Description of a volumetric type testing and FPC procedure for SMA to prevent premature permanent deformation

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ABSTRACT:

One of the main reasons for using SMA as a surface layer is its excellent resistance to permanent deformation under heavy traffic loadings. This is caused by the fact that SMA is a stone skeleton mix. This implies that the traffic loading is carried by the large mineral aggregate parts in the mix which are in mutual contact. This is only possible in case the air voids in the mineral aggregate part of the SMA are not completely filled with mortar (sand, filler and bitumen). In normal situations an air void content of about 4%V/V should be available in the SMA.

However, due to compaction during construction or due to traffic loading these air voids can reduce to zero. In this case SMA becomes instable and permanent deformation occurs. In the Netherlands this problem occurs regularly. One of the main causes is the fact that the characteristics of the constituent materials vary through the year. This implies that it is possible that the materials, which are used during production, are slightly different from the materials which are used in the type testing procedure. In case e.g. more weak parts are present in the coarse mineral aggregates during production than in type testing it is possible that these weaker parts are crushed during production, compaction and traffic loading and the SMA will be overfilled.

To tackle this problem an adjusted type testing and factory production control procedure is developed in the Netherlands. In this procedure the characteristics of the coarse mineral aggregate, which are used in the type testing procedure, are established in an extra test using gyratory compaction. With this test the FRS-value (Filling Ratio Stone Skeleton) is determined. During production of the SMA the FRS-value of the coarse mineral aggregate is constantly compared with the VRS-value in the type testing procedure. In case there is a discrepancy between the two values, the amount of coarse aggregates in the SMA is adjusted.

In the paper the background of this new type testing and factory production control procedure will be presented. Also the extra tests, which will be part of this procedure, will be discussed. Finally, the field experiences with the new procedure will be evaluated.

INTRODUCTION

The favourable characteristics of Stone Mastic Asphalt (SMA) like stability and durability are based on the stone-to-stone contact of the coarse mineral aggregates (stone skeleton) and the fixation of the stone particles by the mortar with a high amount of binder. The volume of voids in the compacted stone skeleton of the SMA should be high enough to contain the mortar volume (=sand+filler+bitumen+drainage inhibitor). If this is not the case, the stone-to-stone contact is lost. In case of overfilled voids of the compacted stone skeleton, the stability of the SMA will decrease and the likelihood of permanent deformation will increase drastically. In this respect SMA is a

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critical mix. Also during its life span (with traffic and climatic loadings), the SMA should still have a considerable amount of air voids to prevent an overfilled situation.
In the present Dutch mix design method [1] a fixed amount of bitumen is required; a variation in percentage stones (4 different stone percentages) is applied to determine the correct amount of coarse aggregates to meet the voids requirements of SMA. The specimens (4 per stone percentage) are compacted using impact compaction (Marshall), although gyratory compaction can be used. However, this possibility is still hardly used in the Netherlands. In the future the gyratory will be used more often because in the Netherlands the gyratory compaction will be used as the preferred compaction method.

To decrease the possibilities of overfilling SMA during its life span the CROW-working group "Mix design SMA" has carried out research to prevent premature rutting problems. It is proposed to change the mix design method and the factory production control procedure. In this paper the results of this research program is presented step-by-step, in which attention is paid to the determination of the quality of the coarse aggregate and the verification of its quality during production using gyratory compaction.

CHARACTERISATION OF THE DUTCH MIX DESIGN METHOD

In [1] for SMA the desired grading, the amount of bitumen and their margins are given. All data are presented in mass percentages, in which the amount of bitumen is based on the mean density of the mineral aggregate of 2650 kg/m^3. In case the density of the total aggregate mix differs more than 50 kg/m^3 from 2650 kg/m^3, the amount of bitumen has to be adjusted volumetrically. This is the only volumetric correction for the composition of an asphalt mix. It also should be mentioned that no mechanical properties are required for SMA: only the void content is an essential requirement. The background of this is the fact that the stone skeleton of SMA provides for a good resistance to permanent deformation, while the high bitumen content ensures a high durability level. The mortar takes care of the partly filling of the air voids in this skeleton and the bonding and fixation of the individual coarse aggregate parts. In case of an under filled mix like porous asphalt the amount of mortar is much smaller than the voids in the compacted stone skeleton. Overall, in this mix the amount of voids is large causing the noise reducing and the porosity characteristics of this mix. In SMA the voids in the stone skeleton are almost completely filled with mortar. There are some large air voids left, but these voids are not interconnected. These properties are characteristic for the so-called gap-graded mixes. In case of overfilled mixtures the amount of mortar is much more than the air voids in the mineral aggregates. The resistance to deformation for these mix types is directly related to the stiffness of the mortar. These mixtures will have a reduced resistance to permanent deformation, because the mortar is overfilled with bitumen.
Based on the volume of mortar and the percentage bitumen in the mix the various Dutch asphalt mixtures can be distinguished. This type of mix characterisation, which was developed by Van Bochove [2] and used by Goos et.al.[3] is presented in figure 1.

