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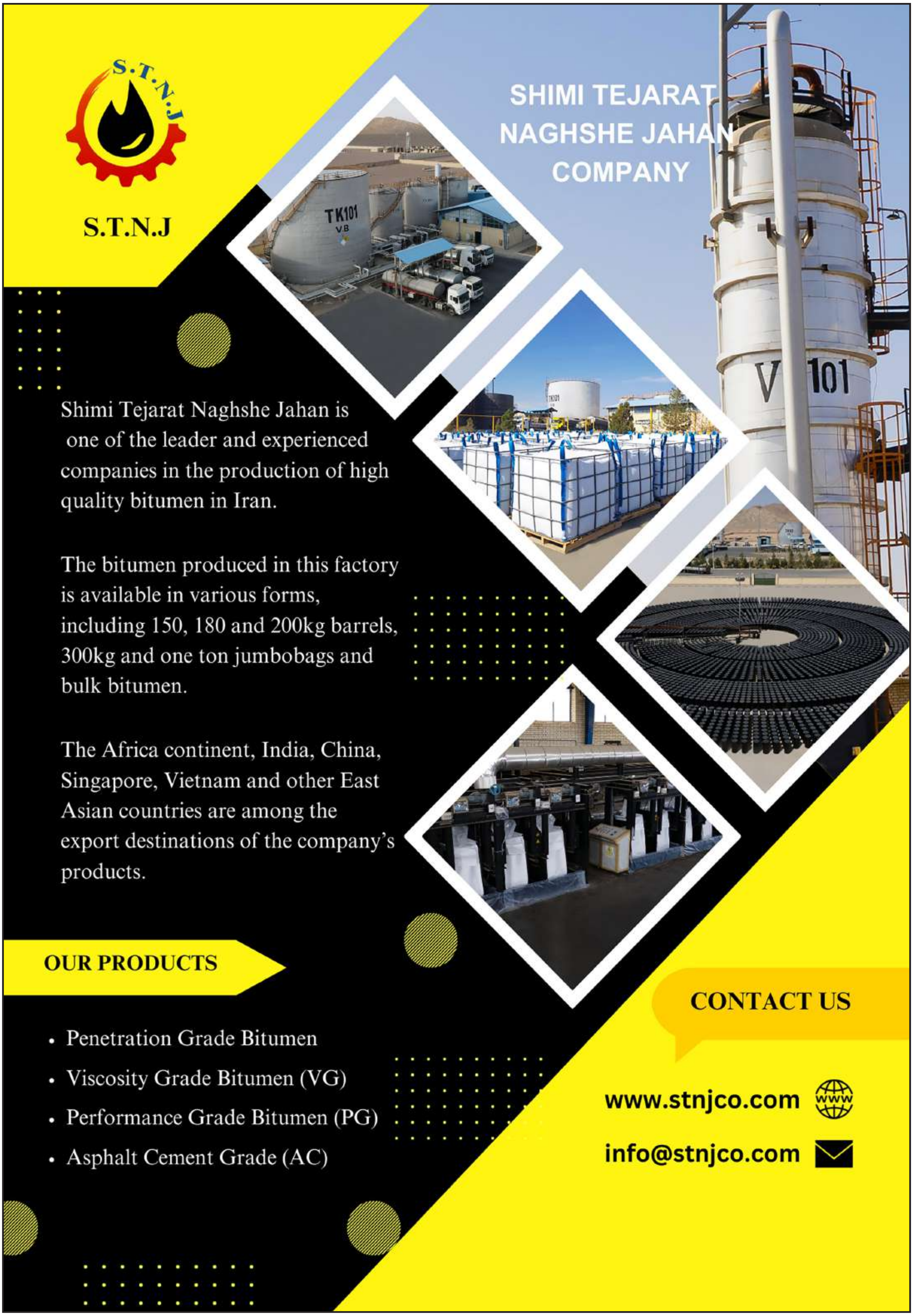
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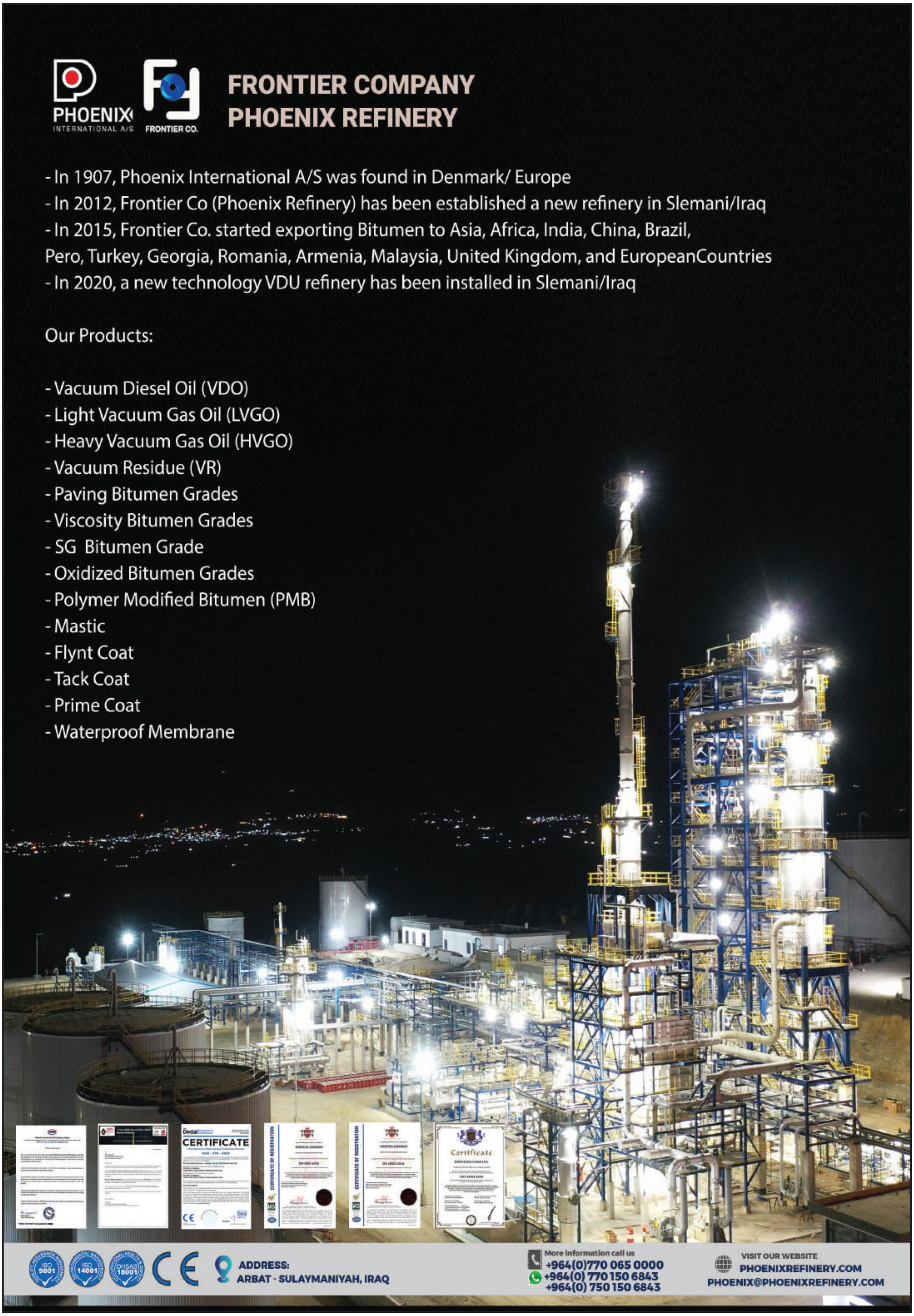
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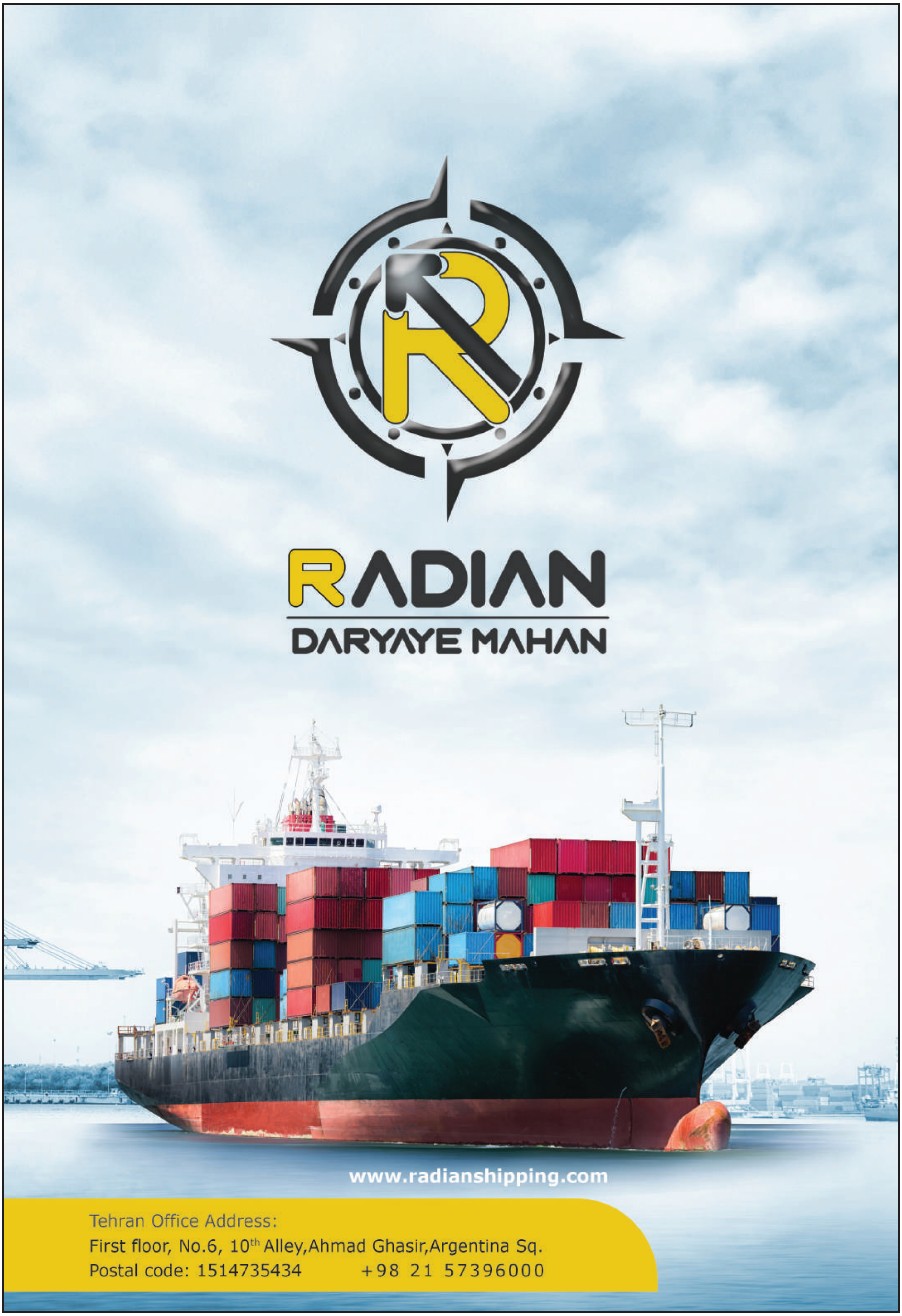
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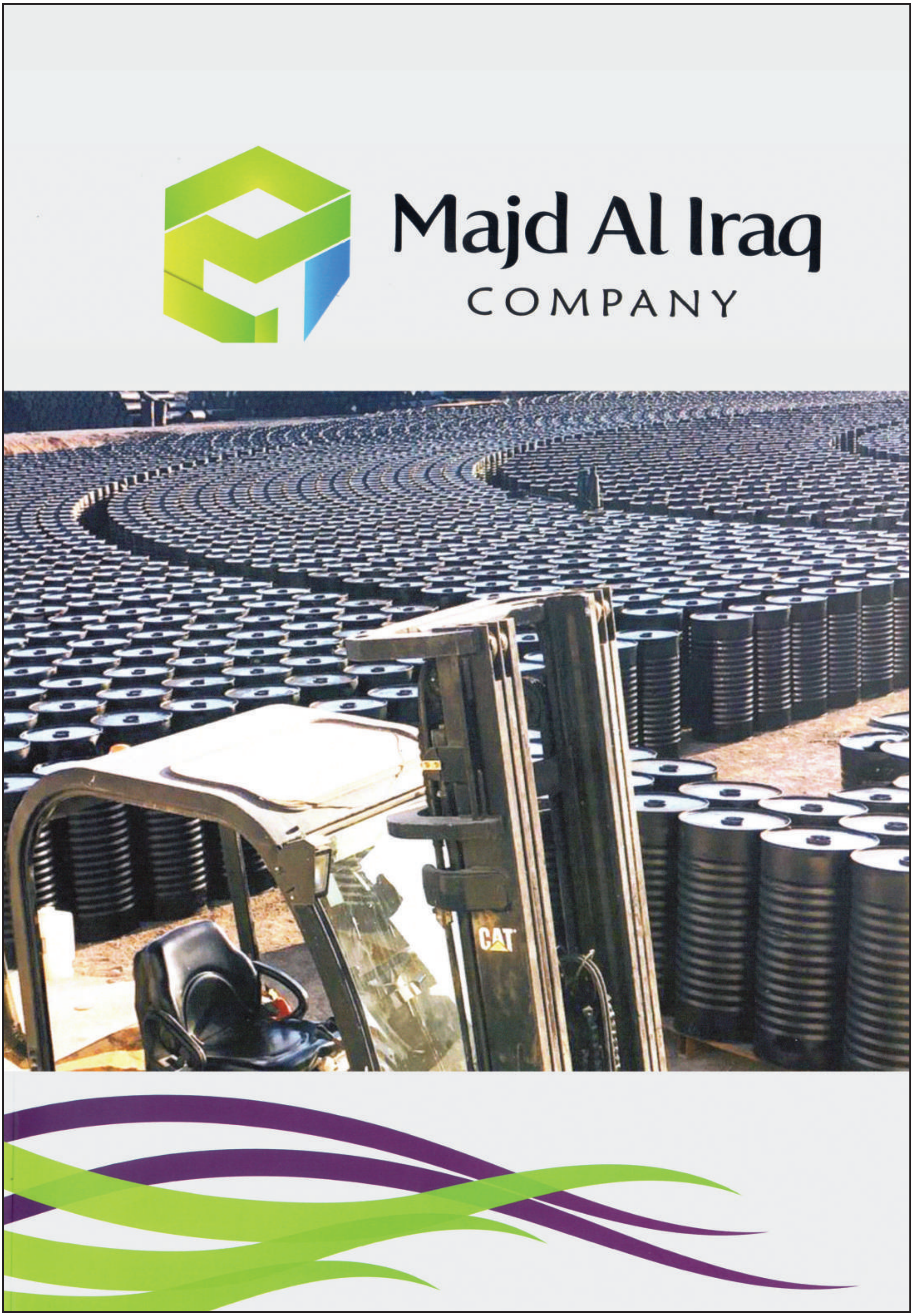
