HMA Volumetrics Revisited - A New Paradigm

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ABSTRACT

As early as 1905, Richardson recognized the importance to performance of the relative proportions, by volume, of the material components of bituminous mixtures. In the 1940's Marshall explicitly addressed the volumetric percentages of air voids, V_a, and of the degree of void saturation by asphalt, (VFA). In the late 1950's McLeod clearly demonstrated and justified the appropriate aggregate specific gravities to be used in volumetric computations, and emphasized the importance of the combined volumes of the air voids and effective asphalt binder (VMA). These various volumetric parameters have since formed a principal part of the Marshall design method and have, more recently been enshrined into the Superpave system.

This paper seeks to revisit the definitions of the various volumetric parameters and their inter-relationships. It develops an instructive and useful chart with which mixtures of different volumetric characteristics may be compared, and through trajectory analysis, reduced to a common basis. A further simple graphical method is developed that may be used to analyze, volumetrically, mix designs both Marshall and Superpave. This latter method can be used as a point-estimate method to identify the binder content which will yield any given air void content. While the paper offers no new technology, it presents old information in a new way - a new paradigm.

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INTRODUCTION

As early as 1905, Richardson (*1*) recognized the importance to performance of the relative proportions, by volume, of the material components of bituminous mixtures. In the 1940's Marshall (*2*) explicitly addressed the volumetric percentages of air voids, V_a, and of the degree of void saturation by asphalt, (VFA). In the late 1950's McLeod (*3,4,5*) clearly demonstrated and justified the appropriate aggregate specific gravities to be used in volumetric computations, and emphasized the importance of the combined volumes of the air voids and effective asphalt binder (VMA). These various volumetric parameters have since formed a principal part of the Marshall design method (*6*) and have, more recently been enshrined into the Superpave system (*7*).

Simplistically, a hot-mix asphalt (HMA) material comprises three material components:

- Air Voids
- Mineral Aggregate
- Bituminous Binder

In production, the latter two materials are proportioned by mass (weight). It has long been acknowledged that the performance of HMA mixtures is more significantly influenced by the relative *volumetric* proportions of the three components. The study and use of the volumetric proportioning of HMA mixtures is called "volumetrics". This paper does not seek to investigate nor justify the critical design values assigned to any of these, or other, volumetric parameters, but to clarify their meanings and inter-relationships.

The nomenclature used throughout this paper is based on the modified Asphalt Institute system adopted by the Superpave system.

VOLUMETRICS

Primary volumetric parameters

The primary volumetric parameters are those relating directly to the relative volumes of the individual components:

- Air Voids, V_v - the volume of air voids
- Binder Volume, V_b - the volume of the bituminous binder
- Aggregate Volume, V_s - the volume of the mineral aggregate

Due to the phenomenon of absorption, some of the bituminous binder is absorbed into the external pore structure of the aggregate - this leads to the situation wherein a portion of the aggregate and bituminous binder share space, or where the sum of the individual volumes ($V_b + V_s$) is greater than their combined volume (V_{b+s}).

This leads to further sub-division of the primary volumetric parameters given above:

- Effective Binder Volume, V_{be} - the volume of bituminous binder *external* to the aggregate particles, i.e., that volume *not* absorbed into the aggregate
- Absorbed Binder Volume, V_{ba} - the volume of bituminous binder *absorbed* into the external pore structure of the aggregate
- Bulk Aggregate Volume, V_{sb} - the total volume of the aggregate, comprising the "solid" aggregate volume, the volume of the pore structure permeable to water but not to bituminous binder and the volume of the pore structure permeable to the bituminous binder
- Effective Aggregate Volume, V_{se}, - the volume of the aggregate comprising the "solid" aggregate volume and the volume of the pore structure permeable to water but not to bituminous binder.
- Apparent Aggregate Volume, V_{sa} - the volume of the "solid" aggregate, i.e., that volume permeable to neither water nor bituminous binder.

These various volumetric components are conventionally represented by a "phase diagram" (Figure 1).

Secondary volumetric parameters

For many years, at least since 1905 (*1*), three further volumetric parameters have been widely used, and at various times, have formed critical design thresholds. These are the Percent Air Voids, V_a, the Voids in the Mineral Aggregate, VMA, and the Voids Filled with Asphalt, VFA.

- Percent Air Voids, V_a - the volume of the Air Voids, V_v, expressed as a percentage of the total volume of the mixture.
- Voids in the Mineral Aggregate, VMA - the sum of the Air Voids, V_v, and the Effective Binder Volume, V_{be}, expressed as a percentage of the total volume of the mixture. This parameter is directly analogous to "porosity" in soil mechanics.
- Voids Filled with Asphalt, VFA - the degree to which the VMA are filled with the bituminous binder, expressed as a percentage. Once again, this is directly analogous to the "degree of saturation" in soil mechanics.

It is important to recognize that Air Voids, V_a, VMA and VFA are not independent of the degree of compaction, and, strictly speaking, should never be quoted without referencing the degree of compactive effort used (50-blow Marshall, 75-blow Marshall, Superpave N_{des}, etc). This applies equally to cores, for which some estimate of traffic (ESALS) should be given.

With reference to Figure 1 and the above definitions, the following relationships may be derived:

$$\begin{gathered} V_a = \frac{V_v}{V_{total}} \times 100 \\ VMA = \frac{V_v + V_{be}}{V_{total}} \times 100 \\ VFA = \frac{V_{be}}{V_v + V_{be}} \times 100 \end{gathered} \tag{1}$$

Simple algebraic manipulation reveals that these are not mutually independent, since:

$$\mathrm{VFA} = \frac{\mathrm{VMA} - \mathrm{V_a}}{\mathrm{VMA}} \times 100 \qquad \textbf{(2)}$$

In practice, two of these parameters (V_a and VMA) are obtained from measurements of various specific gravities (G_{mb} - the bulk specific gravity of the compacted mixture, G_{mm}, - the maximum theoretical (void-free) specific gravity of the mixture, and G_{sb} - the bulk specific gravity of the blended aggregate) and a knowledge of the mass percentage of bituminous binder in the mixture, P_b. The third (VFA) is derived using Equation (2) above.

In the process of mixture design, or of production, it is frequently necessary to seek to change the magnitude of one or more of these parameters; for example, upon analyzing a mixture, it may appear desirable to increase the VMA (a relatively common problem), or to increase or decrease the air voids. Various recommendations and techniques exist to do this. However, it is not always clear what effect such a change might have on the other parameters nor whether that change may in itself compromise compliance in another direction. Indeed, no such change in any one parameter should ever be contemplated without checking the effects on the other two.

Volumetric Chart

McLeod (*3,4,5*), *inter alia*, developed a number of charts to show the interaction between these parameters. The problem with these charts was that being based, typically, on binder content *by mass*, P_b, it was necessary to re-plot each chart for the specific material specific gravities of the materials involved, and the resulting graphs were often non-linear.

