A Comparison of Voids in Stone Skeleton Mixtures and Voids in Aggregate Fractions

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ABSTRACT: The voids in the stone skeleton play an important role in the properties of stone mastic asphalt mixtures. The voids in these types of asphalt mixtures are to a large extent a product of the proportions of the different aggregate fractions that form the stone skeleton. However, the relationship between the voids in the asphalt mixture and the voids in the individual aggregate fractions that form the skeleton is not clearly understood. The aim of this study was to investigate and if possible quantify this relationship.
The voids in the stone mastic asphalt mixtures were determined from gyratory compacted specimens while the voids in the aggregate fractions were determined from rodded aggregate fractions specimens. The aggregate fractions were compacted using the rodding method that is used in the determination of the rodded unit weight in the Bailey mix design method.
The study showed that the voids in the stone mastic asphalt mixtures can be related to the voids in the aggregate fractions that form the skeleton in a logical manner.

KEY WORDS: Voids, stone skeleton, aggregate fractions, stone mastic asphalt.

1 INTRODUCTION AND BACKGROUND

Asphalt mixtures consist of aggregate fractions, bitumen and air. In stone mastic asphalt mixtures, the skeleton is composed of the coarse aggregate fractions while the fine aggregates, bitumen and air occupies the voids in the skeleton. The air voids play an important role in the properties of the stone mastic asphalt mixtures. Many highway agencies specify voids content as a part of the requirements for stone mastic asphalt mixtures. It is therefore desirable to accurately estimate available voids in the aggregate skeleton in order to determine the amount of fine aggregates and bitumen required to attain the desired air voids content.

The voids in the skeleton are to a large extent a product of the different aggregate fractions. The voids depend on the gradation of the aggregate blend, degree of compaction, shape and surface texture. The shape and the surface texture of the aggregates are largely influenced by the mineralogy of the aggregates and the method of crushing at the plant where the aggregates are sourced. In addition to this, the lubrication of the binder also influences the amount of voids in the skeleton.

The effect of the gradation on the voids content depends on the size and the content of the aggregates fractions in the blend. An elegant demonstration of the effect of size and content of the aggregates on the voids can be found in one of the pioneering studies performed by Furnas on the voids in mixtures containing two fractions of different average diameters (Furnas, 1928). The study showed that the voids in these mixtures depended on the relative content of the fractions by weight and the ratio between the average diameters of the particles in the two fractions.

Following the work done by Furnas, many models for estimating the voids in mixtures based on shape properties of the aggregates have been developed. Examples of such models include Compact (Semmelink, 1991), Prado (Francken and Vanelstraete, 1993) and Pavdam (Smit, 2002). However, it is difficult to accurately estimate the voids since it is difficult to quantify the factors that influence the voids content (Smit, 2002). Volumetric characterization of the aggregate fractions can offer a simpler means of guiding the voids content at the mix design stage.

The objective of this study was to study the relationships between the voids in the aggregate skeleton composed of aggregate fractions only, and the voids in the aggregate skeleton in stone mastic asphalt and if possible quantify this relationship. Such a relationship can be used to vary the content of individual aggregate fraction in order to approach the desired voids content during the mix design stage.

The voids in the aggregate skeleton composed of aggregate fractions were determined based on densities of individual aggregate fractions determined using three separate methods, namely loose, rodding, and vibration. The loose and rodding methods involved processes similar to the methods used in the determination of the loose and rodded unit weight in the Bailey mix design method (Vavrik et al, 2001). The voids in the aggregate skeleton in the stone asphalt mixture were determined from gyratory compacted specimens in accordance to a method developed for Norwegian asphalt mixtures (Lerfald, 2006).

The gradations of the stone mastic asphalt mixtures considered in this study were selected on the basis of weight ratios of aggregates between two consecutive sieve sizes. The ratios were obtained by dividing the cumulative weight percentage passing the smaller sieve by the cumulative percentage weight passing the larger sieve.

