

MODIFIED ASPHALT BY COFFEE CUP FIBRES: AN OPTIMUM MIX DESIGN USING RESPONSE SURFACE METHOD

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ABSTRACT

Stone Mastic Asphalt uses fibres to stabilise high binder contents. The fibres are typically made from natural cellulose, and prevent binder draindown. This study investigates the use of post-consumer coffee cups (liquid paperboard) as a recycled fibre alternative. Coffee cups (CC) use laminated polyethylene as a liquid barrier, making them challenging to recycle in existing paper and plastic recycling systems; approximately one billion coffee cups are landfilled annually in Australia. In this research, coffee cup fibres are used up to 0.6% by total weight of the asphalt mixture across fourteen mix designs. The mixes are optimised by the response surface methodology using the Design-Expert software. Models are created based on Marshall and draindown test results. This study finds that shredded coffee cups effectively reduce the draindown, reduce flow of the asphalt mixture, increase stability, and increase the air voids. The LDPE content slightly increased the viscosity and the softening point of the asphalt binder and dropped its penetration value. Overall, the asphalt mixture containing 0.4% coffee cups (by total weight of the mixture) met all specifications in Australian Standards and performed similarly to the commercial cellulose fibre. This paper also provides practical insights from field trials conducted in Western Sydney using the optimised parameters identified. The pavements will continue to be monitored to develop long term performance comparison between CC and traditional fibres in SMA applications.

1. INTRODUCTION

Fibres have been used to modify asphalt mixtures for many years [1], and a range of their length, width, diameter, and material compositions are applied [2]. The common materials that are used to produce fibres for asphalt modification are carbon [3], glass [4], basalt [5], polyethylene terephthalate (PET) [6], nylon [3], polypropylene fibre (PP) [7], metal [8], and cellulose [9]. Generally, fibres are used to modify the viscoelasticity of the asphalt mixture [10], increase the dynamic modulus [11], improve creep and rutting resistance, and enhance the fatigue life of the mixture [12]. In addition, fine fibres, such as cellulose fibre, are usually used to prevent the draindown in asphalt mixtures with high binder content such as SMA [12,13].

Cellulose fibres are mainly composed of cellulose, hemicellulose, and lignin from natural wood [14,15]. Wood chips are pulped to manufacture paper, cardboard and many other products, and represent 6% of total global energy consumption [16, 17,18] Annually, 16 billion coffee cups are used worldwide, which leads to the logging of 6.5 million trees [19]. In Australia, around one billion coffee cups are landfilled each year [20]. This is due to the hard-to-recycle nature of the cups [21]. Paper cups need to hold liquid, and to do so; they are lined with a plastic layer as a moisture barrier [22].

The lining is typically low-density polyethylene (LDPE), and needs to be separated prior to processing through existing recycling systems; this separation process is expensive and complex [22]. Since the decomposition of plastic-lined coffee cups takes around thirty years [23], a domestic solution to recycle liquid paperboard is indispensable. In this study, we examine the application of the post-consumer waste coffee cups, as an alternative source for cellulose fibre in stone mastic asphalt.

The utilisation of waste fibres in stone mastic asphalt and open-graded asphalt has been investigated before [24,25], and constructive impacts are reported. For instance, It has been revealed that carpet fibres can increase resistance against moisture damage [24], old corrugated paper and recycled magazines can improve rutting resistance and decrease binder draindown [26], and recycled textile fibre can improve the fatigue life of the mixture [27]. Composite fibres and liquid paperboard have not been previously investigated in this application.

This study has been conducted in cooperation with State Asphalt NSW and Closed Loop Environmental Solutions [28], and assesses the potential for this waste as a replacement for commercial fibres in SMA[29].This research benchmarks the properties of SMA mixes with CC, against a commercially available fibre (JRS Viatop).

Table 1: Abbreviations

Abbreviation	Definition	Abbreviation	Definition
CC	Coffee Cups	PET	Polyethylene Terephthalate
HV	High Viscosity Binder	PP	Polypropylene
LDPE	Low Density Polyethylene	RSM	Response Surface Methodology
LPB	Liquid Paperboard	SMA	Stone Mastic Asphalt
MFR	Melt Flow Rate	TfNSW	Transport for New South Wales

2. MATERIALS AND METHODS

2.1. MATERIALS

Bitumen C320 and C450, typical bitumen used in Australia, were used in this study [30]. These bitumen grades were obtained by mixing bitumen C170 and high viscosity (HV) bitumen as instructed by the supplier, Viva Energy Australia Ltd. The aspects of bitumen C170 and HV are shown in Table 2. To obtain bitumen C320, 56% C170 was mixed with 44% HV, and to obtain bitumen C450, 40% C170 was mixed with 60% HV.

