EXPLORING THE POTENTIAL OF CATALYTIC CRACKING OIL SLURRY AS HIGH AROMATIC RUBBER FILLING OIL

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Abstract:

The utilization of catalytic oil slurry furfural extract as a high aromatic filling oil holds immense potential for enhancing rubber performance and properties. This study focuses on the properties and composition analysis of oil slurries extracted from the Maoming Petrochemical No. 2 and No. 4 catalytic cracking units, revealing a high content of aromatic hydrocarbons up to 70%. Systematic experiments identified 2# slurry oil as optimal for butadiene rubber (BR) and 4# slurry oil as suitable for styrene-butadiene rubber (SBR). Furthermore, a market feasibility comparison evaluates the performance of synthetic rubber infused with high aromatic oil, providing insights into the potential market acceptance of the 2# and 4# slurry oil extractions. This comprehensive study not only highlights the technical advancements in rubber manufacturing but also emphasizes the competitive edge and economic viability offered by catalytic oil slurry furfural extract as a high aromatic filling oil.

1 Introduction

Rubber industry advancements have long been intertwined with the quest for innovative materials that can enhance the performance and properties of rubber products [1, 2]. In this context, the utilization of catalytic oil slurry furfural extract as a high aromatic filling oil presents a promising avenue for improving the quality and characteristics of rubber compounds. The selected oil from the Maoming Petrochemical No. 2 and No. 4 catalytic cracking units, subjected to furfural refining and extraction [3], has emerged as a focal point of research due to its rich composition, particularly with aromatic hydrocarbons reaching up to 70%. Fluid Catalytic Cracking (FCC) is a petroleum refining process that converts heavy hydrocarbon feedstock into lighter, more valuable products like gasoline and diesel, utilizing a powdered catalyst in a fluidized bed reactor [4-6]. The analysis of these oil slurries shows their potential as raw materials for rubber softeners, specifically for certain types of rubber. Through meticulous experimentation and analysis, it has been determined that the slurries from the 2# devices are well-suited for butadiene rubber (BR), while the slurries from the 4# devices exhibit compatibility with styrene-butadiene rubber (SBR). This strategic alignment between oil slurry types

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and rubber varieties underscores the importance of tailored solutions in optimizing rubber performance. FCC slurry oil is typically used as a feedstock for cokers or blended into fuel oils in refineries [7-9]. The research examines how different oil quantities affect rubber properties, aiming to determine the optimal amount for the best results. This study identifies optimal conditions for using oil slurries in rubber formulations to improve processing efficiency, reduce energy consumption, ensure uniform additive dispersion, and enhance the elasticity and elongation of vulcanized rubber.

The findings highlight both the technical and economic advantages of using catalytic cracking oil extracts in rubber production. Unlike prior studies that focused on the use of catalytic cracking oil slurry for fuel blending or asphalt modification, this work explores its potential as a high aromatic rubber filling oil. Furthermore, a comparative analysis with conventional rubber oils prevalent in the market sheds light on the competitive edge offered by catalytic cracking oil extraction oils. The study evaluates the feasibility of market adoption by assessing the performance of synthetic rubber infused with high aromatic oil under standardized conditions. This market feasibility comparison [10, 11] serves as a crucial benchmark for gauging the potential acceptance and scalability of the $2^{\#}$ and $4^{\#}$ slurry oil extractions in commercial rubber applications. In essence, the exploration of catalytic oil slurry furfural extract as a high aromatic filling oil represents a significant stride towards advancing the rubber industry's quest for superior materials and processes. By elucidating the intricate interplay between oil slurry properties, rubber characteristics, and market dynamics, this research sets the stage for transformative innovations in rubber manufacturing, with far-reaching implications for product quality, operational efficiency, and economic viability.

2 Methodology

2.1. Materials and Instruments

Two kinds of FCC slurry oil were used in this experiment. The oil was extracted from the oil slurry from the $2^{\#}$ and $4^{\#}$ Catalytic Cracking Units of the Sinopec Maoming Petrochemical Company, after the extraction of furfural refining. Chemicals of particular interest in this study were 60-90℃ petroleum ether and pure aniline. A host equipment used were Wechsler's balance, 30-90℃ constant temperature water tank, 1-4 mm internal diameter capillary viscometer, 0.1℃ indexing thermometer, JSR1104 kinematic viscosity tester, YN-8 kinematic viscosity tester, WYA-25 Abbe refractometer, aniline point detector, 5 mL pipette and iron rack. The raw materials and excipients of this synthetic rubber used are shown in Table 1. After referring to various literature and drawing on the opinions of relevant scholars, the basic formula of the synthetic rubber employed is showcased in Table 2. All experimental equipment for rubber preparation and performance test used are listed in Table 3.

Table 1. Raw Materials and Excipients for Synthetic Rubber [12].

Items	Name of Material
Raw glue	Natural rubber (NR), styrene butadiene rubber (SBR), butadiene rubber (BR) and chlorinated polyethylene (CPE)
Activator	Stearic acid (SAO) & zinc oxide (ZnO)
Reinforcing agent	Carbon black
Plasticizer	$2^{\#}$ oil slurry pumping out oil & $4^{\#}$ slurry to extract oil
Accelerator	Sinopec high aromatic oil 260
Crosslinking agent	2, 2- two thiosulfate two benzothiazoles (DM)
Vulcanizing agent	Three allyl isocyanoureone (TAIC)

Table 2. Basic Synthetic Formulations (Mass Fraction Basis) of Various Types of Rubber.

Item	**NR Formula**	**SBR Formula**	**BR Formula**	**CPE Formula**
Raw glue	100	100	100	100
Carbon black	50	50	50	50
Stearic acid	2	2	2	2
Zinc oxide	3	3	3	10
Filling oil	15	15	15	15
DM	1	1	1	-
TAIC	-	-	-	3
BIPB	-	-	-	3
S	2.5	2.5	2.5	-

Table 3. List of Experimental Equipment.

