Chapter: Two

Pavement Design

2.1 Introduction

Pavement are among the costliest items associated with highway construction and maintenance, and are largely responsible for making highway system the most expensive public works project undertaken by any society. Because the pavement and associated shoulder structures are the most expensive items to construct and maintain, it is important for highway engineers to have a basic understanding of pavement design principles.

Highway pavement is a structure consisting of superimposed layers of processed materials above the natural soil sub-grade, whose primary function is to distribute the applied vehicle loads to the sub-grade. The pavement structure should be able to provide a surface of acceptable riding quality, adequate skid resistance, favourable light reflecting characteristics, and low noise pollution. The ultimate aim is to ensure that the transmitted stresses due to wheel load are sufficiently reduced, so that they will not exceed bearing capacity of the subgrade.

2.2 Requirements of Pavement

An ideal pavement should meet the following requirements:

- Sufficient thickness to distribute the wheel load stresses to a safe value on the sub-grade soil,
- Structurally strong to withstand all types of stresses imposed upon it,
- Adequate coefficient of friction to prevent skidding of vehicles,
- Smooth surface to provide comfort to road users even at high speed,
- Produce least noise from moving vehicles,
- Dust proof surface so that traffic safety is not impaired by reducing visibility.

- Impervious surface, so that sub-grade soil is well protected, and
- Long design life with low maintenance cost.

2.3 Factors affecting pavement design

2.3.1 Traffic and loading

Traffic is the most important factor in the pavement design. The key factors include contact pressure, wheel load, axle configuration, moving loads, load, and load repetitions.

- ***Contact pressure***: The tyre pressure is an important factor, as it determines the contact area and the contact pressure between the wheel and the pavement surface. Even though the shape of the contact area is elliptical, for sake of simplicity in analysis, a circular area is often considered.
- ***Wheel load***: The next important factor is the wheel load, which determines the depth of the pavement required to ensure that the subgrade soil is not failed. Wheel configuration affects the stress distribution and deflection within a pavement. Many commercial vehicles have dual rear wheels which ensure that the contact pressure is within the limits. The normal practice is to convert dual wheel into an equivalent single wheel load so that the analysis is made simpler.
- ***Axle configuration***: The load carrying capacity of the commercial vehicle is further enhanced by the introduction of multiple axles.
- ***Moving loads***: The damage to the pavement is much higher if the vehicle is moving at creep speed. Many studies show that when the speed is increased from 2 km/hr to 24 km/hr, the stresses and deflection reduced by 40%.
- ***Repetition of Loads***: The influence of traffic on pavement not only depends on the magnitude of the wheel load, but also on the frequency of

the load applications. Each load application causes some deformation and the total deformation is the summation of all these. Although the pavement deformation due to single axle load is very small, the cumulative effect of number of load repetition is significant. Therefore, modern design is based on total number of standard axle load (usually 80 KN single axle).

2.3.2 Structural models

The structural models are various analysis approaches to determine the pavement responses (stresses, strains, and deflections) at various locations in a pavement due to the application of wheel load. The most common structural models are layered elastic model and visco-elastic models.

2.3.3 Material characterization

The following material properties are important for both flexible and rigid pavements.

- When pavements are considered as linear elastic, the elastic moduli and Poisson ratio of subgrade and each component layer must be specified.
- If the elastic modulus of a material varies with the time of loading, then the resilient modulus, which is elastic modulus under repeated loads, must be selected in accordance with a load duration corresponding to the vehicle speed.
- When a material is considered non-linear elastic, the constitutive equation relating the resilient modulus to the state of the stress must be provided. However, many of these material properties are used in visco-elastic models which are very complex and in the development stage.

