Influence of Crumb Rubber Gradation on Asphalt-Rubber Properties

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ABSTRACT: *Asphalt rubber is a material produced by the incorporation of crumb rubber obtained from ground tires in straight asphalt and its properties are influenced by the components properties. The crumb rubber gradation is one of the variables which have a significant influence on asphalt rubber properties. Thus, this work studies the influence of crumb rubber gradation on the asphalt rubber properties expressed by penetration, rotational viscosity (using the Brookfield viscometer), resilience and softening point. Test samples were produced with a 50/70 penetration grade straight asphalt and a crumb rubber obtained by the grinding process which basically consists in a tearing and crushing the old tires at ambient temperature. The digestion time was 60 minutes and the digestion temperature was 170 ºC. The results show that the rotational viscosity and the resilience are the properties most affected by the crumb rubber. It was also observed that the increase of the crumb rubber specific surface (fine crumb rubber) produces asphalt rubber with higher viscosity and lower resilience. The use of coarse crumb rubber influences mainly the resilience.*

KEY WORDS: *asphalt-rubber, crumb rubber, rubber gradation*

1. Introduction

Improving the characteristics of straight asphalts used in the asphalt hot mixes is necessary to increase the design life and reduce the maintenance costs of flexible pavements. This can be attained with the incorporation of crumb rubber in straight binders, which results in a product known as asphalt-rubber binder.

Asphalt-rubber binders are obtained by the incorporation of crumb rubber from ground tires in straight asphalt under certain conditions of time and temperature. There are three processes to produce asphalt-rubber: wet process, dry process and terminal blending (Takallou and Takallou, 2003).

The properties of asphalt-rubber binders produced by wet process depend basically on the characteristics of both crumb rubber and straight asphalt used in the process (Dantas Neto, 2004). It can be observed that the grain size distribution of crumb rubber used to produce the asphalt-rubber binders is one of parameters that has a great influence on the physical properties of these modified binders.

The influence of crumb rubber gradation on the behavior of asphalt-rubber binders can be related to intensity of chemical reactions that occurs between rubber particles and straight asphalt during the manufacturing process. Thus, the objective of this paper is to present the results obtained from laboratory tests that show the influence of crumb rubber gradation on the physical properties (penetration, rotational viscosity, softening point and resilience) of asphalt-rubber samples produced in laboratory by wet process.

The asphalt-rubber samples produced in laboratory were obtained from a 50/70 penetration grade straight binder (AC 50/70) and a crumb rubber obtained by the grinding process (Dantas Neto, 2004). The digestion time was 60 minutes and the digestion temperature was 170ºC.

2. Crumb rubber obtained from used ground tires

The primary component of crumb rubber obtained from ground tires used to produce asphalt-rubber binders is the natural rubber. Natural rubber is obtained from extraction of latex found in a plant called *Hevea Brasiliensis*. The first records about use of natural rubber were reported by Spanish sailors in the beginning of the XVIth century, when they observed indians playing with latex balls made (Costa *et al.*, 2003).

The novelty was introduced in Europe, but the application of natural rubber was very restrict, since it was soft at high temperatures and very rigid at low temperatures (Costa *et al.*, 2003). Only after many efforts, Faraday, in 1826, established the chemical structure of natural rubber as being a polymer $(C_5H_8)_n$.

The instability problem of natural rubber with the variation of temperature was accidentally solved in 1840 when Charles Goodyear, in the USA, and Thomas Hancock, in England, established the heating time and temperature that lead to stabilization of natural rubber with the addition of sulfur (Costa *et al.*, 2003). This process, known as vulcanization, also turned the natural rubber chemically more resistant. The process of vulcanization of natural rubber allowed the implantation of first vulcanized rubber plants between 1820 and 1830.

In the 1860's, Greville started the studies to produce synthetic rubber, one of constituents of crumb rubber used to obtain asphalt-rubber binders. However, synthetic rubber was produced only in 1857, when Euller obtained the isoprene in laboratory.

2.1. Manufacturing processes

The crumb rubber from used ground tires can be produced by two processes: grinding process at ambient temperature or cryogenic process.

The grinding process is basically tearing and crushing the old tires at the ambient temperature. A combination of grinders or granulators followed by sieves, transport conveyers and different kinds of magnets are used to crush and extract the steel of the carcass, as shown in Figure 1.

