Validation of the Polygon-Of-Voids Tool for Asphalt Mixtures with RAP

Validación de la herramienta de polígono de huecos para las mezclas asfálticas con RAP

Carlos Rodolfo Marín Uribe (Autor Principal)
Pontificia Universidad Católica de Chile
Facultad de Ingeniería
Departamento de Ingeniería y Gestión de la Construcción
crmarin@uc.cl
Casilla 306, correo 22, Santiago de Chile.

Guillermo Alfonso Thenoux Zeballos
Pontificia Universidad Católica de Chile
Facultad de Ingeniería
Departamento de Ingeniería y Gestión de la Construcción
gthenoux@ing.puc.cl

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Abstract

Durability of an asphalt mixture is directly related to the optimum asphalt binder content, which guarantees coverage of the aggregate particles and suitable volumetric properties to ensure a good performance in service, producing an asphalt mixture that is less susceptible to aging and moisture damage. Previous research has shown that the polygon-of-voids tool, or polyvoids, is an analytical technique to determine the optimum asphalt binder content of asphalt mixtures with virgin aggregates based on the specification limits of voids, allowing a saving in time and material. However, current trends to develop new asphalt mixtures which incorporate reclaimed asphalt pavement (RAP) have created additional challenges given the nature of the design of a mixture containing aggregates with residual asphalt that make the property measurement of the bulk specific gravity of the RAP aggregate (G_{sb}^{RAP}) difficult. This paper aims to demonstrate the application of the polygon-of-voids tool for the design of recycled hot-mix asphalt. The results show that the method of substitution, where the value of the actual specific gravity of the RAP aggregate (G_{se}^{RAP}) is assumed as the bulk specific gravity of the RAP aggregate (G_{sb}^{RAP}), gives the optimum asphalt contents closest to those determined by the traditional Marshall method for the design of asphalt mixtures.

Keywords: Reclaimed Asphalt Pavement (Rap); Polyvoids; Asphalt Mixes; Volumetric Properties.

INTRODUCTION

Generally, the design process of an asphalt mixture initially consists of a volumetric design and subsequently of mechanical or empirical tests to verify the design. The quality of the asphalt mix can vary due to many factors such as variations in asphalt binder content and particle size, which usually occur during production in the plant, and variations in temperature and compaction energy, which can happen during compaction in the field, so that the compacted mixture on site may have different volumetric parameters and mechanical properties from those considered in the design (Garnica et al, 2005). It is desirable that the mixture produced in the plant has uniform properties and characteristics similar to those of the design of the laboratory mix, which seeks to select the materials (aggregate, asphalt binder, mineral filler, additives), the grading, the optimum asphalt binder content, the mixing and compaction temperatures, and the volumetric properties of the mixture, so that the requirements chosen for a particular project are met.

The goal of the design process of hot-mix asphalt (HMA) is to select a single optimum asphalt binder content that allows to balance appropriately the properties looked for by the designer and that ensures adequate service performance regarding common failures such as fatigue, low temperature cracking and permanent deformation. That is to say, to find the optimum asphalt binder content which ensures a thickness of asphalt film that delays aging of the mixture and subsequent cracking, sufficient stiffness to meet the demands of traffic without distorting or rutting, and convenient volumetric properties which have historically been related to their performance and durability. For any state of a compacted geo-material there are three properties of voids and its relation to the name of any other geo-material is shown in Table 1.

Over the years, designers have established maximum and minimum standards for these volumetric properties in order to exclude those asphalt mixtures which have a poor performance. For instance, low air voids may produce rutting and shove while high air voids causes accelerated aging, high permeability, brittleness, premature cracking, raveling and moisture damage (McLeod, 1959; Asphalt Institute, 2007). The distribution of air voids also affects the presence and movement of water in asphalt mixtures. Water in asphalt mixture has harmful effects on the pavement structure, which weakens the adhesion between aggregates and asphalt and the cohesion of the mixture itself, producing disintegration and subsequent failure of the pavement structure. Voids in the mineral aggregate (VAM) quantify the area between the aggregate particles filled with air and the effective asphalt binder content, control the minimum asphalt binder content in the mixture and are basically related to the asphalt covering of the aggregate particles, the durability and stability (McLeod, 1956; Kandhal et al, 1998; Attia et al, 2009). VAM is the measure used to ensure proper asphalt film thickness on the aggregate particle for acceptable durability of the mixture.

