td>180 μm - 63 μm</td>
<td>56</td>
<td>41.1</td>
<td>3.31</td>
<td>48.3</td>
<td>34.6</td>
</tr>
</tbody>
</table>

Properties of the recovered bitumen

| Penetration (in 0.1-mm units)            | 53 | 48.2| 6.35 | 71   | 38   |
| Softening point (ring-and-ball method) °C| 53 | 53.7| 1.75 | 57.5 | 48.5 |
| Penetration index                       | 53 | -0.4| 0.19 | 0.0  | -0.8 |
| Void content, vol. %                    | 112| 4.3 | 1.29 | 6.8  | 1.9  |
| Degree of compaction, %                 | 61 | 99.9| 1.12 | 102.4| 97.1 |

### 6.9 Results obtained in the evaluation period

As mentioned earlier, an evaluation period was introduced in the work, the results for which are described below.
6.9.1 Results of the production control

About 80,000 t of asphalt were made in the Renofalt plant in 1981. Instead of giving all the production-control results for this output, Tables 6.3-6.5 show the results for about 40,000 t of asphalt (the data for the other 40,000 t were similar). By the end of 1982 altogether about 180,000 t of regenerated asphalt had been produced, giving the same production-control data.

It should be mentioned, however, that some deposition was found in certain parts of the drum after the production of about 30,000 t of asphalt, but the deposit could be removed mechanically after cooling the drum down. Starting in the beginning of 1982, the deposit was removed mechanically from the drum after every 10,000 t of production, partly because of its undesirable effect on the heat transfer in the drum.

6.9.2 Results of the deformation tests

After the production of about 30,000 t of regenerated asphalt, samples taken from three points in the fourth layer of the test section were tested again in the laboratory for rutting, creep (only at 40°C), and composition as described in Section 6.6.1 in the case of the deformation tests.

After 10% of the total number of wheel passes the mean permanent deformation was 3.9%, which met the requirements. The creep test gave a value of 12.6 MN/m² for the mean stiffness modulus at 40°C after a load time of 60 min, which similarly satisfied the requirements.

However, the deformation values differed appreciably from one sampling to the next. As can be seen from Table 6.6, these differences are connected with differences in the mix properties.

6.10 Energy aspect and economics

The energy aspect is very important when assessing the recycling of old asphalt. The energy consumption for the Renofalt process can be calculated on a theoretical basis for a regenerated product consisting of 95% of old asphalt and 5% of sand. The old asphalt is brought to the production temperature in two steps: steaming and heating in the drum. The sand is brought to the production temperature in the drum. The calculation is shown in Table 6.7.

Some heat losses occur in the drum and the associated recirculating pipes, owing to radiation and the entry of outside air. These losses amount to about 20% of the net
energy needed (not including the energy contained in the exhaust gases that leave the plant through the stacks). The total energy needed is then \(1.20 \times 185.40\) MJ (see Table 6.7), which amounts to 222.50 MJ. Assuming that the oil is burned with a 20% air excess, its combustion provides 35.50 MJ of useful energy at an exhaust-gas temperature of 200°C. The fuel consumption is therefore \(222.50/35.50 = 6.3\) kg oil per tonne of regenerated asphalt. This energy is transferred from two heaters (one direct and one indirect), in principle in equal amounts, the direct heater operating as a regulator.

Table 6.6  Results of tests done in the evaluation period

<table>
<thead>
<tr>
<th></th>
<th>Sampling point 1</th>
<th>Sampling point 2</th>
<th>Sampling point 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Permanent deformation*, %</td>
<td>2.6</td>
<td>4.4</td>
<td>4.6</td>
</tr>
<tr>
<td>Stiffness modulus**, MN/m²</td>
<td>16.0</td>
<td>12.2</td>
<td>9.5</td>
</tr>
<tr>
<td>Bitumen content</td>
<td>5.4 and 5.1</td>
<td>4.5 and 4.6</td>
<td>6.1 and 5.2</td>
</tr>
<tr>
<td>Void content, vol. %</td>
<td>4.0 and 3.9</td>
<td>6.0 and 4.1</td>
<td>2.8 and 2.6</td>
</tr>
<tr>
<td>Degree of filling, vol. %</td>
<td>74.8 and 74.3</td>
<td>63.5 and 71.5</td>
<td>82.7 and 81.7</td>
</tr>
</tbody>
</table>

Properties of the recovered bitumen

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Penetration (at 0.1 mm)</td>
<td>41</td>
<td>38</td>
<td>41</td>
</tr>
<tr>
<td>Softening point (ring-and-ball method), °C</td>
<td>52.0</td>
<td>51.5</td>
<td>52.5</td>
</tr>
</tbody>
</table>

* \(\varepsilon_w(N = 10^5)\) after 100,000 wheel passes.

** At 40°C with a load time of 60 min

As regards the heating conditions in the drum, two prerequisites must be fulfilled, namely:

- the heating gases in the indirect system must not be hotter than 850°C, in view of the structural materials used for the plant, and
- the heating gases in the direct system must not be hotter than 400°C, for reasons connected with the asphalt.

A cooling gas is therefore needed for cooling down the heating gases coming from both the direct and the indirect heater. To reduce the energy losses with the exhaust gases, this cooling gas is obtained entirely by recycling of the heating gases.

The energy requirement of the Renofalt plant is therefore \(3.3 + 6.3 = 9.6\) kg oil per tonne of regenerated asphalt. This is a theoretical amount in the case of continuous production. Heating the plant up from cold every day adds another 1 kg oil per tonne of asphalt. Finally, another 1 kg is needed per tonne of asphalt for operating the
loading shovel for the steaming compartments, heating the rejuvenating agent, and heating various components of the plant such as the mixing section and the valves of the storage silo.

Table 6.7 Data used for calculating the energy consumption

<table>
<thead>
<tr>
<th>Data Point</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture content of the asphalt before steaming</td>
<td>1%</td>
</tr>
<tr>
<td>Moisture content of the asphalt before heating in the drum</td>
<td>3.5%</td>
</tr>
<tr>
<td>Moisture content of the sand before heating in the drum</td>
<td>8%</td>
</tr>
<tr>
<td>Moisture content of asphalt/sand mixture after heating in the drum</td>
<td>zero (0.1%)</td>
</tr>
<tr>
<td>Temperature of the asphalt before steaming</td>
<td>10°C</td>
</tr>
<tr>
<td>Temperature of the asphalt after steaming</td>
<td>85°C</td>
</tr>
<tr>
<td>Temperature of the asphalt before heating in the drum</td>
<td>75°C</td>
</tr>
<tr>
<td>Temperature of the sand before heating in the drum</td>
<td>10°C</td>
</tr>
<tr>
<td>Temperature of the asphalt/sand mixture after heating in the drum</td>
<td>165°C</td>
</tr>
</tbody>
</table>

In addition, the following thermodynamic data were used:

<table>
<thead>
<tr>
<th>Component</th>
<th>Specific heat, kJ/kg/°K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asphalt</td>
<td>0.96</td>
</tr>
<tr>
<td>Sand</td>
<td>0.92</td>
</tr>
<tr>
<td>Heating gases</td>
<td>1.00</td>
</tr>
<tr>
<td>Water</td>
<td>4.18</td>
</tr>
<tr>
<td>Steam</td>
<td>1.88</td>
</tr>
</tbody>
</table>

Heat of evaporation of water: 2260 kJ/kg

Step 1: The energy consumption of the steaming process (per tonne of regenerated asphalt) is as follows:

- asphalt: 950 × (85 − 19) × 0.96 = 68.40 MJ
- water: 0.01 × 950 × (85 − 10) × 4.18 = 3.00 MJ

Total: 71.40 MJ

If the thermal efficiency is 60%, the amount of energy needed is 119.00 MJ. This can be supplied by the condensation of 119.00/2.26 = 52.7 kg of steam, which calls for about 3.3 kg oil per tonne of regenerated asphalt.

Step 2: Energy consumption of the heating process in the drum:
The heating in the drum is of the cocurrent type, i.e. the asphalt and the heating gases are moving in the same direction. It is assumed that the heating gases and the moisture (steam) present in the cases on leaving the drum have a temperature of 200°C (exhaust-gas temperature). The energy consumption of heating in the drum per tonne of regenerated asphalt is as follows:

- asphalt: 950 × (165 − 75) × 0.96 = 82.10 MJ
- water in the asphalt: 0.035 × 950 (100 − 75) × 4.8 + 2260 + (200 − 100) × 1.88 = 84.90 MJ
- sand: 50 × (165 − 10) × 0.92 = 7.10 MJ
- water in the sand: 0.08 × 50 (100 − 10) × 4.18 + 2260 + (200 − 100) × 1.88 = 11.30 MJ

Total: 185.40 MJ
Table 6.8 Energy content of the regenerated asphalt and gravel asphalt, kg oil per tonne of asphalt (1 kg oil = 42 MJ)

<table>
<thead>
<tr>
<th></th>
<th>Per t of raw material</th>
<th>Per t of regenerated material</th>
<th>Per t of new asphalt made with gravel</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Raw material production</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gravel and sand</td>
<td>1</td>
<td>0.05</td>
<td>0.9</td>
</tr>
<tr>
<td>Filler</td>
<td>2</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>Old asphalt</td>
<td>0.5</td>
<td>0.48</td>
<td></td>
</tr>
<tr>
<td>Bitumen</td>
<td>17.5 + 1000*</td>
<td>= 1017.5</td>
<td>43.8</td>
</tr>
<tr>
<td>Rejuvenating agent</td>
<td>17.5 + 1000*</td>
<td>= 1017.5</td>
<td>3.05</td>
</tr>
<tr>
<td>2. Transport of raw materials to the plant</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gravel and sand (by barge and truck)</td>
<td>3</td>
<td>0.15</td>
<td>2.7</td>
</tr>
<tr>
<td>Filler</td>
<td>6</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>Old asphalt</td>
<td>2</td>
<td>1.90</td>
<td>0.3</td>
</tr>
<tr>
<td>Bitumen</td>
<td>6</td>
<td></td>
<td>0.3</td>
</tr>
<tr>
<td>Rejuvenating agent</td>
<td>6</td>
<td>zero</td>
<td></td>
</tr>
<tr>
<td>3. Preparation</td>
<td></td>
<td>12.0</td>
<td>9</td>
</tr>
<tr>
<td>4. Transport to the construction site</td>
<td></td>
<td>1.8</td>
<td>1.8</td>
</tr>
<tr>
<td>5. Construction</td>
<td></td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Total</td>
<td>19.9</td>
<td>59.4</td>
<td></td>
</tr>
</tbody>
</table>

Composition
- New asphalt: 57% of gravel, 37% of sand and 6% of filler, plus 4.5% of bitumen (on 100% of mineral aggregate)
- Regenerated asphalt: 95% of old asphalt and 5% of new sand, plus 0.3% of rejuvenating agent (on 100% of mineral aggregate)

* Calorific value

The total calculated energy consumption of the Renofalt plant is therefore about 11.6 kg oil per tonne of regenerated asphalt. The actual figure for 1981 was on average about 15 kg/t, of which about 5 kg/t went on steaming. The actual figures are thus higher both for steaming and for heating the drum. The efficiency of the steaming process can be raised by definitely not using lumps larger than $40 \times 40 \times 40$ cm and choosing a smaller size such as $30 \times 30 \times 30$ cm for the average lump.

Furthermore, a test done at the end of 1981 to discover the reason for the high fuel consumption revealed that the heating effect had not been utilized fully in the drum.
for reasons connected with the type of the structural materials used in the plant. After improving this aspect, the average fuel consumption in 1982 fell to about 13.4 kg/t.

Table 6.8 gives the energy contents of the various materials and processes involved in the production of both Renofalt asphalt and gravel asphalt, taking 12 kg/t for the oil consumption involved in the preparation of the new asphalt. If the corresponding figures for the extraction and transport of the raw materials are also taken into account, which in the case of regenerated asphalt means breaking up the pavement and transporting it to the plant, then the total energy content of Renofalt asphalt is about one-third of that of new asphalt made with gravel. The difference is due mainly to the re-use of bitumen as a binder.

However, it is difficult to express the economic advantages of the regeneration of asphalt in exact terms. Firstly, the charges for tipping the old asphalt as a waste material are saved, and secondly a large part of the cost of raw materials, particularly bitumen, is also saved. On the other hand, the preparation of the regenerated asphalt

Figure 6.11 Activities at the access of highway 16 and highway 15 at Ridderkerk (Photo: Aerocamera Rotterdam).
is more expensive. The pretreatment of the old asphalt, in which it is broken up into smaller pieces and freed from sand by sieving, constitutes an additional cost item. Besides, the Renofalt plant is associated with both a higher capital investment and a higher labour cost than ordinary asphalt plants. It is particularly the cost of safeguarding quality that is greater here than usual. However, the economics are clearly in favour of regeneration. In the case of the highway-16 project, as at 1 January 1981, the re-use of asphalt by the Renofalt process was 10-15% cheaper than the use of new asphalt made with gravel. The activities on highway 16 are shown in Fig. 6.11.

6.11 Final considerations [29, 30]

When it was decided to build the Renofalt plant, basically only laboratory investigations and small-scale field tests had been done, so that some scaling-up problems had to be solved. In addition, the regulation of the Renofalt process differs from that of the ordinary asphalt preparation in some important aspects, owing to the high proportion of old material used. The problems to be solved can be put under the following three headings:

a  THE STARTING MATERIAL

We cannot stress enough the need to break up the old pavement as selectively as possible. It is always advisable to screen the material to remove contaminants having a fine particle size. When rubble was used in concrete and asphalt in West-Germany in the early 1950's, it was first put through a 30-mm-mesh screen before being crushed, and this greatly improved the quality. The size of the asphalt lumps that can be used in the Renofalt process mainly depends on the degree of disintegration achieved by the steaming, and it should not exceed $40 \times 40 \times 40$ cm. The work described here was done with old asphalt that had already been taken to a collection point, and it was virtually impossible to obtain a sufficiently accurate picture of its composition by taking samples and testing them. It was thus difficult to determine what additions were needed to ensure the required composition and properties of the regenerated asphalt. It is therefore better to establish the composition of the old asphalt before it is taken up. Furthermore, steaming of the old asphalt gives a much more homogeneous product, which in turn gives much more reliable values for the composition and hence for the additions needed.

b  PRELIMINARY TESTS AND PRODUCTION CONTROL

The Renofalt process calls for a different preliminary test procedure from that used in the preparation of new asphalt. The aim here is to determine the composition of the old asphalt before and after comminution with steam. The method used gives satisfactory results. The same applies to the method of heating the old asphalt in small closed tins for the Marshall tests.

The production control is mainly based on Marshall tests done on the regenerated
asphalt. However, it is important to add sand quickly during the production if the bitumen content of the old asphalt is too high, so that this content must also be determined, for which the BIMO process was found suitable.

C THE PLANT

The experience with steaming largely agrees with the results of the previous optimization work. The operation of the heating drum can be assessed only after several tens of thousands of tonnes have been produced, but Dutch and other experience shows that both the direct and the indirect heating of old asphalt are critical. The first can burn the bitumen and the second can cause sticking of the old asphalt to the hot metal surface, resulting in serious production problems. The first risk can be ignored in the Renofalt process, but some deposition was found to occur, especially on the hollow blades on the walls. This was solved by regular cleaning (e.g. after every 10,000 t) and some modifications to the plant, without any drop in the quality of the end product.

To supplement the information obtained from the test sections and to clarify some points, the mechanical properties of the re-used pavement and the operation of the plant were thoroughly investigated after 30,000 t of regenerated asphalt had been produced.

6.12 Summary and conclusion on the Renofalt process

Regeneration of old asphalt is very important for reducing the need for new quarried materials and bitumen, and for helping to solve the problem of the disposal of waste materials from old road pavements.

The Renofalt company, set up jointly by several road building contractors, and the Rijkswaterstaat have together carried out some work since 1974 with a view to finding a process for the most value-restoring regeneration of asphalt pavements, giving a regenerated asphalt that is at least as good as new gravel asphalt. After extensive laboratory investigations and field tests, it was decided to build a special plant for achieving this aim.

The Renofalt process uses more old asphalt in the mix (at least 90%) than most of its counterparts, emphasized mainly in the United States and Japan (20-70%). In this process the old asphalt is subjected to thermal comminution by heating with steam at atmospheric pressure. The steamed material is passed through a screen and introduced into a heating drum, where it is brought to the mixing temperature by a combination of direct and indirect heating with hot gases. This system prevents further oxidation of the old bitumen. The material is then mixed batchwise with the rejuvenating agent, which restores the required binder properties of the bitumen. The regenerated asphalt is laid on the road in exactly the same way as new asphalt. The moisture content, which is raised to a few percent by steaming, falls again in the
end product to below the permissible maximum of 0.1%.

If the old asphalt contains more than 4.7% of bitumen, some sand must be added after steaming if the end product is to meet the requirements. If the old asphalt has already been broken up, the amount of sand and rejuvenating agent to be added should be determined on a sample of steamed product, since this is more homogeneous and gives more representative samples. If the pavement has not yet been broken up, a preliminary test can be done on each type of asphalt present. When old asphalt is heated for the Marshall tests, the entry of air must be prevented to minimize the changes in the binder (hardening by oxidation).

The production control is based mainly on Marshall tests done on material mixed in an asphalt plant. In addition, the amount and binder properties of the bitumen and the moisture content are regularly determined. The determination of the binder content by the BIMO method is very useful for deciding on the nature and the amount of additions needed as a function of the binder content.

A test section was constructed on highway 16 near Ridderkerk with the asphalt regenerated by the Renofalt process. The properties of this pavement were compared both with previously established standards for creep, deformation in the wheel tracking apparatus, and fatigue performance, and with the results obtained for a reference road section constructed with gravel asphalt for traffic of category No. 4. This showed that, without the addition of sand to correct high binder contents, the creep and the mean resistance to deformation just met or only just did not meet the standards laid down. This was probably due to the fairly high binder contents (and the high degree of filling) of the material in the test sections. The addition of sand solved this problem. As regards its fatigue characteristics, the regenerated asphalt satisfied the requirements and was in fact significantly better than the reference mix. On the basis of these results the Rijkswaterstaat decided to have about 300,000 t of asphalt regenerated by this process in 1983-85 for the reconstruction of highway 16.

When 30,000 t had been produced, a set of new tests was carried out, especially on the mechanical properties of the pavement in the road, to see if the mix design and the production control system gave a product that met the requirements in every respect. These tests again showed that the set standards were invariably reached. Admittedly, caking in the drying and heating drum is a problem that needs constant attention, but regular cleaning seems to solve it.

The regeneration of asphalt by the Renofalt process represents a large saving on energy (about 60%) in comparison with the use of ordinary gravel asphalt. The cost saving amounts to about 10-15%, which is the resultant of saving on raw materials and the use of a more expensive process. In the case of highway 16 there was an additional advantage: the price of gravel, filler, and bitumen went up in 1981, but this did not raise the cost of the regenerated asphalt, so that about 1.4 million guilders had been saved by December 1982.
7 Hot partial recycling of warm asphalt

7.1 Introduction

As mentioned in Section 5, the Rijkswaterstaat was interested in the recycling of asphalt by hot mixing in an asphalt plant by two methods:

- without using any new material, i.e. using only old warm asphalt (if necessary mixed with a rejuvenating agent to restore the required binder properties of the bitumen in the end product), and
- by admixing new mineral materials to the old asphalt, i.e. by re-use on a partial basis or partial recycling.

In this second case the new mineral materials (sand and coarse aggregate) to be added are heated to such an extent above the normal temperature that the entire mixture of sand, coarse aggregate, old asphalt, filler, and bitumen reaches the required laying temperature. The amounts of the new mineral additions depend on the composition of the old asphalt and on the composition and properties required in the end product. The desired penetration value of the bitumen to be added can be calculated in advance, after determining the characteristics of the bitumen in the old asphalt.

Partial recycling has a number of attractive features, the most important of which are as follows:

a By choosing the properties of the new components, any desired mix composition can be obtained with the required properties. The larger the proportion of the new components, the less effect any variations in the properties of the old asphalt will have on the characteristics of the end product.

b Any conventional asphalt plant can be used after a relatively cheap modification. Avoiding new capital investments is economically important in the present situation of road-building in the Netherlands; besides, there is no need for more asphalt production capacity in this country.

A possible drawback of partial recycling is that the ratio between the old asphalt and the new minerals can be varied only within rather narrow limits without making particularly costly investments for the pre-heating of the old material. Since the new material cannot be heated to above 300°C in an asphalt plant, the amount of old asphalt that can be added is at most 30-35% (more could not be heated to the right temperature by the new minerals). This means that to use up all the old asphalt
removed from the pavement the plant must produce at least three times as much old/new mix as there is old asphalt. If a large amount of old asphalt is to be taken up from the road, it may be that not all of it can be re-used in the same project; however, it can of course be stockpiled and re-used elsewhere (see Section 4).