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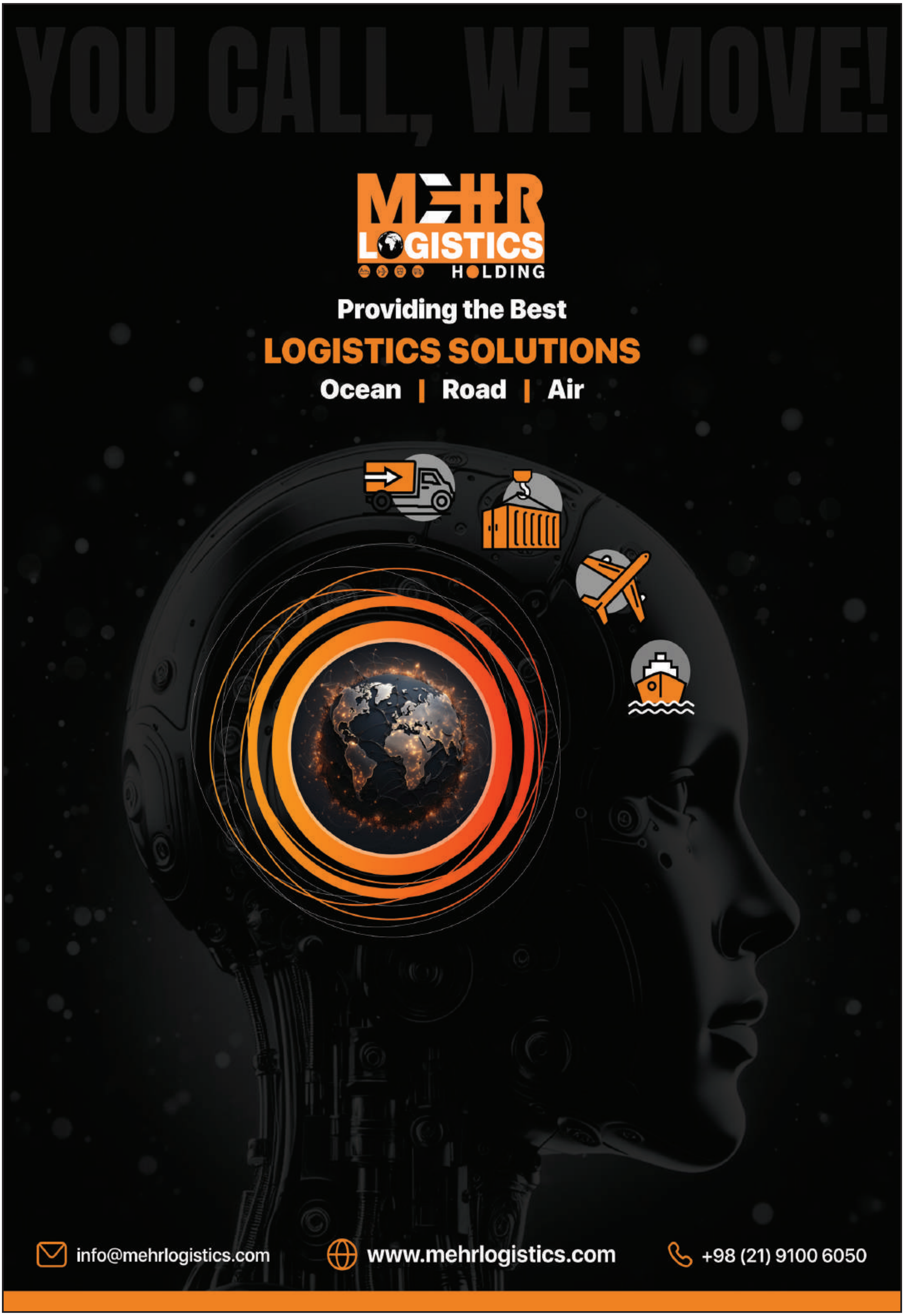
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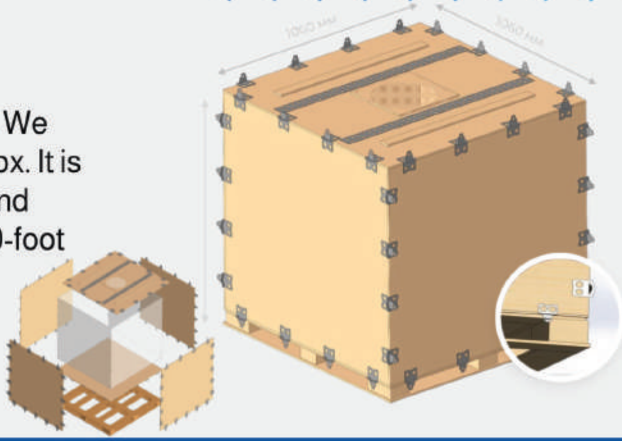
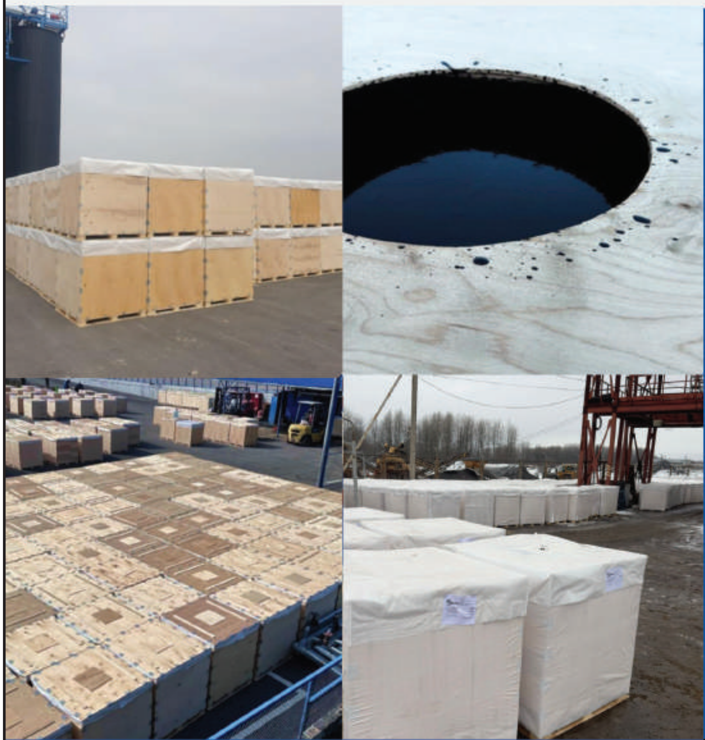
RUSPROMPAK company was established in 2012. We offer a container for filling with hot bitumen BitumBox. It is used for packing hot bitumen and further storage and transportation by any type of transport. A marine 20-foot