Structural Analysis of Hot-Mix Asphalt Samples Containing Ashes of Pinus Wood Skin Burned for the Production of Medium Density Fiberboard (MDF) Wooden Panels

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ABSTRACT: The industrial production of MDF – Medium Density Fiberboard – uses Pine trees bark as a fuel, which, after the burning process, generates a fine gradation residue, an ash that is an environmental problem due to the high content of some substances, above the quantity allowed by the NBR 10004:2004, which classifies it as a class II-A – non-inert product. The production of 1 m3 of MDF generates approximately 2.5 kg of ash, which can be compared to the production of MDF in Brazil in 2005 and 2006, that was, respectively, 1.4 and 1.7 millions of m3.The general purpose of this work is to test the hypothesis that the ash – residue can be used as a filler in hot-mix asphalt. Mechanical properties of asphalt mixtures containing ash – residue are compared to the ones obtained with asphalt mixtures produced with mineral filler from basalt rock, through the following laboratory tests: indirect tension, resilient modulus, fatigue life, moisture susceptibility and Marshall stability and flow. It is also performed a mechanistic analysis based on laboratory test results. The Marshall mix design for mixtures containing the ash – residue resulted in binder content approximately constant for both residue contents considered in this work, 3.5% and 6.0%. The indirect tension test results showed higher values for mixtures containing 3.5% of mineral filler, being the lowest values associated to mixtures that use ash - residue. The higher the filler content, the higher the resilient modulus and mixtures with mineral filler presented higher resilient modulus values. Only the mixture with 6.0% of mineral filler passed the moisture susceptibility test. Based on the mechanistic analysis, it can be concluded that it is possible the use of the ash- residue as a filler for hot-mix asphalt, particularly for thinner pavement structures, using lower resilient modulus materials. Under these structural conditions the asphalt mixture with 3.5% of ash - residue presented better behavior than the mixture with 6.0% of mineral filler.

KEY WORDS: Hot-mix asphalt, mineral filler, solid waste, ashes, reuse.

1 INTRODUCTION

The MDF (Medium-Density Fiberboard) is, among panels made of wood, one of the most technologically advanced. It is formed by pressing the dried and unlimbered wood with synthetic resin, usually urea-formaldehyde, and also smaller quantities of other additives. It is a relatively new product that was manufactured for the first time in the early 60's in the United States. In the mid 70's it arrived to Europe, where it was initially produced in the German

Democratic Republic and later on it was introduced into Western Europe through Spain. In Brazil, the industry first started the production of MDF in 1997.

Actually, the Brazilian market for forest products is extremely attractive, showing high rates of growth. The panels' industry is of relevant importance to the Brazilian economy, not only for the generation of jobs, but also due to the dynamism that it irradiates, especially for the furniture sector and building construction. According to ABIPA - Brazilian Association of Panels Wood Industry, the production of MDF in the years 2005 and 2006 was, respectively, 1.4 and 1.7 million m3.

Sustainable development aims at matching economic development to environment preservation. The recovery and recycling of residues, to be used in other processes or products, are alternatives that should be developed. Although it is important to emphasize the very satisfactory results obtained with reforestation species, the industrial process for the manufacture of MDF uses Pine trees bark as a fuel, what, after the burning, generated a waste, ash, with very fine particles, classified as a Residue Class II – non-inert according to a Brazilian Environmental Agency. Currently, the ashes are improperly dumped on reforestation fields. The reuse of this ash can bring benefits to the environment and also to the industries, reducing the pollution and the quantity of natural resources used, as well as minimizing the problem of final destination of the waste, because the removal of ashes to industrial landfills increases the final cost of the product.

The Brazilian road network, according to the Brazilian Confederation of Transport, in its several levels (federal, state and municipal), is approximately 1.6 million kilometers, but only 196 thousand km are paved. The lack of paved highways and the large amount of residue generated by the MDF industry motivated this research work that aims at the use of the ashes as mineral filler in hot-mix asphalt.

