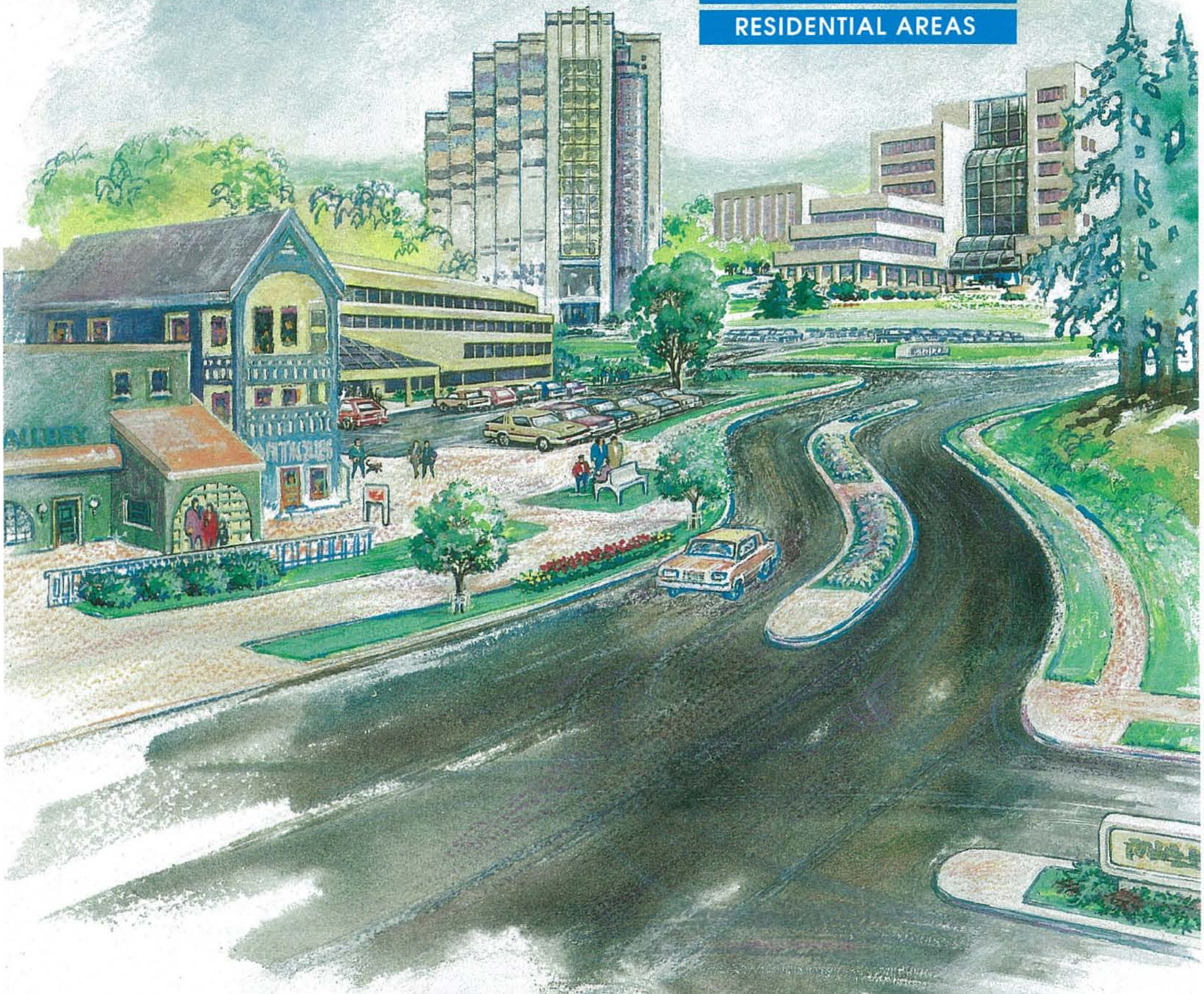
Design of Hot Mix Asphalt Pavements

For Commercial, Industrial, and Residential Areas



NAPA

NATIONAL ASPHALT PAVEMENT ASSOCIATION

Information Series 109

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This publication is provided by the members of the National Asphalt Pavement Association (NAPA), who are the nation's leading Hot Mix Asphalt (HMA) producer/contractor firms and those furnishing equipment and services for the construction of quality HMA pavements.

NAPA Members are dedicated to providing the highest quality HMA paving materials and pavements, and to increasing the knowledge of quality HMA pavement design, construction, maintenance and rehabilitation. NAPA also strongly supports the development and dissemination of research, engineering and educational information that meets America's needs in transportation, recreational and environmental pavements.

This publication is designed to provide information of interest to HMA specifiers and is not to be considered a publication of standards or regulations. The views of the authors expressed herein does not necessarily reflect the decision making process of NAPA with regard to advice or opinions on the merits of certain processes, procedures or equipment.

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Design of Hot Mix Asphalt Pavements

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FOREWORD

This manual is published by the National Asphalt Pavement Association (NAPA) as an aid to designers. All reasonable care has been exercised in its preparation; however, NAPA makes no claim as to its accuracy. It remains the responsibility of professional designers to correctly interpret and verify the information presented.

The design procedure presented in Part Two is based on the following published methods of pavement design; the procedure was derived from these methods but has been modified for the purposes of this manual: *AASHTO Guide for Design of Pavement Structures*, 1986, published by the American Association of State Highway and Transportation Officials. *Thickness Design — Asphalt Pavements for Highways and Streets*, 1984, (Manual Series MS-1), published by the Asphalt Institute.

The National Asphalt Pavement Association

The National Asphalt Pavement Association (NAPA) is the national trade association for Hot Mix Asphalt (HMA) producers, paving contractors, and associated firms. In addition to a membership representing every state in the United States, NAPA has international member firms in 22 nations.

NAPA is a non-profit organization committed to developing and promoting quality in asphalt pavements. Supporting an active program of research and development, NAPA has published an extensive list of manuals on asphalt paving technology as well as health, safety, and environmental topics. NAPA conducts a continuing and well-attended training program courses and seminars for its member firms and works cooperatively with federal and state agencies in joint of paving material and design research efforts. NAPA's engineers serve on a number of technical committees and task forces, and representatives of public agencies participate in NAPA's meetings and committees.

Membership in NAPA is a mark of leadership among firms involved in the Hot Mix Asphalt industry, and the Association's commitment to excellence reflects the concerns of the member firms themselves.

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INTRODUCTION

This publication presents a method for designing Hot Mix Asphalt (HMA) pavements for parking lots, storage yards, low-volume roads, and other areas which are not subject to abnormally large or frequent overloads and for which traffic counts are often estimated. It describes alternative layer systems and construction strategies which may obtain better quality, economy, or construction efficiency, depending on the circumstances of the project. Fundamentals of specifying asphalt mixtures are also explained, and recommended tolerances and construction guidelines are provided as an aid to the specifier.

This book is intended for use by consultants, corporate engineers and architects, construction management firms, and contractors. If you are among these groups of users, it is likely that the paved area you are designing is not a separate project, but belongs to a larger enterprise involving one or more vertical structures and representing a major financial venture. If so, the scheduling, construction time, and coordination of the paving with other activities are important design considerations which affect financing and business opportunity costs.

PART ONE addresses these time-related factors in terms of their influence on the selection of materials and construction methods. It discusses certain alternatives and techniques in terms of their efficiency, quality, and cost, and it explains how paving mixtures should be specified and monitored for quality assurance purposes. A checklist of items to consider is found at the end of Part One.

PART TWO presents the structural design procedure which covers both full-depth asphalt and multi-layer systems. It provides methods for classifying soils and traffic loads and for determining thicknesses required for either layer system. Variables to consider in comparing alternatives are discussed, and examples are used to explain and clarify the procedures.

PART THREE contains technical guidelines for designing and specifying pavements, based upon concepts introduced in Parts One and Two. Utilizing the soil and traffic classifications in Part Two, it covers mix design criteria, recommended test methods, and acceptance limits for subgrades and pavements. A glossary of technical terms and a list of references on related subjects are also provided.

How to proceed

The crucial phase of any design process is not the collecting of data nor the steps of plugging them into formulas and tables. It is developing one's acquaintance with the concepts and choices involved. Although some topics presented here will be useful for quick reference, most of this manual is intended to provide a working knowledge of HMA pavements which will assist the designer in identifying alternatives and choosing among them. It is recommended that all sections of the text be read by those involved in designing and specifying pavements.

Project information. In addition to obtaining data on soil properties and projected traffic, the designer must be cognizant of the topography and drainage plan, subsurface drainage and groundwater, the average depth of frost penetration, and the proximity of base and paving materials to the site.

Constraints which may be imposed by seasonal or environmental restrictions, other construction activities, or a need to maintain access should also be identified. Above all, the designer needs to be well informed of the owner's wishes and future plans, which determine the design period of the pavement and the feasibility of the stage construction approach explained in Part One.

Comparing alternatives. The design period, soil data, and projected traffic are used to determine layer thicknesses for the alternatives considered, which may then be compared in terms of their costs and special advantages. Estimated in-place prices of Hot Mix Asphalt and any unbound base materials or subgrade treatments being considered will be needed for this phase. An important concept advanced in this manual is the importance of basing cost estimates and material selection on project-specific knowledge as opposed to conditions assumed to be typical. This is because haul distances, local materials, mobilization, and other site-related variables have large effects on paving costs. The advantages of alternate bid items and negotiated contracts are discussed, and designers are encouraged to make early contact with local contractors to obtain valid cost data and information on local materials.

A note on terminology

Hot Mix Asphalt (HMA) is known by many names, both colloquial ("blacktop") and technical (see glossary.) Other terms refer to specific types of HMA, such as asphalt base, open-graded friction course, sand asphalt, and so on. In the interest of establishing a common term not easily confused with other paving processes or with materials which contain coal tar, the industry and many major users have adopted "Hot Mix Asphalt" and its acronym to identify their product. This policy has been followed in this publication, except where a specific type of HMA is mentioned.

PART ONE: SELECTING AND SPECIFYING THE STRUCTURAL ELEMENTS

A shopping mall had been open less than three years when an area of closely spaced cracks appeared in one section of the parking lot. The surrounding pavement was unaffected, and the cracks followed no pattern related to traffic flow or construction. Around the cracks a residue of light gray silt could be seen where water had risen to the surface. Uphill from the affected area was a landscaped traffic island with shrubbery irrigated by sprinklers. The subgrade was a fine, cohesive soil, fairly strong at low moisture content but spongy when saturated and of low permeability. The pavement design had called for three inches of Hot Mix Asphalt over a six-inch granular base. The base layer, a crushed granite, was the source of the silty residue.

As is true of most early pavement failures, the cause was not in the pavement itself but in the supporting layers. The permeable base layer had become a conduit through which a large volume of rainwater and irrigation runoff, trapped between pavement and subgrade, migrated to the area downhill. There it was confined, keeping the soil saturated and unstable, and damaging the pavement during freezing cycles. A more successful design might have included a system of subdrains, a different type of base, or both.

Design of durable, trouble-free pavements involves more than layer thicknesses. The layer system must be appropriate for the climate, soil, and drainage at the site and should also complement other construction operations as much as possible. Whether pavement problems originate in design or during construction, they can often be prevented through design decisions. Many defects arise out of common and avoidable chains of events. For example, a pavement will be poorly compacted if it is placed over spongy, wet soil in adverse weather. In turn, these conditions are liable to occur when delays in other phases of the project push back the schedule and the paving is rushed in order to open on time. In this respect a paving alternative which reduces construction time and avoids delays due to wet soil and bad weather is likely to improve quality. It may also yield economic benefits from earlier use of the facility.

Designing for purposes such as these sometimes involves less familiar ways of doing things, but past practice need not conform to a designer's thinking. Part One describes a number of construction techniques which may be new to many designers and specifiers. These techniques, such as site paving and stage construction, have been successful on many projects and can be applied with confidence.

I.A SUPPORTING LAYERS

This section discusses base and subgrade materials and their preparation and acceptance. Guidelines for classifying soils and evaluating their properties are presented in Part Two, and recommended specification limits in Part Three.

Soil conditions

The properties of a soil are of concern to the designer in determining the thicknesses of base and pavement, in selecting the type of base, and in deciding whether the subgrade should be improved. Poor soils require uneconomical quantities of base and pavement to obtain adequate bearing strength and may warrant stabilization or replacement. They are often difficult to prepare, and their resilience also makes it more difficult to compact the base and pavement. As the moisture content of a subgrade is subject to change, sensitive soils undergo changes in volume and strength which are not accounted for in thickness determinations. For these reasons, the design procedure in Part Two is not recommended for extremely weak, moisture-sensitive, or highly plastic soils. Such materials should be stabilized or replaced, and in localities where such soils occur this is generally a common procedure. Strong soils should receive special consideration for the opposite reason. As the bearing strength of a soil comes nearer to that of crushed stone or gravel, the structural benefit of a layer of these materials is less, so that a very good soil, or one which can be improved at low cost compared with processed base materials, may be reason to adopt a full-depth asphalt design.

No factor is more critical to pavement durability than the reaction of subgrade soil to changes in moisture content over the life of the pavement. On one hand the designer seeks to hold the moisture constant by providing good drainage and an impervious pavement free of joints and cracks. On the other, he must consider how a particular soil will be affected by moisture changes. Shrinkage of cohesive soils due to drying can cause a pavement to settle slightly, but is accompanied by increased strength. More serious are the effects of moisture saturation, which in some soils produces dramatic loss of strength sometimes accompanied by swelling.

Frost heave is another moisture-related problem which is characteristic of certain soils. It occurs mainly in fine-grained soils through which moisture can be drawn upward at an appreciable rate by capillary tension, producing lenses of ice just below the base layer or, in colder climates, deeper in the soil. In moderate climates, frost heave occurs mainly in silty soils. Where frost penetrates more deeply and for longer periods, silty clays, sandy silts, and other soils are also susceptible. Frost heave is prevented by ensuring that the thickness of non-susceptible layers exceeds the normal depth of frost penetration. Special measures, such as inserting a blanket of coarse sand, are applied in regions of extreme cold. References on this subject are given in Part Three.

One soil condition which is involved in a surprising number of pavement problems is intruding groundwater. A building site cut into a hillside may intercept groundwater which has been confined between impervious layers, a condition often found in laminated residual soils and folded sedimentary strata. Migrating groundwater may appear at the surface as wet weather springs, but often it is not evident until the confining layer is excavated. Interceptor ditches and subdrains are needed to prevent this water from weakening the subgrade and intruding into the pavement structure. Many other sources of intruding water are artificial, including drainage from roofs, air conditioning condensate, and ponded run-off water. The man-made condition recounted in the introduction to this chapter, in which a large volume of water was trapped between the pavement and a nearly impervious layer below, must also be avoided. A layer of stabilized soil, sand-clay base, or Hot Mix Asphalt base course, unlike crushed stone or gravel, will not retain a large volume of water to saturate the soil.

Obtaining soil data

Often the soil data needed for a pavement design will be obtained as part of the site investigation for a larger project in which the paving is included. If possible, the soil should be classified according to the Unified Soil Classification System (ASTM D 2487), which is helpful in the design procedure in Part Two. Where a large volume of soil is to be removed, or when the pavement is to be built on borrow material, the designer must be careful that the information obtained applies to the material which is actually to become the subgrade.

Additional sources

When soil data for designing the pavement must be obtained as a separate study, especially for a small project, the cost of a site investigation may be difficult to justify in terms of total outlay, or there may be no funds allocated for this purpose. As a less costly resort, the designer may need to rely on other ways of characterizing the soil. Basic information can usually be obtained from studying the geology of the area, from inquiry into past experiences and tests on neighboring sites, and from personal inspection of the site. State highway departments, the U.S. Geological Survey, the Soil Conservation Service, and state geologic surveys can usually provide data reflecting the types of soils in a local area, and state and local roadbuilding agencies may be able to furnish soil data from adjoining rights-of-way. The Department of Agriculture publishes county maps and other data which characterize the topmost layers of soils. During visual inspection of soil at the site, penetrometer measurements can be made to provide a rapid, low-cost approximation of soil strength.

Data requirements

The type and amount of data to obtain should be considered carefully. The owner needs to be aware of any risk of expense and delay for replacing or modifying a problem soil, and the designer must have a reasonable estimate of the strength and suitability of the subgrade, including the classification of the soil, if possible, under the Unified Soil Classification System (to be covered in Section II.B.) The architect or engineer supervising the work must know the maximum dry density and optimum moisture of the soil in order to measure the degree of compaction. Beyond these needs, local conditions should indicate the need to investigate such possibilities as proximity to groundwater, frost problems, moisture-sensitive clays, or the presence of rock or hardpan. The purpose of a soil investigation is to reduce the risk of failure, delay, and added expense caused by unknown conditions and to avoid overdesign. It is these potential costs which determine the value of soil data and to which the cost of obtaining it should be compared.

Grades, slope, and drainage

Minimum slope — roadways

Roads and longer driveways with two or more lanes should be crowned, with a cross-slope of 2.0 per cent except in superelevated curves. If curbs are not used for an entire section, it is important to add them on hills where downhill flow will be swift and may otherwise erode the shoulder.

Minimum slope — Parking areas, connectors, etc.

Design standards often include a minimum slope rule, typically 1.0 per cent, for these areas, to ensure that the surface will drain and that standing water will not seep into the soil. A minimum total slope of 1.0 per cent is a good rule for all types of pavement, rigid or flexible. However, proper drainage depends just as much on the adequacy of the elevation data in the plans. There is a tendency among designers to overlook the need for grade information at key points in intersections, cross-overs, and transitions between grade lines.

Control of grade

A second factor critical to good drainage is how closely shaping and compacting the subgrade will be controlled and inspected. Slopes greater than 1.0 per cent may be advisable if the surface to be paved cannot be checked to close tolerance. Grading hubs are recommended when preparing subgrade and granular base for pavements as wide as 40 feet. Where the amount of fall available is limited and slope must be minimal, the surface to be paved should be held to within 0.05 ft. of design elevation.

In parking areas and pavements around buildings it is often necessary for the slope to vary in both directions, which complicates the task of insuring complete drainage. Flat spots and "bird baths" tend to occur along curbs and in transition areas, where the slope may approach zero transversely and longitudinally at the same spot. The amount of fall along curb lines is a drainage parameter which is sometimes overlooked. A minimum fall of 0.5 per cent *in the flow line along the curb* is recommended. Where a curb or sidewalk parallels the front of a building, especially an entrance area, some architectural device may be desirable to avoid a very slight skewed appearance.