Figure 2 presents a linear plot that presents all three volumetric components of a mixture, and *which is universal in application*, i.e., it is independent of differing specific gravities and can be used *without modification* for any mixture. The y-axis represents the percent air-voids, V_a. The x-axis represents the percent effective binder volume, V_{be}, and is found by the difference between the VMA and the air voids, V_a, or V_{be} = VMA - V_a.

The diagonal lines are lines of equal VMA. Since VMA = $V_a + V_{be}$ (or VMA = x + y), lines connecting equal values on the two axes are lines of VMA of those magnitudes. This shows, for example, that a VMA of 13 can be achieved with an air voids, V_a of 3% and an effective binder volume of 10% *or* an air voids, V_a of 5% and an effective binder volume of 8%, etc.

The lines radiating from the origin are lines of equal VFA. This is a consequence of the relationship in Eqn. 2, whence:

$$\mathrm{VFA} = \frac{\mathrm{VMA} - \mathrm{V_a}}{\mathrm{VMA}} \times 100 = \frac{\mathrm{V_{be}}}{\mathrm{V_{be}} + \mathrm{V_a}} \times 100 = \frac{x}{x + y} \times 100$$

$$y = \left(\frac{100 - \mathrm{VFA}}{\mathrm{VFA}} \right) \cdot x \qquad \textbf{(3)}$$

There is a further series of lines shown, sloping slightly left-to-right off the vertical. These are referred to as *trajectories* and are explained below.

Utility of Volumetric Chart

The Volumetric Chart has a number of uses, and some are explained as follows:

1. Feasible Region: Pre-Superpave, specifications typically stated that, following laboratory compaction, the air-voids, V_a, should be in the range 3-5%, and the VMA not less than, say, 14%, and perhaps that the VFA be in the range 65-75%. This type of specification may be examined by plotting this region directly on the chart (Figure 3), and the shaded area defines the *feasible region* for mixtures. In this manner, unrealistic, or unfair, specifications can be identified.
2. Trajectory: As stated above, the secondary volumetric parameters are dependent upon the degree of compaction. Thus the *same* mixture can exhibit *different* volumetrics at different degrees of compaction. For example, if a mixture is designed to have an air void content, V_a, of 4% and a VMA of 13% at N_{des}, then what would its state be when compacted in the field to 92% G_{mm}? From the design point A (9, 4) in Figure 3, follow the trajectory line through that point up to an air void, V_a, of 8% (= 92% G_{mm}). At this point, B, it can be seen that the full volumetrics are: V_a = 8%, VMA = 16.6% and the VFA = 51.9%. The Author has used this method to find out how mixtures prepared against an older specification (target V_a = 6%) would rate when judged by a different specification (say V_a = 4%). Trajectory lines are constructed by joining any point on the plot (V_{be}, V_a) to the point (0, 100).

3. QC/QA: The author has also used the trajectory lines in a QC/QA monitoring function. All samples of the same mixture, *at whatever level of compaction*, should fall on the same trajectory line. Indeed, even during production, they do so to quite a close tolerance. If a sample plots significantly off its trajectory line, the implication is that something has changed in the mixture itself. In other words: any point on the trajectory line represents the same mixture *regardless of compaction*, while a point off the trajectory line indicates a change in the mixture - *regardless of level of compaction*.

The trajectory line has been used to demonstrate to students and practitioners that volumetrics change continuously as a mixture is compacted, and that such characteristics as VMA are not inherent to the mixture, but are compaction dependent. Further, some engineers have been surprised that a design mix examined at construction density conditions (say 92% G_{mm}) have a higher VMA than in the design, and even more so by the value of the VFA at this condition (often less than 50%).

This chart has proven useful as a teaching aid and has helped in explaining the relationships between the secondary volumetric parameters and the mechanism of compaction from a volumetric viewpoint. What it *does not do* is to shed much light on the primary volumetric parameters, nor can it be used predictively. For example, given the results from a single sample, say A in Figure 3, what bituminous binder content, P_b, would yield an air void, V_a, content of 3.5% under the same compactive effort?

MIXTURE DESIGN CHART

A further chart, which uses the following methodology, again appeals to basic volumetric principles and relationships, permitting the designer to:

- Display graphically all of the primary volumetric parameters simultaneously, including the various shared volumes (absorption)

- Provide a means of predicting the volumetric state of a mixture at any binder content, P_b, given either a full design (3, 4 or 5 binder contents) or a single test (point-estimate)

- Pin-point errors of measurement in either the sample bulk specific gravity, G_{mb}, the maximum theoretical specific gravity, G_{mm}, or in the bulk specific gravity of the blended aggregate, G_{sb}.

Unlike the previous charts (Figure 2 and 3), this chart has to be developed individually for each mixture analyzed; however, once again, the relationships are simple and most are linear. A point-estimate problem can be solved with a four-function calculator in a couple of minutes. A full mix design problem can be solved *graphically* (pencil, paper and calculator only), or with a spreadsheet - all in about the same time.

Basis

Air-free mixture

The basic concept can be demonstrated using the standard relationship for maximum theoretical specific gravity of a mixture, G_{mm}, where:

$$G_{mm} = \frac{100}{\frac{P_b}{G_b} + \frac{100 - P_b}{G_{se}}} \qquad \textbf{(4)}$$

This relationship may be re-arranged, thus:

$$\frac{100}{G_{mm}} = \frac{P_b}{G_b} + \frac{100 - P_b}{G_{se}} = \frac{100}{G_{se}} + \left(\frac{1}{G_b} - \frac{1}{G_{se}} \right) P_b \qquad \textbf{(5)}$$

It is clear that each term in Equation 5 represents a volume, and that the relationship is linear in binder content, P_b. The author refers to these individual components of volume (i.e., $100/G_{mm}$, say) as *specific volumes*, and uses the general symbology $V_{xx} = 100/G_{xx}$.

If Equation 5 is plotted on a graph of Specific Volume against binder content by mass, P_b (Figure 4) it will be seen that the intercept (at $P_b = 0$) represents the *effective specific volume* of the blended aggregate, and by inverting that magnitude, the effective specific gravity of the aggregate, G_{se}, is found. Since the Rice, or Maximum Theoretical Specific Gravity of the mixture is (or should be, á la Superpave) measured at each binder content used, the line through the plotted points gives an unbiased estimate of the intercept and a particularly robust estimate of the effective specific gravity of the blended aggregate, G_{se}, using *all the information available*.

Aggregate lines

Three lines related to the blended aggregate may be plotted on the graph - those relating to the *bulk*, *effective* and *apparent* specific volumes. The specific gravities (bulk and apparent) are measured on uncoated aggregate and therefore these specific volumes are plotted on the y-axis ($P_b = 0$). However, at other binder contents the following argument applies: if we have $P_b = 5\%$ (say), then we have 95% aggregate by mass; therefore the aggregate in this mixture occupies 95% of the volume of a dry mix ($P_b = 0$). So therefore a line may be plotted from each of the aggregate specific volumes plotted on the y-axis by simple proportion, such that:

$$V_{sx}(@\, P_b \neq 0) = \frac{100 - P_b}{100} \times V_{sx} \qquad \textbf{(6)}$$

were V_{sx} indicates a generic aggregate specific volume.