2 ASHES GENERATED DURING THE PRODUCTION OF WOOD PANELS

The use of timber products and derivatives presents a number of advantages over other construction materials: it is a renewable material, widely available, biodegradable or durable, depending on the treatment to which it is submitted, recyclable and that immobilize carbon from the atmosphere in its structure. In turn, the use of the wood-based panels keeps many advantages of solid wood, adding others as: the dimensions of the panels are not strictly related to the size of the trees; it can add value to materials of low acceptance, like residues from sawmills and thinning; it is much more homogeneous than sawn wood (Maloney, 1989).

There is, globally, with the replacement of native forests by planted forests, a significant increase in production and consumption of wood-based panels. The MDF is intended mainly for furniture, particularly for parts that require special care. In construction the MDF can be used as thin floors, footers, pillows' doors, walls etc.

The process of producing MDF includes: mechanical reduction of wood to chips, fibers refining, drying, mixture of fiber with resin, formation of a material with a resin mattress and hot pressing. In the process of MDF production all parts of the wood are used, i.e., the Pine trees bark is used as a fuel for the generation of energy consumed for the following purposes: heating water to generate steam used to transform wood into chips; heating the air used to dry the fibers; heating the oil used in the densification process of MDF.

However, the burning of biomass is incomplete, generating ash, which stays suspended in air, being captured by multi cyclones positioned next to the burning ovens. Moreover, the ash has become an environmental problem, because of the content of phenols, manganese and sulfate in quantities above the permitted by the Brazilian environmental regulation, and it is classified as Residue Class II - not inert.

3 MINERAL FILLER IN HOT-MIX ASPHALT

Mineral fillers are inert materials, finely divided, passing at least 65% in the # 200 sieve (0.075 mm). There are two main points of view about the influence of the type of filler on the asphalt binder (Santana, 1995): mastic with total filler (according to Ruiz) and mastic with active filler (according to Puzinauskas). In the view of Ruiz, all particles of filler are in suspension in the asphalt and its particles do not touch each other, forming homogeneous mastic. From Puzinauskas´ point of view, part of the filler still behaves like a very fine aggregate and its particles touch each other forming a mineral skeleton, while the other part is in suspension, forming the mastic.

Craus et al. (1978) consider two forms of action of filler in hot-mix asphalt:

- the larger particles fill the voids in the mineral aggregates, increasing the points of contact among larger particles and increasing the mixture strength;
- the smaller particles are mixed with the asphalt binder, increasing its consistency, cementing the larger particles and constituting the mastic.

AASHTO (1991) shows that an ultra-thin filler, with significant percentage of material smaller than 20 μm and even with some portion smaller than 5 μm, can be incorporated into the asphalt binder, involving particles of aggregates. Otherwise, if most of the mineral filler is relatively large, it fills the voids in the mineral skeleton and it changes the content of asphalt binder.

The nature, chemical and physical properties, and the content of filler in the mixture have direct effect on the mechanical properties of hot-mix asphalt (Kavussi and Hicks, 1997). To prevent the damages caused by the excess or the lack of mineral filler, McGennis et al. (1994) stipulated the ratio by weight between the filler and the asphalt binder, the so called "dust proportion", which must be between 0.6 and 1.8 for all sorts of mixture.

4 MATERIALS

4.1 Asphalt Binder

It was used an AC 50/70, classified by Penetration Test result, whose properties, obtained from laboratory tests performed at one of Petrobras refineries (REVAP – located in the city of Sao Jose dos Campos, State of Sao Paulo, Brazil), are presented in Table 1.

4.2 Aggregates

It was used a basaltic aggregate, from the quarry Bandeirantes, located in the city of Sao Carlos, State of Sao Paulo, Brazil. The test results are presented in Table 2, and the grain-size analysis is presented in Figure 1.

4.3 Ash-Residue

The ash – residue from the burning of the Pine trees bark for the manufacture of MDF (Medium-Density Fiberboard) presents fine gradation and it is classified as a filler for hot-mix asphalt. It was used a residue collected at Duratex Co., located in the city of Agudos, State of Sao Paulo, Brazil.

The material was tested for specific gravity determination, but it fluctuated in kerosene, which has average specific gravity of 0.8. In another attempt, with other low- gravity liquid, alcohol, the residue also fluctuated. It was decided then to perform the helium pycnometry test, which is not generally performed in road and paving laboratories. It was followed the ISO 1183-3 - "Plastics - Methods for determining the gravity of non-cellular plastics - Part 3: Gas pycnometer method" and the test was conducted at the Center for Development and Characterization of Materials - CCDM, Federal University of Sao Carlos. Table 3 shows the values of five measures and the average gravity of the residue - ash.