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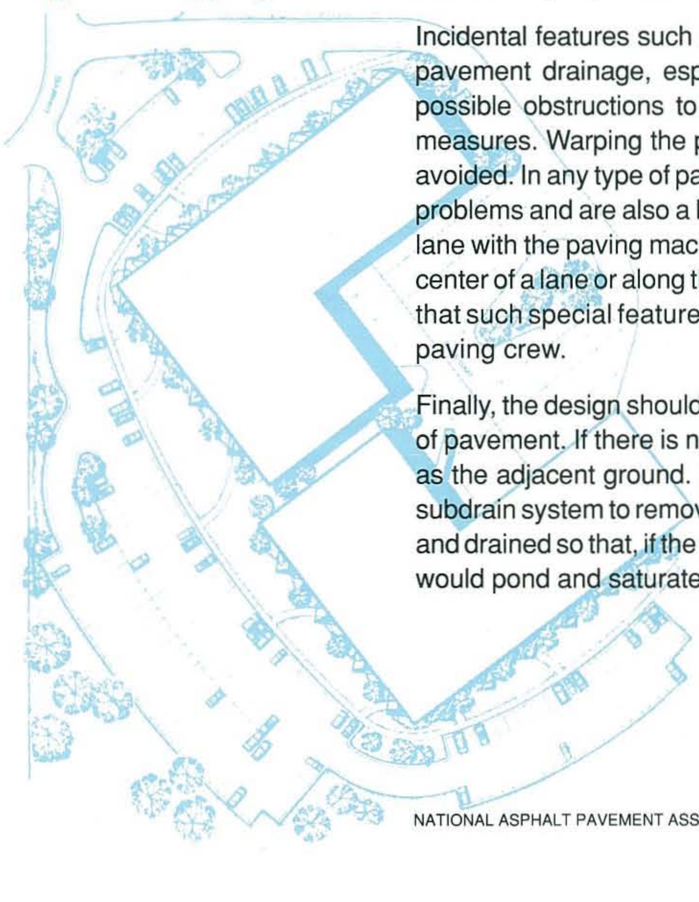


Incidental features such as raised crosswalks and wheelchair ramps often interfere with pavement drainage, especially along curbs. It is important to check the drawings for possible obstructions to flow and to provide appropriate drainage structures or other measures. Warping the pavement to channel runoff water across traffic lanes should be avoided. In any type of pavement, swales and irregular contours pose special construction problems and are also a hazard to traffic. It is feasible, however, to form a crown in a traffic lane with the paving machine or to form a shallow inverted crown to guide runoff down the center of a lane or along the edge. Detailed notes should be included in the plans to ensure that such special features are clearly described for both the subgrade preparers and the paving crew.

Finally, the design should not create undrainable basins in the subgrade or along the edge of pavement. If there is no curb, the subgrade of a full-depth pavement should be as high as the adjacent ground. Except over well-drained soil, a granular base should include a subdrain system to remove intruding surface water. Ideally the subgrade should be shaped and drained so that, if the pavement were taken away, there would be no spots where water would pond and saturate the soil.

Controlling urban runoff

Conventional concepts and practices in drainage design for streets and private facilities have recently been undergoing fundamental changes. Concerns for protecting water quality and controlling local flooding have led to enactment of new regulations by the U.S. Environmental Protection Agency affecting drainage requirements of local communities and/or municipalities. In November of 1990 the Agency published rules for a National Pollutant Discharge Elimination System (NPDES), which require many local jurisdictions to establish permitting practices to protect waters which receive storm runoff. Control methods which act at the source of runoff are to be applied.

Under NPDES rules, conventional closed drainage systems which collect and channel all runoff into streams will be discouraged in favor of systems designed to increase infiltration into the soil or to increase the time of collection. Among other techniques, the use of porous pavements is expected to become an important means to this end. Porous pavements have been found to perform very satisfactorily not only as infiltration systems but also as concealed detention basins and as water treatment systems which remove pollutants prior to their entry into lakes and streams. Development of such pavements to control runoff was begun in the late 1960's at the Franklin Institute Research Laboratories under the sponsorship of the U.S. Environmental Protection Agency. Since that time the technique has been used successfully on numerous projects. While alternative construction methods and materials are still evolving, design criteria based on early applications have been published. Two excellent references on the subject will be found under "Drainage" in Section III.D.

Specifying subgrade work

> ***"Soil preparation is everything in paving, and drainage is the heart of soil preparation. Does it get enough attention? No, not by a long shot. And, of course, that's a completely self-defeating attitude. In pavement, you can bury your problems, but they won't stay buried."***
>
> *— Clyde Coe, consulting engineer, Louisville, Kentucky*

The loss of subgrade support is the most frequent cause of premature failures in privately constructed pavements. While the importance of subgrade strength is recognized by experienced professionals, in practice the interests of quality often give way to pressures to save time and reduce costs.

Many problems with subgrades are related to how the work is specified and accepted. When specifications are incomplete and acceptance requirements are minimal, good workmanship is put at a competitive disadvantage, and a low standard of quality is established for the one component of the pavement which is least accessible for repair.

When a suitable soil is brought to the right moisture content, shaped to grade, compacted to the specified density, and protected from moisture, the likelihood that it will perform satisfactorily is excellent. The challenge, of course, is in meeting these conditions under the pressures of a construction schedule, given adverse weather and the high costs of delay.

In designing a project and preparing the contract, attention must be given not only to specifications and tolerances but also to project management and to problems which may arise due to weather and scheduling. The following contracting guidelines are suggested:

(a) The specifications should fully describe the work to be performed and methods of checking it, such as setting grading stakes, proof-rolling, and testing. It is important to state the basis of acceptance, grade and compaction tolerances, and actions to be taken in event of deficient test results, incorrect grades, soft spots, etc. (Further treatment of these topics will be found under "Controlling quantities and thickness" in Section I.C below and in Part Three.) It should be noted that acceptance plans used by state D.O.T.'s are, in general, inappropriate for private contracts, since they involve the state's testing and inspection resources and often some form of statistically-based acceptance criteria, which are appropriate only for large-scale construction projects.

(b) Grading tolerances should be consistent with requirements for pavement thickness, smoothness, and finished grade. It is contradictory to allow the subgrade to vary 0.1 or 0.2 ft. while specifying much closer requirements for layer thickness, finished grade, and drainage.

(c) Testing and inspection services should be provided by the owner's representative — the architect or engineer — who should approve the subgrade before work proceeds on the paving phase.

(d) Final preparation of the surface to be paved should be performed by the paving contractor whenever this is feasible. In no case should the paving contractor be asked to pave over wet or poorly prepared soil.

(e) The contract should make provision for conditions which may appear during construction, requiring stabilizing or replacing poor soil, undercutting mucky areas, installing interceptor drains, or other necessary measures. Soil conditions which may involve extra work include moisture intrusions from natural or man-made sources, buried rock or old structures, and pockets of poor soil or uncompacted fill.

(f) When circumstances are favorable, site paving and other techniques described under "Materials and Methods" in the next section should be utilized.

Types of layer systems

The selection of the type of base is one of the designer's major decisions. In the following sections this publication provides design criteria for full-depth, granular, and stabilized bases. A full-depth HMA pavement is constructed directly on the subgrade, eliminating the use of unbound or stabilized material. Granular and stabilized base designs consist of a layer of HMA over a base of suitable processed material or soils mixed in place with a stabilizing agent.

It is sometimes advisable to improve the subgrade in order to reduce quantities of manufactured materials required or simply to facilitate construction. (Improved subgrade is discussed further below and in the sections to follow.) Thus there are four choices of layer systems: (1) full-depth asphalt, (2) full-depth with improved subgrade, (3) asphalt pavement over a granular base, and (4) asphalt pavement over a stabilized base. The best combination is determined by the following factors:

Factors required for facilitating construction:

- *Soil conditions*
- *Project needs*
- *Economics and availability*

- **Soil conditions:** Strength, moisture sensitivity, frost susceptibility, and proximity to groundwater.
- **Project needs:** How each alternative fits into the project schedule and the construction season, and how it may affect other project operations.
- **Economics and availability:** Relative costs of alternatives. The major economic variable for Hot Mix Asphalt is haul distance, both from sources of materials to the mixing facility and from the mixing facility to the site. For most projects, time is also a critical factor. Since construction time has a very significant economic value in terms of interest costs and opening for business, differences in construction time required and risk of delay should be evaluated as part of the estimated in-place costs. Availability of various base materials and good replacement soils will be different on every project. Alternative bases, such as cement stabilized and emulsified asphalt stabilized soil, are more commonly used where no quarry materials occur, but their use is also a matter of local and regional construction practice.

Note: Costs of paving materials, especially HMA, are sometimes compared incorrectly, using unit costs for areas and thicknesses substantially different from those being designed. A better approach is discussed in Section I.B.

Improved subgrade

This refers to several procedures for treating or replacing the soil, when the improvement is significant but does not attain the strength required of a true base course. For some soil conditions, improving the subgrade is a necessary step; in other cases it may be desirable for reasons of economy and durability. Improving the soil may be advisable (1) to correct frost susceptibility where the frost penetration zone is deeper than the base layer, (2) to add bearing capacity and reduce sensitivity of very weak, expansive, or highly plastic soils, (3) to upgrade weak soils in order to reduce pavement thickness (as explained in section II.C), (4) to take advantage of the closer control and inspection involved in this type of construction, and (5) to avoid construction delay brought on by soaking rains followed by uncertain drying conditons.

Soil can be improved by many methods; especially suitable for private projects are: Replacement with select borrow, soil-aggregate blends, and stabilization with portland cement, fly ash, or, for sensitive clays, hydrated lime. More specialized methods include treatment with bituminous materials, calcium chloride (to control drying), and various proprietary stabilizing agents.

Each method, of course, has its special applications and limitations. Select borrow can be an ideal method where very firm borrow material is already on site, in a layer to be excavated for foundations and grading. Hydrated lime is particularly effective for strengthening and correcting sensitive clayey soils, but it may aggravate a tendency to frost heave. Sand-clay mixtures may also be frost-sensitive. Cement or lime/fly ash treatment of subgrade differs from cement-stabilized base in that a smaller proportion of cementing agent is used, so that shrinkage is not a problem. These materials are mixed in place. They increase strength significantly, but effectiveness of cement may be reduced in soils containing sulfates. Also, in clayey soils care is required in blending the materials uniformly. Soil-aggregate blends and sand-clays perform well in many areas, and the use of crushed concrete as the aggregate for such blends is increasing. Low-cost quarry materials — fine screenings and crusher runs — are also effective in soil-aggregate blends.

A very common form of subgrade improvement is undercutting, which is removing and replacing mud, muck, or very weak soil, usually as extra work when a compaction problem is encountered during construction. Processed materials are most often used for this purpose. This kind of undercutting is costly in lost time as well as materials — a fact which supports the use of procedures and materials which involve less risk of delay.

Effect of improved subgrade on design. A method for considering improved subgrade in determining pavement thickness is given in Section II.B. Further information on quality assurance for subgrades and bases appears in Part Three.

Stabilized soil bases. Use of stabilized subgrade as a base layer is also discussed in Section II.B, which includes design data and information on various stabilizing materials.

I.B MATERIALS AND METHODS

Obtaining information on materials

Cost and availability of paving and base materials vary considerably from one location to another. Given also differences in soil and climate, it would be unlikely for one mode of construction to be best for all locations or for "typical" cost figures or costs from other areas to be valid for comparing alternatives. The designer should search out information on local materials utilized as base. In some regions, materials such as shell and coquina, sand-clay, limerock, gravel, and treated soil make excellent bases and are less costly than crushed stone shipped from distant sources. Paving contractors who serve the local area can provide detailed information and advice on material selection, since they purchase materials for many types of public and private work.

Standard specifications of state highway agencies are a good source of information on aggregate materials and the types and grades of asphalt cement, prime coat, and tack coat normally used in the state. However, with regard to composition of asphalt mixtures, it should be kept in mind that the requirements of lightly travelled pavements are somewhat different from those of highways. In paving mixtures, for example, surface mixes for highways require aggregates which provide good resistance to skidding at high speeds. Applying this requirement to a parking area could needlessly rule out materials which are otherwise very suitable, and it would greatly increase cost where state-specified skid-resistant aggregates — slag or crushed siliceous materials — must be shipped from other areas. Mixes designed for highways also reflect a greater need for resistance to rutting — plastic deformation in the wheel paths under repeated heavy loads — with less emphasis on resistance to environmental factors than is needed in off-road pavements. Regarding types of paving mixes to specify, the reader should refer to "Types of paving mixes" in Section I.C and Section III.B in Part Three.

Stage construction

The purpose of stage construction is to reduce the initial cost of a pavement and to take advantage of the fact that HMA pavements can be structurally augmented after several years of service, with only minor disruption of traffic. In stage construction the original pavement is designed for a shorter period than the intended service life, and additional thickness is scheduled to be added *prior to the onset of structural distress.* This has the advantages of reducing initial cost and interest, renewing the surface, and providing an opportunity to revise the design after service conditions are better known. Since traffic predictions and design strength are necessarily conservative, actual performance of a pavement may be better than predicted. It may be possible to postpone construction of the second stage or reduce thickness. Conversely, if predicted traffic loads are exceeded because of changes in use, the second layer can be strengthened. Stage construction is of further advantage for commercial facilities where pavement sealers are applied to the parking area at regular intervals to renew its appearance. At least one resealing is avoided, and surface scars and irregularies are corrected. Perhaps the most attractive advantage of the stage construction concept is to defer part of the paving cost to a future year, but this is not always desirable.

The chief disadvantage of stage construction is that the second stage is in effect a second project, involving a separate funding commitment, re-mobilization of equipment, and possible disruption of business. Where funding would be complicated by a change of ownership, where even brief interference with customer access is undesirable, or on small projects where mobilization is a larger part of total cost, it may be advisable to design the pavement for the full life of the facility with minimum maintenance.

Full-depth design

Several reasons to consider a full-depth design have been mentioned. Depending on project conditions, a full-depth HMA pavement may be the best choice for reasons of quality and durability, shorter construction time, and lower overall cost. Full-depth pavements offer savings through increased service life over aggregate-base pavement designs which may have a lower initial cost. Costs of paving materials are greatly affected by shipping and hauling distances, availability, and other variables. For this reason economic comparisons should be based on prices from similar projects in the same locality. Although the materials for a full-depth design will sometimes cost more, the total cost may well be less when hauling and placement costs are added. Moreover, the time saved by eliminating a granular base will often result in a substantial saving to the owner through earlier use of the facility.

...it is important to use unit prices based on comparable thicknesses and project sizes.

In estimating or comparing pavement costs *it is important to use unit prices based on comparable thicknesses and project sizes.* Except in very large projects, the cost of mobilizing paving equipment and personnel is a major component of the total paving cost, though it is usually included in the price *per ton* or per unit of area. Thus the unit price for asphalt pavement will not be determined by thickness alone, and the price per ton will normally be lower for a full-depth pavement than for a thin pavement over granular base. The greater durability and reliability of full-depth pavement may be difficult to evaluate in economic terms; however, where subsurface moisture and freezing are cause for concern, these factors clearly take precedence over cost. Discussion on identifying and evaluating different options will be found under "Comparing alternatives" at the end of this section.

Site paving and other techniques

Full-depth designs also lead to other time-saving strategies, one example of which is site paving. The term site paving refers to placing a layer of HMA as early in the project as the grading and other operations will permit. Site paving is of special advantage in connection with building construction, since it provides a work and storage platform for other operations. If the structure is to be founded on a slab, the subgrade for the slab and the areas to be paved can be prepared in one operation. In all cases, contractors report a substantial reduction in clean-up problems and improvement in overall productivity at the jobsite. Above all, site paving protects the prepared subgrade as soon as it is shaped and compacted. It is an excellent way to avoid the problems of weather delays and defects brought on by paving in cool weather or on wet subgrade.

Site paving also keeps the streets clean. Many cities and counties now require contractors to take special measures to prevent tracking of soil by trucks leaving a jobsite. Where these rules are in effect, site paving offers a considerable economic advantage in addition to those mentioned.

It is important to note that the quality advantage of site paving may be lost if scheduling pressures tend to rush the subgrade work, if effective standards of compaction and smoothness are not applied, or if a "we'll fix it later" mentality prevails. In compacting backfill it must not be assumed that less care is needed because weak spots can be corrected before the final paving course. This kind of correction never does the job. Compacting the base and subgrade in a small patch is difficult at best, involving inefficient methods and usually no quality control. For the same reason, minor trenches for lighting conduits and communications cables should not be put off or overlooked and later saw-cut into place. Careful planning and coordination of the early site work will be repaid many times in the latter stages of the project.

Site paving works best with a full-depth design. This is because the interval between compacting the subgrade and protecting it with pavement tends to be much shorter, reducing the risk of damage by construction traffic or heavy rains. It may also promote better subgrade work, where there may be a tendency to cut short the shaping and compacting of a subgrade before covering it with crushed stone. Thickness of the stone layer may vary excessively, and a poorly compacted subgrade deforms and weakens the pavement through consolidation and loss of support.

Single-layer construction

To improve performance and reduce material costs, highway pavements are usually built in multiple layers of specialized base, binder, and surface mixes, but this practice does not always benefit smaller projects. For low-volume traffic and normal axle loads, a single asphalt mixture, properly formulated, can provide both the weather resistance of a surface mix and the stability required in a structural layer. Neither are multiple layers necessary to achieve compaction in pavements of 6.0 in. (150 mm) or less. It is practicable, therefore, and a considerable advantage on certain types of projects, to place the entire pavement in one operation.

Single-layer construction is a special technique which can be of great advantage in certain types of projects. It eliminates the labor and equipment costs and additional workdays often required to place multiple layers. Mobilizing a fully equipped paving crew for one day may cost thousands of dollars, depending on crew size and equipment, and the cost in construction time to the owner may be a comparable amount. A single, thicker layer is also much less affected by cold weather during placement than two thinner layers, so that it can be placed late in the season with less risk of compaction problems.

Single-layer paving also has its disadvantages. Obviously, if the pavement is installed early in the project, damage caused by equipment, utility cuts, fuel spills, and the like would require patching in the finished surface. Likewise, there is no second chance to correct subgrade defects and areas of poor drainage, which might otherwise be found and corrected between the first and second paving courses. Single-layer construction is not recommended for projects where construction equipment may damage the pavement. It is always a good idea to discuss the advantages of single-layer construction with the paving contractor.

As already mentioned, the mixture must meet the requirements of a structural layer as well as a surface mix. Mixture parameters for structural and surface layers are discussed in Section I.C and in Part Three, Section III.B.

When minor structures... are installed early in the project, there can be interference with final grading and compaction, paving, utilities, and other operations.