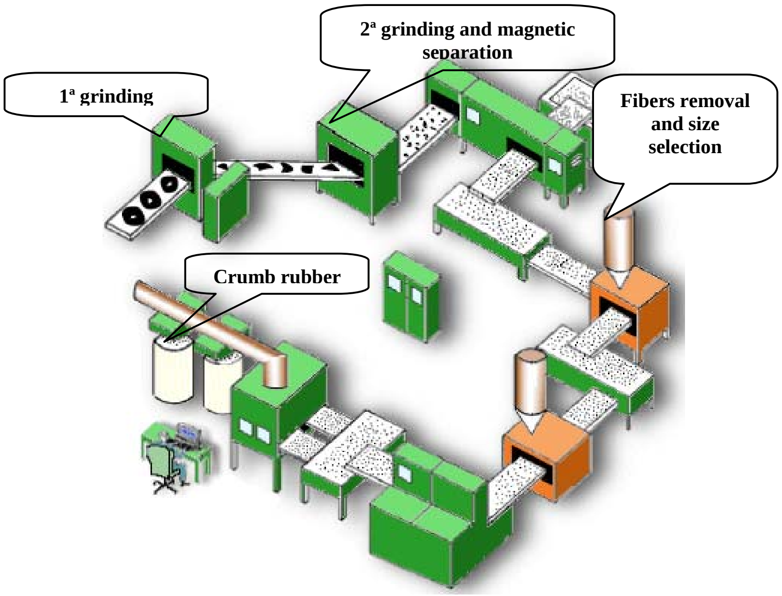

Figure 1. *Grinding process at ambient temperature*

The grinding process method has been widely adopted and is also the most productive. The final product is generally an irregular particle with high specific surface, as can be observed in Figure 2. When working with granulators, more regular particles with lower specific surface can be obtained.

Figure 2. *Crumb rubber obtained by grinding process*

The cryogenic process is carried at very low temperatures (-87°C to –198°C). In this case, the rubber of the tires is dipped into liquid nitrogen. At very low temperatures, the rubber becomes very brittle and it can be easily broken apart on a press, into the desired particles dimension. These particles of crumb rubber are more regular and have lower specific surface than the ones obtained by the grinding process, as can be observed in Figure 3.

Figure 3. *Crumb rubber obtained from cryogenic process*

Figure 4 shows the steps of the cryogenic process used to obtain crumb rubber from used ground tires. This process begins with the fragmentation of used tires and steel removal (Figure 4a). The following step consists of the application of liquid nitrogen to the pieces of tires obtained from previous step in the cryogenic tunneling (Figure 4b). Then, the frozen pieces of tires are carried to the granulators (Figure 4c) where the crumb rubber is obtained with a given grain size distribution. The final step of cryogenic process consists of the removal of textile and steel fibers (Figure 4d).

(a) Tires fragmentation (b) Cryogenic tunnel

(c) Granulators (d) Final step

Figure 4. *Grinding by cryogenic process*

4. Asphalt-rubber: manufacturing processes

According to ASTM D6114/97, the asphalt-rubber binders are obtained from a combination of straight asphalt, crumb rubber recycled from used ground tires and others additives, as necessary. These additives are normally extender oils used to improve the workability of asphalt-rubber or the compatibility between the straight binder and the crumb rubber used.

The use of binders modified with rubber started in the 1940’s. However, only in the 1960’s the process of manufacturing asphalt-rubber known as wet process or McDonald process was developed and patented by Engineer Charles McDonald. There are three processes for producing asphalt-rubber, known as the wet process, the dry process and the terminal blending (Takallou and Takallou, 2003).

In the wet process, shown in Figure 5, the straight binder is initially pre-heated to around 190^{o}C in a tank under hermetic conditions and then transported to a blending tank, where crumb rubber is added. The digestion process, which is the incorporation of rubber in the conventional binder, continues for a period of 1 to 4 hours, at a temperature of 190^{o}C. The process is facilitated by a mechanical agitation produced by a horizontal shaft (Visser, 2000).