The lines for bulk, effective and apparent specific volumes are shown on Figure 5. The line of effective specific volume, V_{se}, should, of course, plot *between* those of the bulk and apparent specific volumes. The apparent specific volume line is often not drawn since it is not used in the ensuing analysis, however it is interesting to note that the volume represented by the difference between the effective and apparent specific volumes lines represents the volume of water permeable pores *not* filled with binder. Whether these unfilled voids at the heart of the aggregate-binder interface may be a factor in stripping is an open question.

There is a further, and independent, means of deriving the line for the effective specific volume of the blended aggregate. The maximum theoretical specific gravity (minimum theoretical specific volume?) line represents the sum of the binder and the effective aggregate volumes (eqn 5). Thus the effective specific volume line may be obtained by subtracting the specific volume of the binder from the maximum theoretical specific gravity line: $100/G_{se} = 100/G_{mm} - P_b/G_b$. This can act as an independent check, and as is shown later has saved an anomalous analysis.

The lines represented thus far are invariant, and are independent of the degree of compaction. However, in order to complete the picture, the bulk specific volume of the mixture, V_{mb}, can be drawn, and this is compaction dependent.

Bulk mixture

If the measured values of G_{mb} are transformed to specific volumes, $V_{mb} = 100/G_{mb}$, and plotted, it will be seen that these do *not* normally plot as a straight line. This is to be expected since in the Marshall method the plot of unit weight vs binder content is (or should be) concave downwards, and the specific volume plot is merely the invert of that plot.

In order to work with this information, it is necessary to idealize the bulk specific volume relationship in the following manner. Consider a box filled with the compacted blended aggregate. The contents have a mass and a volume. Add, say, 5% bituminous binder. This will fill some of the voids in the aggregate, but as long as it doesn't fill all the available voids, the mass of the material in the box will have increased while the volume remains constant. This leads to the relationship:

$$V_{mb}(@\,P_b \neq 0) = \left(\frac{100}{100 + P_b}\right) \cdot V_{mb}(@\,P_b = 0) \qquad \textbf{(7)}$$

This relationship is non-linear in P_b, however, over the likely range of use, it is almost linear, and for hand-plotting purposes can be treated as such.

In most cases, it will not be possible to plot Eqn. 7 through the plotted bulk specific volumes, V_{mb}. Consequently, and conservatively, whichever of the plotted points results in the least value of $V_{mb}(@P_b = 0)$ is selected and plotted (Figure 6). In most cases, the plotted points will plot in a gently curve (concave upwards) tangential to the plotted line.

A final and last line may be drawn. This line is used only to aid the designer in identifying the design binder content, P_b. If, for example, the design air voids, V_a, are required to be 4% (i.e., 96% G_{mm}), then a line is drawn to represent 96% of the total volume, or 96% V_{mb}. Where this line intersects the theoretical maximum specific gravity line, V_{mm}, indicates the binder content at which the 4% V_a occurs. All other parameters may now be computed at this, or any other, condition.

The Full Picture

The picture is now essentially complete (Figure 7). All elements of volume can now be identified and quantified.

- Bulk Specific Volume of the mixture, V_{mb}, can be estimated at any binder content, P_b. Of course, the further that that point departs from the point of tangency to the plotted data points, the more approximate that estimate becomes.

- Air Voids, V_v, are easily identified as the volume represented by the difference between the Bulk Specific Volume of the mixture, V_{mb}, and the maximum specific gravity line, V_{mm}.

- Percent Air Voids, V_a, are computed as a percent of the total volume, or:

$$V_a = \frac{V_{mb} - V_{mm}}{V_{mb}} \times 100 \qquad \textbf{(8)}$$

- The effective binder volume, V_{be}, is represented as the difference between the maximum specific gravity line, V_{mm}, and the bulk specific volume of the blended aggregate line, V_{sb}; thus $V_{be} = V_{mm} - V_{sb}$.

- The absorbed binder volume, V_{ba}, is represented by the difference between the aggregate bulk specific volume line, V_{sb}, and the aggregate effective specific volume line, V_{se}; thus $V_{ba} = V_{sb} - V_{se}$.

- The percentage of absorbed binder *by mass* is identified at the point of intersection of the maximum theoretical specific gravity line, V_{mm}, and the aggregate bulk specific volume line, V_{sb}.

- The VMA is computed as the difference between the bulk specific volume of the mixture, V_{mb}, and the bulk specific volume of the blended aggregate, V_{sb}, expressed as a percentage of the total volume, thus:

$$\text{VMA} = \frac{V_{mb} - V_{sb}}{V_{mb}} \times 100 \qquad \textbf{(9)}$$

- The VFA is found as the effective binder volume, $V_{be} = V_{mm} - V_{sb}$, expressed as a percentage of total VMA, thus:

$$\text{VFA} = \frac{V_{mm} - V_{sb}}{V_{mb} - V_{sb}} \times 100 \qquad \textbf{(10)}$$

This plot, which with a little practice, is easy to perform, has proven to be useful in the classroom in clearly identifying the volumes of the various components as the binder content varies. In effect, it is like a *two-dimensional phase diagram, drawn to scale*. It has proven useful as:

- Teaching Aid: to demonstrate the volume components of the mixture - and to give a graphical and clear explanation of the components involved in calculating the secondary volumetric parameters

- Diagnostic Tool: plotting the data points quickly identifies any bad bulk or Rice data point

- Predictive Tool: In the Superpave system, single tests are performed to identify the optimal aggregate structure. In this process, the results are "massaged" to provide an estimate of the binder content, P_b, that would yield an air void content, V_a, of 4%, and of the volumetric parameters at that state. This method provides a quick and usually accurate means of doing so that is both intuitive and no less accurate (typically within ± 0.1%) than the prescribed Superpave method.

- Statistical Strength: notwithstanding the idealized bulk specific volume of the mixture line, V_{mb}, , the other information (V_{mm} and consequently V_{se}) is strengthened by being treated as part of a relationship rather than as three or four independent observations. Thus the maximum theoretical specific gravity line provides better (and unbiased) estimates of V_{se} and the measured Rice values, than is available by treating them independently and individually at each tested binder content.

Recently, the Author has analyzed some mixtures wherein the asphalt absorption appeared to increase as the binder content increased. Plotting the results as suggested above, yielded an obviously spurious plot, where the effective specific volume of the blended aggregate, V_{se}, plotted *above* that of the bulk specific volume of the blended aggregate, V_{sb}. This is, of course, impossible. The same plot also misrepresented the specific volume of the binder, V_b, when this line was plotted using Eqn. 6 based on the computed V_{se}.

To address this problem, it was necessary to:

- Realize that of all the information available, the binder volume was reasonably well known *a priori* (certainly better than the effective specific volume of the blended aggregate, V_{se}).