Figure 1 shows that SMA is a critical mixture. In heavy loaded situations with slowly driving and turning traffic the voids in the stone skeleton can decrease due to abrasion and re-orientation of the stones. Under these conditions SMA can become filled and even overfilled. For this reason in [1] the percentage voids for the various types of SMA is prescribed: in the mix design the amount of voids for a SMA type 1 (for normal loaded situations) is 4%, whereas for a SMA type 2 (for heavy loaded situations) 5% is required. These voids in the mix design method are based on Marshall compaction (2*50 blows). However, in practice air voids of 2 to 3 %V/V or even less occur after laying, however these mixtures are designed on 5 % voids. It can be mentioned here that in the Dutch system a contractor gets a penalty for bad construction in case the voids are lower than 2 or 3 %V/V for an SMA type 1 respectively 2. Generally the design procedure using Marshall compaction works well. However due to a difference in voids between mix design and in practice the risk of overfillment occurs: the surface turns black, the texture depth decreases and permanent deformation occurs. For this reason the mix design and factory production methods must be improved to reduce these types of risks, especially under heavy traffic with slow moving and turning traffic. Especially during production the composition of the SMA should be changed quickly in case the characteristics of the delivered coarse aggregates differ substantially to the aggregates used in mix design. A sensitivity analysis [4] showed that changes in void content of compacted stones have the highest influence on the FR_S value of SMA.

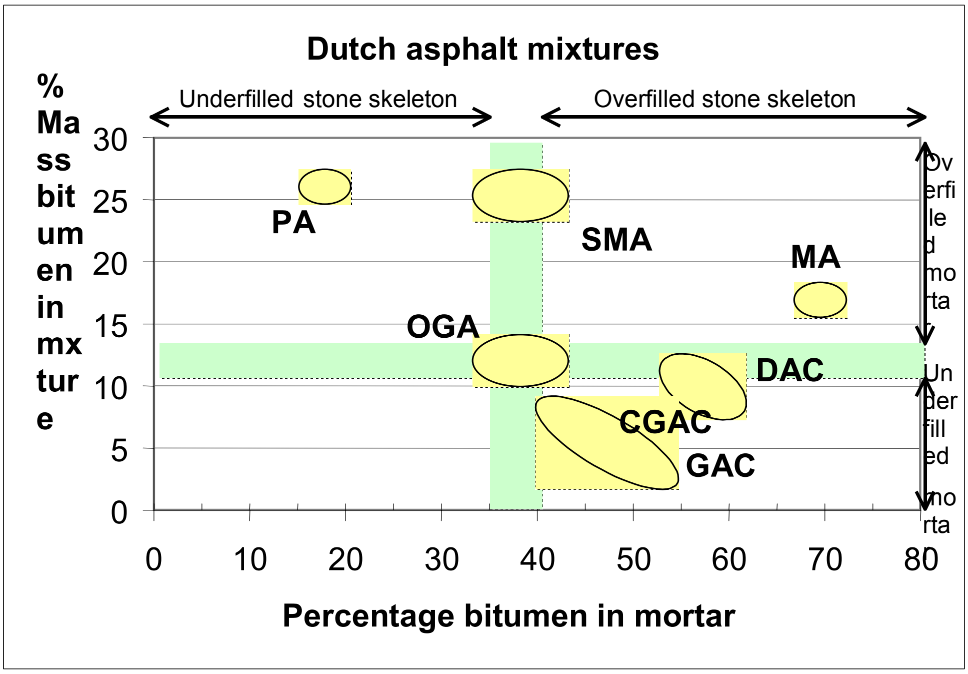

Figure 1: The volumetric characterisation of Dutch asphalt concrete mixtures

GYRATORY TESTS

The gyratory compactor was used to compact SMA specimens for mix design and to determine the quality of the coarse aggregates. The following test conditions for the gyratory were applied: axial pressure: 0.6 MPa, external angle 1.25° and 30 rotations per minute.