In 1978 ADUCO-International B.V. agreed with the Rijkswaterstaat on cooperating in the development and testing of a method for the partial recycling of asphalt. This company has been formed from the following Dutch companies as a ‘cooperative association’: Bruil Apeldoorn B.V., Bruil-Arnhem Groep B.V., J. G. Nelis en Zn IJmuiden B.V., Ooms Avenhorn B.V., Schagen-Zwolle B.V..

ADUCO and the Rijkswaterstaat have carried out joint investigations both in the laboratory and in the field, the practical tests having been as follows:

a About 350 t of old gravel asphalt were laid on the premises of Schagen-Zwolle B.V. at Hasselt (the ‘Hasselt test section’) to find the best ratio between old asphalt and new material (‘old/new ratio’) in partial recycling from among: 0:100, 15:85, 20:80, 25:75, and 30:70.

b About 3000 t of gravel asphalt were laid on highway 313 at Harderwijk (the ‘Harderwijk test section’) to see if any problems arise in a fairly large-scale production and whether the screening of the old asphalt into two fractions (0-16 mm and 16-45 mm) makes any difference. About 2200 t of this quantity was partially recycled asphalt with an old/new ratio of 25:75; half of it was made with 0-16 mm and 16-45 mm old asphalt, and the other half with 0-45 mm old asphalt. The companies involved later also made partially recycled asphalt for others. By December 1980 some 10,000 t of such asphalt had been made, giving a fair amount of experience with both production and laying.

The results obtained in these two experiments will be described later in this section, after dealing with the following questions which had to be settled first: a) the requirements the old asphalt had to fulfil before re-use, b) the way to modify the mix design on the basis of the Marshall test in order to make the old asphalt suitable for partial recycling, and c) the best way of operating the asphalt plant after adapting it to the task in question.

**7.2 Requirements to be met by the old asphalt**

We have already stressed in Section 4 the need for a selective breaking up of asphalt pavements and discussed the way of stockpiling the material obtained. The following points are important in connection with the pretreatment of the removed asphalt with a crusher and a screen.
If the pavement consists entirely of asphalt, the fine and the coarse fraction are similar in composition, so that any separation (demixing) phenomena in the comminuted old asphalt have a relatively minor effect on the composition of the end product.

A vibrating screen must be used upstream of the preliminary crusher to eliminate the fines, mainly sand and humus, entrained with the asphalt despite the precautions taken.

To prevent dusting during the crushing operation, water can be sprayed on the asphalt in advance. The amount of water so used must be as small as possible and in any case should not exceed 1%, calculated on the crushed asphalt.

Finally, since the maximum permissible particle size of the crushed asphalt is generally 45 mm, a second vibrating screen with the required mesh size is used to remove the oversized material, which is recycled to the crusher.

It may be desirable to separate the crushed asphalt into two fractions. In fact, this is necessary when the composition of the fine fraction differs greatly from that of the coarse one. However, this considerably complicates the process (since it calls for example for screening, separate storage, and proportioning), and should be done only if the required homogeneity of the end product cannot be ensured otherwise.

The asphalt must be treated and stockpiled in such a way as to prevent or minimize contamination, demixing, and absorption of moisture. Moisture can affect the temperature of the end product. However, variations in the moisture content can be corrected within certain limits by varying the temperature of the new aggregate. It is advisable to cover up the asphalt during storage and to keep it under a roof. Unfortunately, this is not always easy to do with large stocks, so that other solutions must be found. If the material is not covered up, its moisture content will vary with the weather, being 0.5-1% in dry weather, and 2-3% in wet. It can be as much as 5% immediately after a heavy rain, but it drops to the above values after 24 h. The question of the moisture content will be discussed in more detail in Section 7.4.

A special problem that can occur during storage is congealment or caking, which makes proportioning and sometimes even separation into lumps impossible. Caking probably depends on the type and amount of the bitumen, the particle size and the moisture content of the asphalt, as well as on the height of the heap in storage, which must not exceed 3 m. To counteract caking, a German patent application [37] advocates the addition of an anti-caking agent, such as a filler or sand.

No caking occurred in the fairly wet autumn of 1980, when the outside temperature
was up to 15 °C and the moisture content of the material amounted to about 2.5%. Previous tests at Hasselt did give some caking problems, particularly in the case of the 0-16 mm fraction at outdoors temperatures of up to 19 °C and a moisture content of about 1%. On that occasion caking occurred during 24 h. It is interesting to note that the coarser fraction (16-45 mm) showed no caking at all. Storage under cover might stop or reduce caking.

7.3 Preliminary tests

The existing regulations for new asphalt stipulate the determination of its properties before it is laid to check if they meet the criteria laid down. This is also important for mixtures in which old asphalt is incorporated, first of all as regards the properties, such as the penetration of the bitumen in the old asphalt, and the composition of the latter [38], but also as regards the corresponding parameters of the final mix.

7.3.1 Determination of the penetration value of the bitumen mixture

The penetration of the bitumen in the end product (pen\textsubscript{mix}) depends on the penetration of the new bitumen 1 and the old bitumen 2 (pen\textsubscript{1} and pen\textsubscript{2}) and on the volume ratio of these two starting bitumens:

\[ \text{pen}_{\text{mix}} = \text{pen}_1 a + \text{pen}_2 b \]

where \( a \) and \( b \) are the proportions of the new and old bitumen (\( a + b = 1 \)). Fig. 7.1 shows the penetration of the bitumen mixture \( \text{pen}_{\text{mix}} \) at various mixing ratios and penetrations of the two bitumens.

By the correct choice of the new bitumen, partially recycled asphalt that has the required bitumen characteristics can be produced with old bitumen having any penetration value and used in any amount of up to 40\% (\( b = 0.4 \)). Penetration values of 15-50 were found in a large number of tests on bitumen from old asphalt obtained from different road constructions. This wide range emphasizes the need for a frequent determination of the bitumen penetration value. Even for one and the same construction the variations are generally by about 5 points. The following conclusions can therefore be drawn from Fig. 7.1:

a If no more than 15\% of old bitumen is incorporated in the mix, and if the new bitumen has a pen\textsubscript{1} value of 50, a final mix penetration of pen\textsubscript{mix} = 40 can be obtained with any old-bitumen penetration occurring in practice.

b If the penetration value of the bitumen from the old asphalt (pen\textsubscript{2}) does not vary by more than ± 5 points, then it is possible to find, for any penetration pen\textsubscript{2} and
a/b value, a new bitumen with a pen\textsubscript{1} value with which the penetration of the mix is within the required limits (see Table 7.1). However, for pen\textsubscript{2} = 15 and b = 0.4 the penetration of the new bitumen must be pen\textsubscript{1} > 90.

Figure 7.1 Penetration of the mixture of bitumens (pen\textsubscript{me}) as a function of the penetration values of the two bitumens and their mixing ratio (b).

7.3.2 Composition of the mixture

The composition of the old asphalt tells us how much new coarse aggregate, sand, filler and bitumen must be admixed to obtain the right composition for the end product. The following points should be considered in connection with the ratio between the old asphalt and the new material (old/new ratio):
CONCERNING THE OLD ASPHALT
- composition and its variations,
- properties of the bitumen,
- moisture content,
- available quantity.

CONCERNING THE TOTAL MIXTURE
- required composition of the end product,
- required properties of the bitumen mixture.

The most important aspects of choosing these are discussed in more detail later.

Table 7.1 Scatter of the penetration values of the mixture of bitumens due to the scatter of the penetration values of the bitumen in the crushed asphalt

<table>
<thead>
<tr>
<th>Pen&lt;sub&gt;1&lt;/sub&gt;</th>
<th>50</th>
<th>65</th>
<th>90</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pen&lt;sub&gt;2&lt;/sub&gt;</td>
<td>15</td>
<td>25</td>
<td>35</td>
</tr>
<tr>
<td>b proportion of old bit.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.1</td>
<td>42-46</td>
<td>46-48</td>
<td>48-49</td>
</tr>
<tr>
<td>0.2</td>
<td>44-51</td>
<td>51-56</td>
<td>56-59</td>
</tr>
<tr>
<td>0.3</td>
<td>46-52</td>
<td>52-56</td>
<td>56-60</td>
</tr>
<tr>
<td>0.4</td>
<td>47-57</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

7.3.3 Preparation of laboratory specimens

Heating the old asphalt to be mixed with the new material in the preliminary tests proved to be a problem. Laboratory mixers differ from the pugmills used in conventional full-scale plants, because the heat transfer in them is slower and the mixing intensity is considerably lower. The old asphalt must therefore be already at the required temperature when the new material is introduced into the mixer. This calls for a method that permits rapid heating without affecting the characteristics of the bitumen in the old asphalt.

ADUCO developed such a method for heating about 200-500 g of the old asphalt for each sample with a high-frequency generator (27.12 MHz) shown in Fig. 7.2. In this apparatus the material is inserted between the electrodes (see Fig. 7.3), where it reaches the required temperature of 150°C within 3 min. The mortar heats up considerably faster than the coarse mineral particles, but this is not harmful for the mixture of these components. Investigations show that the penetration value of the bitumen does not change during such short heating (see Table 7.2).
Figure 7.2  High-frequency generator for heating the crushed asphalt in the laboratory (ex Colpitt, output 1250 W).

Table 7.2  Effect exerted on the properties of bitumen from crushed asphalt by heating of the crushed asphalt to 145°C with a high-frequency radiator (mean of three determinations)

<table>
<thead>
<tr>
<th></th>
<th>Penetration</th>
<th>Softening point ring-and-ball, °C</th>
<th>Penetration index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bitumen from crushed asphalt before heating</td>
<td>39</td>
<td>55.2</td>
<td>-0.5</td>
</tr>
<tr>
<td>Bitumen from crushed asphalt after heating</td>
<td>39</td>
<td>55.3</td>
<td>-0.5</td>
</tr>
</tbody>
</table>

7.4 Preparation of the asphalt mix

As already mentioned, a conventional plant with a batch mixer can be used to recycle up to about 35% of old asphalt in a mix without a large capital investment. The proportion is higher in a drum mixer (or in a modified asphalt plant in which the
old asphalt can be first preheated), but it is questionable whether the considerable investment needed here is justified in the Netherlands, apart from in a few cases (see also Section 7.9).

There are also some other ways of adapting an existing batch-type plant for partial recycling [22], but they are neither simpler nor cheaper than the one described here. The use of two mixers and two mixing steps, proposed by Fortmann and Potschka [37], has been found unnecessary on the basis of Dutch experience, at least at the mixing ratio mentioned.

The plant must be such that:
- the proportioning, weighing, and mixing of the old asphalt can be incorporated in the normal production process,
- the temperature of the components and of the end product can be controlled with sufficient accuracy, and
- the mixing in the mixer is intense enough to give a constant homogeneous product at the right temperature.
7.4.1 **Feeding in the old asphalt**

To modify the conventional asphalt plant with a batch mixer for the operation, we need extra feed facilities for introducing the old asphalt into the existing weigher or into an extra weigher and hence into the mixer (see Fig. 7.4). The choice depends on whether the old weigher can be reached through a new feed hopper. In some plants it is also possible to use one of the existing storage bunkers for the storage and proportioning of old asphalt, the normal function of the bunker being to store dried mineral material. However, the bunker must be well insulated to prevent caking of the old asphalt. Besides, the residence time in the bunker must be short, because caking leads to the undesirable ‘bridge’ formation at the walls.

![Diagram](image)

**Figure 7.4** Asphalt plant modified for partial recycling of old asphalt.

Fig. 7.5 shows a modified plant, in which the old asphalt is taken to the weigher on a long conveyor belt, which is covered up to protect the material from rain. To maximize the time of contact between the cold old asphalt and the hot new minerals it is advisable to weigh out first the coarse aggregate, then the old asphalt, and finally the sand.

7.4.2 **Mixing**

The hot new material and the cold old asphalt must be made into a fully homogeneous mixture. The mixture must have the right temperature, and its moisture content must fall to below the permitted maximum. This cannot be done without increasing the normal mixing time by 5-10 sec, the individual steps being as follows:
- dry mixing of the aggregate and the asphalt: about 20 sec,
- addition of bitumen and filler: 10-15 sec,
- final mixing: 5-10 sec.
This gives an overall mixing time of about 40 sec. The mixing in the dry state before the addition of bitumen is absolutely essential for raising the mixing intensity and improving the heat transfer, but its main purpose is to prevent any contact between the new bitumen and the hot mineral material. To allow the evolving water vapour to escape from the mixer it is advisable to create an outlet facility above the mixer (in the worst case about 15 m$^3$ of water vapour are formed per tonne of asphalt).

7.4.3 Temperature control during production

Temperature control is essential in this process. The temperature of the asphalt mix depends on many factors and can be calculated [39] with the formula given in Table 7.3, which shows that the following factors have a great effect on the temperature of the asphalt under normal conditions:

- $a$ the temperature of the new material ($T_{\text{new}}$),
- $b$ the moisture content of the old asphalt,
- $c$ the old/new ratio,
- $d$ the heat losses from the new mineral material during production ($\Delta Q_1$),
- $e$ composition.
Table 7.3 Formula for calculating the mix temperatures

\[
T_{\text{mix}} = \frac{(0.2M_{m1}T_{nm})(1 - \Delta Q_1) + 0.5M_{b1}T_{b1}(1 - \Delta Q_2) + M_wT_{cr} + 0.5M_{b2}T_{cr} + 0.2M_{m2}T_{cr} + 0.2M_fT_f - 539M_w}{220 + M_w + 0.2M_f}
\]

where

- \(M_{m1}\) = weight of new mineral (sand and gravel), kg/1000 kg mix
- \(M_{b1}\) = weight of new bitumen, kg/1000 kg mix
- \(M_w\) = weight of the water in the crushed asphalt, kg
- \(M_{m2}\) = weight of the mineral in the crushed asphalt, kg
- \(M_{b2}\) = weight of the bitumen in the crushed asphalt, kg
- \(M_f\) = weight of the filler, kg/1000 kg mix
- \(\Delta Q_1\) = heat loss from the new mineral before the addition of the crushed asphalt
- \(\Delta Q_2\) = heat loss from the new bitumen before addition to the mix
- \(T_{nm}\) = temperature of the new mineral materials (sand and gravel), °C
- \(T_{cr}\) = temperature of the crushed asphalt, °C
- \(T_{\text{mix}}\) = temperature of the asphalt mix, °C
- \(T_{b1}\) = temperature of the new bitumen, °C

These will be discussed in detail below. The composition of the old asphalt (and the required composition of the mix) is as follows:

- gravel: 57%
- sand: 37%
- filler: 6%
- bitumen: 4.5%

Fig. 7.6 shows the combined effects of the temperature of the new material (sand and gravel) \((T_{nm})\) and the moisture content of the old asphalt. Under the conditions assumed here the temperature of the new sand and gravel must be about 6°C higher for a 1% rise in the moisture content of the old asphalt if the same final temperature of the mixture \((T_{\text{mix}} = 160^\circ\text{C})\) is to be reached. If the temperature of the new sand and gravel is 20°C lower, the temperature of the mix will be about 10°C lower.

The old/new ratio is obviously very important for the final mix temperature. Table 7.4 shows the calculated temperature the new sand and gravel must have, to ensure that the required mix temperature \(T_{\text{mix}}\) is reached at various mixing ratios. The figures indicate how important this factor is. It is theoretically possible to control the mix temperature by adjusting the mixing ratio to the given temperature of the new sand and gravel, but this approach can be used in practice only if all the mixing ratios give the required properties. The setting of the plant must of course be changed correspondingly at the same time.
Figure 7.6 Mix temperature $T_{\text{mix}}$ as a function of the temperature of the new sand and gravel $T_{\text{new}}(T_{\text{m1}})$ at various moisture contents ($v$) of the old asphalt.

Table 7.4 Effect of the old/new ratio on the necessary temperature of the new sand and gravel

<table>
<thead>
<tr>
<th>Old/new ratio (%)</th>
<th>$T_{\text{mix}}$, °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>15:85</td>
<td>242</td>
</tr>
<tr>
<td>25:75</td>
<td>284</td>
</tr>
<tr>
<td>35:65</td>
<td>337</td>
</tr>
</tbody>
</table>

Assumed values:
- $T_{\text{mix}} = 160^\circ\text{C}$
- $T_{\text{filler}} = 10^\circ\text{C}$
- $\Delta Q_1 = 0.05$
- $T_{\text{crushed asph.}} = 10^\circ\text{C}$
- $T_{\text{new bit.}} = 170^\circ\text{C}$
- $\Delta Q_2 = 0.05$

Moisture content of the old asphalt: 2 %

The consequences of the heat losses from the new material ($\Delta Q_1$) for the mix temperature were also investigated. This can make a large difference during the start-up, but once the large mass of the plant has been heated up to the operating temperature hardly any heat losses occur any longer, unless the new sand and gravel have a long residence time in the bunkers (see Table 7.5). The heat losses from the bitumen ($\Delta Q_2$) make much less difference, owing to the small amount of bitumen involved.
Table 7.5  Effect of the heat losses from the new minerals (ΔQ₁) on the mix temperature

<table>
<thead>
<tr>
<th>ΔQ₁</th>
<th>T_{mix} °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>160</td>
</tr>
<tr>
<td>0.05</td>
<td>152</td>
</tr>
<tr>
<td>0.10</td>
<td>144</td>
</tr>
<tr>
<td>0.15</td>
<td>136</td>
</tr>
<tr>
<td>0.20</td>
<td>128</td>
</tr>
<tr>
<td>0.25</td>
<td>120</td>
</tr>
</tbody>
</table>

Assumed values:
- 25% of crushed asphalt
- T_{new min.} = 270°C
- T_{filler} = 10°C
- T_{crushed asph} = 10°C
- T_{new bit.} = 170°C
- ΔQ₂ = 0.05
- Moisture content of the crushed asphalt: 2%

Finally the mixing ratio to be used was calculated in order to obtain the required mix temperature of T_{mix} = 160°C at a given value of T_{nm} under specified conditions (see Fig. 7.7). It can thus be seen that, under the conditions assumed here, the amount of old asphalt cannot exceed 27%, at which the maximum temperature of the new material is 300°C. However, Fig. 7.7 also shows that the mix temperature can be readily controlled via the ratio between the old asphalt and the new sand and gravel. It should be emphasized again that these calculations apply only to the asphalt compositions involved here.

Figure 7.7  Amount of crushed asphalt in the mix (x) at various new mineral temperatures T_{nm} (T_{m₁}) needed for reaching a mix temperature T_{mix} = 160°C; moisture content of crushed asphalt, 2%.
7.4.4 Product specifications

As mentioned earlier, nearly all the required compositions and Marshall properties of the mix can be obtained in the partial recycling of old asphalt, so that the existing requirements need not be changed. However, there is not enough information about the variations in the old-asphalt composition and about their effect on the mix design. Admittedly, the tests done so far do not point to a significant difference between the product and a reference mix as regards the variations in the composition. Contrary to some foreign specifications, we believe that the mix must not contain more than 0.1% of moisture. The long-term effect of the residual moisture content of the mix is still largely unknown, and a higher moisture content may prove dangerous.

These calculations indicate that the production of asphalt mixes by partial recycling under the above conditions is entirely feasible.

7.4.5 Production experience

In the tests conducted the temperature was often measured both in the plant (in the

![Figure 7.8](image)

Figure 7.8 Temperature fluctuations in the asphalt plant at Hasselt during the production of the mix for the Harderwijk test sections.

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elevator bucket) and during laying (in the hopper of the laying and finishing machine). The results were the same as in the usual method without recycling. Fig. 7.8 shows the variations in the temperatures $T_{nm}$ and $T_{mix}$ in the asphalt plant at Hasselt during the production of gravel asphalt for test sections at Harderwijk. The moisture content was always below the permissible maximum of 0.1%, so that no weak mix ('soup') was formed by a high residual moisture content either in these tests or later, in the full-scale application of the method. Bridge formation by the fine asphalt fraction (0-16 mm) in the feed device at first caused some problems (it did not occur with the 16-45 and the 0-45 mm fraction). However, it was not observed later (in October to December 1980), possibly because of the higher moisture content of the old asphalt, the lower air temperature, and the fact that some sand had adhered to the moist surface of the old asphalt, preventing caking that leads to bridge formation.

### 7.4.6 Energy consumption

The temperature to which the new sand and gravel must be heated depends largely on the mixing ratio, the moisture content of the old asphalt, and the heat losses from the new sand and gravel prior to mixing. Since these materials are hotter here than in the conventional method, the heat losses are also greater. In addition, extra energy is needed for the longer mixing time and the use of a feed device for the old asphalt. On the other hand, the energy consumption is reduced by the fact that the old asphalt generally has a considerably lower moisture content than the new sand and gravel to be heated up in the conventional process. The energy balance depends on the local conditions, but it can be said that partial recycling does not require more energy in the asphalt plant than the conventional method.