Name	**Factory/Manufacturers**
Rubber mixer (water cooling)	Dongguan Zheng Gong mechanical and electrical equipment Technology Co., Ltd.
No rotor vulcanization instrument, model M-2000N	-
The flat vulcanizing machine, model 300T+2RT	-
Slice machine, model GT-7016*	Suzhou Jie He Industrial Co., Ltd.
Tension test machine, model UT-2080 less than 0.25%	-
Rubber resilience test machine, model XY-6074	-
Rubber DIN abrasion tester, model XY-6073	Jiangdu Xuan Yu experimental Machinery Factory
The rubber fatigue testing machine, model XY-607	Jiangdu Xuan Yu experimental Machinery Factory
LX-A shore hardness tester	-
Rubber aging test box, model GT-7017-EM	High-speed rail testing instrument (Dongguan) Co., Ltd.

2.2. Crude Oil Properties

Relevant national standards or industry standards was adopted in the determination and calculation of some properties of the two oil slurries, as shown in Table 4.

Table 4. Main Standard Determination Methods.

Items	**Test Method**
Oil viscosity	GB/T 265-88
Oil density	Determination of liquid specific gravity (Wechsler) balance
Refractive index (RI) of oil products	SH/T 0724
Aniline point of oil	GB/T 262-88
Calculation of molecular weight of oil fractions	SH/T 0730-2004
Calculation of viscosity gravity constant (VGC) of oil products	NB/SH/T 0835-2010
Oil carbon distribution and structure family composition (n-d-M method)	SH/T 0729-2004

Using Wechsler balance method of measuring the liquid specific gravity, by changing the oil temperature (30-90℃) and measuring at 10℃ interval, the density-temperature relationship was also explored. On the other hand, the temperature of the oils was measured from 30-99.5℃ using GB/T265-88 standard method and the

viscosity change with the two oil products were observed and the trend explored. Next, the viscosity of the most commonly used oil in the market was researched and compared with those of $2^{\#}$ and $4^{\#}$ slurry oil.
Viscosity index (VI) of the oils was calculated following the GB/T2541-88 method in accordance with Equation 1.

$$VI = \frac{L - U}{L - H} \times 100 \tag{1}$$

where, L = kinematic viscosity of the oil products with the same kinematic viscosity at 100°C and the VI of 0 at 40°C; H = kinematic viscosity of the oil products with the same kinematic viscosity as the sample at 100°C and the VI of 100 at 40°C, mm^2/s; U = viscosity of the specimen at 40°C and; Y = the movement sticky at 100°C of the sample, all measured in mm^2/s. L and H can be obtained by interpolation from GB/T2541-88 table. In order to more scientifically and intuitively evaluate whether the test oil can meet the requirements of market oil consumption, VGC of $2^{\#}$ oil slurry pumping oil and $4^{\#}$ slurry extraction oil, was calculated. This calculation was mainly based on the viscosity calculation method of the NB/SH/T 0835-2010 petroleum fraction given by Equation 2 [13].

$$VGC = \frac{G - 0.0664 - 0.11541\, g\,(V - 5.5)}{0.94 - 0.1091\, g\,(V - 5.5)} \tag{2}$$

In Equation 2, G is defined as 15°C density (g/cm^3) and V = 40°C of motion viscosity (mm^2/s).

2.2.1. Carbon Distribution Measurement

Density of the two oil kinds at 20°C can easily be obtained from density-temperature relationship. In this study, RI, density and molecular weight of the test oil at 20°C of the two kinds of oil were calculated using the viscosity at 37.8 and 98.9. The coefficients v and ω were calculated using Equations (3) and (4), respectively. RI at 20°C is denoted as 'n_D^{20}' [14].

$$v = 2.51(n_D^{20} - 1.4750) - (d_4^{20} - 0.8510) \tag{3}$$

$$\omega = (d_4^{20} - 0.8510) - 1.11(n_D^{20} - 1.4750) \tag{4}$$

These data were brought into the corresponding formula to calculate the carbon distribution of the sample (%C_A、%C_N、%C_P). Percentage of carbon atoms (C_A) in the aromatic rings was calculated by means of the molecular weight (M), in line with Equations 5 and 6.

$$\%C_A = 430v + \frac{3600}{M} \qquad \text{(if 'v' is +ve)} \tag{5}$$

$$\%C_A = 670v + \frac{3600}{M} \qquad \text{(if 'v' is –ve)} \tag{6}$$

The percentage of carbon atoms in the total ring (aromatic ring and naphthenic ring), C_R, was calculated using ω and M, as given by Equations 8 and 9.

$$\%C_R = 820\omega - 3S + \frac{10000}{M} \quad \text{(when } \omega \text{ is +ve)} \tag{7}$$

$$\%C_R = 1400\omega - 3Sv + \frac{10600}{M} \quad \text{(when } \omega \text{ is -ve)} \tag{8}$$

Next, the percentage of carbon atoms (C_N) in the naphthenic ring and the percentage of carbon atoms in alkane (C_P) were calculated using Equations 10 and 11, respectively.

$$\%C_N = \%C_R - \%C_A \tag{9}$$

$$\%C_p = 100 - \%C_R \tag{10}$$

2.2.2. Molecular Weight Estimation

Molecular weight of the 2# oil slurry was extracted from the viscosity-molecular weight relationship in Figure 1.

