Validation of New Dutch Volumetric Mix Design Method for SMA with Mechanical Tests and Field Trials

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ABSTRACT: SMA is used worldwide and known as a very durable mix with excellent functional properties when well designed. In the Netherlands early rutting of SMA has been reported in some cases with the existing mix design method. For this reason a renewed volumetric mix design method was developed.

The core of the new volumetric method is the determination of the voids in the compacted stone skeleton (HRS) and the abrasion of the stone fraction of the mix. With a computer program the volumetrics of the mix are calculated based on the volumetrics of the compacted available stone fraction. A shift factor for the voids content has been developed based on compaction results of mixes that perform well. Before production at the plant the HRS value of the available stone fraction at the asphalt plant has to be determined and compared with the mix design. The results of three field trials with SMA 0/11(maximum stone size 11 mm) are described and compared with the new mix design procedure.

KEY WORDS: HRS test, mix design, volumetric, rutting test, field trials.

1 INTRODUCTION

Stone Mastic Asphalt (SMA) is known as a very durable mix with important functional properties, based on the stone skeleton and high bitumen content. However, it is a sensitive mix and in the Netherlands sometimes premature rutting of SMA has been reported. These failures happened with well-designed SMA mixtures. To solve this problem a renewed volumetric mix design method and an extra production control procedure were developed.

In the Dutch mix design of SMA (CROW, 1993) a fixed amount of bitumen is required; at the fixed bitumen content the fraction above 2 mm (here called stone content) is changed to determine the correct amount of coarse aggregates to meet the voids requirements of SMA. Together with the stone content the total sand /filler content is changed at a fixed ratio sand:filler = 65:35, while keeping the bitumen content constant. Four stone fraction contents are used to determine the right composition at 4 or 5% voids content after Marshall compaction (2*50 blows). For highly trafficked roads the design voids content is 5% and for lower trafficked roads the design voids content is 4% in the Marshall mix design. No mechanical testing is required in the mix design, because of the fixed mix composition in the specification. The results with the mix design are good in general. However, it could not prevent unexpected permanent deformation in some SMA mixes in the field.

In this paper the renewed volumetric mix design method is described first. Then the mechanical testing is discussed to check if the rutting problem can be prevented. The results of three field trials are described and compared with the old and new mix design procedure. For the three field trials SMA 11 mixes were placed. A visual inspection after 5 years of two field trials is included to show the performance in time.

2 NEW VOLUMETRIC MIX DESIGN

2.1 Summary of the new approach

The new approach (van de Ven and Jacobs 2007) is very simple and in fact assumes that a compacted stone skeleton has a fixed voids content called HRS. Theoretically these voids are filled with the mastic till 4 or 5 % voids remain. All calculations are carried out in volume parts.

The basis of the new approach was the determination of the "refusal density" (after 300 gyrations) of the used stone fraction larger than 2 mm with gyratory compaction of specimens with 150 mm diameter and internal gyratory angle of 0.82º (EN 12697-31, July 2004). Two parameters are determined: the voids in the compacted stone skeleton (HRS value) and the fraction smaller than 2 mm due to crushing and abrasion after compaction. Both parameters are needed in the volumetric calculation.

A spreadsheet is developed to calculate a target composition based on the volumetrics of the compacted available stone fraction filled with mortar. Due to the enlarging effect of the stone skeleton in a compacted mix a shift factor for the voids content of the stone skeleton has been developed based on compaction results of mixes that perform well.

During the research the existing mix design method with Marshall compaction was used as reference. Based on the results of Marshall mix designs and tests on cores a regression line has been determined showing a linear relation between HRS and the shift factor for the voids content in the mixture, see equation 1:

$$f(x) = a^*x + b \qquad (1)$$

In equation 1 the HRS value is presented by x and f(x) is the shift factor. The parameters a and b are regression constants.

The shift factor f(x) has to be added to the calculated voids content with the HRS model to determine the real voids content. From research it became clear that the shift factor is dependent on the HRS of the Stone type (Wierda et al. 2008).