2 MATERIALS

One type of stone mastic asphalt mixture with a maximum aggregate size of 11 mm (SMA 11) mainly composed of Vassfjell type of aggregate was selected for this study. The SMA 11 was selected as a starting point. Other types of stone mastic asphalt mixtures composed of different types of aggregates could be considered later on depending on the results obtained from the study on SMA 11.

Stone skeleton asphalt mixtures are considered to be composed of an aggregate skeleton and a mortar that occupies the spaces in the skeleton. The stone skeleton in this study was assumed to be composed of aggregates larger than 2 mm and the content of the fractions in the aggregate skeleton labeled a, b and c, as shown in Figure 1. The symbols a, b, and c represent the percentage by weight of the aggregates between 2 to 4 mm sieve, 4 to 8 mm sieve and 8 to 11,2 mm sieve respectively

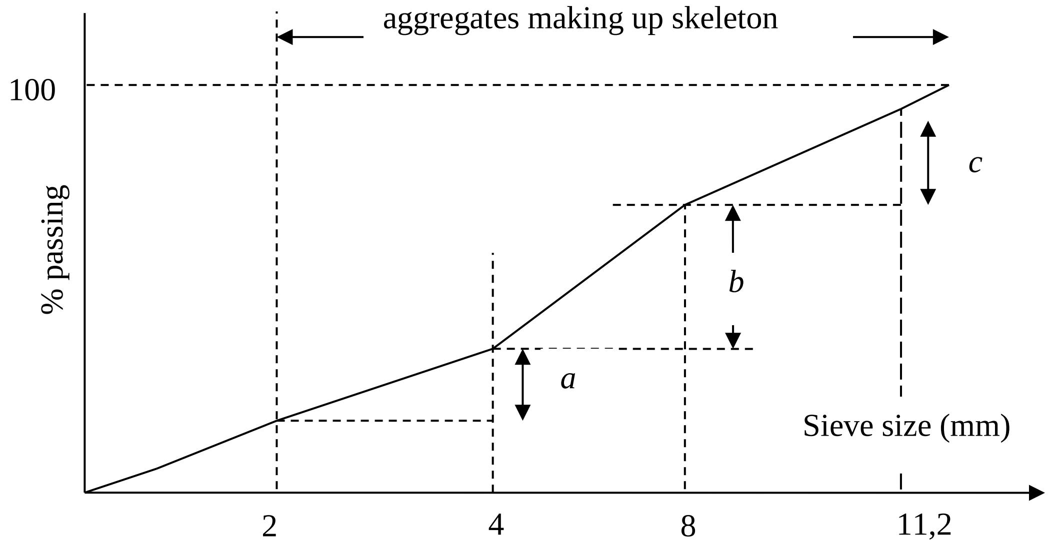

Figure 1: Aggregates making up the aggregate skeleton

For purposes of selecting the gradations to be considered in this study, the possible combinations of the a/b and b/c ratios were determined. Figure 2 shows the possible combinations a/b and b/c ratios and the selected combinations for this study. Five gradations for five different mixes were considered in this study. These gradations and the minimum and maximum limits specified in the Norwegian pavement specifications are shown in Figure 3 and Table 1.