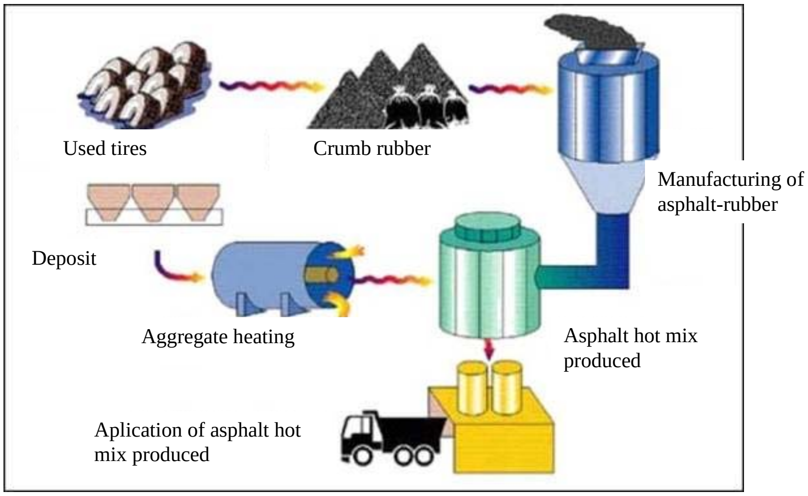

Figure 5. *Steps of wet process*

In the dry process, shown in Figure 6, particles of crumb rubber are added to preheated mineral aggregates before the addition of the straight bituminous binder (Visser, 2000). Aggregates are heated to temperatures of approximately 200^{o}C, then crumb rubber is added and mixed for about 15 seconds until a homogeneous mixture is obtained. Straight binder is then added in a conventional mixing plant.

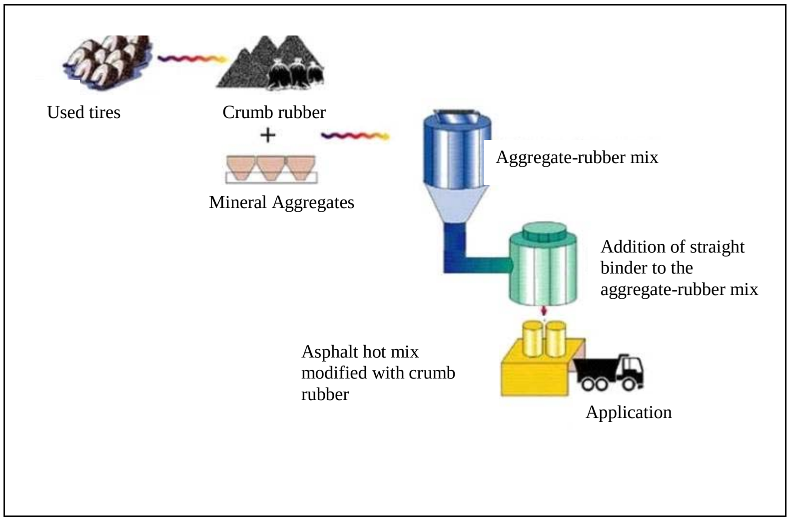

Figure 6. *Steps of dry process*

In the dry process, modified mixes rather than modified binders are produced, since there is little digestion of the rubber by the conventional binder. The time of contact between the rubber and the binder in the dry process is relatively short and not enough to produce all necessary reactions between the two materials. The dry process does not fit the conventional definition of asphalt-rubber binders, and the product would be more appropriately described as aggregate-rubber.

In the terminal blending process the digestion of crumb rubber into straight binder occurs at high temperature. This process has been used in Texas since 1989 and its main characteristic is to use lower crumb rubber contents than the wet process (Takallou and Takallou, 2003).

Physical properties of asphalt binders are generally expressed in terms of penetration grade, softening point, thermal susceptibility, viscosity and ductility, among others. Previous studies (Anderson *et al.*, 2000) with asphalt-rubbers, incorporating up to 20% of crumb rubber by weight, have demonstrated that there is an increase in viscosity in comparison with conventional binders. Other studies (Sebaaly *et al.*, 2000) show that the incorporation of rubber into asphalt binders enhances their viscoelastic properties.

3. Materials

Crumb rubbers with three different grain size distributions, recycled from unserviceable tires using the ambient grinding process, were used in this work. They were constituted approximately by 20% from truck tires and the remaining 80% from passenger vehicles of different types and origins. Figure 7 shows the grain size distribution curves for these three rubber types as described in Table 1. The grade envelope, prescribed by Arizona Department of Transportation (ADOT) for crumb rubber to be used in the production of asphalt-rubber, is also shown in the Figure 7.

