Experimental analysis of asphalt-concrete composite beams subjected to four point bending test

Vianna, N.J.[1], Ruiz, A.N.[2]

[1]*Master student in Urban Infrastructure Systems, Pontifical Catholic University of Campinas*
Rua Professor Doutor Euryclides de Jesus Zerbini, 1516, 13087-571, São Paulo, Brazil
nicolas.jv1@puccampinas.edu.br
[2]*Dept. of Civil Engineering, Pontifical Catholic University of Campinas*
Rua Professor Doutor Euryclides de Jesus Zerbini, 1516, 13087-571, São Paulo, Brazil
adilson.ruiz@puc-campinas.edu.br

Abstract. For thin and ultrathin whitetopping, the bond between the uppermost layer and the lower one has been pointed out crucial for a proper performance. However, the adherence is gradually lost along time due to mechanical loads and environmental conditions. Fiber reinforced concrete is an effective solution and improves the general performance of the structure. This work proposed a four-point bending test for composite beams in order to investigate the initiation and propagation of cracking at the interface between layers, thus evaluating the mechanical behavior in a mixed mode failure (combination of shear and normal stresses). It was tested, in static conditions, two types of overlays (plain concrete and steel fiber reinforced concrete) applied over an asphalt concrete layer. The experimental results obtained for both concrete overlays were compared. An analysis of variance was performed to find out if there was no variation between both experiments. It was found that the addition of fibers did not enhanced the resistance of the composite, however it allowed the material to withstand greater deformations and not failing abruptly during the test. Therefore, the addition of fibers to the cementitious matrix has proved to be beneficial to the overall performance of the structure.

Keywords: whitetopping, concrete overlay, steel fiber reinforced concrete.

1 Introduction

According to the National Transport Confederation (CNT) [1], the Brazilian road network extension in 2018 corresponds to 1,720,700.0 km, in which 213,453.0 km are paved. Regarding pavement quality, among 108,863.0 km surveyed around the country in 2019, it was found that 47.57% are in an excellent or good conditions, while 34.96% are regular, and 17.47 % are in poor or precarious conditions.

In Brazil, most of the highways are built on asphalt concrete. Although, the tropical whether plus the elevate traffic solicitation cause severe deformations on the asphalt [2]. Toward the expressive amount of pavements for restoring and repairing, alternative rehabilitation techniques ought to be considered. Also, sustainable rehabilitation techniques have drawn significant focus in the field of civil engineering [3].

Concrete overlays can serve as sustainable and cost-effective solution, and can also be applied for all pavement types, such as concrete, asphalt, and composite pavements. This technique consists of pouring a concrete layer over the old pavement with the objective to restore its service life and/or its load capacity [4]. When the overlay is applied on an asphalt pavement, it is coined by the industry as whitetopping [5].

Based on the thickness and the bond with the HMA, the whitetopping is further classified into three sub-categories: (i) conventional whitetopping (WT); (ii) thin whitetopping (TWT); and (iii) ultrathin whitetopping (UTW) [3; 5].

Conventional whitetopping is an unbonded concrete overlay of 200 mm or greater constructed without considering structural contribution from the old pavement. Also, this technique must be used in cases that the pavement presents a high deterioration level (e.g., severe rutting, potholes, alligator cracking, subbases issues, shoving, and pumping) and heavily traffic load. Thin whitetopping (100 – 200 mm) is a bonded concrete overlay constructed with an intentional bond to the HMA, while for ultrathin whitetopping (thickness of 100 mm or less) the bond condition is mandatory because the layers are assumed to work together, as a monolithic pavement [5, 6].

However, the bond is gradually reduced along time either by effects of external mechanical loads or different length changes between the layers. The debonding process due to flexure occurs because part of the concrete overlay is subjected to tensile stresses, while shrinkage and temperature changes cause variations in length between layers. In both cases, the debonding initiates in vulnerable locations, such as edges, saw-cut joints, and cracks because of their deficiency in transfer stresses [7].