2.3.4 Environmental factors

Environmental factors affect the performance of the pavement materials and cause various damages. Environmental factors that affect pavement are of two types, temperature and precipitation:

- ***Temperature***. The effect of temperature on asphalt pavements is different from that of concrete pavements. Temperature affects the resilient modulus of asphalt layers, while it induces curling of concrete slab. In rigid pavements, due to difference in temperatures of top and bottom of slab, temperature stresses or frictional stresses are developed. While in flexible pavement, dynamic modulus of asphaltic mixture varies with temperature. Frost causes differential settlements and pavement roughness. Most detrimental effect of frost penetration occurs during the spring break up period when the ice melts and subgrade is in a saturated condition.
- ***Precipitation***. The precipitation from rain and snow affects the quantity of surface water infiltrating into the subgrade and the depth of ground water table. Poor drainage may bring lack of shear strength, pumping, loss of support, etc.

2.4 Pavement materials

2.4.1 Soil

Soil is an accumulation or deposit of earth material, derived naturally from the disintegration of rocks or decay of vegetation that can be excavated readily with power equipment in the field or disintegrated by gentle mechanical means in the laboratory. The supporting soil beneath pavement and its special under courses is called sub grade. Undisturbed soil beneath the pavement is called natural sub grade. Compacted sub grade is the soil compacted by controlled movement of heavy compactors. In general, the desirable properties of sub grade soil as a highway material are:

- Stability
- Incompressibility
- Permanency of strength

- Minimum changes in volume and stability under adverse conditions of weather and ground water
- Good drainage, and
- Ease of compaction

2.4.2 Aggregate

Aggregate is a collective term for the mineral materials such as sand, gravel, and crushed stone that are used with a binding medium (such as water, bitumen, Portland cement, lime, etc.) to form compound materials (such as bituminous concrete and Portland cement concrete). By volume, aggregate generally accounts for 92% to 96% of bituminous concrete and about 70% to 80% of Portland cement concrete. Aggregate is also used for base and sub-base courses for both flexible and rigid pavements. Aggregates can either be natural or manufactured. Natural aggregates are generally extracted from larger rock formations through an open excavation (quarry). Extracted rock is typically reduced to usable sizes by mechanical crushing. Manufactured aggregate is often a by-product of other manufacturing industries. Figure 2.1 illustrates some types of aggregate . Aggregate used in asphaltic mixtures are either:

1. **Crushed aggregate** (such as limestone, granite),
2. **Natural aggregate** (such as gravel and sand) or
3. **Secondary aggregate** (such as RAP, demolition aggregate, ...etc.)

Figure 2.1: Some types of aggregates

The main desirable properties of aggregate are:

- ***Strength.*** The aggregates used in top layers are subjected to (i) Stress action due to traffic wheel load, (ii) Wear and tear, (iii) crushing. For a high quality pavement, the aggregates should possess high resistance to crushing, and to withstand the stresses due to traffic wheel load.
- ***Hardness.*** The aggregates used in the surface course are subjected to constant rubbing or abrasion due to moving traffic. The aggregates should be hard enough to resist the abrasive action caused by the movements of traffic. The abrasive action is severe when steel tyre vehicles moves over the aggregates exposed at the top surface.
- ***Toughness***. Resistance of the aggregates to impact is termed as toughness. Aggregates used in the pavement should be able to resist the effect caused by the jumping of the steel tyre wheels from one particle to another at different levels which causes severe impact on the aggregates.
- ***Shape of aggregates***. Aggregates, which happen to fall in a particular size range, may have rounded, cubical, angular, flaky or elongated particles. It is evident that the flaky and elongated particles will have less strength and durability when compared with cubical, angular or rounded

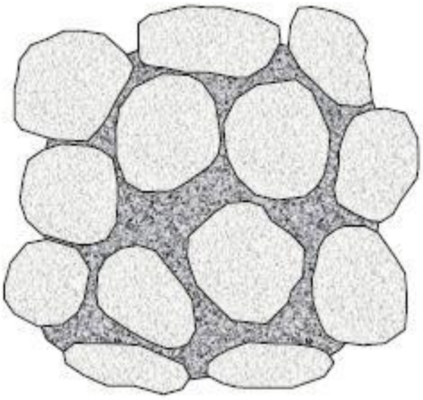
particles of the same aggregate. Hence, too flaky and too much elongated aggregates should be avoided as far as possible.