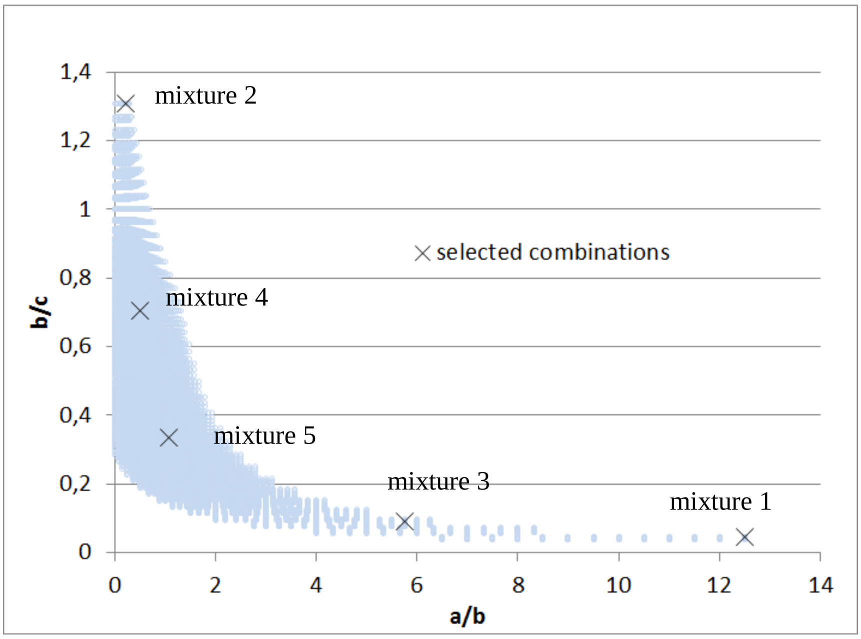

Figure 2: Possible range of the a/b and b/c ratios, and the selected ratios

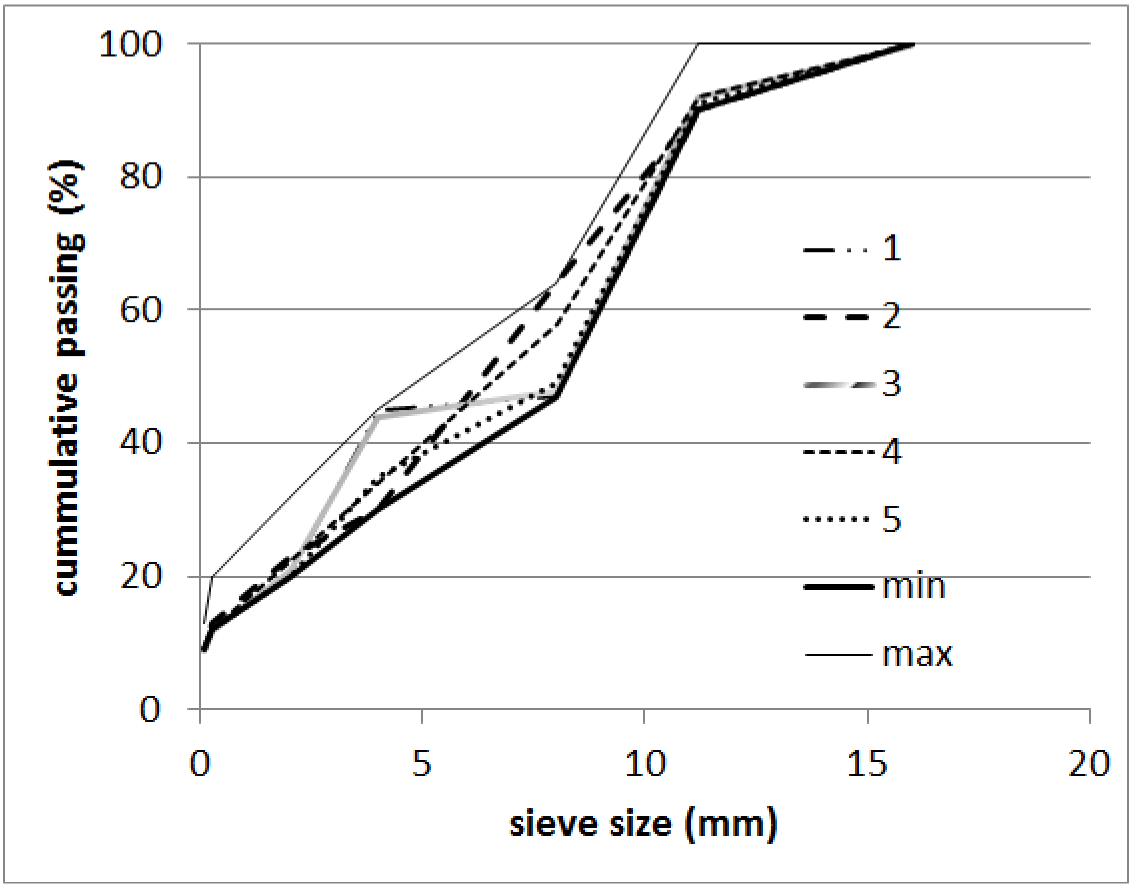

Figure 3: Gradations of the selected mixtures, minimum and maximum limits

Table 1: Gradations of selected SMA 11 mixtures

Mix - Cummulative passing by weight (%)							
Sieve (mm)	1	2	3	4	5	min	max
16	100	100	100	100	100	100	100
11,2	90	90	92	92	91	90	100
8	47	64	48	58	49	47	64
4	45	30	44	34	35	30	45
2	20	23	21	22	20	20	32
0,25	12	13	12	12	12	12	20
0,063	9	9	9	9	9	9	13
a/b	12,50	0,21	5,75	0,50	1,07		
b/c	0,05	1,31	0,09	0,71	0,33		
bitumen content (%)	5,8	5,8	5,8	5,8	5,8		

3 COMPACTION

The aggregate fractions were compacted using three different methods, namely loose, rodding and vibration. Prior to compaction of the aggregate fractions, the aggregates fractions were sieved to assess the gradation of each aggregate fraction and to remove particles that were smaller or larger than the limits of the aggregate fraction. After sieving, the aggregate fractions were sorted in to 8/11,2 mm, 4/8 mm and 2/4 mm fractions. These sieved fractions were used in the preparation of the aggregate fractions specimens.

The asphalt mixture was compacted using gyratory compaction. In contrast to the aggregate fractions used in the aggregate fractions specimens, the fractions used in the composition of the asphalt mixture specimens were not sieved. The required amount of each aggregate fraction was based on the gradation of the individual fraction.

3.1 Loose Density

The loose density of each fraction was determined using a method similar to the method used in the determination of the loose unit weight in the Bailey mix design method. The loose density was determined by carefully pouring the aggregate fraction in to a Modified Proctor mould measuring 152 mm diameter by a height of 160 mm including the collar. The modified Proctor mould together with the collar is shown in Figure 4 (a). After pouring the aggregates in to the mould, the top part was struck level using a straight edge. The weight required to fill the container was then determined. The loose density of the aggregate fraction was calculated as the ratio of this weight to the volume of the mould. Three test repetitions were performed for each fraction as recommended in the Bailey method (Vavrik et al, 2001).