### 7.5 Laying the asphalt

During the laying of about 10,000 t of asphalt made by partial recycling no difference from the reference mixtures was observed. Nor was in fact a difference to be expected on the basis of the laboratory tests on the properties. The mix could be spread and compacted in the usual way.

### 7.6 Properties of the asphalt mixes made by partial recycling

Many determinations were carried out to establish these properties before, during, and after the above laboratory and in situ investigations, and the results can be summed up as follows:
Table 7.6 shows the Marshall properties of the reference mixture and the test mixture containing 25% of old asphalt, both having been tested in the preliminary tests.

### Table 7.6 Marshall properties of the gravel asphalt for base-courses and sub-bases, used in the Harderwijk test sections

<table>
<thead>
<tr>
<th>Mix</th>
<th>Stability $P_M$, N</th>
<th>Flow $F_M$, mm</th>
<th>Quotient $Q_M$, N/mm</th>
<th>Density, kg/m$^3$</th>
<th>Void content, vol. %</th>
<th>Degree of filling, vol. %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference mix</td>
<td>6200</td>
<td>1.8</td>
<td>3440</td>
<td>2354</td>
<td>5.1</td>
<td>65.3</td>
</tr>
<tr>
<td>Mix with 25% of old asphalt</td>
<td>8020</td>
<td>1.9</td>
<td>4220</td>
<td>2369</td>
<td>4.1</td>
<td>68.3</td>
</tr>
</tbody>
</table>

Notes:
1) The reference mix contained 4.3% of bitumen (on 100% of mineral aggregate), while the test mix contained 4.2% of bitumen (on 100% of mineral aggregate)
2) The figures shown in this table were obtained by linear interpolation between the values for bitumen contents of 4.0 and 4.5%

It is important to find out whether the use of somewhat aged bitumen from the old asphalt influences the adhesion properties of the bitumen mixture. To answer this question, half of the specimens prepared for the Marshall tests were first kept under water at room temperature for 10 weeks before being tested; the results are shown in Table 7.7.

### Table 7.7 Marshall properties determined for laboratory specimens from the Harderwijk test sections after water immersion for 10 weeks

<table>
<thead>
<tr>
<th>Mix</th>
<th>Stability $P_M$, N</th>
<th>Flow $F_M$, mm</th>
<th>Quotient $Q_M$, N/mm</th>
<th>Density, kg/m$^3$</th>
<th>Void content, vol. %</th>
<th>Degree of filling, vol. %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference mix before</td>
<td>5800</td>
<td>2.1</td>
<td>2870</td>
<td>2357</td>
<td>4.8</td>
<td>66.8</td>
</tr>
<tr>
<td>after 4540</td>
<td>2.3</td>
<td>1970</td>
<td>2356</td>
<td>4.9</td>
<td>66.6</td>
<td></td>
</tr>
<tr>
<td>Mix with 25% of old asphalt before 5920</td>
<td>2.0</td>
<td>2960</td>
<td>2343</td>
<td>5.3</td>
<td>64.1</td>
<td></td>
</tr>
<tr>
<td>after 4950</td>
<td>2.3</td>
<td>2130</td>
<td>2342</td>
<td>5.3</td>
<td>64.0</td>
<td></td>
</tr>
</tbody>
</table>

Table 7.8 shows the properties of bitumen recovered from various asphalt samples from the Harderwijk test sections.

The moisture content of all the samples taken from the Hasselt and the Harderwijk test sections was invariably below 0.1%.
Table 7.8  Properties of bitumen recovered from the asphalt laid on the Harderwijk test sections

<table>
<thead>
<tr>
<th>No. of samples</th>
<th>Penetration</th>
<th>Softening point (ring-and-ball method), °C</th>
<th>Penetration index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crushed asphalt</td>
<td>6</td>
<td>53</td>
<td>53.5</td>
</tr>
<tr>
<td>New bitumen</td>
<td>5</td>
<td>57</td>
<td>52.2</td>
</tr>
<tr>
<td>Reference mix</td>
<td>4</td>
<td>51</td>
<td>53.6</td>
</tr>
<tr>
<td>Test mix (25% of crushed asphalt)</td>
<td>8</td>
<td>42</td>
<td>55.2</td>
</tr>
</tbody>
</table>

Table 7.9  Composition of mixes laid on the Harderwijk test sections (6 samples were used for each test section)

<table>
<thead>
<tr>
<th>Mix</th>
<th>Layer</th>
<th>Fractions (%) retained on the following screens:</th>
<th>Fraction passing through 63 μm</th>
<th>Amt of bit. (on 100% of minerals)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>C22.4   C16    C11.2  C8  C5.6  2 mm  63 μm</td>
<td>2 mm  63 μm</td>
<td>63 μm</td>
</tr>
<tr>
<td>Reference mix</td>
<td>Lower mean</td>
<td>4.2      23.6     40.4  49.1  54.0  58.2  94.5</td>
<td>5.5</td>
<td>4.2</td>
</tr>
<tr>
<td></td>
<td>s.d.</td>
<td>3.4      3.2        3.0  2.9   2.9   3.5   3.5</td>
<td>0.51</td>
<td>0.30</td>
</tr>
<tr>
<td></td>
<td>Upper mean</td>
<td>7.6      24.7     42.8  51.1  55.9  59.6  95.0</td>
<td>5.0</td>
<td>4.2</td>
</tr>
<tr>
<td></td>
<td>s.d.</td>
<td>4.5      5.2        4.1  3.5   3.0   4.9   2.6</td>
<td>0.42</td>
<td>0.19</td>
</tr>
<tr>
<td>Test mix with</td>
<td>Lower mean</td>
<td>1.7      10.0     24.8  39.6  48.5  57.6  94.4</td>
<td>5.6</td>
<td>4.0</td>
</tr>
<tr>
<td>0-45 mm old</td>
<td>s.d.</td>
<td>1.4      2.3        4.5  5.0   3.6   2.2   2.2</td>
<td>0.29</td>
<td>0.21</td>
</tr>
<tr>
<td>asphalt</td>
<td>Upper mean</td>
<td>2.6      12.6     29.8  43.1  51.0  59.2  94.2</td>
<td>5.8</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>s.d.</td>
<td>2.3      2.7        6.5  4.1   3.6   3.2   3.0</td>
<td>0.53</td>
<td>0.24</td>
</tr>
<tr>
<td>Test mix with</td>
<td>Lower mean</td>
<td>2.0      10.1     25.4  40.0  48.6  57.3  94.1</td>
<td>5.9</td>
<td>4.0</td>
</tr>
<tr>
<td>0-16 mm and 16-45 mm old asphalt</td>
<td>s.d.</td>
<td>2.9      4.3        5.4  3.7   2.1   2.0   1.7</td>
<td>0.50</td>
<td>0.16</td>
</tr>
<tr>
<td>Requirements-reference mix</td>
<td>4.0</td>
<td>14.3     29.1     43.3  51.9  56.8  93.6  6.4</td>
<td>4.3</td>
<td></td>
</tr>
<tr>
<td>Requirements-test mix with 0-45 mm old asphalt</td>
<td>4.0</td>
<td>14.6     23.3     36.6  47.2  58.0  94.0  6.0</td>
<td>4.2</td>
<td></td>
</tr>
<tr>
<td>Requirements-test mix with 0-16 mm and 16-45 mm old asphalt</td>
<td>3.2</td>
<td>11.3     22.9     36.8  48.0  58.6  94.0  6.0</td>
<td>4.2</td>
<td></td>
</tr>
</tbody>
</table>

e  Table 7.9 shows the composition of the mixtures, determined on a number of random core samples drilled out of the test sections at Harderwijk.

f  Table 7.10 shows the mean values of density, void content, degree of filling, and degree of compaction, found for core samples taken from the test sections at Harderwijk.

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Table 7.10 Properties of drilled core samples taken from the Harderwijk test sections

<table>
<thead>
<tr>
<th>Mix</th>
<th>Layer</th>
<th>Density, kg/m³</th>
<th>Void content, vol.%</th>
<th>Degree of filling, vol.%</th>
<th>Degree of compaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference mix</td>
<td>Lower</td>
<td>2373</td>
<td>4.4</td>
<td>67.1</td>
<td>102.2</td>
</tr>
<tr>
<td></td>
<td>Upper</td>
<td>2375</td>
<td>4.2</td>
<td>68.3</td>
<td>102.3</td>
</tr>
<tr>
<td></td>
<td>s.d.</td>
<td>24.5</td>
<td>1.04</td>
<td>5.00</td>
<td>0.89</td>
</tr>
<tr>
<td></td>
<td></td>
<td>11.9</td>
<td>0.47</td>
<td>2.63</td>
<td>0.39</td>
</tr>
<tr>
<td></td>
<td>s.d.</td>
<td>24.5</td>
<td>1.04</td>
<td>5.00</td>
<td>0.89</td>
</tr>
</tbody>
</table>

Test mix with 0-45mm old asphalt

<table>
<thead>
<tr>
<th>Mix</th>
<th>Layer</th>
<th>Density, kg/m³</th>
<th>Void content, vol.%</th>
<th>Degree of filling, vol.%</th>
<th>Degree of compaction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lower</td>
<td>2371</td>
<td>4.8</td>
<td>64.5</td>
<td>101.8</td>
</tr>
<tr>
<td></td>
<td>Upper</td>
<td>2380</td>
<td>4.2</td>
<td>67.6</td>
<td>101.8</td>
</tr>
<tr>
<td></td>
<td>s.d.</td>
<td>25.1</td>
<td>1.03</td>
<td>5.26</td>
<td>1.09</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7.4</td>
<td>0.52</td>
<td>3.90</td>
<td>0.64</td>
</tr>
<tr>
<td></td>
<td>s.d.</td>
<td>25.1</td>
<td>1.03</td>
<td>5.26</td>
<td>1.09</td>
</tr>
</tbody>
</table>

Test mix with 0-16 and 16-45mm old asphalt

<table>
<thead>
<tr>
<th>Mix</th>
<th>Layer</th>
<th>Density, kg/m³</th>
<th>Void content, vol.%</th>
<th>Degree of filling, vol.%</th>
<th>Degree of compaction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lower</td>
<td>2374</td>
<td>4.5</td>
<td>65.6</td>
<td>102.2</td>
</tr>
<tr>
<td></td>
<td>Upper</td>
<td>2379</td>
<td>4.3</td>
<td>67.2</td>
<td>102.2</td>
</tr>
<tr>
<td></td>
<td>s.d.</td>
<td>4.5</td>
<td>0.24</td>
<td>1.90</td>
<td>0.68</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7.1</td>
<td>0.35</td>
<td>2.04</td>
<td>0.43</td>
</tr>
<tr>
<td></td>
<td>s.d.</td>
<td>4.5</td>
<td>0.24</td>
<td>1.90</td>
<td>0.68</td>
</tr>
</tbody>
</table>

Notes
1) 6 samples were used for each test section.
2) The density was determined in accordance with the 1978 specifications, using method No. 67.2 (without paraffin). For the work done here we have that \( y = 1.40 \times - 978.91 \), where \( x \) is the density without paraffin and \( y \) is the density with paraffin, in kg/m³ (the correlation coefficient is \( r = 0.97 \)).

The stiffness modulus of the mix \( S_{mix} \) at 40 and 25°C was determined as a function of that of the bitumen \( S_{bit} \) on two specimens in each case, and the results are shown in Figs. 7.9 and 7.10. These samples were taken from the Hasselt test sections. The tests were done [40] under a load of 0.1 MN/m², using a load time of 60 min and a recovery time of 60 min.

![Figure 7.9](image.png)

Figure 7.9 Stiffness modulus of the reference mix (\( S_{m} \)) as a function of that of the bitumen (\( S_{bit} \)) (Hasselt test sections).
Figure 7.10  Stiffness modulus of the asphalt mix (Sm) containing 25% of old asphalt as a function of the stiffness modulus of the bitumen (Sbi') (Hasselt test sections).

Figure 7.11  Permanent deformation (s) as a function of the number of wheel passes (N) for the reference mix, in the Hasselt test sections.

Figs. 7.11 and 7.12 show the results of the wheel tracking tests [41], i.e. the deformation of the samples in percent as a function of the number of wheel passes for samples taken from the Hasselt test sections constructed with the reference mix (Fig. 7.11) and the test mix made with 25% of old asphalt (Fig. 7.12).
Figure 7.12 Permanent deformation (s) as a function of the number of wheel passes (N) for the test mix containing 25% of old asphalt in the Hasselt test sections.

Cylindrical specimens for which the void content was closest to the mean value were chosen for the fatigue test from among a number of specimens. The test was done in quadruplicate by the dynamic three-point bending measurement at 40 Hz, two temperatures, and three deflection values, using samples from the Hasselt test sections. Figs. 7.13 and 7.14 show the service life of the asphalt mixtures as a function of the strain applied.

These results lead to the following conclusions:

- There are appreciable differences between the test and the reference mix as regards the penetration value of the bitumen in them and as regards the density of the specimens (owing to the different particle compositions), but otherwise the two mixtures have the same Marshall properties. The results are also similar as regards the deterioration of the Marshall stability after ageing under water.
- The properties of the recovered bitumen are largely in line with the expectations. The drop in the penetration value during mixing and laying is within the normal limits established in earlier investigations [42].
- Given a careful operation, the production and laying of partially recycled asphalt do not involve any problems. The accuracy of the mix production is comparable to that with conventional asphalt mixes. This is particularly surprising because the composition of old asphalt, sampled by the usual method, generally shows greater scatter. Relatively small samples taken from old asphalt are not entirely representative.
The compactibility of the mix containing 25% of old asphalt is comparable to that of the conventional mixtures. No difference was found in the compaction results between the mixes, including the reference mix, in the test sections at Hasselt and Harderwijk.

The resistance to permanent deformation as determined by the creep test for the asphalt mix containing old asphalt is similar to, and possibly even better than, that for the reference mix. The same conclusion can be drawn from the wheel tracking test.

Under the conditions prevailing during the fatigue test the asphalt mix containing 25% of old asphalt showed the same fatigue characteristics as comparable conventional mixes.
7.7 Other results obtained for the Harderwijk test sections

7.7.1 Composition (grading and bitumen content)

Taking into account the tolerance incorporated in the existing requirements, we can state that the latter were fulfilled by the mineral grading and the bitumen content of all three partially recycled asphalt mixes (see also [43]). The values found for the void content and the degree of compaction invariably met the requirements. The degree of compaction was high in all three test sections, the mean values being as follows:

- 102.6% for the mix containing 25% of 0-45 mm crushed old asphalt,
– 103.0% for the mix containing 25% of 0-16 mm + 16-45 mm crushed old asphalt, and
– 102.3% for the reference mix (new asphalt made with gravel).
In the determination of these values the mixing temperature was always 170 ± 5°C and the compaction temperature always 157 ± 5°C (same as in the case of the original bitumen).

7.7.2 Determination of the properties of the bitumen recovered

Table 7.11 shows the penetration value, the softening point, and the penetration index of the bitumen recovered from the different mixtures involved here. Ac-

<table>
<thead>
<tr>
<th>Test mix with 25% of 0-45 mm old asphalt</th>
<th>Test mix with 25% of 0-16 + 16 – 45 mm old asphalt</th>
<th>Reference mix (gravel-type asphalt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper layer</td>
<td>Lower layer</td>
<td>Upper layer</td>
</tr>
<tr>
<td>Penetration (in 0.1-mm units)</td>
<td></td>
<td>Lower layer</td>
</tr>
<tr>
<td>mean</td>
<td>49</td>
<td>46*</td>
</tr>
<tr>
<td>s.d.</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>no.</td>
<td>5</td>
<td>9</td>
</tr>
<tr>
<td>max.</td>
<td>54</td>
<td>60</td>
</tr>
<tr>
<td>min.</td>
<td>45</td>
<td>40</td>
</tr>
<tr>
<td>Softening point (ring-and-ball method)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>mean</td>
<td>52.4</td>
<td>52.9</td>
</tr>
<tr>
<td>s.d.</td>
<td>0.9</td>
<td>1.0</td>
</tr>
<tr>
<td>no.</td>
<td>5</td>
<td>9</td>
</tr>
<tr>
<td>max.</td>
<td>53.5</td>
<td>54.5</td>
</tr>
<tr>
<td>min.</td>
<td>51.5</td>
<td>52.0</td>
</tr>
<tr>
<td>Penetration index</td>
<td></td>
<td></td>
</tr>
<tr>
<td>mean</td>
<td>−0.7</td>
<td>−0.6</td>
</tr>
<tr>
<td>s.d.</td>
<td>0.04</td>
<td>0.2</td>
</tr>
<tr>
<td>no.</td>
<td>5</td>
<td>9</td>
</tr>
<tr>
<td>max.</td>
<td>−0.7</td>
<td>−1.0</td>
</tr>
<tr>
<td>min.</td>
<td>−0.6</td>
<td>−0.3</td>
</tr>
</tbody>
</table>

s.d. = standard deviation; no. = number of determinations
* Outlier values ignored (pen = 60; T<sub>ring/ball</sub> = 52.0°C; penetration index = −0.3)
According to earlier work, the penetration of a 46-60 pen bitumen decreases by about 20%, owing to the additional hardening that occurs during the preparation of new asphalt in batch mixtures and during its laying. The penetration values for the reference mix were generally somewhat higher than expected on this basis. The mean values obtained for the characteristics of the bitumen in the various partially recycled mixtures showed quite good agreement; the scatter was the same as, or somewhat greater than, that found for the bitumen in the reference mixture (this scatter is now being investigated further).

7.7.3 Wheel tracking test

This was done at a wheel contact pressure of 0.5 MN/m\(^2\) (initial value) and a temperature of 40°C [28]. For a road destined for traffic of category No. 3*, the mean relative permanent deformation \(\varepsilon_w\) after \(10^5\) wheel passes should not exceed 6.5%. As the data in Table 7.12 show, the values obtained amply fulfil this requirement in the case of all three test sections. Student’s t-test, carried out on \(\ln \varepsilon_w\) after \(10^5\) wheel passes, shows no significant difference between the two test mixes and the reference mix at a confidence limit of 95%.

Table 7.12 Results of the wheel tracking test

<table>
<thead>
<tr>
<th>Mix</th>
<th>Mean relative permanent deformation (\varepsilon_w) (%) after (10^5) wheel passes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Requirement for traffic of category No. 3</td>
<td>&lt; 6.5</td>
</tr>
<tr>
<td>Reference mix (gravel asphalt for base courses)</td>
<td>2.2</td>
</tr>
<tr>
<td>Test mix with 25% of 0-45 mm crushed asphalt</td>
<td>1.8</td>
</tr>
<tr>
<td>Test mix with 25% of 0-16 + 16-45 mm asphalt</td>
<td>1.5</td>
</tr>
</tbody>
</table>

7.7.4 Creep test

This was done at 25 and 40°C, using a load of 0.1 MN/m\(^2\), a load time of 60 min, and a recovery time of also 60 min [32]. Since the layer thickness of the course laid on the road was smaller than 100 mm (the necessary height of the specimens), two polished specimens were placed on top of each other for the creep test. At 40°C and with a load time of 60 min, the mean stiffness modulus of the mix \(S_{mix}\) must not be less than

---

* Daily mean number of motor vehicles: 10,000-20,000 for a two-lane road and 20,000-50,000 for a road with four or more lanes.
6.5 MN/m² for a road with traffic of category No. 3. The figures in Table 7.13 show that all three road sections amply fulfilled this requirement at 40°C. At this temperature, the permanent deformation for the reference section was significantly higher than for the two test sections, which did not show a significant difference between them. At 25°C there was no significant difference between the three asphalt mixtures (Student’s t-test on In ε_{irr} with a load time of 60 min and at a confidence level of 95%).

Table 7.13 Results of the creep test

<table>
<thead>
<tr>
<th>Mix</th>
<th>Mean stiffness modulus S_{mix} at 40°C and a load time of 60 min, MN/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Requirement for traffic of category No. 3</td>
<td>≥ 6.5</td>
</tr>
<tr>
<td>Reference mix (gravel asphalt for base courses)</td>
<td>13.1</td>
</tr>
<tr>
<td>Test mix with 25% of 0-45 mm crushed asphalt</td>
<td>17.0</td>
</tr>
<tr>
<td>Test mix with 25% of 0-16 + 16-45 mm asphalt</td>
<td>17.6</td>
</tr>
</tbody>
</table>

Figure 7.15 Results of the measurements with the falling weight deflectometer for an asphalt mix containing 0-45 mm of old asphalt and laid on highway 313.
7.7.5 Deflection measurements by the falling-weight method

These measurements were done directly after laying and before the road sections were opened to the traffic [46]. The aim was to investigate the dynamic stiffness, i.e. the bearing capacity, of the three mixtures under practical conditions. The results were interpreted by a 'best-fit technique' for two-layer systems consisting of subgrade and pavement. In this curve-fitting technique every point on the deflection curve is approximated as closely as possible by a calculated curve obtained with the aid of a BISAR computer program. We varied the values of the stiffness modulus $E_1$ of the asphalt (both layers together), the layer thicknesses $h_1$ of the asphalt pavement and subgrade, and the modulus of the subgrade $E_3$. Fig. 7.15 shows an example of the results obtained in the interpretation of the deflection data. The results obtained

![Graph](image_url)

*Figure 7.16 Relationship between the mean stiffness modulus ($E_1$) and the asphalt temperature ($T$).*

...
indicate fairly large variations in the dynamic stiffness modulus along the test sections [33]. Fig. 7.16 shows the mean stiffness modulus as a function of the asphalt temperature. The curve shown here for comparison refers to the $S_{1-50}$ values with a load time of 0.02 sec, taken from the Shell Pavement Design Manual [33]. In view of the scatter shown by our values, the differences between the asphalt mixes in the dynamic stiffness are not significant.

