Marshall Mix Design

Asphalt Concrete Properties

Good

Stability

Workability

Skid Resistance

Durability

Bad

Stripping

Fatigue Cracking

Thermal Cracking

Bleeding

Stability

The ability to withstand traffic loads without distortion or deflection, especially at higher temperatures.

To get good stability, use strong, rough, dense-graded, cubical aggregate with just enough binder to coat the aggregate particles. Excess asphalt cement lubricates the aggregate particles and lets them slide past each other more easily, which reduces stability.

Workability

The ability to be placed and compacted with reasonable effort and without segregation of the coarse aggregate.

Too much asphalt cement makes the mix tender and difficult to compact to the proper density. Asphalt cement with a low viscosity at compacting temperatures can also make a mix tender as can too much natural sand because it has smooth, round grains. Too little asphalt cement can make the mix stiff and difficult to compact as well.

Skid Resistance

Proper traction in wet and dry conditions.

To get good skid resistance, use smaller aggregate so there are lots of contact points, use hard aggregate that doesn't polish and make sure you have enough air voids to prevent bleeding.

Some states now use an open-graded friction course (OGFC) that goes on top of the pavement and allows water to drain through the open pores to the dense graded layer below where it flows to the sides of the pavement, eliminating hydroplaning.

Durability

The ability to resist aggregate breakdown due to wetting and drying, freezing and thawing, or excessive inter-particle forces.

To get good durability, use strong, tough, nonporous aggregate and lots of asphalt cement to completely coat all of the aggregate particles (to keep them dry) and fill all of the voids between particles (to slow the oxidation of the asphalt cement).

Stripping

Separation of the asphalt cement coating from the aggregate due to water getting between the asphalt and the aggregate.

To reduce stripping, use clean, rough, hydrophobic aggregate and add lots of asphalt cement to provide a thick coating of asphalt on every aggregate particle.

Bleeding

The migration of asphalt cement to the surface of the pavement under wheel loads, especially at higher temperatures.

To prevent bleeding, incorporate enough air voids so the asphalt can compress by closing air voids rather than by squeezing asphalt cement out from between the aggregate particles. If the VFA is too high, there is no place for the asphalt cement to go when the pavement compresses.

Fatigue Cracking

Cracking resulting from repeated flexure of the asphalt concrete due to traffic loads.

To minimize fatigue cracking, use the proper asphalt cement grade and have a thick asphalt cement coating to make the concrete flexible.

Thermal Cracking

Cracking that results from an inability to acclimate to a sudden drop in temperature.

To minimize thermal cracking, use the proper asphalt cement grade and have a thick asphalt cement coating to make the concrete flexible.

Summary

Use dense-graded, cubical aggregate that is strong, tough, hydrophobic, and nonporous.

Use the correct asphalt cement grade for the job environment to prevent thermal cracking, fatigue cracking, draindown, and tenderness.

Incorporate enough air voids to prevent bleeding but not so much as to reduce stability.

Summary

Too little asphalt cement is bad because it can promote poor stability, poor workability, poor durability, stripping, and fatigue cracking.

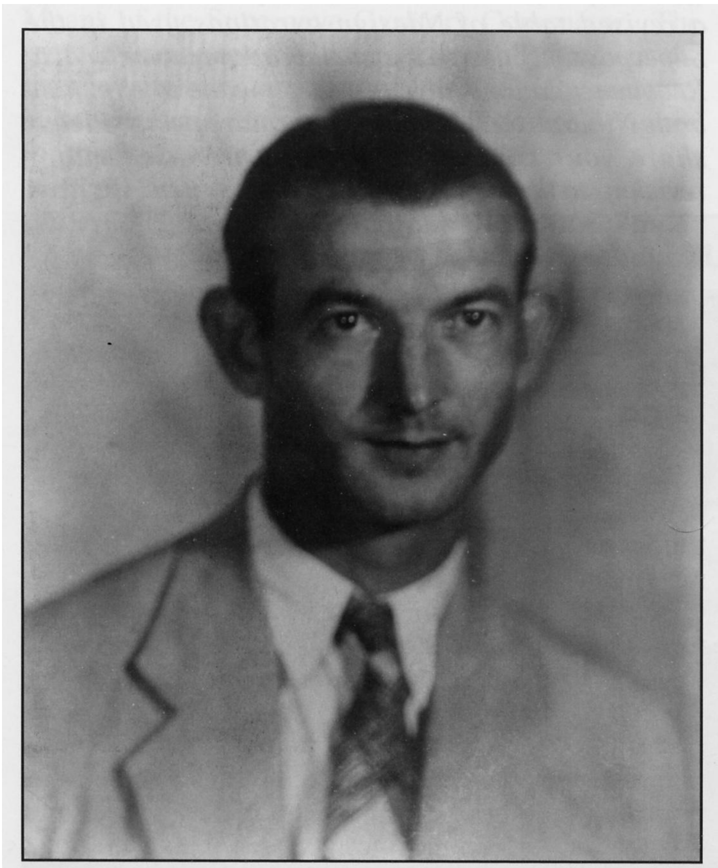
Too much asphalt cement is bad because it can promote poor stability, poor workability, poor skid resistance and bleeding.

The goal of mix design is to balance all of these competing interests.

Mix Design Basics

- **The right grade of asphalt cement**
  Relates to stability, workability, fatigue cracking, thermal cracking
- **The right type of aggregate**
  Relates to stability, workability, durability, stripping, skid resistance
- **The right gradation of aggregate**
  Relates to stability, workability
- **The right mix volumetrics**
  Relates to stability, durability, stripping, bleeding, skid resistance

Marshall Mix Design



During WWII, the U.S. Army Waterways Experiment Station (WES) in Vicksburg, Mississippi was tasked with developing a mix design method for airfield pavements to address the poor performance exhibited by existing asphalt pavements under ever increasing aircraft wheel loads.

They refined a method first developed in 1939 by Bruce Marshall at the Mississippi Highway Department into what we know today as the Marshall Mix Design Method by adding additional performance criteria to the ones that Marshall used and creating rigorous test specifications.

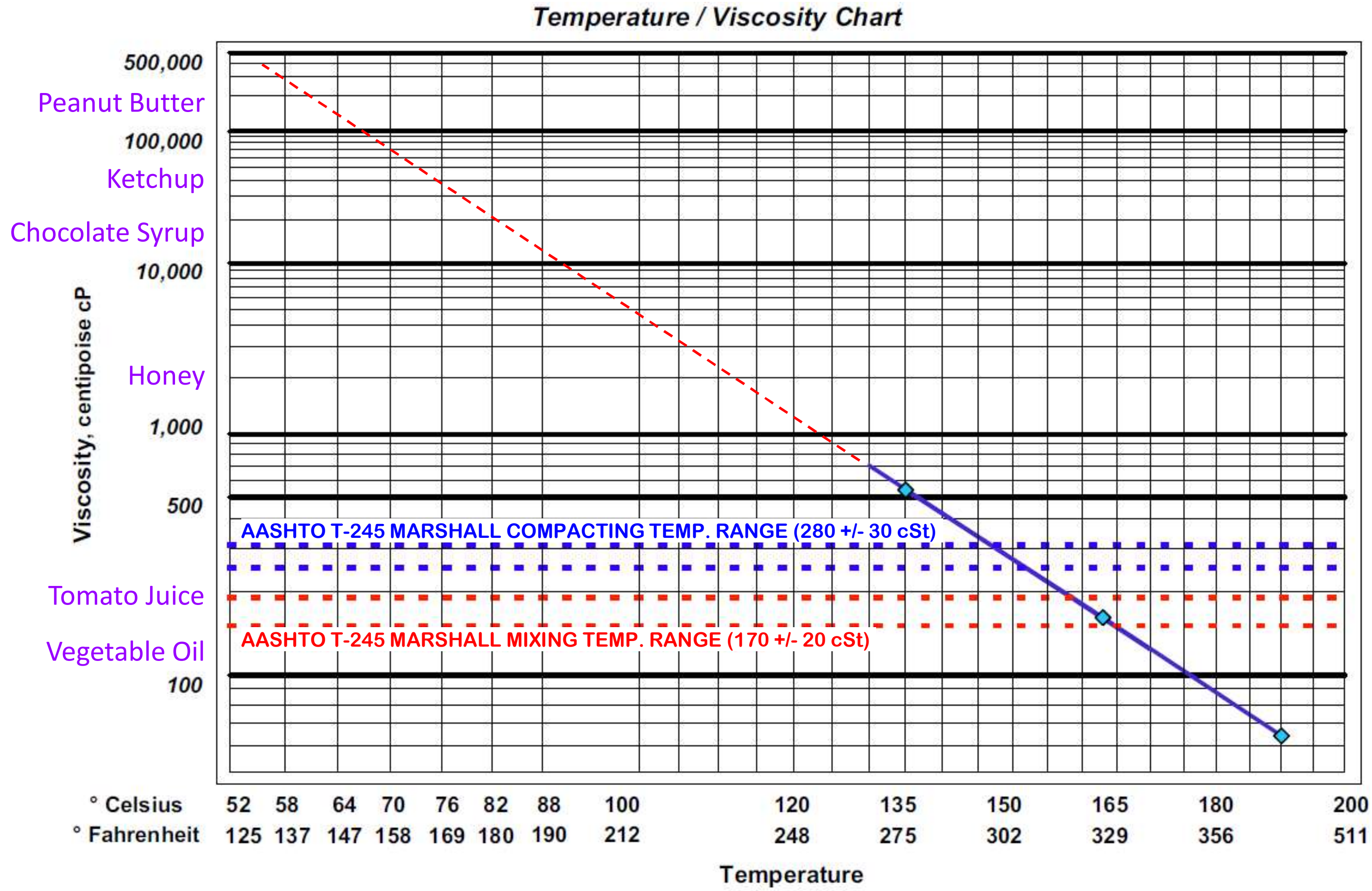
Marshall Mix Design Steps

1. Select an asphalt cement suitable for the climate.
2. Select aggregates that meet the suitability criteria.
3. Create an aggregate blend that meets the gradation criteria.
4. Establish specimen mixing and compaction temperatures from the viscosity-temperature chart for the asphalt cement.
5. Compact three specimens at each of five asphalt contents 0.5% apart spanning the expected optimum asphalt content.
6. Determine the mix volumetrics (G_{mb}, G_{mm}, VTM, VMA, VFA) of each specimen.
7. Measure the performance properties of each specimen at the high service temperature of 60ºC (140ºF).

