THE REUSE OF CONSTRUCTION AND DEMOLITION MATERIALS AS A SUBSTITUTE FOR PEBBLES TAKEN FROM RIVER BEDS IN THE AMAZON (BRAZIL) FOR USE AS AGGREGATE IN ASPHALT MIXTURES

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ABSTRACT: This research studied the structural behavior of pavements applying in the Amazon region, Brazil, reusing the construction and demolition waste (CDW) materials as aggregate in asphalt mixtures. This material was used to substitute the pebbles taken from the Amazon River bed, considering the removal these pebbles produces a negative impact on the environment. The influence of the fine part of the material in the structural behavior of the mixture was analyzed, according to the restricted zone in Superpave (Superior Performing Asphalt Pavements) aggregate gradation. Numerical analysis using the finite element method enabled the development of a viscoelastic model for the wearing surface and an elastic model for sub layers of the pavement. Three mixtures were tested, with regard to grain size distribution: Mixture 1 went above the restricted zone, with respect to that proposed by Superpave, Mixture 2 passed through the restricted zone and Mixture 3 was below this zone. The results showed that: (1) Mixture 1 and Mixture 3 are more susceptible to cracking from fatigue; (2) Mixture 2 is more susceptible to permanent deformation; (3) the fine part of the aggregates influences the structural behavior of the asphalt mixtures; (4) the utilization of CDW is a good alternative to replace the round pebbles removed from the Amazon River.

KEY WORDS: Asphalt, mixture, pebble, Amazon River, recycling, demolition waste, CDW, environment

1. INTRODUCTION

Manaus city, capital of the Amazon State in Brazil, is undergoing a major development in its civil construction sector; mainly due to the expansion in high-rise buildings. This process is generating a considerable amount of waste material, an average of 103 kg/hab/year of demolition waste. This CDW material originating from construction of buildings and demolition waste has a great impact on the environment. Regrettably, this material is not being recycled and incorporated as an aggregate in the construction process. In many parts of the world, the reuse and recycling of the waste materials generated by the construction sector [1-11] is being studied, as this practice will make a major contribution to the preservation of the environment, conservation of natural resources, and sustainable development.

Furthermore, Manaus, like other towns in the Amazon State, is known for its lack of natural deposits of aggregates, a significant obstacle to the construction of pavement and the production of asphalt concrete. The quarry deposits, in general, settle in the sedimentary rocks of the Paleozoic and Cenozoic. In the case of Manaus, these deposits arising from the Alter do Chão and constituted, in predominant form, from sandstones and siltstone of low mechanical resistance and degree of consolidation. The intense process of weathering, besides reducing the degree of consolidation of these rocks, creates a thick cover of residual soil, making it difficult to extract. Such natural characteristics, together with the great distances from other sources of aggregates and consequently high transportation costs, greatly raise the price of construction; the price of transportation is one of the main factors in the cost of construction materials.

In the last two decades this situation has become worse, which makes the development of new materials to adequately substitute the natural aggregates an urgent issue. The quarry deposits near the Manaus city have been entirely consumed and the solution to this lack of aggregates, proposed by the civil construction industry, was to use pebbles taken from the Amazon River bed. This has many different negative impacts on the Amazon environment.

1.1 Objectives and Scope

The primary objective was to study CDW aggregate as a substitute of this pebble material from river bed. The goal was to satisfy the principles of conservation of natural resources, preservation of the environment and the sustainable development of the Amazon region. We studied the use of aggregates produced from CDW as an alternative to substitute the use of this pebble material. We assessed the use of this waste material in the production of asphalt mixtures and its influence on the structural behavior of the pavements. The finite element method was used to develop a viscoelastic model for the asphalt wearing surface and an elastic model for the sub layers of the pavement.