SMA10 using C450 binder was used as a control group for Marshall specimens in this study. C320 was used for bitumen tests to investigate the sensitivity of dry-mixed binder modification from the plastic fraction in CC. C450 has a viscosity of 1000pa.s at 60°C [31] and is less prone to viscosity change than C320 (with a viscosity of around 300 at 60°C) [32].

Table 2: Bitumen properties

Specification	Test	HV	C170	Units	Limit
AS 2341.7	Density @ 15°C	1042.6	1040.3	kg/m ³	
	Ductility @15°C after RTFO ¹	15	-	Pa. s	140 - 200
	Dynamic Viscosity @ 60°C	763	171	Pa. s	
AS 2341.2	Dynamic Viscosity @ 60°C after RTFO	2290	362	Pa. s	
	Dynamic Viscosity @ 60°C - as % of original after RTFO	301	212	%	
AS 2341.3	Dynamic Viscosity @ 135°C	0.717	0.37	Pa. s	0.25 - 0.45
AS 2341.14	Flash Point - Frequency	>300	>300	°C	Min 250
AS 2341.8	Matter Insoluble in Toluene - Frequency	<0.1	<0.1	mass %	Max 1.0
AS 2341.12	Penetration @ 25°C/100g/5s	33	72	0.1 mm	Min 62

1- RTFO stands for rolling thin-film oven.

Aggregates (coarse and fine) and mineral fillers (baghouse dust and hydrated lime) were supplied by State Asphalts NSW. The SMA10 mix design conforms to TfNSW R121 – Stone Mastic Asphalt specification particle size distribution requirements [33].

The coffee cups were supplied by Closed Loop Environment Solutions from post-consumer collection sources through Simply Cups. The coffee cups are shredded to 5mm minus and estimated to contain 8-10% LDPE and > 92% paperboard by weight from State Asphalts NSW quality audits. A comparable LDPE film grade (LD2426K) was identified and supplied by Primaplas Pty Ltd from GC Marketing with [MFR (g/10min), Density (g/cm³), Melting point (°C)] = [21, 0.91, 106].

The reference fibre is Viatop supplied by J.Rettenmaire and Sohne [34] for making a control sample. Viatop is a pelletised blend of bitumen and cellulose fibre which is added to the asphalt as a binder drainage stabiliser.

2.2. PREPARATION OF BINDER SAMPLES

The base C320 binder was modified with 0%, 0.5%, and 1% LDPE to provide a characteristic reference depending on the level of binder dissolution and dispersion from the CC, assuming zero binder dispersion, to complete binder dispersion. At a maximum of 0.6% CC (by total weight of the mixture), and 6-7% binder content, the estimated LDPE weight fraction in binder is between 0.4%-0.9%.

For the binder preparation, 700 g of C320 binder was heated 180 °C in an oven, then placed on a 180 °C thermostatically controlled hot plate. The binder was gradually blended with LDPE using a Silverson LM5-A Shear Mixer at 3000 rpm for 60 minutes to achieve a homogeneous blend.

The modified binder samples were tested for their softening point, penetration, and viscosity at 60, 135, and 165 °C and the results were compared with the properties of virgin bitumen C320 and C450.

2.3. PREPARATION OF ASPHALT MIXTURES

Aggregates and bitumen were preheated two hours at 160 ± 5 °C. The hot aggregates were added to a temperature-controlled Bitumen Asphalt Mixer (160°C) with ambient temperature fibres and mixed for 60 seconds. The hot bitumen was introduced into the asphalt mixture and mixed for 10 ± 1 minutes before placement into a Marshall specimen mould. Specimens were compacted by 50 blows of the hammer at the temperature of around 150 ± 3 °C, as specified in AS 2891 [35].

2.4. CONVENTIONAL TESTS OF BITUMEN

Given low polymer modification rates, the 0%, 0.5%, and 1.0% LDPE modified bitumen was evaluated against Australian viscosity-grade tests; penetration at 25 °C, viscosity at 60 and 135 °C, penetration at 25 °C after short-term ageing, and viscosity at 60 °C after short-term ageing. The penetration test indicates the stiffness or consistency of an asphalt binder [36]. Penetration testing was conducted in accordance with AS 2341.12. The viscosity of an asphalt binder is an indication of its resistance to flowing [37,38].