- Subtract the known specific volume of the binder from each plotted V_{mm} point to yield estimates of points on the V_{se} line.

- Realizing that the effective specific volume of the blended aggregate, V_{se}, line *must* follow the pattern of eqn. 6, that line was plotted through the statistical center of the V_{se} data points to yield a new estimate of the intercept value of V_{se}.

- A new V_{mm} line was plotted from the new intercept through the statistical center of the plotted V_{mm} points.

After this exercise, all information abstracted from the plot yielded values that were both credible and sensible. The question as to whether some aggregates may have an increasing capacity for absorption with increasing binder content remains under investigation.

Worked Example

A mix design for a Superpave project has yielded the following information:

Table 1 Raw Data

Binder Content, P_b	Bulk SG, G_{mb}	Max Th. SG, G_{mm}
4.1	2.370	2.496
4.6	2.399	2.477
5.1	2.415	2.459
5.6	2.401	2.44

Aggregate Bulk SG, G_{sb} 2.636

Binder SG, G_b 1.015

First, the above SGs are transformed to Specific Volumes (SV) and plotted on Figure 7:

Table 2 Specific Volumes

Binder Content, P_b	Bulk SV, V_{mb}	Min Th. SV, V_{mm}
4.1	42.194	40.064
4.6	41.684	40.371
5.1	41.408	40.667
5.6	41.649	40.984

Aggregate Bulk SV, V_{sb} 37.936

Next, the Minimum Theoretical Specific Volumes, V_{mm}, are regressed against the binder contents, P_b, to yield an estimate of the effective bulk specific volume of the blended aggregate, V_{se}. This is found to be 37.566, which yields an estimate of $G_{se} = 2.662$. Using the values of V_{sb} and V_{se}, the aggregate lines are plotted on Figure 7. Note that the intersection of the V_{sb} and V_{mm} lines identifies the percent of binder absorption, $P_{ba} = 0.38\%$.

The Bulk Specific Volumes are plotted (V_{mb}). Using Equation 7 to estimate the value of $V_{mb}(@P_b=0)$ for each V_{mb}, identifies the minimum at $P_b = 5.1\%$. This line, V_{mb}, is then plotted.

Plotting the 96% V_{mb} line (i.e., the 4% V_a line), it is seen to intercept the V_{mm} line at $P_b = 4.17\%$.

At $P_b = 4.17\%$, the following values are obtained: $V_{mb} = 41.778$, $V_{mm} = 40.107$ and $V_{sb} = 36.355$, from which the secondary volumetric parameters may be found: $V_a = 4\%$, VMA = 13.0% and VFA = 69.2%.

SUMMARY

Two charts have been developed and presented. The first provides a universal and simultaneous representation of all of the secondary volumetric parameters in linear form. The second, with a little practice provides a quick and robust means of displaying all of the primary volumetric parameters simultaneously, and allows for a more logical means by which to identify a design binder content and secondary volumetric parameters under the Superpave system. It also permits a "quick and not-so-dirty" means of arriving at the same information from a single test result (point estimate).

These charts have proven useful for teaching volumetrics to undergraduate and graduate students, and to practicing engineers and technicians.

REFERENCES

1. Richardson, Clifford, *The Modern Asphalt Pavement*. John Wiley & Sons, New York, NY. 1905 (First Edition)

2. The Asphalt Institute, *Mix Design Methods for Asphalt Concrete and Other Hot-Mix Types,* MS-2, pre-1962

3. McLeod, N.W. *Relationship between Density, Bitumen Content, and Voids Properties of Compacted Paving Mixtures.* Proceedings, Highway Research Board, Vol. 35, 1956

4. McLeod, N.W. *Selecting the Aggregate Specific Gravity for Bituminous Paving Mixtures.* Proceedings, Highway Research Board, Vol. 36, 1957

5. McLeod, N.W. *Void Requirements for Dense-graded Bituminous Paving Mixtures,* American Society for Testing and Materials,, STP-252, 1959

6. The Asphalt Institute, *Mix Design Methods for Asphalt Concrete and Other Hot-Mix Types,* MS-2, 1962 - 1996

7. Cominsky, R.J., *et al.*, *The Superpave Mix Design Manual for New Construction and Overlays,* Strategic Highway Research Program, SHRP-A407, Washington, D.C., 1994