3.2 Rodding Method

The rodded density of each aggregate fraction was determined using a method similar to the method used in the determination of the rodded unit weight in the Bailey mix design method. The determination of the rodded density involved rodding the aggregates in a Modified Proctor mould measuring 152 mm diameter by a height of 160 mm including the collar. A steel rod measuring 16 mm in diameter by 600 mm length was used to rod the aggregates. The aggregates were rodded in three layers with each layer being rodded 25 times. The modified Proctor mould together with the collar and the steel rod are shown in Figure 4 (a). After rodding the final layer, the aggregates are struck level using a straight edge. The rodded density of the aggregate fraction was then determined as the ratio of the weight of the rodded aggregates to the volume of the container. Although three test repetitions are recommended in the Bailey method (Vavrik et al, 2001), only two test repetitions were performed for each fraction since the difference between the two test repetitions was insignificant.

(a)

(b)

Figure 4: (a) Modified Proctor cylinder and steel rod, (b) Proctor cylinder, upper plate and vibrating table.

3.3 Vibrating Table

In this method, the aggregate fractions were compacted by vibration in a standard Proctor mould. The standard Proctor mould was chosen in order to study the possibility of using a smaller specimen size to determine the loose and rodded densities. The standard Proctor mould required less sieved aggregates in comparison to Modified Proctor mould that was used in the rodding method. The standard mould measured 102 mm in diameter by a height of 172 mm including the collar. An additional upper plate weighing 1509 g was placed on top of the aggregates during vibration. The aggregate fractions were vibrated in three layers with each layer weighing about 500 g. The Proctor mould together with the collar, the upper plate and the vibrating table are shown in Figure 4 (b). After compacting the third layer, the height of the specimen between the bottom plate and the upper plate was determined. The density of the aggregate fraction was then determined as a ratio of the weight of the aggregates to the volume between the bottom plate and the upper plate in the standard Proctor mould.