Gyratory compaction level during mix design

For mix design the SMA specimens have to be compacted in a mould with a diameter of 100 mm and a specimen height of about 60 mm. First the candidate mixtures with different percentages coarse material have to be compacted with 200 gyrations. Then from the compaction curve the amount of gyrations (=x) is determined that agrees with the point at which the decrease of the height of the specimen during the last 10 gyrations is equal to 0.2%. This amount of gyrations is used to determine the reference density. After that 4 specimens per candidate mixture are compacted with x gyrations.

Gyratory compaction of the coarse aggregate

To determine the quality of the coarse aggregate, 4 kg of the fraction larger than 2 mm with the same grading as in SMA has to be compacted in a 150 mm diameter mould with 300 gyrations. To simulate the greasing effect of the binder and to prevent too much abrasion and crushing 1.5 %m/m of white medicinal oil is mixed with the coarse stone fraction. The 300 gyrations are chosen to take into account the abrasion and crushing of the coarse aggregates during compaction with rollers in the field and a number of years of traffic loading. After compaction the density of the aggregates is determined and the voids content is calculated. After extraction of the oil the coarse aggregate is sieved over 2 mm. The quality of the coarse aggregate is quantified as the voids content in the optimal compacted stone skeleton and the amount of material passing sieve 2 mm. The last result will give information about the resistance to crushing.

VOLUMETRICAL APPROACH OF STONE SKELETON MIXTURES

The most important condition to accomplish a high resistance to permanent deformation is the fact that the stone skeleton has to remain under filled with mortar. In this case the stability of the SMA is due to the stone-to-stone contact of the larger aggregate parts. This contact is caused by the discontinuous grading of SMA (gap between the mortar and the stone fraction). The working group has used the method described in chapter 3.2 to determine the air void content in the stone skeleton. As already stated in chapter 2 the volume of voids in the sand-filler mix is too small for the volume of bitumen: the mortar is overfilled. The filling of the voids in the stone skeleton with mortar, and with the remaining air voids in the compacted mix, depends on the volumes of the sand, filler, bitumen and drainage inhibitor. This volumetric approach is presented in figure 2.

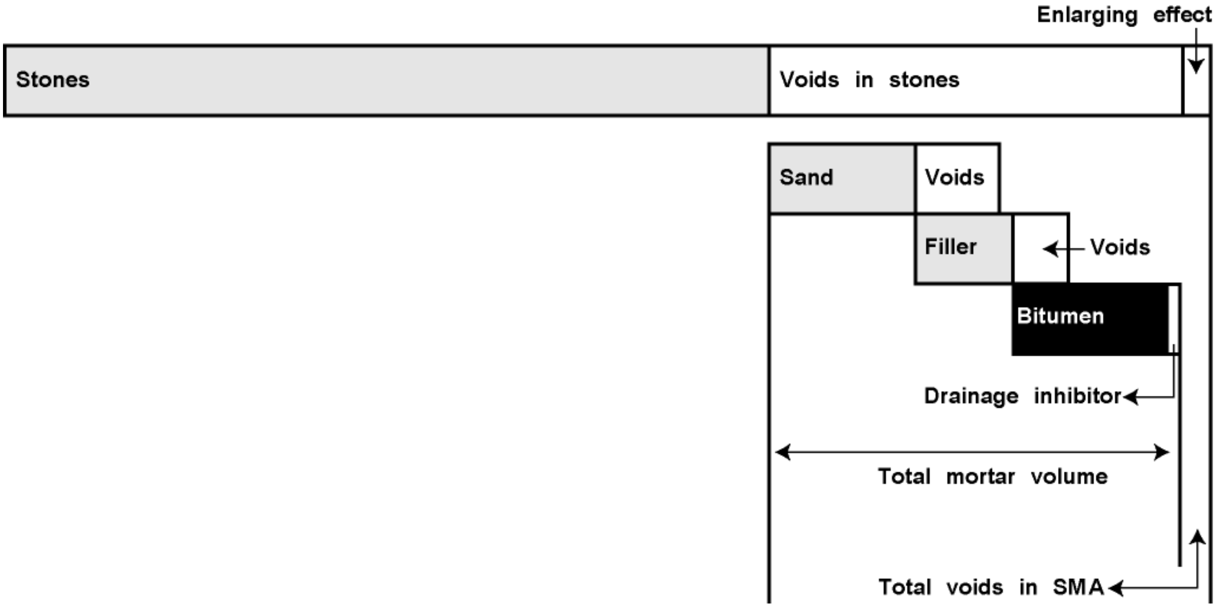

Figure 2: Volumetrical composition of SMA (schematically)

Figure 2 shows that the total amount of air voids in the compacted mix consists of pores in the stone fraction which are not completely filled with mortar. It is also shown that the air voids in the stone skeleton is somewhat enlarged. This is caused by the fact that mortar, especially the sand grains, will enlarge the stone skeleton.

