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Evaluation of the addition of short coconut fibers on the characteristics of asphalt mixtures

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Abstract

The damage path beginning at the surface layers of the failure receives the load of the traffic and a change in temperature of 20-50 °C. Structural changes in the asphalt mixture cause an increase in the temperature of the surface of the road, approaching the softening point of asphalt. Short coconut fibers are waste from coconut processing, with a length of 5-12.5 mm. The addition of 0.5%, 0.75%, 1%, 1.25%, and 1.50% coconut fiber changed the characteristics of the asphalt. The fiber size was varied (5, 7.5, 10, and 12.5 mm) to determine its effect on the asphalt characteristics. The fiber size variation was also conducted to determine its effect on the asphalt-aggregate mixture at 60 °C using the Marshall immersion test. The addition of 0.75% 5-mm fibers by weight of the asphalt increased the value of the Marshall stability by 10-15% and produced a lower penetration-grade bitumen. The temperature of the mixing fibers in the asphalt must be below the flash point of the fibers during the heating of the asphalt-fiber mixture.

Keywords: coconut fiber, temperature, resilient modulus, asphalt mixtures, Marshall test

1. Introduction

In general, some asphalt mixes for road pavement flow in response to the load due to their plastic deformation at high temperatures. Such deformation properties accumulate due to repetitive loads. Changes in the surface layers are cause early damage to the road pavement structure.

Damage to highways mostly occurs in the top layer, in the binder and erosion layers, rather than the foundation and lower layers. Damage to the binder and erosion layers generally includes surface cracks, deformations, wheel ruts, and potholes (Ozgan, 2011). Damage to roads in Indonesia is caused by environmental factors, overloading, and construction. Environmental factors, such as rainfall and road surface temperature changes, are often difficult to predict (Hadiwardoyo et al, 2013). Asphalt obtained from refineries is too soft for paving in high-temperature areas in the summer and too brittle for subzero temperatures in winter in various parts of the country (Attaelmanan et al, 2011).

As a tropical country, Indonesia has a problem with increases in the road surface temperature. Therefore, a surface layer able to resist temperature changes is required. To address this problem, research has been conducted to improve the performance of asphalt as the road surface layer. One approach is the use of fiber additives mixed into the asphalt. Fiber-added materials are derived from synthetic fiber or natural fiber. Coconut husks are plentiful in Indonesia, which is the producer of 10% of the world demand for coconuts. However, these husks are most readily available as processed waste coconut husks. Standard-sized coconut fibers have been utilized in the coir industry, but short waste fibers have not yet been utilized. A study conducted by Oda et al (2012) showed that the addition of coconut coir fiber increased the resilient modulus by approximately 14%. The coconut is comprised of several parts, including the exocarp, which is a very thin layer covering the fibrous mesocarp. These elements form the bark of the coconut (approximately 5-mm-thick, depending on the species). Underneath this layer lies the woody endocarp, which is very hard. Natural fibers are cheap and locally available in many countries. Their use as a construction material to improve the properties of the composites costs very little when compared to the total cost of the composites (Ali et al, 2012).

The utilization of coconut coir waste can play a role in reducing environmental pollution. Efforts to improve the performance of asphalt by the addition of natural materials are expected to reduce the ever-increasing need for asphalt as a road construction material. The reduction of the use of natural materials can also be accomplished by recycling materials as material additives. The recycling of existing asphalt pavement materials produces new pavements with considerable savings in material use, money, and energy. Aggregate and binder from old asphalt pavement retain their value even after these pavements have reached the end of their service lives (Xiao, 2009).

In this study, short coconut fiber is added to asphalt heated to a certain temperature so as to avoid burning the coconut fiber. The asphalt-fiber characteristics are tested to determine such characteristics as the penetration, softening point, burning point, ductility, density, and Marshall immersion. At high temperatures, the asphalt binder tends to flow more easily due to the natural decrease in viscosity associated with higher temperatures. This condition creates a “softer” asphalt mixture, which is prone to rutting (Fontes et al, 2010).

The objective of this study was to evaluate the laboratory performance of different sizes of coconut fiber present in virgin asphalt in different percentages. This goal was achieved by evaluating various engineering properties. The behavior of coconut fiber asphalt (CFA)-modified mixtures was compared to that of conventional asphalt mixtures.