The addition of plastics to bitumen, regardless of its type, increases the viscosity [39]. The viscosity test was conducted at three temperatures: 60, 135, and 165 °C, and the viscosity at 60 °C was measured by a vacuum capillary viscometer according to AS 2341.2 using a PSL-100 tube. The viscosity of the samples at 135 and 165 °C was measured by a Brookfield viscometer following AS 2341.4.

Short-term ageing samples were conditioned using a rolling thin film oven (RTFO) for 85 minutes at 163 °C according to ASTM 2872.

2.5. MARSHALL AND DRAINDOWN TESTS

As outlined in ASTM 6927 [40], a minimum of three Marshall specimens, for each mix design, must be tested. In this study, four Marshall specimens for a given mix design were prepared, and the average of the test results (Stability, Flow number, AV, etc) was considered representative of the mix [40]. Binder content and CC content were optimised across binder content ranges from 6-7% by mass and CC content ranges from 0 to 0.6% by mass of the asphalt mixture respectively.

Although AASHTO M 325 recommends a maximum stabiliser content of up to 0.4% of the total weight of the mixture [42], this study evaluates the inclusion of up to 0.6% coffee cups to attain a better understanding of their impacts. Fourteen different mix designs, and three samples for each mix design (a total number of 42 specimens), are considered. An SMA mixture with 0.3% Viatop by total mass of the mixture, as recommended by the manufacturer, was also prepared to compare commercial fibres and the coffee cups.

Specimens were cooled to room temperature to determine their bulk specific gravity (G_b) [43], theoretical maximum specific gravity (G_t) [44], air voids (AV) [45–47], and thickness [48]. The specimens were conditioned in the water bath for 30-40 min at the temperature of 60 °C before Marshall stability, and the flow tests were conducted [40]. The measured stability values were corrected based on the volume and thickness of the specimens according to ASTM 6927 [40]. A draindown test was also conducted for each mix design according to RMS T648 [49].

2.6. RESPONSE SURFACE METHODOLOGY (RSM)

RSM uses a collection of statistical methods to evaluate the effects of the experimental factors [50]. RSM is used in this study to create a model based on the Marshall and draindown test results to optimise the mix design. The experiments are conducted based on the Central Composite Design (CCD) strategy using the Design-Expert software [51,52]. CCD is a fractional factorial experiment design that provides relationships between responses (dependent variables) and factors (independent variables) at different levels [50]. Given the large number of test permutations and factors evaluated, RSM and CCD provides a significant reduction in experimental cost whilst providing insight into parameter optimisation.

Binder content is the first factor ranging from 6% to 7%, and CC content is the second factor ranging from 0 to 0.6%. Therefore, experiments with 6% or 7% binder content and 0% or 0.6% CC are factorials, experiments with 6.5% binder content and 0.3% CC are centrals, and the rest of the experiments are axials. In this study, six central, four axial, and four factorial points were considered for the CCD strategy (a total of 14 mixes).

Independent variables (factors), defined as (x_1) and (x_2), are binder and CC contents, respectively. For statistical calculations, the real values of a factor (X_i) was converted to a coded value (dimensionless) as (x_i) by Equation 1 [53].

Equation 1:

$$x_i = (X_i - X_0) / \delta X$$

Where X_0 is the real value of a factor at its central level, and δX is the step change value between the low level (-1) and the high level (+1). The dependent variables (responses), which are the indicators of the performance of the mixture, are defined as the (Y) function. The responses are Marshal stability, flow number (FN), Air Voids (AV), and the draindown. To calculate the dependent variables (responses) the polynomial model presented in Equation 1 was introduced [54,55].

Equation 2:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_{12} X_1 X_2 + \beta_{11} X_1^2 + \beta_{22} X_2^2 + \varepsilon$$

Where Y is the dependent variable and X_i , X_i^2 , and X_{ij} are the effects, square effects, and interaction effects on the independent variable, respectively. β_i , β_{ij} , and β_{ii} are the coefficients of the linear, interaction, and squared effects. β_0 is the intercept parameter and ε is the error. Table 3 lists the variables and the acceptable ranges according to Australian Standards. These values will be considered as the basic criteria to optimise the mixture containing CC. To justify the adequacy and significance of the predicted model, analysis of variation (ANOVA) and (P-Value>0.05) significance were used [56,57,58, 59].