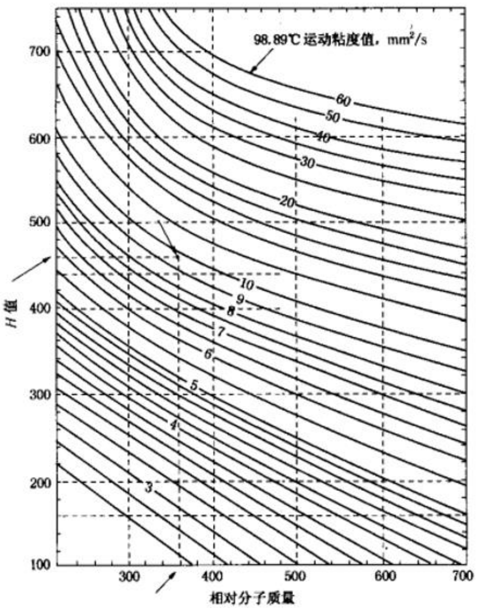

Figure 1. Schematic Diagram of Viscosity Molecular Weight Association.

2.3. Rubber Mixing and Performance Testing

Rubber and ingredients were mixed together to form a homogeneous mixture. According to the basic formula in Table 3, the raw rubber and various ingredients were mixed evenly in two roll mixing machine. Initially, the machine was switched ON and the tap connected to it was opened to prevent it from overheating. About 100g of the rubber was rolled on the machine at least 5 times. The distance between the rollers was adjusted to 2mm using 2 gears on the machine to ensure proper mixing and homogenization. ZnO and stearic acid were added to the rubber and the rolling was continued for few minutes. Then, ¾ of the rubber was cut from right-to-left or from left-to-right using a knife to facilitate thorough mixing of the three items. Carbon black was slowly added to the rubber and the same principle used while adding ZnO and stearic acid was used. After that, slurry oil was added to the rubber and allowed to roll for few minute in order to ensure proper mixing and the cutting and rolling was continued. The remaining additives (sulfur, DM, or TAIC) was added to the rubber and the rolling and cutting continued for few minutes. Lastly, the gears were adjusted to increase the space between the rollers and rolled 2-3 times. This last step completes the mixing. The rubber performance was tested following various standards shown in Table 5.

Table 5. Performance Test Standards.

Items	Related Standards
Vulcanization characteristics	GB/T 16584-1996
Tensile property	GB/T 528-2009
Tear strength	GB/T 529-2008
Shore of hardness	GB/T 531-1999
Resilience	GB/T 1681-2009
Aging properties of hot air	GB/T 3512-2014
Abrasion	GB/T 9867-2008

In this study, a series of tests on the properties of vulcanized rubber was carried out following relevant standards, including tensile strength, tear strength, wear resistance, hardness, hot air aging, resilience, flexural fatigue, wear degree and elongation change.

2.4. Optimum Oil Quantity Determination

In the rubber filled with oil, the index affecting the performance of the oil filled rubber is not only the choice of suitable rubber oil types but also the selection of suitable rubber oil filling amount. Therefore, in order to explore the optimum conditions for the filling of oil slurry in rubber, the optimum oil filling amount in BR and SBR for $2^{\#}$ oil pulping oil and $4^{\#}$ slurry oil extracted from the selected matching rubber was explored.

2.4.1. Market Feasibility Comparison

In order to investigate the feasibility of the application of oil slurry oil in the market, in addition to the longitudinal study, a horizontal study was adopted to determine the performance of synthetic rubber with high aromatic oil under the same conditions in some market. That way, the feasibility of the market promotion of the $2^{\#}$ oil slurry extraction oil and $4^{\#}$ slurry oil extraction was compared. Due to the time of the experiment, the quantity of oil filling quantity is 10, and the raw glue BR is used as the invariants. The oil is extracted from the 260 and the $2^{\#}$ slurry by changing the filling oil.

3 Results and discussion

3.1. Effect of Oil Density of Furfural Extracted Oil on Temperature

Table 6 reveals the density of the oil types at various temperatures.

Table 6. Density of Oil Extracted from $2^{\#}$ & $4^{\#}$ Slurry at Various Temperatures.

Run	$2^{\#}$ Oil Slurry Extraction Oil		$4^{\#}$ Oil Slurry Extraction Oil	
	Temperature (℃)	Density(g/cm^3)	Temperature (℃)	Density(g/cm^3)
1.	29.9	1.08155	30	1.07095
2.	40	1.07545	40	1.06465
3.	50	1.0665	50	1.05945
4.	60	1.0578	60	1.05425
5.	70	1.05255	70	1.04695
6.	80	1.04795	80	1.0376
7.	90	1.0376	90	1.02555

Trends between the two relationship in Table 6 is shown in Figure 2.

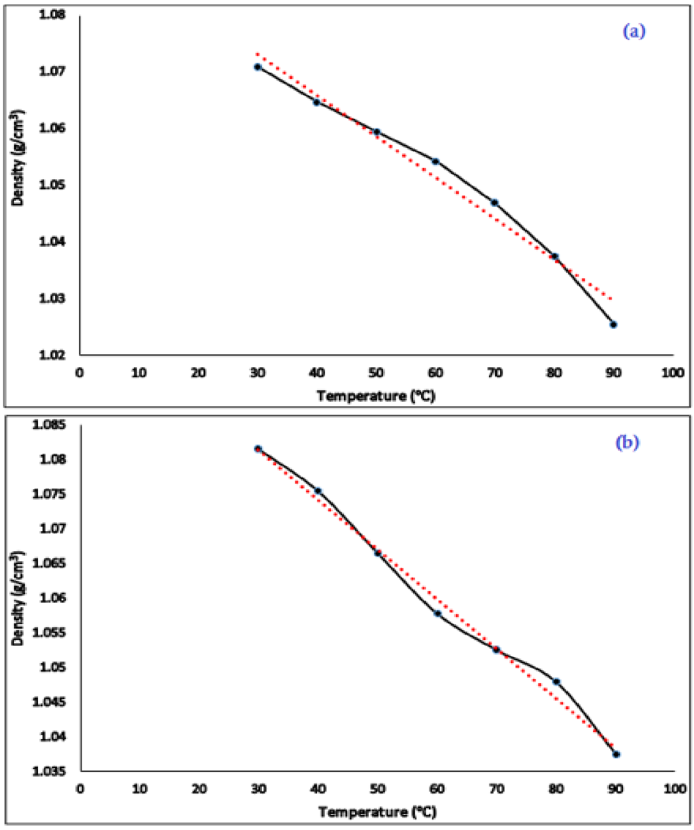

Figure 2. Density-Temperature Relationship of (a) 2# and (b) 4# Oil Extraction Oil.