Table 1. *Volumetric parameters of a geo-material. Source: Self Elaboration.*

Properties of voids	Generic name of a geo-material
Air voids (V_a)	Total voids
Voids in mineral aggregate (VMA)	Porosity
Voids filled with asphalt (VFA)	Degree of saturation

PROBLEMS ASSOCIATED WITH THE DESIGN OF HOT ASPHALT MIXTURES WITH RECLAIMED ASPHALT PAVEMENT (RAP)

When it is necessary to determine the optimum asphalt binder content and assess the volumetric properties of HMA with contents of RAP, one of the most important properties that must be determined is the effective specific gravity of the RAP aggregate (G_{se}^{RAP}). This parameter is critical to determine accurately the volumetric parameters of the mixture, especially the voids in the mineral aggregate (VAM), a value that is one of the key properties used for the design and the assurance of the quality of the mixture, as mentioned above. Owing to the fact that the bulk specific gravity of the RAP aggregate (G_{sb}^{RAP}) cannot be measured directly, it is necessary to estimate it. If the source of the RAP is known and the records of the original building are available, the bulk specific gravity (G_{sb}) value of the virgin aggregate established in these records could be used as value for the G_{sb}^{RAP}. However, if these records (of the original construction) are not available, the G_{sb}^{RAP} value must be estimated in accordance with one of the methodologies historically proposed for this (see Table 2) (Mc Daniel, 2001; NCHRP, 2001, Horan, 2003; Anderson, 2004, Al-Qadi et al. 2012).

The implication of this is that depending on the methodology used to determine the G_{sb}^{RAP}, the optimum asphalt binder content might be different from the volumetric properties found in the new HMA, a situation that could undermine a good performance when in service. For example, in a mixture containing 25% RAP, an error of 0.04 in the specific gravity can affect the VAM calculated by approximately 0.5 percent. This value can make a difference between a mix being accepted or rejected in accordance with the quality requirements imposed, or to the fatigue life being reduced significantly (Anderson, 2004).

Where:
(G_{sb}^{RAP}) = bulk specific gravity of RAP aggregate
G_{se}^{RAP} = effective specific gravity of RAP aggregate
G_{mm}^{RAP} = theoretical maximum gravity of RAP aggregate (RICE)

Table 2. *Methodologies for calculating the bulk specific gravity (G_{sb}^{RAP}) of the RAP aggregate. Source: Self Elaboration.*

Methodology	Description
Direct	Direct measurement of the G_{sb}^{RAP} after being recovered.
Substitution	Estimate of the G_{se}^{RAP} through the value of the G_{mm}^{RAP}. The G_{se}^{RAP} value is assumed as that of the G_{sb}^{RAP}.
Back calculation	Estimate of the G_{se}^{RAP} through the value of the G_{mm}^{RAP}. The G_{se}^{RAP} value is assumed as that of the G_{sb}^{RAP}. Then, the asphalt absorption value of the aggregates is assumed in order to estimate the G_{sb}^{RAP}.

The polygon of voids as an analytical tool for the design of recycled asphalt mixes

The polygon of voids, or polyvoids, is an analytical tool used to get the job formula or the optimum asphalt binder content for any hot asphalt mixture based only on the specifications of voids (Sanchez et al; 2011) and its rationale is supported by the implementation of the gravimetric and volumetric relationships of asphalt mixtures. Using this technique the volumetric parameters of HMA, represented by the asphalt content (P_b) and the compacted density (G_{mb}), can be shown graphically and analytically. That is to say, they determine the density of the compacted asphalt (G_{mb}) according to their volumetric properties: air voids (V_a), voids in the mineral aggregate (VAM) and voids filled with asphalt (VFA) and the constants of the bulk specific gravity of the combined aggregate - virgin aggregate and RAP aggregates - $(G_{sb\,comb})$, the effective specific gravity of the combined aggregate $(G_{se\,comb})$ and the specific gravity of the asphalt binder (G_b). The formulation proposed for construction of the polygon of voids is described below, where the compacted density of the asphalt mixture is defined in terms of air voids (see Table 3).

Figure 1 shows the construction of a polygon, using the mathematical formulae described above. The intersection of these curves, corresponding to the maximum and minimum levels required by the specifications, gives rise to the vertices of the polygon (Sanchez et al; 2011). There are at least ten intersections that are converted into the key points for the determination of the polygon of voids and they are shown in Table 4. The definition of these points is given by the intersections of the fundamental curves.

Table 3. *Mathematical formulae for construction of the polygon of voids. Source: Self Elaboration.*