Temperature Requirements

- In order to thoroughly mix the asphalt cement and aggregate together, the asphalt cement should be heated to a temperature that produces a viscosity of 170 ± 20 cS during mixing.
- In order to properly compact the resulting mixture, it should either be reheated or allowed to cool to a whatever temperature produces an asphalt cement viscosity of 280 ± 30 cS.

Temperature-Viscosity



Marshall Specimens

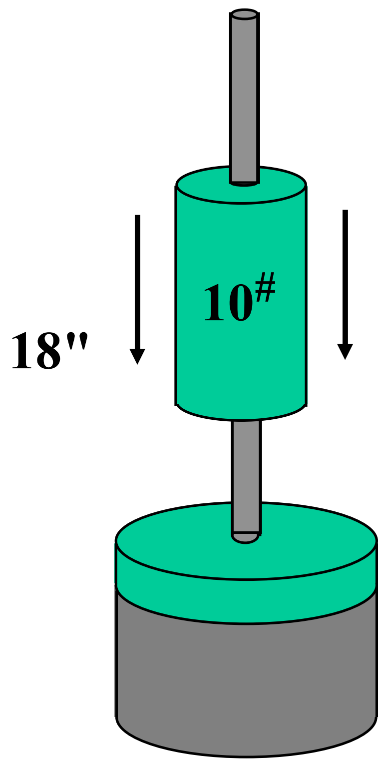
Marshall specimens are prepared one at a time by mixing approximately 1200 g of the trial aggregate blend with enough asphalt cement to produce the desired asphalt content (P_b).

The aggregate, asphalt cement, spoons, spatulas, and mixing bowls all must be heated to the proper mixing temperature. Otherwise, the asphalt cement will not properly coat all of the aggregate particles and will stick to the tools rather than the aggregate.

Marshall Specimens

As soon as the binder and aggregate have been mixed together, a 4-in-diameter by 2½-in-high specimen is prepared by compacting the asphalt into a mold with a compaction hammer (called a Marshall hammer). The hammer consists of a 10 lb mass falling 18 in. per blow. Depending on the design traffic loads, either 35, 50, or 75 blows of the hammer are applied to each side of the specimen. The goal is to replicate the density of the asphalt after years of traffic has been applied to it.

Marshall Specimens

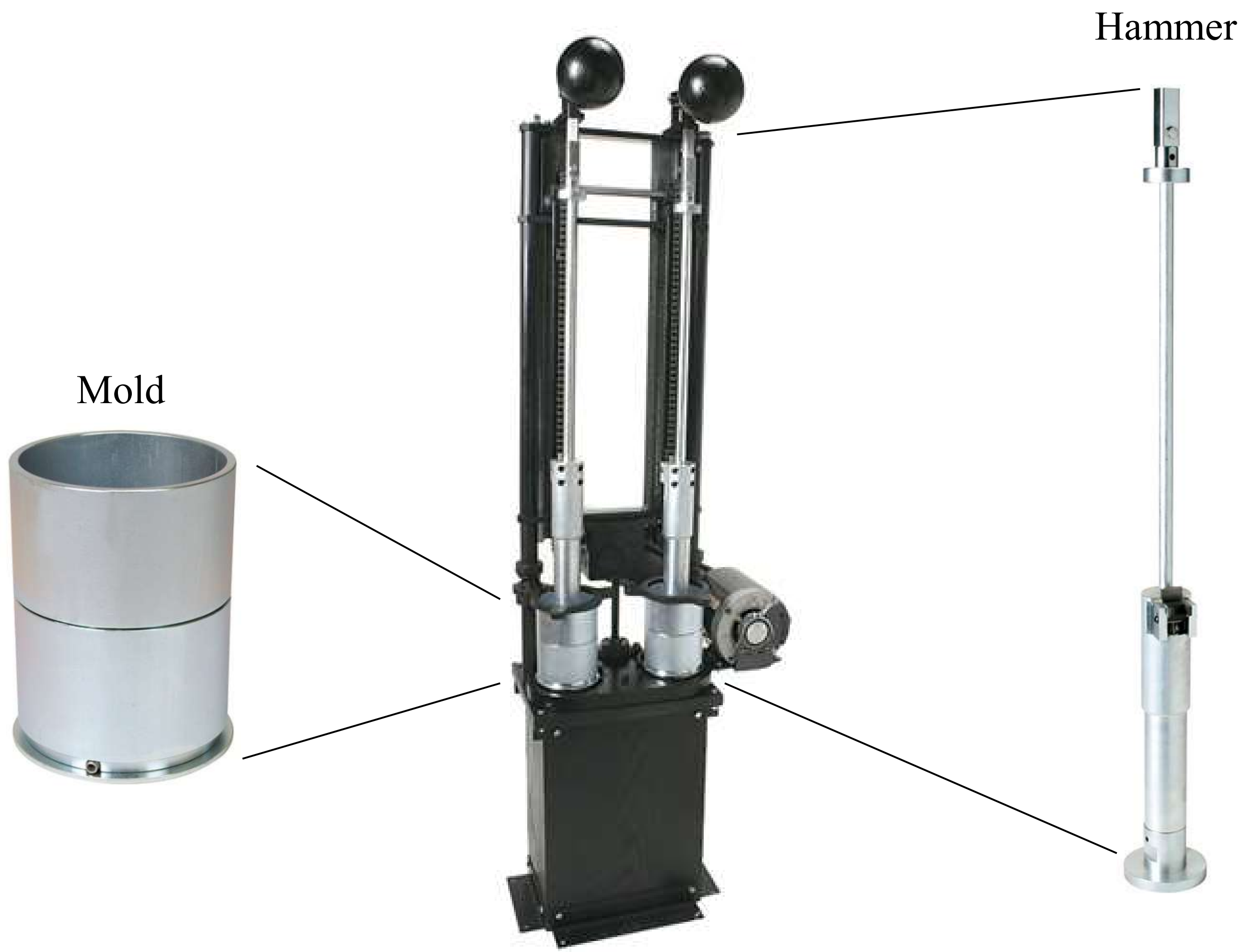


Make 3 specimens at each of 5 different asphalt contents

Traffic	Blows / Side
Light	35
Medium	50
Heavy	75

More traffic = more compaction over time = denser asphalt

Marshall Hammer



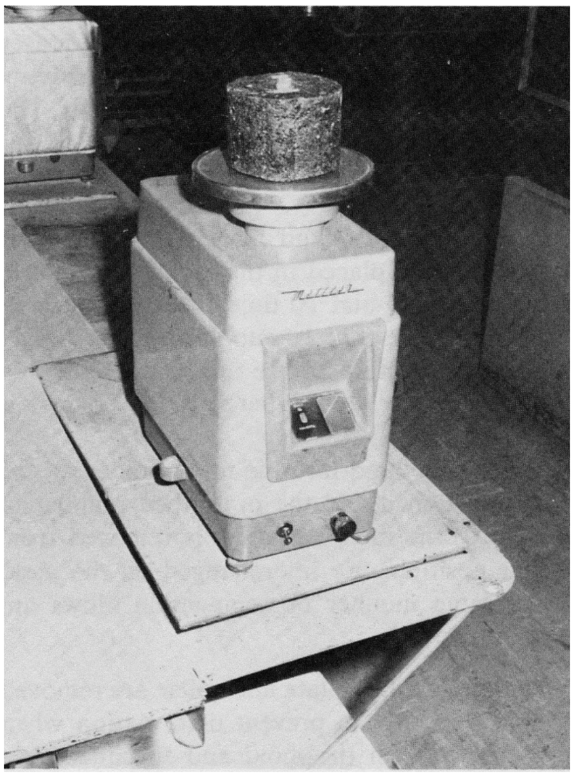
Marshall Specimens

After curing overnight, the compacted specimen is weighed in air and suspended in water to determine its unit weight (density), voids in total mix (VTM), voids in mineral aggregate (VMA), and voids filled with asphalt (VFA).

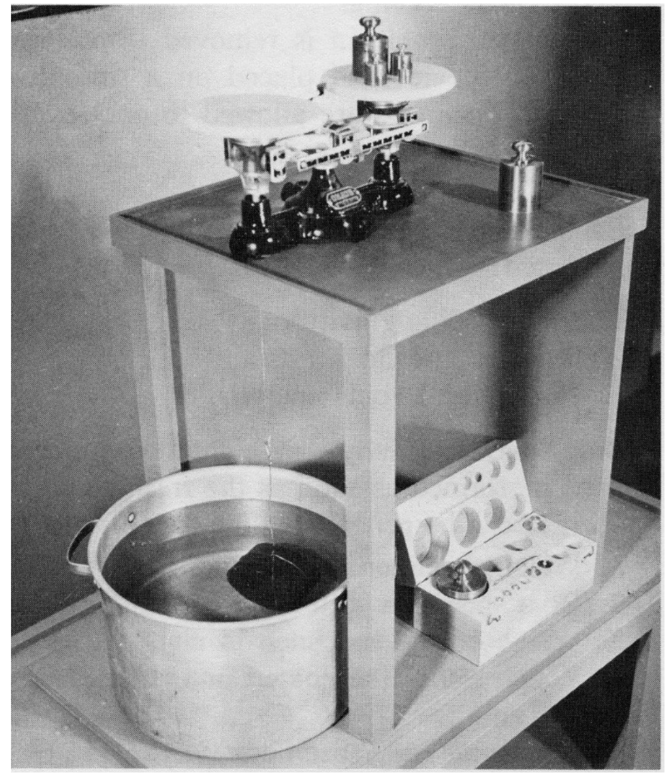
Of course this assumes the bulk specific gravity of the aggregate blend (G_{sb}) and the maximum specific gravity of the asphalt concrete (G_{mm}) ***at that asphalt content*** were previously determined.