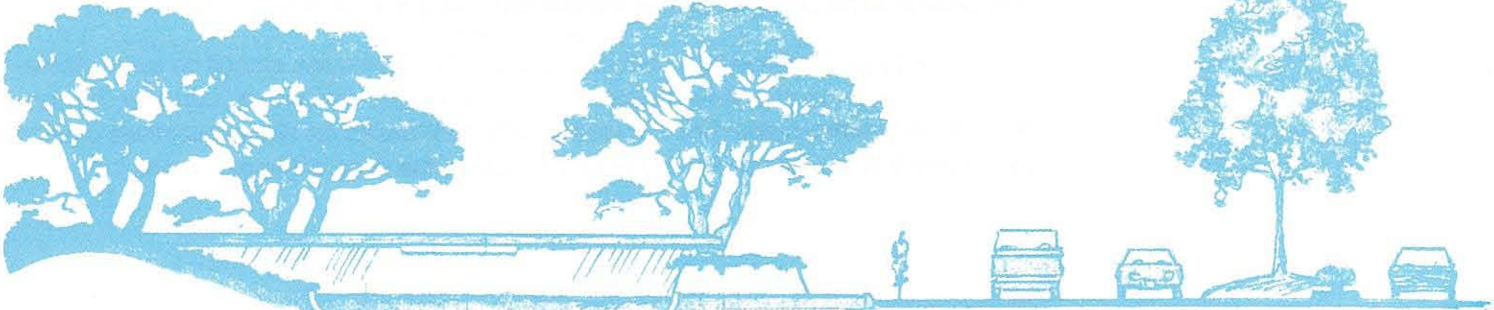
When minor structures such as dumpster pads, drainage inlets, and curb and gutter are installed early in the project, there can be interference with final grading and compaction, paving, utilities, and other operations. Accidental damage to the structures themselves can be a problem. Sometimes it is necessary or advisable to put off constructing certain structures until the pavement is in place. Greater freedom of movement for equipment during grading and paving can make a significant improvement in the quality and speed with which the subgrade and pavement can be constructed.

The handicap of working around and between minor structures is often an impediment to subgrade preparation. Wetting, mixing, shaping, and compacting the soil are accomplished with large machines, which are difficult to maneuver around structures and are less effective where they must reverse direction within the limits of the work. Subgrades prepared in this way tend to be uneven, with potential drainage problems. Curbs are often constructed early in the project to provide grade references for fine grading and paving. Since the introduction of the laser level pre-forming of curbs and other structures is no longer necessary, since grades can be checked with this instrument by one worker at any time during grading.

Likewise, paving is more difficult in confined areas. When asphalt pavement must be placed by hand, the surface texture, finished grade, and density are not equal to that of machine-laid mix, and the work itself is slow and labor-intensive. In these circumstances, a better pavement will be obtained by delaying installation of obstructing features such as dumpster pads which tend to fragment an area to be paved into time-consuming stops and starts. Where paving is continuous, the surface will be more regular, and drainage will be greatly improved.

An alternative method of constructing curbs is to form them on the first layer of pavement. This is very convenient in conjunction with site paving. Concrete curb and gutter or asphalt curb is slip-formed onto the asphalt base course, which extends slightly beyond the back of curb. For concrete curbs, steel dowels are first driven into the pavement. In addition to simplifying and improving compaction in the subgrade and base courses, this technique closes the joint between curb and pavement, which removes a major threat of water intrusion into the subgrade. Note: In climates with extreme seasonal changes in temperature or humidity, shrinkage and expansion of concrete may not be sufficiently relieved by jointing, and this technique should not be utilized. In all cases, contraction joints in concrete should be cut clear through and spaced not less than ten feet apart.

Drainage structures which extend into a paved area are often built in two steps, because of the problem of matching pavement grades with grades of the tops or inlets of these structures. Manholes and valve boxes are usually built completely prior to final grading and paving and are adjusted in height after paving. Another, less common technique is to build the base slabs and walls to just above the tops of the pipes, then bury them during grading. After paving, the opening for the top of the structure is sawed into the pavement, and the soil is re-excavated. The upper walls are then cast using the soil as the outer form, and the inlet grade is matched to the pavement without the need to distort the cross-slope. Soil density around the structure will be greater and more uniform than that of backfilled soil; thus the pavement will not settle in front of the inlet.



The use of techniques such as the ones described above will be found to vary from region to region, reflecting differences in climate and materials as well as local practice. Designers should be alert to the reasons behind the various approaches available and the problems they are meant to avoid. Local contractors known for quality work are good sources of advice on how best to approach a particular question.

Asphalt curb

Installed quickly and without forms, asphalt curb is an economical alternative to concrete and is better suited to some site conditions. It does not require expansion and contraction joints, and it makes a watertight, vegetation-proof seal with the pavement. Asphalt curb is extruded from a slipforming device which compacts and shapes the hot mixture. It presents a smooth and pleasing appearance and resists weather and de-icing salts. During the first several weeks of service, asphalt curb becomes stiff and scuff-resistant as the asphalt cement in the mix increases in viscosity. During this period the curb should not be subject to accidental heavy impacts or static loads. Painting with a non-shrinking, water-based traffic paint improves night visibility and maintains a smooth surface. Mixture formulation is important. Some paving mixes may not be suitable for curbs or may require minor adjustment. Special mixes for curbs, which usually include mineral filler, are generally available from Hot Mix Asphalt producers.

Prime coat and tack coat

The need for prime coat is a topic of debate among paving specialists. On subgrades and aggregate base courses, prime coat is intended to maintain the prepared surface prior to paving, although for subgrades this may be unnecessary or counterproductive. Prime coat is effective on unbound aggregate bases and is also useful to protect the work from rain when paving will be delayed. It should be used on cement-stabilized soils as a barrier to moisture intrusion. There are several disadvantages in using prime coat, including cost and delay. Prime coat should not be applied to a subgrade when it is wet. Highly cemented soils which harden as they dry out may soften if prime coat is applied. Cutback asphalts used as prime coat have the further disadvantage of releasing hydrocarbons into the air, and their use has been discontinued in some areas. Both cutback and emulsified asphalt prime coat require a curing period, usually 24 hours.

Tack coat is used to improve bonding between layers of Hot Mix Asphalt. On a freshly placed layer which is clean and free of dust, it should be applied lightly or omitted. If a freshly laid mix slips during rolling, it is usually because the mix is either "harsh" or too hot, because excess tack coat was applied, or because the emulsified or cutback tack coat is not completely cured. Tack coat is applied immediately before paving, after the surface has been cleaned of dust, debris, and oil spots. Emulsified tack coat and cutback asphalt require a brief curing period, normally less than 30 minutes, depending on the amount applied and on weather conditions. Emulsified asphalt tack coat cures most rapidly at its interface with the air, changing color as it cures from brown to black. For this reason it may appear to be ready for paving long before curing is complete.

The use of prime coat and tack coat and their rates of application should be at the discretion of the engineer or architect supervising construction, who should consider the contractor's recommendation. For this reason, payment based on actual quantities used is recommended, as opposed to including this item in the price of the pavement.

Controlling quantities and thickness

An important step in specifying asphalt pavements is to establish well-defined and reasonable methods of controlling grades, thickness, and paving quantities. These items are interrelated, and how they are specified should be clearly pointed out in dealing with prospective paving contractors. In many projects, paving quantities are measured in units of area (usually square yards), and thickness is checked by removing test cores from the finished surface. Besides the expense and the destructive nature of coring, it is a very unrepresentative measure of thickness, providing too few data points for the quantity measured. A much better measure of both quantity and thickness is to record the weights of material delivered, obtained from the weight ticket for each truckload. Average thickness is calculated as follows:

$$\text{Thickness(inches)} = \frac{\text{total tons of HMA} \times 2000 \times 12}{\text{compacted unit weight} \times \text{paved area}}$$

In which unit weight is in lbs/cu ft; area, in sq ft.

As a check, any number of spot thicknesses can be obtained by taking level readings before and after paving. For calculating quantities, the compacted unit weight may be determined from the mix design data (described in Section I.C), which is adjusted for the required degree of compaction.

If payment is to be based on weight, thickness may be specified as weight of mix per unit of area (e. g., pounds per square yard, tonnes per meter square). In this case a reasonable limit on quantity overruns should be established in the contract. In areas where both porous and dense aggregates are used, unit weights and actual quantities should be adjusted to a standard value for purposes of estimating and payment. For example, to pave 10,000 square yards at four inches thickness requires 2130 tons of material weighing 142 lbs per cubic foot, but only 2040 tons at 136 lbs per cubic foot. Adjusting all quantities to a normal weight — say, 140 lbs per cubic foot — has the effect of pricing all mixes by volume and avoids overrunning the estimate when a dense mix is used.

As pointed out under "Subgrade preparation", grade tolerances allowed in the subgrade or granular base must be consistent with the tolerances for pavement thickness and finished grade. In practical terms, it is relatively easy to check and adjust grades in the supporting layer and quite another matter in the pavement. Holding the supporting layer to a close tolerance is justified many times over by the improved smoothness and drainage of the pavement, closer control of paving quantities, and the quality of the supporting layer itself.

Comparing alternatives

As the preceding sections indicate, there are many possibilities to consider in deciding how best to pave a given area, and the best approach is to explore all likely options. It is not uncommon, after a contract is awarded, that a better and less costly alternative is accepted from the contractor, who points out cost-saving materials or procedures of which the designers were unaware. Ideas for reducing costs or adding to the value of the work are always worth considering, but preferably they should be evaluated in the design stage and included in the proposal as alternate bid items. In preparing the design, local paving contractors and geotechnical consulting firms should not be overlooked as sources of ideas and information on possible alternatives.

Negotiating better value

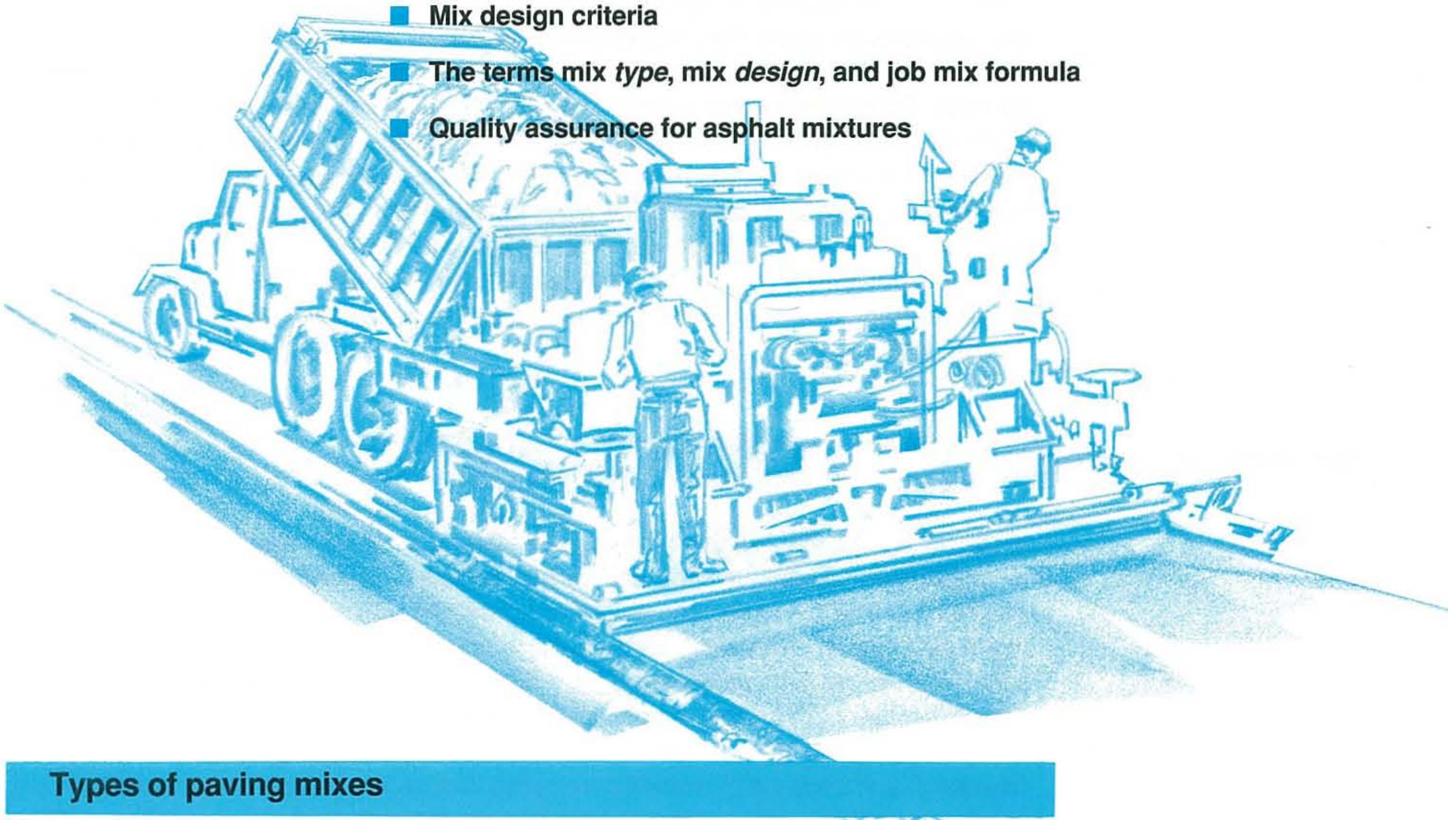
Promising alternatives often come to light in the process of negotiating with a well-qualified contractor. Contractors should be invited to offer alternatives which make best use of their own capabilities, and a flexible range of services should be considered in awarding the work. Choosing a contractor solely on the basis of price, on the other hand, has special disadvantages in private paving, the worst of which is the difficulty of defining and assuring the level of quality. Unlike highway work, in which the same well-defined system of qualifications, specifications and acceptance procedures applies from project to project, private construction relies more on the standards and reputation of the individual contractor. The overall value of the proposed work — never price alone — should determine the choice of a contractor.

Comparing alternatives with different service lives or with costs incurred in different years involves the time value of money. Helpful references for applying the methods of engineering economy to paving costs will be found in Part Three, Section III.C under "Life cycle costs."

I.C HOT MIX ASPHALT

For users of this manual not acquainted with paving materials this section explains key terms and concepts pertaining to HMA and how it is specified. It discusses:

- **Types of mixes and their applications**
- **Specifications for mixture ingredients**
- **Mix design criteria**
- **The terms mix *type*, mix *design*, and job mix formula**
- **Quality assurance for asphalt mixtures**



Types of paving mixes

State and local roadbuilding agencies specify a variety of mix types to provide special characteristics for different traffic conditions and different layers within the pavement. For example, a structural layer, or "binder", for a major highway must be highly resistant to deformation and fatigue cracking under repeated heavy loads. It must not be susceptible to damage by internal moisture, and it should also be economical, especially in the amount of asphalt cement required. A binder may, on the other hand, contain aggregate particles too large to be placed in thin layers, and it need not be as watertight and skid-resistant as a mixture used in wearing courses. Similar requirements apply to mixtures for asphalt base course, except that more emphasis may be placed on coarser, more economical aggregate which demands less asphalt cement. Surface mixtures are more diverse than structural types, since they may require special abrasion resistance, stability, or weather-resisting qualities, and since some are intended to be placed in thinner layers than others. All mixes for highways, whether in the surface, binder, or base course, must be constituted to withstand thousands of vehicles per day — more than pass through some parking areas in a year. This does not imply that mixtures designed for low-volume roads and parking areas may be inferior in quality to highway mixes. In some respects they need to be better, and more to the point, they should be different.

Mix types differ from each other mainly in the size of the largest particles, in the types of aggregates which may be included, and in gradation and asphalt cement content. Larger particles improve stability and reduce cost, but they must be placed in thicker lifts. Certain types of aggregates may be required in order to improve skid resistance or stability, to improve the gradation, or to make the mix more resistant to moisture. Most base mixes are coarse, dense-graded, and relatively low in asphalt cement, while surface mixes tend to be finer, with more void space between particles and more asphalt cement needed to occupy some of this space.

Older parking lot pavements reveal an interesting fact about Hot Mix Asphalt. After aging, a properly constructed parking lot will usually have more thermal cracks and a more weathered appearance where there has been no passage of vehicles — evidence that a certain amount of traffic tends to work out thermal stresses and to restore adhesion between particles. For pavements not subject to frequent heavy loads (those which fall into Class I of the classes defined in Section II.A), time and weather are a greater threat than traffic loads, and mixtures for them should be designed accordingly. Unfortunately, highway agencies generally do not specify mix types for this kind of pavement and have no criteria by which to approve them. However, mixes designed for low-traffic pavements are available and usually better suited for these applications than state-approved mixes formulated for highways. Further information and *suggested criteria for mix types are given in Part Three, Section III.B.*

Specifying ingredients

In specifying Hot Mix Asphalt it is also necessary to establish criteria for the ingredients — aggregates, asphalt cement, and certain additives. State specifications are a good source of criteria for ingredient materials. Low-traffic pavements may differ from major roads as to which ingredients are needed, but the properties of the ingredients themselves should meet the same standards. Aggregates must be sound and inert to moisture, with a favorable particle shape and gradation. Bonding between the asphalt cement and the aggregates must not be affected by moisture. Loss of bonding is referred to as "stripping", and additives to prevent it are called "anti-stripping additives". Asphalt cement needs to be stiff in warm weather but not brittle in cold. Different climates demand different grades and properties in asphalt cement, and there is at present no single grade which is best for all regions. Accordingly, each state highway agency specifies the grade or grades best suited to its own conditions. Because of the very large role of state governments in the paving market, the grades of asphalt cement available in a given area will be appropriate for local conditions and special sampling and testing for quality assurance is generally not warranted for most private projects.

As with asphalt cement, state specifications for aggregates also reflect local experience and availability. A material which meets the state's requirements for aggregate ingredients for asphalt mixes will be acceptable in private pavements as well. Here a distinction is made between a state's specification for the aggregates used in Hot Mix Asphalt and other provisions which require or rule out some aggregates for certain types of mix. As discussed under "Materials and Methods" above, a state's requirements for certain aggregates in surface mixes may be unnecessary for pavements other than highways.

Mix design

Designing a paving mix refers to performing certain laboratory tests on a particular set of ingredients to determine whether, and in what proportions, they can be combined to meet the specifications for a certain type of mix. These tests belong to one of two standard procedures commonly used in the United States and other countries. The Marshall mix design procedure, the more widely used of the two, is standardized in ASTM D 1559 and is utilized in some form by most state agencies. Several states, especially in the West, prefer the Hveem procedure, ASTM D 1560, which is similar in some respects to the Marshall method but applies a different test for stability, or resistance to deformation. Both procedures measure resistance to deformation by empirical methods, since stress-strain conditions in flexible pavements are highly indeterminate. Both also require an analysis of density and voids relationships, which are essential to any mix design. Mix designs are generally approved on the basis of these empirical measurements and physical properties, the appropriate values of which are derived from experience rather than theoretical analysis. For recommended design values for various classes of pavements, see Part Three.