- ***Adhesion with bitumen.*** The aggregates used in bituminous pavements should have less affinity with water when compared with bituminous materials; otherwise, the coated aggregated by bitumen will be stripped off in the presence of water.
- ***Durability***. The property of aggregates to withstand adverse action of weather is called soundness. The aggregates are subjected to the physical and chemical action of rain and bottom water, impurities there-in and that of atmosphere, hence it is desirable that the road aggregates used in the construction should be sound enough to withstand the weathering action.
- ***Freedom from deleterious particles.*** Specifications for aggregates used in bituminous mixes usually require the aggregates to be clean, tough, durable in nature, and free from excess amount of elongated pieces, dust, clay balls and other objectionable material. Similarly, aggregates used in Portland cement concrete mixes must be clean and free from deleterious substances such as clay lumps, silt and other organic impurities.

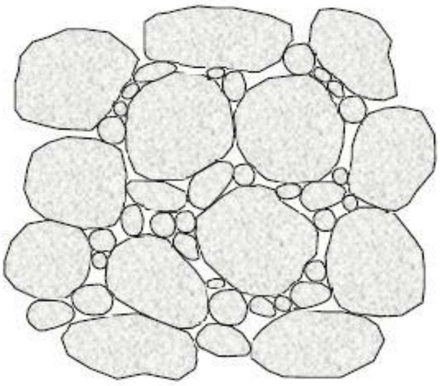
2.4.3 Bitumen

Bituminous materials are widely used all over the world in highway construction. These hydrocarbons are found in natural deposits or are obtained as a product of the distillation of crude petroleum. The bituminous materials used in highway construction are either asphalts or tars. All bituminous materials consist primarily of bitumen and have strong adhesive properties with colours ranging from dark brown to black. They vary in consistency from liquid to solid; thus, they are divided into liquids, semisolids, and solids. The solid form is usually hard and brittle at normal temperatures but will flow when subjected to long, continuous loading. The liquid form is obtained from the semisolid or solid forms by heating, dissolving in solvents, or breaking the

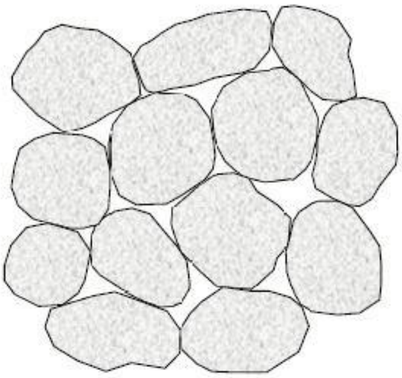
- ***Gap Graded Aggregate***

Illustrstion	***Characteristics***
	• Missing middle sizes • No Grain to grain contact • Moderate void content • Moderate permeability • Low stability • Easy to compact

- ***Open Graded Aggregate***

Illustration	***Characteristics***
	• Few fine particles • Grain to grain contact • High void content • High permeability • High stability • Difficult to compact