Therefore, a high bond strength is essential for a satisfactory performance of bonded concrete overlays [9]. In that context, the addition of fibers in the mortar matrix, even at low dosage, is an effective solution that improves the general performance of the concrete because fibers can transfer stresses thought cracks (bridging effect) and limit crack formation and propagation [7; 8].

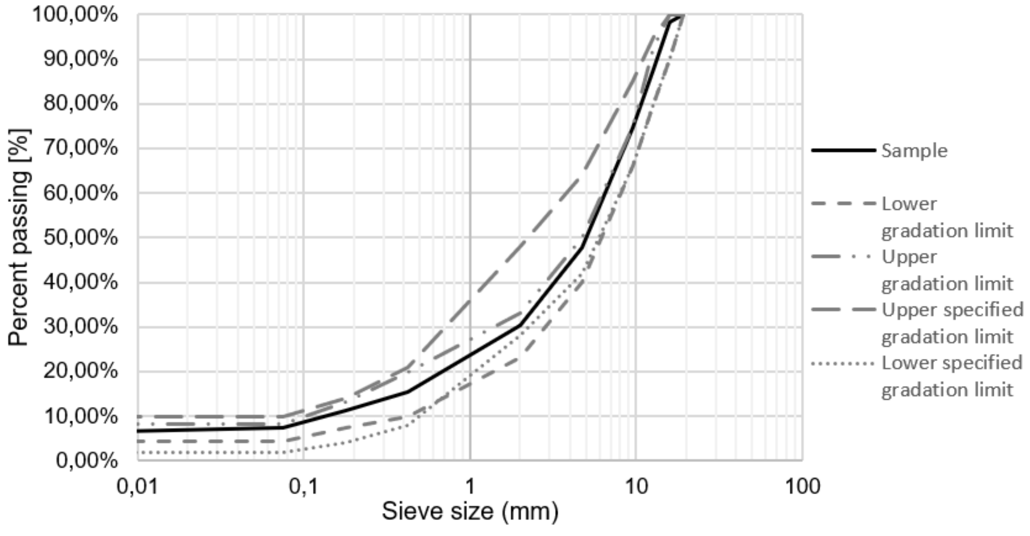
Nowadays, studies have focused on the interface bond between asphalt-concrete [3; 9; 10]. The debonding process might occur due to pure tension, pure shear, or a mixed mode (combination of tension and shear stresses) [3]. Three- and four-points bending tests have been used to analyze the bond resistance, as well as to induce cracking and cause delamination between both materials [3;9;], which failure occurs due to a mixed mode situation. Thus, the objective of this work was to evaluate the response of concrete-asphalt composite beams under a four-point bending test and to investigate the effect of fibers in the cement matrix.

2 Methodology

The experimental program proposed in this study aimed to investigate the mechanical behavior of substrate-overlay composite beams under a 4-point bending test. The methodology was divided into three parts: hot-mix asphalt concrete (HMA) beams casting; study on Portland cement concrete (CCP) dosage; and 4-point bending test on composite beams.

2.1 Hot-mix asphalt concrete

A hot-mix asphalt concrete was used in this study. The sample was collected directly on a continuous asphalt mixing plant (ACM 140 PRIME AMMANN), at the Neopav: Engenharia, Pavimentação e Infra-Estrutura facilities. The granulometric composition of aggregates is presented at Graph 1. A Petroleum Asphalt Cement (PAC) 30/45 was used in a content of 4,690%.



Graph 1: Granulometric composition of aggregates for hot-mix asphalt concrete

Also, three cylindrical specimens of HMA were molded in accordance with DNER-ME 043/95 [11], in which 75 blows were applied in each face. The air void content, density, and Marshall stability are presented in Table 1.

