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Paper Mill Sludge as Fiber Additive for Asphalt Road Pavement

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This study evaluated the properties of stone mastic asphalt mixtures made with paper mill sludge from four paper mills, as well as wastepaper, as fiber additive. Marshall specimens were prepared with asphalt content of 4.5, 5.0, 5.5, 6.0 and 6.5% and sludge or fiber contents of 0.2, 0.3, 0.4 and 0.5 percent. Properties tested were bulk specific gravity, stability, flow, air voids, voids in mineral aggregates and voids filled with asphalt. Effects of asphalt and fiber contents on flow and stability were analyzed statistically. Asphalt contents between 5 and 6 percent and sludge or fiber contents between 0.3 and 0.5% from any of the four paper mills resulted in Marshall specimens with properties generally passing the Department of Public Works and Highways specifications for both medium and heavy traffic road pavement.

Key Words: asphalt, fiber, Marshall specimens, paper mill sludge

INTRODUCTION

A good road is paved or covered with a structure to supplement the natural strength of the soil foundation. The pavement may either be rigid (portland cement concrete) or flexible (hot-mix asphalt) [HMA]. HMA pavements suffer damage in the form of cracks that result in high maintenance cost. These cracks are caused by any or the combination of several factors, namely: asphalt, mix, traffic, environment, pavement structure, construction, geology, and pavement design (Soupe 2001). For all types of cracks, the quality of the asphalt and the mixture used is of prime importance.

In the early 60s, Germany began developing stone mastic asphalt (SMA) for the reduction of wear caused by studded tires. SMA is a dense, gap-graded bituminous mixture with high contents of stone, filler and bitumen, modified with a suitable binder carrier such as cellulose fiber (Richardson 1999).

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The cellulose fiber additive used in SMA is said to prevent drainage of asphalt binder and thus improve binding with aggregates. Such additive has been introduced in the Philippines and pilot-tested. After some years of observation, the Department of Public Works and Highways (DPWH) has released a technical report (Faustino and Valencia 2003) specifying the material and construction requirements of SMA containing fiber.

Cellulose fiber can be derived from any lignocellulosic plant material by pulping. There is, however, an unavoidable residue also called sludge that goes into the wastewater stream of the pulping and papermaking processes. Paper mill sludge still has fiber in it together with some inorganic matter. In one local paper mill alone, 100-120 tons of sludge is generated per day and there have been efforts to utilize some in cement-bonded boards (Fernandez et al. 2001). Other mills, however, are not taking this course. As in other locations (SHWEC 2008), landfilling is the major disposal method practiced by local mills.

This study used paper mill sludge from four paper mills and also of wastepaper as fiber additive in SMA to determine their effects on the stability, flow and volumetric properties of Marshall specimens.

MATERIALS AND METHODS

Paper mill sludge samples were requested from each of four wastepaper-based paper mills (A, B, C, and D). A, B, and C sludge samples were the final filter cakes from the wastewater treatment facilities of the respective mills; D was deinking sludge for disposal. The sludge samples were air-dried. Old newspaper (W) sheets were shredded and the sludge samples and the shredded newspaper were passed through a mechanical grinder at the Industrial Technology Development Institute (ITDI) Department of Science and Technology (DOST). These were analyzed for size distribution and chemical composition. Fiber materials passing the No. 30 sieve were used in mixing with aggregates and asphalt binder.

The asphalt (60/70 penetration grade), aggregates, and filler were all provided at the laboratory of the asphalt batch mixing plant.

Determination of Size Distribution

The size distribution of the ground sludge and wastepaper samples was determined using the Bauer McNett Fiber Classifier at the Forest Products Research and Development Institute (FPRDI), DOST. Two 10-gram samples (oven-dry basis) of each material were fed into the instrument, with its four tanks in a cascade arrangement set with screens of No. 14, 28, 48 and 100 sieves and provided with collecting filter papers at the discharge point of each tank. The oven-dry weights of the collected fractions were then determined.

Analysis of Chemical Composition

The ash content of the samples was calculated as the residue after complete combustion at 525^o C of a 2-g sample in a furnace following the Technical Association of the Pulp and Paper Industry (TAPPI) T 211 om-93 test method (1994). The difference from the original dry weight of the sample was taken as the organic matter. The alcohol-hexane and hot water extractives were determined following the test methods TAPPI T 204 om-88 and T 207 om-93, respectively. For lignin, a value of 2.31%, based on reported average values of different pulps, was used for all samples. Holocellulose was then calculated as the difference between the dry solids and the sum of ash, extractives and lignin.