From the composition of SMA the theoretical filling degree of the optimal compacted stone skeleton with mortar can be calculated as follows [4]:

$$VR_s = \frac{V_m - V_s}{V_s} \cdot 100\%$$

where: FR_S = filling ratio for stone skeleton mixes;
V_m = volume of mortar;
V_S = volume of voids in optimal compacted stone skeleton.

The volume of voids in the optimal compacted stone skeleton (=V_s) can be calculated from:

$$V_s = \frac{m_{st}}{\rho_{st}} \cdot \frac{V_s}{(100 - V_{st})}$$

where: M_{st} = mass of stones (% m/m);
ρ_{st} = density of bitumen (g/cm^3);
V_{st} = voids in stones (% v/v).

The volume of the mortar (=V_m) can be calculated as follows:

$$V_m = \frac{m_b}{\rho_b} + \frac{m_f}{\rho_f} + \frac{m_s}{\rho_s} + \frac{m_a}{\rho_a}$$

where: m_b = mass of bitumen (g);
ρ_b = density of bitumen (g/cm^3);
m_f = mass of filler (% m/m);
ρ_f = density of filler (g/cm^3);
m_s = mass of sand (g);
ρ_s = density of sand (g/cm^3);
m_a = mass of the drainage inhibitor (g);
ρ_a = density of drainage inhibitor (g/cm^3).

The volume of the mortar can be calculated from the sum of the individual ratios between mass and density of bitumen, filler, sand and drainage inhibitor in the SMA. Because the sand and filler parts are surrounded by an excess of bitumen it is assumed that the mortar has no air voids. A negative FR_S-value implies that the SMA is under filled with mortar. A mix with a negative FR_S-value cannot reach a state of overfillment during its life span. In case the $FR_S = 0$ the SMA is theoretically exactly filled with mortar and a positive FR_S-value indicates an overfillment of the mix with mortar. In this case the SMA becomes a overfilled mix with a sand skeleton. Because the mortar is also overfilled with bitumen, such a mix will have a reduced resistance to permanent deformation.
Notice that the FR_S is calculated with the void content of a real stone skeleton. In reality the stone skeleton of SMA will be enlarged, because during mixing mortar will move between the coarse aggregate. This means it is possible that a theoretically just filled SMA ($FR_S = 0$) can have a void content of 4 or 5%.

THE VOLUMETRICAL MIX DESIGN OF SMA

Step-by-step approach of the mix design procedure for SMA

In this section the advised mix design method for SMA is presented which is based on the determination of the air voids in the compacted stone skeleton and the filling ratio of the stone skeleton. The following steps can be distinguished:

a) It is a volumetric mix design method, so first all densities of the components (stone larger than 2 mm, sand between 2 and 0.063 mm, filler smaller than 0.063 mm, bitumen and drainage inhibitor) have to be determined. All calculations are carried out in volume parts.
   Determine with gyratory compaction the optimal density of the used stone fraction larger than 2mm (= minimum voids content). The loss of the fraction smaller than 2 mm (due to crushing and abrasion) has to be corrected in the mix, because the fraction smaller than 2 mm does not belong to the stone skeleton. Due to the fact that the amount of sand in SMA is rather small, the amount of sand larger than 2 mm is neglected in the considerations. To determine the voids in the stone skeleton not only the particles size is important, but also the particle shape. For this reason it is very important that all materials larger than 2 mm will be used in the research in

accordance to the mixing ratios of the various fractions of the crushed aggregates. It should be noted that an increase in the percentage stone of 1 %m/m results in a decrease of the FR_S-value of about 2.5 % and visa versa.;

b) Calculate the volume of the mortar of the first candidate mix with a FR_S-value of -4 as follows:

$$V_m = \left(\frac{FR_S}{100} + 1 \right) \cdot V_S$$

c) With the information of the mortar volume, the composition of the mortar can be calculated. To ensure the durability of SMA 0/11 a fixed bitumen content (7%m/m on 100% mineral aggregate) is used. The desired volume of drainage inhibitor is also a part of the mortar. Now only the remaining volume of sand and filler has to be calculated. The sand to filler ratio is fixed at 65/35 (%m/m), so if necessary the density of those two components is taken into account;

d) Now the mortar composition in volume parts and the stone content being known, the composition of SMA can be calculated in mass percentages with the help of the densities of the components. The calculated percentage of stone > 2 mm is set to X;

e) Calculate the composition of 2 other candidate SMA mixtures with stone percentages of (X–2.5) and (X+2.5) %m/m;

f) Prepare per candidate mix 3 specimens with the determined amount of gyrations;

g) Determine the void contents of the 3 candidate SMA mixes;

h) Plot the results in a graph: on the x-axis the percentage of stones in SMA and on the y-axis the voids content in SMA;

i) Determine by interpolation the desired SMA mixture which meets the voids requirements (see table 1);

j) Calculate the FR_S-value of the chosen mixture.

Table 1. Voids requirements in volume percentages for SMA in mix design.

SMA 0/11	Marshall compaction	Gyratory compaction
Type 1	4	3
Type 2	5	4

The working group used for the development of this new mix design procedure only the data which were determined for an SMA 0/11 type 2 mix. Despite this limitation the working group is confident that this procedure is applicable for all SMA's. The use of this procedure will decrease the changes of overfillment of the SMA. However, further research has to be carried out to validate the value of the presented criteria for other types of SMA.

Correlation between mix design and factory production control

The mix design is carried out with building materials which are available at that time. At the time the actual production of the mix takes place, the building materials or the quality can differ from the mix design, especially the crushed coarse aggregates. The quality of the crushed coarse aggregate can differ because it is a natural product, which originates from a quarry or/and because the mining and process activities can change (e.g. due to wear of the crusher). However, deviations in particle shape and resistance to crushing can influence the volumetric composition of the produced asphalt mix. Until now only the mix composition and percentage voids are checked during production. In [4] no relation was found between the grading and the void content of the compacted stone skeleton of the same stone type. This implies that the effects on air voids of variations in characteristics in the constituent building materials are only verified indirectly after compaction in the road. For this reason it is important that information about the volumetric ratios, which are determined in the mix design, is also used during the quality control of the supplied materials. It is advised to determine the voids content for each supply of crushed coarse aggregates. In case the difference in voids

content is higher than 1,5 % compared to the value determined in mix design, the shipment should not be accepted or the mix composition should be changed.
The composition of the mix can be corrected by comparing the air voids content of a SMA specimen after marshall or gyratory compaction using the calculated FR_S-value of the SMA and the percentage crushed aggregates in the SMA. In figure 3 this approach is illustrated graphically.