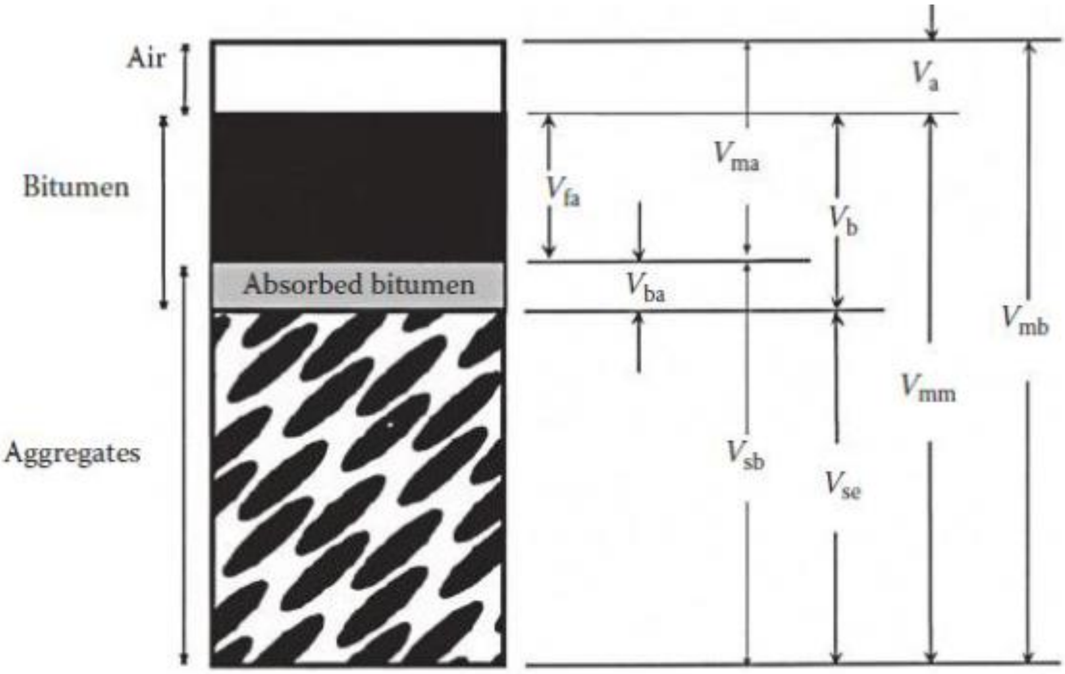
- ***Uniformly Graded Aggregate***

Illustration	***Characteristics***
	• Narrow range of sizes • Grain to grain contact • High void content • High permeability • Low stability • Difficult to compact

2.5.2 Compacted bituminous mixture

The volume of the compacted specimen of any bituminous mixture consists of the volume occupied by aggregates, the volume occupied by bitumen and the volume of air voids. The volume, which is occupied by bitumen and air voids, is known as volume in mineral aggregates (VMA). When bituminous binder is added, part of the volume of air voids is filled with bitumen (asphalt). The volume is known as voids filled with asphalt (VFA). The above volumetric characteristic properties are presented in Figure 2.3. Aggregates (attributed to the surface pores) normally possess and absorb a certain quantity of bitumen. As a consequence, the remaining bitumen quantity is in fact the one that coats the aggregates, fills the voids and provides cohesion in the mixture. This quantity of bitumen is designated as 'effective' bitumen quantity, and it is always less than the initial quantity of bitumen added, unless the aggregate's absorption is zero (ideal case).

The surface pores, in the absence of bitumen, absorb water (surface voids permeable to water). Because of the lower viscosity of water in comparison to bitumen's viscosity, water absorption is always higher than bitumen absorption. The schematic representation of an aggregate-coated particle given in Figure 2.4 the above, as well as other concepts.



V_{mb} = volume of compacted mix
V_a = volume of air voids
V_b = volume of bitumen
V_{ma} = volume of voids in mineral aggregates (VMA)
V_{sb} = volume of mineral aggregate (by bulk specific gravity)
V_{se} = volume of mineral aggregate (by effective specific gravity)
V_{fa} = voids filled with asphalt (VFA)
V_{mm} = voidless volume of paving mix
V_{ba} = volume of absorbed bitumen