Extraction of Fibers from the Test Specimens

Extraction of fibers, following the standard procedure for extracting bitumen from bituminous pavement American Association of State Highway and Transportation Officials (AASHTO) 1990, was first conducted to verify the fibers would not be consumed or burned during hot-mixing with asphalt. Fibers from SMA mixtures with 0.5% sludge were extracted using an extraction apparatus consisting of a bowl and a centrifuge (Method A, Centrifuge Method).

Preparation of Marshall Stability Test Specimens

Marshall test specimens were prepared following the Marshall mixture design method (AASHTO T 245). The aggregates and minus No. 30 sludge fraction were mixed and heated to 150^o C on a pan. When this was completed, asphalt heated to 150^o C, was added and additional mixing completed. The mixture was then placed into heated (95^o-150^o C) molds lined with paper at the bottom and top and immediately compacted in the mold and hammer set-up. Compaction was accomplished with 50 blows of the hammer on each side of the specimen. Three test specimens were prepared for each treatment combination of asphalt content (AC) (4.5, 5.0, 5.5, 6.0, and 6.5%) and fiber content (FC) (0.2, 0.3, 0.4, and 0.5%). After evaluation of data from this experiment, three specimens without fiber additive were also produced with an AC based on the optimum range obtained from specimens with fiber additive.

Testing of Properties of Compacted Asphalt-Aggregate-Sludge Mixes

The different properties of the Marshall specimens were determined following the prescribed methods: Bulk Specific Gravity (AASHTO T 166-88), Stabilityand Flow Properties (AASHTO T 245-90) and Density and Void Analysis (AASHTO T 209-90).

Calculation of Optimum Asphalt Content

The optimum asphalt content (OAC) is the average of the AC at maximum specific gravity, maximum stability (both taken from the property graphs) and the median of limits in air void (4 percent). That is,

$$OAC = (AC_{max.\ sp.\ gr.} + AC_{max.\ stability} + AC_{4\ \%\ air\ voids}) / 3$$

where, $AC_{max.\ sp.\ gr}$ = AC at maximum specific gravity
$AC_{max.\ stability}$ = AC at maximum stability
$AC_{4\ \%\ air\ voids}$ = AC at 4% air voids

Using the OAC, the optimum values for stability, flow, and air voids were obtained from the graphs.

Statistical Analyses

Statistical analyses were conducted to evaluate the effects of the variables on the stability and flow properties of the Marshall specimens. Stability is affected by specific gravity while flow is not. Therefore, analysis of co-variance (ANACOVA) with specific gravity as co-variate was used for stability and only analysis of variance (ANOVA) for flow. Duncan Multiple Range Test (DMRT) was further conducted on the treatment means to further explain the differences in effects of the variables.

RESULTS AND DISCUSSION

Characteristics of the Sludge Samples and Wastepaper

Table 1 shows the size distribution of the fibers from sludge and wastepaper. Mills A and D showed very similar size distribution, with around 30-34% retained on the No.14 sieve (mainly of fiber and clay lumps) and around 27% passing the No.100 sieve (considered as fines). Mill B had the greatest amount of fines of about 74%, followed by Mill C with about 49% fines. Only Mill B showed a distribution that increased in amount with decreasing size. The others had no specific trend.

Table 1. Size distribution of the fibers used

Mesh Fraction	Percent Retained, %				
	Sludge				Old News Paper W
	Mill A	Mill B	Mill C	Mill D	
14	30	1.9	12.2	34.2	13.8
28	15.4	3.8	9.3	12.7	24
48	18.8	5.9	24.5	18.5	28.5
100	8.6	14.2	4.7	6.9	11.8
Fines	27.2	74.2	49.3	27.7	21.9