2. THEORETICAL BASIS

The structural response of viscoelastic materials depends on the rate of application of the load (or displacement) and on time. That is why the constitutive relations of the viscoelastic materials are no longer algebraic relations (as in the case of elastic relations) and are represented, in the uniaxial case, by the Boltzmann convolution integrals:

$$\sigma(t) = \int_0^t E(t-\tau)\frac{\partial\varepsilon}{\partial\tau}\partial\tau \qquad (1)$$

$$\varepsilon(t) = \int_0^t D(t-\tau)\frac{\partial\sigma}{\partial\tau}\partial\tau \qquad (2)$$

where *E(t)* is the relaxation modulus, *D(t)* is the creep compliance, *t* is the time counted after any reference point, ε is the strain under the stress σ, and τ is the time elapsed since the start of the application of the load. Expressed by the equation $D(t) = \varepsilon(t)/\sigma_0$, the creep compliance is obtained by means of a simple test, based on the application of the constant axial stress σ_0. The modulus of relaxation is given by $E(t) = \sigma(t)/\varepsilon_0$ and is related to *D(t)* through Eq. (3) [12].

$$\int_0^t E(t-\tau)\frac{dD(\tau)}{d\tau}d\tau = 1 \text{ ,} \qquad \text{for t} \rangle\ 0 \qquad (3)$$

The constitutive viscoelastic relationships can be obtained from a mathematical description of the stress-strain data determined in the laboratory for the creep compliance and the relaxation modulus. The laboratory behavior is modeled by the Prony series, given by equations (4) and (5) for the creep compliance and relaxation modulus, respectively. Such equations take into account, respectively, the generalized models of Maxwell shown in Figure 1(a) and Voigt illustrated in Figure 1(b).

$$D(t) = D_0 + \sum_{i=1}^{N} D_i \left(1 - e^{-\frac{t}{\tau_i}} \right) \tag{4}$$

$$E(t) = E_\infty + \sum_{i=1}^{N} E_i \cdot e^{-\frac{t}{\rho_i}} \tag{5}$$

where D_0 , D_i , τ_i , E_∞ , E_i and ρ_i are the coefficients of the Prony series and N is the number of terms.

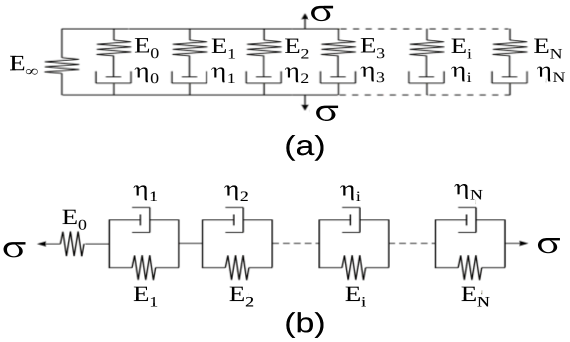
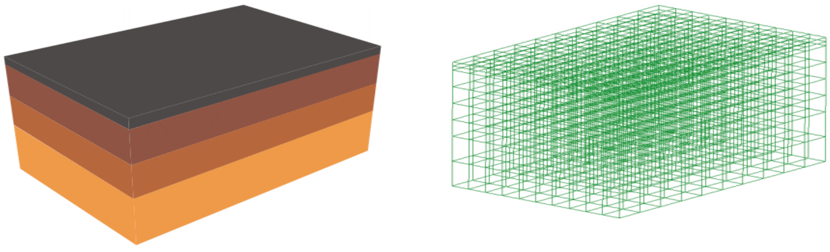


Figure 1. Viscoelastic models: (a) generalized Maxwell, (b) generalized Voigt

3. GEOMETRY, MATERIALS AND LOADING

3.1 Geometry

In the finite element method (FEM) simulation, the following thicknesses were adopted for the layers: 5 cm for asphalt surface, 20 cm for the base, 20 cm for the subbase, and 30 cm for the subgrade. In Figure 2(a) the geometry of the problem is shown while Figure 2(b) demonstrates the appropriate mesh of finite elements used to solve the problem. Eight node elements were used resulting in a total of 1089 nodes and 800 elements in the discretization of the pavement FEM model.



(a) (b)

Figure 2. (a) Geometry model of the problem; (b) Mesh of the finite element used.

3.2 Materials

<u>3.2.1 Construction and Demolition Waste Materials</u>: The CDW material samples collected from construction and demolition waste stockpiles in the city of Manaus, were taken to the processing plants, where the concrete was separated from the iron and ceramic materials. After these parts were separated, the concrete was crushed into small pieces to form the aggregate material. Three grain size distribution curves were selected in such a way that the results permit the evaluation of the influence of the fine aggregate material in the structural behavior of the asphalt mixtures made from this processed residue. Figure 3 shows the grain size distribution curves of the aggregate, which is stipulated to agree with the zone (restricted zone) proposed by the Superpave specifications [13]. Mixture 1 went above the restricted zone, Mixture 2 passed through the restricted zone and Mixture 3 went below this zone. Such dosages show the same quantity of coarse aggregate was used (the difference was only in the fine aggregate part).