Formula	Description
$G_{mb} = \frac{(1-V_a)}{\frac{P_b}{G_b}+\frac{(1-P_b)}{G_{se\,comb}}}$ (1)	There is a specific situation when $V_a = 0$. In this case, the equation represents a limit because any combination of P_b and G_{mb} may be found above this curve called 'saturation curve´´ and the equation becomes: $G_{mb} = \frac{1}{\frac{P_b}{G_b}+\frac{(1-P_b)}{G_{se\,comb}}}$ (2)
$G_{mb} = \frac{(1-VMA)}{(1-P_b)} \times G_{sb\,comb}$ (3)	Similarly, the compacted density of an asphalt mixture is related to its voids in the mineral aggregate of the following:
$G_{mb} = \frac{VFA}{\frac{P_b}{G_b}+\frac{(1-P_b)}{G_{se\,comb}}-(1-S)\times\frac{(1-P_b)}{G_{sb\,comb}}}$ (4)	The proportion of voids filled with asphalt (VFA) is a degree of saturation, that is, the relationship between the volume of voids filled with liquid and the total volume of voids. In the case that there is a 100% saturation, i.e. $VFA = 1$, this equation represents the 'saturation line' and becomes: $G_{mb} = \frac{1}{\frac{P_b}{G_b}+\frac{(1-P_b)}{G_{se\,comb}}}$ (5)

If one wanted to represent all the specifications of the voids for a given asphalt mix within the plane $(P_b - G_{mb})$, there would be a maximum area where all the specifications would be complied with. This area is known as 'polygon of voids' or 'polyvoids'. In accordance with this definition, any combination of asphalt binder content and density inside the polygon should simultaneously comply with all the void specifications (see Figure 2). The job formula dealing with the content of optimum asphalt binder is obtained by calculating the centroid of the area of the polygon that the intersections of the curves of voids generate (Sanchez et al, 2011).

Some previous work (Sánchez-Leal, 2002; Sánchez-Leal, 2004; Sanchez et al, 2011) has demonstrated the application of this tool in the analysis and design of HMA developed by both the Marshall and Superpave methods with virgin materials. However, due to the increase in the use of RAP in new asphalt mixes, an interest has emerged to test whether the tool of polyvoids allows to obtain the optimum asphalt binder content and whether this result would be comparable to that obtained with the traditional Marshall design proposed by the Asphalt Institute (2007).

Figure 1. *Construction of the polygon of voids. Source: Self Elaboration.*

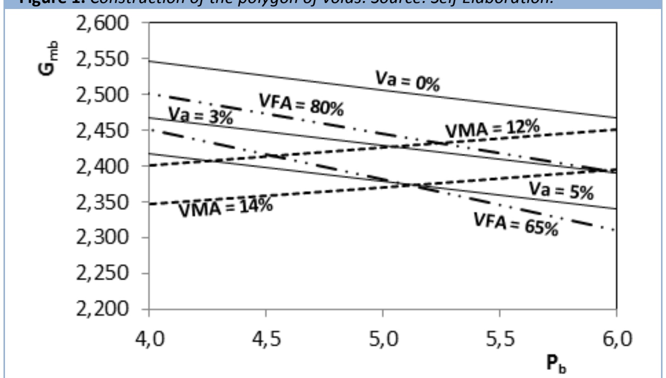


Table 4. *Key points of intersections of the fundamental curves of voids. Source: Sanchez et al (2011).*

Intersection N°	Intersection curve	
1	$(Va)_{max}$	$(VMA)_{min}$
2	$(Va)_{min}$	$(VMA)_{min}$
3	$(Va)_{min}$	$(VMA)_{max}$
4	$(Va)_{max}$	$(VMA)_{max}$
5	$(VFA)_{min}$	$(VMA)_{min}$
6	$(VFA)_{max}$	$(VMA)_{min}$
7	$(VFA)_{max}$	$(VMA)_{max}$
8	$(VFA)_{min}$	$(VMA)_{max}$
9	$(VFA)_{max}$	$(Va)_{min}$
10	$(VFA)_{min}$	$(Va)_{max}$

Advantages of the employment of the polygon of voids

The volumetric analysis in the Marshall as well as the Superpave method for HMA design is performed by the production of approximately 15 samples, i.e. three asphalt samples for each of five different asphalt contents. The tool of polyvoids not only makes a considerable saving in the design time of the asphalt mixture possible but also in the number of samples used, because it gets the same results as a complete design with only a fourth or a fifth of the number of samples, i.e. with approximately three samples. As Sanchez has expressed in his reports (2011), the savings due to the acceleration of the results are not only for the benefit of the designers of asphalt mixtures but also for that of researchers who state that applying this technique can evaluate between four and five different combinations of aggregates with the same resources and time that would be used by applying the Marshall or Superpave method in the conventional way.

METHODOLOGY

Figure 3 shows the methodology proposed to carry out this study, which presents two well-defined phases. The first one is to implement the traditional Marshall design method for each of the proposed mixtures and thus obtain the optimum asphalt binder content. The second phase corresponds to the application of the tool of polyvoids in accordance with the characteristics of the materials and the design requirements of the mixture in order to then also ascertain the optimum asphalt binder content. This tool was implemented with the aid of a spreadsheet programmed by the principal author. Subsequently, the results were calibrated in accordance with the data presented by Sanchez-Leal (2011) and compared with those obtained by the traditional method.