2. Materials and methods

2.1. Asphalt cement and aggregate

The aggregate used in the construction of the asphalt sample is derived from Rumpin-Bogor West Java aggregate quarry and grade 60/70 bitumen. The grading of the aggregate can be characterized as influential for the asphalt mixture deformation resistance. Poor aggregate composition refers to the use of too many fine or coarse aggregates, which fails to provide the necessary resistance to deformation.

Table 1 Design aggregate gradation

Sieve	Sieve (mm)	Passing (%)	Undesirable range	Lower-upper limits
¾ in	19	100	-	100
½ in	12.5	91	-	90-100
⅜ in	9.5	81	-	90
No. 4	4.75	59	-	-
No. 8	2.36	43	39.1	28-58
No. 16	1.18	33	25.6-31.6	-
No. 30	0.6	25	19.1-23.1	-
No. 50	0.3	16	15.5	-
No. 200	0.075	6	-	4-10

In general, a higher content of fine aggregate and a perfect balance between the distribution of coarse aggregates, fine aggregate, and filler may imbue asphalt mixtures with increased resistance (Mirzahosseini et al, 2011).

This study used an asphalt concrete wearing course mix (AC-WC) in which the largest aggregate size was 19 mm. The test results for the characteristics of the coarse aggregate and fine medium are displayed in Tables 1 & 2. Only one aggregate gradation shown in Figure 1 was selected for use in the study.

The characteristics of asphalt must conform to the requirements specified in the Indonesian standard. Thus, tests were conducted to determine the penetration, ductility at 25 °C, loss due to heat and air, specific gravity, and softening point. The physical properties of the asphalt samples are given in Table 3.

Table 2 Basic properties of the aggregate

Aggregate	Method	Value		
Property		Coarse	Medium	Fine
Bulk sp. gr.	AASHTO T84/T85	2.52	2.52	2.53
Surface saturated dry gravity (SSD)	AASHTO T84/T85	2.58	2.59	2.58
Apparent sp. gr.	AASHTO T84/T85	2.68	2.69	2.66
Absorption (%)	AASHTO T84/T85	2.40	2.44	2.04
Los Angeles abrasion (%)	AASHTO T96	18.82	22.12	
Solubility (%)		98		
Impact	SNI 03-4426-1997	8.54		
Angularity (%)		> 95		
Toughness (%)	BS-812	8.42		

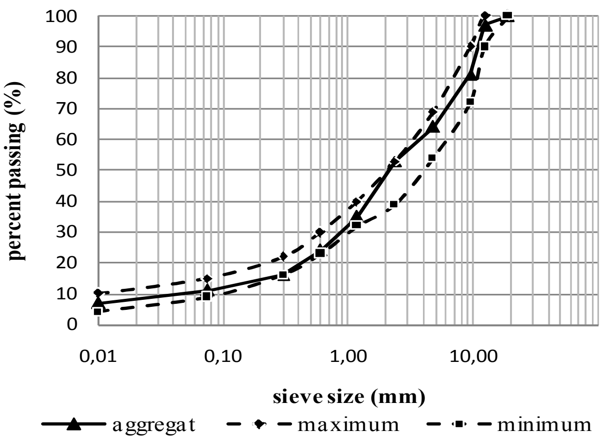


Figure 1. Aggregate gradation

Table 3 Physical properties of asphalt cement

Properties of the asphalt cement		Specification used
Penetration grade	60/70	ASTM D 5
Penetration (25 °C, 100 g, 5 s, dmm)	64.39	ASTM D 5
Specific gravity	1.087	ASTM D 70
Softening point (°C)	48.5	ASTM D 36
Flash point (°C)	280	ASTM D 92
Ductility (25 °C, 5 cm/min)	110	ASTM D 113

2.2. *Coconut fiber properties*

The coconut fiber used in this study is derived waste coconut husk for industrial processing. Short coconut fibers were washed to remove dust and other impurities. The fibers were then dried at 30 °C for 24 h and filtered to separate the remaining impurities. The physical properties of the short fibers are as follow: length, 5 mm to 12.5 mm; diameter, 0.80-0.15 mm; and density, 600 kg/m^3. Short coconut fibers after drying are as shown in Figure 2.