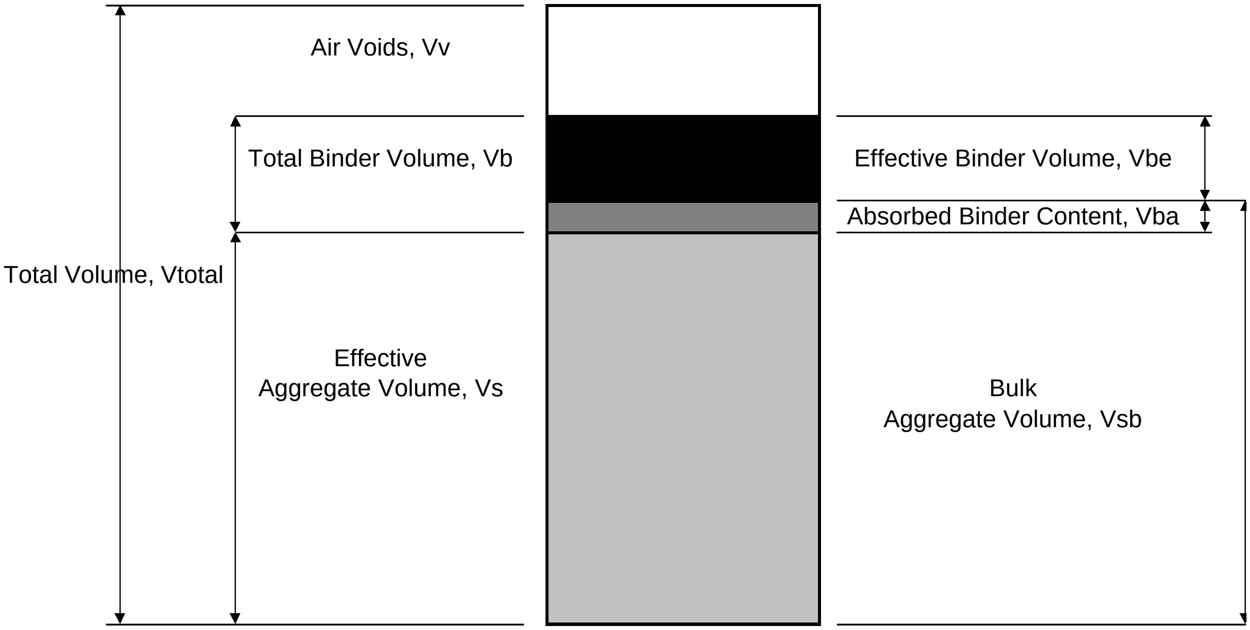

FIGURE 1: Traditional Block or Phase Diagram

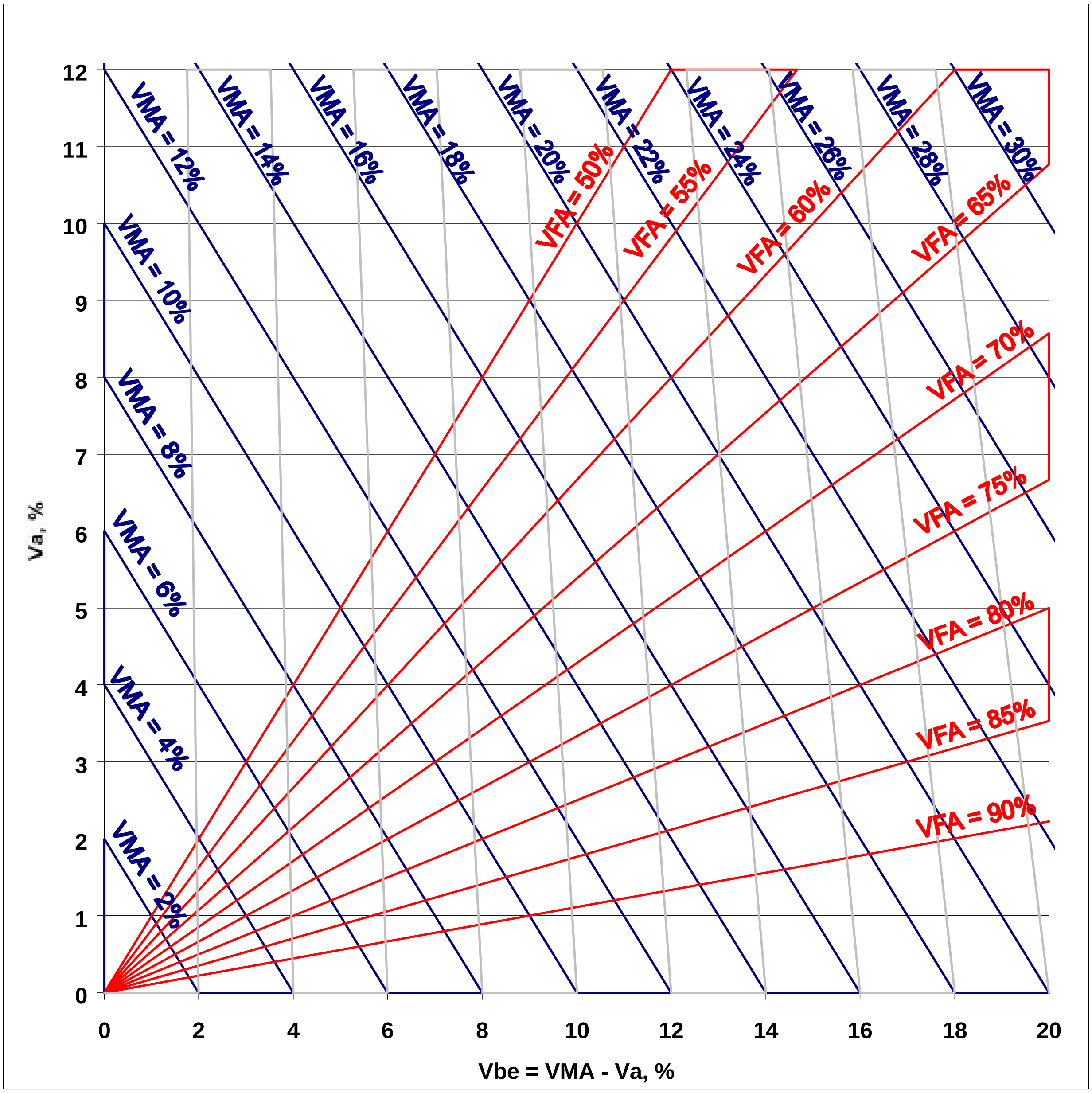

FIGURE 2: Universal Volumetric Chart

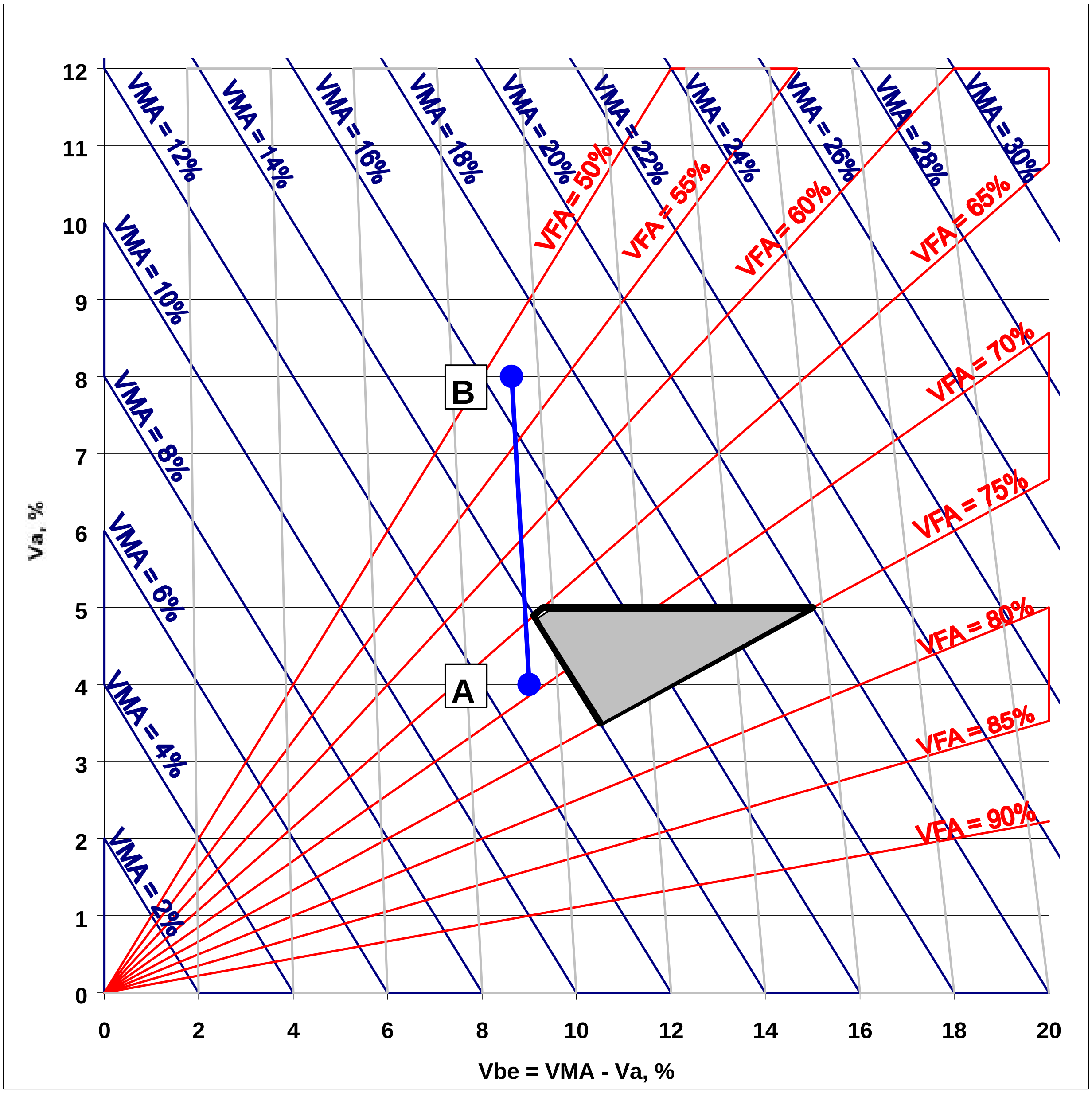