The regression line is dependent on the mix type. The results of mix designs of different asphalt producers for one mix type have been combined to determine the regression line for the shift factor. The values for the correlation-coefficient R and the parameters of the regression line are given in table 1.

Table 1: Regression parameters for the determination of the shift factor for mixes of different asphalt producers

Asphalt mix	Correlation coefficient R	a*	b*
SMA 0/11 type 1	0.87623129	1.28184173	- 48.42370647
SMA 0/11 type 2	0.93654656	1.10854676	- 41.06545036

*the many numbers behind the comma are necessary to keep the accuracy of the spreadsheet at a high level.

With equation 1 the shift factor at a certain HRS for the stone fraction can be calculated. Example: the voids content of an SMA 0/11 type 2 with an HRS value for the stone fraction of 36,6% has to be corrected (see table 1) with a shift factor of:

$$f(x) = 1.10854676*36.6 + (-41.06545036) = 40.57281142 - 4106545036 = -0.492638944 .$$

The shift factor is then approximately – 0.5. In this case the calculated voids content of the mix has to be decreased with 0.5% to find the real voids content.

The accuracy of the shift factor is dependent on the number of mix designs added to the database for a certain HRS value of the stone fraction. With more results the robustness of the linear relation can be checked. It is possible to use a non-linear relation if necessary. In the spreadsheet it is possible to recalculate the regression after a large number of mix designs have been added to the spreadsheet. In the first phase of the new mix design method Marshall compaction results were used. However, also mix designs with gyratory compaction can be added to the database in the spreadsheet. First the HRS model was compared with Marshall mix compaction. At the moment gyratory compaction is used to develop the regression line.

The new mix design method is tested in practice with full scale test trials. This paper discusses the practical verification of the new mix design method. This verification is done by simultaneously using the old (Marshall) and the new (gyratory) compaction method for a number of jobs. A final step procedure for the volumetric design of SMA has been developed (Wierda et al. 2008).

2.2 HRS gyratory test with 100 mm diameter

For the development of the method all the compaction tests on the stone fraction were done with a diameter of 150 mm. This requires some 5 kg of granular material for each HRS test (van de Ven and Jacobs 2007). The total sample in the gyratory mould is heavy and difficult to handle by the lab technicians. Because we are studying SMA mixtures with a maximum grain size of 11 mm it was considered realistic to use 100 mm diameter sizes to determine the HRS value.

Another reason to use this size is that the gyratory compaction of the mix will also be done with 100 mm diameter gyratory specimens. The advantage is then that at least the same volumetric effects play a role both for the stone skeleton and the mix. Two investigations were done: the influence of the change in diameter on the HRS value of the same stone fraction was determined and the influence on the voids content of the mix was followed.

In table 2 the influence of the diameter on the HRS value is shown. Comparison of the results suggests that with the smaller diameter lower HRS values can be expected. Important is that the differences are smaller than 1 % and the ranking between the Stone types stays the same.

Table 2: Influence of the specimen diameter on HRS values for different stone types.

Stone type	HRS value (%)	
	Diameter 100 mm	Diameter 150 mm
Morene	38.9	39.3
Bestone	38.0	38.9
Porphyry	39.0	39.9

So the first conclusion is that a change to a diameter of 100 mm for the HRS test will result in small changes in the HRS value. From the results it is concluded that no problems are expected when changing from 150 mm diameter test specimen to 100 diameter test specimen.

3 RESULTS OF MECHANICAL TESTS

3.1 Investigated SMA mixtures

To investigate the sensitivity for rutting of SMA mixes, a range of mixes from under to overfilled were investigated. To design these mixtures the so-called FRS parameter is used (Voskuilen and van de Ven 2009). FRS is defined as the filling ratio of the voids in the stone skeleton with mortar for SMA, see equation 2:

$$FRS = \frac{V_m - V_s}{V_s} \cdot 100\% \tag{2}$$

V_m is the volume of the mortar and V_S is the volume of voids in the optimal compacted stone skeleton determined with gyratory compactor.