Table 3: Dependent variables and the acceptable ranges based on Australian specifications.

Response	Name	Units	Acceptable range	Desirable value	Reference
R1	Stability (corrected)	kN	> 5.5	Peak point	[60]
R2	Flow Number	mm	1.5 - 4	2 - 3.5	[60]
R3	Air Voids (AV)	%	4 - 6	4 - 6	[60]
R4	Bulk specific gravity (Gb)	g/cm ³	NA	-	-
R5	Theoretical maximum density (Gt)	g/cm ³	NA	-	-
R6	Draindown	%	< 0.3	Minimum point	[33]

2.7. SCANNING ELECTRON MICROSCOPY (SEM)

SEM (TM4000Plus with a Bruker SDD-EDS detector) was used to compare the physical microstructure features between CC and Viatop [61,62]. The fibre samples are mounted, then applied with a 15nm gold-coating by Emitech K550x Gold sputter coater.

3. RESULTS AND DISCUSSION

3.1. Size Distribution

Figure 1:1 shows the images of shredded CC and Viatop pellets used in this study. Figure 1:1 a and b are images with a 30-time magnification of both materials, Figure 1:1-c and Figure 1:1-d are CC and Viatop SEM images respectively. The images show comparable physical properties, such as the fibre length and the width and fibre agglomerations (marked in the images as 2 and 3). The Viatop fibres appear to have greater dispersion compared to the CC. Figure 1:1-c also shows the thin layer of LDPE in the CC sample, marked as 1.

3.1.1. Bitumen Properties

The results from the viscosity and penetration tests are shown in Table 4. The penetration value of bitumen C320 before and after RTFO conditioning is 51.6 and 30.5 dmm, respectively. After adding 0.5 and 1% LDPE to bitumen C320, the penetration decreased to 45.8 and 43.6 dmm, and after RTFO conditioning, the values dropped further to 27.2 and 26.1 dmm, respectively. The LDPE modified samples are compared with the viscosity classes C320, C450, and C600 shown in Table 4.

Table 4: Summary of the properties of the binder's properties

Properties	Results of this study			Australian bitumen-grading specification		
	Virgin C320	0.5% LDPE	1% LDPE	C320	C450	C600
Viscosity at 60° C (Pa.s)	367.6	414.4	438.6	260 – 380	Report	500 – 700
Viscosity at 135° C (Pa.s)	0.606	0.66	0.726	0.4 – 0.65	0.70 max	0.6 – 0.85
Penetration at 25° C (dmm)	51.6	45.8	43.6	40 min	Report	20 min
Viscosity at 60° C after RTFO (Pa.s)	772	898.7	963.7	Report	750 – 1150	-
Penetration at 25° C after RTFO (dmm)	30.5	27.2	26.1	Report	26 min	-

The results suggests that C320 modified with 0.5% LDPE is comparable to C450, whilst 1.0% LDPE lies between C450 and C600 classes.