Mix Volumetrics

(Taken from The Asphalt Institute Manual ES-1, Second Edition)



Weigh in Air



Weigh in Water

Unit Weight / Density

$$G_{mb} = \frac{W_{\text{in air}}}{W_{SSD} - W_{\text{in water}}}$$

$$\rho_{mb} = G_{mb} \times 997.0 \text{ kg}/\text{m}^3$$

$$\gamma_{mb} = G_{mb} \times 62.24 \text{ lb}/\text{ft}^3$$

Voids in Total Mix (Air Voids)

$$VTM = \left(1 - \frac{G_{mb}}{G_{mm}}\right) \times 100\%$$

G_{mb} = bulk specific gravity of compacted mixture

D 2726 - Bulk Specific Gravity and Density of Compacted Bituminous Mixtures

G_{mm} = maximum specific gravity of the mixture

D 2041 - Theoretical Maximum Specific Gravity and Density of Bituminous Paving Mixtures

Voids in Mineral Aggregate

$$VMA = \left(1 - \frac{G_{mb}\left(1 - P_b\right)}{G_{sb}}\right) \times 100\%$$

G_{mb} = bulk specific gravity of compacted mixture

G_{sb} = bulk specific gravity of the aggregate blend

P_b = asphalt binder content of mixture

Voids Filled with Asphalt

$$\text{VFA} = \left(1 - \frac{\text{VTM}}{\text{VMA}}\right) \times 100\%$$

VFA is the percentage of the available space between the aggregate particles (the VMA) that is occupied by asphalt binder rather than by air voids.

Performance Testing

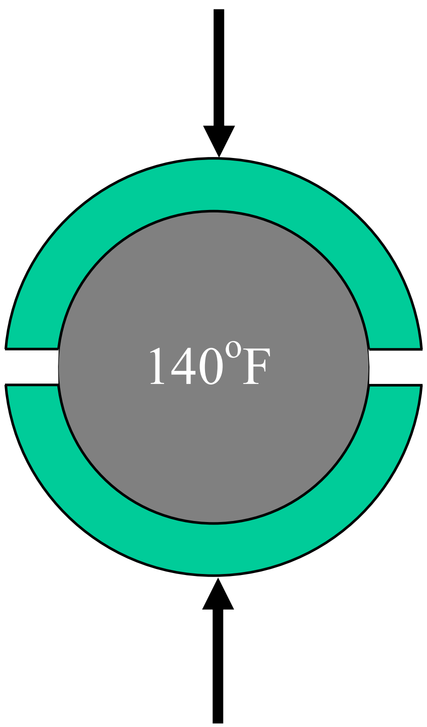
After being weighed in air and water, the specimen is heated for 20-30 minutes in a water bath at 140ºF in preparation for ***performance testing***.

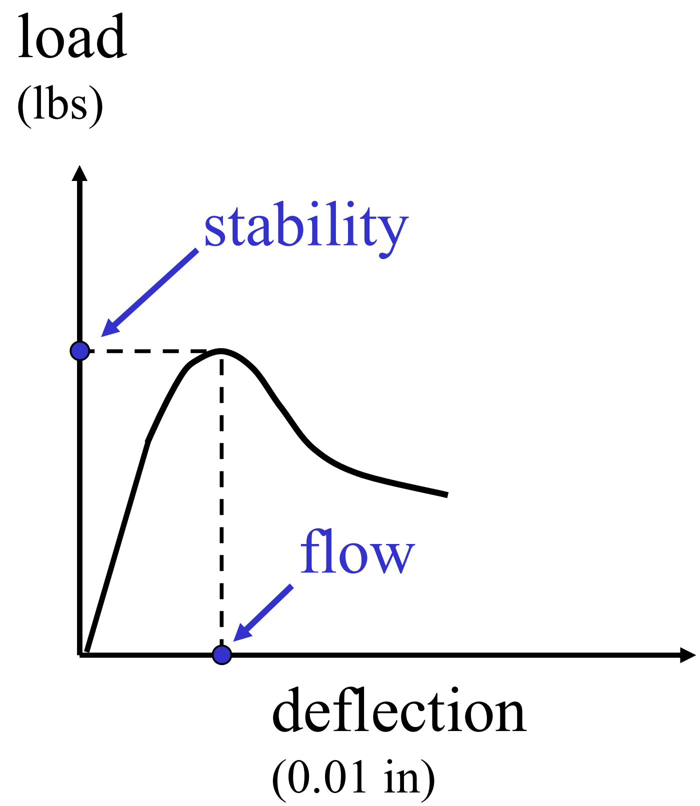
The performance test used in Marshall mix design is called the ***stability and flow*** test. The heated specimen is placed in a compression testing machine (called a Marshall tester) between two semi-circular loading heads. It is then loaded at a constant rate of 2 in/min until a peak load is determined.

Performance Testing

The maximum load (in pounds) recorded during the test is termed the Marshall ***stability*** and the amount of head travel (specimen compression) needed to reach that load (in units of 0.01 in) is termed the ***flow***.

Performance Testing





Stability and Flow Tester

Marshall Mix Design Steps

The previous steps are repeated 15 times (to make 3 specimens at each of 5 different asphalt contents). At that point, we have collected all of the information that we need to do our mix design.

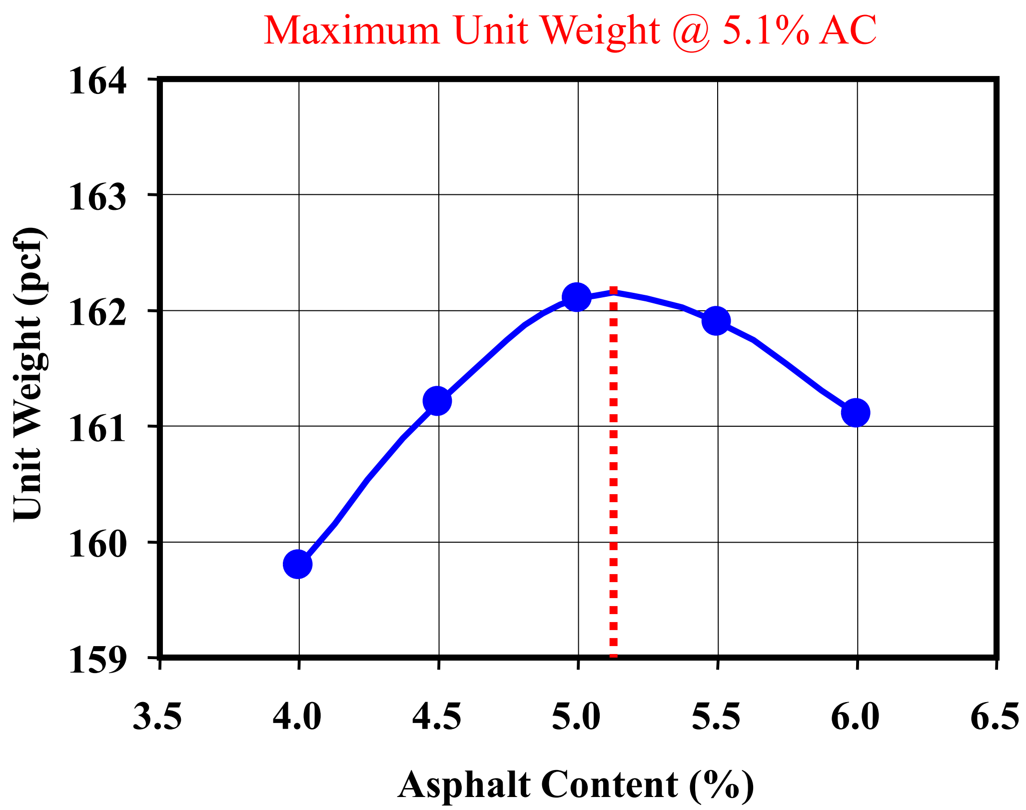
Here "mix design" means finding an asphalt content for this trial aggregate blend that produces specimens whose mix volumetrics (VTM, VMA, and VFA) and performance properties (stability and flow) meet all of the specifications.

Marshall Mix Design Steps

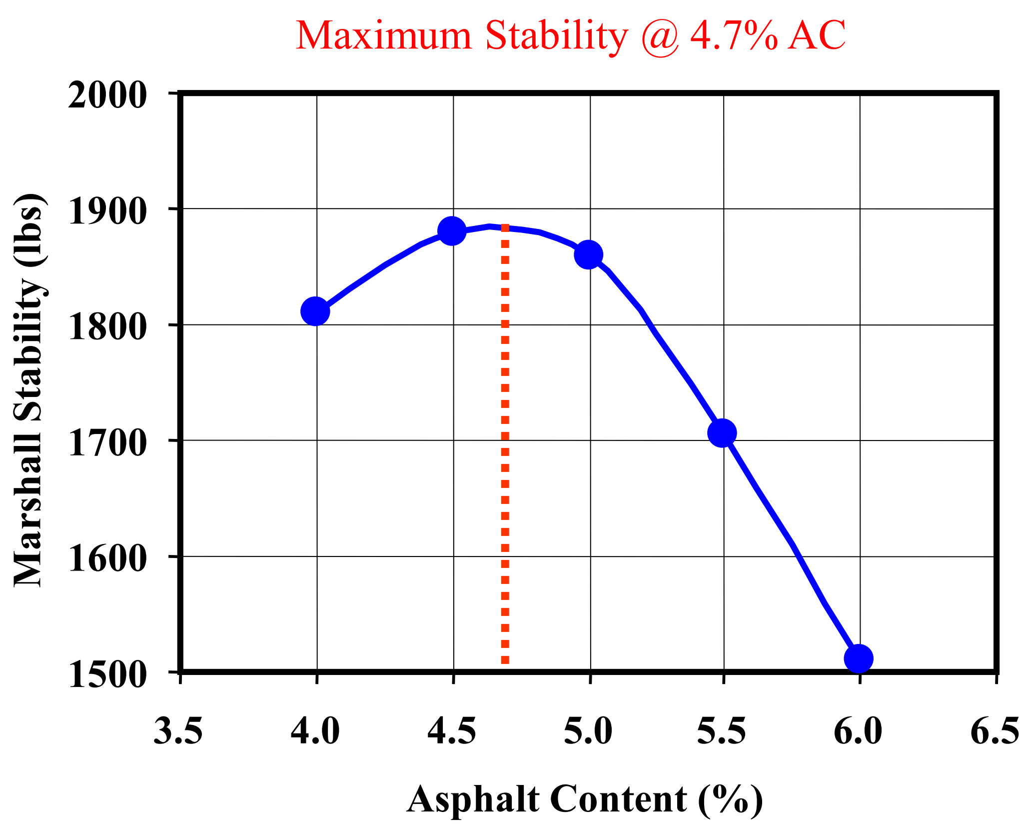
For each asphalt content, we calculate the average unit weight, stability, VTM, VMA, VFA, and flow then plot those averages as a function of the asphalt content.