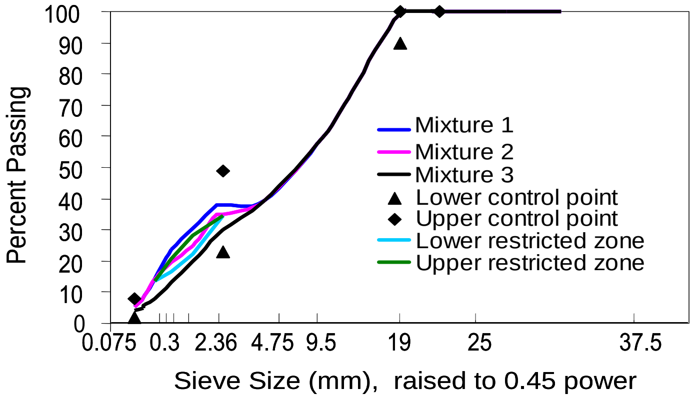


Figure 2. Grain size distribution curves of the processed residue for the utilization in asphalt mixtures

3.2.2 Asphalt layer: Table I shows the physical indexes of the asphalt mixtures, which were made with aggregates and filler of the processed residue, with 8% of asphalt binder. Considering the inherent variety of the asphalt mixture composite materials, the physical properties were practically same for all mixtures, despite the fact that Mixture 1 included a greater quantity of finer particles than Mixture 3. To proceed with the finite element analysis we needed to identify the mechanical properties of the mixtures via a static creep test, which was used due to its simplicity and facility of execution. The test results are shown in Figure 4. In this figure, Mixtures 1 and 3 share similar same results and larger deformations appeared for Mixture 2 compared to the others. As Mixtures 1 and 3 presented identical mechanical behavior, only one of them (Mixture 3) was used for the numerical analysis using FEM models.

Table 1. Physical indexes of asphalt mixtures

	Voids (%)	Voids filled with asphalt (%)	Mineral aggregates voids (%)	Relation voids-asphalt (%)
Mixture 1	7.98	4.93	22.91	65.15
Mixture 2	8.88	15.13	24.01	63.02
Mixture3	8.19	15.31	23.50	65.14

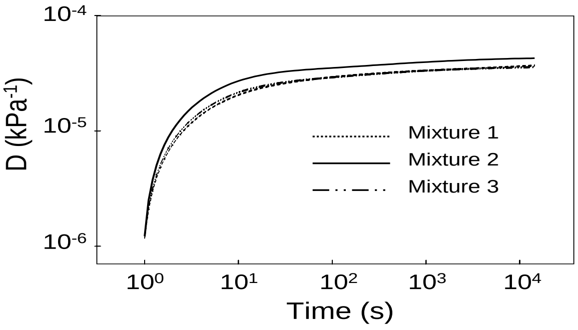


Figure 4. Laboratory curves of the static creep for the asphalt mixtures

Schapery's collocation method [12] was used to fit the experimental creep curve shown in Figure 4, from which the coefficients of Eq. (4) were obtained, as listed in Table 2. The conversion method between viscoelastic properties proposed by Park and Schapery [14,15] presuppose that knowing the coefficient of the Prony series (relative to the original function) and the coefficients for determined times, the coefficients of the Prony series of the target function can be obtained by means of a simple linear equations system. The time coefficients τ_i of the target function were determined taking into account the results presented in Figure 5, noting that the peaks are approximately the retardation times and the valleys are the relaxation times of the material. Using the reference coefficients to the creep compliance (Table 2) in Eq. (4) and substituting this equation and Eq. (5) into Eq. (3), the coefficients for the relaxation modulus were obtained, which are represented in Table 3. From these results the tensile stresses $\sigma(t)$ and the strains $\varepsilon(t)$ were calculated for the asphalt surface.