Figure 2. *Definition of the polygon of voids. Source: Self Elaboration.*

Vertex	P_b	G_{mb}
1	4.53	2.414
2	5.05	2.427
3	5.91	2.393
4	5.13	2.374
5	5.08	2.376
1	4.53	2.414
Centroid	*5.1*	*2.397*

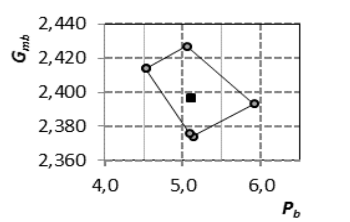
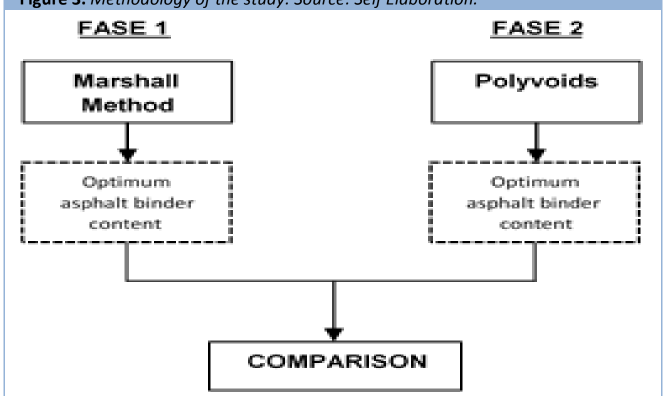


Figure 3. *Methodology of the study. Source: Self Elaboration.*



Experimental Plan

During the first phase of the methodology, an experimental plan was developed to apply the Marshall design to HMA with different RAP contents (0%, 10%, 25%, 40%, 50% and 70%). For the development of the entire design, various tasks were carried out in order to characterize the materials used, define the grading structure and obtain the optimum asphalt binder content as is shown in Figure 4.

Characterization of the virgin aggregate and RAP

The recycled material (RAP) has its origin in the milling of a layer of asphalt in the street Colonel Souper in the Commune of Santiago Centro (Santiago, Chile). Its characterization and that of the virgin aggregate consists of three fundamental parts. The first part corresponds to the separation of all aggregates, including those of the RAP, according to size in the laboratory, which helps to ensure a continuous distribution of particle sizes when they are mixed in addition to facilitating the constitution of an objective grading structure. These sizes are represented by the sieves: ¾" (12.7 mm), ½" (9.51 mm), 3/8" (9.5 mm), #4 (4.75 mm), #8 (2.38 mm), #30 (0,599mm), #50 (0,297mm), #100 (0,152 mm), # 200 (0,075 mm). In the second part the residual asphalt content of RAP material is evaluated, and finally the gravimetric properties of the aggregates are identified. Table 5 shows the laboratory tests carried out to define the three parts of the characterization of the aggregates and Table 6 illustrates the properties of the RAP aggregate.

Definition of the trial blend aggregate

Figure 5 shows the particle size chosen that corresponds to the semi-dense type IV-A-12 established by the Manual of Roads of Chile (2013) and recommended for surface layers.

Combination of the virgin aggregate and the RAP

The mixtures were designed while maintaining the same grading regardless of the percentage of RAP added. Subsequently, the values of the theoretical maximum gravity (G_{mm}) in accordance with the standard AASTHO T209 were obtained for all asphalt mixtures. Also, the G_{sb}^{RAP} values were estimated in accordance with the three methodologies available. The combined bulk specific gravity $(G_{sb\ comb})$ measured of each blend with a different content of RAP was determined by using the equation (6). Where P_i is the percentage of aggregate source i and G_i is the aggregate bulk specific gravity of source i.

Design of reclaimed asphalt mix using the Marshall Method

The samples were manufactured by the Marshall method to 75 blows per side. This method was chosen given that it is still current in Chile and the design of asphalt mixtures by the Superpave method has not yet been implemented. An asphalt of the type CA-24 was used, which is the one most commonly used in the country. The design procedure was then followed appropriately, producing three specimens for each of a total of five asphalt contents, based on the initial content of asphalt binder calculated using the procedure recommended by the Asphalt Institute (2007), which was the starting point for the complete design of the asphalt mixture (see Table 7).