From the plots we determine (a) the asphalt content that produces the maximum unit weight, (b) the asphalt content that produces the maximum stability, and (c) the asphalt content that produces exactly 4% air voids (VTM).

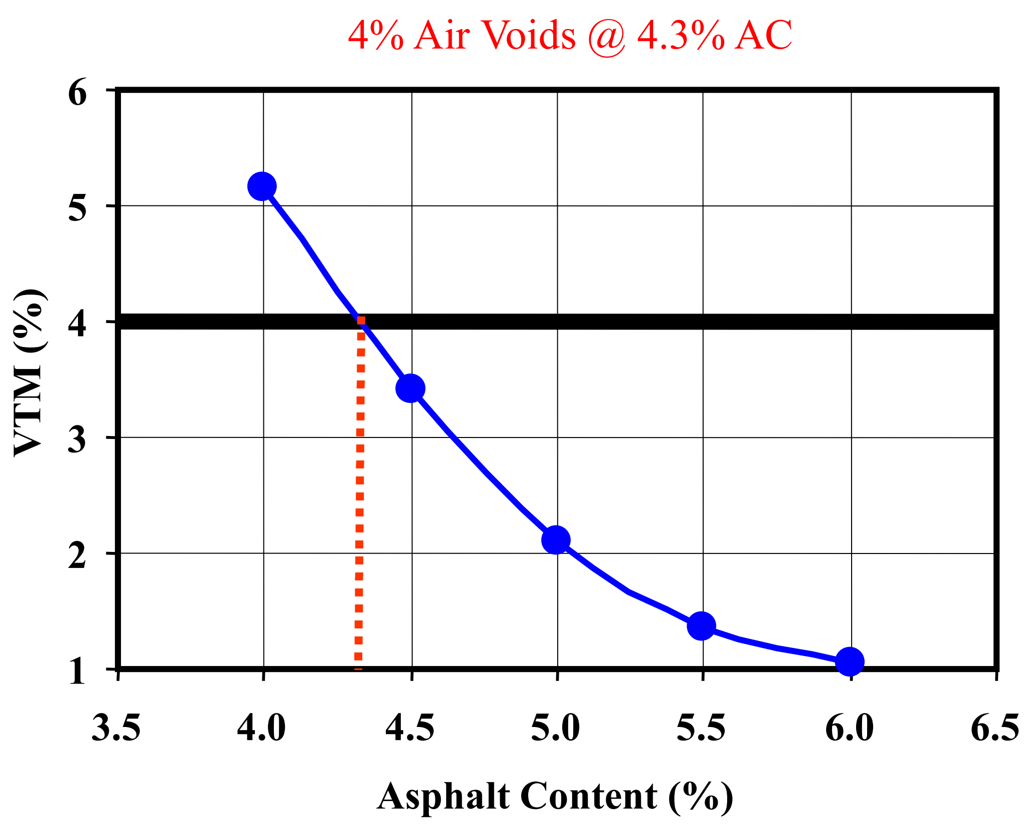
Unit Weight Results



Stability Results

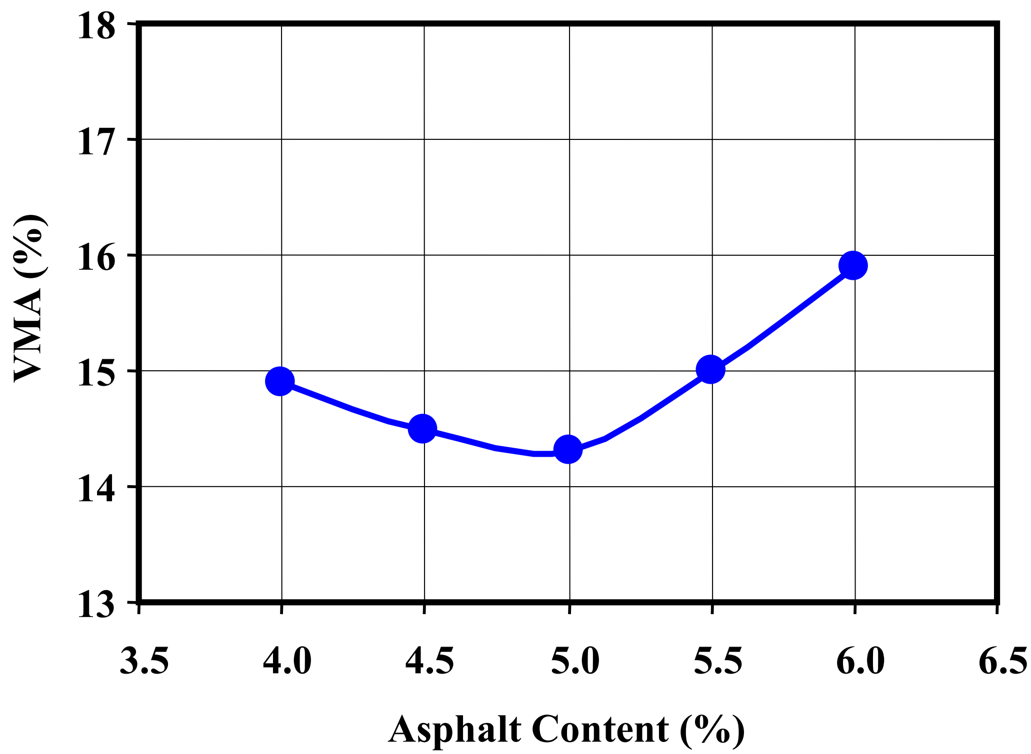


VTM Results

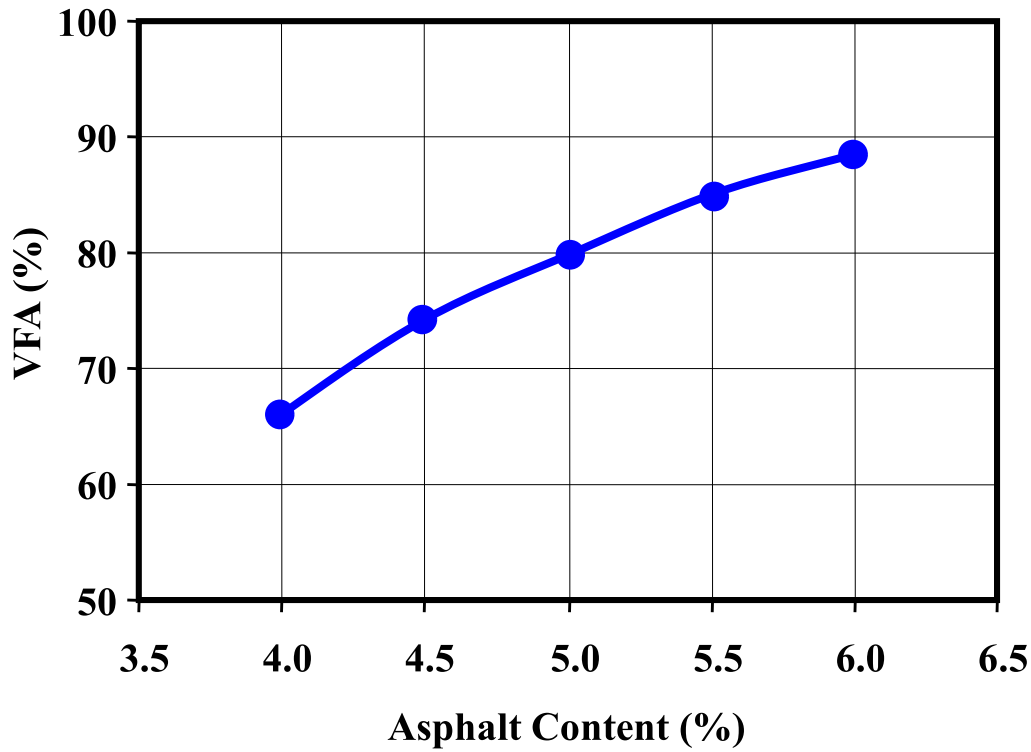


4% Air Voids @ 4.3% AC
6
5
4
3
2
1
VTM (%)
3.5
4.0
4.5
5.0
5.5
6.0
6.5
Asphalt Content (%)

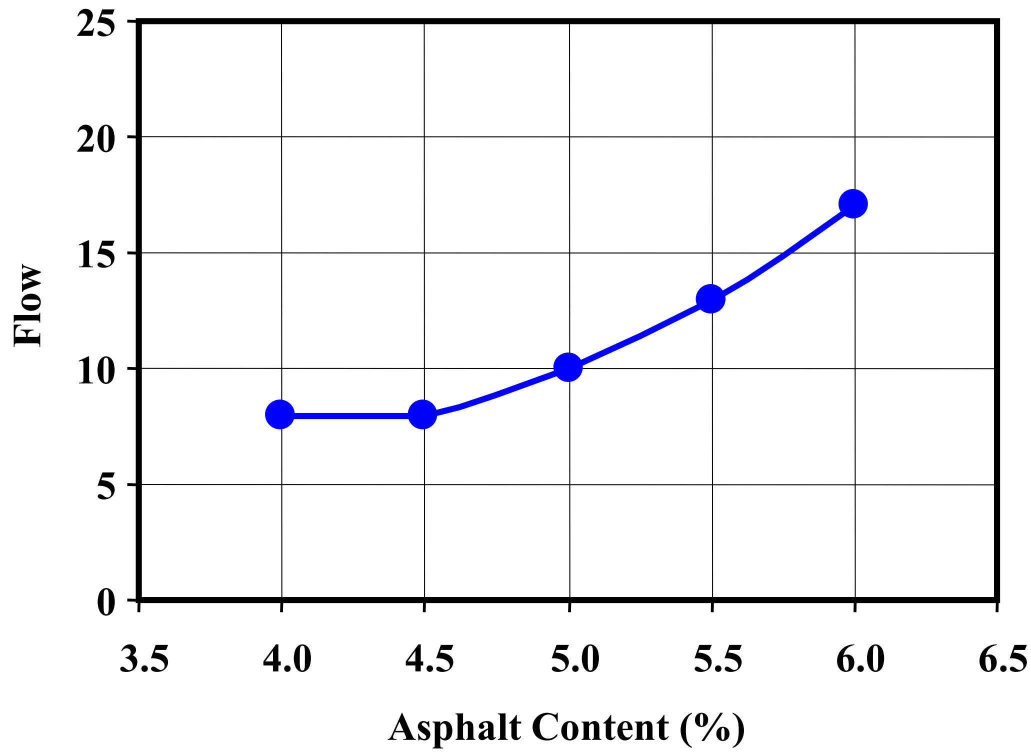
VMA Results



VFA Results



Flow Results



Optimum Asphalt Content

The Asphalt Institute suggests the optimum asphalt content is the average of the three asphalt contents determined from the plots. Based on the values taken from the example plots, the optimum asphalt content for this trial aggregate blend is 4.7%.