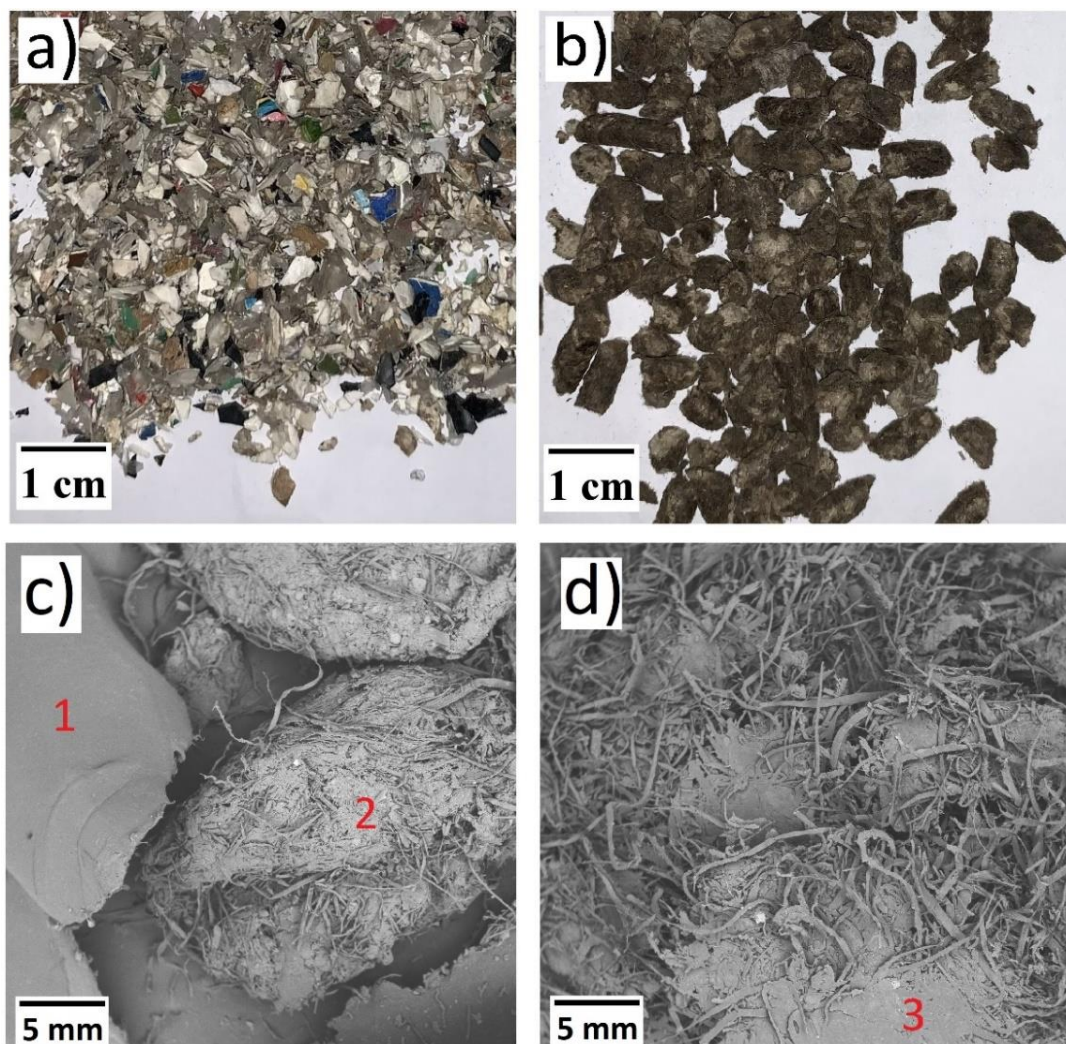


Figure 1: Photographs of a) CC fibres and b) Viatop fibres. SEM images of the c) CC fibres and d) Viatop. Number 1 is an LDPE particle in the shredded CC, 2 is a paperboard particle in shredded CC, and 3 shows the condensed fibres in Viatop

3.2. MARSHALL AND DRAINDOWN TEST RESULTS

Figure 2 shows the effect of CC and binder content on the Marshall properties of the mixture, including stability, flow, air voids (AV), and draindown. Increasing shredded CC % by mass increases stability and reduced flow number values compared to the control mixture. The former indicates increased stiffness, while the latter signifies decreased permanent deformation [41,63]. The Einstein relation describes that when particles are combined with a liquid the mixture viscosity

increases [64] This impact may also be due resultant binder viscosity increase from LDPE modification and subsequent increased mixture stiffness [41].

Figure 2c illustrates that increasing CC % by mass increases mixture air voids (AV) for investigated binder contents. This is possibly to the fibre absorption of free binder, leaving larger inter-particle voids. The effect of LDPE on the viscosity also has impacts on the AV. Workability is inversely related to viscosity; the mixture is expected to compact less for equivalent compactive effort, leaving higher AV.

The draindown test results, depicted in Figure 2d, demonstrate that higher CC content corresponds to lower draindown. The most significant draindown reduction occurs between 0.3-0.4% CC are added. Impacts on draindown beyond 0.4% are limited; CC optimised % by mass is considered to be within 0.3-0.4%. Higher contents do not improve draindown performance and may introducing excessive stiffness.