Figure 4. *Flow chart of work for the design of asphalt mixtures with RAP. Source: Self Elaboration.*

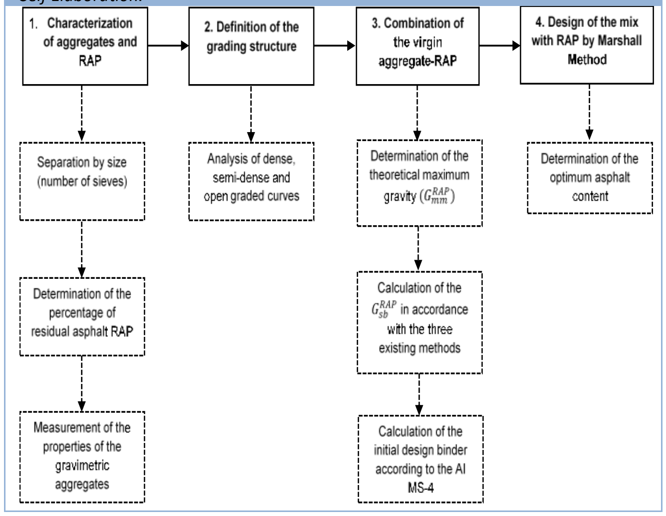


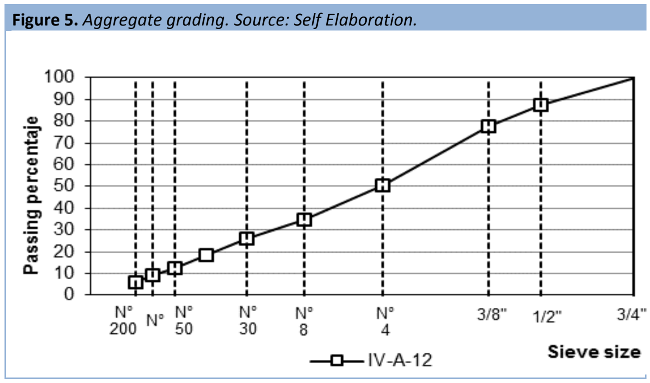
Table 5. *Laboratory tests for the characterization of the aggregates. Source: Self Elaboration.*

Property	Standard test
Determination of the residual asphalt of the RAP (centrifuge method)	AASHTO T 164 (Method A)
Determination of the properties of the gravimetric aggregates (virgin and retrieved from the RAP)	
Specific Gravity and absorption of fine aggregates	AASHTO T84
Specific Gravity and absorption of the coarse aggregates	AASHTO T85
Specific weight of the solid	AASHTO T100

Table 6. *RAP aggregate properties. Source: Self Elaboration.*

Property	Standard test
Residual asphalt content	5.5 %
Average of the theoretical maximum gravity (G_{mm}^{RAP})	2.308 gr/cm^3
Average of the bulk specific gravity (G_{sb}^{RAP}) – Direct method	2.643 gr/cm^3

Figure 5. *Aggregate grading. Source: Self Elaboration.*



$$G_{sb\ comb} = \frac{\sum_{i=1}^{n} P_i}{\sum_{i=1}^{n} \frac{P_i}{G_i}} \qquad (6)$$

Traditionally when a design of an asphalt mixture is carried out by the Marshall method, the optimum amount of asphalt binder is obtained by determining the average of the three values that represent the most important design properties: air voids (generally 4%), maximum stability and maximum density. However, it is current practice to calculate the optimum amount of asphalt binder for the percentage of air voids (V_a) of reference and then check the thresholds required for the other properties of the mixture. This is the procedure that was applied in this study and the results are shown in Table 8.

Table 7. *Asphalt binder content according to the initial procedure of the asphalt Institute MS-4. Source: Self Elaboration.*

Content of RAP (%)	Initial binder content (%)
0	5.5
10	5.0
25	4.1
40	3.3
50	2.8
70	1.7

Table 8. *Optimum content of asphalt binder (%) - Marshall method. Source: Self Elaboration.*

Amount of RAP in the mix (%)	Optimum content of asphalt binder for:	
	4% V_a	5% V_a
0	5.4	5.1
10	5.2	4.9
25	5.6	5.3
40	5.4	5.0
50	5.7	6.0
70	6.1	5.8

Note: The percentages of optimum content of asphalt binder are established in relation to the total weight of the mixture.

Table 9. *Volumetric properties of control for obtaining the optimum asphalt binder content. Source: Self Elaboration.*

Volumetric property	Symbol	Target value	Range	Observation
Air voids	V_a	4% 5%	3% – 5 % 4% – 6%	This was also calculated for the Chilean conditions for nominal maximum size of 19 mm according to Superpave.
Voids in mineral aggregate	VAM	Minimum 13%	12% – 14%	
Voids filled with asphalt	VAF	-	65% – 80%	

Generally, the HMA design requires a minimum and maximum value for each one of the volumetric properties already defined. Some researchers have recommended that the value of VAM is limited to a maximum level, usually 1.5 - 2.0% above the minimum value, in order to prevent a low resistance to rutting (Christensen and Bonaquist 2006). Similarly, the V_a has generally been established at 4%, ranging between 3 and 5%. In Chile for example, the V_a of design was established at 5% with a range of between 4% and 6%. Table 9 shows the control values for the volumetric properties used to establish the various job formulae.