7.7.6 Production experience

7.7.6.1 Crushing and stockpiling old asphalt

Between 1980 and the middle of 1983, ADUCO broke up and stockpiled about 60,000 t of old asphalt of very different mineral gradings and bitumen contents with a view to recycling. No problems were experienced either here or when storing the material crushed to a size of 0-45 mm. No caking occurred during the summer. However, the material to be crushed generally contained 10-20% of sand from the subgrade.

One particular case is worth mentioning. Since the bituminous surface dressing had failed along a certain stretch of a road, it was necessary to take it up by milling together with the underlaying layer of asphalt, which gave about 800 t of old surfacing material. This was first mixed with about 20% of sand to prevent caking, which was in fact successfully suppressed in this way, so that the lumps could later be easily separated with a loading shovel. Admittedly, the material was not piled higher than 3 m.

The moisture content of the crushed asphalt, which was stockpiled without a cover, varied between 2 and 6%, depending on the weather. The original old asphalt contained less than 1% of moisture, so that the material can pick up a fair amount of moisture when stockpiled in the open. The moisture content of the old material also depends on the grading and the amount of sand in it or the fresh sand added to it. The 0-12 mm fraction of the crushed asphalt contained 2-3 times as much moisture as the 12-45 mm fraction. It is advisable to keep the stocks of crushed asphalt small, because the storage and covering of large quantities are at present difficult for financial and practical reasons. It is best to crush just as much old asphalt as is needed for re-use, cover it up, and bring it under supervision as part of the production control. At the same time, the search for a cheap and efficient way of covering crushed asphalt should be continued.

7.7.6.2 Production

Since the first publications [43-45] the members of ADUCO have produced about
20,000 t of partially recycled asphalt, with old/new ratios between 15/85 and 30/70 according to the production conditions and the envisaged use. The results for the test section on highway 313 show that crushed asphalt can be used in a single fraction (0-45 mm).

This method was used for making the first layer with gravel asphalt (and later also the second layer) of the new provincial road T 20 between Houten and Nieuwegein, which comes under the Utrecht Provincial Waterstaat. Since part of the asphalt was made without the admixture of old asphalt, it is easy to make a comparison. Altogether about 5,000 t of gravel asphalt were used, with the admixture of 25 wt-% of old asphalt.

The bitumen recovered from the mixture containing 25% of old asphalt had a penetration of 44 (in 0.1-mm units). The mean penetration value of the new bitumen introduced during the production was 55, and the corresponding value for the bitumen recovered from the old asphalt was 37. With the mixing ratios used here, the calculations described earlier indicate a value of pen$_{\text{mix}}$ = 50 for the penetration of the bitumen mixture, which is 12% higher than the observed value. The drop probably occurs during mixing and can be regarded as quite normal even in the conventional production process, and is particularly understandable if the presence of old and new bitumen is taken into account.

The temperature of the new aggregate at the outlet of the drying drum and the mix temperature in the bucket elevator were measured during five production days, during which the partial recycling method was used with a 25% admixture of old asphalt. The highest mix temperature measured was 188°C and the lowest 156°C. On the assumption of a 2% moisture content of the old asphalt and a value of 0.05 for both $\Delta Q_1$ and $\Delta Q_2$ (see below), the calculated mix temperature was $T_{\text{mix}} = 160°C$, which is lower than the average temperature observed (173°C). The calculation and the assumptions made have been discussed earlier in this section. It will be recalled that $\Delta Q_1$ is the heat loss from the new mineral before the addition of the crushed asphalt, and $\Delta Q_2$ the heat loss from the new bitumen before it is added to the mix. If no extra heat loss occurs during production (in which case $\Delta Q_1$ and $\Delta Q_2$ are zero), then the calculated mix temperature is $T_{\text{mix}} = 169°C$, which agrees reasonably well with the observed value.

On the basis of these results, a new/old ratio of 75:25 is entirely feasible in partial recycling under normal production conditions. However, a year's experience with asphalt plants of different makes has shown that it is better to use less of the old asphalt in the mixture. The reasons for this are as follows:

- the higher temperatures in the plant cause a relatively large expansion of metal components, as a result of which rotating parts such as engines and gears can seize up in their housing,
Figure 7.17 Relationship between the moisture content of the old asphalt (v) and asphalt mix temperature (T) for various old/new ratios (\%\textsubscript{a}).
- the exhaust-gas temperature must be below a certain value in the case of plants fitted with cloth filters (in one of the asphalt plants the mineral temperature could not exceed 230°C for this reason),
- very high mineral temperatures reduce the working life of the screens in the asphalt plant.

These factors may urge one to choose a ratio with less old asphalt, although a ratio with more old asphalt is entirely feasible both technically and economically [45].

For these reasons the maximum recommended temperature for the mineral aggregate is 275°C, and one must often take 250°C to be on the safe side. As a result, a maximum is imposed on the amount of old asphalt that can be incorporated in the mix, mainly by the moisture content of the old asphalt (the old asphalt is to be heated up to the necessary temperature by the new aggregate). As Fig. 7.17 shows, if the required temperature for the mix is 150°C, the moisture content of the old asphalt cannot be higher than 2.3% if 20% of this material is to be incorporated in the mix. Further work is needed to find out what effect the overheated mineral aggregate has on the properties of the binder, because this will also restrict the maximum temperature on the aggregate. Experimental and calculated results obtained so far indicate, however, that this effect is very small.

7.8 Energy consumption of partial asphalt recycling

This was determined after the first test, and the results indicated that the process was attractive from this point of view as well.

Much work has recently been done on the energy consumption involved in the road-building in general. Thus, Brouwers investigated this topic immediately after the first energy crisis [49]; Bolk et al. [50] have recently compared different ways of recycling asphalt for the energy aspect, and Wester has also reported on the energy consumption involved in road-building [47, 48, 114].

We can now discuss this topic on the basis of these publications and our own studies and calculations. Table 7.14 shows the specific energy consumption of the different stages in litres of oil equivalent (LOE; 1 GJ = 25 LOE). The energy content of 1 t bitumen was taken to be 900 LOE. This value was not of course included again for the old asphalt in the recycling phase. Wester's values were used for the energy content of new asphalt [47, 48], and ADUCO data for the production.

The re-use of 25% of crushed asphalt in the partial recycling process saves about 11 LOE per tonne of asphalt mix, mainly by saving on bitumen. The energy consumption of crushing (see the first section in Table 7.14) was added to the direct
### Table 7.14: Energy consumption (litres of oil equivalent – LOE) for the partial recycling of old asphalt

<table>
<thead>
<tr>
<th>1. Production of crushed old asphalt, per t</th>
</tr>
</thead>
<tbody>
<tr>
<td>. excavation from the pavement, with a layer thickness of 25 cm</td>
</tr>
<tr>
<td>. transport ($2 \times 10$ km)</td>
</tr>
<tr>
<td>. crushing (impact breaker with an output of 30 t/h)</td>
</tr>
<tr>
<td><strong>total</strong></td>
</tr>
</tbody>
</table>

2. Preparation, (per t of crushed old asphalt)
   - weighing and mixing with new material | 0.3 |
   - additional energy consumption of the plant due to the lower thermal efficiency | 0.5 |
   - heating up the crushed old asphalt ($T_{\text{mix}} = 160^\circ$C, $\Delta Q = 0.05$, and 2% of moisture in the old asphalt) | 6.8 |
   **total** | **7.6** |

3. Comparative figures, per t of material (not including transport and laying; $T_{\text{mix}} = 160^\circ$C)
   - new asphalt [47, 48] | 57.4 |
   - mixed asphalt containing 25% of old asphalt | 46.0 |

Energy consumption (see the second section in Table 7.14), but the energy consumption of breaking up the pavement and possibly transporting it to the collection point should not be taken into account here.

The data listed in Table 7.15 show the energy consumption involved in the production of 1 t of partially recycled asphalt with an old/new ratio of 25/75 as a function of the moisture content of the old asphalt. As can be seen, this moisture content makes little difference in this respect.

Table 7.16 shows the energy consumption data for some alternative uses of old asphalt. The value for partial recycling was taken from Table 7.14 (section 2), to which were added the energy needed for crushing (2.9 LOE) and the energy needed for breaking up the pavement (0.4 LOE). Bolk’s data [50] were used for the hot regeneration of asphalt, in which the end product mostly consists of old asphalt, but a

### Table 7.15: Energy consumption (litres of oil equivalent – LOE) involved in the preparation of mixed asphalt containing 25% of old asphalt with various moisture contents

| New gravel asphalt for base courses and sub-bases | 57.4 |
|--------------------------------------------------|
| Crushed asphalt with a |
| moisture content of 0% | 45.4 |
| moisture content of 1% | 45.7 |
| moisture content of 2% | 46.0 |
| moisture content of 3% | 46.3 |
| moisture content of 4% | 46.6 |
| moisture content of 5% | 46.9 |
20% sand addition was assumed in the present case. The figure for partially recycled asphalt is broken down to a component for old asphalt and a component for new asphalt made with sand and gravel. The figures are also converted into the corresponding values for equivalent structural design.

It can be concluded that partial recycling is an economically attractive method of re-using old asphalt. It should be mentioned that the great difference is due to the fact that the energy content of the old bitumen is also taken into account.

Table 7.16 Energy consumption (litres of oil equivalent – LOE) involved in some alternative ways of re-using asphalt (values per t, including laying but not transport)

<table>
<thead>
<tr>
<th>Mixture of cement and crushed asphalt [50]</th>
<th>Energy consumption</th>
<th>Corrected for equivalent structural design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot regenerated asphalt with rejuvenator and 20% of sand</td>
<td>7.5</td>
<td>17.5</td>
</tr>
<tr>
<td>Regenerated asphalt with 25% of crushed asphalt</td>
<td>17.4</td>
<td>17.4</td>
</tr>
<tr>
<td>composed of: crushed asphalt</td>
<td>46.5</td>
<td>46.5</td>
</tr>
<tr>
<td>new gravel asphalt</td>
<td>11.4</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>57.9</td>
<td>–</td>
</tr>
</tbody>
</table>

7.9 Conclusions

1. Both laboratory and field tests have given good results for partial recycling. Further assessment of the test sections is now in progress.
2. Partial recycling in a modified batch mixer is also attractive from the point of view of the energy consumption.
3. Some important information has been obtained about the specifications to be stipulated and the feasibility of meeting them. The contractor’s knowledge of the production and testing methods is also very valuable.
4. Old asphalt crushed to 0-45 mm is adequate; it is not necessary to separate it into a 0-16 mm fraction and a 16-45 mm fraction.
5. The maximum amount of old asphalt that can be incorporated partly depends on the nature and quality of the apparatus used and partly on the amount of wear and tear on it that is considered acceptable. The composition of the old asphalt – and particularly its moisture content – is also important (see Table 7.15).
6. The best method for the prolonged storage of possibly large amounts of crushed asphalt is to be investigated further.
7. The results obtained so far have been used for drafting some guidelines and specifications of general applicability [51].
Both the authorities and the contractors are keen to promote the use of this method. When enough experience has been gained with partially recycled asphalt, and the product satisfies all the requirements, the extensive testing of the mechanical properties can be stopped. The remaining tests should then also be reviewed.

The method should closely match the production of new asphalt (except that the composition of the old asphalt and the properties of the binder in it must be determined regularly). Constructing a test section is therefore no longer necessary for contractual purposes either.

7.10 Further developments

After the completion of the tests described above, several authorities commissioned projects involving the partial recycling of old asphalt, and altogether about 300,000 t of asphalt were made in this way by October 1983. The first report on this work has already been published [52]. Road-building contractors have reacted favourably to the recycling of asphalt [53], and many of them already have suitable modified asphalt plants for partial recycling. In fact, of the total of 90 asphalt plants in the Netherlands, about 30 have already been so adapted.

Furthermore, the company Hollandsche Wegenbouw Zanen B.V., the Rotterdam City Council, and the Rijkswaterstaat have started tests to see whether partial asphalt recycling can be done in a drum mixer with an admixture of up to 50% of old asphalt. The first results obtained in 1982 showed that it would be sensible to do further tests in 1983, using the scheme involved in the ADUCO tests.

The idea has so far always been to incorporate old asphalt in the production of gravel asphalt for base-courses and sub-bases. However, the trend in road-building is away from new constructions and towards maintenance, and hence away from gravel asphalt for these lower layers and towards open-graded asphalt for binder courses and dense asphalt for wearing courses. It is therefore necessary to find out whether old asphalt can be incorporated into open-graded asphalt and if possible into dense asphalt. A further reason for this is that other recycled materials such as gravel asphalt waste granulate could also be used for base-courses and sub-bases instead of regenerated asphalt. In comparison with the re-use of old asphalt in gravel asphalt, its re-use in open-graded asphalt has the following features:

a The aggregate composition is more critical.

b The maximum particle size now allowed in crushed old asphalt (screen C-45, i.e. 0-45 mm) is greater than the normally stipulated layer thickness of binder courses made with open-graded asphalt (40 mm).
c Generally 80-100 pen bitumen is used in open-graded asphalt for binder courses and 45-60 pen bitumen in gravel asphalt for base-courses and sub-bases. The effect of this difference on the penetration value of the new bitumen to be added must be investigated.

d Crushed old asphalt mostly contains some unbroken mineral particles larger than 2 mm. The effect of this on the stability and the skid resistance of open-graded asphalt for binder courses should be investigated.

e The recycling into open-graded asphalt for binder courses differs from the recycling into gravel asphalt for base-courses and sub-bases as regards preparation and laying.

ADUCO International B.V. and the Rijkswaterstaat started some laboratory investigations in 1983 to answer the above questions, the procedure being exactly the same as in recycling into gravel asphalt for base-courses and sub-bases. The first test sections should be down before the end of the year 1984.
8 Cold recycling of asphalt into crushed asphalt cement

8.1 Introduction

In one of the feasible versions of the cold recycling of asphalt outlined in Section 5 the hot-mix asphalt pavement is broken up and reduced in a crusher to 0-40 mm, 3-6% of cement is added, and the resulting material, called crushed asphalt cement, is used as a bound base-course and sub-base material [35]. A few test sections have been constructed with this material in the Netherlands since 1975. With the addition of cement a hydraulic bound base course is obtained, with reasonable mechanical properties. However, it is generally only used in areas where no differential or other settling is expected.

The old asphalt has been crushed with different types of crushers or combinations of crushers (jaw-cone crusher, jaw-jaw crusher) as well as in impact pulverizers alone. The results obtained for the test sections show that the crushed asphalt often does not contain enough particles smaller than 4 mm [54]. However, the addition of 15-20% of sand to the crushed old asphalt generally ensures the 0-40 mm grading needed for base-courses and sub-bases consisting of unbound aggregates [55].

Specifications for the re-use of asphalt in the form of crushed asphalt cement have been prepared [56], which deal with the requirements to be met by the material, the procedure of making it, the checks to be carried out, and the preliminary tests to be done. The design criterion for the crushed asphalt cement is a compressive strength of 3.0 MN/m$^2$ after a 28-day hardening period at 20°C. In this criterion the load-spreading capacity of the crushed asphalt cement is taken into account. The relatively low design compressive strength is chosen partly to prevent a susceptibility to frost and deformation and partly to restrict cracking. This criterion and the other specifications for this product have been derived from the requirements laid down for a sand-cement mix (i.e. sand stabilized with cement), which had long been in use. The design compressive strength of the sand-cement mix is 5 MN/m$^2$ [35].

8.2 Preliminary tests

These must always be carried out in advance to establish the correct ratio between the old asphalt and any new sand and to find the amount of cement and water needed to reach the required compressive strength of 3.0 MN/m$^2$. The samples used must be
representative of the bulk materials, particularly in the case of the old asphalt. This is not always so in practice, as a result of which the amount of cement indicated by the preliminary tests may prove either insufficient in practice (leading for example to a low compressive strength) or too large (giving too high a compressive strength with cracking as a result).

The contractor must regularly determine the particle distribution of the crushed asphalt as part of his production control routine. If different materials are used, it may be necessary to repeat the preliminary tests. The first of these tests is the determination of the particle distribution of the old asphalt. If the material does not have the required 0-40 mm grading, the fine fraction is supplemented with sand, which must satisfy the Requirements 1978 [35]. The best asphalt/sand ratio is found by a calculation in which the Fuller best-mix curve is approximated [63]. It has been shown that asphalt mixes that follow Fuller’s best-mix curve generally give the highest maximum compaction.

Fuller’s formula is \( p = 100 \sqrt{d/D} \), where

- \( p \) = amount passing through a given screen %,
- \( d \) = any given particle diameter between zero and \( D \),
- \( D \) = maximum particle diameter present in the mix.

The next step is to determine the amount of cement needed, for which purpose the maximum Proctor density is first determined for three different cement contents, the corresponding optimum moisture content being determined at the same time. Cylindrical test specimens are then prepared that have the same cement contents but 2% less than the corresponding optimum moisture content. The compressive strength is measured at 20°C, after 28 days, and the cement content that gives the required compressive strength of 3.0 MN/m² is found graphically.

8.3 Mixing

The ratio indicated by the preliminary tests should obviously be used. The materials can be mixed in place or in plant, but the method affects the quality and the cost, as shown below.

a. MIXING IN PLACE

The materials are placed on the proposed sand subgrade in separate layers. The crushed asphalt is first delivered from the crusher in trucks and tipped on the subgrade, spread by a bulldozer, and levelled off with a grader. The sand and the cement are then placed on top one after the other, but sometimes they are mixed together first. If the sand forming the subgrade does not contain any components
detrimental to the binding of cement, it can be mixed with the already spread layer of crushed asphalt. In such cases the layers of materials were mixed in two passes with a soil stabilizing and milling machine, with the addition of water. The mix is finally subjected to static and vibrating compaction. A layer of bitumen emulsion is then poured on top as a tack coat to prevent the surface from drying out and to ensure a good bond with the asphalt wearing course to be applied next.

Some problems arose here when mixing in place was used. For example on highway 76, the bottom layer did not contain enough cement, so that the base-course was not strong enough. It might be possible to obtain a better result by making the milling machine work deeper in the second mixing pass. Another problem lay in the considerable variations of the mix composition and in the thickness of the base-course when the three components were applied separately, using the layer thickness as the control parameter. Better results are expected if first the layer with the mixture of sand and cement is laid, compacted and levelled and then the crushed asphalt is dumped on top and consequently spread and mixed.

b. Mixing in Plant
The components are first mixed in a pugmill and then taken to the site in trucks, tipped, spread, levelled, compacted by vibrating and static rollers, and covered with a layer of bitumen emulsion; sand is then sprinkled on top to make it easier to walk on the surface. This method generally ensures a good mixing of the components, which is definitely an advantage.

From our experience, both methods give a base-course and sub-base with at least the same strength and bearing capacity as a conventional base-course and sub-base made with sand and cement only. The way the compressive strength develops is greatly influenced not only by the ratio between the old asphalt, sand and cement, but also by the temperature of the asphalt. Laboratory work shows that this strength decreases with increasing temperature, because the bitumen present then becomes less viscous. This means that the higher the mean 24-h temperature, the longer one should wait before allowing any vehicles on the road. The temperature also influences the way the compressive strength develops; this process is accelerated by the hardening of the cement. Final conclusions cannot yet be drawn as regards the effects of the temperature on the compressive strength.

8.4 Practical experience

8.4.1 General

The first practical experience with crushed asphalt cement was gained in the Neth-
erlands in 1975-79, when a number of test sections were constructed on several roads, together with some reference sections, made with a conventional sand/cement mix having a design compressive strength of 6.0 MN/m² [50]. The main aim here was to gain further information about some aspects of laying of the base-course and sub-base.