Table 1. *Grain size distributions*

Sieve size		%Passing				
inch	mm	ADOT		CRM_1	CRM_2	CRM_3
Nº 4	4,75	100	100	100	100	100
Nº 8	2,36	100	100	99,9	77	66,7
Nº 10	2,00	100	100	96,8	59,6	44,1
Nº 16	1,18	65	100	47,7	31,1	31
Nº 30	0,60	20	100	18,7	15,5	15,6
Nº 50	0,30	0	45	7,5	5,5	6,2
Nº200	0,075	0	5	0	0	0

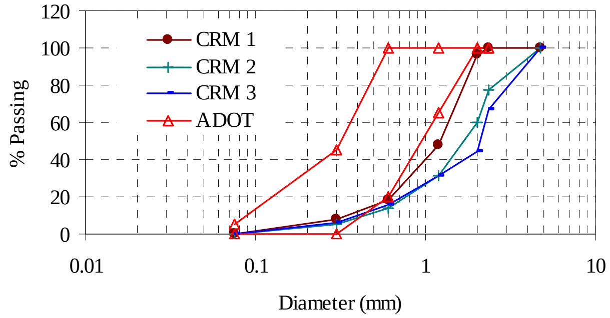

Figure 7. *Grain size distribution curves for the crumb rubbers.*

The three crumb rubber samples used in this work and previously described present the following specific surface: CRM1=7.53 m²/kg, CRM2=5.74 m²/kg and CRM3=5.79 m²/kg. These values were computed from grain size distribution curves of crumb rubber samples using the following equation (Dantas Neto, 2004):

$$\xi = \sum \left(\frac{6}{d_{i-j}} .P_{i-j} \right)$$

Where:
ξ: specific surface (m²/kg);
P_{i-j}: percent of material retained between sieves *i* and *j*;
d_{i-j}: geometric average diameter of material retained between sieves *i* and *j* (m);
ρ: specific mass of the crumb rubber (kg/m³).

The specific mass determined for the crumb rubber was 1.15 kg/m³, and the average diameter of retained material between *i* and *j* sieves was computed by the following equation (Dantas Neto, 2004):

$$d_{i-j} = \sqrt{d_i .d_j}$$

where:
d_i: mesh of sieve *i* (m);
d_j: mesh of sieve *j* (m).

A straight asphalt of penetration grade 50/70 was used to mix with the crumb rubbers previously described. Table 2 presents the results of standard characterization tests preformed for the conventional binder.

Table 2. *Characterization of the conventional binder*

PHYSICAL PROPERTIES	**50/70**
Penetration, ASTM D 5-95 (1/10 mm)	52,0
Softening point, ASTM D36-97 (ºC)	50,6
Brookfield viscosity at 175ºC, ASTM D 4402-87 (cP)	87,5
Resilience, ASTM D5329 (%)	14,0

4. Asphalt-rubber: production, tests, results and discussion

4.1. Production of different types of asphalt-rubber and testing methods

The following straight binder and crumb rubber combinations were used to produce asphalt-rubber samples using the wet process:

- Combination C_1: binder AC 50/70 + CRM_1;
- Combination C_2: binder AC 50/70 + CRM_2;
- Combination C_3: binder AC 50/70 + CRM_3.

All asphalt-rubber samples studied were produced with the following characteristics:

- Crumb rubber content: 21%;
- Digestion time: 15, 30, 45, 60, 120, 180, 240 and 300 minutes;
- Temperature of digestion: 170ºC.

The following tests were performed to study the physical properties of the asphalt-rubbers samples produced for this research:

- Penetration (ASTM D5);
- Softening point (ASTM D36);
- Resilience (ASTM D5329);
- Rotational viscosity using Brookfield viscometer (ASTM D2196).

Figure 8 shows the equipments used in the production of asphalt-rubber binders. These comprise an oven, equipped with temperature control system, and an assembly of engine and paddle that facilitates the mixture between the conventional binder and the crumb rubber. Table 3 presents the target values specified in ASTM D0114-97 for asphalt binders modified with crumb rubber recycled from unserviceable tires.