The commercial fiber additive is specified with an ash content of approximately 15 percent (Faustino and Valencia 2003). In this study, chemical composition other than ash content was analyzed for better comparison among the sludge samples and wastepaper. The major organic component of sludge is wood fiber and fines, while the inorganic fraction may contain clay, calcium carbonate, titanium dioxide and other materials (Renewable Resource Data Center 1998). Paper mill sludge from different paper mills analyzed for organic content exhibited values ranging from 40 to 60% (Moo-Young and Zimmie 1997). Table 2 shows that only Mill B sludge falls within such range, with an organic content of about 40 %, the others having 66.5 to 77.4% and the wastepaper, more than 93%. A high organic content in the sludge may indicate wastage of fibers that otherwise should have been used in papermaking. It was also noted that Mill C sludge, followed by Mill B's, had the greatest amount of extractives; and Mill D's, the least. The high percentage of ash (60.38%) or inorganic matter in Mill B sludge indicates the high percentage of mineral filler used, which is usual for writing and printing paper. The other sludge samples, A, C and D, had ash contents between 22.5 to 33.5%. All ash values of the sludge samples were higher than the specified limit of 15% for the commercial fiber additive. In contrast, the wastepaper fiber showed a low 6.77% ash content, which was just a little higher than the range for virgin wood, 0.3-3.8% (Escolano and Tamolang 1981). Bamboo, due to its high silica content, is generally known to have the highest ash content ranging from 2.4 to 9.7% (Espiloy et al. 1999). Ash content much higher than those of the original fiber indicates mineralization of the fibers. This appears to have happened to the sludge fibers and the commercial fiber.

Table 2. Chemical composition of the fibers used

Composition	Sludge				Old News Paper W
	Mill A	Mill B	Mill C	Mill D	
Dry Solids, %	92.96	95.72	86.47	93.79	90.8
Organic Matter, %	77.45	39.62	74.08	66.5	93.23
Alcohol-Hexane Ext.,%	2.31	2.89	8.82	1.97	0.86
Hot Water Ext., %	2.16	4.41	6.72	1.87	2.26
Lignin, %*	*Assumed at 2.3 %*				
Holocellulose, %	63.64	25.74	42.71	54.15	78.61
Ash, %	22.55	60.38	25.92	33.5	6.77

* Approximate value based on lignin content for sulfite and kraft pulps from different wood species (Sjostrom 1977; Estudillo et al. 1972)

Extraction of Fibers from Asphalt Mixtures

The masses of extracted fiber were 7.0, 0.70, 0.20, 6.25 and 6.25 g for Mills A, B, C, D sludge and wastepaper, respectively. Thus, based on the original mass of 6.25 g for a 0.50% addition to the SMA mixture, recoveries were 112, 11.2, 3.2, 100, and 100%, for Mills A, B, C, D sludge and wastepaper, respectively. The higher recovery of Mill A sludge could indicate residual asphalt on the fibers. For Mills A and D sludge and wastepaper, the results indicate that the fibers withstood the harsh processing, including the high mixing temperature. The much lower recoveries of Mills B and C fibers, 11.2 and 3.2%, respectively, may have been due to their high percentage of shorter fibers and fines that could have mixed well with the asphalt binder during hot mixing making separation from the aggregates difficult.

Properties of Marshall Test Specimens

Figure 1 is a representative set of graphs showing the relationships between AC and the different SMA mixture properties, namely; (a) bulk specific gravity, (b) stability, (c) flow, (d) air voids (Va), (e) voids in mineral aggregates (VMA) and (f) voids filled with asphalt (VFA) using Mill A sludge at 0.2, 0.3, 0.4 and 0.5%. According to Pagbilao (2003) test property curves follow a reasonably consistent pattern. Bulk specific gravity follows a trend where the highest value is between the lowest and the highest AC levels. Similarly, the stability value increases with increasing AC up to a maximum, after which, the value