3.4 Gyratory Compaction

The asphalt specimens were compacted in accordance to a gyratory mix design method developed by Lerfald for Norwegian mixes (Lerfald, 2006). In this method, the asphalt mixture is compacted at a vertical stress of 600 kPa and a gyratory angle of 1^0. Prior to compaction, the 1200 g of the aggregates were heated to 170^0C while the bitumen was heated at 160^0C. The aggregates and the bitumen were then mixed together and compacted in a 100 mm diameter mould to 200 gyrations as recommended in the gyratory mix design method

(Lerfald, 2006). The density after 200 gyrations was determined based on the surface dry method. This density was used to back calculate the density of the specimen at 80 gyrations and the packing density of the aggregate skeleton determined based on the specimen density at 80 gyrations.

The voids in the aggregate skeleton were determined using Equation 1. In this equation, the aggregate skeleton in the stone mastic asphalt was assumed to be made up aggregates retained on the 2 mm sieve. These aggregates retained on 2 mm sieve are referred to as coarse aggregates. The voids in the coarse aggregates were then expressed in terms of the density of the coarse aggregates and the specific density of the coarse aggregate as illustrated in the equation.

Four different types of coarse aggregate densities for each mixture were determined based on the four compaction methods described in the previous section. The coarse aggregate density based on the loose, rodding and vibrating compaction methods was calculated by assuming that the volume occupied by the asphalt mixture is equal to the volume occupied by the coarse aggregate. In addition, it was assumed that the volume occupied by the coarse aggregates was the sum of the volumes occupied by the individual aggregate fractions. The coarse aggregate density was then further rewritten as a function of the proportion and the density of each individual aggregate fraction as shown in Equation 2. The combined specific of the coarse aggregates was calculated using Equation 3 and the density of the coarse aggregates in the asphalt mixture was determined using the relationship in Equation 4.

$$VCA = \frac{V_{vc}}{V_c} \times 100 = \left(\frac{V_c - V_{sc}}{V_c}\right) 100 = \left(1 - \frac{\rho_c}{\rho_{sc}}\right) 100 \qquad 1$$

$$\rho_c = \frac{M_c}{V} = \frac{M_c}{V_c} = \frac{(M_{c1} + M_{c2} + \cdots)}{(V_{c1} + V_{c2} + \cdots)} = \frac{\sum P_{ci}}{\sum \frac{P_{ci}}{\rho_{ci}}} \qquad 2$$

$$\rho_{sc} = \frac{M_c}{V_{sc}} = \frac{\sum P_{ci}}{\sum \frac{P_{ci}}{\rho_{sci}}} \qquad 3$$

$$\rho_c = \frac{M_c}{V} = \frac{P_c M_s}{100V} = \left(\frac{P_c}{100}\right)\left(1 - \frac{P_b}{100}\right)\rho \qquad 4$$

Where: VCA = Voids in aggregate skeleton (%), V = Volume occupied by the mix, V_{vc} = Air voids in the coarse aggregates, V_c = Volume occupied by the coarse aggregates, V_{sc} = Specific volume of the coarse aggregates, V_{ci} = Packing volume of the coarse aggregate i, ρ_c = Density of coarse aggregates, ρ_{ci} = Density of coarse aggregate fraction i, ρ_{sc} = Combined specific density of the coarse aggregates, ρ_{sci} = Specific density of coarse aggregate fraction i, M_c = Total weight of coarse aggregates, M_s = Total weight of aggregates in the mix, M_{ci} = Weight of coarse aggregate i, P_c = Proportion of the coarse aggregate (% by total weight of aggregates), P_{ci} = Proportion of coarse aggregate i (% by total weight of aggregates), ρ_b = Density of bitumen (% by total weight of mix), ρ = Surface dry density of the mix.

4 RESULTS

Table 2 shows the densities of aggregate fractions determined using the loose, rodding and vibration method. The table shows that the aggregate fraction densities were sensitive to the loose and rodding methods but hardly sensitive to the vibration method.