Figure 2.3: Illustration of volumes in compacted asphaltic mixture

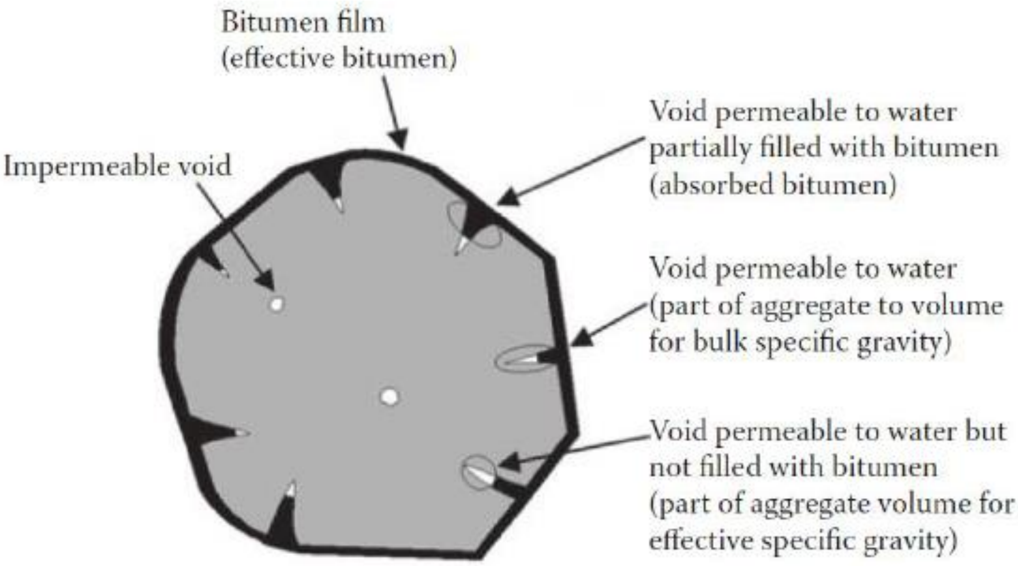


Figure 2.4: Coated aggregate particle

Provided that the bulk specific gravity (G_{sb}) and the effective specific gravity (G_{se}) of the total aggregate, as well as the specific gravity of the bitumen (G_b), are known, the volumetric properties of bituminous mixture (asphalt mixture) may be determined. The bulk density of the sample usually is determined by weighing the sample in air and in water. It may be necessary to coat samples made from open-graded mixtures with paraffin before determining the density. The bulk specific gravity G_{mb} of the sample—that is, the compacted mixture—is given as

$$G_{mb} = \frac{W_a}{W_a - W_w} \qquad \text{...(2.1)}$$

where

W_a = weight of sample in air (g)

W_w = weight of sample in water (g)

2.5.3 Determination of the design asphalt content of the mix

Analysis of Results from Marshall Test

The first step in the analysis of the results is the determination of the average bulk specific gravity for all test specimens having the same asphalt content. **The average unit weight of each mixture is then obtained by multiplying its average specific gravity by the density of water**. A smooth curve that represents the best fit of plots of unit weight versus percentage of asphalt is determined, as shown in Figure 2.5(a). This curve is used to obtain the bulk specific gravity values that are used in further computations as in Example 1.