From the composition of SMA the theoretical filling degree of the optimal compacted stone skeleton with mortar can be calculated. Four series of SMA mixtures were investigated with FRS values of -12, -4, +4, +12 and +20. If the FRS is negative, the SMA is theoretically under filled. If the FRS is equal to 0, the SMA is theoretically just filled with mortar and the mix has no voids anymore. If the FRS is positive, the SMA is overfilled. The expectation was that the turning point would be around an FRS value of –4, because in (CROW, 2003) it was determined that SMA with an FRS of –4 gives a voids content in the mix (AV) of about 5% (requirement of the SMA mixture for heavy trafficked roads). The SMA 0/11 mix from the Ureterp test trial (see chapter 4) was selected. The coarse material of the Ureterp SMA mixture was Bestone with an HRS value of 38.4%. To investigate if the sand type had influence on the rutting resistance (compared to the standard crusher sand) the Ureterp mixture was also tested with only fine natural sand and with weaker Scottish granite sand. The mix compositions of the three groups are given in table 3.

Table 3: Mix composition in mass percentages of the tested SMA mixtures.

Mix variation	FRS	-12	-4	4	12	20
Standard Ureterp Mixture	Ureterp SMA test site mix (moraine)					
	Passing sieve 2 mm	25.1	27.4	29.6	31.6	33.4
	Passing sieve 0.063 mm	93.6	92.9	92.1	92.9	90.7
	Bitumen in mix	6.5	6.5	6.5	6.5	6.5
Sand fraction in Ureterp mixture replaced	Ureterp SMA Scottish crusher sand					
	Passing sieve 2 mm	25.1	27.4	29.6	31.5	33.4
	Passing sieve 0.063 mm	93.6	92.9	92.1	91.4	90.7
	Bitumen in mix	6.5	6.5	6.5	6.5	6.5
	Ureterp SMA natural sand					
	Passing sieve 2 mm	25.0	27.3	29.5	31.4	33.3
	Passing sieve 0.063 mm	93.7	92.9	92.1	91.5	90.7
	Bitumen	6.5	6.5	6.5	6.5	6.5

All mix series have the same FRS values, the bitumen content is constant, the fine material increases if the FRS value increases and the coarse material content decreases if the FRS value increases. As a consequence of this the free bitumen content decreases in the mortar when the FRS value increases resulting in a mortar that will become stiffer. In figure 1 the volumetric compositions of mixtures with FRS values varying from –12 to +20 are presented. These volumetric compositions are used for the FRS series of the mixtures summarized in table 3.

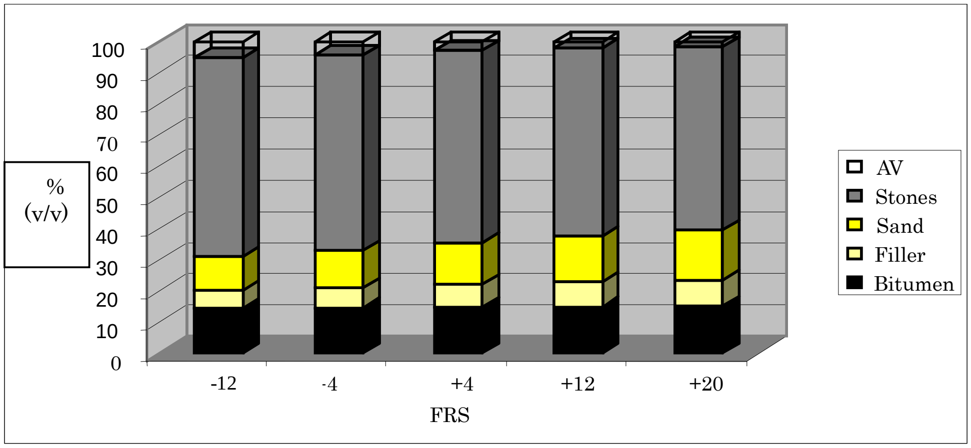

Figure 1: Volumetric composition of investigated SMA mixtures.