FIGURE 3: Universal Volumetric Chart - Feasible Region and Trajectory

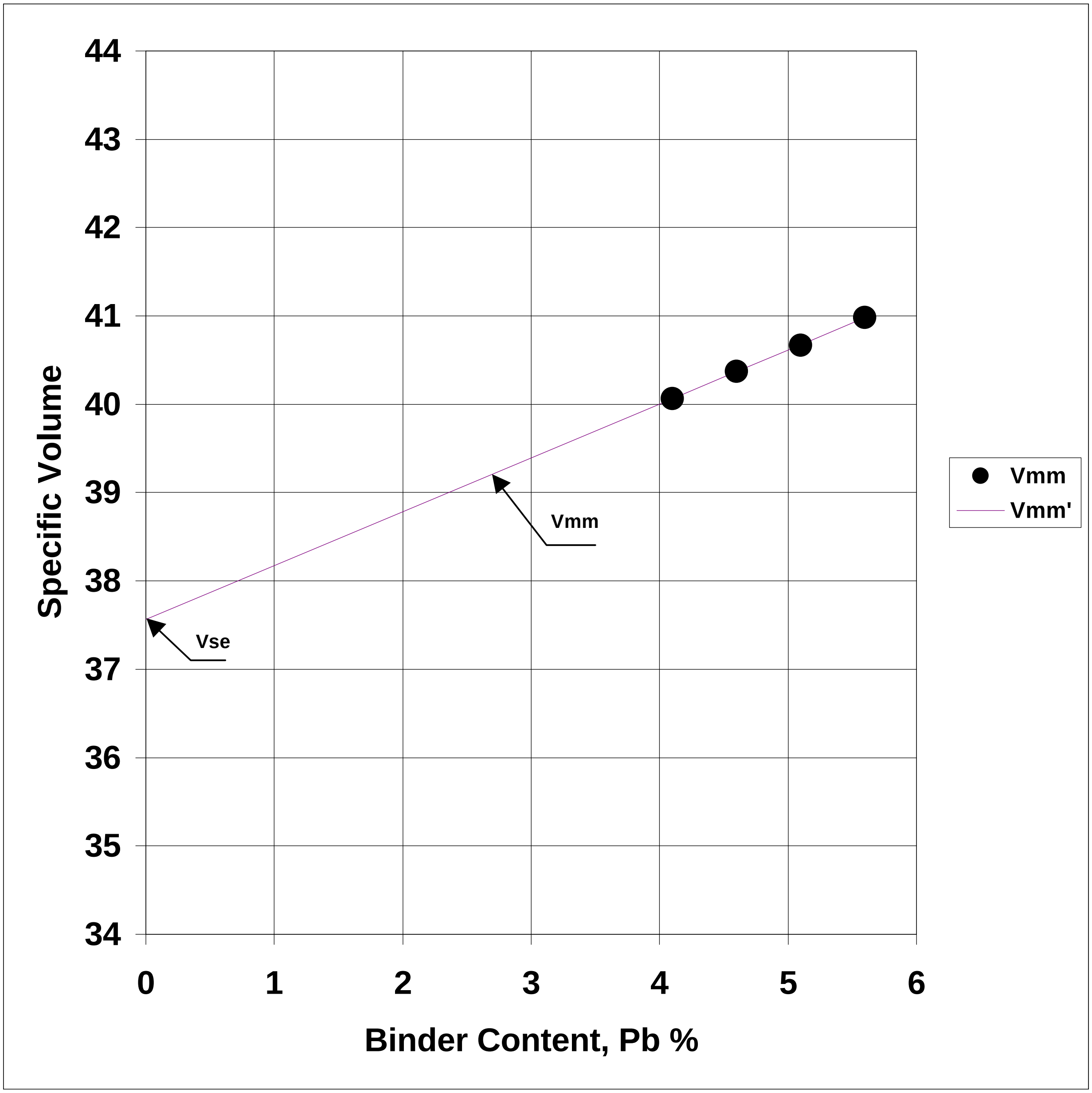

FIGURE 4: Mixture Design Chart – Minimum Theoretical Specific Volume. Vmm