Figure 2. Micro-optic coconut fiber images

2.3. *Coconut fiber-asphalt (CFA) formulation*

The coconut coir was cut to lengths of 5 mm, 7.5 mm, 10 mm, and 12.5 mm and added to the bitumen 60/70 in levels of 0.5%, 0.75%, 1%, 1.25%, and 1.5% by weight of asphalt. The fibers were added upon heating of the asphalt temperature to 150-160 °C by stirring for 5 min until the fibers were evenly mixed. Asphalt fiber can be stored and reheated when used for mixing with aggregate.

Fiber size affects the ease of mixing between the asphalt and fiber: the smaller the fiber, the easier the mixing process. Coconut fiber will burn before the flash point of asphalt; thus, the mixing of the fibers and asphalt must be performed below the burning temperature of the coconut fibers.

At the end of the test, the fibers were extracted from the bitumen to verify that the coconut fibers did not burn during the hot asphalt concrete mixing process. The results show that 96% coconut fiber mixed with bitumen remained after mixing.

2.4. *Mix design and optimization*

The content of coconut fiber asphalt in the asphalt concrete mixture is equal to 6.36%. The asphalt was modified and the aggregate mixed at 155 °C. The samples were then brought to the compaction temperature of 10 °C less than the corresponding mixing temperature using a Marshall mechanical compactor. The specimens were compacted using 75 heavy-duty Marshall blows for each face, corresponding to a tire pressure of 1.379 kPa. Samples with a variety of fiber sizes and percentages of the asphalt were tested by Marshall, Marshall immersion, and wheel tracking tests.

3. Results and discussion

3.1. *Rheological tests*

The CFA binder rheological properties were evaluated, and the results are presented in Table 4. The results show that the CFA is effective in improving the rheological properties of the asphalt cement. Table 4 reveals that the addition of CFA content reduces the penetration and ductility and increases the softening point. The results showed that the softening point of CFA modified increased by 2.3% and the penetration decreased by 11.5% with the addition of 0.75% coconut fiber (5 mm). The results also reveal that 0.75% CFA decreased the ductility to 47 cm, which shows that the CFA can still be used in asphalt cement. The increase in the softening point and decrease in the penetration can be attributed to the consistency of the CFA binder.

3.2. Temperature susceptibility

The penetration index was used to investigate the effect of CFA on the temperature susceptibility of the asphalt mixtures. Figure 3 illustrates the relationship between penetration index and CFA content. All the modified binders were less susceptible to changes in temperature than virgin asphalt cement. This finding is associated with the higher softening point and lower penetration value of CFA-modified asphalt compared to virgin asphalt. Figure 3 shows that the Penetration Index (P.I.) values for virgin asphalt and 0.75% CFA-modified asphalt are -0.463 and -0.302, respectively. Increased CFA content has increased the P.I., as shown in Figure 3. This important fact shows that CFA makes the binder less susceptible to temperature and climate.