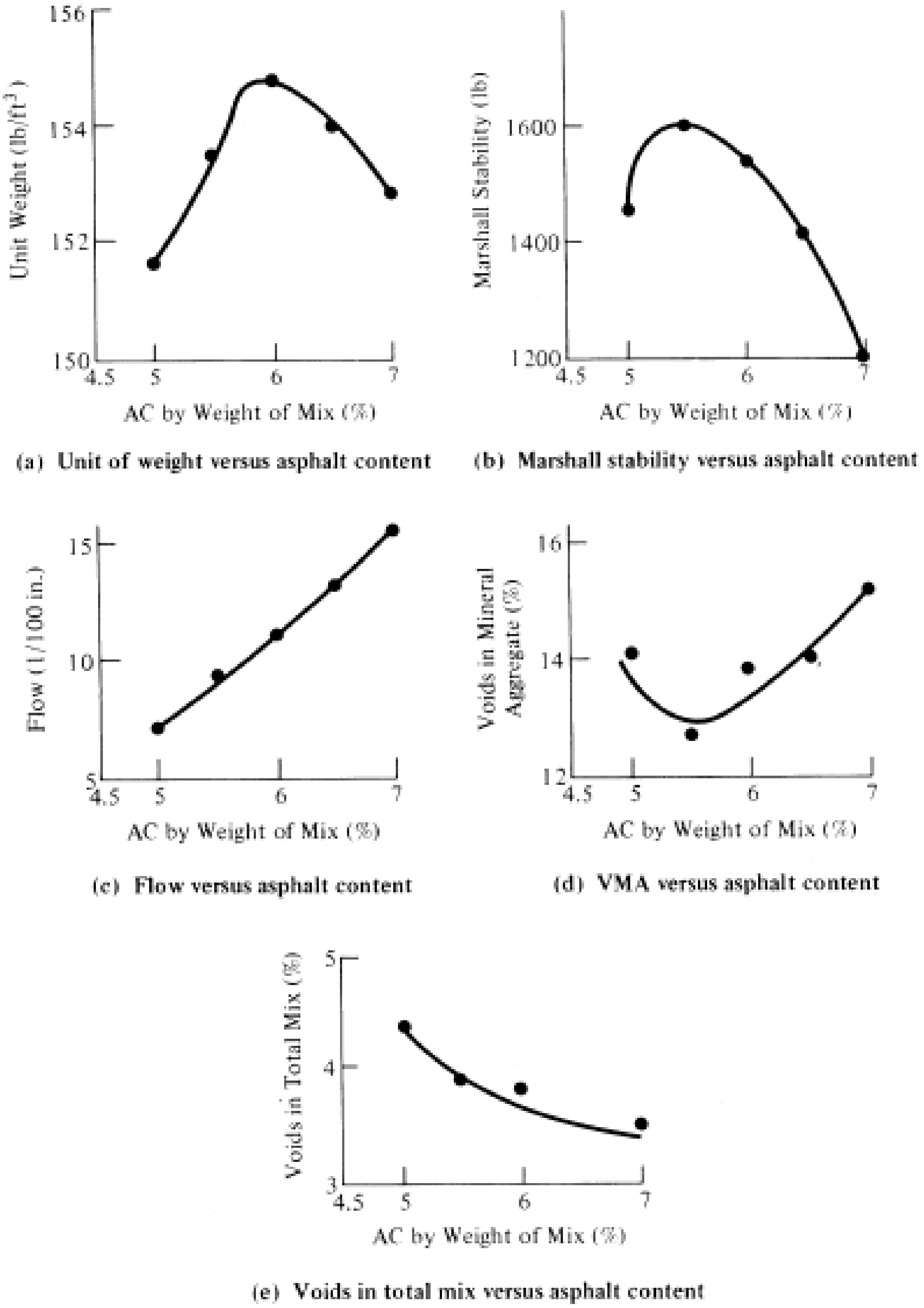


Figure 2.5: Determination of optimum binder content (OBC) using volumetric properties

In order to compute the percent air voids, the percent voids in the mineral aggregate, and the absorbed asphalt in pounds of the dry aggregate, it is first necessary to compute the **bulk specific gravity of the aggregate mixture, the apparent specific gravity of the aggregate mixture, the effective specific gravity of the aggregate mixture, and the maximum specific gravity of the paving mixtures for different asphalt contents**. These different measures of the specific gravity of the aggregates take into consideration the variation with which mineral aggregates can absorb water and asphalt.