RESULTS AND DISCUSSION

Bulk Specific Gravity of the RAP aggregate

It has been argued that if the G_{sb}^{RAP} is incorrect, it will affect the VMA calculated for the mixture, which could result in durability issues. The magnitude of the VMA error will depend on the error of the G_{sb}^{RAP} (Kvasnak, 2010). Figure 6 illustrates the values of G_{sb}^{RAP} obtained from each methodology as well as the error bars that indicate the 95% confidence interval. As can be seen, a lower dispersion occurs in the values of bulk specific gravity measured by the direct method while a greater dispersion was obtained by the method of substitution, which may be due to the sensitivity of the measurements for the determination of G_{mm}^{RAP}.

Figure 6. *Bulk specific gravity of RAP aggregate. Source: Self Elaboration.*

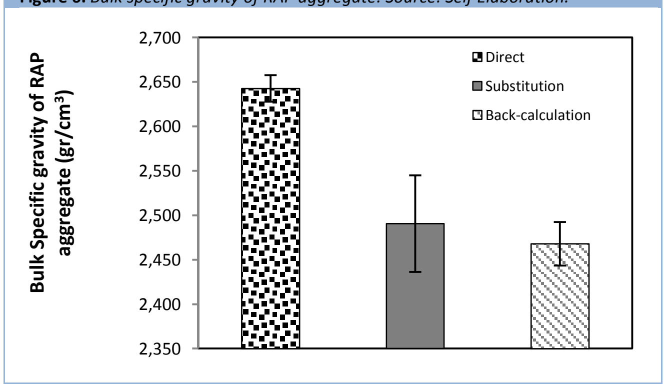


Table 12. *Optimum asphalt content for 4% of V_a. Source: Self Elaboration.*

Amount of RAP in the mix (%)	Marshall	Polyvoids		
		Direct	Substitution	Back-calculation
0	5.4	5.1	5.1	5.1
10	5.2	4.8	5.0	5.0
25	5.6	4.9	5.4	5.5
40	5.4	4.4	5.3	5.4
50	5.7	4.9	6.0	6.1
70	6.1	4.5	6.2	6.4

The results show that the G_{sb}^{RAP} values obtained by the direct method are higher while the other two methods give, on average, similar results. This could be due to the extraction process of the asphalt binder, which can change the properties of the aggregate and may result in a change in the amount of fine material, which can affect the specific gravity (NCHRP, 2001). In addition, the value of G_{sb}^{RAP} found by the direct method is greater than that obtained by the method of substitution (where G_{se}^{RAP} is substituted by G_{sb}^{RAP}), which is inconsistent with what is mentioned by the NCHRP (2001), which states the first property is always smaller than the second one for a given aggregate.

Optimum asphalt binder content by Polyvoids

Table 10 and 11 show the input data and the implementation of the polygon of voids for the calculation of the optimum asphalt binder content. This procedure was repeated for each of the percentages of addition of RAP and the three methodologies of calculating the value of G_{sb}^{RAP}. The optimum contents of asphalt binder for each of the asphalt mixtures with different contents of RAP were obtained in the same way. Table 12 shows the values that were established for 4% of V_a.

As shown in Figure 7, the values closest to the optimum content of asphalt binder obtained by the Marshall method, correspond to those calculated by the substitution method of, followed by those of the method of back-calculation and finally, very far off, were the values of the direct method. The values obtained by the method of back-calculation deviated from those produced by the Marshall method from as much as 50% of RAP.

Given the dispersion of the values of G_{sb}^{RAP}, one can calculate the maximum and minimum asphalt binder content using the polygon of voids and determine the respective ranges within which this optimum asphalt binder can be found.

Figure 8 shows the average values of optimum asphalt content and their respective limits according to the dispersion values of G_{sb}^{RAP} calculated using the methodologies mentioned above. It can be seen that as more RAP is added to the asphalt mixture, the range of values of the optimum asphalt binder becomes larger. This means that there is a higher dispersion of possible values of optimum asphalt binder content when RAP aggregate is added to the asphalt mixture. Therefore, the magnitude of the VAM error will depend not only on error of the G_{sb}^{RAP} measurement but also on the RAP content in the mixture.

Table 13 and Figure 9 show the values of optimum asphalt binder content that were established for 5% of V_a. It can be seen that the values closest to the optimum content of asphalt binder obtained by the Marshall method again correspond to those calculated by the method of substitution, followed by those of the back-calculation method and finally, very far off, the values of the direct method. The optimum asphalt contents determined by the method of back-calculation deviated from those established by the Marshall method from 70% of RAP onwards.