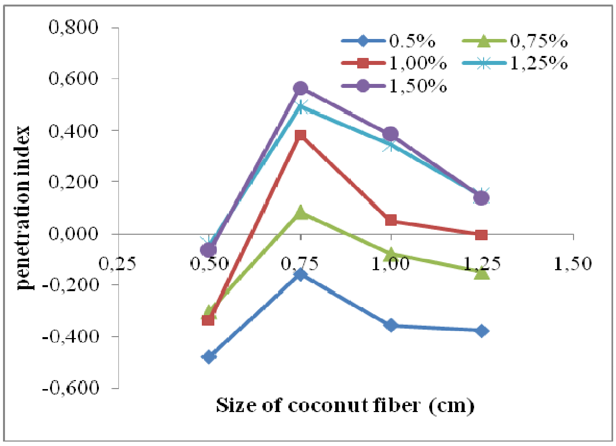


Figure 3. Relationship between size of coconut fiber and penetration index

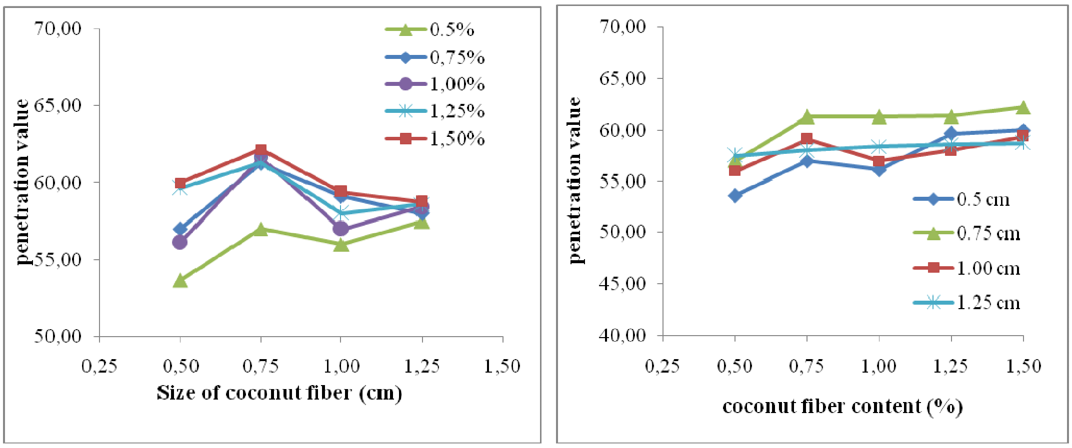
Table 4 Basic rheological properties of CFA

% coconut fiber	Length of fiber (mm)	Penetration (25 °C, 100 g, 5 s, dmm)	Ductility (25 °C, 5 cm/min)	Softening point (°C)	Penetration index
0	-	64.39	110	50.50	-0.463
0.50	5.0	53.64	52.33	52.28	-0.479
0.50	7.5	57.03	47.50	53.00	-0.158
0.50	10.0	56.00	46.47	52.36	-0.355
0.50	12.5	57.50	45.90	52.00	-0.377
0.75	5.0	57.00	47.57	52.40	-0.302
0.75	7.5	61.30	44.33	53.25	0.086
0.75	10.0	59.10	44.07	52.95	-0.080
0.75	12.5	58.00	43.96	52.85	-0.151
1.00	5.0	56.11	44.17	52.42	-0.336
1.00	7.5	61.67	42.70	54.46	0.384
1.00	10.0	57.00	42.23	53.90	0.051
1.00	12.5	58.40	42.10	53.40	-0.004
1.25	5.0	59.66	42.17	53.00	-0.044
1.25	7.5	61.33	40.50	55.00	0.493
1.25	10.0	58.00	40.10	55.00	0.347
1.25	12.5	58.60	40.00	54.00	0.145
1.50	5.0	60.00	41.70	52.85	-0.065
1.50	7.5	62.20	40.10	55.15	0.565
1.50	10.0	59.40	39.20	54.90	0.386
1.50	12.5	58.75	39.00	53.95	0.140

3.3. *Influence of coconut fiber on bitumen properties*

3.3.1. *Asphalt penetration value*

Figure 4 shows the penetration value of bitumen as a function of coconut fiber length (Figure 4a) and is based on the bitumen content of coconut fiber (Figure 4b). The coconut fiber length affected the penetration value of the asphalt, especially the length of 0.75 cm, which yielded the highest penetration bitumen. Similarly, the percentage content of coconut fiber affected the penetration value of the asphalt. A coconut fiber content of 1.5% with a size of 0.75 cm produced the highest asphalt penetration value, 62.2.