Table1: Characterization of the AC 50/70 Asphalt Binder.

Property	Result	Specification
Penetration	6.2 mm	5.0 to 7.0
Softening Point	47.5ºC	46 minimum
Brookfield Viscosity @ 135ºC	336 cP	274 minimum
Brookfield Viscosity @ 150ºC	168 cP	112 minimum
Brookfield Viscosity @ 177ºC	62 cP	57 to 285
RTFOT Penetration Retained	56%	55 minimum
RTFOT Increasing in Softening Point	4.3ºC	8 maximum
RTFOT Ductility @ 25ºC	>150 cm	20 minimum
RTFOT Mass Loss	0.270%	0.5 maximum
Solubility in Trichloroethylene	100%	99,5 minimum
Ductility @ 25ºC	>150 cm	60 minimum
Safety Test (Flash Point)	298ºC	235 minimum
Thermal Susceptibility Index	-1.3	-1.5 to 0.7
Specific Gravity	1.013	-

Table2: Characteristics of the Basaltic Aggregates.

Test	Stone 1	Intermediate	Dust	Mineral Filler
Apparent Specific Gravity (g/cm^3)	2.965	2.976	3.068	2.853
Bulk Specific Gravity (g/cm^3)	2.828	2.810	2.844	-
Absorption (%)	1.635	1.986	2.570	-

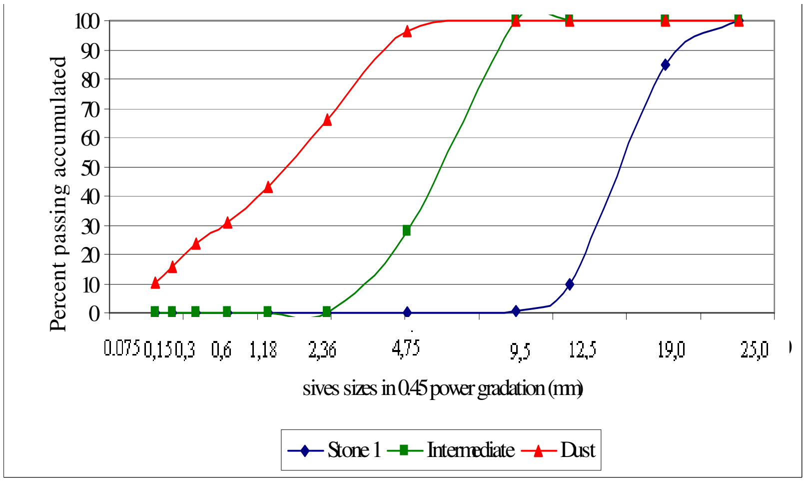


Figure1: Gradation of the Aggregates.

Table3: Ash - residue specific gravity.

Test Results					Average
1	2	3	4	5	
2.463	2.343	2.286	2.264	2.256	2.322±0.086

5 METHOD

5.1 Gradation Curves of Hot-Mix Asphalt

The gradation curves respected the Superpave control points and passed above the restrictive zone. Two filler contents were considered: 3.5% and 6.0% of material passing the 0.075 mm sieve (Table 4).

Table4: Gradation Curves: Above the Restrictive Zone (3.5 and 6.0% of filler).

Sieve Size (mm)	Percent Passing (with 3.5% of filler)	Percent Passing (with 6.0% of filler)
25	100	100
19	95	95
12.5	85	85
9.5	75	75
4.75	55	55
2.36	40	40
1.18	30	30
0.6	21	21
0.3	16	16
0.15	10	10
0.075	3,5	6,0

5.2 Exploratory Tests

The replacement of mineral filler by ash – residue was done in terms of volume, i.e., keeping constant the volume of filler. After the Theoretical Maximum Density determination through the Rice Method, which gave a specific gravity value for the ash – residue around 0.8, the replacement was established in terms of the ratio 1:3 (ash – residue : mineral filler) for replacement by weight. The optimum asphalt binder content obtained was 6.2 and 6.3% respectively for ash - residue content of 3.5 and 6.0%.