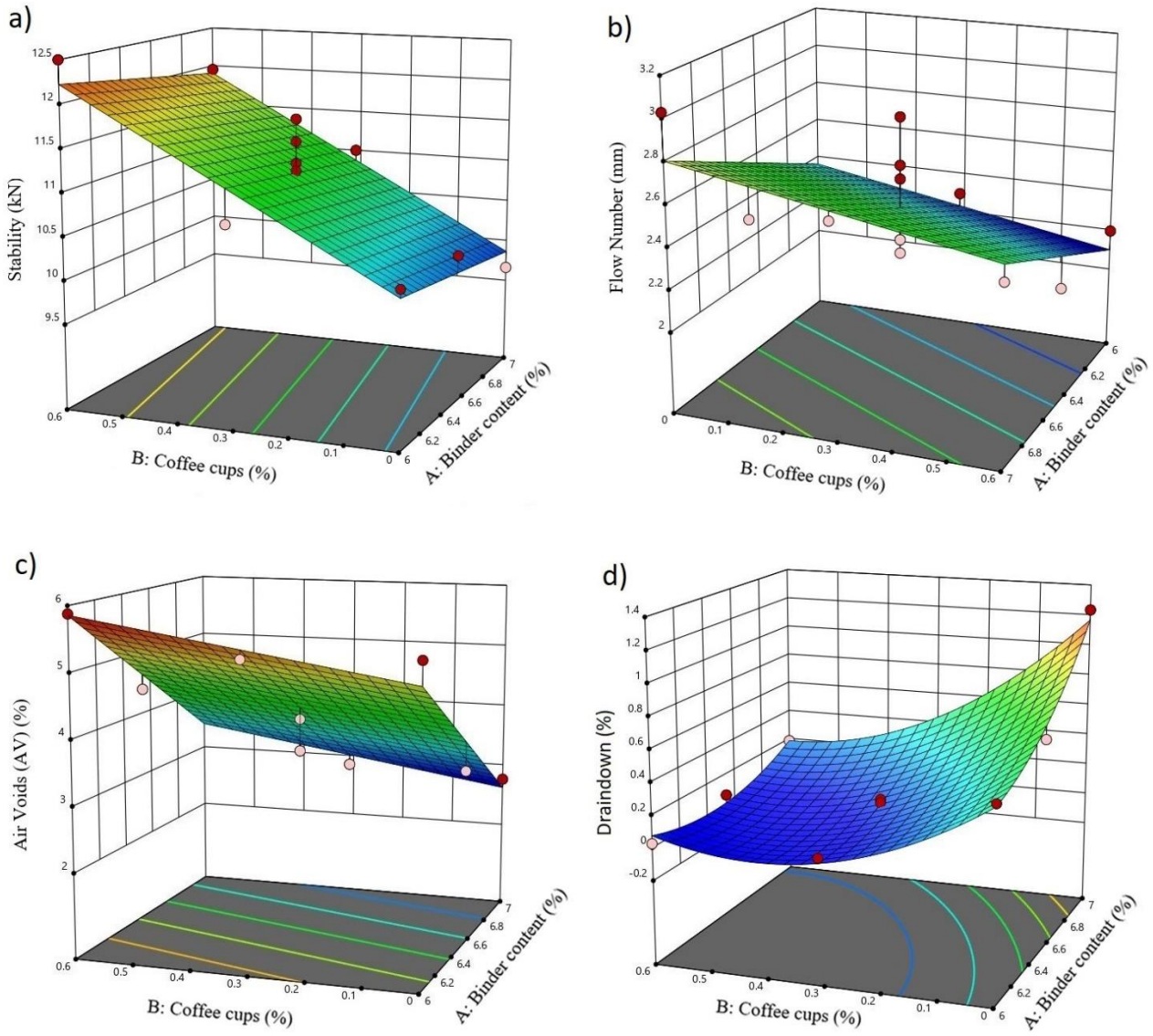


Figure 2: The effects of shredded CC and binder content on; a) stability, b) flow number, c) air voids, and d) draindown.

Table 5 tabulates the developed equations for stability, flow number, AV, and draindown. The coefficients suggest CC content has a relatively higher impact on stability and a lower impact on AV compared with binder content, whilst flow number is more influenced by binder content than the CC content. Draindown is more influenced by CC content than the binder content. Analysis of variance (ANOVA) results (P-values < 0.05) indicate factor significance.

Table 5: Predicted equations and Analysis of variance (ANOVA) for the experimental results (x_1 = coded binder

content, x_2 = coded CC content).