Optimum Asphalt Content

Asphalt Institute Procedure

Maximum Density | **Maximum Stability** | **4% Air Voids**

$$AC = \frac{5.1 + 4.7 + 4.3}{3} = 4.7\%$$

Optimum Asphalt Content

The National Asphalt Pavement Association (NAPA) suggests the optimum asphalt content is simply the asphalt content that produces exactly 4% air voids. From our example plots, this would be 4.3%.

Which one is correct? Keep in mind that these are just trials. Like the mix design method for concrete, the idea is to get you in the ballpark, then you can tweak the design as needed.

Optimum Asphalt Content

NAPA Procedure

Maximum Density **Maximum Stability** **4% Air Voids**

$$AC = \frac{\cancel{5.1} + \cancel{4.7} + 4.3}{1} = 4.3\%$$

This is what TDOT uses

Optimum Asphalt Content

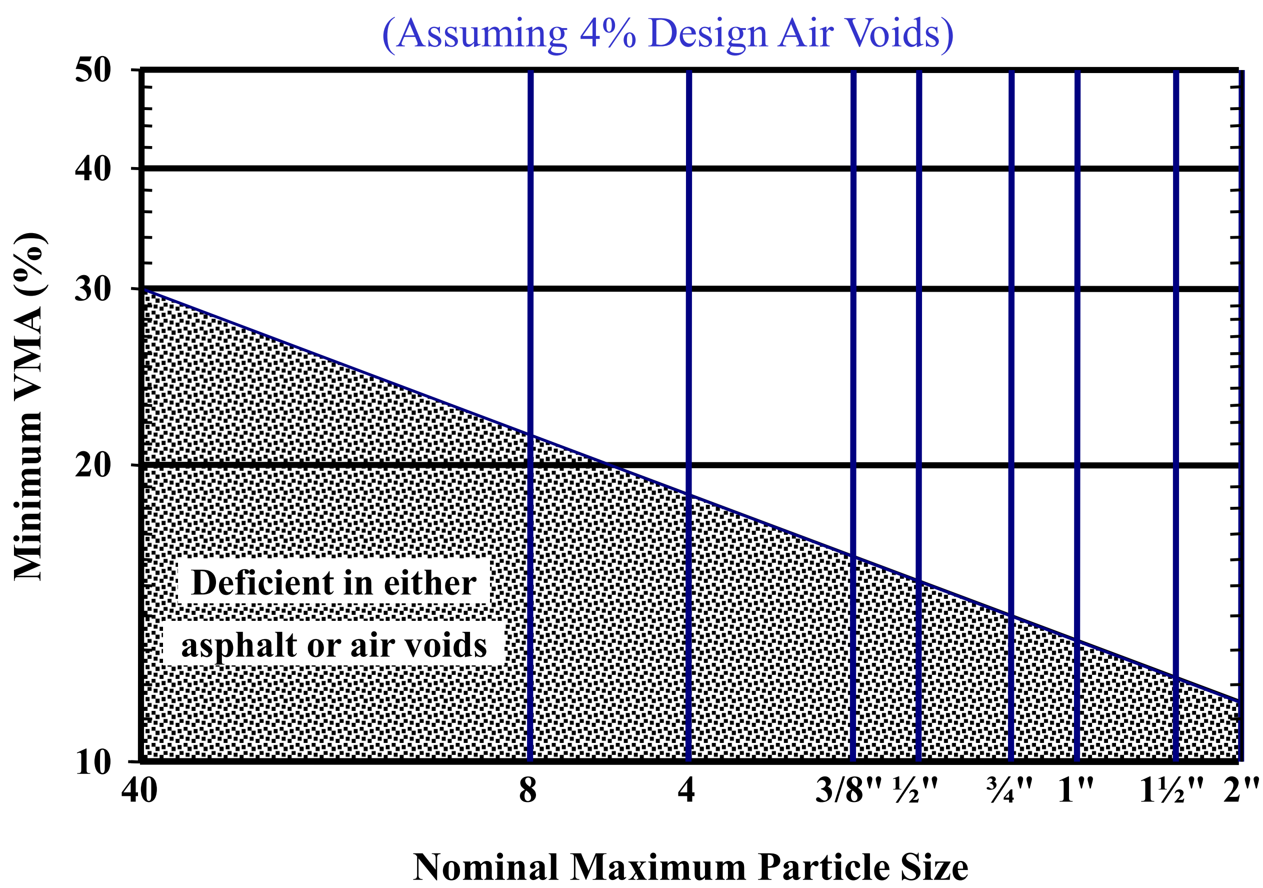
Once you've estimated the optimum asphalt content, you need to go back to the plots and estimate the VTM, VMA, VFA, stability and flow of a specimen made at the optimum asphalt content (which probably isn't one of the asphalt contents you used to produce the specimens). If these values meet the requirements in the next slide, you're done. Otherwise, you need to either tweak the asphalt content (if possible) or try a different aggregate blend.

Marshall Criteria

(Asphalt Institute Criteria)

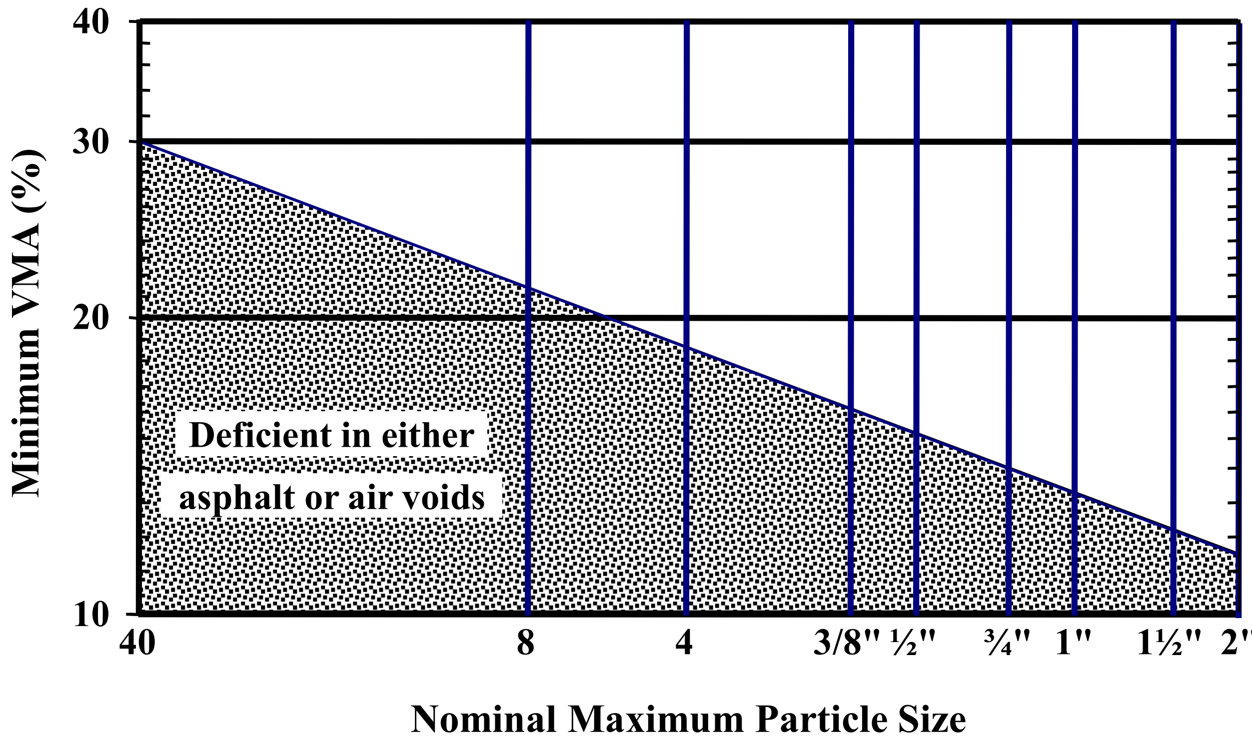
	Light Traffic		Medium Traffic		Heavy Traffic	
Criteria	Min.	Max.	Min.	Max.	Min.	Max.
Number of Blows	35		50		75	
Stability (lbs)	750		1200		1800	TDOT uses 2000
Flow	8	18	8	16	8	14
Air Voids (%)	3	5	3	5	3	5
Voids Filled (%)	70	80	65	78	65	75

Marshall VMA Criteria



Question to Ponder

Why does the minimum VMA requirement increase with a decrease in the NMAS?