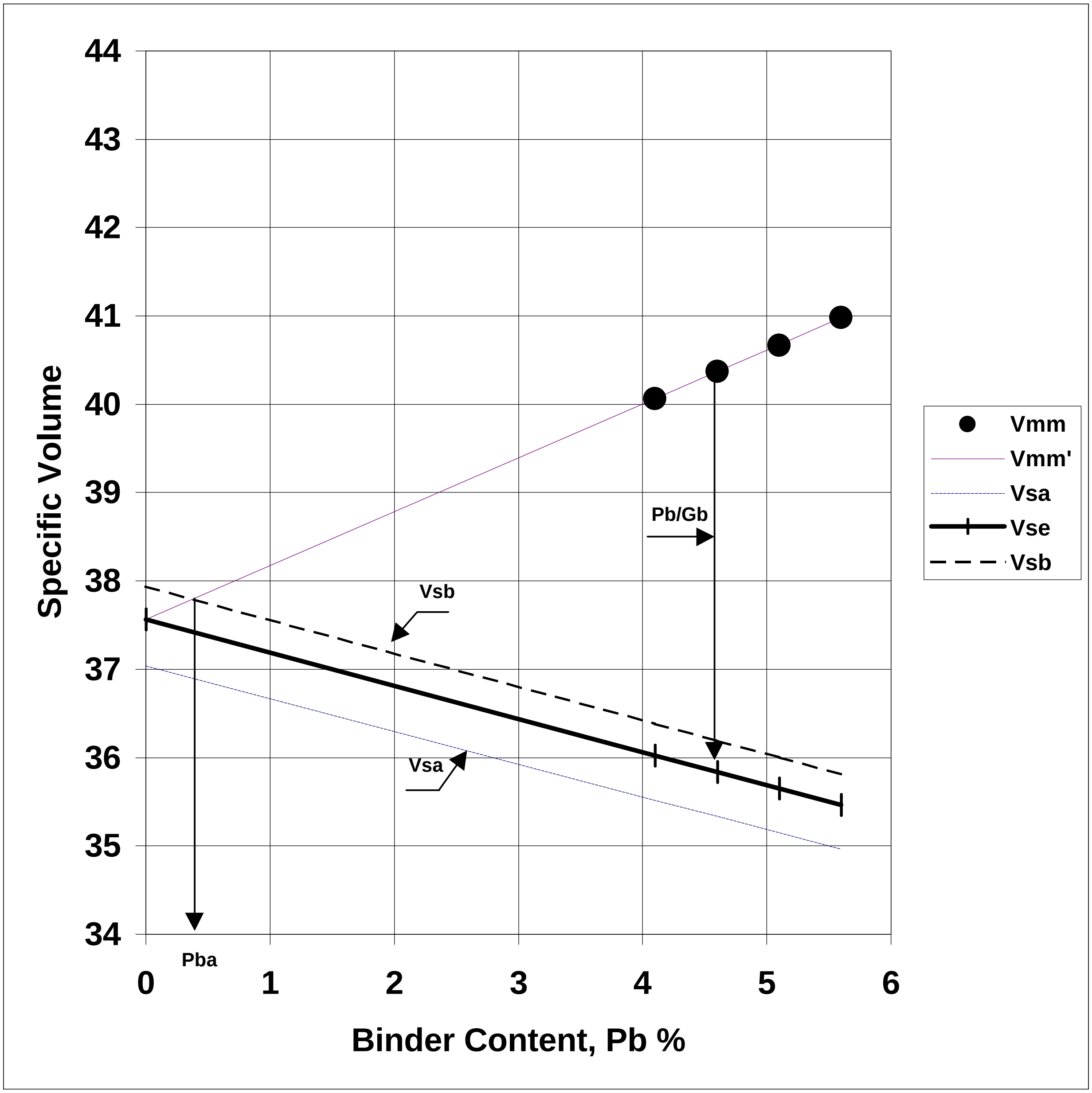

FIGURE 5: Mixture Design Chart – Aggregate Specific Volumes, Vsb, Vse, Vsa

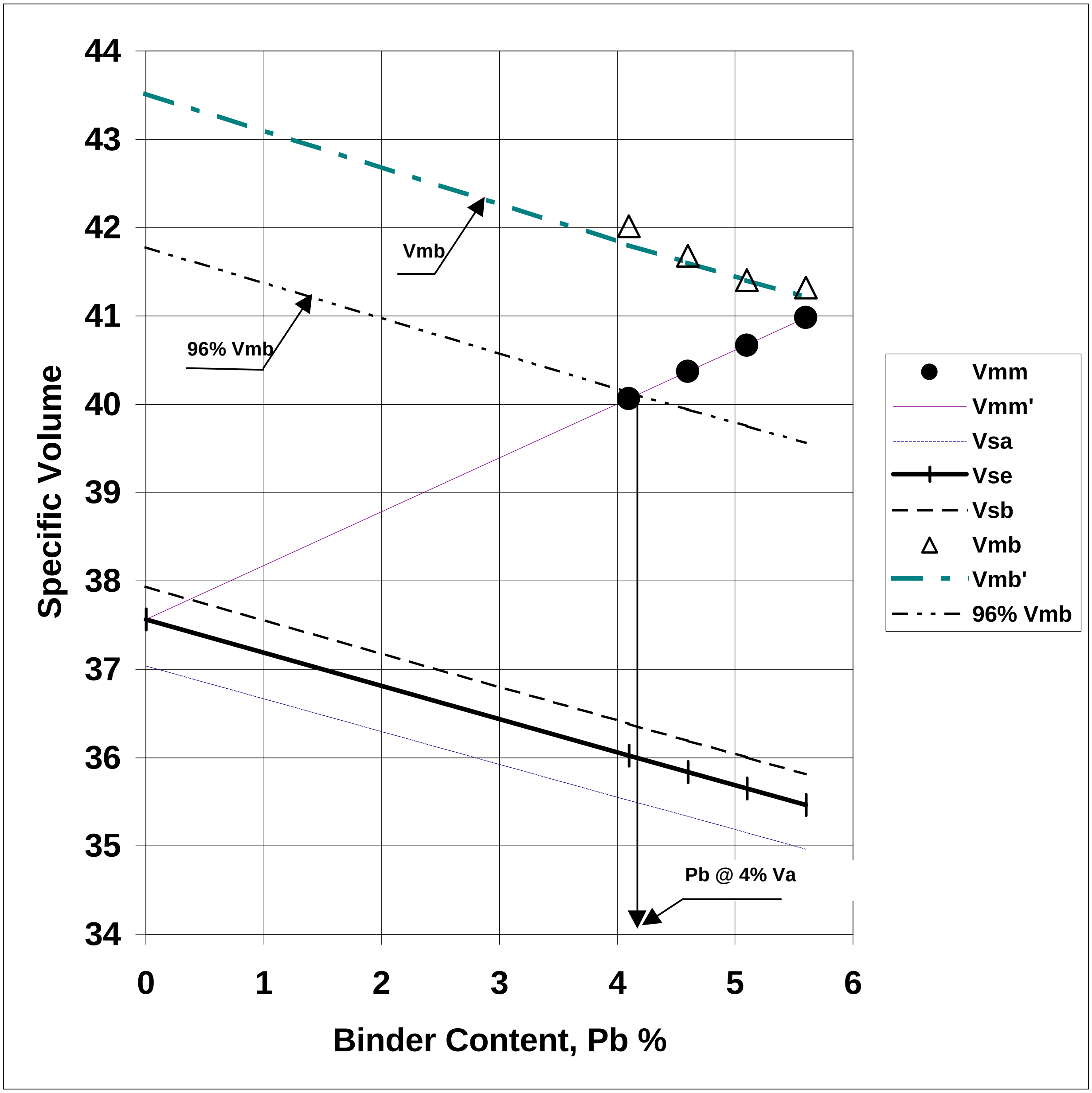

FIGURE 6: Mixture Design Chart – Bulk Mixture Specific Volume, Vmb