Table 3. *Target physical properties of asphalt-rubber (ASTM D0114-97)*

Physical property	**Unit**	**Range**
Apparent Brookfield viscosity, 175ºC (ASTM D2196)	cP	1500 - 5000
Penetration, 25ºC, 100g, 5s (ASTM D5)	1/10 mm	25-75
Softening point (ASTM D36)	ºC	> 57,2
Resilience, 25ºC (ASTM D5329)	%	> 25

Figure 8. *Equipment used for the production of asphalt-rubber binders*

4.2. Results and discussion

The proposed testing programme was not concluded for C_1 and C_2 asphalt-rubber because samples presented an extremely high viscosity after 180 minutes digestion time which did not allow mixing the asphalt with the rubber. For these two combinations there are results up to 180 minutes digestion time.

Figure 9 present the results of penetration tests performed in both the straight asphalt (AC 50/70) and asphalt-rubber samples studied (C_1, C_2 and C_3). The results show a reduction of penetration of asphalt-rubber samples in relation to straight binder samples at same conditions of digestion time and temperature. Besides, no significant differences were observed between penetration values of asphalt-rubber samples studied. Thus, it can be concluded that the grain size distribution of crumb rubber did not influence the penetration values of asphalt-rubber binders. It can also be observed that while penetration values decrease with digestion time for the straight asphalt, there is an increase in the penetration values of the asphalt-rubber binders. Stiffening of the straight binder is explained by the volatilization of oils. Softening of the asphalt-rubber binders may be due to depolymerization of the crumb rubber particles for longer digestion periods.

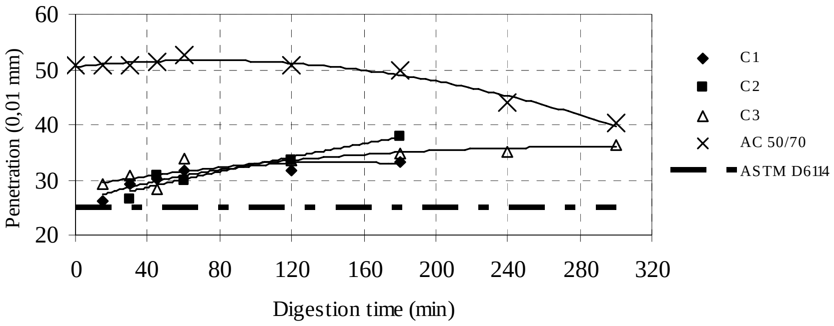

Figure 9. *Results of penetration tests*

The results of rotational viscosity (Figure 10) measured by Brookfield viscometer show that asphalt-rubber samples produced with C_2 and C_3 combinations presented less absolute viscosity than those produced with C_1 combination. This suggests that the increase of specific surface of crumb rubber used to produce the asphalt-rubber samples leads to an increase of rotational viscosity of asphalt-rubber samples.

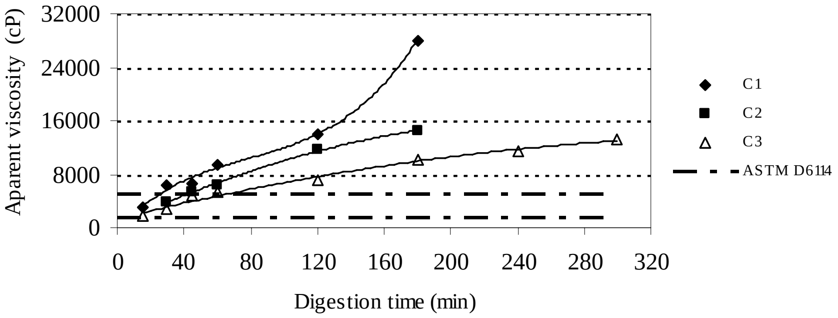

Figure 10. *Results of rotational viscosity tests at 170ºC*

The decrease of rotational viscosity with the increase of specific surface of crumb rubber can be explained by the decrease of contact area, and consequently of the possible chemical reactions, between straight asphalt and rubber particles. Figure 10 also shows that for a crumb rubber content of 21% and the use of CRM_1 rubber it would be necessary to reduce the digestion time used to produce asphalt-rubber samples with rotational viscosity within the limits specified by ASTM D6114.

Figure 11 shows that the increase of specific surface of crumb rubber also produces an increase of softening point of asphalt-rubber samples. The results of softening point tests for the asphalt-rubber binders produced with CRM_2 and CRM_3 were very close. This can be explained because these types of crumb rubber present approximately the same grain size distribution as can be observed in Figure 7.