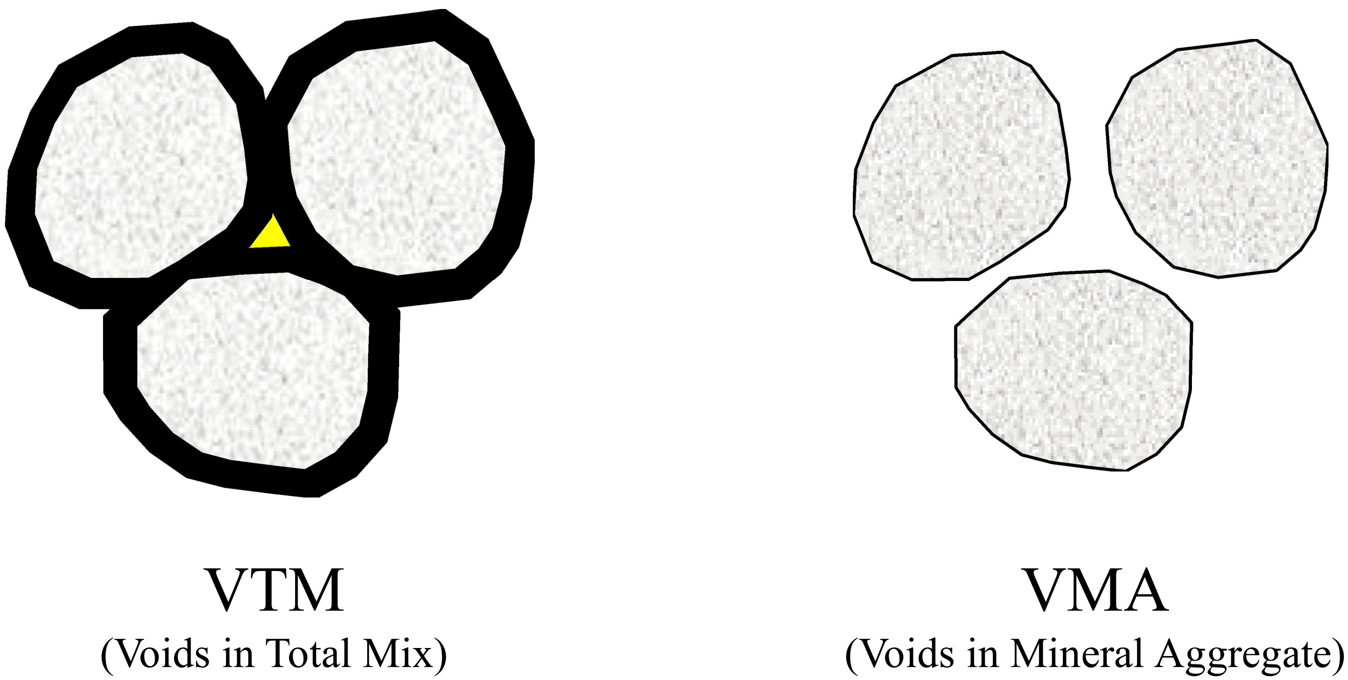


Question to Ponder

Recall that the VMA is the void space around all of the aggregate particles in the compacted specimen if you could make all of the asphalt cement disappear.

Mathematically, this is equal to the volume of the air voids between the particles plus the volume of the ***effective*** asphalt cement coating the particles.

Voids in Mineral Aggregate



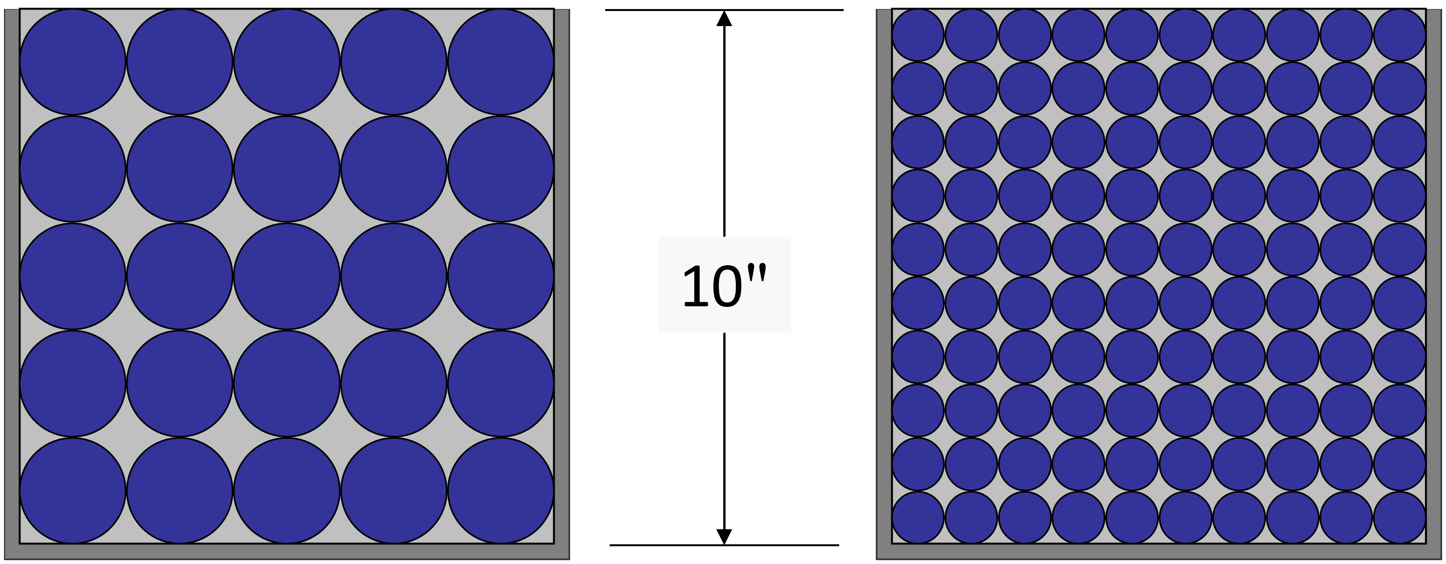
$$VMA = \frac{\text{air void volume} + \text{effective asphalt volume}}{\text{total volume}}$$

Question to Ponder

As we've mentioned numerous times, the smaller the aggregate, the larger the surface area per unit volume. So asphalt concrete that is made with an aggregate blend having a small NMAS requires more ***effective*** asphalt cement to coat all of those surfaces. Thus the VMA must be higher in order to have enough room in the aggregate skeleton for all that extra binder.

Effect of NMAS on Surface Area

effective asphalt volume $\propto$ aggregate surface area



surface area = 11 ft^2

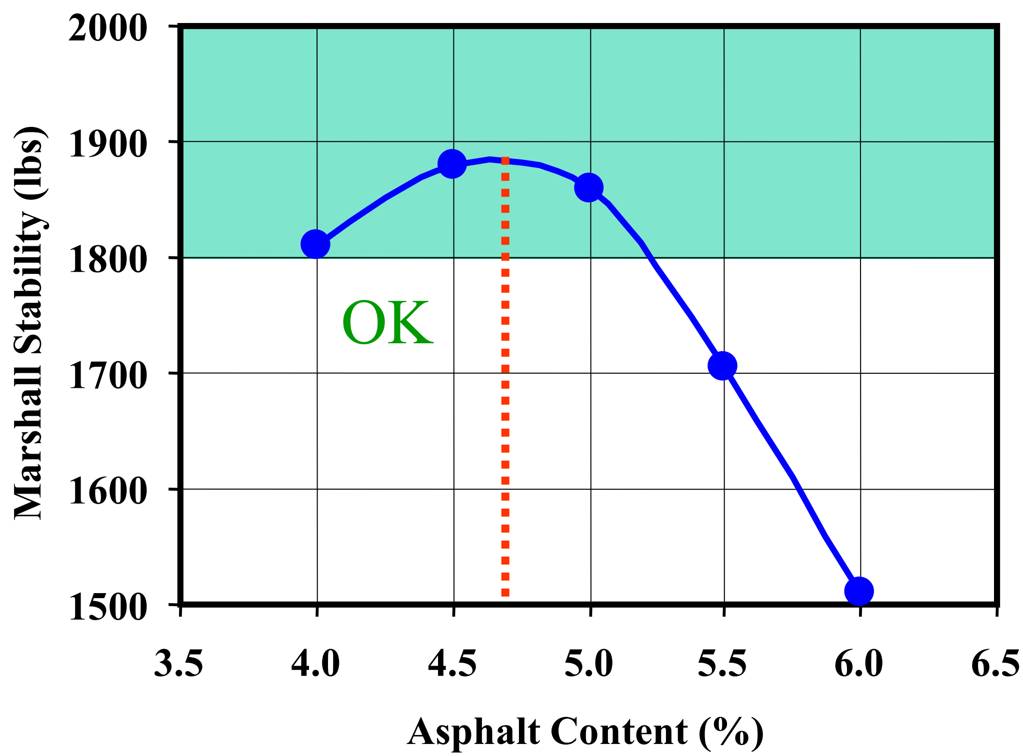
surface area = 22 ft^2

Marshall Criteria

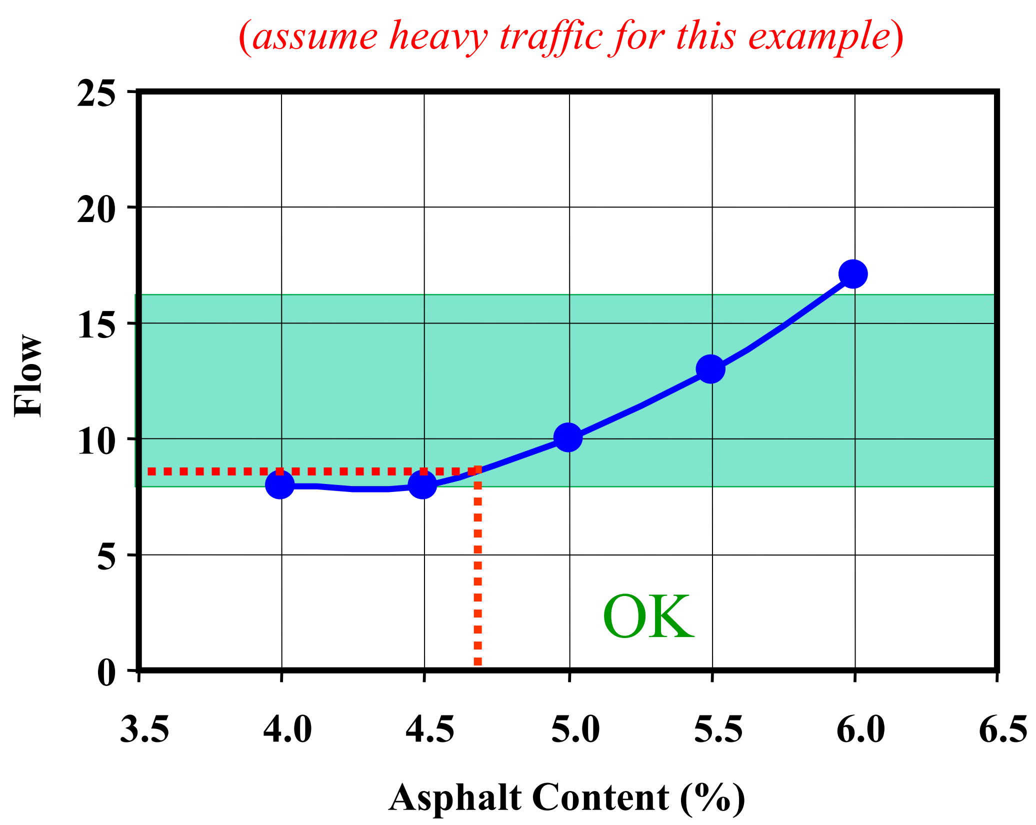
For the purpose of our example, let’s assume we are designing our mix for heavy traffic. That means the stability at our optimum asphalt content must exceed 1800 lb, the flow must be between 8 and 14, the air voids must be between 3% and 5%, the VFA must be between 65% and 75% and, if we assume that the NMAS of our aggregate blend is ¾", the VMA must be at least 14%. Let’s see how we did.