10-16% of sand was first added to crushed old asphalt to obtain a good 0-40 mm grading. To ensure a sufficiently high compressive strength, 5-7% of cement and 4-6% of water were added to the mixture of crushed asphalt and sand. The following conclusions can be drawn from the laboratory investigations:

a) After the addition of 10-16% of sand to the crushed old asphalt, the grading in all three test sections met the 0-40 mm requirement reasonably well.

b) The design compressive strength of 3.0 MN/m² was not reached in all the test sections, the value being 2.2 MN/m² in one case, mainly because of a low cement content.

c) The distance between the cracks was considerably greater than in the case of a conventional sand/cement mix, being between 13 and 22 m, depending on the cement content.

d) In two test sections the crushed asphalt and the cement were applied to the sand subgrade and the milling machine then mixed them, together with approximately 0.05 m of the underlying sand. However, this method was later changed, because the first results were not satisfactory as regards the thickness and the homogeneity of the course. In the next test section a layer of a sand/cement mix was applied to the crushed old asphalt, and the milling machine was used to mix them in two passes. This method gave satisfactory results.

e) Not only the compressive strength of the asphalt/cement mix depends on the temperature but also its dynamic stiffness modulus, which is the ratio between the stress amplitude and the strain amplitude. In addition, the method of testing also makes a great difference in this connection. At compressive strengths of 3-6 MN/m² and a temperature of 20°C the dynamic stiffness modulus was $E_{\text{dyn}} = 7500-20,000$ MN/m². At compressive strengths of 3-4 MN/m² and a temperature of 20°C, the preliminary $E_{\text{dyn}}$ values were in the range 7500-12,000 MN/m². Somewhat higher values are normally assumed for a sand/cement mix.

f) The fatigue life of the crushed asphalt cement, measured at a constant amplitude of deflection, was qualitatively comparable to that of a sand/cement mix. It was found that, particularly at a low temperature such as 0°C, a slight increase in the
strain of the crushed asphalt cement caused a marked drop in the fatigue life. Furthermore, the fatigue life decreased with increasing temperature, contrary to what happens in the case of mixtures with only bitumen as a binder.

The resistance to permanent deformation, determined by the creep test, was at least 10 times as high as in the case of fully bituminous materials.

Some specific aspects of the three test sections are discussed below. On the basis of the results, the crushed asphalt cement was later used in two rehabilitation projects, to be discussed in Section 8.4.3.

8.4.2 Specific aspects of some of the test sections

Five test sections were constructed on a highway in September 1975 for testing various base-courses and sub-bases, including one for testing crushed asphalt cement [57]. A pavement was later applied to this base-course, in the form of two 6-cm-thick layers of gravel asphalt and a 4-cm-thick layer of open-graded asphalt. The preliminary tests suggested that 85% of crushed old asphalt should be mixed with 15% of sand, and 7% of cement and 6% of water should then be added.

To obtain the prescribed base-course or sub-base thickness of 35 cm, a 30-cm-thick layer of crushed old asphalt was laid, with 40 kg/m² of cement spread over it. This layer was milled together with the top 5-cm-thick layer of sand of the subgrade. A self-propelled vibrating roller with a static weight of 8.6 t was used to compact the base-course. The following conclusions can be drawn from the laboratory tests carried out on a number of core samples drilled out of the base-course:

- The actual layer thickness was 31.6 cm (s.d. 5 cm), which is below the thickness aimed at (35 cm).
- The mean density of the core samples was 2092 kg/m³ (s.d. 26 kg/m³).
- After 28 days at 20°C the mean compressive strength of the core samples was 3.2 MN/m² (s.d. 0.47 MN/m²). The corresponding values of the 28-day compressive strength at 0 and 40°C were respectively 5.9 and 1.9 MN/m².

Another test section was constructed with crushed asphalt cement on a municipal road in June and July 1976 [58]. We investigated some general aspects of this, such as the density and the compressive strength, and some special aspects, such as the cracking of the crushed asphalt cement. The results were compared with those obtained for a specially constructed reference section consisting of a conventional sand/cement mix. The test section made with the crushed asphalt cement was 150 m long and extended over the north and the south lane.
The preliminary tests suggested that reasonable grading could be obtained by adding 16% of sand to 84% of crushed old asphalt. The addition of 6% of cement and 4% of water (optimum minus 2%) was needed to reach the design compressive strength of 3.0 MN/m².

The test section constructed in the north lane had the above composition. However, whilst constructing the test section in the south lane it was found that the grading of the crushed asphalt differed considerably from that of the sample on which the preliminary tests had been done. To ensure a sufficiently high compressive strength, therefore, not 6 but 7% of cement was now added. However, a laboratory test carried out later showed that even 5% of cement would have been sufficient.

To reach the design thickness of 30 cm for the layer of crushed asphalt cement, a 25-cm-thick layer of crushed old asphalt was applied to the sand subgrade, the necessary amount of cement was added, and the components were mixed in two passes using a milling machine with a 30 cm-deep setting. Water was added after the first mixing stage. The base-course was compacted with a vibratory roller with a static weight of 8.5 t and then rolled smooth with a pneumatic-tyred roller.

After a hardening period of 24 days the test sections were covered with a 6-cm-thick layer of gravel asphalt to investigate the cracking.

The investigations yielded the following results:

- The density of the sand subgrade did not meet the requirement.
- The mean compressive strength after 130 days, measured on core samples drilled out of the north lane, was 2.8 MN/m² (s.d. 1.3 MN/m²). It was much higher, namely 5.8 MN/m² (s.d. 1.9 MN/m²) for the south lane, where 1% more cement had been used.
- The thickness of the base-course was 27.3 cm (s.d. 1.8 cm) in the north lane and 27.8 cm (s.d. 2.8 cm) in the south lane.
- The reference section made with a conventional sand/cement mix showed a much denser cracking pattern than the test section made with the crushed asphalt cement. This also applied to the south lane made with the crushed asphalt cement, where the compressive strength was the same as that of the sand/cement mix. The cracks generally came through the overlying layer of gravel asphalt.

Two base-course test sections made with crushed asphalt were constructed on a highway [69, 70] in May 1979, and more specifically one with unbound crushed asphalt and one with crushed asphalt cement, which was of course bound. In this second case special attention was paid to the application, and particularly to the homogeneity. The test sections had a length of 170 m and a width of 11.15 m.
The preliminary tests showed that 10% of sand had to be added to the crushed old asphalt to obtain a good grading, and 5% of cement was needed to ensure a sufficiently high compressive strength. In contrast to the previous tests, the sand and the cement were mixed in a concrete mixing plant. An asphalt spreader was used to apply the mix in a 3.5-cm-thick layer on top of the already spread crushed asphalt layer having a mean thickness of 23.5 cm (s.d. 2 cm). Again a milling machine was used to mix these components together in two passes. Care was taken not to remove any extra sand from the subgrade. Water was added after the first mixing stage. The measurements and the laboratory tests gave the following results:

- The mean layer thickness was 26 cm (s.d. 2.3 cm), meeting the requirement of 25 cm.
- Chemical analysis showed that the sand/cement mix used contained 12.2% of lime, calculated as CaO (s.d. 1.4%). This means that only 3.5% of cement had been added instead of the calculated 5%.
- The mean dry density of the crushed asphalt cement was 2059 kg/m\(^3\) (s.d. 57 kg/m\(^3\)).
- The mean compressive strength was 1.8 MN/m\(^2\) after 28 days and 2.2 MN/m\(^2\) after 50 days, so that the required value of 3.0 MN/m\(^2\) was not reached, largely because of the low cement content.

8.4.3 Use of crushed asphalt cement in two road rehabilitation projects

This application was decided on the basis of the experience gained with the above test sections, and the results obtained in this way on the highways in question are described below.

Highway 76 had shown cracking and areas of subsidence over a stretch of 1435 m, and it was decided to reconstruct it [61, 64]. The asphalt broken up from this road was used as a 25-cm-thick layer of crushed asphalt cement, acting as a base-course. The amount of asphalt removed here was enough for doing this over a length of 1035 m. The layers from top to bottom were as follows:

- 4 cm of dense asphalt,
- 4 cm of open-graded asphalt,
- 7 cm of gravel asphalt,
- 25 cm of crushed asphalt cement,
- 60 cm of prepared sand subgrade.

The asphalt broken up was comminuted in a hammer crusher to a maximum particle size of 4 cm and the crushed material was stockpiled at a depot. Three samples were
taken from it for the preliminary tests. The mean grading of these samples was used to fix the ratio between the asphalt and sand at a value of 83:17. 5.5% of cement had to be added to reach a required compressive strength of 3.0 MN/m² after 28 days. The components were mixed in place, for which purpose the crushed asphalt, the sand, and the cement were applied successively in layers and then mixed in the dry state with a soil-stabilizing machine. 4.5% of water was added and the mixing was repeated in a second pass. The theoretical layer thickness was 25 cm for the crushed asphalt and 5 cm for the sand. Tests were carried out on the base-course and the sand subgrade over two 100-m-long sections, the main results being as follows:

- The mean degree of compaction of the sand subgrade was 100%.
- Both the crushed asphalt and the sand were coarser than expected on the basis of the preliminary tests.
- Determination of the actual layer thicknesses gave 24 cm (s.d. 1 cm) for the crushed asphalt and 5.7 cm (s.d. 1 cm) for the sand, the amount of cement being at least 26.5 kg/m².
- The mix had the required 0-40 mm grading.
- After compaction, the dry density was 2039 kg/m³ (s.d. 58 kg/m³), in good agreement with the value for the test sections.
- There was so little cement present at the bottom of the base-course that no binding occurred there in a layer with a thickness of 2-5 cm.
- The ultimate compressive strength, determined after 580 days, was 5.2 MN/m² in one section and 4.2 MN/m² in the other, i.e. considerably higher than the design value of 3.0 MN/m².
- The layer thickness, determined on the core samples was 20.7 cm in one section and 23.9 cm in the other, being therefore definitely lower than the design value of 25 cm.
- The mean cement contents in the two sections (5.95 and 5.65%) were somewhat higher than the required 5.5%, the reason being the unsatisfactory mixing of the cement in the lower region.
- The dynamic elasticity modulus, determined in the laboratory, was 18,800-19,800 MN/m² for the first section and 14,500-18,100 MN/m² for the second. The higher value in the first case matches the higher cement content and the higher compressive strength there.

On the basis of these results it can be concluded that crushed asphalt cement is at least equal to the conventional sand/cement mix here as regards strength and bearing capacity. However, the method of construction used led to great fluctuations in the mix composition and in the thickness of the layers, which could possibly be restricted by a careful (perhaps modified) way of execution.

In another project, a 975-m-long section on highway 28 near Harderwijk had to be reconstructed, owing to the jacking-up and widening of a railway viaduct [62]. On
the basis of experience gained elsewhere, it was decided to use the asphalt to be broken up as crushed asphalt cement for forming a base-course. A 275-m-long stretch of this project was considered as a test section. The various layers used were as follows:

- 4 cm of dense asphalt,
- 4 cm of open-graded asphalt,
- 6 cm of gravel asphalt,
- 25 cm of crushed asphalt cement.

The asphalt broken up was comminuted first in a jaw crusher and then in a hammer crusher (primary and secondary crushing, respectively).

Since no crushed asphalt was yet available at the time of the preliminary tests, samples were taken from another batch. The tests done on these samples indicated that 15% of sand should be added to 85% of old asphalt. The amount of cement needed was 5%. However, it was found during the laying that the crushed asphalt had a finer grading than had been supposed, and therefore only 4.5% of cement was added, partly on the basis of the previous experience.

The components were mixed in plant, using a concrete mixing plant fitted with a pugmill for mixing the components separately. The material dumped on the subgrade was spread and shaped with a grader and compacted with a vibrating roller having a static weight of 8.5 t. The investigations yielded the following results:

- The mean degree of compaction of the sand subgrade amounted to 100%, which met the requirement.
- Comparison between the grading of the crushed asphalt as determined in the preliminary tests and that found for the test section showed that the sample used for the preliminary tests was not representative and gave a low result.
- The mixing ratio suggested by the preliminary tests was achieved in practice with the method used for batching the components.
- The mean density of the crushed asphalt cement was 2052 kg/m$^3$ (s.d. 49 kg/m$^3$) in the north lane and 2105 kg/m$^3$ (s.d. 34 kg/m$^3$) in the south lane, the higher second value being due to the finer grading.
- Investigations of core samples showed a cement content of 4.5%, matching the amount of cement actually used.
- The mean ultimate compressive strength after 18 months was 3.6 MN/m$^2$ in the north lane (s.d. 0.7 MN/m$^2$) and 3.5 MN/m$^2$ in the south lane (s.d. 0.3 MN/m$^2$).
- The mean layer thickness was 26.5 cm in the north lane (s.d. 1.6 cm) and 25.3 cm in the south lane (s.d. 2.1 cm), i.e. a little more than the design value of 25.0 cm.
- The dynamic modulus found for the core samples was 12,400-16,700 MN/m$^2$ in
the north lane and 12,000-15,200 MN/m² in the south. These variations were due to the variation in the density across the thickness of the base-course.

- Visual inspection of the road about 18 months after construction revealed no reflected cracking.

It can be concluded that the method used here gives an excellent base-course or sub-base of crushed asphalt cement.

8.5 Conclusions

The results indicate that crushed asphalt cement gives an excellent base-course or sub-base that at least matches the conventional sand/cement mix in its strength and bearing capacity. The following conditions must be satisfied to obtain an asphalt/cement mix of good quality:

- The preliminary tests must be done on samples representative of the material planned for the construction.
- The materials must be carefully applied. A satisfactory batching of the components and the correct depth setting of the milling machine are very important, particularly when the ingredients are mixed in place.
9 Cold recycling of asphalt as unbound aggregate for base-courses and sub-bases

9.1 Introduction

As mentioned earlier, the term ‘cold-recycling’ covers all the methods in which old asphalt is re-used without heating. The asphalt broken up can be re-used directly on the site or first be treated in a plant, possibly with the addition of new material, and then laid. The old asphalt can be removed for instance by milling or by cutting out in slabs (which are then comminuted in a crusher elsewhere) or by breaking up and mixing with new materials in a machine. The asphalt obtained in any of these methods can be used as an unbound aggregate for base-courses or sub-bases. For this purpose, various materials can be admixed to it singly or in combination, namely sand, bitumen emulsion, rejuvenator, lime, and cement [71]. However, the residual value of the bitumen present in the broken-up asphalt is hardly utilized here if at all, as mentioned in Section 5.4.

Dallaire [65] has reported on a machine, the Midlandpaver, that removes a thin layer of broken-up asphalt and possibly the gravel course under it. A bitumen emulsion and other additives are admixed, giving an asphalt mix that is used for paving low-grade roads. However, no trials have been done with this method in the Netherlands. On the other hand, we have experimented with the use of crushed old asphalt for re-use in base-courses or sub-bases of pavements, using it in the form of:

- unbound crushed asphalt,
- crushed asphalt mixed with sand,
- crushed asphalt mixed with a bitumen emulsion,
- crushed asphalt mixed with sand and cement.

The use of the last form was described in Section 8, and the use of the other three, with which tests have been carried out in the Netherlands since 1975, are discussed below. No special attention is given here to the asphalt obtained by removing old pavements by milling; it is assumed that this material can generally be re-used in the same way as crushed old asphalt. However, it must be borne in mind that, in the case of hot-milled asphalt the material obtained is prone to caking, which opposes its satisfactory re-use and must therefore be prevented. Tappert and Brus [66] have reported in detail on German tests in which milled asphalt was re-used, possibly after an admixture of sand, solvent, emulsion or cement.
9.2 Tests carried out in 1975

9.2.1 General

The following five base-courses or sub-bases, including three made with old asphalt, were constructed in five 100-m-long test sections in September 1975:

I - sand/cement mix
II - mixture of crushed old asphalt and cement
III - unbound crushed old asphalt
IV - silex
V - crushed old asphalt with a bitumen emulsion

All these layers had a thickness of 35 cm. In the case of No. II, a 30-cm-thick layer of crushed asphalt was first applied and then stabilized with a 5-cm-thick layer of sand under it, giving a 35-cm-thick layer.

An asphalt pavement was always laid on top, consisting of two 6-cm layers of gravel asphalt and a 4-cm-thick layer of open-graded asphalt. Over part of test section I regenerated gravel asphalt was used instead of fresh gravel asphalt.

The tests have been reported before [23], and Gerardu et al. [67] have described in detail all the aspects of the work. Only the tests with crushed asphalt will be discussed below (the tests on crushed asphalt cement were described in Section 8).

9.2.2 Results of the investigations

The asphalt broken up was comminuted in a jaw crusher in a single pass. However, the grading of the crushed asphalt was very irregular, with somewhat too little of the fine fraction to satisfy completely the 0-40 mm requirement [35].

The contractor carried out some laboratory tests to determine the amount of bitumen emulsion to be added in the case of test section V. It should be remarked here that a jaw crusher is now considered less suitable for comminuting the asphalt than a hammer crusher, partly because it gives a less good grading and partly because the asphalt tends to cake in it, particularly in warm weather. The crushed old asphalt was mixed with an asphalitic bitumen emulsion in a mixing plant used for the preparation of cold-mix asphalt. In view of the apparatus and the materials, the batching of the asphalt and the bitumen emulsion was not perfect.

The crushed asphalt and the mixture of crushed asphalt and bitumen emulsion were
first compacted with a self-propelled vibrating roller having a static weight of 8.6 t. Determination of the dry density by the method with the use of carboxymethylcellulose (CMC-method) in situ gave a mean value of 1608 kg/m$^3$. The mean degree of compaction, based on the Proctor density, was 86.2% (s.d. 13.2%). Since this was on the low side, the test sections were re-compacted with one or more different rollers, whereupon the level of the base-course sank. A 25-t steam roller was also tried, which similarly produced a lowering of the level. This phenomenon had likewise been observed in Germany [66], where milled asphalt was used instead of crushed asphalt and had a different grading.

The samples of crushed old asphalt on which the Proctor density was determined were also used for tests according to the California Bearing Ratio (CBR) method at about 20 and 40°C with a load of 4.5 kg applied from above [111]. This gave 6-7.5 CBR at 20°C and 2.5-4 CBR at 40°C. Plate-bearing tests were also carried out on the test section, together with vibration measurements at certain points [68]. The test section made with crushed old asphalt alone showed both elastic settling and plastic deformation. The values followed a virtually linear course during the period of measurements, so that it was not possible to determine the final value; the material continued to suffer plastic deformation. Even if the low density is taken into account, it must be concluded that the base-course had a low stability, which furthermore depended on the temperature. Partly for these reasons, and partly because the road had to be opened to the traffic quickly, both sections made with crushed old asphalt were further stabilized with sand and cement. Test section V was stabilized with 5% of cement, and a thin layer of sand from the subgrade was introduced into the mixture by the method of mixing in place. In the case of test section III 7% of cement and sand was added to the unbound crushed old asphalt. On the basis of the results it was considered useful to investigate further the use of crushed old asphalt in thinner layers and if necessary mixed with sand.

### 9.3 Tests carried out in 1979

#### 9.3.1 General

Two base-course test sections, having the following characteristics, were constructed in May 1979 [68]:

<table>
<thead>
<tr>
<th>Test section</th>
<th>Material</th>
<th>Length</th>
<th>Width</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Crushed old asphalt</td>
<td>150 m</td>
<td>8.35 m</td>
<td>0.30 m</td>
</tr>
<tr>
<td>2</td>
<td>Crushed asphalt cement</td>
<td>170 m</td>
<td>11.15 m</td>
<td>0.25 m</td>
</tr>
</tbody>
</table>

An asphalt pavement consisting of an 8-cm layer of gravel asphalt and a 4-cm layer
of open-graded asphalt was laid on the base-course in both test sections. However, only the results for test section 1 will be discussed here, since those for the cement-bonded old asphalt were dealt with in Section 8. On the basis of previous tests (see Section 9.2), the crushed asphalt was mixed with 10% of sand in these test sections. Furthermore, the base-course was laid in two 15-cm-thick layers.

9.3.2 Results of the investigations

Some preliminary tests were carried out in the laboratory to find the correct ratio between the crushed asphalt and the sand. The best theoretical mixing ratio was determined on the basis of the sieve analysis of both components. The grading of various asphalt/sand mixtures was compared with the requirements for unbound aggregate base-courses and with the ideal grading on the basis of Fuller's best mix curve for 0-40 mm material [35]. A composition of 90% of crushed asphalt and 10% of sand was chosen on the basis of these investigations.

The crushed old asphalt was applied to the subgrade in a 16-mm-thick layer and levelled off with a grader. An asphalt-spreading machine was next used to place a 1.5-cm-thick layer of sand on top. The two layers were then mixed by way of milling twice, being wetted with water in between the two passes. The milling depth of the machine was set at 16 cm, in order to keep sand from the subgrade from being milled too. The layer of crushed asphalt/sand was then subjected to vibrating and static compaction with a Tramac vibrating roller having a static weight of 8.6 t. A second layer of the same thickness was then applied in the same way. However, the presence of fairly coarse fractions in the crushed asphalt affected the application of sand, the layer of which was therefore relatively thick in places, the mean value being 1.8 cm. The second layer of crushed old asphalt was also milled twice to a depth of 17 cm, to ensure a gradual transition between it and the first layer. The layer was again wetted with water between the two passes with the machine. When the surface was being shaped with a grader it was noticed that large pieces of crushed asphalt were being pulled out of the base course. Although these were pushed back again during rolling, the result was an open structure at the top of the base course.