Once it is approved, a mix design becomes the basis of acceptance for the mix itself, listing the aggregate ingredients and their proportions, the asphalt cement content, the gradation of the combined aggregates, and the compacted density. The process begins with the selection of suitable aggregates by the producer. The gradation of each aggregate is determined by a sieve analysis, and a blend of the aggregates is calculated by trial combinations, which will produce an even, continuous distribution of particle sizes, thereby reducing the voids among particles and the amount of asphalt cement needed to coat the particles and bind the mix together. (In certain types of mix the size distribution is not continuous, and stability is obtained from the structure of the large particles.) Specimens of the blended aggregates are then combined with asphalt cement in varied amounts. These are compacted, analyzed, and tested to determine how the properties of the mix vary with asphalt cement content. The optimum amount of asphalt cement is determined according to these properties. When the test results meet the design criteria, the design is approved, and the gradation of the combined aggregates, together with the optimum asphalt cement content, become the target values to be met during production. In other words, they become the Job Mix Formula (JMF).

The Job Mix Formula is the standard to which the mixture is compared for quality control and acceptance.

The Job Mix Formula is the standard to which the mixture is compared for quality control and acceptance. It lists the percentages of aggregates passing a series of standard sieves, plus the asphalt cement content, normally expressed as a per cent of the weight of mix. For each of these values the specifications must define appropriate tolerances, based on the probable error in the test as well as the allowable variation in the material. Notice that the JMF does not also specify exact percentages of ingredients to formulate the mix, since the producer may need to make small adjustments in these percentages to account for variations in the ingredients. It should be noted as well that the gradation limits for a mix *type*, as found in many standard specifications, are not to be confused with the gradation limits of a particular approved mix, as established in the mix design and the Job Mix Formula. The specifications merely establish the upper and lower limits of the gradation band which defines each mix type.

Because aggregate gradations vary somewhat in stockpiles, minor adjustments in the JMF are sometimes appropriate during production, if the change is not critical to mix characteristics. This involves expert judgment, however, and on smaller projects the production run is too brief for the adjustment to take effect. Specification tolerances for gradation must reflect the normal variability of materials and also testing error. To specify a paving mixture, the specification should list the design criteria to be met by the mix design, along with other criteria for the ingredients. It should next provide that the contractor shall submit a mix design and a proposed JMF to the owner for approval. Finally, it should establish test methods and a sampling plan, tolerances for compliance with the JMF, and provisions which apply in event of failure of the mixture to meet the requirements. All applicable test methods should be stated, including tests which may be made at the owner's discretion (and at whose expense). Appropriate remedies for materials out of specification depend largely on the nature and degree of the defect and the loads and rigors of climate which the pavement is intended to withstand.

Quality assurance and quality control

The term quality assurance commonly refers to inspecting and testing paving materials for acceptance and payment, while quality control refers to inspecting and testing them during manufacture or placement to detect variations in the process or ingredients. The latter is usually not a specification requirement, but some state agencies require the contractor to implement a quality control plan and to submit test results for review and verification. Usually the contractor is given some latitude in choosing the methods and frequency of testing. Contractors who are equipped and staffed to maintain a program of quality control testing are clearly able to deliver a better product.

For quality assurance testing, normally the services of an engineering testing firm are obtained. Acceptance criteria most often include the compacted density of the layer (discussed below), the conformity of the mixture to the Job Mix Formula, and the requirements established for mixture ingredients.

Acceptance plans

In addition to the criteria which the pavement must meet, the contract documents should state how the work is to be tested, the extent of testing services to be furnished, and how they will be paid for. On large public projects which go on for an extended time, work items for paving are often divided into lots and are tested and accepted for payment lot by lot, following statistical sampling procedures. This requires extensive laboratory and sampling resources, and is generally inappropriate for other categories of projects. However, even the simplest sampling and testing plans should provide enough test data to be representative of the work covered. Testing tolerances specified should reflect the precision of the test method, and remedies for defects should be stated, as discussed above. Since core samples can be obtained after the work is in place if defective material is suspected, acceptance tests on small to medium-sized projects are often specified on a contingency basis. Acceptance of ingredient materials is commonly based on the contractor's certification that they meet the contract specifications. Alternatively, samples may be set aside for testing at the discretion of the engineer or architect.

Mixture composition

This is usually tested by extracting the asphalt cement with trichloroethane or a biodegradeable solvent and performing a sieve analysis on the aggregates remaining. Standard methods for these tests are given in ASTM D 2172 and C 136. Samples for extraction testing may be obtained either during production and paving operations or afterward as cores from the compacted pavement. Recommended tolerances for gradation and asphalt cement content by the extraction method are provided in Table I, Part Three.

Recently, problems in disposal of used solvents and possible ill effects of solvents on health have led to increased use of alternatives to the extraction method. These include testing of asphalt cement content by the nuclear method (ASTM D 4125) and, for testing gradation, sieve analysis (ASTM C 136) of aggregate samples taken from the production process just prior to the mixing stage. It should be noted that for these methods, samples must be taken during production and set aside for testing, since core samples are not suitable. Testing by the nuclear method is rapid and non-destructive, but the testing device must be calibrated for each mix.

Automatic recordation of ingredient proportions is another alternative to extraction testing. The modern Hot Mix Asphalt mixing facility is highly automated, especially in the system which proportions ingredients of the mixture. A typical proportioning system is configured to record the batch weights or the rates of flow of the ingredients (depending on which mixing process the facility applies) and to print a summary of the mixture for each truckload. For smaller projects this information will generally suffice for acceptance purposes, subject to confirmation by other methods at the discretion of the owner's representative. Alternatively, it may be supplemented with asphalt cement measurements by the nuclear method and samples of the aggregates as mentioned above.

Density and compaction

Recommended standards for specifying compaction are provided in Part Three, Table J. The compacted density of a pavement is determined from the weight and volume of core samples (ASTM D 2726), or it may be measured in place by the nuclear method, ASTM D 2950. The latter method requires that the testing device be calibrated with core samples from the same material. With either method, the property actually measured is the bulk specific gravity of the pavement; its validity as a measure of compaction depends on how closely the mixture being tested resembles the mixture used as the density standard. If, for example, the asphalt cement content or the amount of dust-size particles in the mixture has varied, it is no longer comparable to the reference mix, and the compaction measurement may be higher or lower than the correct value.

One way to reduce this type of error is to compact samples of the mix during production by the same method used in the mix design laboratory, to obtain a new reference density. Where "field Marshall (or Hveem) samples," as they are called, are being prepared to monitor production, they provide density values which are more representative as a reference for determining the degree of compaction than the densities obtained from laboratory specimens in the mix design procedure. Hot samples of the mix are compacted in the same manner as the laboratory specimens. After cooling, they are tested for density and resistance to deformation, and the results should match the results obtained in the mix design within tolerances established in the specifications.

Besides providing reference values for compaction testing, field Marshall (Hveem) samples provide a check of other mix design parameters, measuring performance properties rather than actual composition. Density values tend to verify mix composition. Results are generally available sooner than those of extraction tests and indicate whether the mix has deviated from the design and, more significantly, how the deviation affects its quality. Field-compacted samples provide a very suitable method of monitoring the mixture, though they too may exceed the budget of a small project. Recommended tolerances for such samples are given in Part Three, Table I.

Recycled asphalt

Since the late 1970's, the development and utilization of efficient, smoke-free manufacturing equipment for processing Reclaimed Asphalt Pavement (RAP) has proceeded with increasing momentum. This has been greatly assisted through the leadership of a number of highway agencies which have incorporated recycling into their work as a routine procedure. For example, the State of Florida has for many years accepted mixtures containing RAP *on an equal basis with mixtures of unprocessed, or "virgin", materials.* Not only has this policy reduced costs by many millions of dollars, it has done so at no detriment to the quality and durability of pavements, as several studies have shown. It has also lessened the serious and growing problem of solid waste disposal.

Most RAP is obtained from cold milling of pavements which are being rehabilitated, although an increasing share is produced by crushing large fragments of removed pavement. Growing availability of equipment and increasing landfill charges are making cold milling of distressed pavements an increasingly common and economical procedure. Compared with conventional overlays, cold milling restores the pavement without the need to raise the grades of curbs and drainage structures, and it affords an effective solution to the problem known as reflective cracking— the propagation of cracks into a pavement overlay from an old asphalt layer below. Recycling also facilitates the total removal of a pavement, which is sometimes necessary to change the elevation of a surface or to correct a defective subgrade.

At present, RAP is most commonly used as a small percentage of the total ingredients in a mix — generally ten percent or less. Modern mixing facilities are capable of producing mixtures containing 60 percent or more, and many mixes for state highways may contain as much as 50 percent. In these cases the new asphalt cement in the mix may be a softer grade designed to restore the recycled asphalt cement to the consistency specified for virgin mixes. In many areas the procedures for analyzing and rejuvenating RAP are now quite routine, and as a less costly ingredient it reduces the cost of materials as it relieves a major solid waste problem. Best of all, it does all this without any loss of pavement quality. Some engineers, in fact, report that RAP actually improves pavement performance. Major corporations in growing numbers are adopting the use of recycled materials as part of their programs to become more environmentally responsible. For further information on this aspect of recycling, references on the subject may be found in Part Three, Section III.C.

ASPHALT
100% RECYCLABLE

I.D DESIGNER'S CHECKLIST FOR PART ONE

SITE CONDITIONS

Do the soil conditions, climate, and topography indicate a need for:

- ❑ Stabilizing or replacing subgrade soil?
- ❑ Installing subdrains?
- ❑ Special measures to prevent frost heave?
- ❑ Improving pavement slope in some areas?

Are specifications provided for:

- ❑ Undercutting and extra work?
- ❑ Grade tolerances, testing soil density and moisture?
- ❑ Acceptance of the work?

BASE AND CONSTRUCTION OPTIONS

Do local conditions and project needs favor any of the following base materials:

- ❑ Local materials — sand-clay base, limerock, etc.
- ❑ Treated base
- ❑ Granular base
- ❑ Hot Mix Asphalt base

- ❑ If stage construction is considered, how will the second stage be funded?
- ❑ Is site paving a desirable option?
- ❑ Single layer construction?
- ❑ Should some concrete work be completed after paving?
- ❑ Are estimates and cost comparisons based on local cost data?

SPECIFICATIONS

- ❑ Are prime coat and tack coat correctly specified?
- ❑ How will paving quantities be controlled and measured for payment?
- ❑ How is layer thickness specified?
- ❑ Are tolerances for subgrade elevations, pavement thickness, and finished grade consistent with each other?
- ❑ Do the specifications identify the mix types required?
- ❑ Are mix design criteria appropriate for the type of pavement?
- ❑ How will the mix design be approved?
- ❑ Are specifications for mixture ingredients based on state specs?
- ❑ What quality assurance and acceptance criteria will apply?

PART TWO: THICKNESS DESIGN PROCEDURE

Introduction

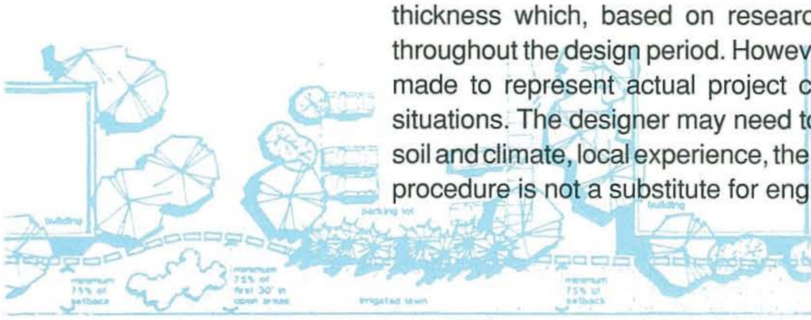
Part Two presents the methods for quantifying the effects of predicted traffic loads and assigning a structural value to the subgrade. Layer thicknesses are then found for these values by means of design tables. A design table is provided for each base and pavement combination — HMA over treated or granular base, or full-depth HMA. The design procedure can be summarized in five steps:

- **Traffic analysis** — determining the traffic class and design period with which to enter the design tables
- **Subgrade evaluation** — assigning a design class to the subgrade as determined by its properties
- **Materials selection** — identifying the different layer systems to be evaluated and compared, based on local availability and other factors, as discussed in Part One
- **Thickness determination** — obtaining layer thicknesses from the design tables for each layer system
- **Evaluating alternatives** — according to cost, engineering qualities, and construction advantages

Section II.A explains the traffic analysis procedure, and Section II.B provides guidelines for classifying the subgrade. The design tables are presented, with directions and examples, in Section II.C, which also explains the procedure for upgrading the subgrade design class through the use of improved subgrade. These steps are demonstrated by examples in Section II.C, which include an economic comparison of alternative layer systems.

Role of the designer

Determining layer thicknesses, it should be noted, involves the exercise of the designer's judgment. Much care and effort should be given to obtaining the data with which to enter the design tables, especially in estimating future traffic. The design tables indicate a thickness which, based on research and experience, will ensure good performance throughout the design period. However, this depends on how closely the entry data can be made to represent actual project conditions, which are rarely as simple as textbook situations. The designer may need to adjust the data based on personal appraisal of the soil and climate, local experience, the needs of the owner, and other intangibles. The design procedure is not a substitute for engineering judgment but a basis for applying it.



Risk assessment

Compared with building design, the structural design of low-speed pavements involves a somewhat lesser risk to public safety. Thus it is more concerned with the economic risks of investing too much or too little in materials and construction. It is important to consider what is meant by "conservative" design in this sense. When interest cost is included, a grossly over-designed pavement which never needs patching may prove more expensive than one which must be overlaid before the end of its design period. The cost of early repairs is normally greater than the cost of excess thickness, but repair costs in the final year or two of service may not be. Clearly, neither outcome obtains optimum value for the owner.

The design values in this manual should approximate the economic optimum. They are slightly conservative in the sense that, given minor flaws in construction and somewhat heavier traffic than predicted, a normal pavement will reach its intended design life without widespread cracking or major repairs. Assessing the risk of high maintenance expense versus initial cost has a bearing on all design decisions, but especially in traffic analysis, in selecting an appropriate value for the design period, and in obtaining adequate soil data.

II.A Traffic Analysis

Analysis and estimation of future traffic is a key step in the design procedure and should be researched as thoroughly as time will allow. There is a tendency to underestimate traffic loads, neglecting the probability that construction vehicles will operate on the pavement and that private access roads for trash pick up, delivery trucks, and buses will receive as much heavy traffic as a residential street.

Concepts and terminology

The traffic analysis procedure is based upon the following important concepts and terms:

Design period

This is the length of time the pavement is designed to last before rehabilitation or major maintenance becomes necessary. (This definition also applies to stage construction, even though the pavement thickness will be increased before maintenance is actually needed.) It should be noted that the design period selected for a flexible pavement may be different from that of a rigid pavement for the same use. The relative ease with which flexible pavement can be rehabilitated tends to influence this decision and also the state of wear to which it is allowed to deteriorate.

Design periods vary according to type of facility. Public highways are usually designed for twenty years and residential pavements for shorter or longer periods, reflecting public policy and financial resources as well as engineering decisions. Commercial establishments, institutions, and industrial sites, on the other hand, are more specialized in their needs. Retail facilities such as restaurants and filling stations are sometimes operated for periods as brief as ten years, while the grounds of a college, church, or hospital may be intended to remain for generations. For thickness design purposes the design period is used to project the total number of wheel loads which will act on the pavement. Should the designer also be called upon to prepare an economic analysis of life-cycle costs of different design periods for the owner, the reference on this subject in Section III.C will be especially helpful.

Categories of trucks

In preparing the design tables for this manual, truck traffic was divided into the following representative categories, all considered to be operating within legal weight limits:

— two-axle light delivery trucks
— light three-axle tractor semi-trailer trucks
— heavy trash pick up trucks
— heavy five-axle tractor semi-trailer trucks

In some areas, it should be noted, coal and logging trucks, ore and aggregate haulers, construction equipment, and military vehicles sometimes exceed legal weight limits, with and without special permits. Pavements liable to occasional minor overloads should be designed for a higher traffic category (as defined below) than otherwise; if overloads are either large or frequent, the pavement should be designed according to special procedures for heavy duty pavements. References on design of heavy duty pavements are found in Section III.C.

Equivalent Single Axle Loads (ESAL)

This important term is used to express the pavement distress caused by an axle load of given magnitude, in relation to the distress caused by a single 18,000 pound axle load. In the AASHO research on which most design methods are based, 18,000 pounds was taken as a standard load and assigned a damage factor of one. Heavier axle loads have ESAL factors greater than one and lighter axles, less, according to an exponential relationship derived from experimental data. The advantage of the ESAL concept is that factors for different axles — of one truck and also of trucks of different types — may be added, and thus the cumulative effects of many trucks of different types may be evaluated. *It is not necessary to calculate ESAL for the design procedure,* but if a design ESAL is given, it can be used to enter the design tables in place of the traffic class from Table A. Likewise, traffic and thickness relationships in this manual may be related to those found elsewhere by means of ESAL values. ESAL represents total axle loads during the design life; hence the values in the design tables are multiples of the ESAL for the design periods, in five-year increments.

Selecting the traffic class

Table A presents a set of criteria for selecting traffic classes. The common types of pavement facilities have been grouped into four classes, designated I through IV, according to the frequencies and sizes of axle loads typical of each class. The designer may select the appropriate traffic class by finding the class description most closely matching the type of facility being designed. The number of trucks per month for each class is also given and can be matched with the number predicted for the site. This may be helpful where no description resembles the facility being designed.