Responses	Coded equation	P-Values for the factors					Model
		x_1	x_2	x_1x_2	x_1^2	x_2^2	
Stability	$= 11 - 0.158 * x_1 + 1.02 * x_2$	0.323	< 0.0001	-	-	-	0.00012
Flow number	$= 2.46 + 0.22 * x_1 - 0.133 * x_2$	0.0325	0.17	-	-	-	0.0476
Air Voids	$= 4.24 - 1.22 x_1 + 0.4 * x_2$	< 0.0001	0.0193	-	-	-	< 0.0001
Draindown	$= 0.101 + 0.206 * x_1 - 0.338 * x_2 - 0.149 * x_1 x_2 + 0.123 * x_1^2 + 0.251 * x_2^2$	< 0.0001	< 0.0001	0.00063	0.0056	< 0.0001	< 0.0001

4. COFFEE CUPS COMPARED WITH VIATOP

Using the RSM method, the asphalt properties are optimised using the mix design parameters; 6.5%, 0.4% by mas CC. The results show [stability, FN, AV, Gb, Gt, and draindown] = [11.39kN, 2.41, 4.38%, 2.34, 2.45, 0.016%]. To evaluate the performance of the CC, the proposed solution is compared with Viatop. The design parameters of these two mixes are identical, with the exception of 0.4% CC and 0.3% Viatop by mass respectively. Flow, Gb, and Gt of both mixtures have high similarities (<0.1 mm difference FN and 0.02% for Gb and Gt). CC has higher AV and stability than Viatop. It is hypothesised that the increased stiffness and AV is due to LDPE modified binder CC material.

5. FIELD TRIAL - ON-GOING EVALUATION

Three field trials were conducted in Western Sydney between December 2022 and May 2023 under the NSW EPA Resource Recovery Framework to evaluate the field efficacy of CC fibres compared with Viatop in SMA10. The optimized fibre contents (0.3% Viatop and and 0.4 and binder percentages from this study were used over Trial 1 (100m private heavy vehicle roadway in Preston, NSW), Trial 2 (470m collector road in Penrith, NSW) and Trial 3 (330m residential road in Erskine Park, NSW). The trials used a control (SMA10 with Viatop) and treatment pavement (SMA10 with Coffee Cup Fibres) on identical Dense Graded asphalt base courses in continuous traffic lanes, as shown in figure 3.