Table 1: Marshall test

Test	Unity	Average	Standard deviation	Coefficient of variation [%]
Density	g/cm³	2,164	0,002	0,1
Air void content	%	3,900	0,100	2,6
Voids Filled with Asphalt (V.F.A.).	%	12,150	0,010	0,1
Voids in Mineral Aggregates (V.M.A.)	%	14,633	0,058	0,4
R.B.V.	%	73,800	0,100	0,1
Stability	kgf	606,667	5,774	1,0
Marshall Stability (after correction)	kgf	1.459,321	13,888	1,0

2.2 Portland cement concrete

The dosage of the reference concrete was prepared using a CP V-ARI cement, a mix between two coarse aggregates (82,61% of a crushed basalt with particle size distribution of 9,5-25 mm and 17,39% of a crushed basalt with particle size distribution of 4,75-12,5 mm), and a composite fine aggregate (70,49% river sand and 29,51% stone powder). The granulometry of each composite aggregates are presented in Table 2.

Table 2: Granulometric composition of coarse and fine aggregates – Accumulated (%)

Sieve (mm)	River sand (70,49%)	Stone powder (29,51%)	Composite fine aggregate	crushed basalt (9,5/25) (82,61%)	crushed basalt (4,75/12,5) (17,39%)	Composite coarse aggregate
25,0	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
19,0	0,00%	0,00%	0,00%	2,20%	0,00%	1,82%
12,5	0,00%	0,00%	0,00%	62,53%	0,00%	51,65%
9,5	0,00%	0,00%	0,00%	92,79%	10,56%	78,49%
6,3	0,66%	0,00%	0,47%	99,80%	63,04%	93,41%
4,8	0,82%	0,42%	0,70%	100,00%	91,18%	98,47%
2,4	1,68%	25,79%	8,79%	100,00%	99,90%	99,98%
1,2	2,90%	49,45%	16,64%	100,00%	99,90%	99,98%
0,6	4,84%	65,47%	22,73%	100,00%	99,90%	99,98%
0,3	31,41%	76,10%	44,59%	100,00%	99,90%	99,98%
0,15	83,80%	85,20%	84,21%	100,00%	99,90%	99,98%
0,075	98,48%	92,56%	96,73%	100,00%	99,90%	99,98%
Bottom (<0,075)	100,00%	100,00%	100,00%	100,00%	100,00%	100,00%
Fineness modulus	1,254	3,02	1,78	6,95	6,01	6,79
Maximum size	0,60 mm	4,75 mm	4,75 mm	19,00 mm	9,50 mm	19,00 mm
Specific gravity	2,63 g/cm³	2,73 g/cm³	-	3,04 g/cm³	2,91 g/cm³	-

In addition, a multifunctional plasticizer produced by MC Bauchemie, MC-Muraplast FK 440, was incorporated to enhance the workability of concrete mixes. For the SFRC samples, crimped steel macrofibers (40 mm length and diameter of 0,55 mm) were employed in a content of 30 kg/m³. These materials aimed to investigate the influence of fibers on the cement matrix behavior. Table 3 indicates the mix proportions for the concrete.

Table 3: Mix proportions for the plain concrete (PC) and steel fiber reinforced concrete (SFRC)

Materials	PC (kg/m³)	SFRC (kg/m³)
Water	180	180
CP V-ARI Portland cement	370	370

Materials	PC (kg/m³)	SFRC (kg/m³)
Composite coarse aggregate	1150	1150
Composite fine aggregate	795	795
Plasticizer	2,035	2,035
Crimped steel macrofiber	-	30

The concrete was prepared accordingly to the following steps: the cement, aggregates, and 80% of the water were mixed for 120 s; then the plasticizer was added by weight, followed by the remaining water, with 120 s for mixing; finally, exclusively for SFRC specimens, the fibers were gradually added and mixing process continued for 120 s until homogenization.

The mixture consistency was determined at the fresh state through the slump test, accordingly to the NBR NM 67 [12]. The PC resulted in a slump of 120 mm. The addition of fiber affected its consistency, resulting in a slump of 60 mm. Also, the hardened concrete properties determined, at 28 days of age, were compressive strength, splitting tensile strength, and tensile strength in flexure. Concrete specimens were casted and cured accordingly to the NBR 5.738 [13].