Table 1. The Prony series coefficients of the creep compliance *D(t)* for the asphalt mixtures

Mixture 1	
D_0 (kPa^{-1}) = 1.17E-06	
D_i (kPa^{-1})	τ_i (s)
1.45E-05	2.00E+00
1.19E-05	2.00E+01
3.92E-06	2.00E+02
4.84E-06	2.00E+03

Mixture 2	
D_0 (kPa^{-1}) = 1.22E-06	
D_i (kPa^{-1})	τ_i (s)
2.17E-05	2.00E+00
1.03E-05	2.00E+01
4.42E-06	2.00E+02
4.82E-06	2.00E+03

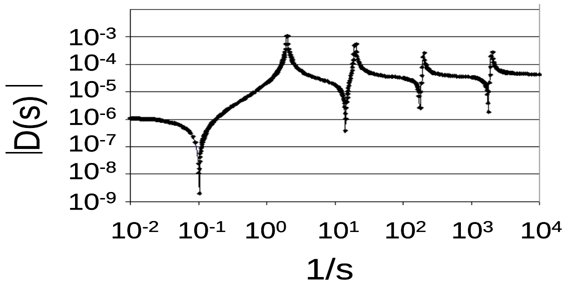


Figure 3. Determination of the relaxation times (Mixture 2)

Table 2. The Prony series coefficients of the relaxation module E(t) for the asphalt mixtures

Mixture 1	
E_∞ (kPa) = 2.75E+04	
E_i (kPa)	ρ_i (s)
7.91E+05	1.39E-01
2.03E+04	1.20E+01
4.03E+03	1.75E+02
4.10E+03	1.72E+03

Mixture 2	
E_∞ (kPa) = 2.35E+04	
E_i (kPa)	ρ_i (s)
7.81E+05	1.02E-01
1.02E+04	1.43E+01
3.40E+03	1.75E+02
2.88E+03	1.79E+03

3.2.3. Sublayers (Base, Subbase and Subgrade): All of the sublayers are assumed to show linear elastic behavior. The values which represent the material properties of the base, subbase and subgrade are 0.3, 0.35, and 0.45 for the Poisson coefficient and 300,000, 200,000, and 100,000 kPa for the modulus of resilience, respectively.

3.3. Loading

A load moving over the pavement model was simulated by a load whose intensity varied with time, according to the function represented by Figure 6, approximated by a half-sine pulse. The duration of a load depends on the vehicle speed and the tire contact radius. For a vehicle speed of 48 km/h, (which is a value that equates to the average velocity found in urban areas in Amazon cities) and a contact area of 100 cm^2, the load pulse is taken as

0.03s. When the load is at a considerable distance from a given point, *t* = ± 0.015s, the load intensity above the point is zero. When the load is directly above the given point, or *t = 0*, the load intensity is 560 kPa, which corresponds to the contact pressure between the pavement and the wheel, distributed in the contact area of 100 cm^2.

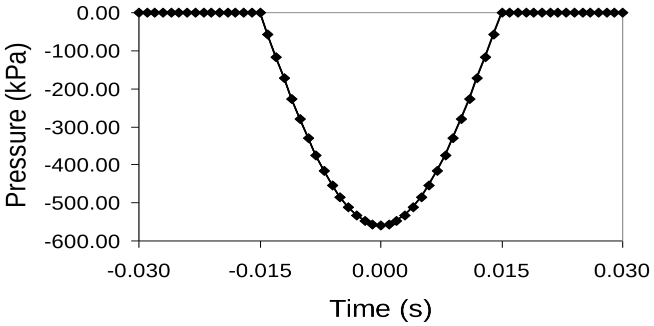


Figure 4. Evolution of the load

4. RESULTS

The results were analyzed in accordance with the horizontal stress and strain on the bottom of the asphalt surface for each mixture studied. These parameters are related to the cracking through fatigue of the asphalt surface and the deflection of the surface of the pavement. As the material properties, geometry and contour conditions of the problem were known, the calculations of the tensile stresses and strains imposed on the pavement could be developed. The results of the stress, the strain, and the displacement related to Mixtures 2 and 3 are shown in Figures 7–9.