Samples were taken both from the crushed old asphalt and from its mixture with sand, and the grading was determined on them. The sieve analysis was also done for some samples of the sand used. Comparison with the existing requirements [70] for unbound 0-40 mm aggregate for base courses showed that a large part of the samples satisfied these requirements, but the grading had a large scatter, and excessively large pieces were often found in the material. Many samples needed no sand admixture for a 0-40 mm grading. In general, the first layer of crushed asphalt had a better grading than the second. Calculations from the sieve analysis showed a ratio of
90:10 between the crushed asphalt and sand in the first layer, and a ratio of 95:5 in the second. The sieve analysis also indicated that the milling machine improved the homogeneity, for the crushed asphalt/sand mixture showed considerably less fluctuation in its grading than did crushed asphalt alone.

The density was measured both for the first layer and for the whole base-course after levelling off. The mean dry density and the mean degree of compaction for the whole base-course were respectively 1998 kg/m³ (s.d. 59 kg/m³) and 100.7% (s.d. 3.0%). The mean maximum density determined in the laboratory was 1985 kg/m³. The mean layer thickness was 29.8 cm (s.d. 1.9 cm). The maximum Proctor density and the optimum moisture content were determined for some samples in this set of tests. The usual Proctor test was used, with specimens measuring 15 cm in height and diameter. The compaction was done in three layers, each receiving 56 blows. The best moisture content was 6-7%. The degree of compaction was virtually the same for the first layer as for the whole base-course. The use of a relatively heavy vibrating roller on a 15-cm or 30-cm layer of crushed asphalt and sand probably means that, owing to the great striking force, mainly the subgrade was compacted, while the base course was not compacted enough. Plate-bearing tests were done a week and a half after constructing the test section (see Table 9.1). Furthermore, long-term durability tests were carried out at three points, and the results indicated a settlement of 5, 6.5, and 9 mm after a 10-min period under load.

Table 9.1  Results of the plate-bearing tests

<table>
<thead>
<tr>
<th>Measuring point No.</th>
<th>Force, N</th>
<th>$\varepsilon_w$, mm</th>
<th>$E_v$, N/mm²</th>
<th>Distance of measuring point from the start of the test section, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>15.000</td>
<td>0.850</td>
<td>53.5</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>15.000</td>
<td>0.480</td>
<td>94.8</td>
<td>30</td>
</tr>
<tr>
<td>3</td>
<td>15.000</td>
<td>0.575</td>
<td>79.1</td>
<td>50</td>
</tr>
<tr>
<td>4</td>
<td>15.000</td>
<td>0.425</td>
<td>107.0</td>
<td>70</td>
</tr>
<tr>
<td>5*</td>
<td>15.000</td>
<td>0.550</td>
<td>82.7</td>
<td>90</td>
</tr>
<tr>
<td>6</td>
<td>15.000</td>
<td>0.400</td>
<td>113.8</td>
<td>110</td>
</tr>
<tr>
<td>7</td>
<td>15.000</td>
<td>0.275</td>
<td>105.5</td>
<td>130</td>
</tr>
</tbody>
</table>

Notes:
1) Measuring point 5 was on a concrete bridge, where the asphalt/sand layer was 16 cm thick.
2) The tests were done with a stiff disc with a diameter of 300 mm, loaded with up to about 20 kN; the beam for measuring the deflection was 4.5 m long.

9.3.3 Conclusions

- Constant application of a force of 0.3 MN/m² to the crushed asphalt/sand base course for 60 min caused a creep of 5-9 mm.
The calculated value of the static modulus of elasticity agrees with that for a good subgrade.

The products of the asphalt crusher need careful control, and the particle-size distribution of the products must be closely monitored.

The sand to be admixed to the crushed old asphalt can be accurately applied to the spread crushed asphalt with the aid of the spreader. Another possibility is to mill some sand from the subgrade and mix it with the crushed asphalt. It must be possible to control accurately the depth of the milling. This of course applies only to the first layer of crushed asphalt.

The crushed asphalt and the sand are mixed by a milling machine in two passes. Water must be added after the first roller pass to ensure the best distribution of moisture and the best compaction.

The test section has been used by traffic only for a short time, and no special observations have been made.

9.4 Tests carried out in 1981

9.4.1 General

Previous test sections indicated a high creep for a base-course made with unbound crushed old asphalt (see Sections 9.2 and 9.3). The principal aim of one of the tests carried out in 1981 was to find out whether this caused rutting sooner, or to a greater extent, than is normal for conventional road constructions. Another aim was to compare the structural strength of unbound crushed asphalt with that of conventional base-courses made with materials such as lava.

The test section was constructed on a temporary exit slip road, which was considered a suitable location, apart from its somewhat variable gradient and width. It had been dimensioned only for about a year on the basis of empirical equivalent factors, so that any effects were expected to be manifested quite soon. However, it later turned out that the structural strength of the two sections had been overdimensioned, so that the service life was much longer than it was supposed to be. The base-course of the 100-m-long test section consisted of a 30-cm-thick layer of unbound crushed old asphalt, while the surfacing consisted of a 6-cm-thick layer of open-graded asphalt. A 60-m-long bituminous reference section was constructed immediately afterwards, using two 5-cm-thick layers of gravel asphalt and a surfacing of a 4-cm-thick layer of open-graded asphalt (this being the layer thickness to be laid down in the contract specifications for this project).

The exit slip road was in fact in use for 414 days, during which period the evenness of the surface was measured regularly with the aid of a transversoprofilograph, and a
traffic count was taken on the site. Dynamic deflection measurements were taken with the falling-weight deflectometer (FWD) both before opening the road and after the end of the 414-day period, and the stiffness of the crushed old asphalt and the subgrade was established from the results [110]. It was examined whether the crushed asphalt exhibited a structural decline at the end of the period, and the service life was determined in terms of equivalent 80-kN axles both for the test and for the reference section. The rut depth was found from the results of determining the cross-fall with a transversoprofilograph. A model for the rut depth [109] was then used to predict the service life of both sections on the basis of the rut depths measured on them.

9.4.2 Tests and results

As mentioned before, the test sections whose base-course was made of unbound crushed old asphalt and sand showed a permanent deformation. Since crushed old asphalt is structurally a reasonable alternative to stony materials such as lava and crushed concrete rubble, it was considered sensible to measure its creep. Laboratory tests were started to do this in comparison with crushed lava under a load, and the first preliminary results show that, under the test conditions used, lava exhibited a settling of about 2.5 mm that did not continue, and the crushed asphalt exhibited a continuous settling, the value of which was about 12 mm after 24 h [72]. The measurements on the test section were used to work out a model for estimating the permanent deformation [73]. While the investigations are still in progress, the following partly provisional conclusions can be drawn from the work done so far:

- The rutting measured on the test section could not be compared with that on the reference section (it was not appreciably greater than for a conventional unbound base-course).
- The unbound crushed asphalt had a higher structural strength than an unbound base-course under the same conditions.
- The stiffness modulus of the unbound crushed asphalt varied with the temperature and was hardly affected by the modulus of the subgrade, as in the case of lava or silex.
- This indicates that unbound crushed asphalt is an attractive alternative for lower-grade roads where the modulus of the subgrade is mostly low.

It should be emphasized that the traffic over the test sections had a strong tracking effect, so that it is desirable to repeat the measurements on test sections where the traffic has a normal tracking effect.
10 Hot in-place regeneration of asphalt (‘surface regeneration’)

10.1 Introduction

Various methods can be used for the maintenance and repair of bituminous road pavements, including the application of one or more layers of asphalt in the form of overlays, if the pavement structure makes this necessary. In some cases, however, the thickness of the pavement and the nature of the damage are such that the structure needs no reinforcement. This is the case when the problem lies in an insufficient skid resistance or a damaged surfacing.

As already mentioned, the economical use of valuable raw materials and the recycling of usable waste materials are a dual task confronting us in every field. In addition, some building materials such as bitumen have recently become much more expensive. These factors have led to the increasing use of the in-place recycling of the top layer of pavements, i.e. of ‘surface regeneration’ [11], which has the following variants:

1) Reshaping or reforming (thermal regeneration of the surface without any additions): Here the pavement surface is heated and rooted, the material is redistributed across the width if necessary, any excess material is removed, and the asphalt is rolled again. In any case, no new material is introduced. The main aim is to improve the geometry of the road.

2) Regripping (thermal regeneration of the surface, with the addition of fresh chippings distributed on the surface): Here the pavement surface is heated and rooted, the material is redistributed across the width if necessary, any surplus material is removed, and precoated chippings are sprinkled on and rolled into the surface.

3) Repaving (thermal regeneration of the surface including the addition of new asphalt over the existing surface): Here the pavement surface is heated and rooted, the material is redistributed across the width if necessary, any surplus material is removed, new asphalt is placed on top without mixing it with the old, and the road is rolled.

4) Remixing (thermal regeneration of the surface with the addition of new asphalt mixed with the old): Here the pavement surface is heated, rooted, and taken up into
the rooting machine, in which it is mixed with bitumen, bitumen emulsion, rejuvenating agent, aggregate, or new hot asphalt, after which the new mix is spread and rolled. In principle this can also be done in the cold state, but without the addition of bitumen and hot fresh asphalt (in this case it is of course not thermal regeneration). The mix is then used to construct the base-course of a new road.

A fair amount of experience has been accumulated in the Netherlands with thermal surface regeneration, and particularly with repaving, which will be described below.

### 10.2 Repaving

As mentioned above, this is a form of thermal surface regeneration in which new asphalt is added to the existing pavement, and possibly part of the latter is removed, the procedure being as follows (see also Fig. 10.1):

- The old pavement is heated with gas-burners.
- The heated old asphalt is rooted with tines.
- If necessary, the heated and rooted asphalt is redistributed across and along the road with a shaping blade and a spreader screw. It is also possible to discharge some of this old asphalt from the machine sideways to remove it from the road.
- A certain amount of fresh asphalt is introduced over the resulting surface, spread, and subjected to a preliminary compaction with the finisher smoothing beam of the spreading machine.
- The surface is then compacted in the usual way, and 2-6 mm chippings are sprinkled on it.

A Cutler Repaver, now the property of the Nederlandse Frees Maatschappij B.V. was used in all the Dutch tests reported below.

![Figure 10.1 The repaver train.](image-url)
This machine can do all the above steps in a single operation, except for compaction and the sprinkling of chippings (see Fig. 10.2). As far as we know, Wirtgen and Vögele repavers have also been tested in the Netherlands, the latter consisting of two separate working units. The results have not been published, but the international literature contains a number of descriptions [19, 77, 78].

Repaving can be carried out in the following three ways:

a Overlaying: The old asphalt is not removed at the side, but new material is added in an amount that will determine the height of the new road surface.

b Inlay: Some old asphalt is removed at the side and some new asphalt is added, the level of the new road surface being determined by the amounts of material removed and added.

c Removal: The old layer is removed in the first step and new asphalt is laid in the second as in overlaying. The level of the new road surface is again determined by the amounts removed and added.
10.3 Field tests

The repaver was used in 1975 to treat stretches of three highways, and the experience gained was reported in detail by Ganzeveld et al. [76]. The work was done with a Cutler repaver, imported from the USA in the same year.

There were some problems with the temperature control of the asphalt, and the surface obtained was not perfectly even; these problems have also been encountered elsewhere [19, 77]. However, the contractor at once remedied the defective stretches. On visual inspection in June 1982 the surface appeared the same as that of pavements of the same age laid by a conventional asphalt spreading and finishing machine (4-cm-thick overlay).

![Graph showing evenness of south lane of highway 263 between Breda and Tilburg in May-June 1981.](image)

Figure 10.3 Evenness of the south lane of highway 263 between Breda and Tilburg in May-June 1981.
The machine was then modified in a number of ways, so that the earlier problems are not expected to recur. Three further test sections were constructed on some highways in 1980 and 1981. Altogether 59,000 m² were treated, mainly by overlaying, and in places by the replacement method (which was necessary because of great differences in the longitudinal and transverse profile of the road at certain places). Fig. 10.3 shows an example of the surface evenness obtained, as measured with the aid of a viagraph (profilometer).

10.4 Results of the field tests

The following conclusions can be drawn from the field tests carried out so far.
- The evenness of the surface in longitudinal and transversal direction of the road must be carefully assessed first, and when the unevenness exceeds a certain value the surface must be pretreated.
- The temperature is generally an influential factor. The rooted old asphalt layer must have a temperature of 100-140°C almost over its entire depth. The new asphalt should also have a sufficiently high temperature.
- Continuity of the operation is generally very important.
- The amount of asphalt used is generally only half of that needed for conventional overlaying.
- Even if the temperature control is satisfactory, the compaction must be carried out directly after the use of the repaver, in order to obtain a good bond between the old and the new asphalt.

The overall conclusion is that under the conditions used here, repaving gives a pavement that is sufficiently compact, even, and skid-resistant, as well as having a composition that satisfies the requirements.

10.5 Economics and energy aspects

We have already seen that the repaving technique gives a pavement whose overall performance does not differ from that of a pavement obtained with the aid of a conventional asphalt spreader. To compare the economics of the two methods of pavement maintenance, we must consider three factors:
- the cost of the machine (repaver versus asphalt spreader),
- the amount of asphalt needed (e.g. 50 or 100 kg/m²),
- nature, area, and circumstances of the pavement to be treated.

Ganzeveld et al. [76] have compared the costs for a given set of circumstances (the main one being a fixed budget) in the case of 20,000 m² with a constant width. The
figures show that the overlay version of repaving using 50 kg of new asphalt per m² is financially competitive with overlaying with an asphalt spreader using 110 kg of asphalt per m². Repaving is even cheaper if the surface is to be treated over a variable width, i.e. only where needed.

The same authors [76] have also done some calculations and made some comparisons as regards the energy consumption, and found that if the energy consumption of conventional overlaying at a rate of 110 kg/m² is taken as 100%, then that of the repave process in its overlaying version at a rate of 50 kg/m² is about 65%. This of course applies to the weather conditions in the Netherlands. If the energy content of bitumen is also taken into account, the 65% comes down to about 50%. Foreign data lead to similar conclusions [79].

10.6 Fields of application

The repaving method can generally be used on bituminous pavements with the following defects [74-76, 80-82]:

- Insufficient skid resistance as the chippings become polished. If the asphalt surfacing has ‘fatted up’ or the surface dressings have worn smooth, it must be checked whether repaving can be employed.
- Insufficient evenness. For evenness in the longitudinal direction, a Cs value of 8% or more obtained by a viagraph is no longer considered acceptable. Transverse elevations exceeding 15 mm are similarly not permissible, nor are local depressions in the transverse profile that exceed 30 mm. Before repaving can be used in these cases the evenness must be corrected to below these values, either with the repaver or by milling.
- Damage to the surfacing made of dense asphalt. This happens when, owing to its age, the surface shows loss of material, mostly mortar and in places coarse aggregate.
- Damage to a temporary surfacing made of open-graded asphalt, characterized by the same phenomena as the last type of damage.
- Cracking in the surfacing. It must first be checked whether this occurs only in the surfacing (and sporadically in the binder course) and is not due to an insufficient bearing capacity of the road as a whole.
- Deformation of the surfacing. It must first be examined whether this is in fact restricted to the surfacing and whether repaving makes a layer sufficiently stable to carry the traffic without the appearance of new deformations.

There are also some general conditions: The damage must not be caused by an insufficient bearing capacity of the pavement construction. Before repaving it must
be ascertained that the road has an adequate bearing capacity. Repaving can of course also be combined with treatments aimed at reinforcing the pavement. Furthermore, the new asphalt mix constituting the surfacing must be suitable for the repaving method, i.e. it must have a) a sufficient thickness in relation to the thickness of the old layer to be rooted, b) a sufficient adhesion between the materials, c) a sufficient stability of the layer, and d) a sufficient flexibility of the binder present in the layer. If these conditions are not fulfilled, local treatment can be carried out to remedy the situation before the repaving.

10.7 General remarks

1) As already mentioned, the temperature is important for the success of repaving. This applies to the temperature of the surface to be treated, the temperature of the new asphalt, and the air temperature (to which must also be added some other weather conditions such as humidity and wind velocity). A constant regular forward movement of the repaver is of course also absolutely essential for good-quality work. The amount of asphalt to be used is about half of that involved in overlaying with an asphalt spreading machine when the latter is operated at the rate of 110 kg/m².

2) On the whole, the layer thickness applied is also only half, which means that the new asphalt must be of excellent quality. An incorrect composition can mean expensive corrective measures. The contractor must prevent the occurrence of such problems by using good process control in the production of asphalt and other building materials, this being even more important here than in the case of conventional methods.

3) Owing to the merging between the old and the new asphalt, it is not always possible to rely on the investigation of drilled core samples when determining the composition of the new asphalt. By modifying the specifications it may be stipulated that the mortar in the repaver hopper should be sampled and tested.

4) Drilled core samples with a diameter of 15 cm must be taken to ensure the correct determination of the compaction of the old and the new asphalt separately [76].

5) Before opting for repaving, one must establish whether the surface of the pavement is suitable for this measure, for example by measuring the evenness and if necessary by testing cylindrical specimens for quality of the asphalt.

10.8 Other methods of surface regeneration

As mentioned in Section 10.1, these methods include reshaping, reforming, and
regripping. However, it seems that these have not been tested in the Netherlands. Remixing has been used abroad [78, 82, 84, 85], but as far as we know only one test has been done with it in this country, and the results have not been reported. The machine used for it is essentially the same as the repaver, except that it also has a mixer for mixing the old and the new asphalt and some means for the proportioning and introduction of the binder (bitumen, bitumen emulsion, or rejuvenating agent). The information given here for repaving also applies to remixing, but the following important additional factors must also be considered:

- The old asphalt to be recycled must be appropriately heated, and this requires more energy than in repaving.
- The composition of the old asphalt must be determined accurately to decide on the new asphalt composition possibly for correcting that of the old asphalt. The penetration of the bitumen in the old asphalt to be recycled must also be determined here.
- The design characteristics must be established for the mixture of old and new asphalt. This can be done by the modified Marshall tests, as used in the partial recycling of asphalt in an asphalt plant (see Section 7.3).
11 Recycling old concrete

This comprises all the operations in which the old concrete is comminuted either on
the site or in a central plant, is possibly mixed with new materials and then re-used
e.g. for constructing aggregate-type base courses. It can also be used with or without
added sand or slag as an aggregate in the production of lean concrete, normal
concrete, or asphalt. Old concrete is recycled on a large scale in the United States,
France and Japan [18, 86, 87]. The criteria used in the cold recycling of asphalt (see
Section 5.4) will determine whether in-place or in-plant recycling will be chosen.

Hardened cement no longer acts as a binder in recycled concrete. Some of it goes into
the fine fraction on crushing, and some remains bonded on the surface of the coarses
pieces. This feature and the ratio between the two parts of cement have an important
effect on the properties of crushed concrete waste. As a result, the composition
depends to some extent on the particle size. The coarsest material has a density by
volume of about 2400 kg/m³ (about the same as that of the old aggregate), while the
finest one (mainly hardened cement) has a density by volume of about 2200 kg/m³.

It is therefore advisable to use parts by volume when working out the grading for the
aggregates or base-course material.

The sand fraction of crushed concrete generally has less favourable properties than
its gravel fraction, e.g. as regards strength and the absorption of water. Only the
coarse fraction obtained in the crushing of old concrete is therefore used when
demanding specifications are to be fulfilled.

The normal guidelines for new materials are generally used for the mix design, and
the material is also prepared and laid with the customary equipment.

Crushed concrete is usually regarded as a high-quality base-course material. In all
the countries that have tried it, the reports speak of considerable savings of cost and
energy, although precise data are not yet available.

Crushed concrete has not so far been used much as an aggregate in asphalt, but it is
used to replace sand and gravel in concrete on a large scale, particularly in the USA.
From the technical point of view, this substitution is possible with old concrete of any
quality, but up to 40-50 kg/m³ more of this recycled material are needed than of new
sand and gravel. The scheme is generally economic mainly if the old concrete is
available nearby (at the most 25 km away) [88], while the new mineral materials come from places situated 200 km or more from the site.

