

Abridgment

Design of an Open-Graded Binder Course for Subsurface Pavement Drainage

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The pavement of a freeway recently completed in São Paulo, Brazil, included a layer of hot-mix open-graded binder course designed mostly for subsurface drainage. The problems encountered and the solutions used in the design and construction are discussed. Revised specifications for open-graded binder course for pavement drainage and a method of density testing developed for design and construction control of open-graded asphalt mixes are presented.

The pavement design of Rodovia dos Bandeirantes, a six-lane 90-km (56-mile) freeway recently completed by the state of São Paulo, Brazil, included a layer of hot-mix open-graded binder course mostly for subsurface drainage (see Figure 1 and note the pen provided for scale). The pavement structure has a total thickness of 62 cm (24.4 in) that includes 6 cm (2.4 in) of dense-graded asphalt concrete, 8 cm (3.1 in) of open-graded binder course, 15 cm (5.9 in) of cement-treated granular base, 13 cm (5.1 in) of graded crushed stone base, and 20 cm (7.9 in) of selected soil subbase, [California bearing ratio (CBR) > 30] as well as 0-80 cm (31.5 in) of final grading course (CBR > 12). The principal functions of the binder course are

1. To drain out any rainwater that eventually infiltrates the pavement through thin cracks or minor faults,
2. To contribute structural support by spreading the load on the treated base, and
3. To absorb retraction forces and reduce reflection cracks from the treated base.

To accomplish these functions, the binder course is made of an open-graded hot mix of hard crushed stone and low-penetration asphalt cement that has a maximum size of 19-38 mm (0.75-1.5 in). The compacted mix has a void rate of about 30 percent.

MIX CHARACTERISTICS

Aggregates

The aggregates used were crushed stone from local quarries, mostly granitic, and some basaltic rock. Four grading specifications were used and tested for the binder course:

1. A--British Standards (BS:1621)--38 mm (1.5 in),
2. B--British Standards (BS:1242)--25 mm (1 in),
3. C--NCHRP Synthesis 30 (1)--25 mm, and
4. D--NCHRP Synthesis 30--19 mm (0.75 in).

The four gradations are really very similar and have only small differences in maximum size. The granulometric curves are almost vertical; they define essentially "one-size" aggregates that have an effective maximum size of 19-38 mm. Other requirements for aggregates are the usual ones for asphalt mixes, such as sound and clean matrix rock, Los Angeles wear-test results below 40 percent, and the best possible fragment form. Actually, it was not possible in this project to obtain crushed stone that had less than 30-40 percent noncubical (lamellar or elongated) fragments from the available quarries, even by using the best crushing equipment.

Asphalt

The binder used was 50/60 penetration asphalt cement to give adequate stability to the binder course. The asphalt content in the total mix was between 2.4 and 2.7 percent.

CONSTRUCTION

The conventional construction method for asphalt concrete was used in the binder course. Hauling required special attention to the cleaning of the trucks. While it was still hot, the layer received an initial compression with a light tandem roller; this was followed by compaction with variable-pressure tire compactors and then finished, again with a tandem roller. In a few sections a heavy self-propelled vibratory smooth roller alone was used after static initial compression and before vibratory final compression. The results were very good.

Heating and mixing temperatures were the usual for hot mixes. Rolling temperature, however, was much lower for binder course than for conventional asphalt concrete. The maximum temperature for the initial compression varied between 80 and 100°C (170-212°F), depending on actual grading, asphalt content, and air temperature. At higher temperatures, the uncompacted layer did not present enough stability to support the weight of the rollers, which resulted in reduced thickness and an uneven profile. The temperature of final rolling was between 50 and 60°C (122-140°F).

Compaction at these lower temperatures presented no great problem. Some pickup of aggregate particles by the roller tires occurs at the beginning of rolling, but it is of little significance. As the rolling continues, the loose particles are gradually incorporated into the surface and the pickup ceases. A tack coat applied later further binds the surface particles in place.