Table 2: Loose, rodded and vibration table density

Fraction	loose density (g/cm^3)	rodded density ρ_{ci} (g/cm^3)	vibration ρ_{ci} (g/cm^3)
8/11,2	1,564	1,722	1,575
4/8	1,493	1,610	1,587
2/4	1,556	1,645	1,588

Table 3 shows the skeleton density in the asphalt mixture, the calculated aggregate skeleton densities, the VCA, a/b, and b/c ratios. Mix 5 was damaged during extraction as such it is excluded from these results. The table shows that the density of the coarse aggregates determined using the vibration was not sensitive to the type of mixture. As such the vibration method was not considered further.

Table 3: Skeleton density in the mix, calculated skeleton density, VCA, a/b and b/c ratios

Mix	density of coarse agg ρ_c (g/cm^3)				combined specific density of coarse agg ρ_{sc} (g/cm^3)	VCA (%)			a/b	b/c
	asphalt mix	loose	vibration	rodding		asphalt mix	loose	rodding		
1	1,912	1,560	1,580	1,694	2,968	35,5	47,5	42,9	12,5	0,0
2	1,862	1,531	1,581	1,664	2,991	37,8	48,8	44,4	0,2	1,3
3	1,896	1,558	1,580	1,693	2,970	36,1	47,6	43,0	5,8	0,1
4	1,867	1,540	1,581	1,674	2,984	37,6	48,4	43,9	0,5	0,7

Figure 5 shows a comparison of the voids in the skeleton of the SMA asphalt mixtures and the voids calculated based on the loose and the rodding methods. The figure shows that voids in the asphalt mixture are lower than the voids estimated from the loose and rodding methods. This observation is as a result of the higher degree of compaction in the gyratory compaction in comparison to the loose and rodding methods. The figure also shows that the voids in the asphalt mixtures can be related to the voids based on the loose and the rodding methods using polynomial functions. This observation implies that the voids in the aggregate skeleton of the stone mastic asphalt can be logically estimated on the basis of the loose or rodded densities of the aggregate fractions.