It is observed that the reduction in oil density of the 2# and 4# oil slurry with increasing temperature can be attributed to thermal expansion, which reduces the molecular packing efficiency of the oil constituents, thereby decreasing density. At this point, the performance of the two oil products is not very different from that of most oil products.

3.2. Effect of Oil Viscosity of Furfural Extracted Oil on Temperature

Table 7 showcases the kinematic viscosity of the extracted slurry oils at temperatures ranging from 20.59-99.6°C for 2# and 20-99.5°C for 4# oil, respectively.

Table 7. Kinematic Viscosity of 2# & 4# Slurry at Various Temperatures.

Run	2# Oil Slurry Extraction Oil		4# Oil Slurry Extraction Oil	
	Temperature (°C)	Kinematic Viscosity (mm^2/s)	Temperature (°C)	Kinematic Viscosity (mm^2/s)
1.	20.59	6860.43	20.00	7843.67
2.	30.00	1508.42	30.05	1775.79
3.	40.00	348.45	40.02	525.18
4.	50.00	135.59	50.05	191.92
5.	60.00	68.80	60.05	82.53
6.	70.50	36.88	70.30	44.18
7.	80.40	23.35	80.00	27.52
8.	90.50	15.26	90.05	17.59
9.	99.60	10.87	99.50	11.53

A representative relationship between the oil kinematic viscosity and temperature is illustrated using Figure 3.

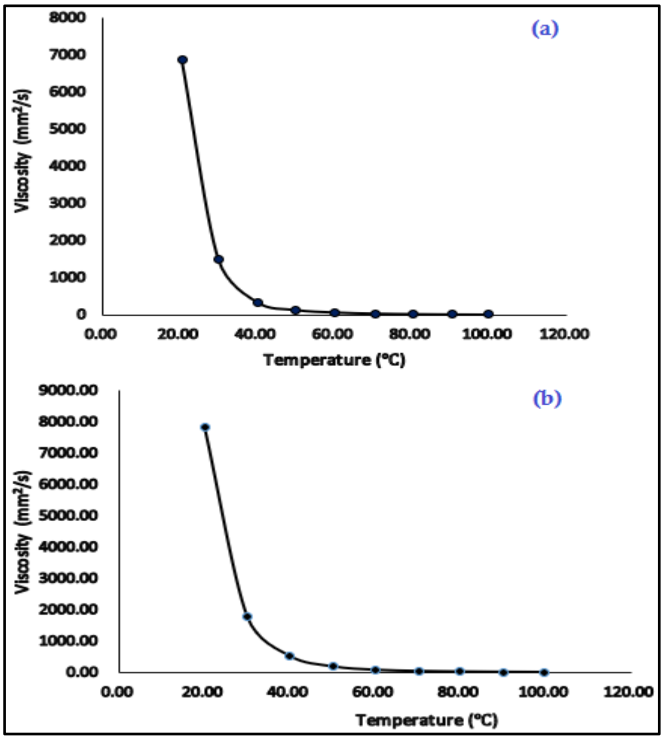

Figure 3. Viscosity-Temperature Relationship of (a) $2^{\#}$ and (b) $4^{\#}$ Oil Extraction Oil.

In Figure 3, it can be seen that the kinematic viscosity of both $2^{\#}$ oil pulps and $4^{\#}$ slurry oil is abnormal at normal temperature. However, as the temperature rises in the region of 20-40℃, the viscosity of the two oils decreases sharply, which indicates that the products viscosity-temperature characteristics are not very good. Because of its solid state at normal temperature, it is necessary to raise the temperature for convenient feeding during its possible use to produce synthetic rubber. This will affect the processing simplicity and processing cost of the factory. Table 8 houses the viscosity of the oils as well as the one sold commercially.

Table 8. Viscosity Comparison of Oil Extraction Oil and the Commonly Used Market Filling Oil.

Item	**$2^{\#}$ Oil Slurry Extraction Oil**	**$4^{\#}$ Oil Slurry Extraction Oil**	**KA8012**	**Special Type II of Meridian Tire**
Dynamic Viscosity at 100℃ (mm^2s^{-1})	10.87	11.53	10-14	15-28

In comparison, it was found that both $2^{\#}$ oil pulping oil and $4^{\#}$ slurry oil can meet the requirements of the viscosity index of market oil, and have the ability to apply in the rubber synthesis market. In addition, they will have a preliminary development prospect.

3.3. Viscosity Index and VGC

Findings show that U of $2^{\#}$ and $4^{\#}$ extraction oil are 348.45 and 525.18 mm^2/s, and Y = 10.87 and 11.53 mm^2/s, respectively. L of $2^{\#}$ and $4^{\#}$ extraction oil are 172.1 and 209.37 mm^2/s after interpolation, and D = 79.29 and 97.85 mm^2/s, respectively. As a result, Table 9 was obtained.

Table 9. VI of FCC Slurry Furfural Extraction Oil.

Oil Sample	**VI**
$2^{\#}$ Extraction Oil	–2
$4^{\#}$ Extraction Oil	–3

As shown in Table 8, VI of the two oils are negative, indicating that the viscosity-temperature characteristics of the two oils are very poor. After the right substitution into Equation 2, VGC of the respective oils are shown in Table 10.