The compressive strength and splitting test were performed on cylindrical specimens (diameter of 100 mm and 200 mm heigh) in accordance with NBR 5.739 [14] and NBR NM 7.222 [15], respectively. Six samples were molded for each type of concrete. Also, three prismatic samples (400 x 100 x 100 mm³), for each concrete type, were molded for the test of tensile strength in flexure, following the procedures according to NBR 12.142 [16]. Table 4 summarizes the compressive strength, splitting tensile strength, and tensile strength in flexure tests of the PC and SFRC, at 28 days of age.

Table 4: Compressive strength, splitting tensile strength, and tensile strength in flexure tests results, at 28 days of age, for the plain concrete (PC) and steel fiber reinforced concrete (SFRC)

Group	Count	Sum (MPa)	Average (MPa)	Variance
Compressive strength				
Plain concrete	3	142,081	47,360	0,273
Steel fiber reinforced concrete	3	136,762	45,587	1,037
Splitting tensile strength				
Plain concrete	3	11,103	3,701	0,025
Steel fiber reinforced concrete	3	10,610	3,537	0,016
Tensile strength in flexure				
Plain concrete	3	14,917	4,972	0,222
Steel fiber reinforced concrete	3	15,119	5,040	0,162

A statistical technique called analysis of variance (ANOVA) was used to analyze if there are significant variations between groups. Table 5 summarizes the P-value obtained for each source of variation. For all tests the P-value was greater than the significance value (α=0,05), indicating, as consequence, that there are no significant differences between both concretes analyzed.

Table 5: Analysis of variance (ANOVA) for hardened concrete properties

Source of variation	SS	d*f*	MS	F	P-value	F crit
Compressive strength						
Between groups	4,716	1	4,716	7,200	0,055	7,709
Within groups	2,620	4	0,655			
Splitting tensile strength						
Between groups	0,041	1	0,041	1,940	0,236	7,709
Within groups	0,084	4	0,021			
Tensile strength in flexure						
Between groups	0,007	1	0,007	0,036	0,859	7,709
Within groups	0,766	4	0,192			

2.3 Composite beams

The substrate was made of hot-mix asphalt concrete (HMA). Two overlays have been studied: a plain concrete (PC) and steel fiber reinforced concrete (SFRC).

The substrates were prepared by molding manually five slabs of 300 x 200 x 50 mm³ with the Marshall compactor hammer (4,54 kg mass and 45,72 cm sliding height) with 600 blows on the top surface. The compacting temperature was kept between 135°C and 90°C. The slabs were cured by 16 hours at room temperature. After demolding, they were exposed to the weather for about 3 months. Then, those slabs were cut, obtaining sixteen prismatic specimens 190 mm long, 100 mm width, and 40 mm height.

Eight composite beams were casted for each type of overlay – PC and SFRC. The concrete overlay (400 x 100 x 60 mm³) was poured directly on the substrate. According to Chabot, Hun, and Hammoum [9], the delamination failure may occur in either side of the symmetric specimen. In order to force it onto just one side, an asymmetric specimen is recommended. Therefore, an asymmetric configuration was adopted for all the composite beams in this study (see Figure 1), in which the cracking formation was expected to occur on the higher distance separating the support and the HMA layer. A 300 mm span length between supports was adopted for all specimens.

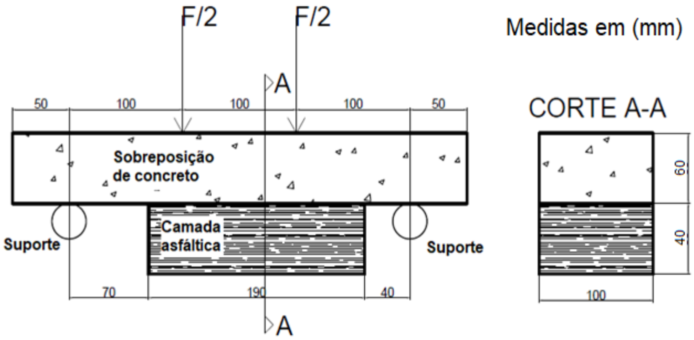


Figure 1: Four-point bending test in composite beams – dimensions and boundary conditions

The curing process for the concrete was carried out by immersing part of the concrete layer inside a container with water, ensuring that the HMA layer was above the water level, as shown in Figure 2. All specimens were kept in these conditions until the test date.