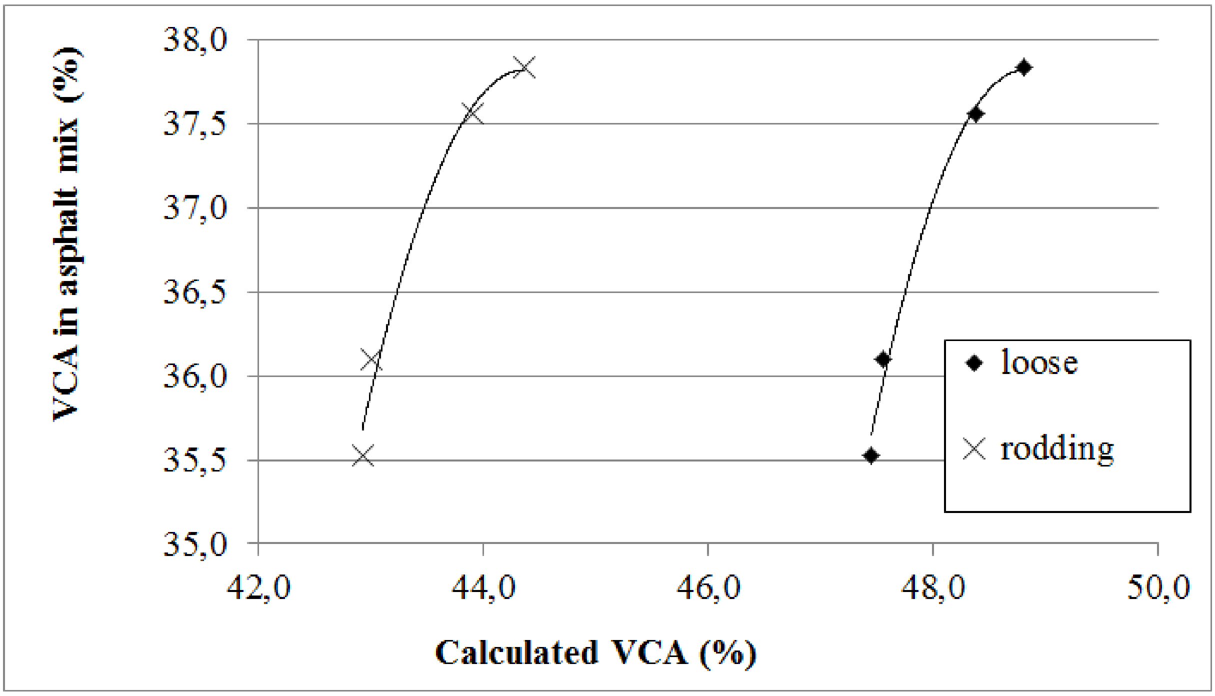

Figure 5: Skeleton density in the mix and calculated skeleton density

Figure 6 shows a comparison of the voids in the SMA asphalt mixtures to the a/b and b/c ratios. The figure shows that the voids in the SMA mixtures can be related to the a/b and b/c ratios using a power function. This observation suggests that the voids in aggregate skeleton of stone mastic asphalt mixtures can be logically estimated on the basis of a/b and b/c ratios.

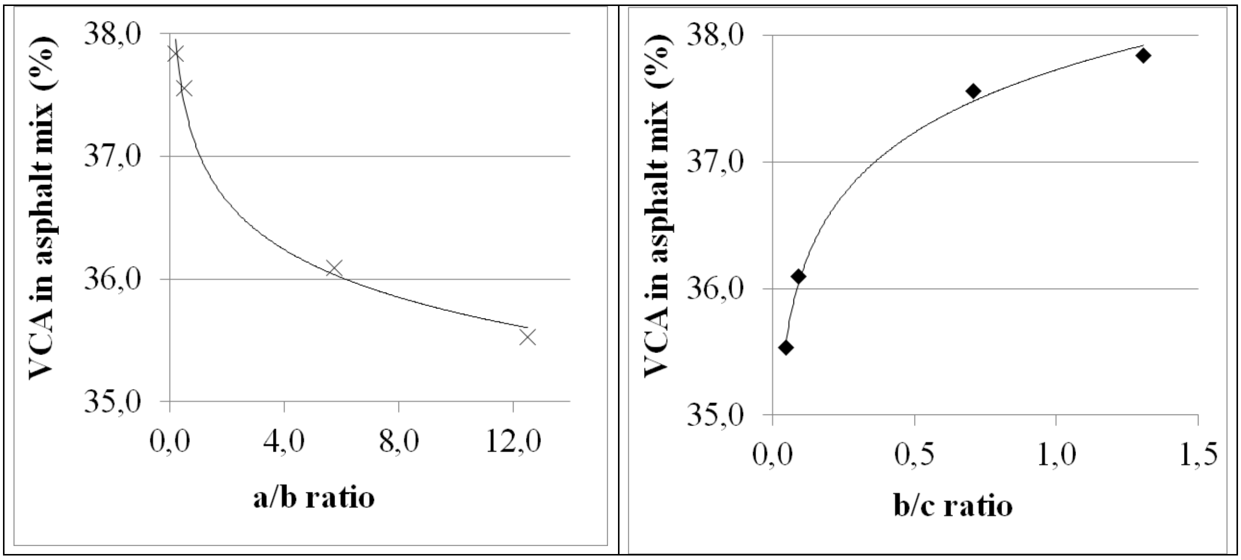

Figure 6: VCA in the mix, a/b and b/c ratios

5 CONCLUSIONS

Based on the results in this study it was concluded that the densities of the aggregate fractions were not sensitive to the vibration method. It was also concluded that the voids in the aggregate skeleton of the stone mastic asphalt can be logically estimated on the basis of the loose or rodded densities of the aggregate fractions or on the basis of a/b and b/c ratios. However, only a limited number of asphalt specimens were considered in this study. More specimens should be considered in order to relate the voids in the asphalt mixtures to the loose density, rodded density, a/b and b/c ratios.

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