Table 10. VGC of 2# and 4# Oil Extraction Oil.

Item	2# Oil Slurry Extraction Oil	4# Oil Slurry Extraction Oil
VGC	0.585	0.895

After testing a variety of oils based on the VGC, the American Solar Petroleum Company found that the general relationship between the type of rubber oil and the viscosity constant are as shown in Table 11.

Table 11. Classification of Rubber Oil by American Sun Oil Company.

Type	Viscosity Constant
Paraffin base	0.790-0.819
Cyclo - like alkyl	0.820-0.849
Naphthenic group	0.850-0.899
Aromatics	0.900-0.939
Aryl group	0.940-0.999

After their comparison, it is found that the extracted oil from the 4# slurry is very close to the law of the VGC of the aromatic base, while the 2# slurry pumping oil relatively deviates from the general oil law.

3.4. Analysis of Aniline Point of Oil Slurry Furfural Extract Oil

The more soluble hydrocarbons are in aniline, the lower the aniline point [15, 16]. Among all kinds of hydrocarbons, the aniline point of aromatic hydrocarbon is the lowest, followed by naphthenic hydrocarbon. Those of alkyl group are basically the highest. Alkenes and cyclic olefin are slightly lower than naphthenic hydrocarbons whose molecular weight is close to that of polycyclic naphthene, and the aniline point of polycyclic naphthene is much lower than that of mono cyclo-naphthene. For the same hydrocarbon, the aniline point increased with the increase of molecular weight and boiling point. Generally, oils with lower aromatic hydrocarbon content have higher aniline points. So, Table 12 show whether the extracted oil from the 2# and 4# slurry is a high aromatic oil or not.

Table 12. Determination of Aniline Point of 2# and 4# Oil Extraction Oil.

Item	2# Oil Slurry Extraction Oil	4# Oil Slurry Extraction Oil
Aniline Point (℃)	< 8	< 8

It can be seen from the experimental results that the aniline point of the extracted oil from 2# slurry and the extracted oil from 4# slurry is still within the range of < 8℃. Thus, the aniline point of the two oils is far lower than that of the normal naphthenic and alkanes, which indicates that the two oils are rich in aromatic hydrocarbons or polycyclic alkanes. In order to further understand the composition and structure of the two oil products, the carbon analysis of the oil products was carried out.

3.5. Analysis of Carbon Type, RI and Molecular Weight

Properties of oil have an inseparable relationship with their physical data, such as density, viscosity, aniline point and RI. The carbon distribution of 2# oil extraction oil and 4# slurry extract oil is shown in Table 13.

Table 13. Carbon Distribution of 2# and 4# Oil Extraction Oil.

Item	2# Oil Slurry Extraction Oil	4# Oil Slurry Extraction Oil
$\%C_A$	76.42	73.83
$\%C_N$	9.08	9.45
$\%C_P$	14.50	16.71

It can be concluded that the carbon distribution of 2# slurry oil in this test is as high as 76.42% of aromatic ring carbon atom, 9.08% of naphthenic carbon atom and 14.50 for alkanes. The carbon distribution of 4# slurry oil is 73.83, 9.45 and 16.71% of alkanes. In the component content of these two oil products, it can be seen that the proportion of aromatic ring is up to 70%, which meets the requirement of high-quality aromatic oil in the market (as high as 70~90% of aromatics). RI of the oils is as shown in Table 14.

Table 14. Refractive Index of 2# and 4# Oil Extraction Oil.

Item	2# Oil Slurry Extraction Oil	4# Oil Slurry Extraction Oil
Refraction Index (20℃)	1.6300	1.6245

The estimated molecular weights of the oil extracted from the 2# oil and the 4# slurry are shown in Table 15.

Table 15. Molecular Weight Estimation for 2# and 4# Oil Extraction Oil.

Item	2# Oil Slurry Extraction Oil	4# Oil Slurry Extraction Oil
Molecular Weight	315	320

3.6. Vulcanization Property of Rubber

Tables 16-19 displays the vulcanization properties of NR, SBR, cis-BR and CPE, without filling oil and after adding oils from two different kinds of oil slurry, respectively. As read on the computer, the minimum torque (M_L), maximum torque (M_H), degree of vulcanization reached 10% (the scorch time, t_{S1}) and the degree of vulcanization reached 90% (t_{C90}), are shown.

Table 16. NR Vulcanization Characteristics (150℃).

Oil Name	M_H (dN.m)	M_L (dN.m)	t_{S1} (m:s)	t_{c90} (m:s)
Blank group	10.37	1.13	1:52	3:10
2# oil slurry extraction oil	8.12	0.73	2:03	6:01
4# oil slurry extraction oil	8.87	0.93	2:03	6:31

Table 17. SBR Vulcanization Characteristics (150℃).

Oil Name	M_H (dN.m)	M_L (dN.m)	t_{S1} (m:s)	t_{c90} (m:s)
Blank group	17.95	1.95	2:47	27:45
2# oil slurry extraction oil	12.94	1.25	3:13	24:13
4# oil slurry extraction oil	12.06	1.29	3:27	22:29

Table 18. BR Vulcanization Characteristics (150℃).

Oil Name	M_H (dN.m)	M_L (dN.m)	t_{S1} (m:s)	t_{c90} (m:s)
Blank group	12.2	2.91	2:56	10:04
2# oil slurry extraction oil	10.17	1.96	3:26	30:46
4# oil slurry extraction oil	9.05	1.66	3:55	8:22

Table 19. CPE Vulcanization Characteristics (190℃).