Figure 2: Curing process for the composite beams

3 Results and discussions

The tests were performed using a load cell with capacity of 4,5 tf and a weighing indicator DIGITRON (Universal Line model) with subdivision of 1kgf.

In this study, for all composite beams, the crack initiated from the bottom of the concrete overlay and propagated to the top of the concrete overlay, where the load was applied. PC overlays showed an abrupt rupture, while SFRC overlays presented a smoother post-cracking behavior (see Figure 3). The asymmetric configuration was able to localize the crack initiation. Only one specimen failed under the lower distance between the HMA-substrate and the support.

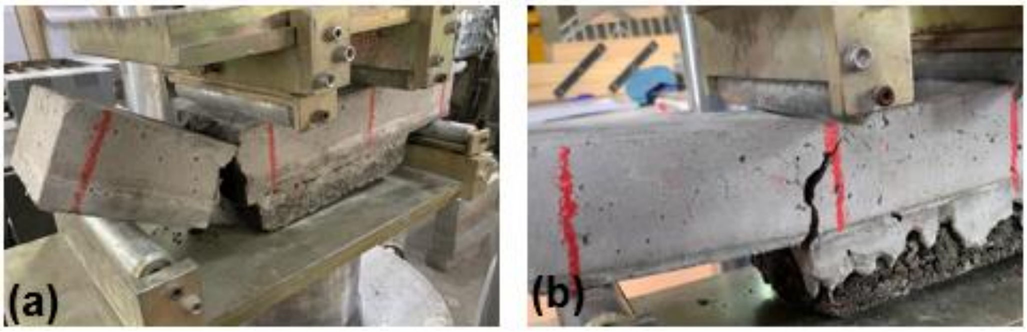


Figure 3: Composite beams failures on composite beams: (a) plain concrete overlay; and (b) steel fiber reinforced concrete overlay

The average maximum load applied for PC and SFRC was 534,571 and 527,375 kgf, respectively. An analysis of variance (ANOVA) was used to verify if there are significant variations between groups (see Table 6). The P-value obtained (0,895) was greater than the significance value (α=0,05), indicating that there are no significant differences between both concrete overlays analyzed.

Table 6: Analysis of variance (ANOVA) for four-point bending tests on composite beams

Group	*Count*	*Sum*	*Average*		*Variance*	
Plain concrete overlay	7	3.742	534,571		16.330,952	
Steel fiber reinforced concrete overlay	8	4.219	527,375		5.975,982	
ANOVA						
Source of variation	***SS***	***df***	***MS***	***F***	***P-value***	***F crit***
Between groups	193,344	1	193,344	0,018	0,895	4,667
Within groups	13.9817,589	13	10.755,199			

4 Conclusions

This study evaluated the mechanical response of concrete-asphalt composite beams under a four-point bending test with the objective to investigate the effect of fiber on cement matrix. The experimental methodology compared the maximum average load that a plain concrete overlay and a steel fiber reinforced concrete overlay withstood.

An asymmetrical configuration showed capable of forcing the failure onto just one side. It was expected that the delamination would occur at the interface between both layers. However, it was not observed in this study, implying that the bond originated with the cement concrete filling the hot-mix asphalt concrete voids was able to withstand the applied load.

An analysis of variance (ANOVA) was carried out to determine if there are significant differences between both overlays analyzed. Based on the results, it can be noted that the addition of 30 kg/m³ of steel macrofibers did not effect on the matrix strength. The fiber promoted a better post-cracking behavior to the concrete, demonstrating its efficiency on controlling crack formation and propagation. Further studies are necessary to quantify the residual capacity that the fibers would promote to the composite beams under a four-point bending test.