The reference density was determined on samples after two times fifty blows Marshall compaction. The asphalt was mixed in conformity with EN 12697-35 and compacted with a segment compactor (Voskuilen and van de Ven 2009). The degree of compaction was between 99 and 101%.

The resistance to permanent deformation of the SMA mixtures is determined with the triaxial and wheel-tracking test (small device), both conform the European norms EN-12697-25B and EN 12697-22. In Gharabaghy (2006) more background information is given about this research.

3.2 Results of voids content (AV) in SMA mixtures

In table 4 the AV of SMA is given for the Marshall compacted specimens of the Ureterp SMA specimens.

Table 4: Void contents (AV) in % versus FRS values of the Ureterp SMA mixtures.

	FRS	-12	-4	+4	+12	+20
Mixture	Used sand					
Ureterp	Scottish granite	5.2	4.2	2.9	1.7	1.6
	Moraine crusher sand	5.1	4.4	3.0	2.0	1.5
	Fine natural sand	5.4	3.0	1.8	1.5	1.2

The standard Ureterp test site mixture contains moraine crusher sand. The moraine crusher sand is substituted by fine natural sand and Scottish granite crusher sand (table 3). From table 4 the following conclusions can be drawn:

- The fine natural sand has lower enlarging effect than both crusher sands. Consequently the AV in SMA with fine natural sand is lower.

- Although overfilled SMA mixtures (positive FRS) theoretically should have an AV of 0%, AV's of these SMAs are between 1.2 to 3%, possibly due to entrapped air in the mortar and the mix.
- SMA mixtures with different types of sand with FRS values of –12 have the same AV level.

3.3 Results of the wheel-tracking test (small device) and triaxial tests

In table 5 results are given of the small wheel-tracking device for the Ureterp SMA mixtures.

Table 5: Rut depths results (mm) of wheel-tracking tests of the Ureterp SMA mixtures (small device).

	FRS	-12	-4	+4	+12	+20
Mixture	Used sand					
Ureterp	Scottish granite	6.3	3.6	2.6	4.4	5.5
	Moraine crusher sand	3.9	4.5	3.6	3.4	4.2
	Fine natural sand	3.2	2.5	1.7	2.8	4.2

In table 6 results are given of triaxial tests on the Ureterp SMA mixes. Parameters used are strain after 1000 and 10000 cycles and the slope of the creep curve in the steady state, see Gharabaghy (Gharabaghy and Scharnigg 2006).

Table 6: Results of the triaxial tests of the Ureterp SMA mixture with moraine crusher sand.

FRS	-12	-4	+4	+12	+20
Parameter					
Slope fc (microstrain/n)	0.33	0.24	3.38	2.19	1.58
Strain after 1000 cycles, calculated (%)	2.24	1.80	3.84	2.87	3.97
Strain after 10.000 cycles (%)	2.55	2.03	5.08	4.84	5.59

The triaxial test as well as the small wheel-tracking test predicts the same trend for field rutting, if the SMA mixtures are overfilled. If the SMA mixtures are under filled, but the mortar is overfilled, the small wheel-tracking test predicts good rut resistance and the triaxial test not. The difference in the trend is schematically summarised in figure 2.

If the designed SMA mixtures consist of standard materials, the mix composition is within the field of experiences and the air void content and the bitumen content is sufficient, a good rutting resistance will be realized. Outside the field of experience (for example high HRS of the coarse material), extra attention should be given to the mortar composition and probably extra mechanical testing is necessary.