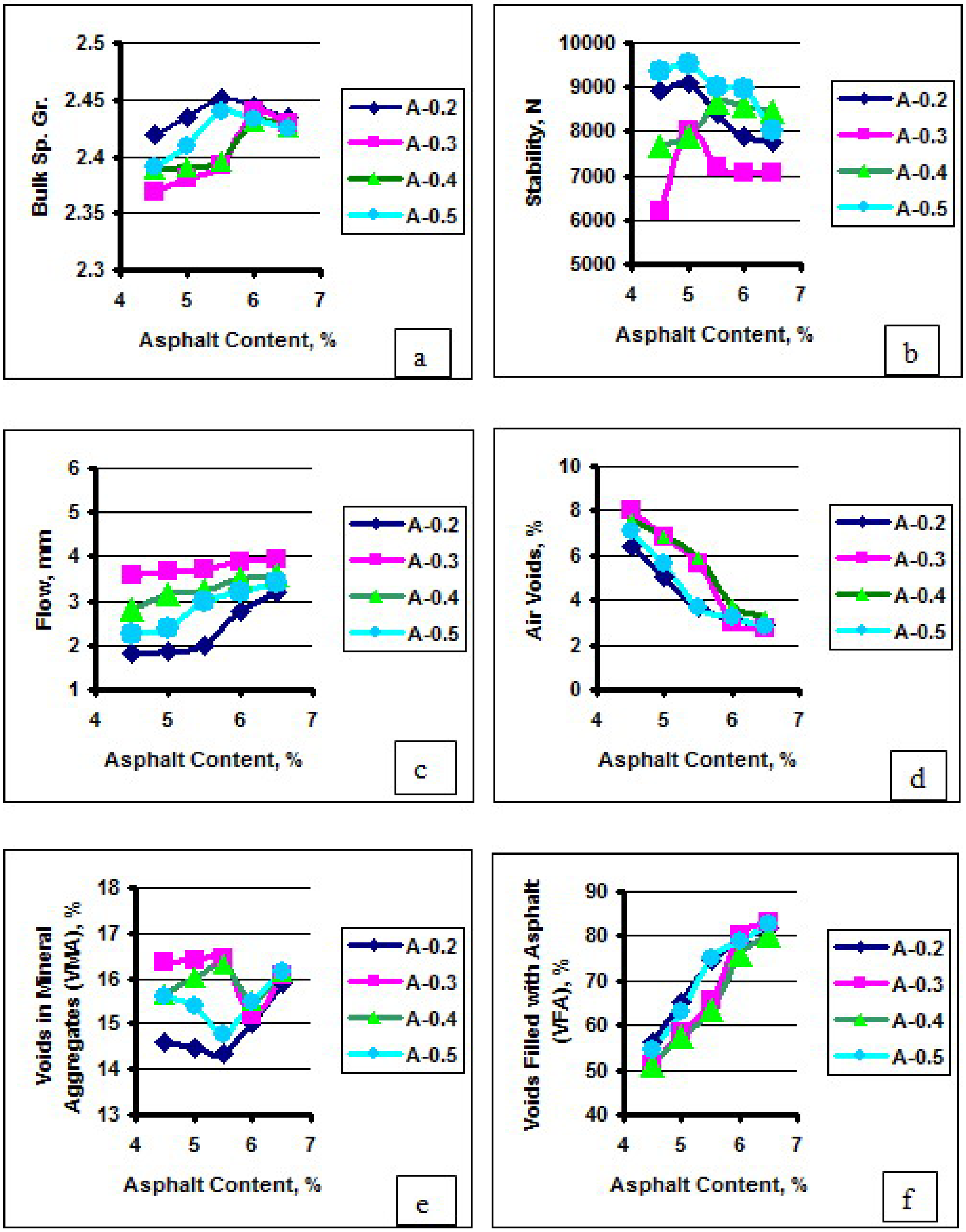

Figure 1. Relationships between asphalt content and the different properties of Marshall test specimens with different amounts of paper mill sludge from Mill A as fiber additive.

Legend: 0.2, 0.3, 0.4 and 0.5 denote % fiber content;
A refers to Mill A sludge

decreases. The flow value increases with increasing AC while Va decrease with increasing AC and approach a minimum. The VMA generally decreases to a minimum value then increases with increasing AC.

The property curves (in Figure 1 and in others not shown here) generally follow the patterns described above, albeit in varying degrees according to type and amount of fibers.

Marshall stability is the maximum load sustained by the Marshall specimen. Stability values of 5338 N and 8006 N are the limits for medium and heavy traffic road pavements, respectively (Faustino and Valencia 2003). All the stability values surpassed the minimum specified value for medium traffic, with many even surpassing the specification for heavy traffic road pavement (Faustino and Valencia 2003).

Flow is the total movement or strain occurring in the specimen between no load and the point of maximum load during the stability test. The strain increases with increasing amounts of asphalt but values within 2 and 4 mm are specified for medium and heavy traffic asphalt SMA pavement, respectively (Faustino and Valencia 2003). The sludge- and wastepaper fiber-added specimens generally exhibited flow values within the specifications.

Va are pockets of air between the bitumen-coated aggregate particles. Filling these voids to a certain limit with a rich bituminous mortar provides high durability (Richardson 1999). Local specifications for SMA set percent Va to be within 3 to 5 percent (Faustino and Valencia 2003).