The results of softening point tests show that all asphalt-rubber tested present softening point complying with the specifications of ASTM D6114. It can also be observed that there was an increase of softening point of both straight and modified binders with the digestion time. For the modified binder there seems to exist an optimal digestion time with respect to this property, which was around 180 minutes.

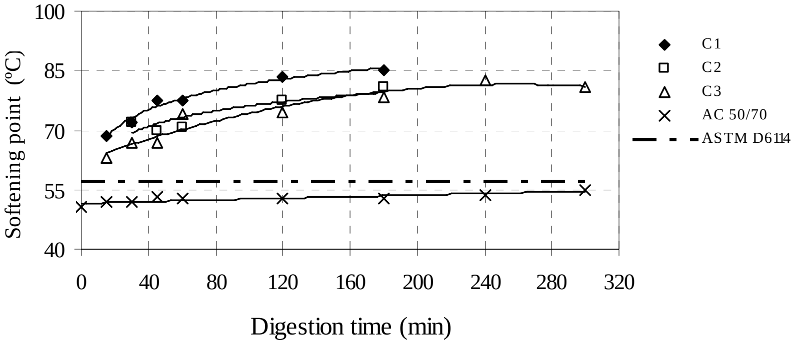

Figure 11. *Results of softening point tests*

Figure 12 show the results of resilience tests carried with asphalt-rubber samples produced with CRM_1, CRM_2 and CRM_3 crumb rubbers. These results show that for digestion times shorter than 120 minutes the increase of specific surface results in an increase of resilience of asphalt-rubber samples tested. For digestion time longer than 120 minutes no significant differences were observed for different grain size distribution of the crumb rubber used to produce the asphalt-rubber samples. The reason for this behavior is possibly related to the degradation of rubber particles that occurs at higher digestion times and temperatures (Dantas Neto, 2004).

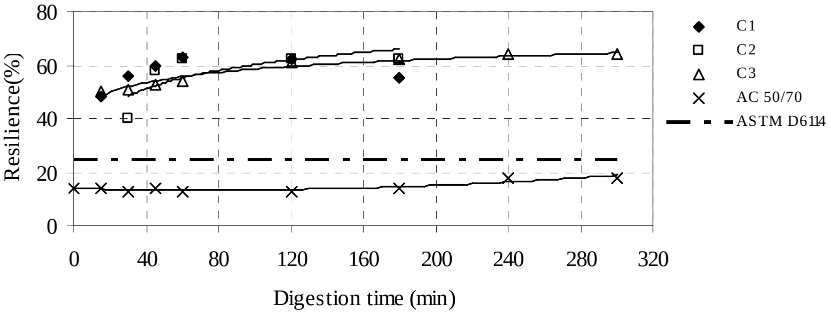

Figure 12. *Results of resilience tests*

The results of resilience tests indicate that degradation of crumb rubber occurred with less intensity in the asphalt-rubber samples produced with CRM_2 and CRM_3. This process of degradation that are possibly occurring affect the elastic recovery of asphalt-rubber submitted to compression loads once since in the resilience test specified by ASTM D5329 the samples are submitted to compression load. However, the elastic recovery of asphalt binders submitted to tensile tests may be affected in a different way. Perhaps such tests can better evaluate the behavior of asphalt hot mixes produced with these modified binders (Dantas Neto, 2004).

5. Conclusions

The results presented in this paper show that the manufacturing process of asphalt-rubber samples in laboratory produce some kind of oxidation in the straight binder used. This can be observed by the decrease of penetration and increase of softening point of straight asphalt samples tested and submitted to high digestion times.

The tests with asphalt-rubber samples show that the physical properties of asphalt-rubber are influenced by the variation of grain size distribution of crumb rubber used to produce these modified binders. It can be observed that the increase of specific surface (smaller particles) produced increases of rotational viscosity, softening point and resiliente of asphalt-rubber samples tested.

The increase of specific surface and consequently of contact area between rubber particles and straight asphalt contribute to the process of absorption of the light fractions of straight binders by the rubber particles (Epps, 1977).

A complete analysis of influence of grain size distribution on behavior of the asphalt-rubber binders must be complemented with the study of mechanical properties of asphalt hot mixes made with asphalt-rubber binders produced with crumb rubber of different gradations.

6. Acknowledgements

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