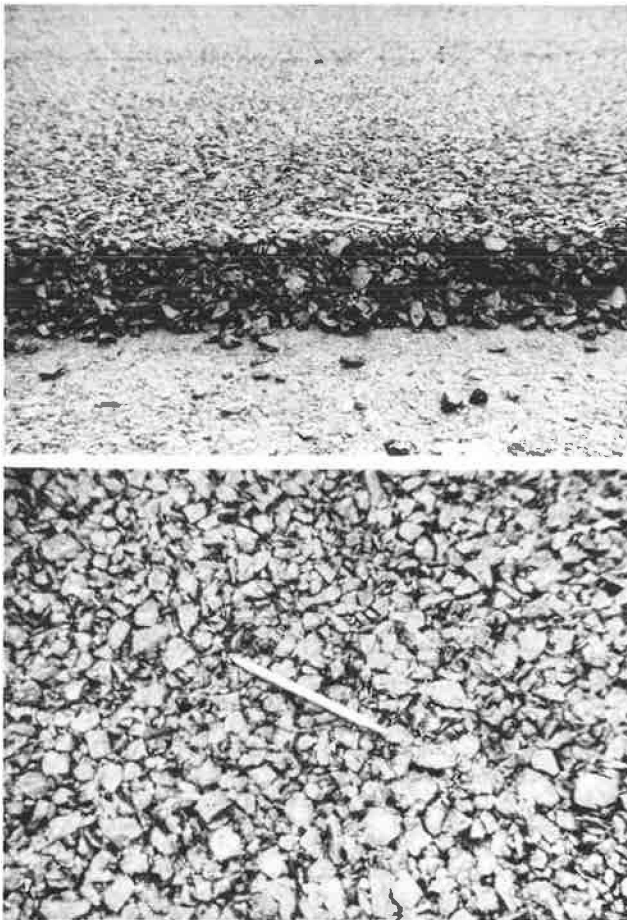
On the first or second day after construction, the surface still moves slightly under the foot action of a person standing on the binder course. This movement ceases completely after two or three days. When needed, a complementary rolling on the second day was used with good results, especially after some sun warming. The finished binder course is left to cure for a period of 7-15 days, after which a tack coat is applied and the asphalt concrete rolling course is laid. The binder course should not be left exposed for more than 15-20 days to avoid clogging by dust or earth carried by wind or construction traffic.

TECHNOLOGICAL CONTROL

The technological control methods for materials and the construction process are generally the same for the binder course as for asphalt concrete except for compaction control.

Sample extraction by rotary drilling of the compacted layer requires great care because sample specimens fall apart easily. Density testing of samples also requires special care and is not

Figure 1. Close-ups of binder course, side and top view.



practical for routine control.

For asphalt-content tests, the Soxhlet apparatus proved to be most reliable. However, granulometric analysis of the aggregate after asphalt extraction was unreliable because of the small size of the samples. The best method of obtaining larger aggregate samples for granulometric analysis was to make a dry run on the mixing plant, feeding aggregates as in normal operation but without asphalt.

EXPERIENCE OF GRADING SPECIFICATIONS

Coarse gradations of maximum size from 25 to 38 mm (1-1.5 in), used at the beginning, caused some problems of segregation, fragment breakage on rolling, harsh finishing, and surface disaggregation under construction traffic. Finer gradations of maximum size from 19 to 25 mm (0.75-1 in) eliminated all these problems and gave much easier handling and better finishing. Permeability tests showed no significant reduction of drainage capacity on the finer gradation.

It was felt, however, that the maximum size of 19 mm (0.75 in) was too small for the desired layer thickness of 8 cm (3.1 in). To achieve a better balance and also lower production costs, a somewhat larger size would be preferable. A compromise solution was proposed: Binder course thickness was reduced, and the asphalt concrete thickness was increased proportionately to maintain the same structural capacity.

Based on the experience of this project, a re-

vised grading specification is recommended for a 5-cm (2-in) thick binder layer (see inset of Figure 2). An aggregate that has this gradation can be produced as a single crusher product that passes through a 25-mm (1-in) screen and is retained in a 9.5-mm (0.38 in) screen (see Figure 2).

MIX DESIGN METHODS

Asphalt content of open-graded mixes is not so critical as that of dense mixes. There is large void space to accommodate a little excess of asphalt, which eventually settles on the bottom without surface bleeding. A lack of asphalt is more detrimental because it affects the cohesion and workability of the mix. Therefore, the optimum asphalt content should be on the rich side.

Specific-Area Method

The specific-area formula proposed by M. M. Duriez for cold mixtures was modified to apply to aggregates that had 100 percent passing a 50-mm (2-in) sieve and less than 5 percent of fines passing a 2.0-mm (no. 10) sieve. The modified formula is as follows for aggregate specific area:

$$S = 0.01(7 + 0.07P_1 + 0.19P_2 + 0.48P_4 + 1.89P_{10}) \quad (1)$$

where

- S = specific surface area (m^2/kg),
- P_1 = percent passing 25-mm (1-in) sieve,
- P_2 = percent passing 12.5-mm (0.5-in) sieve
[or, alternatively, 1.10 x percent passing
9.5-mm (0.38-in) sieve],
- P_4 = percent passing 4.8-mm (no. 4) sieve, and
- P_{10} = percent passing 2.0-mm (no. 10) sieve;

for asphalt content in percentage of aggregate:

$$p' = 3.5 \sqrt[5]{S} \quad (2)$$

and for asphalt content in percentage of total mix:

$$p = 100 p' / (100 + p') \quad (3)$$

The results obtained by this formula were remarkably accurate for such a simple method. For the gradations used, the asphalt content calculated by the specific-area formula ranged between 2.4 and 2.7 percent, which agreed fairly well with other methods and with construction practice.