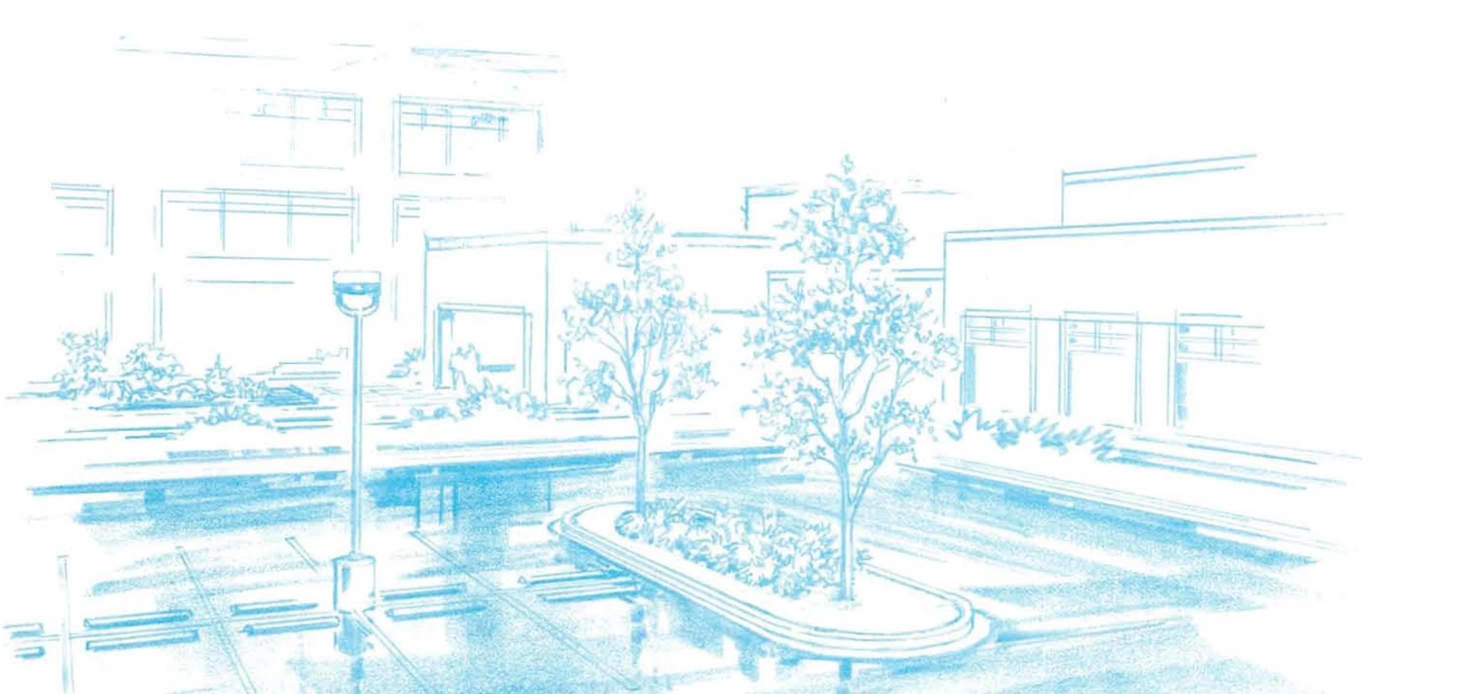
In the design tables, which are presented in Section II.C, the four traffic classes are further subdivided according to design periods of 5, 10, 15, and 20 years, for a total range of sixteen traffic categories with corresponding ESAL's.

When ESAL is known

As mentioned above, an alternate method may be used when a value for ESAL is given or can be estimated. In this case it is not necessary to use the traffic classes of Table A, since the design tables may be entered directly with the ESAL. A method of interpolating between ESAL values is presented in Example Three of Section II.C.

Multiple traffic zones

Where routes of heavy trucks and large numbers of vehicles can be separated from parking bays and other lightly trafficked areas, the designer should consider using a different layer system for each area. In this type of project, the base and binder layers for separate traffic zones differ in thickness and sometimes in type, and they are placed in separate operations. The surface course is usually the same for all areas and can be placed in one operation. Suggestions on the layout of the heavily travelled and lightly travelled zones of a parking area are discussed and illustrated in Part Three, Section III.A Figure III.A.4.



To summarize, the traffic analysis step can be accomplished two ways:

(a) Using Table A, determine the *traffic class* by matching the facility being designed to the nearest description, or find the traffic class corresponding to the estimated number of trucks per month. Second, determine the *design period,* to the nearest five-year increment, according to the nature of the facility and the owner's needs.

(b) If the total number of Equivalent Single Axle Loads (ESAL's) is given or can be estimated from available traffic studies, it is not necessary to refer to Table A, since the design tables can be entered with the ESAL.

TABLE A: TRAFFIC CLASSIFICATION

Type of facility and vehicle types	Maximum trucks per month (one lane)	Traffic class
Residential driveways, parking stalls, parking lots for autos and pickup trucks	<1	class I
Residential streets without regular truck traffic or city buses; traffic consisting of autos, home delivery trucks, trash pickup, occasional moving vans, etc.	60	class II
Collector streets, shopping center delivery lanes; up to 10 single-unit or 3-axle semi-trailer trucks per day or equivalents; average gross weights should be less than legal limit.	250	class III
Heavy trucks; up to 75 fully loaded 5-axle semi-trailer trucks per day; equivalent trucks in this class may include loaded 3-axle and 4-axle dump trucks, gross weights over 40,000 lbs.	2,200	class IV

Traffic analysis examples

1. Design for a shopping center with separate, well-delineated lanes for heavy semi-trailer delivery trucks:

   (1) Parking stalls and aisles are separated from travelled zones by traffic islands. No trucks will use parking zones.

   — See Table A (page 31). Traffic class I is selected for parking zones.

   (2) Light delivery trucks will make curb deliveries in front of small stores.

   — Traffic class II is selected for front access areas.

   (3) Heavy three-axle semi-trailer trucks delivering lumber, canned goods, etc, will be restricted to entrance roads and loading dock areas in the rear of the stores. Not more than five deliveries will be made per day.

   — Traffic class III is selected for entire rear access area.

2. Design for a multi-use road in an industrial park comprising warehouses and light manufacturing plants, with regular bus service and access to a major highway. It is estimated that 25 five-axle semi-trailer trucks per day will use the road in each direction.

   — Traffic class IV is selected.

It should be noted here that estimating both the numbers and sizes of trucks for mixed-use roads is uncertain, which compounds the uncertainty in ESAL's. On larger projects, the cost of over-designing or under-designing thickness will be substantial. It is recommended that data based on traffic studies be obtained whenever possible. State and county agencies can usually furnish traffic count maps showing nearby arterial roads as well as projections of future growth. Estimates of numbers and types of trucks can be based on local businesses.

II.B Subgrade Evaluation

Subgrade classification table

Table B (page 35) is a subgrade classification method based on the Unified Soil Classification System developed by the Corps of Engineers (also published as ASTM D 2487). The table can be entered with the soil type designation used in the Unified system, if known, or with the characteristics of the subgrade material. In either case, the table assigns each soil to one of five design classes, identified as very good, good, medium, poor, and very poor. Values of California Bearing Ratio (CBR) and Resilient Modulus (M_r) representative of these design classes are also given, which are the values which were used in preparing the thickness design tables.

Classifying by CBR or M_r

If the CBR or M_r of the soil is known, the design class corresponding to that value should be selected. This will usually produce a choice between design classes with higher and lower CBR's and M_r's. In this case the design procedure is followed through with both subgrade classes, and the designer should interpolate between the two thicknesses obtained. The interpolation is explained in Section II.C, in the text and Example Three.

Descriptions of design classes

For use in determining the design class, a description of all five classes is given below, followed by a short explanation of soil types, Unified soil classes, and the other parameters in Table B. Selection of a design class should be based on how well the soil matches the class description and the other parameters in the table and, for frost-susceptible soils, on the extent to which the depth of frost penetration in the area poses a danger of frost damage.

Very Good Subgrade

Materials described as Very Good consist of clean sands and gravels, usually well-graded, with no significant amount of particles finer than 0.02 mm. Such soils are not affected by freezing and may be suitable for use as subbase. They are particularly good for use as improved subgrade, or "select borrow," to replace poor soils.

Good Subgrade

Soils rated Good are similar to those rated Very Good but are not as well-graded nor as resistant to severe freezing conditions. They are also excellent as select borrow but may not be suitable as subbase in some cases.

Medium Subgrade

Soils in the Medium class include sandy or gravelly soils which contain significant amounts of silt and clay. Silty and clayey soils vary considerably in strength and are often highly susceptible to being weakened by freezing and by intruding moisture. They are often quite strong at or below optimum moisture. Where depth of frost penetration extends well into the subgrade, strong but silty sands and gravels should be classed as Medium.

Poor Subgrade

This class consists of silts and clays which are severely weakened by freezing or intrusion of water. They are distinguished from the Medium class by the greater amount of silt or clay particles they contain. Silts are especially susceptible to frost heave due to their high rate of capillary flow. Clays are weak and plastic over a significant range of moisture contents and may exhibit some swelling. Both types are weakened significantly by freezing and high moisture. Lime stabilization of clays is very effective in reducing plasticity, but it has been found to aggravate frost susceptibility in some instances.

Very Poor Subgrade

This class consists of organic soils and clays known to swell. They are unsuitable as pavement subgrade in all climates and should be removed and replaced.

Other classification parameters in Table A

Soil Type

Soils are described as gravels, sands, silts or clays, depending on the range of particle sizes present in greatest abundance. Gravels and sands are predominantly coarse-grained. *Gravel* usually refers to soils having a predominant size larger than the No. 4 sieve, and *sand* usually refers to soils finer than this sieve. *Silt* and *clay* soils are composed of very fine particles. Over half of the grains are finer than a No. 200 sieve, and individual particles are not visible without magnification.

Unified Classification

The Unified system classifies soils into groups having certain properties measured by laboratory tests. The following table provides a general description of the prefix and suffix code used to describe soils in this system:

Prefix	*Soil Type*	*Suffix*	*Subgroup*
G	Gravel	W	Well Graded
S	Sand	P	Poorly Graded
M	Silt	M	Silty
C	Clay	L	Clay, LL<50%
O	Organic	H	Clay, LL>50%

The clay subgroups L and H above are distinguished from each other by their liquid limits (LL), which is the moisture content above which a fine-grained soil behaves like a viscous liquid. This property is a good empirical measure of the soil's compressibility. A soil with a high liquid limit (H) is more compressible and thus a poorer subgrade material than a soil with a relatively low liquid limit. (For more information refer to *Atterburg limits* in a handbook on soil mechanics.)

Percent Finer Than 0.02mm

This is the percentage of clay and silt particles; it is particularly useful in describing how susceptible a soil is to frost action. Higher percentages, especially of silts, produce weakening and frost heave where freezing temperatures reach the subgrade. Frost heave is discussed under "Soil conditions" in Section I.A.

TABLE B: Subgrade Classification Guide

Soil Type	Unified Soil Class	Percent Finer Than 0.02mm	Permeability	Frost Potential[1]	Typical CBR[2]	Typical M_r, psi[2]	Design Class
Gravels, crushed stone Little or no fines <0.02mm	GW, GP	0 - 1.5	Excellent	NFS	17	20,000	Very Good
Sands, sand-gravel mix Little or no fines <0.02mm	SW, SP	0 - 3	Excellent	NFS	17	20,000	Very Good
Gravels, crushed stone Some fines <0.02mm	GW, GP	1.5 - 3	Good	PFS	17	20,000	Very Good
Sands, sand-gravel mix Some fines <0.02mm	SW, SP	1.5 - 3	Good	PFS	17	20,000	Very Good
Gravelly soils Medium fines <0.02mm	GW, GP, GM	3 - 6	Fair	Low	8	12,000	Good
Sandy soils Medium fines <0.02mm	SW, SP, SM	3 - 6	Fair	Low	8	12,000	Good
Silty gravel soils High fines <0.02mm	GM GW-GM, GP-GM	6 - 10 10 - 20	Fair to Low	Medium	8	12,000	Good
Silty sand soils High fines <0.02mm	SM SW-SM, SP-SM	6 -15	Fair to Low	Medium	8	12,000	Good
Clayey gravel soils High fines <0.02mm	GM, GC	Over 20	Fair to Low	Medium to High	5	7,500	Medium
Clayey sand soils High fines <0.02mm	SM, SC	Over 20	Low to Very Low	Medium to High	5	7,500	Medium
Very fine silty sands	SM	Over 15	Low	High to Very High	5 Replace in severe frost areas	7,500	Poor
Clays PI >12	CL, CH		Very Low	High	3 Replace in severe frost areas	4,500	Poor
All silt soils	ML, MH		Very Low	High to Very High	3 Replace in severe frost areas	4,500	Poor
Clays PI <12	CL, CL-CM		Very Low	High to Very High	3 Replace in severe frost areas	4,500	Poor
Other fine-grained soils	OL		Very Low	High to Very High	<3 Replace in severe frost areas	3,000	Very Poor
Highly organic soils	OH		Very Low	High to Very High	Replace		

[1] **NFS** = not frost susceptible
PFS = possible frost susceptible

[2] **CBR** = California Bearing Ratios and **MR** = Resilient Modulus values are minimumvalues expected for each subgrade class.

Permeability

This column describes the ability of the soil to drain away moisture which may otherwise lead to saturation or frost heave. Soils with fair to excellent drainage characteristics generally perform satisfactorily in all but the most extreme climatic conditions. Poorly drained soils should be improved where freezing may extend into the subgrade, and subsurface drainage should be provided in all cases.

Frost Potential

Frost potential is related primarily to the percentage of silt sizes present in the soil. Heavy or "fat" clays may not be susceptible to frost damage in moderate climates, since capillary movement and accumulation of moisture is extremely slow in these soils. (They may, however, be prone to swell.) Well-drained, non-cohesive soils are rarely affected by freezing except in very cold climates.

Further discussion of soil characteristics and their evaluation is found under "Supporting Layers" in Part One.

Improved subgrade

As mentioned in Section I.A, it is strongly recommended that pavements not be constructed directly on soils classified as Poor or Very Poor, particularly where frost action is liable to be a problem. Replacing or modifying such soils are the recommended alternatives. Table C (page 37) can be used as a guide for upgrading Very Poor and Poor soils to a medium or good subgrade soil classification for use with the design tables in Section II.C. The table indicates the depth of fill or replacement soil required to upgrade the design class. Note that limits are placed on the plasticity and compressibility of replacement soils which may be considered to upgrade the layer system in this way.

Example

Very Poor Subgrade: The site is marshy but not subject to hard freezing, and the native soil is a silty clay with traces of organic matter. The plans call for raising the grade to improve surface drainage and avoid the high water table. A source of silty gravel and sand is available for use as borrow material, which can be considered a Good class subgrade material since the climate is mild. In Table C it will be seen that by adding 24 inches of the silty gravel, the Very Poor subgrade is upgraded to a Medium class subgrade for design purposes. This will result in a reduction of pavement thickness and, in practical terms, will provide a much more suitable working platform for construction.

Soil stabilization

Soil stabilization involves the addition of materials such as lime, lime/fly ash, fly ash, cement, or emulsified asphalt to a subgrade soil to improve its properties. The percent of the soil material passing the No. 200 sieve and the plasticity index are used to select the type of stabilizer to use. Soils of the Very Good class in Table C (i.e., well-graded granular materials) can be stabilized with cement and used for granular base if they have less than 35 percent passing the No. 200 sieve and a plasticity index of less than 20. The Very Good class of soils also can be stabilized with cutback asphalt or asphalt emulsions if they are nonplastic (plasticity index of less than 6) and have less than 20 percent passing the No. 200 sieve.

Hydrated lime is an effective stabilization agent with clays, silty clays, and clayey gravels — soil classifications CH, CL, ML, MH, CL-MH, SC, SM, GC, and GM in Table C — provided that the plasticity index of the soil is not less than 10. Lime reduces plasticity, increases

TABLE C: Guidelines for Using Improved Subgrade Material to Improve Subgrade Design Class

To Upgrade Design Subgrade Class		Type and Thickness of Improved Subgrade Needed to Upgrade		
From	To	Base Quality	Very Good [1]	Good [2]
Very Poor	Medium	9	14	24
	Good	14	22	36
Poor	Medium	6	9	18
	Good	9	14	24

[1] These materials will fall in the very good subgrade class in Table 2.2 and may be used as select borrow provided the liquid limit (LL) is less than 25 and the plasticity index (PI) = 0.

[2] These materials will fall in the good subgrade class in Table 2.2 and may be used as select borrow provided the liquid limit is less than 30 and the plasticity index is less than 7.

[3] Thickness given in inches.

workability, reduces swell, and increases the strength of clay soils. It is of little effect, therefore, on non-plastic soils, which should be treated by one of the other methods. *Many stabilized soils will meet the criteria below for treated bases and may be treated as such in designing the pavement.*

Treated bases

For purposes of design, treated bases are divided into two classes:

Class I treated bases include asphalt bases that meet mix design requirements and acceptance criteria given in Part III for Hot Mix Asphalt base mixtures.

Class II treated bases include emulsified asphalt, portland cement treated bases, or lime/fly ash mixes made with semi-processed crusher-run or bank-run sands and gravels. Emulsified asphalt treated mixes usually have lower residual asphalt contents and higher voids than Class I bases. These bases may be mixed in place but should be carefully controlled during construction.

Note: Cement-treated and lime/fly ash bases should be not less than six inches thick.

Selecting design subgrade class

Selecting the designing subgrade class is reasonably straightforward if the soil is uniformly of the same type. This may be done by matching the soil description with information given in Table B, as explained above. If the CBR or M_r of the soil is known, the design class corresponding to that value should be used.

If the CBR or M_r of the soil falls between two subgrade classes, a design can be obtained for both subgrade classes, and the appropriate thickness obtained by interpolation. In most cases, the thicknesses obtained for the lower subgrade class and the next higher subgrade class will differ by 1.0 to 1.5 inches, and an interpolated design could result in a significant savings on a large job. The interpolation procedure is explained is Section II.C Thickness Design and Examples.

If the soil type appears to vary over the area to be paved, tests should be performed to determine the extent of each different soil type. If the investigation shows that there are large differences in soil types within the project area, there are several possible ways to come up with a design that will be economical.

On small jobs, designing for the lowest soil class may be acceptable. The areas with the higher class of soil will be somewhat conservative, and on large jobs this may not be economical.

If the area contains poor and very poor soils that are scattered over the entire area to be paved, the poorer soils should be removed and replaced with better soils, as explained in the section on *Improved subgrade*. Alternatively, if the poor soils are confined to well-delineated areas, separate designs can be prepared and constructed for each soil type.

Both conservative and unconservative designs may be produced if the poorer soils are not replaced. For example, a poor class subgrade soil on a site for a parking lot might require a 7.0 inch Hot Mix Asphalt pavement, but a good class subgrade soil would require only 4.5 inches. Constructing 7.0 inches over the entire pavement area would be economical only if the higher soil class is a very small proportion of the entire area, or if replacement is not feasible for some other reason.

Constructing the entire area 4.5 inches thick would produce early failures in the poor soil areas. In fact, the pavement on the poor soil areas would have a projected design life equal to or less than one-tenth of the life of the pavement on the good soil areas.