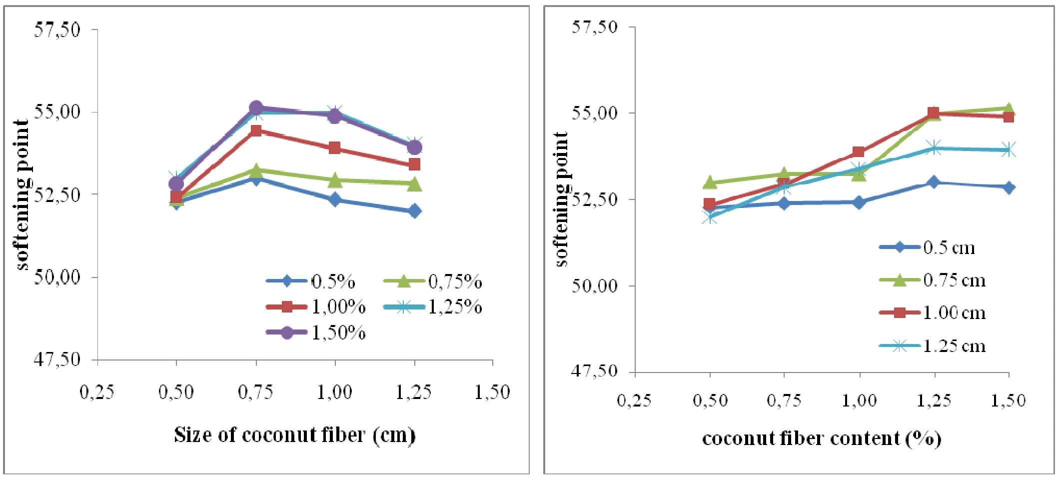


(a) (b)

Figure 4. Relationship between coconut fiber size and asphalt penetration value

3.3.2. *Softening point*

As shown in Table 4, the softening point of virgin asphalt is 50.5. The addition of coconut fiber in virgin asphalt increased the softening point by 4-7% for all sizes and contents of coconut fiber in bitumen. Figure 5a shows that increases in the percentage coconut fiber in bitumen increased the softening point. Regarding the length of coconut fiber, a length of 0.75 cm yields the best softening point (Figure 5b).



(a) (b)

Figure 5. Relationship between size of coconut fiber and softening point

3.3.3. *Ductility*

The addition of coconut fiber has a negative influence on the ductility of the CFA-modified mixtures tested in this study. Table 4 shows that the addition of coconut fiber in the bitumen decreases the ductility, which is 39 for the highest coconut fiber content studied. The coconut fiber size of 0.5 cm corresponds to the highest CFA ductility studied. Figure 6 shows that the longer the coconut fibers and the lower the coconut fiber content, the lower the ductility values were.

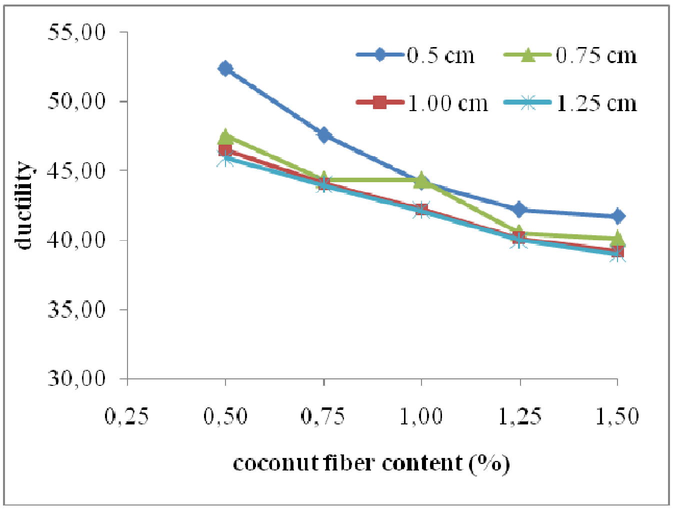


Figure 6. Relationship between CFA content and softening point

3.4. Moisture susceptibility

The adverse effect of moisture on the resistance of asphalt mixtures is expressed by the strength ratio (SR). The SR is defined as the ratio of dry and wet strength specimens. The higher the SR, the better the resistance to moisture damage of the asphalt mixtures.

Most pavement agencies recommend that the SR value be greater than 70-80% in their mixture design specifications (Roberts et al, 1996).

As shown in Table 5, the SR values obtained for both mixtures are greater than 80%, which meets the mixture design specifications. However, the SR of the CFA-modified (94%) is approximately 2% lower than that of the conventional mixture (96%). An SR value of 94% indicates that negligible moisture damage has occurred in the modified CFA wet specimens. This resistance, which meets the minimum requirements of the modified CFA to moisture damage, could be mainly attributed to the anti-stripping agent. Figure 7 shows the Marshall stability of dry and wet samples with different contents of coconut fiber.