Marshall Method

The Marshall method of mix design is not applicable to open-graded mixes. The molding of test specimens by dynamic impact in the Marshall apparatus, even with only 50 blows per face, causes considerable aggregate breakage, which affects the mix conditions. It is almost impossible to extract the specimens from the mold. Most samples fall apart during extraction or soon afterward at room temperature.

An alternative method is to calculate the density by measurement and weighing of samples inside the Marshall mold without extraction. Specimens compacted with 50 blows on each face gave density values comparable with those obtained in samples drilled from the road and close to values obtained by static compression.

Static Compression

Although it is not really a design method, static

Figure 2. Recommended binder gradation.

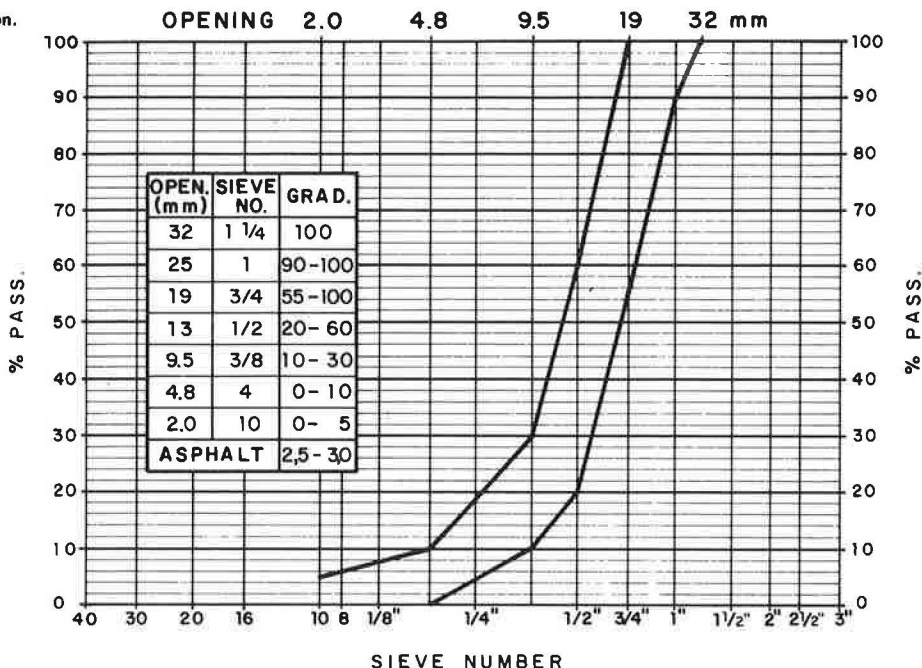


Table 1. Density of static compression samples.

Gradation	Asphalt Content (%)	Maximum Density (g/cm ³)	Average Density (g/cm ³)	Void Rate (%)
A	2.6	2.63	1.78	32
B	2.7	2.62	1.83	30
C	2.7	2.62	1.78	32
D	2.9	2.61	1.78	32

It is very important that all mixtures be prepared at the same temperature, preferably at 150°C (302°F). A difference of ± 15°C (27°F) in mixing temperature can produce an error of ± 0.4 percent in asphalt content design. For the same reason, plant-run mixes that have a fixed asphalt content may appear rich or lean when the plant temperature varies by ± 15°C.

Glass-Plate Method

The glass-plate method was a verification check developed in this project to be used in connection with the mixing-pan method. The procedure is the following.

1. Spread 500 g (about 1 lb) of each of the previously prepared mixes on a thick, transparent glass plate 30x30 cm (12x12 in).
2. Cool the plates at room temperature for 1 h.
3. Raise and fix the plates in an upright position.
4. Observe the adherence of the mixes to the plates. (Lean mixes drop down in a few minutes; rich mixes adhere much longer.) The optimum asphalt content should keep the mix in place for at least 0.5 h.
5. Observe the plates by transparency from the reverse side. The optimum asphalt content should present no bleeding or free asphalt on the plate.
6. Adjust asphalt content accordingly.