Va generally decreased with greater amounts of asphalt, a trend opposite to that of bulk specific gravity up to about 6.0% AC where bulk specific gravity has optimized. Va do not regain after this point, but continue to decrease with increases in AC since the void-filling asphalt is lighter than the aggregates. The sludge- and wastepaper fiber- added samples with AC between 5.0 and 6.0% generally meet the specified limits for Va.

VMA is the total volume minus the bulk volume aggregates. Special mixture designs for SMA put VMA at 17% (Brown et al. 1997). The sludge-added samples exhibited values in the range 14.3 – 16.7% range, slightly lower than such design. The fine particles of inorganic matter in the sludge materials may have acted as additional filler in the mixtures.

VFA is the percentage difference between VMA and Va based on VMA. It gives an indication of the performance of the fiber additive as carrier to increase the thickness of binder coating on the aggregates. Data indicate VFA values increasing with increasing AC and consistently close to each other (51-87%). VFA values in the range 65-78% and 65-75% are specified for medium traffic and heavy traffic pavements, respectively (Faustino and Valencia 2003). Generally AC between 5 and 6% gave the desired VFA but not always the required Va of 3-5%. Actually, if VFA for SMA is set at 75% VMA is expected at 16% if Va is at 4%. Va, VMA, and VFA are inter-related and when any two are fixed, so is the third (Pagbilao 2003).

Optimum Asphalt Content (OAC)

Table 3 shows the values for OAC for the different sources and amount of sludge and the property values at OAC estimated from the graphs. An AC of 5.5% was chosen from the optimum range (5 – 6%) to produce the specimens without any fiber. The results (shown in the last row of Table 3) indicate that without fiber, the stability value is lower than the fiber-added specimens by 2.0 to 23%, although still meeting the minimum limit for medium traffic road. However, the percentage air voids is higher (5.74%) thus failing the 3-5% requirement.

Based on the derived optimum conditions, using any of the sludge samples as fiber additive in SMA mixtures generally appears to be technically feasible.

Statistical Analyses of Data

Table 4 shows a summary of the ANACOVA on the effects of fiber source (FS) (Mills A, B, C, D and wastepaper), FC, AC and their corresponding interactions on stability with specific gravity as co-variate, as well as, the ANOVA on the effects of the same variables on flow. Data indicate that FS and the different levels of AC have significant effect on stability while FC alone has none. On the other hand, FS, FC and AC independently bear significant effect on flow.

The DMRT (Table 5) on the treatment means for each factor further details the differences in effects on stability. Among FS, Mill B, followed closely by Mills D and A, gave significantly higher stability values than Mill C and wastepaper. For AC, 5% gave the highest value closely followed by 5.5 and 6%. As to FC, the values indicate that any amount of fiber would have the same effect on stability.

Although Mill B ranked first, however, the highest stability value (9627 N) was obtained with Mill D sludge at 0.3% FC and 6% AC followed by 9571 N with Mill A at 0.5% FC and 5% AC.

In the case of flow, the DMRT in Table 6 shows that Mills A and D fibers gave values closer to the median 3 mm. Mill

Table 3. Properties of asphalt mix at optimum asphalt content

PROPERTIES AT OPTIMUM ASPHALT CONTENT[a/]					
Specification		Optimum Asphalt Content, %	Minimum Stability, N Medium: 5338 N [b/] High: 8006 N	Flow, mm (M) 2.0-4.0 [b/] (H) 2.0-3.55	Air Voids, % 3-5 [b/]
% Fiber	Fiber Source				
0.2	A	5.3	8630	1.88	4.2
	B	5.8	9675	3.68	2.8
	C	6.3	8674	4.25	4
	D	5.4	9061	3.07	3.4
	W	5.8	7998	3.16	3.7
0.3	A	5.6	7162	3.77	5.2
	B	5.7	9075	3.5	3.75
	C	5.4	8986	4	4.2
	D	5.6	9208	2.87	3.2
	W	5.5	8006	3.77	3.7
0.4	A	5.8	8696	3.4	4.6
	B	5.7	9030	3.53	3.9
	C	5.7	7295	4.3	4.9
	D	5.7	9208	2.87	4.7
	W	5.8	7651	3.53	3.2
0.5	A	5.3	9230	2.8	4.4
	B	5.7	9110	4	4.35
	C	6	7562	3.6	4.8
	D	5.5	8630	3.17	4.4
	W	5.8	8051	3.34	3.4
Without Fiber		5.5	7776	2.38	5.74

a/ - Each property value is the average of three test specimens
b/ - Values in each property headings are local specifications for asphalt mixtures
A, B, C, D – Sludge from paper mills A, B, C, and D; W – wastepaper
M and H – Medium and Heavy traffic roads, respectively