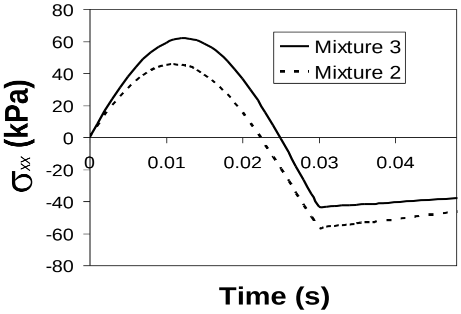


Figure 5. The horizontal tensile stresses in the bottom of the asphalt surface

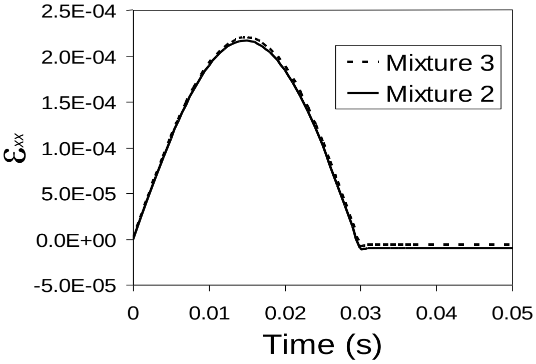


Figure 6. The horizontal strains in the bottom of the asphalt surface

The cracking by fatigue of asphalt surface is caused by the horizontal tensile stress and strains developed in the bottom part of it during the application of the load. According to Figure 5, the horizontal tensile stresses in the bottom part of the asphalt surface for Mixture 3 were larger than the stresses for Mixture 2. On the other hand, the horizontal strains for Mixture 3 showed values slightly superior to those found for Mixture 2 (Figure 6). As seen in Figure 7, the displacements on the asphalt surface of Mixture 3 were slightly lower than those obtained for Mixture 2, revealing that Mixture 2 would be more susceptible to permanent deformation under traffic conditions.

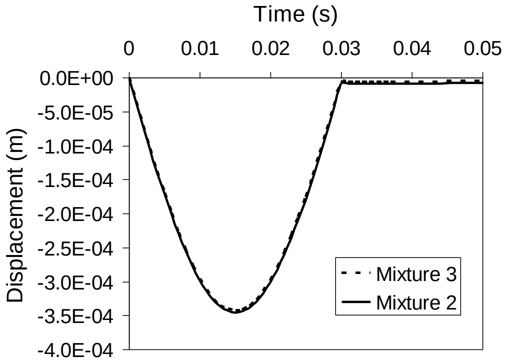


Figure 7. Evolution of the displacement on the surface

While Mixture 3 seemed to be more susceptible to cracking by fatigue, Mixture 2 was more susceptible to permanent deformation. This is explained by the grain sized composition of both mixtures, specifically by the distribution of fine aggregates, once the granular part (above of 4.8 mm of diameter) is identical in all mixtures (Figure 3). Mixture 2 was lying inside the Superpave restricted zone and presented a humped gradation, indicating a mixture that possessed too much fine sand in relation to total sand. The violation of the restricted zone indicates that Mixture 2 had a weak aggregate skeleton that depended too much on asphalt binder stiffness to achieve mixture shear strength.

5. CONCLUSIONS

The analysis of the behavior of the three types of mixtures, which were blended according to the restricted zone of Superpave, and the numerical finite element analysis of the load function over time, resulted in the following conclusions:

- Mixture 3 was more susceptible to cracking by fatigue due to the interlocking of its aggregates, having higher stiffness. Same behavior is expected for Mixture 3 because Mixtures 1 and 3 are assumed to have same material properties.
- Mixture 2 was more susceptible to permanent deformation because its gradation presented a hump, indicating that this mixture possessed too much fine sand in relation to total sand. Hence, the fine part of the aggregates determined the structural behavior of the asphalt mixtures produced and analyzed in this research.

This research shows that, in keeping with the principles of conservation of the natural resource, preservation of the environment, and the sustainable development of the Amazon region in Brazil, the use of construction demolition waste is a good alternative instead of the river pebbles and stony materials used for the civil construction. In addition to the environmental benefit, this alternative waste aggregate resource may also be of particular economic value in Manaus city, the capital of the Amazon State, considering the lack of rock and aggregate material, which has been a great obstacle to the construction of pavements and the production of asphalt concrete.

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