Some designers may be tempted to design for an intermediate soil class. In this example, the design using a medium subgrade class would be 6.0 inches. This would produce a conservative design for the good class soil, but the poor class soil could still be in danger of failing early; it would have a projected life equal to one-third or less of the projected life for the good soil areas.

In other situations, where a substantial amount of soil CBR or M_r test data is available, it may be feasible to interpolate to obtain a design. However, using an average test value should be avoided, and the possibility of underdesign, and early failures in the low strength areas should be considered. The Asphalt Institute recommends the use of the 85th percentile value from the lowest to the highest test value for design where there is considerable scatter in the data for the project. An example of this procedure is given in Section II.C. Thickness Design and Examples.

II.C THICKNESS DESIGN AND EXAMPLES

Procedure

Having (1) checked the site conditions, the materials available, and the construction schedule, (2) analyzed the traffic and classified the soil, and (3) identified the alternatives to be considered, the designer is ready to enter Tables D (page 44), E (page 44), and F (page 45) to determine layer thicknesses. The design tables present the basic relationship between traffic loads, strength of supporting layers, and pavement thickness requirements. The reader may find it helpful to look over these tables briefly and refer to them while completing the remainder of this section.

Table D is for full-depth asphalt pavements (or, applying the definitions of bases above, asphalt pavements over Class I bases.) Tables E and F are for pavements with Class II treated base and untreated granular base, respectively. With the traffic class, design period, (or the ESAL) and subgrade class known, pavement thicknesses required for each base type can be read directly from the tables.

Interpolation

Thicknesses of Hot Mix Asphalt and Class II base courses have been rounded to the nearest half inch in the design tables provided in this section. Thicknesses of untreated granular base courses are provided in two-inch increments. For many design situations this will be adequate. However, it may be desirable to design to closer tolerances for various reasons, as explained in Section II.A Traffic Analysis and Section II.B Subgrade Evaluation.

Some agencies will supply the ESAL and design period to be used for design. In other cases results of traffic predictions may be available for predicting ESAL. Results of soil tests also may be available and used to select a design subgrade CBR or M_r value. If the specified values do not correspond to the specific values given in the design tables, an interpolation procedure may be used to select design thicknesses. The procedures for interpolating between design traffic ESAL or subgrade test values are given below.

Interpolate for traffic ESAL

The first step in the interpolation procedure is to select the ESAL to be interpolated for. This is called the *target value*. Next, determine the thickness design for the traffic ESAL immediately below the target value and the design for the traffic ESAL above the target value. Interpolate between the two by plotting thickness against the common logarithm of ESAL. Example 3 shows how this is done.

There are two cases where interpolation to obtain a subgrade design value may be desirable: (1) when the actual CBR or M_r is known, and it falls between two classes in Table B, or (2) when multiple test data indicates that the subgrade CBR or M_r varies over the project. In either case, refer to the discussion in Section II.B Subgrade Evaluation before interpolating to avoid producing designs which may lead to premature pavement deterioration.

Interpolate for design subgrade value when CBR (or M_r is known).

The first step in the interpolation procedure is to select the subgrade CBR or M_r to be interpolated for. This is called the *target value*. Next, determine the thickness design for the CBR or M_r of the subgrade class immediately below the target value and the design for the subgrade class immediately above the target value. Interpolate between the two by plotting thickness against the CBR or M_r. Example 4 shows how this is done.

Interpolate for design subgrade value when multiple test datas are available

This procedure involves determining the 85th percentile value of all test data available. Once this value is found, the procedure above can be used to find the pavement thickness design. See Example 4 for an explanation of the procedure.

Examples

Example 1: CHOICE OF BASE

The project is a new factory located near the Carolina coast, where the average depth of frost penetration is less than three inches. The facility will have a roadway to and from a loading dock. It is projected that the traffic on this roadway will consist of Class IV traffic over a 10-year design period. In addition, there will be a parking area designed for passenger cars and occasional light panel delivery trucks. Class I traffic is predicted for the parking area. Soils on the site are primarily clayey sands, type SM, with about 25% material finer than 0.02mm. A medium subgrade class is chosen from Table B.

The nearest sources of crushed stone (untreated granular base) are sixty miles away, but excellent sources of sand and sand-clay suitable for use as treated base area are available near the site. Following suggestions of local builders, the designer wishes to compare three choices of base: (1) Full-Depth Hot Mix Asphalt, (2) Class II treated base, and (3) crushed stone base. Determine the thickness of each layer in the system. Tables D, E, and F yield the following alternatives.

Only one alternative is available for the parking area, a 3.0- inch Full-Depth Hot Mix Asphalt. However, there are several possibilities available for the access roadway, as shown in the following table.

	Design Alternative — Thickness, Inches		
Layer	*Full-Depth Hot Mix Asphalt*	*Class II Treated Base*	*Untreated Granular Base*
Hot Mix Asphalt [1]	8.0	4.5	5.5
Alternative Base Course	—	6.0	6.0

[1] Hot Mix Asphalt surface, binder and /or base mixes meeting the requirements given in Section I. Hot Mix Asphalt and Section III.B Quality Control.

Example 2: COMPARING COSTS OF MATERIALS

It will be recalled that estimators' unit prices for Hot Mix Asphalt pavement may include labor, equipment, and mobilization costs and are therefore influenced by the size of the job and the number of pavement layers. When comparing slightly different thicknesses for the same area, however, these costs are roughly equal, and the choice between alternatives can often be resolved by comparing material costs.

Calculate the quantities of materials required for the parking areas in the example above.

The total area of pavement may not be definite at this point in the design process; for convenience, quantities can be calculated for some nominal unit of area. Here we will use 1000 square feet. Multiples of the results can be used later in preparing actual estimates. Since thicknesses are given in inches, first determine the volume of a layer 1000 sq ft by one inch:

$$1/12 \text{ ft times } 1000 \text{ sq ft} = \textit{83.3 cu ft.}$$

By contacting local contractors it is determined that representative asphalt mixes from the materials in the area tend to have design unit weights of about 140 lbs/cu ft for both bases and surface mixes. Project specifications will require compaction to 95% of design density. We will assume an average of 97%. The average compacted unit weight of the mix will be:

$$(140)(0.97) = 136 \text{ lbs/ cu ft.}$$

And 1000 sq ft by one inch will weigh $\frac{(83.3)(136)}{2000} = 5.67$ tons of HMA.

Similarily, 1000 sq ft by one inch of crushed stone (124 lbs/cu ft) will weigh:

$$\frac{(83.3)\ (124)}{2000} = 5.16 \text{ tons of crushed stone.}$$

Having eliminated the treated base alternative, we compare material quantities and costs for full-depth HMA and the granular base alternative.

Quantities	*Full-Depth*	*Stone Base*
Hot Mix Asphalt	19.8 tons	17.0 tons
Crushed stone base	0	31.0 tons

The cost of crushed stone is determined to be $5.80 per ton plus thirteen cents per ton-mile of haul. ($0.13) (60 mi) + $5.80 = $13.60, and ($13.60) (5.16) = *$70.18* per 1000 sq ft of stone. The cost of placing, grading, compacting, and testing the stone is not known at this point.

The high cost of hauling crushed stone is also reflected in the delivered price of Hot Mix Asphalt, although it is partly offset by using locally available fine aggregates. The cost of the material at the site, excluding all installation costs, which are assumed to be equal, is found to be $24.50 per ton.

The full-depth alternative will then cost ($24.50/T)(19.8 T) = *$485.10* (per 1000 sq ft),

while the stone base alternative will cost ($24.50/T)(17.0 T) + *$70.18* = *$486.68* (per 1000 sq ft.).

Such a small difference between estimates is insignificant, since the probable error in estimated costs is much greater. At this point the designer may elect to:

(1) assume that the stone base alternative will always cost more when the installation cost for the stone base and the additional construction time are considered; or

(2) prepare the proposal with alternative bid items in order to compare actual bid prices rather than estimates; or

(3) prefer one alternative or the other on the basis of construction-related advantages and engineering judgment.

Example 3. INTERPOLATION BETWEEN TRAFFIC CLASSES

The owner in this case provides the designer with a target ESAL value of 350,000 for a pavement to carry Class IV heavy truck traffic. The soil is classified as Good and a Full-Depth Hot Mix Asphalt design is selected to reduce construction time.

The target ESAL value of 350,000 falls between ESAL values of 270,000 and 540,000 in Table D. From Table D the following thicknesses are obtained:

ESAL	*Thickness, Inches*
270,000	5.5
350,000	to be determined
540,000	6.5

A logarithmic interpolation between thicknesses is used to determine the thickness for 350,000 ESAL. The procedure is illustrated in Figure II.C.1. The interpolated thickness also can be calculated, as illustrated below.

log of 270,000 = 5.43
log of 350,000 = 5.54
log of 540,000 = 5.73

The adjustment in thickness will be:

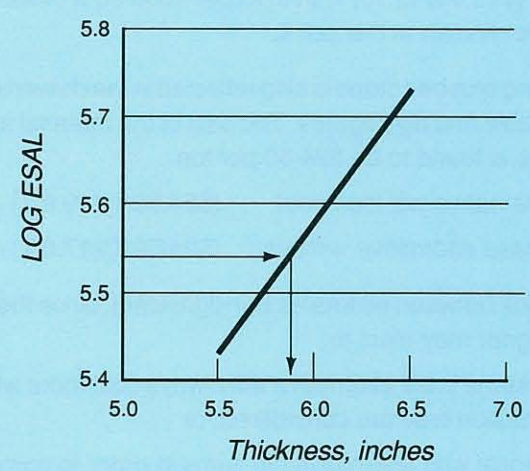
$$\frac{5.54 - 5.43}{5.73 - 5.43} = 0.37 \times 1.0 \text{ inches,}$$

or 37 percent of the difference between 5.5 and 6.5 inches.

The calculated thickness is:

$$5.5. + 0.37 \times 1.0 = 5.87 \text{ inches (use 6.0 inches).}$$

FIGURE II.C.1: ESAL Interpolation



Example 4: INTERPOLATION BETWEEN SUBGRADE CLASSES

A major access road is to be designed for a target subgrade CBR value of 6, which lies between a value of 5 for a Poor subgrade class and a value of 8 for a Medium class. The traffic class is III and a 20 year design is called for. The following thicknesses of Hot Mix Asphalt are obtained from Table D:

Subgrade CBR	*Thickness, Inches*
5	7.0
6	to be determined
8	6.0

Because of the quantity of materials required, it is decided to design for the intermediate CBR value to effect cost savings on the project. The design thickness is obtained by simple straight-line interpolation.

The design value can be calculated, as shown below, or solved graphically as shown in Figure 2

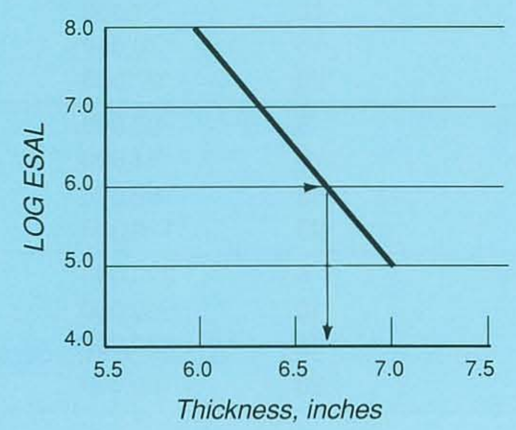
The adjustment in thickness will be:

$$\frac{8.0 - 6.0}{8.0 - 5.0} = 0.67 \times 1.0 \text{ inches,}$$

or 67 percent of the difference between 6.0 and 7.0 inches. The calculated thickness is:

$6.0 + 0.67 \times 1.0 = 6.7$ inches (use 6.75 or 7.0 inches).

FIGURE II.C.2: Subgrade Interpolation



Example 5: DETERMINING DESIGN SUBGRADE CBR OR M_r FROM MULTIPLE TEST DATA

The following CBR values have been obtained for a roadway: 3.0, 4.0, 4.0, and 7.0. The design CBR is calculated as follows:

CBR	*Number of Tests*[1]	*Percent of Tests*[1]
7.0	1	1/4 = 25
4.0	3	3/4 = 75
3.0	4	4/4 = 100

[1] Equal to or greater than the given CBR value.

The design CBR will be between 3.0 and 4.0. Simple straight-line interpolation can be used to determine the exact value, as was calculated in Example 4, or graphically as shown in Figure II. C.2.

The design CBR in this case is 3.6. The pavement thickness design for 3.6 CBR can be determined as shown in Example 4.

FIGURE II.C.3: Interpolation for Multiple subgrade tests

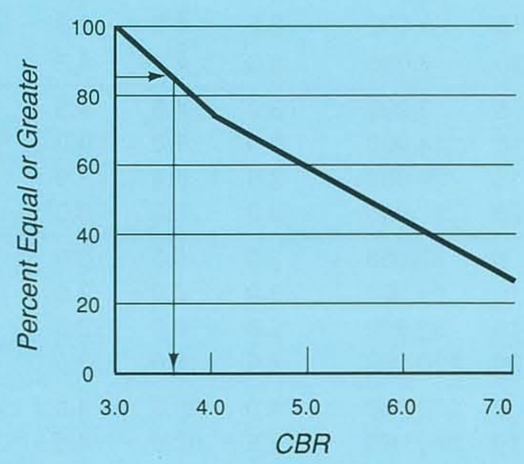


TABLE D: Full-Depth Hot Mix Asphalt Thickness Selection Chart

			Full Depth Asphalt Thickness, inches				
Traffic Class	Design Period Years	Design ESAL	Very Poor Subgrade[1]	Poor Subgrade[1]	Medium Subgrade	Good Subgrade	Very Good Subgrade
I	5	3,000	4.5	3.5	3.0	3.0	3.0
	10	3,000	4.5	3.5	3.0	3.0	3.0
	15	5,000	5.0	4.0	3.0	3.0	3.0
	20	7,000	5.5	4.5	3.5	3.0	3.0
II	5	7,000	5.5	4.5	3.5	3.0	3.0
	10	14,000	6.0	5.0	4.0	3.0	3.0
	15	20,000	6.5	5.5	4.5	3.0	3.0
	20	27,000	6.5	6.0	4.5	3.0	3.0
III	5	27,000	6.5	6.0	4.5	3.0	3.0
	10	54,000	7.0	6.5	5.5	4.0	3.0
	15	82,000	7.5	7.0	6.0	4.5	3.5
	20	110,000	8.0	7.0	6.0	4.5	3.5
IV	5	270,000	9.0	8.0	7.0	5.5	4.0
	10	540,000	10.0	9.0	8.0	6.5	5.0
	15	820,000	10.5	9.5	8.5	7.0	5.5
	20	1,100,000	11.0	10.0	9.0	7.5	6.0

TABLE E: Thickness Selection Chart Using Class II Treated Base

			Design Thickness Using Class II Treated Base, Inches									
			Very Poor Subgrade[1]		Poor Subgrade[1]		Medium Subgrade		Good Subgrade		Very Good Subgrade	
Traffic Class	Design Period Years	Design ESAL	Asphalt Surface & Base[2]	Minimum Granular Base[3]	Asphalt Surface & Base[2]	Minimum Granular Base[3]	Asphalt Surface & Base[2]	Minimum Granular Base[3]	Asphalt Surface & Base[2]	Minimum Granular Base[3]	Asphalt Surface & Base[2]	Minimum Granular Base[3]
I	5	3,000	4.5	0.0	3.5	0.0	3.0	0.0	3.0	0.0	3.0	0.0
	10	3,000	4.5	0.0	3.5	0.0	3.0	0.0	3.0	0.0	3.0	0.0
	15	5,000	3.0	4.0	4.0	0.0	3.0	0.0	3.0	0.0	3.0	0.0
	20	7,000	3.0	4.5	4.5	0.0	3.5	0.0	3.0	0.0	3.0	0.0
II	5	7,000	3.0	4.5	4.5	0.0	3.5	0.0	3.0	0.0	3.0	0.0
	10	14,000	3.0	5.0	3.0	4.0	4.0	0.0	3.0	0.0	3.0	0.0
	15	20,000	3.0	5.5	3.0	4.5	4.5	0.0	3.0	0.0	3.0	0.0
	20	27,000	3.0	6.0	3.0	5.0	4.5	0.0	3.0	0.0	3.0	0.0
III	5	27,000	3.0	6.0	3.0	5.0	4.5	0.0	3.0	0.0	3.0	0.0
	10	54,000	3.0	7.0	3.0	6.0	3.0	4.5	4.0	0.0	3.0	0.0
	15	82,000	3.0	8.0	3.0	6.5	3.0	5.0	4.5	0.0	3.5	0.0
	20	110,000	3.5	8.0	3.0	8.0	3.0	5.5	4.5	0.0	3.5	0.0
IV	5	270,000	4.0	10.0	4.0	8.0	4.0	6.0	3.5	4.0	4.0	0.0
	10	540,000	4.5	10.0	4.5	8.0	4.5	6.0	3.5	6.0	5.0	0.0
	15	820,000	5.0	10.0	5.0	8.0	5.0	6.0	4.0	6.0	5.5	0.0
	20	1,100,000	5.5	10.0	5.5	8.0	5.5	6.0	4.5	6.0	6.0	0.0

Use Full-Depth Asphalt, see Table D

TABLE F: Thickness Selection Chart Using Untreated Granular Base

			Design Thickness Using Class II Treated Base, Inches									
			Very Poor Subgrade[1]		Poor Subgrade[1]		Medium Subgrade		Good Subgrade		Very Good Subgrade	
Traffic Class	Design Period Years	Design ESAL	Asphalt Surface & Base[2]	Minimum Granular Base	Asphalt Surface & Base[2]	Minimum Granular Base	Asphalt Surface & Base[2]	Minimum Granular Base	Asphalt Surface & Base[2]	Minimum Granular Base	Asphalt Surface & Base[2]	Minimum Granular Base
I	5	3,000	3.0	4.0	3.5	0.0	3.0	0.0	3.0	0.0	3.0	0.0
	10	3,000	3.0	4.0	3.5	0.0	3.0	0.0	3.0	0.0	3.0	0.0
	15	5,000	3.5	4.0	4.0	0.0	3.5	0.0	3.0	0.0	3.0	0.0
	20	7,000	3.0	6.0	4.5	0.0	3.5	0.0	3.0	0.0	3.0	0.0
II	5	7,000	3.0	6.0	4.5	0.0	3.5	0.0	3.0	0.0	3.0	0.0
	10	14,000	3.5	6.0	3.0	6.0	4.0	0.0	3.0	0.0	3.0	0.0
	15	20,000	4.0	6.0	3.5	6.0	4.5	0.0	3.0	0.0	3.0	0.0
	20	27,000	4.5	6.0	3.5	6.0	4.5	0.0	3.0	0.0	3.0	0.0
III	5	27,000	4.5	6.0	3.5	6.0	4.5	0.0	3.0	0.0	3.0	0.0
	10	54,000	5.0	6.0	4.0	6.0	5.5	0.0	4.0	0.0	3.0	0.0
	15	82,000	5.5	6.0	4.5	6.0	6.0	0.0	4.5	0.0	3.5	0.0
	20	110,000	6.0	6.0	5.0	6.0	6.0	0.0	4.5	0.0	3.5	0.0
IV	5	270,000	6.5	8.0	5.5	8.0	5.0	6.0	5.5	0.0	4.0	0.0
	10	540,000	7.5	8.0	6.5	8.0	5.5	6.0	6.5	0.0	5.0	0.0
	15	820,000	8.0	8.0	7.0	8.0	6.0	6.0	7.0	0.0	5.5	0.0
	20	1,100,000	8.5	8.0	7.5	8.0	6.5	6.0	7.5	0.0	6.0	0.0

Use Full-Depth Asphalt, see Table D

Footnotes for Tables D, E and F:

1 Very Poor and Poor subgrades should be replaced with higher quality materials. Guidelines for improving these soils to a higher classification are given in Section II.B. Subgrade Evaluation.