The Dutch experience with the recycling of old concrete is discussed in Sections 12-14.
12 Re-use of crushed concrete as unbound base-course and sub-base material

12.1 Introduction

Such recycling has now been done in the Netherlands for a few years, using concrete obtained in the breaking-up of pavements, or in the demolition of roads, other civil engineering constructions (such as bridges and viaducts) and buildings. The rubble is reduced to a 0-40 mm grading in fixed or mobile crushing plants, depending on the location of the demolition and construction sites and on the type of the construction in question [35]. Fig. 12.1 shows the lower and upper limits of this grading.

Unbound base courses are generally laid in areas prone to differential settlement, because the latter then does not lead to cracking. The resulting settlement admittedly makes the ride less smooth, but the pavement escapes serious damage.
Base-course aggregates must fulfil certain requirements as regards grading, density on the site, strength, and composition, these requirements being determined by the function of the construction.

### 12.2 Required properties

Aggregates with a 0-40 mm grading, approximating Fuller's curve [63, 89], are generally chosen for base- and sub-base courses for roads in the Netherlands. This requirement has a functional reason and must be fulfilled by crushed concrete as well. To ensure an adequate stability during laying and use, the existing specifications for the crushing performance must also be satisfied. It is still being investigated whether any requirements should be placed on crushed concrete as regards frost resistance (the absence of which leads to destruction) and susceptibility to frost, which causes heaving. The first results for the latter indicate that the current requirement for the composition of the material ensures an adequate behaviour in this respect. Since the moisture and frost sensitivity of base-course materials depends to a large extent on the percentage of fine particles (especially those smaller than 20 µm), this circumstance has been taken into account when laying down the specifications for the necessary grading.

So far it has been assumed that the crushed material consists only of concrete made with cement. However, it will often inevitably also contain small amounts of asphalt or masonry, with which it has been removed and comminuted, and these can adversely affect the properties, at any rate when present in considerable amounts. This applies mostly to a) weaker materials such as masonry, mortar and plaster, b) to materials that can cause a change in volume under the influence of moisture and frost (e.g. wood and clay), and c) to materials that can lead to deformation (creep), such as asphalt.

Weaker types of concrete made with cement may also fail to meet the requirements stipulated for crushed concrete granulate. Since the strength and the density of concrete are closely connected, the density of the concrete particles must also be above a certain minimum.

Now that we know more about the particle skeleton structure of materials with hard particles like crushed concrete granulate, and about the effects that materials a) – c) listed above have upon it, it has become possible to set an upper limit to their presence in the provisional specification. The behaviour of other weak materials during the laying of a base-course composed of crushed concrete granulate has also been taken into account. Furthermore, investigations particularly of a practical nature are still in progress, with a view to checking the current requirements for the composition.
No requirements have yet been laid down for the mechanical properties. This may be done in future by stipulating a certain CBR value or a dynamic modulus, but it requires further work.

12.3 Constructing the base-course

The crushed concrete is generally tipped on the site by trucks, distributed with loading shovels and compacted with vibrating or other rollers (the best rolling procedure must be found during the laying of the first 5000 - 10,000 m²). Satisfactory results have so far been obtained with vibrating rollers having a static force of 8-12 kN and a dynamic force of 10-15 kN, with which the material is compacted 3-5 times in the vibrating mode and twice in the static mode [35].

In the case of coarse materials the usual Proctor test is not sufficiently accurate, owing to a wall effect. We therefore chose a modified version in which the one-point Proctor density was determined. This is the density the sample reaches in standard compaction when enough water is added to produce a somewhat plastic mixture after thorough stirring [90]. The in-situ density was expressed as a percentage of this standard laboratory density, giving an idea of the density of the base-course. Investigations are still in progress in which various base-course aggregates are compacted by different laboratory methods, and the results are expected to be available in the near future.

12.4 Practical experience

12.4.1 General

As mentioned at the beginning of this section, the re-use of crushed concrete as an unbound base-course aggregate has been practised for a number of years in the Netherlands. Several test sections were constructed when investigating the possibilities involved here. These were located at the Gilze Rijen airfield, at the Valkenburg airfield, and on the Gaasperdammer road, connecting highways A1 and A2. The specimens taken from these test sections were subjected to laboratory investigations to ascertain whether the crushed concrete had met the requirements. The results were as follows:

- The grading amply met the 0-40 mm requirements on all three sites.
- The density varied in the range 1900-2060 kg/m³, and the moisture content in the range 4-7%. On the basis of the one-point Proctor density test, the degree of compaction was 101-105%. 

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The crushing factor of the old concrete was 0.78-0.80, considerably higher than the required minimum (0.65). This surpasses the values for two other comparable base-course aggregates, namely blast-furnace slag and lava, used in the Netherlands, for which the corresponding values are about 0.73 and 0.65.

The crushed concrete used at the two airfields had come from the breaking-up of runways, aprons, etc. This material contained little contamination and easily met the requirements. By contrast, the material used along the Gaasperdammer road had come from various demolition sites, and its composition did not satisfy the specifications, since it contained too much asphalt. Despite this, it was still used, in view of the favourable experience obtained previously with such material in tests in the city of Amsterdam.

Also some field tests were carried out consisting of plate-bearing tests and measurements with the FWD; the latter will be continued for quite a long time to monitor the performance of the test sections.

Official contract specifications were then drawn up for the crushed concrete [112] on the basis of the experience gained with the three test sections and on the basis of laboratory tests carried out at the same time.

The results already indicate that crushed concrete is an excellent base-course material, qualitatively comparable with blast-furnace slag. It can therefore be used for laying an unbound base-course under roads of any kind. It was used in some projects on a number of highways in 1982, and the first results will be reported later in this section.

12.4.2 Specific aspects of the three test sections

a) Gilze Rijen Airfield [91]

A take-off runway extending in the east-west direction was rehabilitated at the airfield of Gilze Rijen in the summer of 1980. The old runway was broken up and the concrete from it was comminuted and re-used as a base-course for the new runway. The concrete lumps broken up, the maximum dimension of which was 50 cm, were taken to a mobile crusher standing on the same site, in which the large pieces were comminuted to a 0-40 mm grading. During the execution of the work measurements were carried out over a 50 × 50 cm section, giving the following results:

- The sand subgrade was not dense enough: its mean degree of compaction was only 95.2% of the maximum Proctor density, which is appreciably lower than the required 100%.
- The grading of the crushed concrete amply fulfilled the 0-40 mm requirement. The mean particle-size distribution is shown in Fig. 12.1.
- The density of the base-course, determined by the sand method [35], was on average 2059 kg/m³ (s.d. 33 kg/m³), and the corresponding moisture content was 4.4% (s.d. 0.33%). The degree of compaction amounted to 108% of the maximum Proctor density determined in this project.
- The mean crushing factor of the old concrete was 0.79.
- Since there was a surplus of crushed concrete, it was used in a mean layer thickness of 26 cm instead of the specified 20 cm.

b) VALKENBURG AIRFIELD [92]

Take-off runways, landing strips, taxiways, aprons, etc. were rehabilitated at the airfield in Valkenburg in 1981. The concrete broken up was reduced to the 0-40 mm grading in a crusher on the site, and the crushed concrete was re-used to construct an unbound base-course for the new construction. During these activities some tests were done on the sand subgrade and on the base-course under one of the taxiways, the overall construction of which had the following characteristics:

- 2 × 4 cm of dense asphalt,
- 5 cm of open-graded asphalt,
- 2 × 6 cm of gravel asphalt,
- 25 cm of crushed concrete granulate.

Under part of the taxiway the base-course was constructed in two layers (section A), and under the rest in one layer (section B). The lengths were respectively 60 and 50 m and the widths 16 m in both cases. Tests gave the following results:

- The prepared sand subgrade was not dense enough, the mean degree of compaction reaching only 92.8% of the maximum Proctor density, instead of the required 100%. This may be due to the poor quality of the sand, its insufficient thickness (50 cm), and the weak soil below it.
- The mean density of the base-course, again determined by the sand method, amounted to 1904 and 1928 kg/m³ for the two sections. The moisture content was around 7%. The degree of compaction was 101.3% in one section and 104.3% in the other, with respect to the one-point Proctor density. Since we wanted to quantify the effect of the compacting equipment on the crushed concrete, we also determined the density of the uncompacted material. This came on average to 1834 kg/m³, which means a degree of compaction of 98.8%.
- The grading of the crushed concrete amply fulfilled the requirements in both sections. The mean curves for the two sections are shown in Fig. 12.1, indicating a good agreement between them.
The layer thickness was very different in the two sections: the mean value was 28 cm in section A, while even a thickness of 43 cm was measured in Section B. The reason for the deviation from the contract specifications is not known. The greater layer thickness in section B may be due to the greater degree of compaction found at the top of the layer.

Since mostly crushed concrete was used, the composition was not investigated.

c) GAASPERDAMMER ROAD [93]

In view of the quality of the sand of the subgrade, the contractor was advised to construct an unbound stone base-course for this road, the overall structure of the latter being as follows:

- 4 cm of dense asphalt 0-16, type C,
- 6 cm of asphalt, made with 57% of gravel,
- 6 cm of the same,
- 25 cm of base-course.

The specifications stipulated 0-60 mm silex or 0-40 mm crushed lava, but 200-m long test section was also constructed with 0-40 mm crushed concrete granulate. This material came from a commercial crushing plant consisting of a jaw crusher and a gyratory crusher and processing rubble not only from old roads but also from other demolition sites. In this test section both the subgrade and the base-course were tested, giving the following results:

- The mean degree of compaction of the sand subbase was 99%, which is below the required 100%.
- The initial test showed that the manufacturer could not entirely meet the requirement about the maximum amount of asphalt permitted in the concrete rubble, which was set at 5%. The initial test indicated 8.4%, but it was still decided to use the material for this test, because favourable results had in the meantime been obtained in Amsterdam with old concrete having asphalt contents of up to 20%.
- The material had the right grading, as can be seen from the mean values shown in Fig. 12.1.
- The density of the crushed concrete rubble, measured by the sand method, was on average 1999 kg/m³ (s.d. 64 kg/m³), the corresponding moisture content being 6.5 wt-% (s.d. 0.6 wt-%). The degree of compaction was expressed here as a percentage of the one-point Proctor density and was found to be 103.4% (s.d. 3.2%), the mean one-point Proctor density being 1925 kg/m³ (s.d. 15 kg/m³).
- The crushing factor of the old concrete was 0.80, which is considerably higher than the required value of 0.65.
- The thickness of the base-course was determined at nine places with a layer-
thickness measuring device, which gave an average value of 25.4 cm (s.d. 1 cm), just above the prescribed 25 cm.

12.5 Large-scale use in projects

Crushed concrete granulate was used in three projects in 1982 and at the beginning of 1983. The experience and the test results obtained here can be summed up as follows:

- The grading of the crushed concrete granulate need not cause any problems, for the required grading can be obtained with suitable equipment, possibly in conjunction with a set of screens.
- The crushing factor was 0.75-0.80, thereby satisfying the requirement (minimum 0.65).
- The proportion of contaminants, including asphalt, can cause problems. This of course depends on the origin of the old materials, on the care taken in its removal and separation from subsequent asphalt overlays, and on the operation of the crushing plant. When assessing the proportion of contaminants, possibly by visual means, large enough samples must be used, weighing a total of 20 kg to obtain representative results.
- If the work is done well, the use of crushed old concrete causes no problems in practice.
13 Crushed concrete granulate as an aggregate for asphalt

This has not yet been studied extensively, unlike the use of crushed concrete in new cement concrete, to be discussed in the next section. The composition and properties of crushed concrete were outlined before, and the material must also meet some specific requirements for use in asphalt. If it is intended for use as the main component in an amount of over 95% (see Section 14), porous or weak types must be ruled out. This stipulation reduces the loss of bitumen by absorption into the aggregate. Since only 5% of other types of aggregate material is allowed, the amount of weak materials such as broken brick is limited. The amount of bituminous material should here too be below 1%, because bitumen burns in the drying drum and a larger amount is bad for the quality of the asphalt that is being prepared. Finally, contaminants that are sensitive to frost and moisture (e.g. wood) should be kept within the same limits as in the case of new concrete.

Asphalt mixes made with crushed concrete have so far been studied only in the laboratory. In the first tests asphalt was prepared with a 2-32 mm crushed concrete instead of with gravel. The rubble came entirely from the gravel concrete used in the pavement of an airfield. The material amply fulfilled the requirements for the Marshall properties laid down in the case of gravel asphalt [35]. Owing to the porous structure of the crushed concrete, the void content of the asphalt was considerably higher (about 7-8 vol-%) than in the case of gravel asphalt. However, tests in which the material was subjected to freezing and thawing cycles did not show any unwanted influence of this on the durability. Adhesion of the bitumen to the crushed concrete was tested on Marshall tablets kept in water for some time. The drop in the Marshall stability that resulted from this pretreatment was about the same as that found for gravel asphalt, so that the adhesion of the binder seems to be equally sufficient.

Although crushed concrete is more porous than gravel, the asphalt mix incorporating it will need virtually the same amount of bitumen. As asphalt mix containing crushed concrete and 4.5% of bitumen showed a deformation of 7.3% after about $10^5$ wheel passes in a tracking test, and so its resistance to rutting amply met the specification for asphalt made with gravel. However, the stiffness modulus was only about 5 MN/m², the creep test having been done at 40°C with a load of 0.1 MN/m² and a load time of 60 min. The tensile strength was fairly high at low temperatures, being 1.8 MN/m² at 10°C, but the values at higher temperatures were about the same as for asphalt made with gravel (0.2 MN/m² at 40°C). The polishing stone value (PSV) was 61-66, which amply met the specifications.
Crushed concrete granulate that had a grading of 2-32 mm and contained about 10% of old asphalt was used in a second series of tests. The crushing percentages easily met the requirements for gravel and – except for the on-fraction of the C22.4 screen – also the requirements for chippings. The fraction retained on the C11.2 screen contained 2-6% of rounded unbroken material. The Marshall test showed that there was some crushing of the coarser components of the crushed concrete granulate in this test series. This may be due to loss of adhesion of parts of the hardened cement from the old aggregate. Further work is needed to find out the extent of this phenomenon in the preparation and laying of asphalt in practice and its effects on composition of the mixture under those conditions.

In a third series of tests, crushed concrete was used to replace all or part of the gravel in asphalt made with gravel, and all or part of the chippings in open-graded asphalt. In the case of the former, the results were comparable with those obtained in the first two series. In the case of the open-graded asphalt, however, the replacement of chippings with 2-16 mm crushed concrete raised both the Marshall stability (at an unchanged value for the flow) and the void content from about 3 to 8-9 vol-%. The increase in the Marshall stability that occurred when chippings were replaced by crushed concrete shows that this material indeed has a high level of strength.

As mentioned earlier, the increase in the void content of the asphalt in due to the porous structure of crushed concrete and need not have an adverse effect on the properties of the asphalt produced.

These laboratory tests show that it is in principle possible to use crushed old concrete for all or part of the coarse fraction of both asphalt made with gravel and open-graded asphalt. However, more work must be done on the mechanical properties and the behaviour in practice before final conclusions can be drawn. The investigations should be extended to explore the possibility of using crushed old concrete also in the fine fractions. The possibility of using it in open-graded and dense asphalt will also be studied in more detail.
Concrete finds limited use in Dutch road-building for making cycle paths and some municipal and provincial roads. However, it may again become an attractive alternative to asphalt if it is placed on a subsoil with a good bearing capacity, in view of the steep rise in the price of bitumen, especially since 1979. The attraction is not only economical, because the technical design of concrete roads has been greatly improved in the last few years, mainly on the basis of experience gained in other countries. In fact, concrete can now be used for heavily trafficked motorways, with the advantage of low maintenance costs during the design life of the road. These technical and cost considerations have recently rekindled the interest in the use of concrete for road-building purposes, which in turn raises the possibility of replacing all or part of the sand, gravel, or chippings in concrete by crushed old concrete. To see if this appreciably affects the quality of the resulting concrete, it was decided to examine the properties of the recycled material.

Crushed old concrete must first of all meet some precise requirements concerning its composition, which were laid down in the following form on the basis of extensive investigations [95]: at least 95% of it must come from old concrete made with gravel, and its granular form must have a dry density of at least 2100 kg/m³. The other 5% can come from other stone or mineral materials such as masonry rubble, but the amount of old asphalt in it must not exceed 1%, since asphalt greatly reduces the compressive strength of the concrete. The other restrictions on the composition concern contaminants that have an adverse effect either on the binding and hardening of cement (e.g. organic substances) or on the durability of the concrete (mainly materials like sulphates and wood that cause swelling). These requirements have been published in the form of a product standard [113].

These constraints are basically the same as those placed on sand and gravel [96]. Concrete rubble produced when a road is broken up generally does not contain contaminants in amounts in which they could be harmful. However, the situation is entirely different in the case of concrete rubble coming from houses and other buildings, where it must be ascertained that the material contains less than 1% of sulphate, less than 1% of organic materials, not too much carbonates, etc. In doubtful cases the concrete rubble is extracted with water and the extract is used for the Vicat test (binding of the cement) and for the determination of the strength of the cement. The results should not differ by more than 15% from those obtained in a reference test with clean water. It should be added that a visual inspection of the
crushed rubble fraction larger than 8 mm gives a rapid and generally reliable indication of the contaminations.

As has been seen in Section 11, the density by volume of crushed concrete depends on the particle size. The lightest (and weakest) components are mainly found in the sand fraction. Various authors have shown [94-96] that, when crushed concrete is used to replace only the coarse mineral aggregate in new concrete made either with gravel or with chippings, the effect on the strength is fairly small, the compressive strength, the tensile strength, and the stiffness modulus being reduced by at the most 5, 10, and 15%, respectively. If the sand is also replaced with crushed concrete then these figures become respectively 15, 20, and 40%. Such values were obtained for concrete mixes with corresponding mineral composition in parts by volume, the same cement content, and the same slump (workability). New concrete made with crushed concrete waste also had a higher creep (at most 40%) than concrete made with gravel.

The density by volume of the crushed concrete fractions used gives the most reliable indication of the expected strength of new concrete, the relationship between them being linear at a constant cement content [94, 95]. As we have seen in the last two sections, crushed old concrete is generally more than sufficiently strong to meet the required values for the crushing factor and the crushing percentage. However, its particle strength is lower than that of sand and gravel, because only about 70% of this material is quartz, the rest being hardened cement. The substitution of crushed concrete rubble for sand and gravel can raise the amount of cement needed especially for higher-grade concrete by an amount that varies with the quality of the hardened cement component and can be up to about 50 kg/m³. Since the crushed old material is angular, more cement and more water are needed than in the case of a rounded material such as gravel. It is an important difference that crushed concrete is more porous than natural mineral aggregates, again because of the hardened old cement in it. The porosity has a number of consequences. Thus, crushed old concrete can take up and release up to about 5% of water. Therefore, to prevent premature loss of water during application, the crushed concrete must first be wetted, as must light aggregates.

The ability to absorb and release water can lead to a higher creep, and indeed under laboratory conditions the creep was twice as high for concrete made with crushed old concrete as for concrete made with gravel. In practice, however, the variations in the moisture content of a cement concrete road pavement are so small that no measurable differences are found. After placement, a pavement made of concrete containing crushed concrete rubble must be cured, and so protected from drying out, in the same way as a pavement made with concrete containing fresh gravel or chippings.
The porosity is also expected to reduce the resistance to frost and de-icing salt. To examine this point, new concrete made with crushed concrete was placed on a cycle path. The mix consisted of 65% of 3-30 mm crushed concrete, 35% of concrete sand, and 365 kg of Portland cement A, the water/cement ratio being 0.47. Core samples were drilled out of the pavement after 28 days and tested for resistance to frost and de-icing salt (the specimens had a 28-day compressive strength of 44 MN/m$^2$). After 40 freezing and thawing cycles the concrete showed about the same loss of material as the reference concrete made with gravel, the two values being 0.11 and 0.13 kg/m$^2$, respectively. The risk of surface scaling under the influence of frost and de-icing salt is therefore no greater with concrete made with crushed concrete rubble.

The porosity of crushed concrete rubble also has an advantage: it makes for a high resistance to polishing; it has a polishing stone value (PSV) of 60-66, which is higher than that for e.g. Dutch chippings. Therefore, this similarly does not oppose the use of this material in surfacings.

Although in principle the same grading range is open for crushed concrete as for sand and gravel [98], it is more economic – because of the cement content – to use a somewhat narrower range if fractionation is carried out. At the lower limit of the existing Dutch specifications [97] the mixture obtained is too stiff, while the upper limit is unsuitable owing to the rather high cement requirement of the fine fraction. We have therefore arrived at the same grading range as that specified in the German Standard DIN 4163 in the 1950’s for the recycling of rubble [99]; this Standard was later withdrawn, because there was not enough suitable rubble for this application. To obtain the best grading it is advisable to compose the recycled material from at least two fractions. This is economically feasible, since the rubble is crushed and screened in any case. In fact, this process can be so regulated that the utilized proportion of the rubble is maximized.