5.3 Marshal Mix Design

The optimum asphalt binder, corresponding to a volume of air voids of 4%, and the parameters of the Marshall Mix Design are presented in Tables 5 and 6, respectively for 3.5% and 6.0% of mineral filler. The optimum asphalt binder content was 5.85% and 5.00%, respectively for 3.5% and 6.0% of mineral filler.

Table5: Marshall Mix Design for filler content of 3.5%.

% AC	Density	Vv (%)	VMA (%)	VFA (%)	Stability(N)	Flow (mm)
4.0	2.456	7.839	17.5	55.3	11,800	2.2
4.5	2.444	7.464	18.3	59.3	10,525	2.3
5.0	2.448	6.509	18.6	65.0	10,875	2.7
5.5	2.464	5.194	18.6	72.0	10,057	2.2
6.0	2.494	3.406	18.2	81.3	10,585	2.9

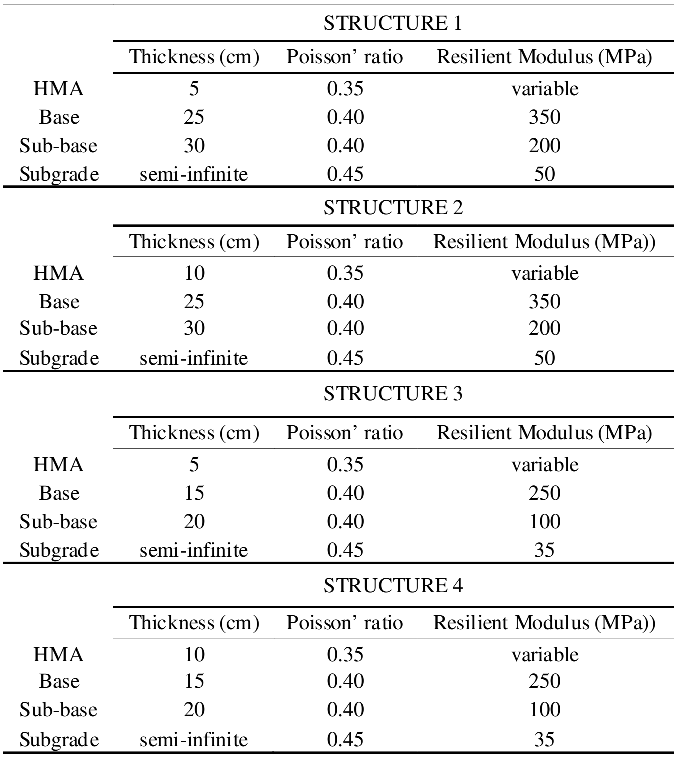
Table6: Marshall Mix Design for filler content of 6.0%.

% AC	Density	Vv (%)	VMA (%)	VFA (%)	Stability(N)	Flow (mm)
4.0	2.462	7.427	17.2	56.7	12,155	2.5
4.5	2.478	6.014	17.0	64.8	13,075	2.8
5.0	2.513	4.013	16.4	75.6	13,050	3.3
5.5	2.521	3.013	16.7	82.0	13,300	2.5
6.0	2.525	2.330	17.3	86.5	10,925	2.7

5.4 Mechanistic Analysis

The performance of hot-mix asphalt surface layers in terms of fatigue life was predicted based on mechanistic analysis performed with four pavement structures, whose mechanical properties are presented in Table 7. It should be noted that structures 1 and 2 show greater base and sub-base thickness and resilient modulus than structures 3 and 4. The surface layer resilient modulus and fatigue life were obtained from laboratory tests.

Table7: Characteristics of the structures used for the mechanistic analysis.



	STRUCTURE 1		
	Thickness (cm)	Poisson' ratio	Resilient Modulus (MPa)
HMA	5	0.35	variable
Base	25	0.40	350
Sub-base	30	0.40	200
Subgrade	semi-infinite	0.45	50
	STRUCTURE 2		
	Thickness (cm)	Poisson' ratio	Resilient Modulus (MPa))
HMA	10	0.35	variable
Base	25	0.40	350
Sub-base	30	0.40	200
Subgrade	semi-infinite	0.45	50
	STRUCTURE 3		
	Thickness (cm)	Poisson' ratio	Resilient Modulus (MPa)
HMA	5	0.35	variable
Base	15	0.40	250
Sub-base	20	0.40	100
Subgrade	semi-infinite	0.45	35
	STRUCTURE 4		
	Thickness (cm)	Poisson' ratio	Resilient Modulus (MPa))
HMA	10	0.35	variable
Base	15	0.40	250
Sub-base	20	0.40	100
Subgrade	semi-infinite	0.45	35