2 Hot Mix Asphalt composed of 1.5 inches of Hot Mix Asphalt surface mix plus binder or base mix. Mixes should meet requirements given in Sections I.C. Hot Mix Asphalt and III.B. Quality Control.

3 Cement treated and lime-fly ash base courses should not be constructed less than six inches thick.

CAUTION:

Layer thicknesses in these tables are not intended to account for the possibility of frost heave. Refer to "Soil conditions" in Section I.A and to Section II.B. The designer should ensure that all layers above the depth of frost penetration consist of HMA or other materials not susceptible to frost heave. Where this is uneconomical because frost penetration is extremely deep, recommendations of local geotechnical engineers should be followed

PART THREE: TECHNICAL SUPPLEMENTS

III.A NOTES TO THE DESIGNER

Horizontal layout and traffic plan

The task of laying out parking areas and access routes for a building complex requires more creative effort than road design, since there are more functional requirements and more possible solutions. Patterns of traffic routing, stormwater runoff, lighting, and landscaping must be tailored to the land area available, while the designer must give close attention to user interests in matters of capacity, security, pedestrian safety, access for the handicapped, etc. Several excellent references on the architectural aspects are available, including *Parking for Industrial and Office Parks,* published by the National Association of Industrial and Office Parks in Arlington, Virginia. Little can be contributed here on these topics, except to point out how certain layout features are related to thickness design and constructability.

Constructability

Both the cost and quality of a pavement may be affected by its shape and dimensions, which have great bearing on how efficiently the area can be paved. Irregular or tightly confined areas, varying pavement widths, and storm drains or utility boxes which extend into the pavement all slow down the paving operation and increase the difficulty of maintaining smoothness and correct grade. Placing the mix by hand should also be avoided whenever possible, since it cannot match the uniform density and smoothness of machine-laid material, and since it proceeds so slowly that compacting all of it at the optimum temperature becomes difficult. It is also extremely slow and labor-intensive. Compaction is also difficult in confined areas where smaller and less effective equipment must be used.

Constructability is greatly improved when the area to be paved can be covered by the paving machine in parallel passes of constant width. Also, there is little real advantage in varying the pavement width merely to conserve small quantities of material. In fact, paving crews sometimes trim away excess material rather than to spend time forming an irregular edge line by hand. Tapered or irregular areas, the presence of obstacles, and the clearances between them determine how much hand placement will be necessary and how many joints there will be in the pavement. A standard paving machine lays the mix in a minimum ten-foot width (3 m) and needs about one-half foot (0.15m) additional clearance on each side. Eight-foot machines and smaller are sometimes available, and for wider paving the fixed width can be extended, usually in increments of one-half foot.

However, changing the paving width requires some delay on most machines.

Layout for multiple classes of traffic

As mentioned under "Traffic analysis" in Section II.A, substantial cost reductions can sometimes be achieved in a multi-use area by isolating zones to be used by heavy vehicles and designing the remaining areas for a lighter class of traffic. Figure III.A.4 illustrates this concept. The concept should not be extended to using different thicknesses within the same bounded areas, as would be true, for example, if the parking bays were designated Class I and the aisles between them, Class II. This is because it is difficult to compact the supporting layer and control grades properly along the joint line between areas of different pavement thickness. The demarcation of traffic zones should follow dividers, fences, or other boundaries where encroachment onto the thinner section is prevented. A good rule is to keep the joint lines between zones of different thickness as short as possible and also transverse to the longer dimensions of the area, or the direction in which grading and paving equipment will be working.

Heavy duty pavements

Loading areas and other pavements subject to heavy vehicles are sometimes needlessly paved with portland cement concrete in the belief that HMA pavements do not withstand slow-moving or static heavy loads. While it is true that underdesigned and poorly supported pavements of either material will fail under such loads, HMA pavements in industrial yards, ports, and similar applications have been very successful. Mix types utilized for this type of project are designed for heavy wheel loads, and proper design, construction supervision, and quality control testing also make an important difference.

Materials and thickness designs for heavy duty pavements

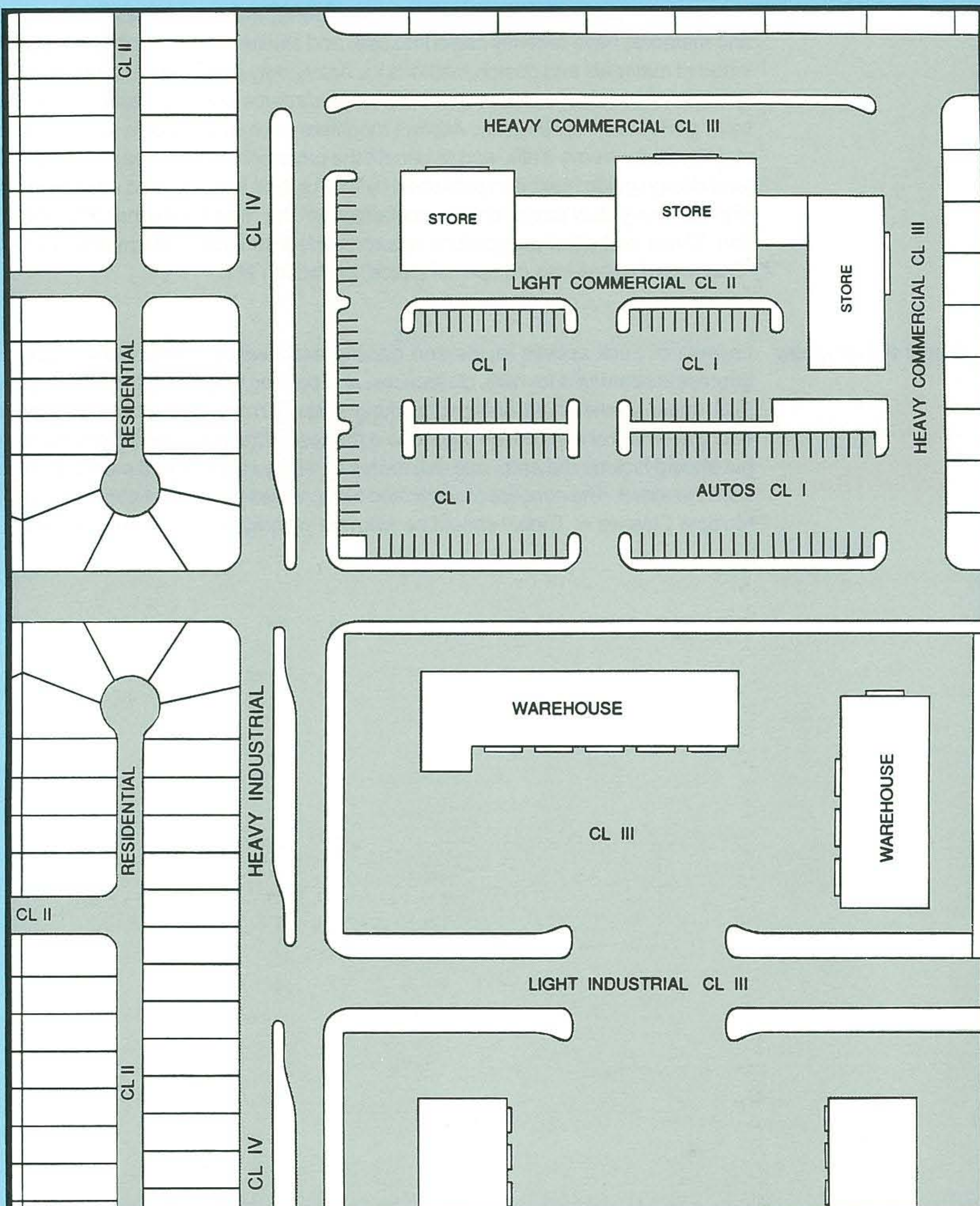
Pavements for traffic normally allowed on public highways (i.e., maximum single axle loads not exceeding 18,000 lbs, with infrequent, minor overloads) should be designed by the methods presented in Part Two. For this class of heavy-duty pavements, conventional structural and surface mixes of the types approved by state DOT's for use on major highways should be specified.

For unusual loads and other extreme conditions, more sophisticated design methods and materials have recently come into use, and studies have enlarged our working knowledge of materials and design methods for heavy duty pavements. Large-stone mixes, for example, have been used in a number of pavements under extremely heavy loads and have performed impressively. Asphalt modifiers have been shown to improve pavement stability under heavy traffic and to benefit the pavement in other ways. An excellent structural design guide has been published by the Asphalt Institute, and a guide to mixture design for heavy-duty pavements is available from the National Asphalt Pavement Association. These and other publications recommended for further information are listed under "Suggested references on special topics" in Section III.C.

Layout of heavy traffic areas

Layouts of truck access routes and parking and loading areas should follow published geometric standards for radii, clearances, and parking space configurations. (See Section III.C, under "Architectural design of parking areas.") In a multi-use facility, the area of heavy duty pavement should not be limited to a modest rectangle in the loading or storage area but should include the entry and exit routes of heavy vehicles and especially the entrance from the street. The concept of separated traffic zones suggested above under "Layout for Multiple Classes of Traffic" should be followed wherever separation is feasible.

FIGURE III.A.4: Multiple Traffic Zone Design Configuration



III.B QUALITY CONTROL: NOTES AND SPECIFIC

Inspection and testing services

On small and medium-sized projects the risks of neglecting quality assurance tend to be underestimated, possibly in the belief that it is less costly simply to repair any obvious defects. Yet the true quality of a pavement will not become evident for several years, when causes of distress may be difficult to establish. For a large construction item such as a pavement, the costs of inspecting and testing the work properly are always a sound investment.

In Part One a number of items were discussed which need to be inspected or tested during construction. The important items of a basic quality assurance plan are summarized in the checklist below, which may be helpful in drafting specifications. Test methods and recommended tolerances are covered later in this section and are listed in Table G (page 52) and Table I (page 56).

1. **Subgrade preparation**
   Observe soil preparation and provide moisture testing as needed. Test moisture and compacted density of the soil for acceptance. Approve soil replacement (undercutting) if needed. Observe proof-rolling and correction of soft spots. Set or check grading stakes and check grades. Inspect prime coat application and quantities, if applicable.
2. **Treated base or subgrade**
   In addition to items above: Check quantities of stabilizer, borrow, or aggregates. Inspect mixing, depth of treatment, etc. as appropriate.
3. **Granular base**
   Approve subgrade preparation before authorizing base work. Verify quantities and layer thickness. Observe compaction operations, inspect for segregated areas. Test compaction. Check grades. Inspect prime coat application and quantities
4. **Pavement and asphalt base course**
   Review and approve mix design. Test mixture composition and design properties. Verify layer thicknesses and quantities of each mix type. Test compacted density of each layer. Inspect smoothness and grades.

It is not always necessary to provide full-time inspection during the paving phase. It is important, however, that someone representing the owner should check and approve all backfilling, subgrade, and paving work before each new phase and keep records of work item quantities and delivered materials. The architect or engineer should be available to approve all changes and extra work. In addition to representing the owner's interest, this avoids many problems arising from poor communication and tardy decision making, which are major causes of disputes and claims. Nothing helps the work go smoothly as when the contractor knows beforehand exactly what the owner wants, but this demands foresight and communication by both parties.

Compaction and testing of the subgrade

The strength of a soil is obtained by densifying it through compaction; a poorly compacted soil will not provide the support value on which the pavement design is based. Excess void space in such a soil consolidates under the pavement and may make the subgrade more erodable by intruding moisture. Also, a compressible material under the first paving course makes it difficult to compact the mixture and is often the true cause of low pavement densities. By far the worst subgrade failures occur in areas built up with fill.

Subgrade compaction is sometimes under-specified. Density values recommended below, like those to be found in reliable geotechnical references, reflect the capabilities of modern compacting machines, which if applied with a knowledge of compaction principles will consistently exceed the limits recommended.

Density

Recommended limits for soil density are presented in Table G. Soil classes in the table are those of the Unified system as used in Table C, Section II.B. Density limits are expressed as percentages of the maximum dry density as determined by the Standard Proctor method, AASHTO T-99 or ASTM D 698, and the Modified Proctor method, AASHTO T-180 or ASTM D 1557. The latter method is preferable where subgrade compaction will be accomplished by large vibratory rollers and other heavy equipment.

The degree of compaction a soil should receive depends on the nature of the structure it is to support, the properties of the soil, and its depth below the pavement. Pavements are among those structures for which a very high degree of compaction is needed. As indicated in Table G, compaction and moisture requirements should be specified differently for non-cohesive, cohesive, and clayey soils.

The depth to which the soil should be prepared and tested is as follows: Native soil in cut areas should be worked and compacted to a depth of at least 6.0 in. (150mm), or deeper in soils of low bearing capacity. This reworked material and the upper three feet (1m) of fill

TABLE G: Recommended Specification Limits for Subgrade Compaction

Soil type	Per cent of maximum dry density			
	AASHTO T-99		AASHTO T-180	
	0 to 3 ft (1m)	below 3 ft	0 to 3 ft (1m)	below 3 ft
GW, GP	97	94	94	90
GM, GC	98	94	95	90
SW	97	95	94	90
SP, SM	98	95	95	90
SC	99	96	95	91
ML, CL	100	96	96	92
OL	–	96	–	92
MH	100	97	–	92
CH	–	97	–	92

material under a pavement should equal or exceed the limits in the first column of Table G. The second column applies to layers of fill below this depth, each lift of which should be tested as it is constructed.

Moisture

Adjustment of moisture content is an integral part of the compaction process, and many problems and delays result from ignorance of this fact. The correct target range for moisture varies somewhat for different soil types. Addition of moisture is very helpful in compacting sandy, cohesionless materials and is necessary for cemented or structured soils which have hardened by drying. Cohesive soils are stronger and less compressible when compacted to a high density at a moisture content slightly below optimum, but in sensitive clayey soils this could increase the potential for swelling. Attempting to compact a cohesive soil well above optimum moisture produces "overcompaction", as evidenced by shearing and cracking under rolling equipment. This is prevented by proper mixing as much as by control of moisture. As a general guideline, moisture content should be maintained within 2.0 per cent of optimum, although the correct upper limit may depend on the degree of compaction specified.

Recommendations on moisture content limits should be obtained through the soil report.

Testing compaction

Density tests should be made on each lift of fill material and on the disturbed layer of native material, which should be tested at more than one depth. By the nuclear method of density testing (ASTM D 2922) it is practical to test at many locations and depths for more representative results. Since the device involved also measures moisture (ASTM D 3017), it is a very useful tool for quality control. The sand-cone method, ASTM D 1556, should be used where the nuclear test is not feasible for some reason or as a method of verifying density results.

Other ways of checking the condition of the subgrade include proof-rolling (or "test-rolling") and deflection tests. Proof-rolling is often performed with a loaded truck, which is adequate as a rough indicator of compaction but which may not reach all points which should be checked. A heavy pneumatic-tired roller (PTR) is more effective and can be used in repairing areas found to be deficient. However, a pneumatic roller is not very effective in compacting highly cohesive soils and so may not be available on site.

The chief object of proof-rolling is to locate areas of slippage and cracking, which usually denote an incorrect moisture condition sufficient to cause shear failure near the surface. The inspector can also observe the amount of further densification and the degree of movement produced by the roller as a sign of whether consolidation has been achieved.

Although deflection testing is rarely used in private paving, the more efficient methods have considerable potential as a means of checking both the in-place strength of the soil and the effectiveness of compaction operations. Such methods may be useful in constructing pavements designed for heavy loads, for instance, or in resolving questions relative to the strength of the supporting soil or the appropriate pavement thickness. The falling-weight deflectometer produces numerous indirect measurements of the resilient modulus of the subgrade, relating the actual strength of the soil directly to the value used in establishing layer thickness. Falling-weight deflectometer measurements have been used effectively for acceptance testing of highway subgrade.

Mix design criteria

Recommended limits for approval of mix designs are presented in Table H (page 55), which contains both Marshall and Hveem criteria. As pointed out in Section I.C, most mix types are defined by highway agencies and typically do not reflect the somewhat different requirements of low-volume pavements. The selection of mix types in Table H has been developed to meet the needs of private construction. They are defined according to their performance characteristics and are differentiated according to the traffic conditions they are intended for. Mixture criteria vary for different traffic levels, and a method of establishing optimum asphalt content and other criteria is specified.

The criteria set forth in Table H are performance-based and do not include a gradation band or other aggregate properties. Gradation and other voids-related properties will be correct when these criteria are met. Mixes based on other specifications will usually meet the requirements of Table H with little or no adjustment, and mixes meeting the requirements of the table will normally conform to gradations specified elsewhere for similar mix types.

Mix types

Mix types in Table H are identified by a two-letter designation as follows:

First letter. Mixes for use as binder courses (which are also suitable as asphalt base) are designated as Type B mixes; those for surface courses are designated Type S.

Second letter. Mixes suitable for lightly trafficked areas — Class I traffic, as defined in Section II.A — are given the secondary designation L (for light). Mixes for traffic Classes II and III are designated M (medium), and those for Class IV are designated H (heavy). Thus the mix referred to as SL in Table H is a surface course for Class I traffic. In addition to the requirements of Table H, the specifications should state that the Nominal Maximum Aggregate Size of the mix may not be greater than half the design thickness of the paving course.

Specifying asphalt cement and aggregates

Generally, specifications for asphalt cement and aggregates should be based on state specifications for highway mixtures, except that requirements for non-polishing aggregates for surface mixtures are unnecessary where average daily traffic will not exceed 500 vehicles per day (one lane) and traffic speed will be less than 30 mph. Particle shape, friability, and percentage of particles with fractured faces are important criteria which should be specified according to state highway requirements or other reliable sources dealing with materials in the region.