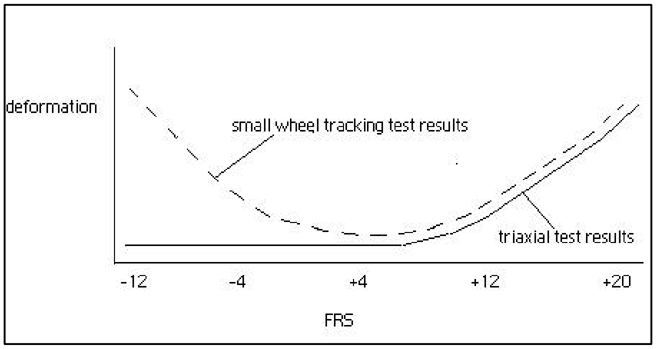

Figure 2: Difference in trend between small wheel-tracking test and triaxial test in relation to FRS.

4. FIELD TRIALS WITH SMA 11

A significant step in the mix design method is the extra quality control that is required on the stone fraction, available at the moment of the production of the SMA mix and the use of this information in a volumetric calculation model for the mix. In case the properties of the available stone fraction deviate considerably from the stone fraction from the mix design, the mix design of the SMA has to be reconsidered and probably be changed according to the actual situation.

Three field test sections have been used to validate the new mix design method. The process from mix design till final coring from the road section has been followed and validated. In table 7 the three test sections used for the validation of an SMA 0/11 mixture are given.

Table 7: Location, mix type and Stone type used for the test sections.

Location	Mix type	Stone fraction
HSL 1 Breda	SMA 0/11 type 1 (AV=4%)	Porphyry, FI = 15
Ureterp	SMA 0/11 type 2 (AV=5%)	Bestone, FI = 18
Zeddam	SMA 0/11 type 2 (AV=5%)	Augit porphyry, FI = 15

4.1.1 HRS-values

It has become clear that the HRS value works for all phases including the field. In table 8 the results of the determination of the HRS-value during three phases for the field trial are given. The coring in the field can have influenced the HRS value as explained later. From table 8 it becomes clear that mix design and production give the same results. In this case exactly the same material was used.

The HRS-values from the stone fraction extracted from cores are equal and in one case (HSL1) lower compared to mix design and production. Coring can result in decrease of the stone size due to side effects. Experience has learned that a finer grading normally will result in higher HRS-values. This is not observed. The stone fraction is taken from 6 cores (diameter 150 mm) in an area of 1 m^2. The results are satisfying.

Table 8: Comparison of HRS-values of the field trials (SMA 0/11)

Location	HRS- value (%)		
	Mix design	Production	Cores from road
HSL1	39.8	39.8	38.9
Ureterp	38.1	38.1	38.1
Zeddam	38.1	38.1	38.1

4.1.2 Production control with Marshall and Gyratory compaction at the plant

In table 9 the results from the production control at the asphalt plant during production and the mix design are given. In this way a good comparison can be made between the reality (production through the asphalt plant) and the laboratory mix design. For all three field trials it was not necessary to change the mix design (see HRS results in table 6).

Comparison of the voids contents during production with the design values shows that in most cases considerable differences were reported between design and production. For example, for HSL1 the production results are significant higher than the mix design value. Even with gyratory compaction (internal angle 0.82) after 300 gyrations the design values can not be reached for two field locations. For HSL in most cases a number of 180 gyrations gave similar voids content as the Marshall results during production. However, this is not valid for the other two field trials. The results of the Zeddam mixture show even lower voids contents after gyratory compaction than the mix design.

Table 9: Comparison of design voids content with production control information

	Design voids content Marshall	Marshall (2*50)		Gyratory (N gyrations)			
				180		300	
Location		A	B	A	B	A	B
HSL 1	4.0	7,0	7.1	8.4	5.5	6.5	5.8
		7.2	6.5	8.5	6.4	7.1	6.7
		7.1	6.8	8.8	5.7	5.5	5.9
		6.1	7.0	7.3	5.9	6.0	7.3
Ureterp	5.0	4.7	5.6	7.9	8.8	6.9	6.5
				9.0	8.6	6.7	7.6
Zeddam	5.0	5.4	6.7	3.9	5.4	3.4	6.1
		5.4	7.1	4.1	5.3	3.5	4.9

4.1.3 Crushing in the HRS test compared to the field

In table 10 an overview is given of the HRS-values of the Stone fraction of the three field trials and the fraction through 2 mm after the test.