Table 4. Summary of analysis of variance

Source of Variation	ANACOVA on Stability		ANOVA on Flow	
	DF	Mean Square	DF	Mean Square
FIBER SOURCE (FS)	4	12347985.24**	4	6.0995**
FIBER CONTENT (FC)	3	476182.64ns	3	2.0984**
FS*FC	12	3503198.80**	12	2.3576**
ASPHALT CONTENT (AC)	4	2402716.22**	4	8.2278**
FS*AC	16	573907.26ns	16	0.0949ns
FC*AC	12	433388.01ns	12	0.1143ns
FS*FC*AC	48	1391060.33**	48	0.2334ns
SP. GR.	1	7754434.68**		
R^2, %	64.2		68.7	
CV	9.705		14.662	

** - Significant at 1 % probability level
* - Significant at 5 % probability level
ns - not significant

Table 5. DMRT on the stability treatment means due to individual effects of fiber source, asphalt content and fiber content

Fiber Source	Mean Stability, N	Asphalt Content, %	Mean Stability, N	Fiber Content, %	Mean Stability, N
A	8197 b	4.5	7967 c	0.2	8051 a
B	8812 a	5	8348 a	0.3	8152 a
C	7824 c	5.5	8269 b	0.4	8174 a
D	8355 b	6	8290 b	0.5	8254 a
W	7600 c	6.5	7915 c		

Means followed by the same letter are not significantly different at alpha=0.05

Table 6. DMRT on flow treatment means due to individual effects of fiber source, fiber content and asphalt content

Fiber Source	Mean Flow, mm	Fiber Content, %	Mean Flow, mm	Asphalt Content, %	Mean Flow, mm
A	3.05 c	0.2	3.12 b	4.5	2.90 e
B	3.41 b	0.3	3.52 a	5	3.11 d
C	3.82 a	0.4	3.39 a	5.5	3.31 c
D	3.06 c	0.5	3.38 a	6	3.63 b
W	3.41 b			6.5	3.81 a

Means followed by the same letter are not significantly different at alpha=0.05

C gave the highest flow value; followed by Mill B. This may be due to the greater amount of fines and extractives in Mill C and B sludge, which might have affected the flow property. Values also significantly increased with increasing AC with the maximum limit of 4 mm almost reached with 6.5% AC.

Results of statistical analyses generally complemented observations based on the derived optimum conditions. That is, that any of the sludge materials can be used as fiber additives for SMA. But from a closer look into the stability and flow values and further considering the results of extraction of the fibers from the asphalt mix, the choice could be in the order of D, A, B and C. In general, AC between 5 and 6% and FC between 0.3 and 0.5% were found sufficient to provide the desired stability, flow and air voids.

CONCLUSIONS AND RECOMMENDATION

The wide range of data obtained to assess the effects of paper mill sludge from four paper mills and also of wastepaper as fiber additive in SMA mixtures for road pavement indicates that any of the fibers can serve as asphalt fiber additive at 0.3 to 0.5% additions. The optimum asphalt content is within 5 – 6%. However, the choice of sludge fiber source will be in the order of Mill D, A, B and C.

Mill D sludge is the first choice for the following reasons: (a) it provides the highest stability value; (b) at any amount of addition of the sludge, flow values are safely within the 2-4 mm limits, even close to the median 3 mm; (c) it has the least extractives that may affect flow; and (d) it is fully extracted from the asphalt mix indicating reliability of the fibers.

Recovery of the fibers after extraction indicates that these can withstand the harsh processing, including the high temperature for mixing with asphalt. Low rates of recovery for Mills B and C sludge may be due to the short to very fine fibers, which may have mixed well with the asphalt during hot mixing.

Further study is recommended on pelletizing the sludge fibers for better handling. Thereafter, an upscale study, from processing of sludge to road application of sludge-asphalt mixtures, is necessary to verify the technical and economic viability of the technology to broaden raw material base for the very expensive currently available asphalt fiber additive.

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