Table 5 Moisture susceptibility results

Coconut fiber content (%)	Dry		Wet		Strength ratio (%)
	Air void (%)	Strength (kPa)	Air void (%)	Strength (kPa)	
0	3.49	1,008.7	3.74	970.2	0.96
0.5	4.14	1,070.3	4.45	1,016.4	0.95
0.75	3.01	1,332.2	3.43	1,216.7	0.91
1	3.52	1,209.0	3.99	1,124.2	0.93
1.25	4.19	1,147.3	4.94	1,062.6	0.93
1.5	4.57	1,093.4	5.42	1,039.5	0.95

The desirable properties of asphalt mixtures for flexible pavement surfacing are stability, durability, flexibility, and skid resistance (Jitsangiam et al, 2013). Conventional hot mix asphalt (HMA) design methods aim to determine the optimum asphalt content at which the asphalt layer performs satisfactorily, particularly with respect to stability and durability (Asi et al, 2007).

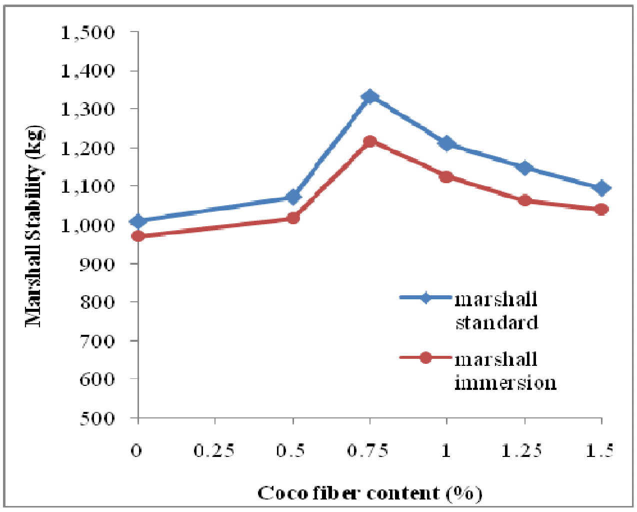


Figure 7. Influence of coconut fiber content on Marshall stability

3.5. *Deformation performance of coconut fiber asphalt mixtures*

Figure 8 compares the rut depth with the load cycle number for the conventional and CFA-modified mixtures. The conventional mixture has a maximum rut depth of 1.5 mm after 1260 cycles. In contrast, the maximum rut depth of the CFA-modified mixture is approximately 1 mm. It can be concluded that the CFA-modified mixture has the potential to reduce permanent deformation. Because the aggregate gradation mixture of both mixtures is the same, the increase in resistance to deformation of the CFA-modified mixture is mainly due to the coconut fiber used in the mixture.

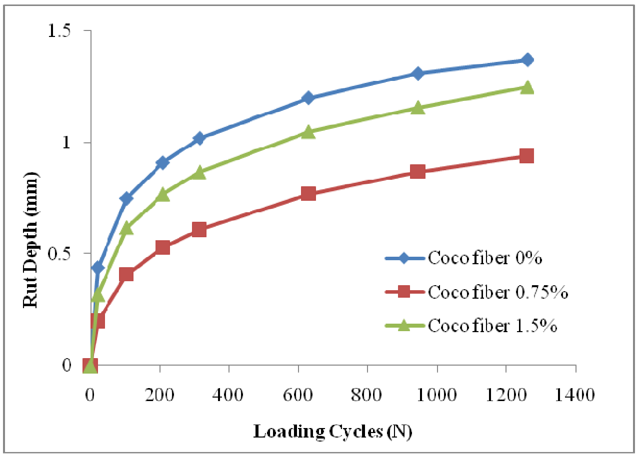


Figure 8. Cumulative rut depths with number of load applications

4. Conclusions

The purpose of this paper was to evaluate the use of short coconut fibers, which are readily available waste products that can disrupt the environment, as an asphalt additive. The results of the use of 5-12.5-mm fibers in the amount of 0-1.5% by weight of asphalt can be summarized as follows:

1. The addition of short coconut fiber reduced the penetration grade of bitumen and ductility but increased the softening point.

2. The increase in fiber length caused difficulties in the process of mixing the fibers with asphalt; the shorter the fiber is, the more the mixing process is facilitated. The 5-mm short coconut fiber yielded the highest ductility.
3. The test results show that the 0.75% coconut fiber content provided the best performance of the contents studied. Additionally, the 0.75% CFA performed better than asphalt mixtures using virgin asphalt.
4. CFA extraction test results show that as much as 96% of the fiber is retained, which suggests that coconut fiber does not burn in the asphalt mixing process.

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