Oil Name	M_H (dN.m)	M_L (dN.m)	t_{S1} (m:s)	t_{c90} (m:s)
Blank group	42.08	2.7	0:12	2:12
2# oil slurry extraction oil	10.81	1.21	0:36	56:18
4# oil slurry extraction oil	8.76	1.39	0:37	20:26

M_L is the processing fluidity, and to a certain extent, reflects the interaction between the fillers – while, M_H generally reflects the maximum cross-linking degree of the vulcanized rubber, and is an indicator of the strength of the rubber. The longer the burning time, t_{S1}, the less the adhesive is burnt and also the better the processing safety of the adhesive. Time of the positive vulcanization of the t_{C90} refers to the curing time of the rubber with the best performance. The theoretical meaning is that the vulcanization time corresponds to the maximum crosslinking density. Moreso, the shorter the t_{C90}, the shorter the vulcanization time and the higher the processing efficiency of the rubber. Regardless of the raw rubber type, the M_H and M_L of the rubber added to the filled oil will decrease as compared with the rubber without filling oil, which indicates that the rubber processing flow can be properly improved after adding the filling oil. Mobility improves rubber processing and also affects rubber strength. Also, the longer scorch time observed with the addition of slurry oil can be explained by the oil's role in delaying the activation of accelerators, thereby prolonging the onset of cross-linking reactions and enhancing processing safety. The variation in normal vulcanization time is complex and requires further explanation. In NR and CPE, adding filling oil increases the vulcanization time compared to mixtures without oil, with the effect being most pronounced in CPE. This is a serious pull down of the processing efficiency for the rubber. In SBR and BR, after adding the filling oil, the positive curing time is reduced accordingly. So, filling the two kinds of oil slurry oil for the two kinds of rubber can improve its processing efficiency.

3.7. Mechanical Properties and Thermal Physical Aging

The rubber filled with oil will not only affect the mixing performance of the rubber but also affect the physical and mechanical properties of the rubbers after vulcanization (Tables 20-23).

Table 20. Physical and Mechanical Properties of NR.

Test Items	**Blank Group**	**2# Oil Slurry Extraction Oil**		**4# Oil Slurry Extraction Oil**	
		Determination Value	**Change Rate (%)**	**Determinatio n Value**	**Change Rate (%)**
100% Fixed Extension Stress (MPa)	2.46	0.98	-	1.48	-
300% Fixed Extension Stress (MPa)	11.48	4.71	-	7.12	-
Tensile Strength (MPa)	13.51	11.68	-13.55	12.58	-6.88
Elongation at Break (%)	337.16	505.34	49.88	462.22	37.09
Tear Strength ($kN\cdot m^{-1}$)	26.23	18.16	-30.77	23.43	-10.67
Shore of Hardness	52	44	-15.38	49	-5.77
Wear Degree (%)	1.76	1.72	-2.27	2.23	26.70
Resilience (%)	9.9	7	-29.29	8	-19.19
Flexural Fatigue Performance / times	24879	323116	-	21759	-
Hot Air Aging					
The Change Rate of Tensile Strength (%)	-8.18	-9.12	-	0.60	-
Elongation Change (%)	8.80	10.15	-	23.84	-
Tearing Strength Change (%)	-22.06	-3.58	-	-0.32	-

Table 21. Physical and Mechanical Properties of SBR.

Test Items	Blank Group	2# Oil Slurry Extraction Oil		4# Oil Slurry Extraction Oil	
		Determination Value	**Change Rate (%)**	**Determination Value**	**Change Rate (%)**
100% Fixed Extension Stress (MPa)	2.93	2.59	-	2.31	-
300% Fixed Extension Stress (MPa)	16.45	14.47	-	12.29	-
Tensile Strength (MPa)	17.45	20.02	+14.73	22.82	+30.77
Elongation at Break (%)	315.50	378.90	+20.10	468.78	+48.58
Tear Strength ($kN·m^{-1}$)	41.86	46.13	+10.20	54.50	+30.20
Shore of Hardness	57.5	51.5	-10.43	52.17	-9.27
Wear Degree (%)	2.92	1.61	-44.86	4.40	+50.68
Resilience (%)	17	14.5	-14.71	15.3	-10.00
Flexural Fatigue Performance / times	482982	301006	-	84677	-
Hot Air Aging					
The Change Rate of Tensile Strength (%)	-25.94	-10.57	-	-9.33	-
Elongation Change (%)	-46.19	14.15	-0	0.76	-
Tearing Strength Change (%)	16.82	31.71	-	22.03	-

Table 22. Physical and Mechanical Properties of BR.

Test Items	Blank Group	2# Oil Slurry Extraction Oil		4# Oil Slurry Extraction Oil	
		Determination Value	**Change Rate (%)**	**Determination Value**	**Change Rate (%)**
100% Fixed Extension stress (MPa)	1.70	1.23	-	1.20	-
300% Fixed Extension Stress (MPa	0.00	5.36	-	5.54	-
Tensile Strength (MPa)	6.87	11.43	+66.38	9.13	+32.90
Elongation at Break (%)	257.84	489.06	+89.68	437.36	+69.62
Tear Strength ($KN·m^{-1}$)	46.16	59.66	+29.25	51.84	+12.31
Shore of Hardness	46	44	-4.35	42	-8.70
Wear Degree (%)	1.63	2.06	+26.38	2.25	+38.04
Resilience (%)	12	13	+8.33	13	+8.33
Flexural Fatigue Performance / times	790050	808699	-	780009	-
Hot Air Aging					
The Change Rate of Tensile Strength (%)	55.72	30.40	-	76.78	-
Elongation Change (%)	-25.22	-11.57	-	-17.00	-
Tearing Strength Change (%)	-42.45	1.84	-	-32.98	-

Table 23. Physical and Mechanical Properties of CPE.