Figure 7. *Polygon of voids construction for 4% of V_a. Source: Self Elaboration.*

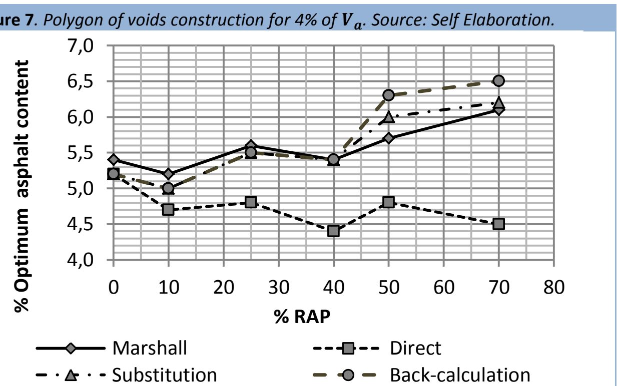


Figure 8. *Percentage variation of optimum asphalt content measured through three methodologies (for 4% V_a). Source: Self Elaboration.*

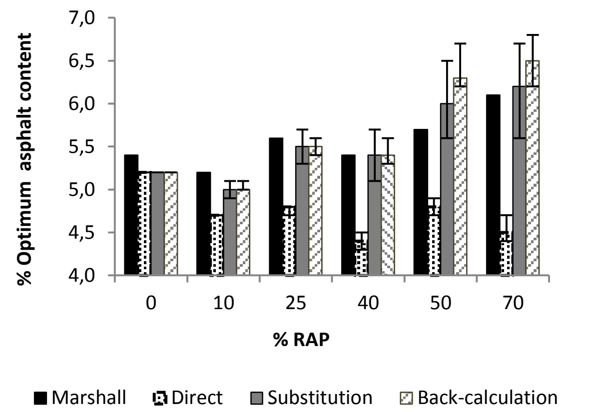


Figure 9. *Polygon of voids construction for 5% of V_a. Source: Self Elaboration.*

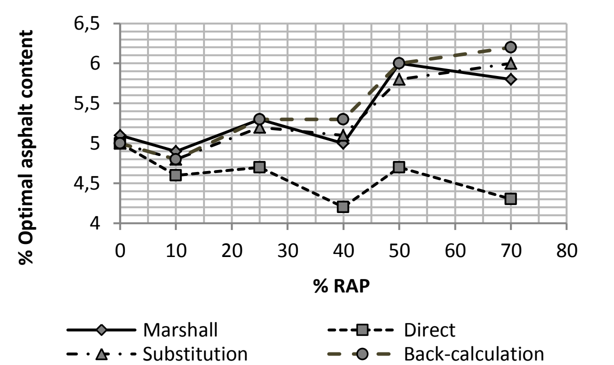


Table 13. *Optimum asphalt content for 5% of V_a. Source: Self Elaboration.*

Amount of RAP in the mix (%)	Marshall	Polyvoids		
		Direct	Substitution	Back-calculation
0	5.1	5.0	5.0	5.0
10	4.9	4.6	4.8	4.8
25	5.3	4.7	5.2	5.3
40	5.0	4.2	5.1	5.3
50	6.0	4.7	5.8	6.0
70	5.8	4.3	6.0	6.2

CONCLUSION

The polygon of voids, or polyvoids, is an analytical tool used to estimate the optimum content of asphalt binder making use only of the volumetric properties of the asphalt mixture. This tool has been tested successfully in asphalt mixes with virgin aggregates according to the Marshall and Superpave methods.

This work was intended to show the validity of the polygon of voids as a predictor for the optimum content of asphalt binder for hot mix asphalt with incorporation of varying amounts of RAP, publicizing the difficulties that arose at the time of the design. The results show that the above mentioned optimum asphalt contents were similar to those estimated by means of a typical Marshall design if the method of substitution is used for the calculation of the bulk specific gravity of the aggregate of the RAP (G_{sb}^{RAP}). This facilitates the preliminary estimate of the asphalt content since the above method only requires the calculation of the G_{se}^{RAP} by measurement of the G_{mm}^{RAP} in the laboratory, which is rather simple and quick to implement. In the case of having the asphalt absorption property of the aggregates, applying the method of back-calculation also gives values close to those of the Marshall design, but they deviate as more than 70% of RAP is incorporated in the new mix. One advantage of this method is less dispersion in the calculation of G_{sb}^{RAP} compared with the method of substitution, which allows having certainty in determining the optimum asphalt binder content. It is also important to establish that the property of the air voids (V_a) was chosen as the criterion for the determination of the optimum content of asphalt binder by the Marshall method.

In summary, the tool of the polygon of voids appears promising for estimating the optimum content of asphalt binder for asphalt mixes containing reclaimed asphalt pavement. However, for future research it is recommended to perform more laboratory tests and confirm the findings of this research using aggregates with different asphalt absorptions, RAP sources, gradations and types of asphalt binder. Moreover, for further validation of the polyvoids it is suggested to discuss in detail about the dispersion of the values of G_{sb}^{RAP} obtained by the three methods in order to determine if there are changes in the interpretation of the polygon of voids and volumetric properties of the asphalt mixture.