6 RESULTS

6.1 Marshall Stability and Flow

The average of three Marshall Stability and Flow tests is presented in Table 8. Mixtures containing 6.0% of mineral fillers show the highest values of stability and flow, and mixtures with the ash – residue present small difference in the results for different filler content.

Table8: Average values of Marshall Stability and Flow.

Filler Content (%)	Stability (N)		Flow (mm)	
	Mineral Filler	Ash - Residue	Mineral Filler	Ash - Residue
3.5	10,430	8,590	2.69	2.34
6.0	13,050	8,650	3.33	2.47

6.2 Tensile Strength and Resilient Modulus

Table 9 presents the average of three indirect tension and resilient modulus test results, obtained through Brazilian Test (diametric compression). Mixtures containing mineral filler present higher tensile strength and resilient modulus than mixtures containing ash – residue.

Table9: Average Values of Indirect Tension and Resilient Modulus tests.

Filler Content (%)	Tensile Strength (MPa)		Resilient Modulus (MPa)	
	Mineral Filler	Ash - Residue	Mineral Filler	Ash - Residue
3.5	1.744	1.454	7,273	6,280
6.0	1.575	1.477	8,022	6,815

6.3 Moisture Susceptibility Test

The evaluation of moisture induced damage was done according to AASHTO T-283, which determines the retained tensile strength (RTS), i.e., the ratio between the tensile strength after the conditioning process and the tensile strength before the conditioning process. The minimum value for RTS is 80%. Based on the test results (Figure 2), only the mix containing 6.0% of mineral filler showed values of RTS higher than the minimum accepted value (80%), while mixtures containing the ash - residue showed more susceptibility to moisture induced damage.

6.4 Fatigue Life

The fatigue tests were conducted under controlled stress, with values of load corresponding to 10, 20, 30 and 40% of the tensile strength. The fatigue life models, obtained from laboratory tests with the analyzed mixtures, are presented in Table 10.

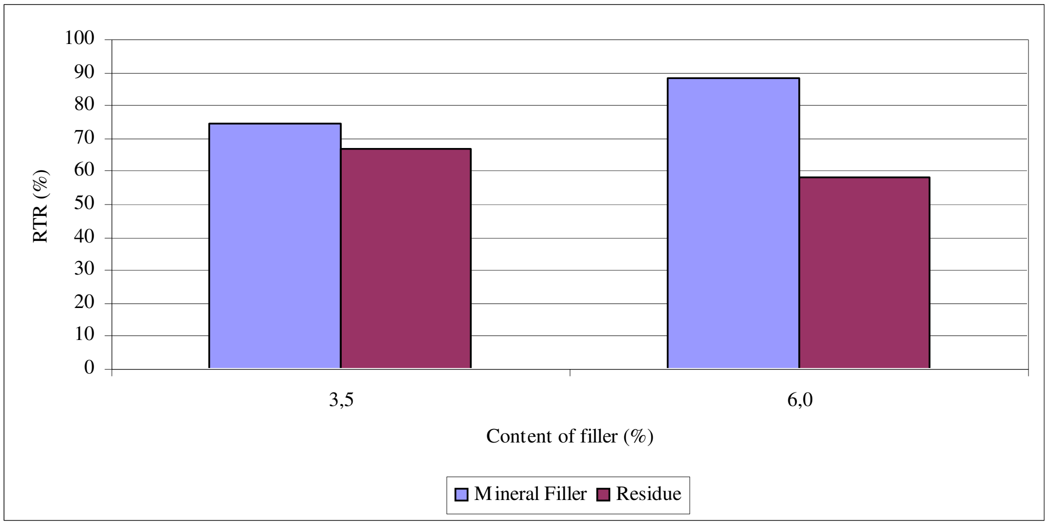


Figure2: Percent of retained tensile strength (AASHTO T-283) for different filler type and content.