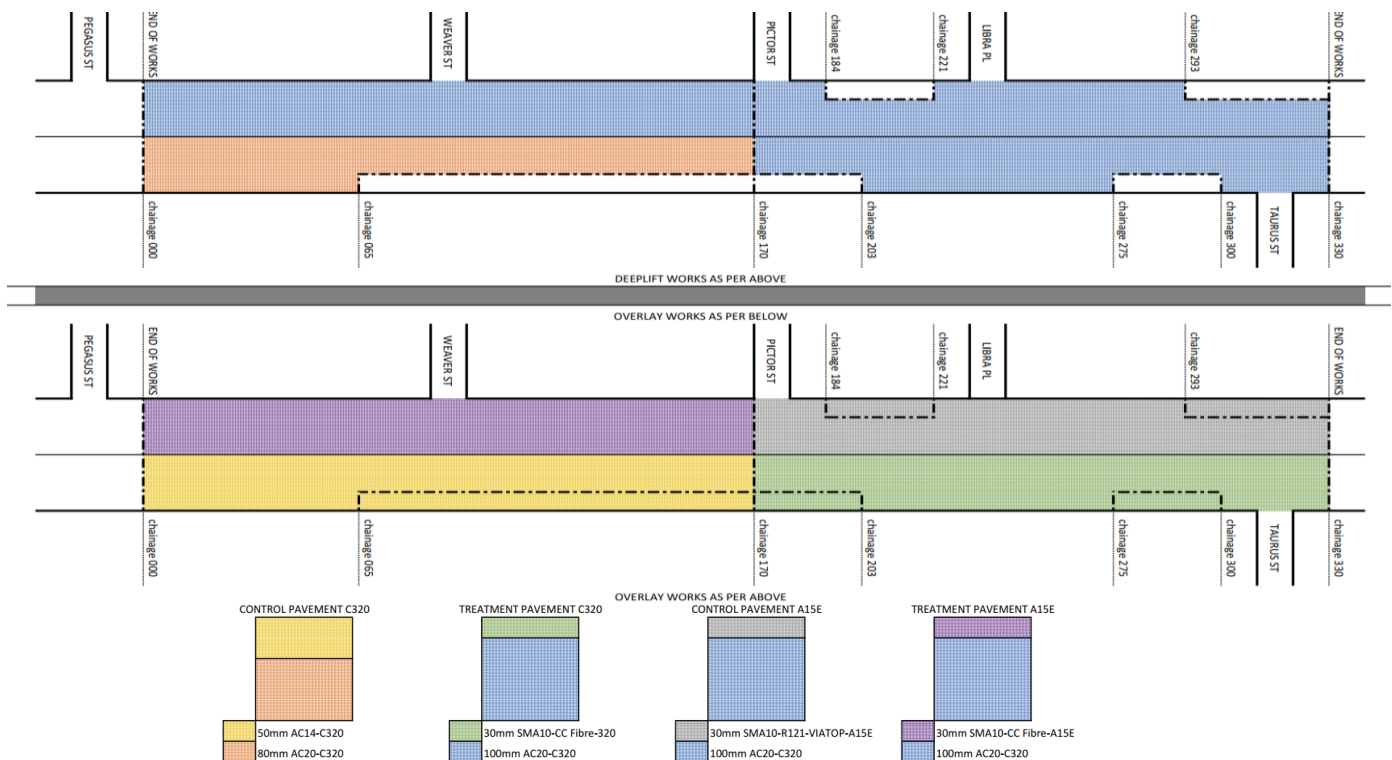


Figure 3: Pavement construction plan used to compare typical dense grade (14mm nominal) asphalt design with thinner SMA10 wearing course (Viatop control compared with CC fibre)

Table 6: Field trial volumetric properties and draindown results

Pavement Trial	Fibre type	Fibre Content	Binder Content (AS2891.3.1)	Air Voids (AS2891.8)	Draindown (TfNSW T648)
Prestons - 19/12/2023	CC	0.4%	6.3%	4.5%	0.10%
Prestons - 19/12/2023	Viatop	0.3%	6.5%	4.8%	0.00%
Penrith – 26/02/2023	CC	0.4%	6.5%	5.2%	0.15%
Penrith – 26/02/2023	Viatop	0.3%	6.5%	5.4%	0.10%
Erskine Park – 26/04/2023	CC	0.4%	6.3%	4.7%	0.10%
Erskine Park – 26/04/2023	Viatop	0.3%	6.6%	5.3%	0.05%

The field trials indicate comparable independent and dependent results to the laboratory testing. The draindown performance is consistent with the laboratory results; the Viatop mixes achieved lower draindown, however, Air Voids were not found to be predicted by binder content for constant Fibre content. This is likely due to minor variation within the asphalt particle size distribution across approximately 500T of SMA10 production across the trials.

6. CONCLUSIONS AND FUTURE WORK

This paper investigates the application of shredded CC as an asphalt additive. Marshall tests, draindown, SEM, and modified bitumen characterisation tests have been conducted, and the optimum shredded CC content is estimated. Based on the test results, the following conclusions are drawn:

- By introducing shredded CC into the mixture, stability and air voids increased, but the flow number dropped. Shredded CC also stiffened the mixture and enhanced resistance to permanent deformation. Based on the RSM method for SMA10 with 6.5% binder content, shredded CC content of 0.4% by total weight of the mixture met all specified limits in Australian Standards for stability, flow number, and air voids.
- Shredded CC significantly reduced the draindown of the mixture. The optimum amount of shredded CC content to prevent draindown was found to be 0.4% by the total weight of the mixture. Addition rates greater than 0.4% had negligible effect on binder draindown.
- Bitumen tests were conducted independently to simulate the impact of mild LDPE modification on the properties of the binder. Samples modified with 0.5 and 1% LDPE were examined for penetration and viscosity before and after RTFO aging and compared with virgin C320 binder.
- Properties of bitumen modified with LDPE with 0.5% LDPE plastic are comparable to C450 grade binder, whilst bitumen modified with 1% LDPE lies between the properties of C450 and bitumen C600 grade binder.
- SEM images show that the physical characteristics of CC and Viatop fibres are very similar; however, Viatop has greater dispersion than CC, and does not contain LDPE.
- The addition of 0.4% shredded coffee cups to the mix resulted in very similar performance to the commercial fibre (0.3% Viatop). The mixture with 0.4% shredded CC achieved higher stability and air voids which is likely due to the LDPE modification from CC.
- Given natural variation in particle size distribution in commercial asphalt production, further research using regression and optimisation approaches may provide deeper insight into predicting asphalt mix design properties for given input parameters.
- The treatment pavements will be monitored fortnightly for typical failure modes; cracking (over-stress), stripping (delamination and adhesion/cohesion impacts), and rutting (permanent deformation). The treatment pavements and control pavements will be assessed for wheel path rut depth using AustRoads Test Method AG:AM/T009 at annual intervals using a vehicle-based laser profilometer to assess permanent deformation over time.
- The field trial provides a promising demonstration of a viable recycling solution and end-market for hard-to-recycle liquid paperboard waste streams in construction materials.

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