In view of the high compressive strength requirement for concrete roads (at least ‘B 37.5’; representing a characteristic of at least 37.5 MN/m$^2$), it is advisable to stipulate an upper limit for the water/cement ratio and a lower limit for the cement content. This also prevents the placement of excessively wet mixtures, which can suffer segregation, thereby reducing the quality of the wearing course and hence its resistance to wear and tear. For these reasons, the concrete should not be more than semi-plastic. To achieve this and to ensure a good workability, it is best to use a super-plasticizer. If this is incorporated, no air-entraining agent is needed to raise the resistance to frost and de-icing salt, which is an advantage, since the air-entraining agent has an adverse effect on the strength.

New concrete made with crushed concrete can be placed with the usual equipment.
Compaction, which must be done by a machine, naturally requires more power than in the case when rounded aggregates such as gravel are used. Designing a concrete pavement incorporating crushed concrete is basically the same as designing concrete pavements containing other aggregates.

The results discussed so far, most of which had been obtained in the laboratory, were subsequently confirmed in practice. A great deal of experience has since been accumulated, especially in the construction of airport pavements in this manner. Thus, the material was tested at the Volkel airbase, using 80 vol-% of 0-40 mm crushed concrete rubble and 20 vol-% of sand, mixed in place with 80 kg/m³ of blast-furnace cement. The compressive strength of the product was 20% lower than that of a corresponding lean concrete [100]. Some test sections were constructed in the same place in 1979, using mixtures with the following compositions [101]:

85-90 vol-% of crushed concrete rubble (grading: 0-31.5),
10-15 vol-% of concrete sand,
350 kg/m³ of Portland cement A,
a super-plasticizer.

The consistency was the same as that of liquid concrete. Like the latter, the mix was difficult to work, owing to the angular aggregate it contained. As mentioned before, this indicates that the material should not be more than semi-plastic. The 28-day compressive strength with 10 and 15% of concrete sand was respectively 20 and 10% lower than in the case of the reference mix (concrete made with gravel), for which the value was about 45 MN/m².

Concrete made with crushed concrete rubble was also used for constructing a taxiway and an apron at Maastricht Airport in South Limburg in 1981 [102]. The rubble came from breaking up the dispersals at the airport; it was comminuted in a mobile crushing unit on the site and screened into a 0-15 mm and a 15-30 mm fraction. The specifications asked for a quality of ‘B-37.5’, with a maximum water/cement ratio of 0.43 and a minimum cement content of 350 kg/m³. A super-plasticizer was also stipulated, and the material had to be not more than semi-plastic. The requirements were amply fulfilled with the following mixture:

15-25 vol-% of concrete sand,
40-60 vol-% of crushed concrete rubble of a 0-15 mm grading,
25-35 vol-% of crushed concrete rubble of a 15-30 mm grading,
380 kg/m³ of Portland cement A,
a super-plasticizer.

After maximum compaction, the mixture even reached a ‘B-45’ quality.
The economic aspect of such re-use of old concrete depends on the savings and the extra costs, the most important ones of which are as follows:

- cost of transporting the concrete rubble, as against the cost of transporting the conventional aggregates,
- cost of crushing and screening the old concrete,
- additional storage of material in the preparation of the concrete mortar,
- cost of pre-wetting the concrete rubble,
- possibly higher cement content than in the case of concrete made with gravel or chippings,
- higher compaction energy than in the case of rounded aggregates,
- less material is needed per m³ (the concrete rubble has a relatively low mass),
- saving on natural raw materials,
- saving the charges of tipping that would otherwise be needed for disposal of the rubble.

Calculations have shown that, at the spring 1982 cost level, there was no significant difference between the production cost of 1 m³ of concrete made with crushed concrete rubble and that of 1 m³ of concrete made with gravel.
15 Recycling clinkers and other stone and mineral materials

15.1 Introduction

We shall discuss here the re-use of the following materials for road-building:
- clinkers,
- broken bricks,
- slag (both blast-furnace slag and phosphate slag),
- crushed lava,
- silex,
- others (tiles, kerbstones, copper-slag stones, and sand cement).

Little has so far been published on the re-use of these materials, and the following discussion deals mainly with laboratory investigations.

15.2 Clinkers

Road pavements made of clinkers can reach a point where they no longer satisfy the requirements mainly as regards evenness and skid resistance. In the first case they can be directly re-paved, provided they are sound. In the second case, their surface can be roughened by a special technique, thereby making them sufficiently skid-resistant again for some time. Another possibility is to remove them, turn them over and put them back again, provided they all have the same shape. Finally, they can be reduced to a size of 0-40 mm and re-used as a base-course and sub-base material.

Apart from having the right grading, the material
a) must have a sufficient crush resistance
b) must not be susceptible to moisture (which causes a volume change) and must be sufficiently frost resistant (have good weathering properties)
c) must contain only limited amounts of the other materials present in clinker hardcore (either weak stones or other materials).

From the point of view of dimensioning, it must be established what contribution 0-40 mm of crushed clinker in the base-course and sub-base makes to the overall pavement structure.

No tests have yet been done on heavily trafficked roads. In the first test in 1983, a highway was reconstructed and the clinkers under its asphalt pavement were re-used.
as base-course or sub-base material. Crushed clinker has been used on a small scale as aggregate for asphalt mixes, giving similar results to those obtained with broken brick.

15.3 Broken bricks

The same considerations apply to the re-use of broken bricks as a base-course or sub-base material. Rubble mostly consisting of broken bricks was tested in the laboratory to see if it can be used as a mineral aggregate in asphalt mixes capable of replacing asphalt made with gravel [103, 104]. The aim of the preliminary part of the work was to establish the mechanical properties of the resulting asphalt mix on the basis of Marshall tests and the creep test [105]. The aim of the second part was to determine the performance of the asphalt in a wheel tracking apparatus and to subject it to a diametral splitting tensile test.

The Marshall test was first done on a sample having the same composition as gravel asphalt, according to the existing requirements [35], but the gravel was replaced by broken brick, the mineral component of the asphalt consisting of:

- 57% of coarse aggregate with a particle size greater than 2 mm
- 37% of sand in the particle-size range between 63 μm and 2 mm, and
- 6% of filler with a particle size smaller than 63 μm.

The bitumen content (4.5% on 100% of mineral aggregate) was also the same for the test composition. However, the bitumen did not provide a good coating for the brick particles, and in addition the mixture looked very dry. It was finally necessary to raise the bitumen content to 6.5% (again on 100% of mineral aggregate). Marshall tests were carried out with this mix, as well as with mixes containing 6.0 and 7.0% of bitumen, all three of which met the requirements for Marshall stability, Marshall flow and the Marshall quotient. However, the mixes had a void content of 19-22%, higher than the permitted maximum for gravel asphalt. This void content was partly due to the pores in the broken brick, so that it need not have an adverse effect on the mechanical properties of the asphalt. The results of the creep test showed a large scatter, and therefore it was not possible to choose an optimum bitumen content.

Despite the high bitumen content and the high void content, the investigations were continued with the sample containing 6.5% of bitumen (on 100% of aggregate) as having the best composition. Test mixes were made up in the laboratory, and these were in turn used to make two test plates, specimens of which were taken for testing in the wheel tracking apparatus [28] (resistance to permanent deformation) and for
the creep test. The tensile strength was measured indirectly by means of the splitting
tensile test.

The results indicated a relatively high resistance to permanent deformation under
the dynamic strains used in the tracking apparatus and—though to a smaller extent—
under the static strains used in the creep test. The tensile strength was greater by a
factor of 2-3 than that of porous asphalt and did not compare unfavourably with
dense and open-graded asphalt.

The samples were subjected to a limited number of freezing and thawing cycles,
which caused no visible damage. The Marshall specimens were also used to deter­
mine the degree of crushing of the broken brick as a result of compaction with the
Marshall hammer. The broken-brick fraction retained on a 2-mm screen initially
amounted to 57%, while the value after testing, extraction and screening was only
about 50%, the rest having been crushed by the treatment [106].

Figure 15.1  Asphalt made with broken bricks. The specimen was tested in the wheel tracking apparatus
and then sawn through to reveal its cross section.
Although the mechanical properties indicated by the Marshall tests and the wheel tracking test seemed reasonable, the material was not suitable for use in practice, especially owing to its high bitumen requirement and high void content. The high bitumen content can be seen from Fig. 15.1, showing darker rings of absorbed bitumen at the edges of the porous broken-brick component.

Groot and Vooght [107] have described some fatigue tests carried out on plates derived from a test section constructed in a municipality, using asphalt that contained broken brick as the aggregate and 8% of 45-60 pen bitumen. The results indicated that a 17-cm thick layer of this asphalt was equivalent to a 10-cm thick layer of asphalt made with gravel.

15.4 Slag, crushed lava and silex

Base-courses and sub-bases consisting of slag, crushed lava, or silex are easy to re-use when the road is broken up. These materials are already often recycled for base-courses and sub-bases and in temporary pavements for diversions and by-passes. If the road is broken up in such a way that contamination with sand does not exceed 5%, the materials in question can be re-used as base-courses and sub-bases, using the same guidelines as those that apply to new materials. However, one should aim at a 0-40 mm grading for unbound aggregates, and this may require some additional operations. Thus, hydraulic material may necessitate crushing to the right grading, possibly followed by sieving, and the addition of a missing fraction. There is no general rule for predicting the extent of residual hydraulicity, and binding can occur again to some extent. The method of re-use discussed above is fairly simple and is probably employed quite often, although no publications are known to us on this subject.

15.5 Other types of stone materials

As mentioned earlier, these are tiles, kerbstones, copper-slag stones, and sand-cement. These materials can in principle be re-used either in their original form, by replacement, or in some other form, such as a base-course or sub-base after crushing. The crushed form can theoretically be used as unbound base-course or sub-base material with a 0-40 grading, or as an aggregate in making asphalt. However, laboratory investigations and if necessary practical tests must first be carried out. The former are currently in progress on the use of sand cement for the bound base-course or sub-base in a certain project, while the field tests are scheduled for 1984.
Recycling of pavement materials began to be studied in the Netherlands about 10 years ago, and is now important in the construction and maintenance of all types of roads.

Ten years of investigations and practical experience have shown that the re-use of road paving materials can become very important, mainly for the maintenance and rehabilitation of existing roads.

The main method for recycling asphalt is *hot regeneration*, which can be done either by the Renofalt process or on a partial basis (in which case 15-30% of the mix is made up of old asphalt). The Renofalt process was largely developed in the Netherlands, mostly for large-scale production.

The special feature of the *Renofalt process* is that the asphalt broken up from the road is reduced to granulate by a steam treatment, and these are then dried and heated. The next step is the batchwise addition of a rejuvenating agent. Some sand is added in advance if the bitumen content of the old asphalt makes this necessary. It is possible to ensure a constant quality for the end product by using a suitable preliminary test procedure and visual assessment for establishing the composition of the old asphalt in advance. This is the case despite the variations in the properties that can occur in the old material, and despite the fact that old asphalt makes up over 90% of the regenerated asphalt. The production control is based on frequent determination of the Marshall properties on samples mixed in an asphalt plant, and on the determination of the bitumen content by the nuclear method. The moisture content of the material and the properties of the binder in it are also determined fairly regularly. The regenerated product is laid in the same way as new asphalt.

About 300,000 t of asphalt have so far been regenerated and laid in the lower layers on a very heavily trafficked part of a highway, and tests have shown that the mechanical properties – deformation and fatigue behaviour – of the regenerated material are not inferior to those of new asphalt.

However, the Renofalt process requires a large capital investment, and the number of plants using it is unlikely to increase in the near future. On the other hand, the existing plant will probably continue producing regenerated asphalt of different compositions for various projects if a) the composition of the old asphalt is established visually and if necessary by laboratory tests before the pavement is
broken up, and b) if the material is handled and stockpiled selectively enough, to prevent appreciable contamination. Under optimum conditions, Renofalt asphalt is about 15-20% cheaper to make than new asphalt. The applicability of the method depends on economic factors, and particularly on the distance over which the material has to be transported.

Fully regenerated asphalt has so far been used only for constructing lower layers (base-courses and sub-bases). For this, nearly all types and grades of old asphalt lying within the currently specified limits are suitable, but steaming does place a restriction on the size of the lumps of old asphalt. If a size of $30 \times 30 \times 30$ cm is exceeded, the steaming requires a disproportionate time and energy, while if the material is too fine, such as milled asphalt, it absorbs a large amount of moisture. It is in principle also feasible to use the Renofalt process for making material for bituminous binder courses, but the amount of angular aggregates in the old asphalt can be a constraint, necessitating a meticulous selection of the old asphalt.

We must still find out how far the regenerated material can meet the more rigorous requirements concerning the mechanical properties, but it already appears that this consideration makes application for surfacings unlikely. For the latter we could only consider old surfacing material in the form of slabs (not milled), but we do not expect a large supply of such material.

Separate specifications have been drawn for the 100% asphalt regeneration, in view of the many and great differences between the methods of producing new asphalt in the Netherlands. These specifications include a number of main points of the production process, the requirements that old asphalt must meet as a building material, the procedure of the preliminary tests, the production control routine, and the required properties of the end product.

The specifications were examined after the production of 300,000 t and modified on some minor points. It is hoped that these specifications will ensure a continuity in the use of the Renofalt process. Certain aspects are still being investigated, namely the efficiency of the addition of the rejuvenating agent, the latter's performance in the long term (for example the susceptibility of the regenerated asphalt to ageing), and hardening of the binder during production.

About 500,000 t of partially recycled asphalt have been made by the Minnesota process since 1980 and applied in lower layers. This method is very similar to that used in the Netherlands for the preparation of new asphalt with batch mixers. The old asphalt is reduced in a crusher and overheated new minerals at 250-300°C are added to it in a weigher or a mixer. The components are dry-mixed for 10-20 sec, during which time the new minerals heat up the old asphalt. After this, filler and fresh bitumen are admixed. The total mixing time is 5-10 sec longer than in the production of new asphalt.
The basic requirement here is that the recycled asphalt must at least match new asphalt destined for the same application as regards its quality, i.e. its strength, homogeneity, bearing capacity, and durability. The mechanical properties have therefore been investigated in a number of test sections in addition to the usual parameters normally examined for acceptance. The results show that the basic requirement mentioned above is amply fulfilled when recycled asphalt is compared with new gravel asphalt.

Some specifications have been drawn up for this partial recycling on the basis of its extensive use in practice in the intervening years. These specifications are now used in road building contracts.

The composition of the old asphalt and the properties of its binder must be determined in the preliminary tests to establish the correct ratio between the old asphalt and the other components. The preliminary test procedure is therefore modified on a few points. This applies particularly to the preliminary Marshall tests (in which the old bitumen must not be damaged) and to the method of determining how much fresh bitumen is to be added.

All types and grades of old asphalt that lie within the existing specifications are in principle suitable for this kind of recycling. The final percentage of old asphalt in the end product is determined mainly by the properties of the bitumen and the moisture content of the old asphalt. If the latter is low, owing to storage under dry conditions, the old-asphalt content of the mix can be raised considerably. This amount is generally between 15 and 30%; the actual figure can be chosen on the contractor’s recommendation, based on the preliminary tests. However, a low figure such as 5% or less is generally not sensible for technical and economic reasons.

The production control is based on the Marshall tests, the determination of the composition, and regular determination of the binder properties and the amount of moisture present. The partially recycled material is laid in the same way as new asphalt. The specifications also comprise a procedure for the contractor to prove (if this has not been done before) that the method used by him gives an asphalt that meets all the requirements. This is done by constructing and assessing a test section. The results will depend not only on the quality of the end product but also on the suitability of the temperature and moisture content during production and on the degree of protection of the old bitumen from undue heating.

Of the approximately 90 asphalt plants now operating in the Netherlands about 30 have since been modified for the partial recycling of old asphalt. There is also a rapid increase in the number of projects in which this process is specified. The method is economically very attractive, offering up to 15% of savings in comparison with the use of new asphalt.

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The use of the partially recycled asphalt mix for bituminous binder courses also seems a possibility, but the requirements for example for grading, binder properties and aggregate content may restrict the amount of old asphalt that can be incorporated in such open-graded asphalt. This subject will be investigated in 1984.

In view of the functional requirements laid down for surfacings, it is much more difficult to use old asphalt for them in the same proportions as for lower layers, unless the old surfacing is broken or milled out selectively and stored in the same way.

A third method has recently been tried on a small scale for the hot recycling of asphalt, in which about 50% of crushed old asphalt is added to new materials in a drum mixer. The mixer length and diameter have been adapted to the regeneration process: the old material is introduced far enough from the heater to prevent the bitumen from burning. More work is being planned for a full assessment, but the first tests seem promising.

The Dutch experience with hot regeneration of asphalt in place (surface regeneration) has so far been confined to the repaving procedure. In this case the surface of the pavement is heated, rooted, and redistributed, any surplus material is removed, new asphalt is applied to the still hot material, and the whole is compacted.

The initial problems concerning the temperature control and the evenness of the surface have since been solved, and some specifications have been drawn up on the basis of the recent results [83]. It has been found that the repaving method is often economically more attractive than other methods aimed at the improvement of surfacings, but high specifications concerning quality must be satisfied in the use of this method.

Good results have also been obtained in the treatment of rutted road surfaces with the aid of methods very similar to the repaving process in their execution. These methods will probably gain ground as more equipment becomes available for their implementation. It is still unclear to what extent this applies to the other methods of surface regeneration. However, remixing, in which the hot rooted surfacing is mixed with new asphalt, will probably be also tested in the Netherlands in view of the good results obtained with it elsewhere. By contrast, cold surface regeneration, in which a rejuvenating agent is sprayed onto the surface, is not considered suitable under the Dutch conditions for technical and practical consideration.

The cold recycling of asphalt utilizes less of the original value of the material than does hot regeneration. Furthermore, tests have shown that, when crushed asphalt is used as an unbound base-course or sub-base the deformation characteristics are unfavourable and the bearing capacity decreases, so that this approach can be
considered only for very lightly trafficked road. The use of crushed asphalt as a bound base-course or sub-base is considerably more promising. The application of a bitumen emulsion with or without sand for this purpose has not yet been examined in detail, but the addition of cement has been widely studied in practical applications. In this case the mix consists of 85-90% of crushed asphalt, 10-15% of sand, and 4-6% of cement. Since both the old bitumen and the fresh cement affect the mechanical behaviour, a lower design compressive strength may be sufficient than in the case of other hydraulically bound stone base-courses or sub-bases.

The bearing capacity and the fatigue life are comparable with those of a sand/cement mixture, but the susceptibility to cracking is considerably lower. Specifications have been drafted for this method, and these have been used with good results for laying base-courses or sub-bases consisting of cement-bound crushed asphalt, for example for heavily trafficked motorways. It is estimated that about 200,000 m² of cement-bound old asphalt with an average layer thickness of 25 cm have been laid. The actual laying can be done by the use of the conventional methods; mixing in place offers low transport costs, and mixing in plant offers a better quality of the mixed product.

The reason why this method utilizes less of the original value of asphalt compared to hot regeneration is that the recycled material must be used in a layer thickness 2.5 times the normal to reach the same bearing capacity. Cement-bound crushed asphalt is economically most attractive when its transport cost is minimal and all the old asphalt removed from the pavement can be re-used in this way.

The method of re-use should be selected before the pavement has been broken up. The required data about the composition and the properties are then obtained in advance, and both the selectivity of removal and handling and the size of the lumps are best adjusted according to the envisaged re-use. Contamination of the asphalt with other materials must always be kept to a minimum. The requirements concerning the composition, which have been drawn up, should be observed in this connection. The same applies to other pavement materials, such as crushed concrete.

Most of the experience with the re-use of concrete relates to its comminution in a crusher into granular 0-40 mm material and to the application of this as an unbound base-course or sub-base. The existing specifications for the latter can be used here to ensure good quality even for heavily trafficked roads.

Crushed concrete granulate is a strong material that is not sensitive to frost or moisture and has a higher bearing capacity than many natural stones used for base-courses and sub-bases. For less heavily trafficked roads one can also use mixtures of crushed concrete, ordinary bricks, and clinkers. About 2 million tonnes
of material are re-used annually in this way. The rubble can come not only from old roads but also from the demolition of houses and other buildings. The applications are economically very attractive.

Some work has also been done, though only on a limited scale, on the use of crushed concrete as an aggregate in the production of new concrete. This gives a very high quality concrete that meets all the functional requirements. To achieve high qualities of concrete, corresponding to 'B 37.5'' and higher, it may be necessary to use up to 40 kg/m³ more cement than when new natural aggregates are used; the exact figure will depend on the quality of the old aggregate and of the hardened cement. Specifications have been prepared for this application as well.

The use of crushed concrete as an aggregate in asphalt mixes is still being investigated. The questions to be answered here concern the bitumen requirement and the mechanical properties.

The material forming unbound base-courses and sub-bases, for instance clinkers and sand, can often be re-used as such.
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