Both the HRS-value and the crushed fraction through 2 mm after the HRS-test are important quality indicators for the Stone fraction. In the theoretical volumetric mix design these two parameters have to be used for the calculations. During production these two parameters will show if the stone fraction during production is similar to the stone fraction of the mix design or not.

Table 10: Percentage through 2 mm of the different Stone types after the HRS-test.

Location	Mix type	Information stone	HRS	through 2 mm
HSL 1	SMA 0/11 type 1	Porfier, FI* = 15	39.7	1.5
Ureterp	SMA 0/11 type 2	Bestone, FI = 18	38.1	3.0
Zeddam	SMA 0/11 type 2	Augit porfier, FI = 15	40.9	4.0

*FI = Flakiness Index

Another important aspect is that in this way an indication can be given of the crushing during construction and how this compares with the mix design. In table 11 the percentages on 2 mm are given as determined during production and for recovered aggregate from cores of the field trials.

Table 11: Comparison of % on 2 mm (stone fraction) based on production information and field cores

Location	Marshall Mix Design % on 2 mm	Production analysis	Stone fraction from cores
HSL 1	76.0	75.6 (n=22)	76.3 (n=10)
Ureterp	80.0		78.9 (n=10)
Zeddam	76.0	75.8 (n=11)	75.2 (n=12)

From table 11 it can be concluded that in general the percentage on 2 mm for the cores is equal or lower than the design value. This could indicate that during production some crushing occurred.

4.1.4 Compaction of the Field Trials compared to the Mix Design

In table 12 a summary is given of the voids content during production control and from cores of two specifically defined places for each field trial.

Table 12: Mean voids content AV (%) for the cores from the field trials.

Location	Production analysis	Cores
HSL 1	6,5 (n = 22)	5.4 (n=10)
Ureterp		2.6 (n=10)
Zeddam	6,5 (n = 22)	6.9 (n=12)

Comparison of the voids content of the field trials with the design voids content shows that for two field trials the realized voids content is approximately 1 to 2% higher as expected, but Ureterp has an extreme low voids content between 2 and 3 %. No direct explanation can be given for this strong deviation. Hot weather resulting in asphalt temperatures high for a long time, combined with high compaction efforts partly explain the extreme low voids content. It shows that also this method cannot automatically predict how the compaction of the mixture will proceed in the field after lab compaction.

4.2 Visual inspections after 4 years

After 4 years a visual inspection was done on the field trial of Ureterp and Zeddam. Ureterp is heavily trafficked and Zeddam is relatively lightly trafficked. No permanent deformation was observed for the Zeddam field section and only a few millimeters of rutting (maximum 4 mm) were measured at some p[laces of the Ureterp site.

5. CONCLUSIONS

The HRS test was introduced to determine the voids in a compacted stone skeleton to improve the mix design of SMA. The new test focuses on the role of the stone skeleton to prevent unexpected rutting. Important aspect is that also during production the stone grading will be controlled.

A spreadsheet was developed to calculate the voids content after compaction with the help of a shift factor between the calculated voids content and voids content of the laboratory compacted mix. The shift factor works well for Marshall compaction and is now used with gyratory compaction.

The triaxial test as well as the small wheel-tracking test predicts the same trend for field rutting if SMA mixtures are overfilled. If the SMA mixtures are underfilled, but the mortar is overfilled, the small wheel-tracking test predicts strong increase in permanent deformation and the triaxial test not. For the Ureterp mix the voids content in the field is related to the situation in the test showing still very good resistance against permanent deformation.

Field trials have shown that it is sometimes difficult to predict with lab mix design the final voids content in an SMA mixture after construction.

More attention to the volumetric composition of an SMA mixture (like in this design) will decrease the chance of permanent deformation.

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