Check Stability @ Optimum

(assume heavy traffic for this example)

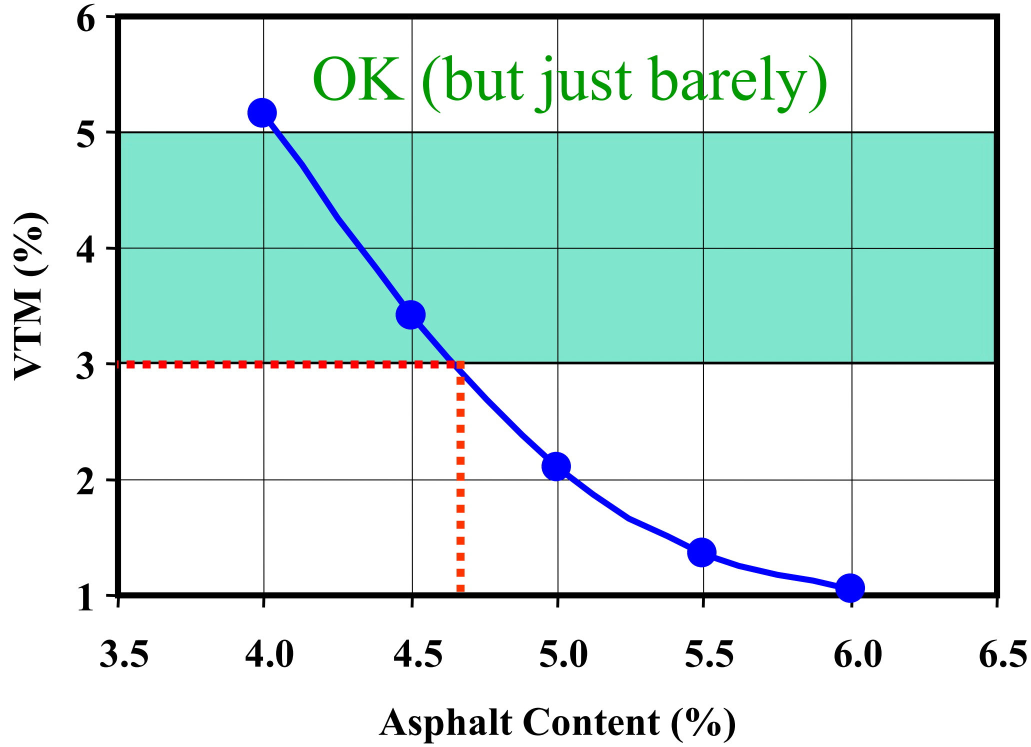


Check Flow @ Optimum

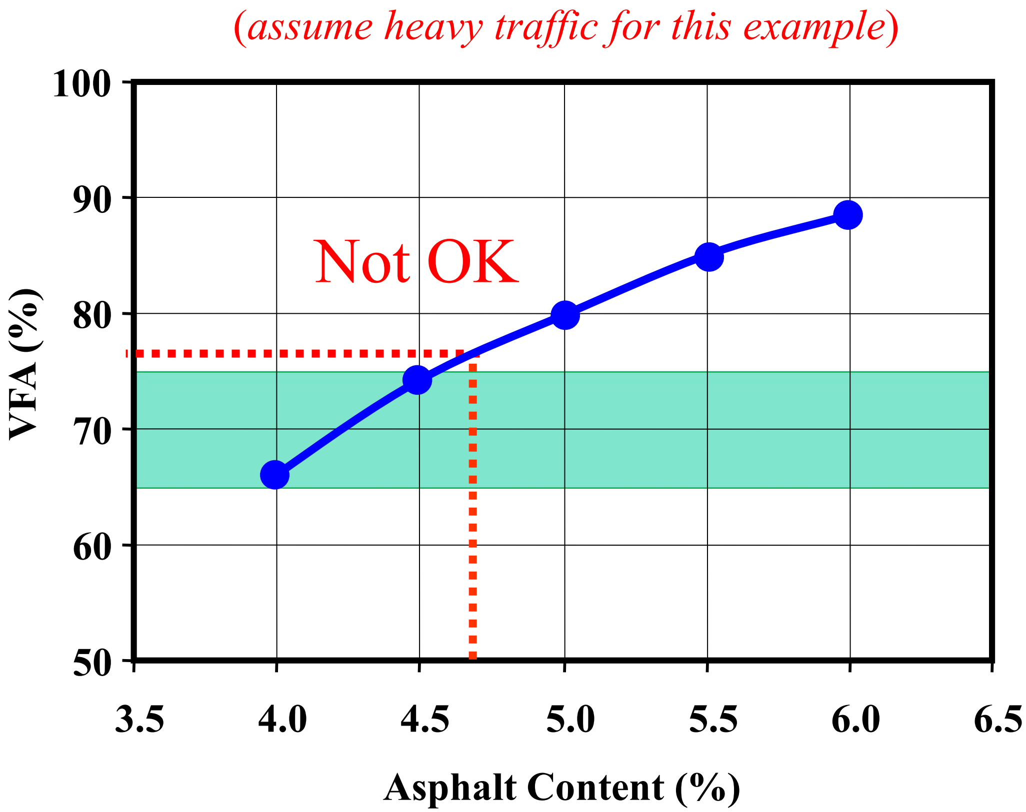


Check VTM @ Optimum

(assume heavy traffic for this example)