***Bulk Specific Gravity of Aggregate*.** The bulk specific gravity is defined as the weight in air of a unit volume (including all normal voids) of a permeable material at a selected temperature, divided by the weight in air of the same volume of gas-free distilled water at the same selected temperature. Since the aggregate mixture consists of different fractions of coarse aggregate, fine aggregate, and mineral fillers with different specific gravities, the bulk specific gravity of the total aggregate in the paving mixture is given as:

$$G_{sb} = \frac{P_{ca} + P_{fa} + P_{mf}}{\dfrac{P_{ca}}{G_{bca}} + \dfrac{P_{fa}}{G_{bfa}} + \dfrac{P_{mf}}{G_{bmf}}} \qquad \text{.................................(2.2)}$$

where:

G_{sb} = bulk specific gravity of aggregates in the paving mixture

P_{ca}, P_{fa}, P_{mf} = percent by weight of coarse aggregate, fine aggregate, and mineral filler, respectively, in the paving mixture. (Note that P_{ca}, P_{fa}, and P_{mf} could be found either as a percentage of the paving mixture or as a percentage of only the total aggregates. The same results will be obtained for G_{sb})

$G_{bca}, G_{bfa}, G_{bmf}$ = bulk specific gravities of coarse aggregate, fine aggregate, and mineral filler, respectively

It is not easy to accurately determine the bulk specific gravity of the mineral filler. The apparent specific gravity may therefore be used with very little error.

$$G_{asb} = \frac{P_{ca} + P_{fa} + P_{mf}}{\frac{P_{ca}}{G_{aca}} + \frac{P_{fa}}{G_{afa}} + \frac{P_{mf}}{G_{amf}}} \quad \text{...(2.3)}$$

where:

G_{asb} = *apparent* specific gravity of the aggregate mixture
P_{ca}, P_{fa}, P_{mf} = percent by weight of coarse aggregate, fine aggregate, and mineral filler, respectively, in the mixture
$G_{aca}, G_{afa}, G_{amf}$ = apparent specific gravities of coarse aggregate, fine aggregate, and mineral filler, respectively

Effective Specific Gravity of Aggregate**.** The effective specific gravity of the aggregate exception of those that are filled with asphalt. It is given as:

$$G_{se} = \frac{100 - P_b}{(100/G_{mm}) - (P_b/G_b)} \quad \text{...................................(2.4)}$$

Where:

G_{se} = effective specific gravity of the aggregates
G_{mm} = maximum specific gravity of paving mixture (no air voids)
P_b = asphalt percent by total weight of paving mixture (thus 100 – P_b is the percent by weight of the base mixture that is not asphalt)
G_b = specific gravity of the asphalt

Maximum Specific Gravity of the Paving Mixture**.** The maximum specific gravity of the paving mixture G_{mm} assumes that there are no air voids in the asphalt concrete. Although the G_{mm} can be determined in the laboratory by conducting the standard test (ASTM Designation D2041), the best accuracy is attained at mixtures near the optimum asphalt content. Since it is necessary to determine the G_{mm} for all samples, some of which contain much lower or much higher quantities than the optimum asphalt content, the following procedure can be used to determine the G_{mm} for each sample.

The ASTM Designation D2041 test is conducted on all specimens containing a selected asphalt cement content and the mean of these is determined. This value is then used to determine the effective specific gravity of the aggregates using equation above. The effective specific gravity of the aggregates can be considered constant, since varying the asphalt content in the paving mixture does not significantly vary the asphalt absorption. The effective specific gravity obtained then is used to determine the maximum specific gravity of the paving mixtures with different asphalt cement contents using below

$$G_{mm} = \frac{100}{(P_s/G_{se}) + (P_b/G_b)} \qquad \text{.................................,,,,,,,,(2.5)}$$

where:

G_{mm} = maximum specific gravity of paving mixture (no air voids)
P_s = percent by weight of aggregates in paving mixture
P_b = percent by weight of asphalt in paving mixture
G_{se} = effective specific gravity of the aggregates (assumed to be constant for different asphalt cement contents)
G_b = specific gravity of asphalt

Once these different specific gravities have been determined, the asphalt absorption, the effective asphalt content, the percent voids in mineral aggregates (VMA), and the percent air voids in the compacted mixture all can be determined.