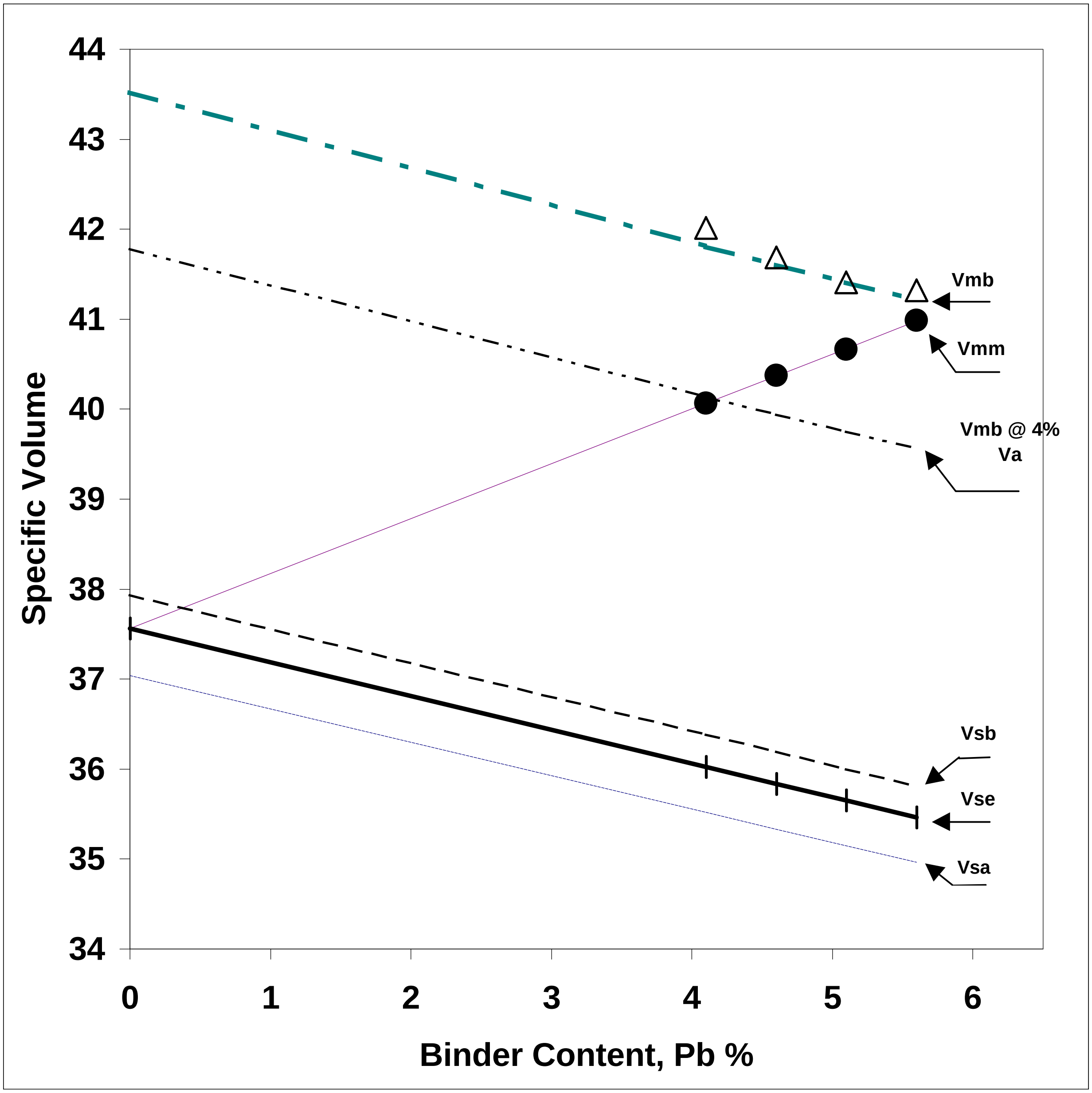

FIGURE 7: Mixture Design Chart – Complete Picture

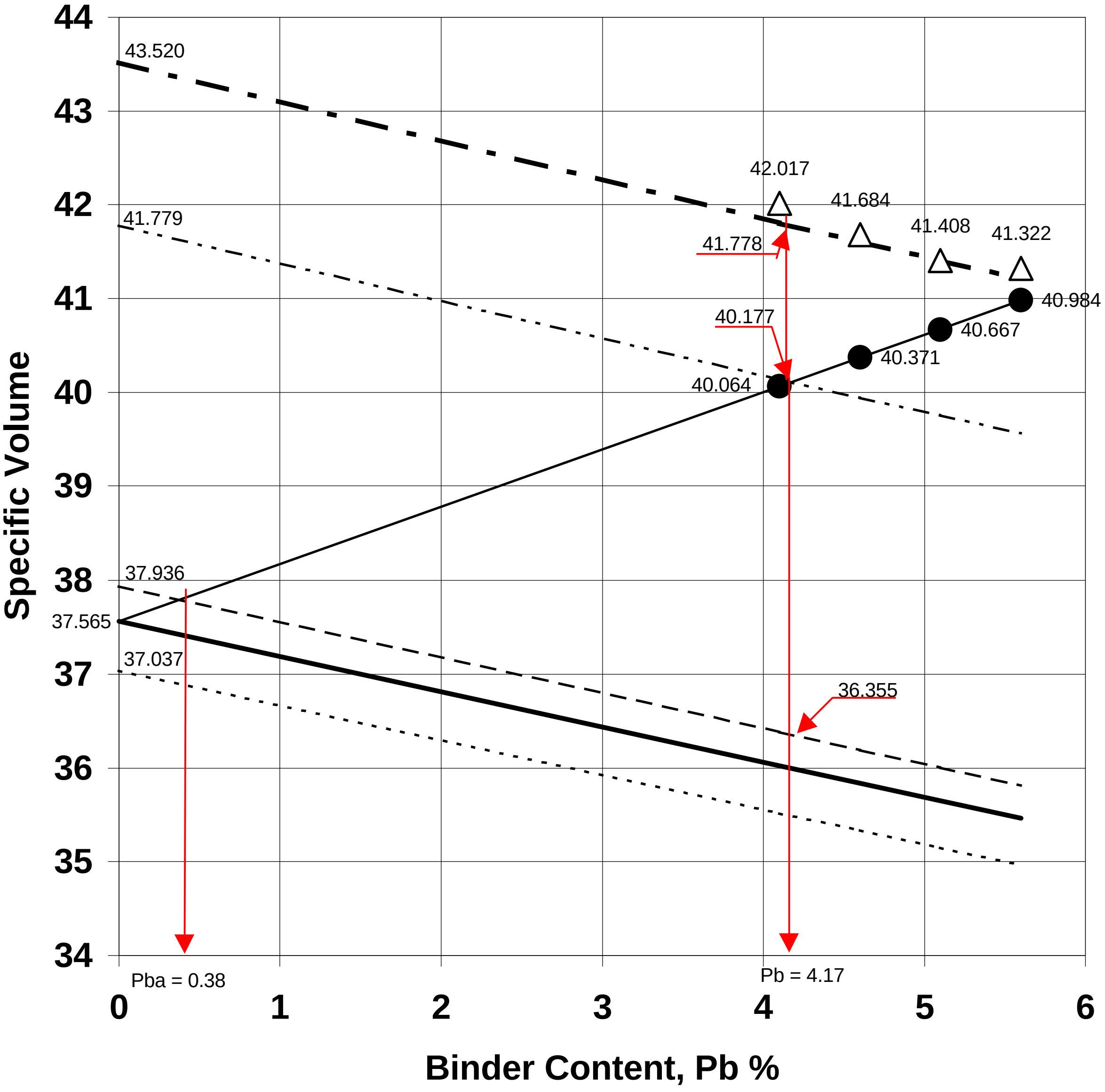

FIGURE 8: Mixture Design Chart – Worked Example