DENSITY TESTING

Density testing of open-graded binder course by sample extraction from the road with diamond rotary drilling is very difficult and requires special care. The regular testing procedure that used 10-cm (4-in) sample cores proved unreliable; many cores disaggregate or break up in drilling, especially in the coarser gradations. Water used for cooling the drill penetrates the sample. After extraction, many samples deform or fall apart when left to dry at room temperature for a few hours before dry weighing. Also, paraffin coating, used for water weighing, penetrates large surface voids and affects density calculation.

compression is a useful process of molding specimens for density and permeability tests.

In an extensive series of tests, specimens 10 cm (4 in) in height by 15 cm (6 in) in diameter were molded at various temperatures in CBR cylinders under a static load of 7000 kPa (1000 lb/in²) applied for 2.5 min. Density values were calculated by measurement and weighing of the samples inside the molds.

Density and void rate results were independent of gradation, asphalt content, and molding temperature. Density values were very close to those obtained from road samples. This series of tests confirmed field experience that compaction temperature is not critical for this type of mix. Table 1 shows the average results obtained by static compression.

Mixing-Pan Method

The trial "mixing-pan" method for asphalt content design was the most reliable. The procedure is as follows:

1. Prepare a series of trial mixtures in an open pan, starting with a low asphalt content of 2 percent and increasing by 0.2 percent in each mix;
2. Compare the visual aspect of the mixes side by side, increasing in order from lean to rich;
3. Determine the lowest asphalt content that completely covers the aggregate particles with a continuous film, without any free asphalt; and
4. Add 0.4 percent to obtain the optimum asphalt content.

Table 2. Permeability tests of static compression samples.

Gradation	Void Rate (%)	Hydraulic Flow [(L/min)/cm ²]	Permeability Coefficient (cm/s)
A	32	0.20	1.50
B	30	0.25	1.72
C	32	0.21	1.58
D	32	0.15	1.13
Avg	32	0.20	1.48

Figure 3. Infiltration test on binder course surface.



A special procedure for binder-course density testing was developed in this project, as follows.

1. Extract cores by using a 15-cm (6-in) drill; use low speed and as little water as possible. Use great care to avoid breaking the samples.
2. Immediately after extraction, wrap thin adhesive tape around the lateral face of each sample.
3. Let the samples dry for a few hours in inverted position (top down) at room temperature, protected from direct sunlight.
4. Apply adhesive tape or a thin impermeable paper disc to the top and bottom of each sample.
5. Weigh samples without removing tapes. Estimate tape weight. Disregard tape volume.
6. Paint samples with a light coat of warm paraffin that is applied over the protecting tape with a brush.
7. Determine the volume by dry and immersed weighing.
8. Discount paraffin and tape weight. Compute density as usual.

Some average results of samples extracted by this method at the end of the project are shown below.

Gradation	Density (g/cm ³)	Void Rate (%)	Compaction Rate (%)
C	1.87	26	102
D	1.77	30	101

RECOMMENDED COMPACTION SPECIFICATIONS

The recommended compaction specifications for open-graded binder course are the following:

1. Compaction rate of 95 to 105 percent of density obtained in the Marshall test with 50 blows per face and
2. Void rate computed by the theoretical maximum density of 25 to 30 percent.

PERMEABILITY TESTS

A direct measurement of surface permeability on the road was not possible because of the high drainage capacity of the binder course. For comparative purposes, the permeability of Marshall and static compression specimen series was measured under constant hydraulic head and steady-flow conditions for the four gradations used. Both series show little influence of gradation in the coefficient of permeability. Table 2 shows some results of permeability tests for 15x10-cm (6x4-in) specimens with hydraulic head at 7 cm (3 in).

CONCLUSIONS

The major findings and recommendations of this study are the following:

1. The thickness of the binder course may be reduced to 5 cm (2 in).
2. A recommended gradation specification is indicated in the first text table.
3. The best method for asphalt content design is the mixing-pan followed by a glass-plate verification check.
4. The best method for gradation control tests is the dry run.
5. Special care is required for density and void rate tests.
6. The recommended compaction specification is 95-105 percent of 50-blow Marshall test.
7. Compaction temperature is not critical. Recommended compaction temperature is relatively low.
8. Heavy vibratory pneumatic compactors are the most efficient.
9. Binder permeability is very high for all open gradations tested.

ADDENDUM

A new study of binder course density was recently done on Rodovia dos Bandeirantes after one year of heavy traffic by the method described in this paper (see Figure 3). The average results found in this study for gradations C and D are included below.

Test	Average	Standard Deviation
Asphalt content (%)	2.8	0.25
Density (g/cm ³)	1.93	0.09
Void rate (%)	27.1	2.32

Densities and void rates after one year are in the same range as those found at the end of construction. So far there is no evidence of significant increase in compaction as a result of traffic.

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