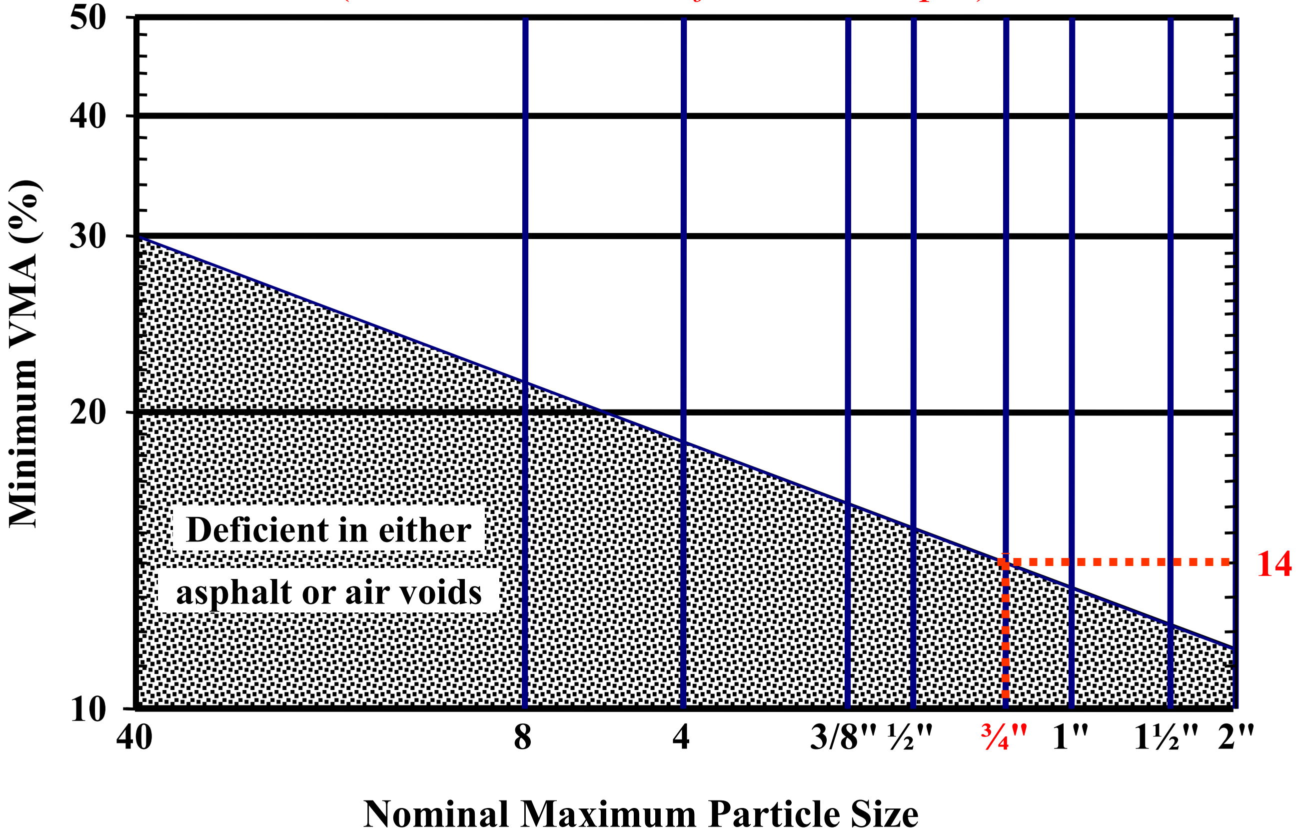


Check VFA @ Optimum

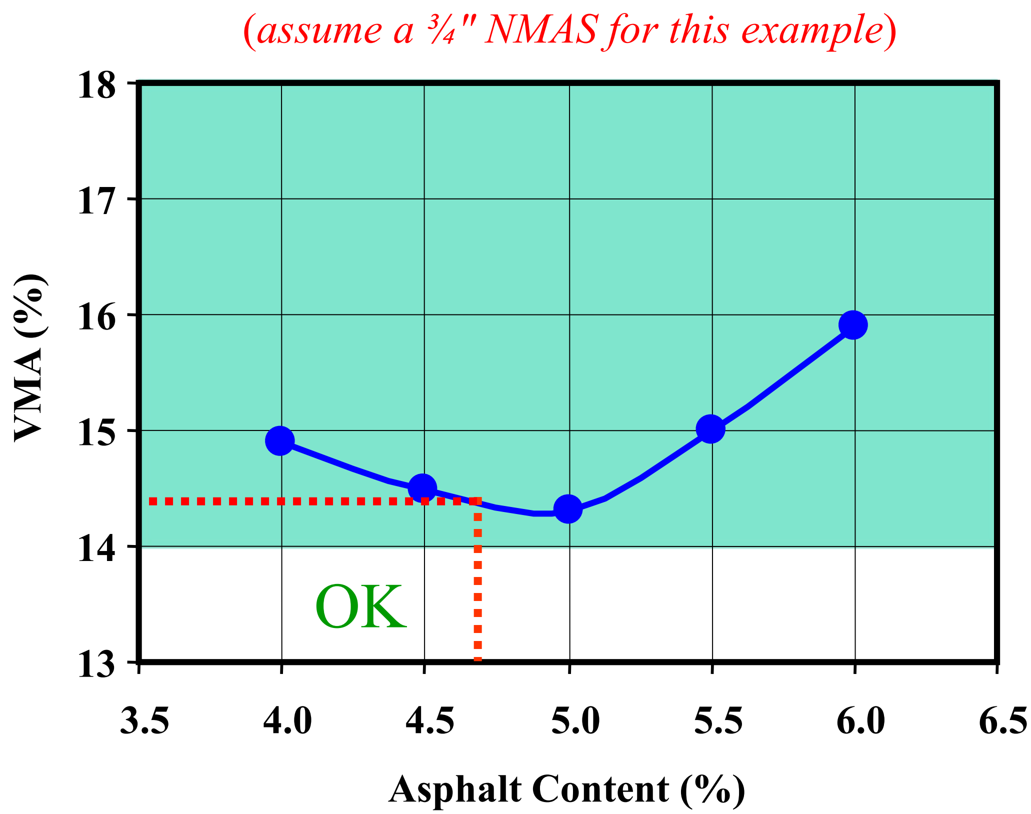


VMA Criteria

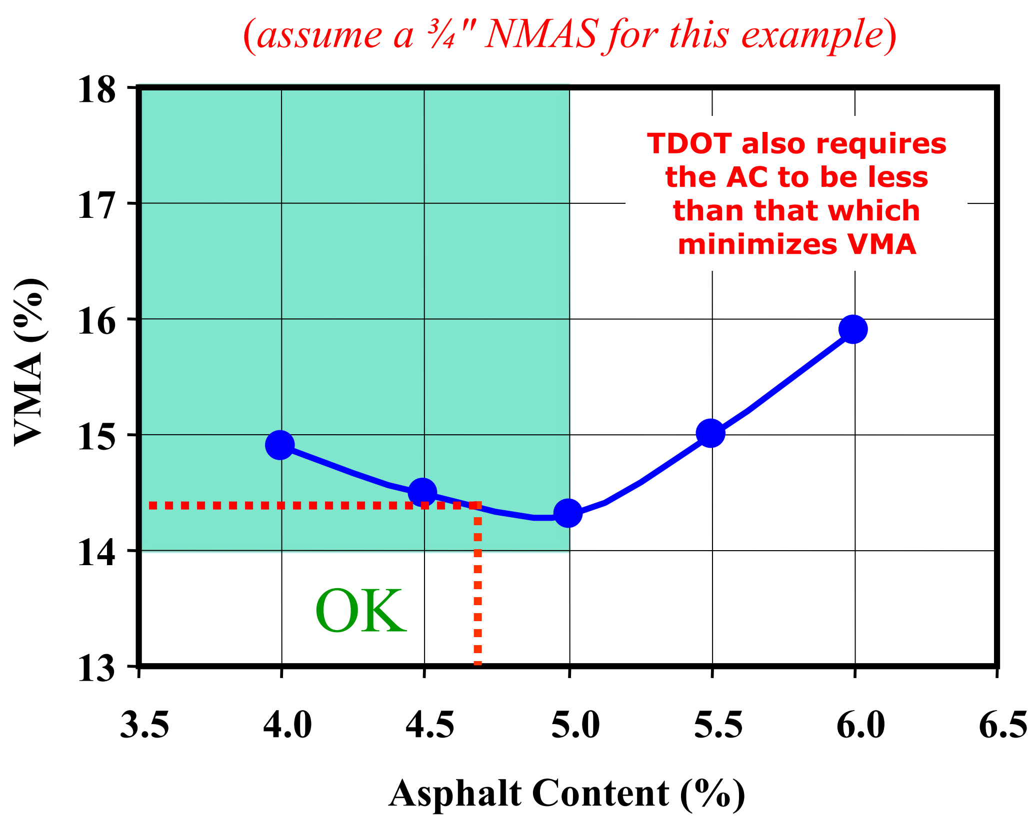
(*assume a ¾" NMAS for this example*)



Check VMA @ Optimum



Check VMA @ Optimum



Marshall Criteria

At an optimum asphalt content of 4.7% we barely meet the VTM requirement and didn't meet the VFA requirement. What does this tell us?

We just barely have enough air voids and too much of the VMA space is filled with asphalt cement, so it is likely that our VMA is actually too low.

Marshall Criteria

If the VMA is higher, there will be more room in the aggregate skeleton for asphalt cement and air voids. If we kept the amount of asphalt cement the same, that means there would be more air voids (VTM) and the asphalt cement would occupy less of the available space, bringing the VFA down. So how could we increase the VMA?

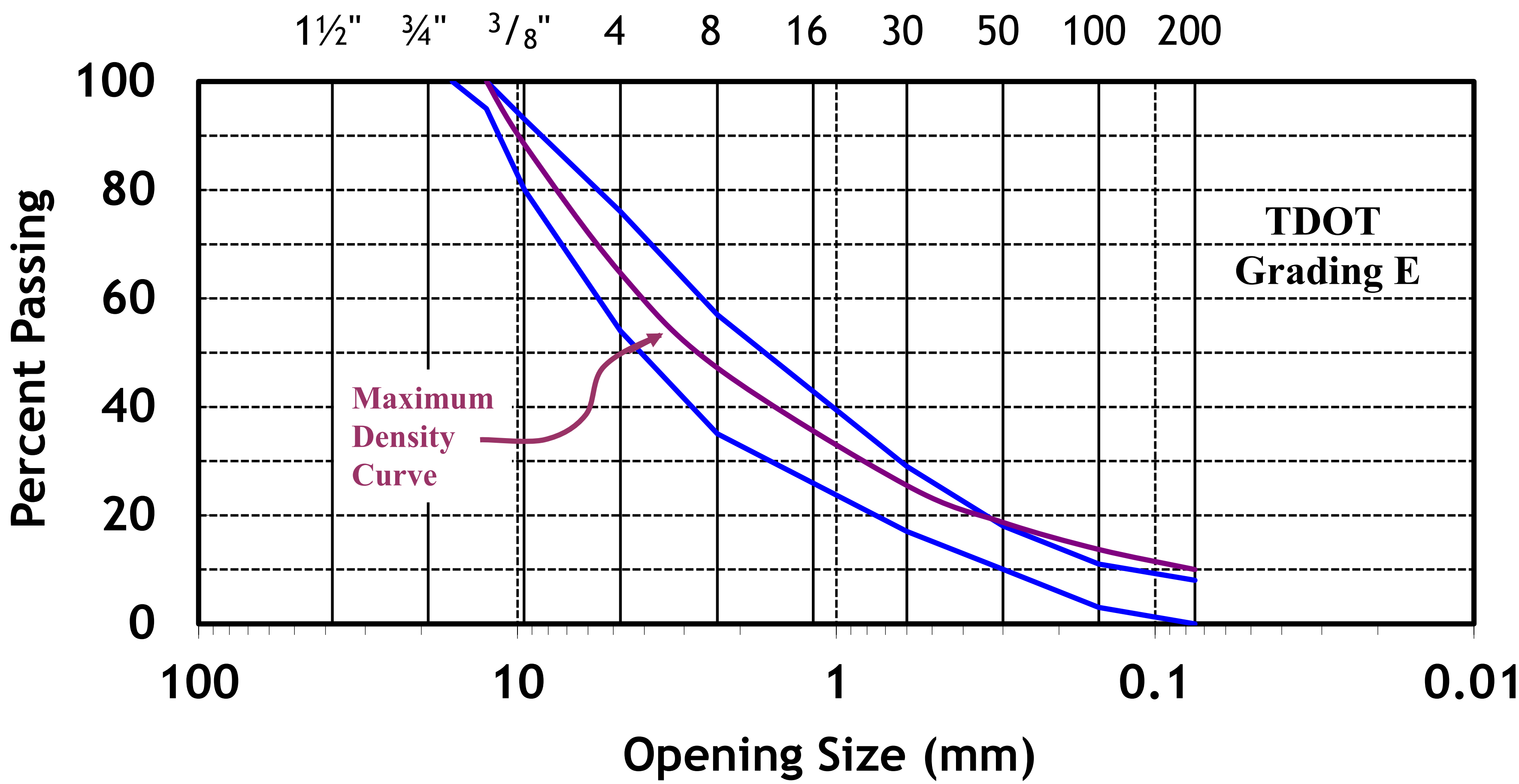
Ways to Increase VMA

1. Reduce the dust (fines) content
2. Reduce the amount of sand
3. Gap-grade the aggregate blend

Ways to Increase VMA

Remember that one of the reasons the TDOT 411-D specifications don't exactly match the theoretical maximum density curve is to "open up" the gradation to allow room for asphalt cement and air. All three of the steps on the previous slide would "open up" the gradation by removing some of the smaller material.

TDOT Specifications



Ways to Increase VMA

1. Reduce the dust (fines) content
2. Reduce the amount of sand
3. Gap-grade the aggregate blend
4. Replace some of the natural sand (if used) with manufactured sand

Ways to Increase VMA

Recall that manufactured sand is angular and natural sand is rounded. Recall, too, that the void content of angular sand is higher than that of rounded sand (which is why void content is used to determine fine aggregate angularity). So replacing some of the natural sand with the same weight of manufactured sand will increase the VMA.

Natural Sand

Manufactured Sand

Ways to Increase VMA

1. Reduce the dust (fines) content
2. Reduce the amount of sand
3. Gap-grade the aggregate blend
4. Replace some of the natural sand (if used) with manufactured sand
5. Increase fractured face percentage
6. Reduce flat-and-elongated particles

Ways to Increase VMA

Assuming you are using a crusher run gravel as your coarse aggregate, you could run the material through the crusher again to increase the fractured face percentage. This would make the coarse aggregate more angular, which has the same effect on VMA as replacing natural sand with manufactured sand.

Ways to Increase VMA

Replacing flat and elongated particles increases VMA by replacing each long skinny rock with two or three smaller equidimensional rocks. Since there will be void spaces between the smaller rocks that didn't exist before, the VMA will increase.

Ways to Increase VMA

If none of the steps above fix the problem, you may want to consider a different aggregate source.