Asphalt absorption is the percent by weight of the asphalt that is absorbed by the aggregates based on the total weight of the aggregates. This is given as

$$P_{ba} = 100 \frac{G_{se} - G_{sb}}{G_{sb} G_{se}} G_b \quad \text{...(2.6)}$$

Where:

P_{ba} = amount of asphalt absorbed as a percentage of the total weight of aggregates
G_{se} = effective specific gravity of the aggregates
G_{sb} = bulk specific gravity of the aggregates
G_b = specific gravity of asphalt

Effective Asphalt Content. The effective asphalt content is the difference between the total amount of asphalt in the mixture and that absorbed into the aggregate particles. The effective asphalt content is therefore that which coats the outside of the aggregate particles and influences the pavement performance. It is given as

$$P_{be} = P_b - \frac{P_{ba}}{100} P_s \quad \text{..(2.7)}$$

Where:

P_{be} = effective asphalt content in paving mixture (percent by weight)
P_b = percent by weight of asphalt in paving mixture
P_s = aggregate percent by weight of paving mixture
P_{ba} = amount of asphalt absorbed as a percentage of the total weight of aggregates

Percent Voids in Compacted Mineral Aggregates. The percent voids in compacted mineral aggregates (VMA) is the percentage of void spaces between the granular particles in the compacted paving mixture, including the air voids and the volume occupied by the effective asphalt content. It usually is calculated as a percentage of the bulk volume of the compacted mixture based on the bulk specific gravity of the aggregates. It is given as:

$$VMA = 100 - \frac{G_{mb} P_s}{G_{sb}} \quad \text{...(2.8)}$$

Where;

VMA = percent voids in compacted mineral aggregates (percent of bulk volume)
G_{mb} = bulk specific gravity of compacted mixture
G_{sb} = bulk specific gravity of aggregate
P_s = aggregate percent by weight of total paving mixture

***Percent Air Voids in Compacted Mixture*.** This is the ratio (expressed as a percentage) between the volume of the small air voids between the coated particles and the total volume of the mixture. It can be obtained from below equation

$$P_a = 100 \frac{G_{mm} - G_{mb}}{G_{mm}} \quad \text{..(2.9)}$$

where:

P_a = percent air voids in compacted paving mixture
G_{mm} = maximum specific gravity of the compacted paving mixture
G_{mb} = bulk specific gravity of the compacted paving mixture

Four additional separate smooth curves are drawn: percent voids in total mix versus percent of asphalt, percent voids in mineral aggregate versus percent of asphalt, Marshall stability versus percent of asphalt, and flow versus percent of asphalt. These graphs are used to select the asphalt contents for maximum stability, maximum unit weight, and percent voids in the total mix within the limits specified (usually the median of the limits). The average of the asphalt contents is the optimum asphalt content. The stability and flow for this optimum content then can be obtained from the appropriate graphs to determine whether the required criteria are met. AASHTO suggested criteria for these test limits are given in Table 2.1. It should be noted that all criteria should be satisfied and not just the criterion for stability.

An example of design an optimum binder content is given separately.

Table 2.1: Marshall mix criteria

(a) Maximum and Minimum Values			
Marshall Method Mix Criteria	*Light Traffic ESAL < 10^4 (see Chapter 19)*	*Medium Traffic 10^4 < ESAL < 10^6 (see Chapter 19)*	*Heavy Traffic ESAL > 10^6 (see Chapter 19)*
Compaction (No. of blows each end of Specimen)	35	50	75
Stability *N* (lb)	3336 (750)	5338 (1200)	8006 (1800)
Flow, 0.25 mm (0.1 in.)	8 to 18	8 to 16	8 to 14
Air Voids (%)	3 to 5	3 to 5	3 to 5

(b) Mineral Percent Voids in Mineral Aggregates

Standard Sieve Designation	*Percent*
No. 16	23.5
No. 4	21
No. 8	18
⅜ in.	16
½ in.	15
¾ in.	14
1 in.	13
1½ in.	12
2 in.	11.5
2½ in.	11

SOURCE: Federal Highway Administration, U.S. Department of Transportation.