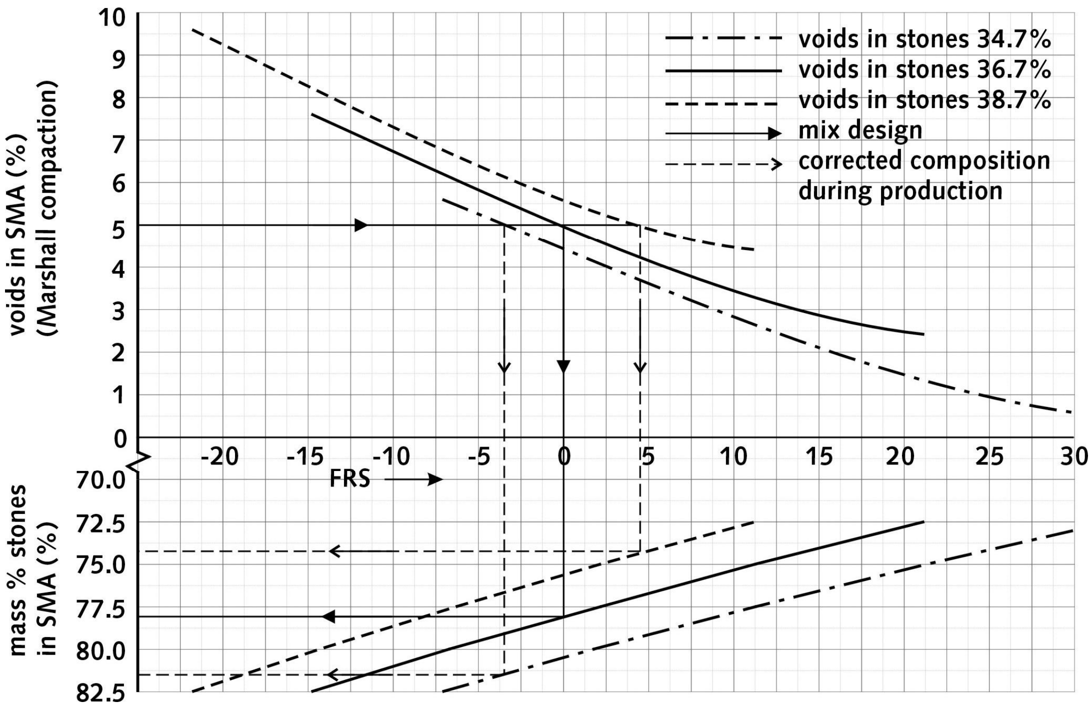

Figure 3: Graphical relation between air voids in the SMA, the FR_S-value and the known percentage crushed aggregates in the SMA

The lines in figure 3 can be used as a tool for the quality control of the crushed aggregates during the production of SMA. This is explained in the next section.

Quality control of the crushed aggregates during production of SMA

In the mix design report the grading of the used stone fractions, the mixing ratios and mix grading after extraction is given. The stone percentage, which is based on the voids requirements in the SMA, is recorded (suppose A%). The percentage air voids in the compacted crushed coarse aggregates and the densities of the various mix components are used to calculate the FR_S-value. The percentage air voids in de compacted crushed coarse aggregates depends on the shape of the particles and the resistance to abrasion and crushing. There can be a difference in these characteristics between the coarse aggregates used during production of SMA and used in mix design. Also differences in grading of the fractions may occur, but this problem can be solved in a usual way. It is important that the percentage air voids in the compacted crushed coarse aggregates and the resistance to abrasion and crushing will be part of the factory production control.
For this reason in the extra quality control the percentage air voids in and the abrasion characteristics of the coarse aggregates (> 2mm; in the identical mix ratios or grain sizes as in the SMA itself) has to be determined using gyratory compaction. Making this extra control not more complicated than necessary and to make the control not very time consuming at first the gross percentage air voids in the coarse aggregate are determined. With gross is meant that the percentage air voids without correction for the crushed material smaller than 2 mm. So after compaction in the gyratory, the material does not need to be extracted and sieved. From the relation in the mix design between the air voids in the coarse aggregates, the air voids in the SMA, the mass percentage coarse aggregates and the FR_S–value, the adjusted mass percentage coarse aggregates during production of

the SMA can be determined. In case the difference between the adjusted mass percentage coarse aggregates and this percentage in the type testing procedure is greater than 1.5%, the determination of the gross percentage air voids is not enough and extra tests are necessary to adjust the composition of the SMA.
In the extra tests the actual percentage crushed coarse aggregates is determined by extraction, sieving and correction for the crushed percentage aggregate smaller than 2 mm. Then from figure 3 the amount of coarse aggregates can be determined which is needed to fulfil the air voids requirement in the SMA (suppose B%). In case the difference between A and B is greater than an arbitrary value of 2%, the type testing procedure has to be repeated or the coarse aggregates should not be used in the mix.

PRESENT SITUATION

The working group wrote a guideline describing the volumetrical mix design procedure and the factory production control for SMA [5]. Contractors will use this procedure for about one year. The working group will support this period with additional tests. After this year an evaluation will be carried out, in which the chances of premature permanent deformation for SMA are determined. In case these changes are small or close to zero, the procedure will be added to the next Dutch Standard Conditions of Contract for Road Works.

CONCLUSIONS

Based on the results of this research program the following conclusions can be drawn:
1. Using the FR_S-value during the type test procedure, the amount of specimens to be tested can be reduced.
2. Due to changes in the quality of the crushed aggregates greater than 2 mm makes the SMA sensitive to overfillment and permanent deformation;
3. Due to the introduction of an extra characteristic for the coarse aggregate in SMA (the filling ratio for stone skeleton mixes, FR_S), the effect of changes in quality of the crushed aggregates greater than 2 mm during production can be checked fast and easy;
4. In case the quality of the crushed aggregates greater than 2 mm for production deviates from the aggregate used in the mix design, the composition of the SMA can be easily adapted.

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