Test Items	Blank Group	$2^{\#}$ Oil Slurry Extraction Oil		$4^{\#}$ Oil Slurry Extraction Oil	
		Determination Value	Change Rate (%)	Determination Value	Change Rate (%)
100% Fixed Extension Stress (MPa)	0.00	3.97	-11.60	4.92	-21.16
300% Fixed Extension Stress (MPa)	0.00	0.00	-12.04	0.00	-25.29
Tensile Strength (MPa)	11.65	9.45	-18.88	9.30	-20.17
Elongation at Break (%)	70.37	219.69	+212.19	168.84	+139.93
Tearing Strength ($KN\cdot m^{-1}$)	23.83	28.56	+19.85	28.80	+20.86
Shore of Hardness	77	60	-22.08	44	-42.86
Wear Degree (%)	3.74	4.27	+14.17	3.00	-19.79
Resilience (%)	3	4	+33.33	4	+33.33
Flexural Fatigue Performance / times	705	301006	-	301006	-
Hot air aging					
The Change Rate of Tensile Strength (%)	79.60	-8.34	-	17.11	-
Elongation Change (%)	0.58	-38.38	-	19.04	-
Tearing Strength Change (%)	13.51	14.43	-	12.90	-

In Table 20, in addition to the elongation, the physical and mechanical properties of NR with oil slurry out of the oil are reduced. In that case, the two kinds of oil slurry are not recommended in NR. Tensile strength, tearing strength and elongation at break of the SBR adding oil slurry oil (Table 21) is further improved than the SBR without oil, of which the tensile strength of the $4^{\#}$ oil pulping oil increases by 30.77% while the tear strength increases by 30.2%. As for the thermal aging test after hot air aging, the decrease rate of the tensile strength of the SBR is lower than that of non-oil. The effect of $4^{\#}$ oil slurry pumping out oil is best observed. But the rise in the tearing strength may be as a result of the hot air aging process, which normally promotes the rubber. Sulphuration improves the crosslinking density of vulcanized rubber [12], thereby enhancing the physical and mechanical properties of rubber. The study then tested and compared the optimum oil charge for SBR filled with $4^{\#}$ oil extraction. It could be observed in Table 22, that the tensile strength, tearing strength, elongation and spring back of BR adding oil slurry oil are further improved than non-oil filled BR – in which the increase in tensile and tear strength for rubber with $2^{\#}$ slurry oil (66.38 & 29.25%) can be linked to the higher aromatic content, which enhances cross-linking density and provides improved mechanical reinforcement of the rubber matrix. For the thermal aging test [17], the tear strength of the $2^{\#}$ slurry oil still keeps high performance, while the blank group and the $4^{\#}$ slurry oil are affected by the thermal aging, as the tear strength of the oil slurry drops greatly. In view of that, the optimum oil charge of BR filled with $2^{\#}$ oil extraction oil was tested. Tensile strength of the CPE added to the oil slurry is 20%, as observed in Table 23, resulting in the improvement of the elasticity. But the wear degree of the rubber with $4^{\#}$ slurry oil is also reduced and the wear resistance of the rubber is enhanced. For the thermal aging test [18], the tensile strength and elongation of the $2^{\#}$ oil pulping oil decreased, while the physical and mechanical properties of the $4^{\#}$ slurry oil still maintain a high performance. In order to make a more rational design experiment, we decided to abandon the search for the best oil consumption in CPE.

3.8. Optimum Oil Quantity for Filling Out Oil from Oil Slurry

Quantity of oil filling is 10, 20, 30, 40 and 50g, as shown in Table 24, for SBR filled with $4^{\#}$ slurry oil of different oil content. On the other hand, Table 25 reveals the physical and mechanical vulcanization performance. The more the rubber oil filled in SBR, the more the M_H and M_L appears to be smaller and smaller (Table 24). The reason is that adding rubber oil improves the plasticity of the rubber as the burning time is increasing; and the time of normal vulcanization is not cut down – thus, it can be seen that the amount of oil is filled with the rubber. Such increase can enhance the safety of rubber processing and improve the processing efficiency.

Table 24. Vulcanization Performance of $4^{\#}$ Oil Extraction Oil Filled with SBR in Different Amounts of Oil.

Filling Oil	M_H (dN.m)	M_L (dN.m)	t_{s1} (m:s)	t_{C90} (m:s)
10	14.29	1.46	3:12	25:50
20	10.47	1.14	3:46	20:17
30	8.25	0.92	4:28	20:10
40	5.74	0.68	4:57	19:24
50	4.01	0.53	6:07	18:56

Table 25. Performance Test of $4^{\#}$ Oil Extraction Oil Filled with Different Oil Content in SBR.

Test Items/Oil Filling	0	10	15	20	30	40	50
100% Fixed Extension Stress (MPa)	2.93	2.71	2.31	2.41	2.18	1.95	1.93
300% Fixed Extension Stress (MPa)	16.45	13.85	12.29	11.56	10.25	9.05	8.59
Tensile Strength (MPa)	17.45	23.02	22.82	22.64	20.76	18.24	16.07
Elongation at Break (%)	315.50	466.58	468.78	573.54	627.10	725.62	740.32
Tear Strength (kN.m^{-1})	41.86	52.40	54.50	58.97	48.91	36.90	30.10
Shore of Hardness	57.5	53	52	48	44	39	36
Wear Degree (%)	2.92	0.55	0.6	0.68	0.64	1.57	1.69
Resilience (%)	17	11	10.6	10	9.5	9	8.5
Hot Air Aging							
Change Rate of Tensile Strength (%)	-25.94	0.96	-9.33	3.85	3.59	3.05	-68.55
Elongation Change (%)	-46.19	-18.66	0.76	-14.00	-11.00	-9.97	-53.03
Tearing Strength Change (%)	16.82	-2.21	22.03	-5.16	-3.44	2.40	10.61

As shown in Table 25, filling with 10 parts oil increases tensile strength by 32% compared to the blank group. When the oil filling amount is 20 parts, the tear strength is largest (> 41% that in the blank group). Improvement of tear strength of NR was also realized by He et al. (2023). With the increase of the oil filling, the elongation at break is also in the race. The gradual increase suggests an improvement in the thermal properties of butadiene rubber filled with $4^{\#}$ slurry extract oil. After comprehensive consideration, oil with 20 mass fractions was picked as the best oil filling amount of $4^{\#}$ oil extraction oil into SBR. Table 26 represents the vulcanizing properties of $2^{\#}$ oil extraction oil filled with SBR in different amounts of oil. Table 27 displays the physical and mechanical properties of SBR $2^{\#}$ oil extraction oil.