Other ingredients

Ingredients often specified for paving mixes include mineral filler, anti-stripping additive (including hydrated lime), and polymeric modifiers. Mineral filler is a fine aggregate which is sometimes included to increase the fraction of dust-size particles. Anti-stripping additives are used to improve bonding of asphalt cement to particle surfaces. The need for an anti-stripping additive is determined by special tests during the mix design process, which should be performed where experience with local materials indicates a risk of stripping. These tests measure both the stripping tendencies of a mixture and the effectiveness of an additive.

Modifiers and mix design

These products generally improve the properties of a mix, such as strength and durability, but they may alter its compaction characteristics and often the absorptiveness of aggregates. Design properties should be rechecked when a modifier is to be added to a previously approved mix. The types, addition rates, and specifications for mineral filler, antistripping additives, and modifiers should follow the recommendations of the mix design laboratory. (For further information on modifiers see especially the reference in Section III.C.)

Air voids and optimum asphalt cement (AC) content

Procedures differ among specifying agencies for establishing optimum asphalt cement content and the other properties of a mix which are to meet the approval criteria. Table H provides a single value for air void content of 4.0 per cent. The design practice recommended by the National Asphalt Pavement Association (which is followed with slight variations by many agencies) is to select the optimum AC content at which the air voids meet the specified value. Minimum Voids in the Mineral Aggregate (VMA), stability, and Marshall flow should be within the recommended limits at this point. Air void content is the critical value which must be controlled to achieve a mix which is both stable and weather-resistant. The recommended value of 4.0 percent has been found to achieve the best balance of these two factors, based upon the experience of many authorities.

Engineering basis of mix design criteria

In actual use, some reduction of air void content occurs under traffic. The different numbers of blows recommended for the Marshall procedure approximate this effect for different levels of traffic. When the Hveem method is used, different minimum stabilometer values apply to mixes for light or heavy traffic, as noted at the end of Table H. Like the mix design methods themselves, criteria established for approval of mix designs are not derived from the theories of mechanics or from controlled experimental data. They are of necessity empirical and subjective in origin. Indeterminate loading conditions, support layer reactions, temperatures, ingredient properties, and other factors affecting pavements are too complex for rational analysis and experimentation. The criteria in Table H, like those established by state highway agencies and other authorities, are based upon experience and observation of engineers specialized in pavement materials, as supported by the findings of others in the field. As such, they will be in reasonably close agreement with values published elsewhere but may not coincide with other sources on all points. Designing and specifying mixtures is a specialized subject involving many considerations which are beyond the scope of this manual. For a fuller treatment of mix design procedures, the two references given in Section III.D will be very useful.

TABLE H: Mix Design Criteria, Marshall Method

Mix type	*BL*	*BM*	*BH*	*SL*	*SH*
minimum stability, lbs.	800	1200	1800	800	1500
No. of blows	35	50	75	50	75
flow, .01 in.	8 to 18	8 to 16	8 to 14	8 to 16	8 to 14
air voids, %	4.0	4.0	4.0	4.0	4.0

Minimum %VMA is determined according to the Nominal Maximum Particle Size as follows:

Nom. Max. Size, inches:	*3/8*	*1/2*	*3/4*	*1*	*1.5*
Min. %VMA:	17	16	14	14	13

MIX DESIGN CRITERIA, HVEEM METHOD

minimum stabilometer value	35*	30*
maximum swell, inches	0.030	0.030
minimum air voids, %	4.0	4.0

* For Class IV traffic, industrial sites, and similar applications, minimum stabilometer value shall be 37 for Type B mixes and 35 for Types S.

Acceptance limits for paving mixtures

The tolerances in Table I below are recommended for the averages of two or three mixture samples. Results of a single sample are useful for monitoring production. For acceptance purposes multiple tests should be averaged to reduce the influence of testing error.

Marshall or Hveem measurements of field samples

Highway agencies in certain states have used mix design tests on samples of production mixes for both quality control and acceptance purposes. As stated in Section I.C, such tests are very effective in providing timely indications of changes in the mixture. However, these measurements are subject to significant testing error and random variability and are not, therefore, appropriate for the purpose of final acceptance of mixtures. They should be used only as part of a quality control program, in which test results outside the normal range lead to further checks and inspections of production and materials to identify and correct possible sources of variability.

Test results on field samples should be considered normal when they fall within the following limits:

Criterion	*How measured*	*Normal limits for quality control*
Marshall stability and flow	ASTM D 1559; 3 specimens per sample	95% of stability in Table H and within flow range
Density	ASTM D 2726	design density ± 2.0%

TABLE I: Acceptance Limits for Paving Mixtures

Criterion	*Property and method of measuring*	*% Deviation from Job Mix Formula* — *two tests*	*three tests*
Asphalt content of mixture	Asphalt cement as % of total mix wt. Extraction test or nuclear asphalt gauge	JMF + 0.6	JMF + 0.5
Aggregate gradation of mixture	% by wt. of aggregates passing the following standard* sieves:	JMF plus or minus:	
	1"	8	7
	3/4"	8	7
	1/2"	6	6
	3/8"	6	5
	No.4	5	4
	No. 8 or 10**	4	4
	No. 16	4	4
	No. 30 or 40**	4	3
	No. 50	4	3.5
	No. 200	3.3	3.0

* Some sieves may not apply to a given mix type. Refer to "Types of mix" in Part One, Section I.C.

** These sizes belong to the Simplified Series; the choice of Standard or Simplified sieve series should be determined by local practice.

Compaction standards

Recommended compaction criteria for pavements are presented in Table J. As explained in Part One, Section I.C, in-place density tests measure the degree of compaction in relation to a reference density which must be representative of the particular mix being placed. Using the mix design density (sometimes called the "laboratory density") as the reference is sufficiently reliable for quality control, but for purposes of acceptance the density of the material actually produced should be verified by compacting field samples. Quality control testing ensures that the rolling procedure is effective and that the mix is being compacted effectively. When the amount of mix produced is small (less than two hundred tons), testing compacted density for quality control purposes is of less benefit, and the need for such testing is chiefly for acceptance of the work. For small projects, testing density on a discretionary basis may be appropriate.

TABLE J: Compaction Density of Paving Mixes

Mix type	*BL*	*BM*	*BH*	*S*	*SH*
Minimum density as a percentage of reference density	94	95	96	95	96

Specifying compaction methods

Older specifications sometimes include basic requirements for the methods and equipment to be used in compacting the pavement in other words, method specifications. Method specifications were used by most state highway departments before the introduction of end-result acceptance testing in the 1970's. When methods are specified it is prudent to leave reasonable latitude as to which equipment and practices are acceptable. *The contractor should not be required to adhere to a specified method if acceptance testing is also specified,* since choosing the method and type of equipment has the effect of assuming some re-sponsibility for the results.

Establishing an optimum rolling pattern with the help of nuclear density gauge.

The specifications should provide sufficient detail to lead to a common interpretation between the contractor and the owner's representatives before work begins. Disputes tend to arise over last-minute surprises which lead to delay. It is also important that inspection personnel be experienced in pavement construction as well as versed in the specifications.

Rolling pattern

Whether compaction is specified by density requirements or by method it is helpful to specify that the rolling pattern be established with the aid of a nuclear density gauge, which the contractor will usually have available. This device can be used to observe the increase in density (without necessarily knowing its actual value, since the gauge may not be calibrated) after each pass of the primary roller. The density reaches a maximum after a few passes. The number, speed, and length of the passes which produced the maximum value then become the rolling pattern for the rest of the work. Also, where acceptance testing is specified, an early check is obtained of possible difficulty in meeting compaction density requirements.

III.C SUMMING UP

As we have several times suggested in these pages, the success of a Hot Mix Asphalt pavement only begins with the design and specifications. Much also depends on pursuing alternatives which take into account the conditions at the site — climate, soil, and materials available — and which make allowance for all construction constraints and contingencies. The importance of proper subgrade preparation, based on a soil investigation and timely testing and inspection, cannot be overstated. The basis on which the contract is awarded — whether on lowest price alone or on an appraisal of total value — is the next key decision affecting the outcome. The best and least costly quality assurance plan is to choose a contractor with a reputation for excellence. Finally, a cooperative approach to the work on the parts of the contractor and the owner's representatives will go far to obtaining the high quality and performance of which Hot Mix Asphalt is capable.

The goal of this text, and the task of most works of this nature, is to fill a void between separate but related fields of knowledge. Persons engaged in architectural and structural design, site planning, residential development, and related fields have little exposure to the language and business of asphalt technology, and those who speak the jargon of mix design, axle loads, and soil types are at best only marginally conversant with fields outside our own. Inevitably, we will be found to have overlooked a need to define one or two esoteric terms or to lay the right groundwork in our explanations. There are also, no doubt, some aspects of site work we have not taken into account. As this is a first edition, we hope that all these shortcomings will be overcome in future versions. To this end NAPA invites your comments, stressing that you are also our best source of insights.

The GLAXO, Inc. Research Facility in Research Triangle Park, North Carolina. Contractor: C.C. Mangum, Inc., Raleigh, North Carolina.

III.D SUGGESTED REFERENCES ON SPECIAL TOPICS

1. Heavy duty pavements

Thickness Design—Asphalt Pavements for Heavy Wheel Loads (MS-23). The Asphalt Institute, Lexington, Kentucky

The Design of Hot Mix Asphalt for Heavy Duty Pavements. The National Asphalt Pavement Association, Lanham, Maryland

Large Stone Mixes: A Historical Insight (IS 103). The National Asphalt Pavement Association, Lanham, Maryland

2. Architectural design of parking areas

Parking for Industrial and Office Parks. National Association of Industrial and Office Parks, Arlington, Virginia

The Aesthetics of Parking: An Illustrated Guide. Thomas P. Smith. The American Planning Association, Washington, DC .

3. Life cycle costs

Pavement Life Cycle Cost Analysis. The National Asphalt Pavement Association, Lanham, Maryland

4. Stage construction

Thickness Design—Asphalt Pavements for Highways and Streets (MS- 1). The Asphalt Institute, Lexington, Kentucky

5. Asphalt modifiers

Using Additives and Modifiers in Hot Mix Asphalt (QIP 114). The National Asphalt Pavement Association, Lanham, Maryland

6. Asphalt curbs

Specifications and Construction Methods for Asphalt Curbs and Gutters (SS-3). The Asphalt Institute, Lexington, Kentucky

7. Drainage

Control of Urban Runoff: A practical manual for planning and designing urban BMP's. Metropolitan Council of Governments, Washington, D.C.

Porous Pavement. Thelen and Howe. The Franklin Institute Press, Philadelphia, Pennsylvania

8. Design of residential streets

Residential Streets. American Society of Civil Engineers, National Association of Homebuilders, and the Urban Land Institute

9. Frost heave

Introductory Soil Mechanics and Foundations. Sowers and Sowers. The Macmillan Company, New York

Pavement Design in Frost Areas. Highway Research Record No.33. Highway Research Board, National Academy of Sciences publication 1153. 1963

10. Recycling

Asphalt Hot-Mix Recycling (MS-20). The Asphalt Institute, Lexington, Kentucky

Recycling Hot Mix Asphalt Pavements (IS-123). The National Asphalt Pavement Association, Lanham, Maryland

11. Mix Design

Hot Mix Asphalt Materials, Mixture Design and Construction. The National Center for Asphalt Technology, Auburn, Alabama

NOTE: A catalog listing all current publications of the National Asphalt Pavement Association may be obtained at no cost by contacting:

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III.E GLOSSARY

As in all technical fields, many specialized expressions are used in the Hot Mix Asphalt industry which may be foreign to some users of this guide. Worse, a familiar term may have a somewhat different meaning here and thereby create confusion. The following are a few important terms not explained in the text, which it may be helpful to define according to industry usage.

Aggregate is the crushed rock, gravel, sand, slag, dust, or other particulate matter, or combinations of these, which are used as the mineral mass in HMA and in unbound base courses. Aggregates are specified according to gradation, maximum size, soundness, particle shape, resistance to abrasion, geologic source, and other characteristics.

Asphalt usually refers to Hot Mix Asphalt (HMA) but may mean asphalt cement or other paving materials containing asphalt cement. Because of this confusion the HMA industry prefers the term Hot Mix Asphalt, which is defined on page 61.

AASHTO (formerly AASHO) is the American Association of State Highway and Transportation Officials.

Asphalt cement (AC) is the black, viscous petroleum product which holds the particles of HMA together. Essentially, it is the unvaporized fraction of crude oil, processed to meet the specifications of various standard grades and grading systems. Chemically it is very complex and naturally variable, including both polar and non-polar compounds of high molecular weight. Asphalt cement is not to be confused with coal tar products nor with oils, emulsions of asphalt cement and water, or cutback asphalts (which consist of asphalt cement dissolved in a petroleum distillate such as naphtha). In some countries asphalt cement is called bitumen.

ASTM is the American Society for Testing and Materials.

Base refers to the layer of bound or unbound granular material between the pavement layer and the prepared soil subgrade.

CBR (California Bearing Ratio) is a standard empirical measure of the bearing capacity of a soil, expressed as the ratio (percentage) of the load required to produce a 0.1 inch penetration by a standard piston into the measured material, to the load required to produce the same penetration in a standard crushed stone. Soil samples are usually tested after soaking in water. The standard test method for CBR is published as ASTM D 1883.

Gradation of a soil, aggregate, or Hot Mix Asphalt is its particle size distribution. The gradation of Hot Mix Asphalt is customarily expressed as the percentages passing a series of standard sieves, by weight. (See Table I, page 56.)

Grades of asphalt cement reflect its nominal viscosity or stiffness as measured by standard AASHTO and ASTM test methods according to criteria established by the various specifying agencies — primarily the state departments of transportation (DOT's). Properties most commonly tested are penetration (defined below) and viscosity. Absolute viscosity at 60 degrees Centigrade (140 Fahrenheit) is the most common criterion of grading. There are two systems of viscosity grading, the AC grades and the AR grades. Grades AC-2.5, 5, 10, 20, 30, and 40 represent materials with absolute viscosities of 250, 500, 1000, 2000, 3000, and 4000 poises, respectively, measured at 60 degrees C, plus or minus 20 per cent. The AR series, AR-1000, 2000, 4000, 8000, and 16000 are graded according to their viscosities after a standard aging procedure. Grade AR-1000 has a viscosity at 60 deg. C of 1000 poises, plus or minus 25 per cent, after aging. These broad ranges of grades reflect the demands of many different climates and traffic conditions and the use of softer grades in mixtures which contain recycled asphalt pavement. Grades available in a particular area are generally limited to those routinely specified by the state DOT.

Hot Mix Asphalt (HMA) is a carefully controlled mixture of aggregates, asphalt cement, and sometimes special ingredients, proportioned according to a mix design study and combined at elevated temperature in a mixing facility designed for this purpose. Other terms which refer to HMA or a category of HMA include asphalt, asphaltic concrete, bituminous concrete, blacktop, hot mix, macadam, plant mix, sand asphalt, and plant mix seal.

Resilient Modulus is a mechanical property of soils which expresses the ratio of repeated, live-load stress to strain under a constant horizontal and vertical confining stress. It may be compared to Young's modulus for ideally elastic materials. Testing is performed in a tri-axial test cell configured to measure horizontal and vertical deformation. In mechanistic analysis of pavements the resilient modulus is used to predict the reaction of the subgrade under applied loads.

Quality assurance is the practice of sampling, testing, and inspecting a product on behalf of its ultimate owner to ensure its acceptability under specifications agreed upon by contract.

Quality control is the ongoing sampling and testing of a product during manufacture for the purpose of controlling the process and detecting deficient material.

Penetration is an empirical measure of the hardness of asphalt cement in the ambient temperature range, where most AC's are not fluids in the strict Newtonian sense. The test measures the depth to which a standard needle weighing 100 grams penetrates a sample of asphalt cement in five seconds. The standard temperature of the sample during the test is 25 degrees C (77 degrees F). Originally, all asphalt cements were penetration-graded, and some specifiers continue to apply this standard. It is worth noting that penetration decreases with increasing hardness.

Subgrade is the prepared soil which supports base and pavement. An upper layer of soil which has been treated or replaced with better soil is referred to in this text as Improved Subgrade. (The term "subbase", which is not widely used in reference to flexible pavement systems, also refers to an improved layer under the base.)

ENGLISH/METRIC CONVERSION FACTORS

To Convert from	To	Multiply by
acre	metre^2 (m^2)	4046 856
acre	hectometer^2 (hm^2)	0.404 686
BTU (International Table)	killojoule (kJ)	1.055 056
Fahrenheit (temperature)	Celsius (°C)	$T_C = (T_F - 32)\ 5/9$
foot	metre (m)	0.304 80
foot^2	metre^2 (m^2)	0.092 903
foot^3	metre^3 (m^3)	0.028 317
foot^3	litre (l)	28.317 0
foot-pound-force	joule (J)	1.355 818
foot/minute	metre/second (m/s)	0.005 08
gallon (U.S. liquid)	litre (l)	3.785 412
gallon/minute	litre/second (l/s)	0.063 09
gallon/yard^2	litre/metre^2 (l/m^2)	4.527 314
horsepower (electric)	kilowatt (kW)	0.746 0
inch	millimeter (mm)	25.400 0
inch^2	centimeter^2 (cm^2)	6.451 60
inch^2	millimeter^2 (mm^2)	645.160 0
inch^3	centimeter^3 (cm^3)	16.387 06
inch/second	metre/second (m/s)	0.025 40
kilogram (kg)	ton (metric)	0.001 00
mile (U.S. statute)	kilometre (km)	1.609 344
mile^2	kilometre^2 (km^2)	2.589 988
mile/hour	kilometre/hour(km/hr)	1.609 344
ounce-mass	gram (g)	28.349 52
ounce-fluid	litre (l)	0.029 574
pint (U.S. liquid)	litre (l)	0.473 176 5
pound-force (lbf)	newton (N)	4.448 222
pound-force-inch	newton-metre (N.m)	0.112 984 8
pound-mass	kilogram (kg)	0.453 592 4
quart (U.S. liquid)	litre (l)	0.946 356 9
tonne	megagram (Mg)	1.000
ton (short-2.000 lb)	kilogram (kg)	907.184 7
ton (long-2.240 lb)	kilogram (kg)	1 016.046 1
ton-mass/yard^3	kilogram/metre^3 (kg/m^3)	1.186.552 7
yard	metre (m)	0.914 40
yard^2	metre^2 (m^2)	0.836 127 4
yard^3	metre^3 (m^3)	0.764 554 9

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