Acknowledgements. This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) – Finance Code 001. Also, the authors wish to thank the Neopav: Engenharia, Pavimentação e Infra-Estrutura and Sarom: Consultoria em Engenharia for the support on casting the hot-mix asphalt concrete slabs and the Portland cement concrete beams, respectively.

Authorship statement. The authors hereby confirm that they are the sole liable persons responsible for the authorship of this work, and that all material that has been herein included as part of the present paper is either the property (and authorship) of the authors or has the permission of the owners to be included here.

References

[1] CONFEDERAÇÃO NACIONAL DO TRANSPORTE (CNT). Anuário CNT do transporte: estatísticas consolidadas 2019. Brasília, CNT, 2019.

[2] INSTITUTO DE PESQUISA ECONÔMICA APLICADA (IPEA). Comunicado do IPEA n° 52: Rodovias brasileiras: gargalos, investimentos, concessões e preocupações com o futuro. 60p, 2010.

[3] LÓPEZ-CARREÑO, R-D. et al. Bond strength of whitetoppings and bonded overlays constructed with self-compacting high-performance concrete. Construction and Building Materials, v.153, p. 835-845, 2017.

[4] HARRINGTON, D.; FICK, G. Guide to Concrete Overlays: Sustainable Solutions for Resurfacing and Rehabilitating Existing Pavements. 3rd ed. National Concrete Pavement Technology Center, Ames, Iowa, 2014.

[5] RASMUSSEN, R.O.; ROZYCKI, D.K. Thin and Ultra-Thin Whitetopping, NCHRP Synthesis of Highway Practice 338, National Cooperative Highway Research Program, National Research Council, Washington, DC, 2004.

[6] ISLA, F. et al. Mechanical response of fiber reinforced concrete overlays over asphalt concrete substrate: experimental results and numerical simulation, Construction and Building Materials, v. 93, p. 1022-1033, 2015.

[7] TURATSINZE et al. Debonding. In: BISSONNETTE, B. et al. (Eds.). Bonded cement-based material overlays for the repair, the lining or the strengthening of slabs or pavements: State-of-the-art Report of the RILEM Technical Committee 193-RLS. Dordrecht: Springer Science & Business Media, 2011. ISBN 978- 94-007-1239-3. vol. 3. cap. 6, p. 107-139.

[8] SINGH, H. Steel fiber reinforced concrete: behavior, modelling and design. Singapore: Springer Science & Business Media, 2017. 172 p. Inclui índice. ISBN 978-981-10-2506-8.

[9] CHABOT, Armelle; HUN, M.; HAMMOUM, F. Mechanical analysis of a mixed mode debonding test for “composite” pavements. Construction and Building Materials, v. 40, p. 1076-1087, 2013.

[10] CHABOT, Armelle; HAMMOUM, Ferhat; HUN, Manitou. A 4pt bending bond test approach to evaluate water effect in a composite beam. European Journal of Environmental and Civil Engineering, v. 21, n. sup1, p. 54-69, 2017.

[11] DEPARTAMENTO NACIONAL DE ESTRADAS DE RODAGEM. DNER 043/1995 – ME: Misturas betuminosas a quente – Ensaio Marshall – Método de ensaio. Rio de Janeiro, 1995.

[12] ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. NBR NM 67: Concreto – Determinação da consistência pelo abatimento do tronco de cone. Rio de Janeiro, 1998.

[13] ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. NBR NM 5738: Concreto – Procedimento para moldagem e cura de corpos de prova. Rio de Janeiro, 2016.

[14] ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. NBR 5739: Concreto – Ensaio de compressão de corpos de prova cilíndricos. Rio de Janeiro, 2018.

[15] ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. NBR 7222: Concreto e argamassa – Determinação da resistência à tração por compressão diametral de corpos de prova cilíndricos. Rio de Janeiro, 2011.

[16] ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. NBR 12142: Concreto – Determinação da resistência à tração na flexão de corpos de prova prismáticos. Rio de Janeiro, 2010.