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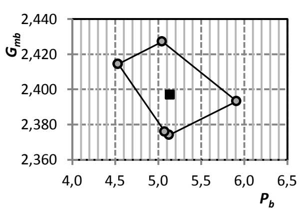
Table 10. *Application of the tool of polyvoids to an asphalt mixture with 0% RAP. Source: Self Elaboration.*

DIRECT METHOD

Inputs		
G_{sb}	2.620	
G_{se}	2.719	
G_b	1.010	
$V_a(min, max)$	3	5
$VMA\ (min, max)$	12	14
$VFA\ (min, max)$	65	80

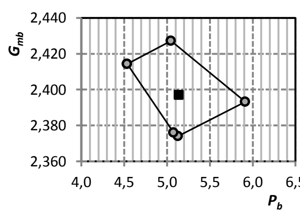
Vertex	P_b	G_{mb}
1	4.53	2.414
2	5.05	2.427
3	5.91	2.393
4	5.13	2.374
5	5.08	2.376
1	4.53	2.414
Centroid	*5.10*	*2.397*



SUBSTITUTION METHOD

Inputs		
G_{sb}	2.620	
G_{se}	2.719	
G_b	1.010	
$V_a(min, max)$	3	5
$VMA\ (min, max)$	12	14
$VFA\ (min, max)$	65	80

Vertex	P_b	G_{mb}
1	4.53	2.414
2	5.05	2.427
3	5.91	2.393
4	5.13	2.374
5	5.08	2.376
1	4.53	2.414
Centroid	*5.10*	*2.397*



BACK-CALCULATION METHOD

Inputs		
G_{sb}	2.620	
G_{se}	2.719	
G_b	1.010	
$V_a(min, max)$	3	5
$VMA\ (min, max)$	12	14
$VFA\ (min, max)$	65	80

Vertex	P_b	G_{mb}
1	4.53	2.414
2	5.05	2.427
3	5.91	2.393
4	5.13	2.374
5	5.08	2.376
1	4.53	2.414
Centroid	*5.10*	*2.397*

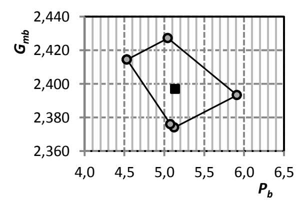
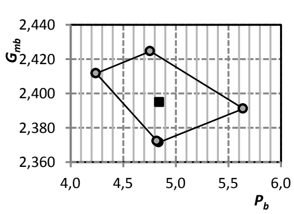


Table 11. *Application of the tool of polyvoids to an asphalt mixture with 25% RAP. Source: Self Elaboration.*

Direct method

Inputs		
G_{sb}	2.625	
G_{se}	2.697	
G_b	1.020	
$V_a(min, max)$	3	5
$VMA\ (min, max)$	12	14
$VFA\ (min, max)$	65	80

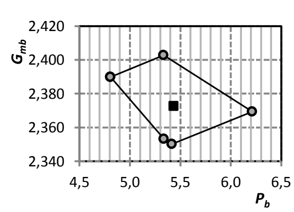
Vertex	P_b	G_{mb}
1	4.24	2.412
2	4.76	2.425
3	5.64	2.391
4	4.84	2.372
5	4.82	2.372
1	4.24	2.412
Centroid	*4.85*	*2.395*



Substitution method

Inputs		
G_{sb}	2.586	
G_{se}	2.697	
G_b	1.020	
$V_a(min, max)$	3	5
$VMA\ (min, max)$	12	14
$VFA\ (min, max)$	65	80

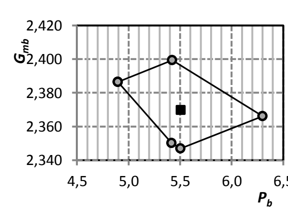
Vertex	P_b	G_{mb}
1	4.81	2.390
2	5.33	2.403
3	6.21	2.369
4	5.42	2.350
5	5.34	2.353
1	4.81	2.390
Centroid	*5.44*	*2.373*



Back-calculation method

Inputs		
G_{sb}	2.580	
G_{se}	2.697	
G_b	1.020	
$V_a(min, max)$	3	5
$VMA\ (min, max)$	12	14
$VFA\ (min, max)$	65	80

Vertex	P_b	G_{mb}
1	4.90	2.386
2	5.42	2.399
3	6.30	2.366
4	5.51	2.347
5	5.42	2.350
1	4.90	2.386
Centroid	*5.51*	*2.370*



Notes:For asphalt mixtures from 25% to 70% RAP, an asphalt density of 1.020 gr/cm^3 was used in accordance with the recommendation made by Mc Daniels (2001). In this study the residual asphalt density of RAP was not measure.