Table 26. Vulcanization Performance of 2# Oil Extraction Oil Filled with BR in Different Amounts of Oil.

Filling Oil	M_H (dN.m)	M_L (dN.m)	t_{s1} (m:s)	t_{C90} (m:s)
10	5.87	1.62	4:40	17:18
20	9.07	1.75	4:05	48:21
30	7.19	1.35	3:06	23:18
40	3.36	1.11	7:00	15:27
50	3.3	0.97	10:43	22:38

Table 27. Performance Test of 2# Oil Extraction Oil Filled with Different Oil Content in BR.

Test Items/Oil Filling	0	10	15	20	30	40	50
100% Fixed Extension Stress (MPa)	1.70	1.55	1.23	1.08	0.74	0.85	0.46
300% Fixed Extension Stress (MPa)	0.00	7.01	5.36	4.11	2.50	2.68	1.10
Tensile Strength (MPa)	6.87	13.86	11.43	11.64	10.26	8.01	4.67
Elongation at Break (%)	257.84	475.94	489.06	570.43	559.42	590.82	708.79
Tear Strength (kN·m^{-1})	46.16	64.62	59.66	47.67	43.66	33.69	9.63
Shore of Hardness	46	43	42	40	33	32	23
Wear Degree (%)	1.63	0.60	2.06	1.24	1.04	1.09	2.69
Resilience (%)	12	11.5	11	10.5	9.5	9	8
Hot Air Aging							
Change Rate of Tensile Strength (%)	55.72	11.83	30.40	8.60	15.35	29.11	29.00
Elongation Change (%)	-25.22	-31.18	-11.57	-15.73	-17.45	-16.02	-24.14
Tearing Strength Change (%)	-42.45	-33.38	1.84	0.75	-3.62	-3.52	163.81

Table 26 show that more rubber oil is filled in cis rubber. As such, the M_H and M_L are first increased and then reduced. While the burning time first decreases and then increased and the positive vulcanization time rises and fall [20]. Furthermore, in Table 27, it can be observed that the tensile and tearing strengths are largest when the oil filling amount is 10 parts. Essentially: the tensile strength is increased by 101.7%, tear strength by 40% compared with the blank group, and then the heat-resisting aging ability is also improved. Hence, after careful assessment of this performance, 10 fractions of oil were selected as the best oil filling amount for 2# oil extraction oil into SBR.

3.9. Comparison with High Aromatic Oil

Table 28 is the vulcanization analysis result of the two different filling oils. Obviously, the burning time of the 2# oil pulping oil is 260 longer than that of the medium. So, its processing safety is higher, but the positive vulcanization time of the 260 is shorter than that of the oil from the slurry. Additionally, its processing efficiency is more significant. Because the chemical industry has higher requirements for safety, it can be seen that the 2# pulping oil is more competitive than the China Fang 260. Alternative accelerators like zinc diethyldithiocarbamate (ZDEC) and tetramethylthiuram disulfide (TMTD) were previously employed [21]. Moreso, Table 29 compares the physical and mechanical properties of the two different filling oils.

Table 28. Analysis of Vulcanization of Different Filling Oil (150℃).

Type of Filled Oil	M_H (dN.m)	M_L (dN.m)	t_{s1} (m:s)	t_{C90} (m:s)
2# Oil Slurry Extraction Oil	5.87	1.62	4:40	17:18
Aromatic 260	10.59	2.16	3:31	14:55

Table 29. Comparison of Physical and Mechanical Properties of Different Filling Oils.

Items	$2^{\#}$ Oil Slurry Extraction Oil	Aromatic 260
100% Fixed Extension Stress (MPa)	1.55	1.5
300% Fixed Extension Stress (MPa)	7.01	5.065
Tensile Strength (MPa)	13.86	10.135
Elongation (%)	475.94	478.1
Tear Strength ($kN.m^{-1}$)	64.62	37.305
Shore of Hardness	43	44.5
Wear Degree (%)	0.60	1.2
Resilience (%)	11.5	13
Hot Air Aging		
The Change Rate of Tensile Strength (%)	11.83	50.02
Elongation Change (%)	-31.18	-21.00%
Tearing Strength Change (%)	-33.38	-12.95

Adding $2^{\#}$ oil pulp increases BR's elongation by over 30% and tear strength by approximately 45% compared to medium aromatic 260 BR. But its heat-resistant aging performance [22] is worse than that of the middle aromatic 260. Therefore, both of them have advantages and disadvantages, which also reflects the feasibility of oil slurry extraction oil being put into the market.

4 Conclusion

The properties and composition of oil slurries from catalytic cracking units reveal their promise as raw materials for rubber softeners, particularly in applications involving butadiene rubber (BR) and styrene-butadiene rubber (SBR). This study demonstrates that optimizing oil consumption levels can significantly improve rubber processing efficiency, reduce energy demands, and enhance the mechanical properties of vulcanized rubber. Furthermore, the $2^{\#}$ and $4^{\#}$ slurry oil extractions show the potential to satisfy market viscosity standards and serve as viable alternatives in synthetic rubber production. These findings contribute to a deeper understanding of the interactions between oil slurry characteristics and rubber performance, offering insights that could reshape material selection in the industry. Future research in this area holds the potential to further elevate product quality, streamline manufacturing processes, and enhance the competitiveness of rubber-based innovations.

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