Table10: Fatigue Life Models for difference of stresses and difference of strains.

Asphalt Mixtures	FATIGUE LIFE MODELS	
	According to difference of stresses	According to the strain
3.5% Mineral Filler	$N = 4087.1 \times \left(\frac{1}{\Delta\sigma}\right)^{3.2957}$	$N = 4 \times 10^{-12} \times \left(\frac{1}{\varepsilon_r}\right)^{3..3798}$
6.0% Mineral Filler	$N = 7139 \times \left(\frac{1}{\Delta\sigma}\right)^{3.527}$	$N = 3 \times 10^{-11} \times \left(\frac{1}{\varepsilon_r}\right)^{3.1729}$
3.5% Ash - Residue	$N = 2814.3 \times \left(\frac{1}{\Delta\sigma}\right)^{2.5928}$	$N = 5 \times 10^{-9} \times \left(\frac{1}{\varepsilon_r}\right)^{2.6723}$
6.0% Ash - Residue	$N = 2374.4 \times \left(\frac{1}{\Delta\sigma}\right)^{2.8568}$	$N = 2 \times 10^{-9} \times \left(\frac{1}{\varepsilon_r}\right)^{2.7021}$

6.5 Mechanistic Analysis

The structural evaluation of the four asphalt mixtures analyzed was based on mechanical properties (resilient modulus and fatigue life) obtained from laboratory tests. With the strain obtained with the computer program ELSYM5 it was possible to determine the parameters k3 and k4 and, mainly, the number of load applications to the rupture, i.e., the material fatigue life (Tables 11 to 14).

For all four analyzed structures, longer fatigue life was obtained with mixes containing 3.5% of residue (structures 3 and 4, lower thickness and stiffness) and 6.0% of mineral filler (structures 1 and 2, higher thickness and stiffness). For all structures, the hot mix asphalt that presents the worst result, i.e., the shortest fatigue life, was the mix with 6.0% of ash – residue.

Table11: Fatigue Life for the analyzed materials - Structure 1.

Mixtures	ε_r	k_3	k_4	N
3.5% ash - residue	5.4777E-05	5.0E-09	2.6723	1221
6.0% ash - residue	5.0001E-05	2.0E-09	2.7021	837
3.5% mineral filler	5.3486E-05	4.0E-12	3.3798	1096
6.0% mineral filler	4.8380E-05	3.0E-11	3.1729	1477

Table12: Fatigue Life for the analyzed materials - Structure 2.

Mixtures	ε_r	k_3	k_4	N
3.5% ash – residue	4.0272E-05	5.0E-09	2.672	2778
6.0% ash - residue	3.6158E-05	2.0E-09	2.702	2010
3.5% mineral filler	3.9938E-05	4.0E-12	3.380	2941
6.0% mineral filler	3.5322E-05	3.0E-11	3.173	4006

Table13: Fatigue Life for the analyzed materials - Structure 3.

Mixes	ε_r	k_3	k_4	N
3,5% resíduo	6,6887E-05	5,0E-09	2,672	716
6,0% resíduo	6,2009E-05	2,0E-09	2,702	468
3,5% fíler mineral	6,4764E-05	4,0E-12	3,380	574
6,0% fíler mineral	5,9995E-05	3,0E-11	3,173	746

Table14: Fatigue Life for the analyzed materials - Structure 4.

Mixes	ε_r	k_3	k_4	N
3,5% resíduo	5,9316E-05	5,0E-09	2,672	987
6,0% resíduo	5,4973E-05	2,0E-09	2,702	648
3,5% fíler mineral	5,8447E-05	4,0E-12	3,380	812
6,0% fíler mineral	5,3803E-05	3,0E-11	3,173	1054

7 CONCLUSIONS

Although the tensile strength results for the asphalt mixtures containing the ash - residue were inferior to the ones obtained by the mixtures containing mineral filler, they were superior to the recommended by Brazilian Highway Agencies, which implies that its use must continue being investigated.

Based on the mechanistic analysis, it can also be concluded that it is possible the use of the ash- residue as a filler for hot-mix asphalt, particularly for thinner pavement structures, using lower resilient modulus materials. Under these structural conditions the asphalt mixture with 3.5% of ash - residue presented better behavior than the mixture with 6.0% of mineral filler.

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