container with a stack of 3 tiers accommodates 20 containers (20 tons of bitumen).





The dimensions of the container when assembled are 1060x1060x1095 mm. The capacity is up to 1040 kg of hot bitumen of various thicknesses. The heat resistance of the package is up to 200 degrees. The container is made only of glued material — FC plywood, glued in a checkerboard pattern. This eliminates the need to process and install the ISMP15 stamp during export. Storage is allowed in 4 tiers on a flat surface. The assembly is carried out using special keys in 3 minutes. When disassembled, the euro trolley holds 350 sets.

Own production: 2 Gagarina Street, Alexandrov, Vladimir region, Russia, The production area is 5,000 sq.m. The number of employees is 72 people. The production capacity is up to 20,000 boxes per month. At the request of the customer, we can produce packaging of any size for any product. For example, for various serial equipment, car batteries, synthetic rubber, etc.

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Contents

BITUMEN MAGAZINE

EDITOR'S MESSGAE

With a decade of activity in the bitumen and petroleum derivatives industry in the field of printing and publishing specialized news and selected scientific articles from conferences, symposiums, research centers and universities, and introducing brands and companies producing petroleum and bitumen, the World of Petroleum and Bitumen Journal has been able to gain the trust of more than 6000 permanent audience in such a way that they would like to receive the print version of the journal every month.

Ali farjam

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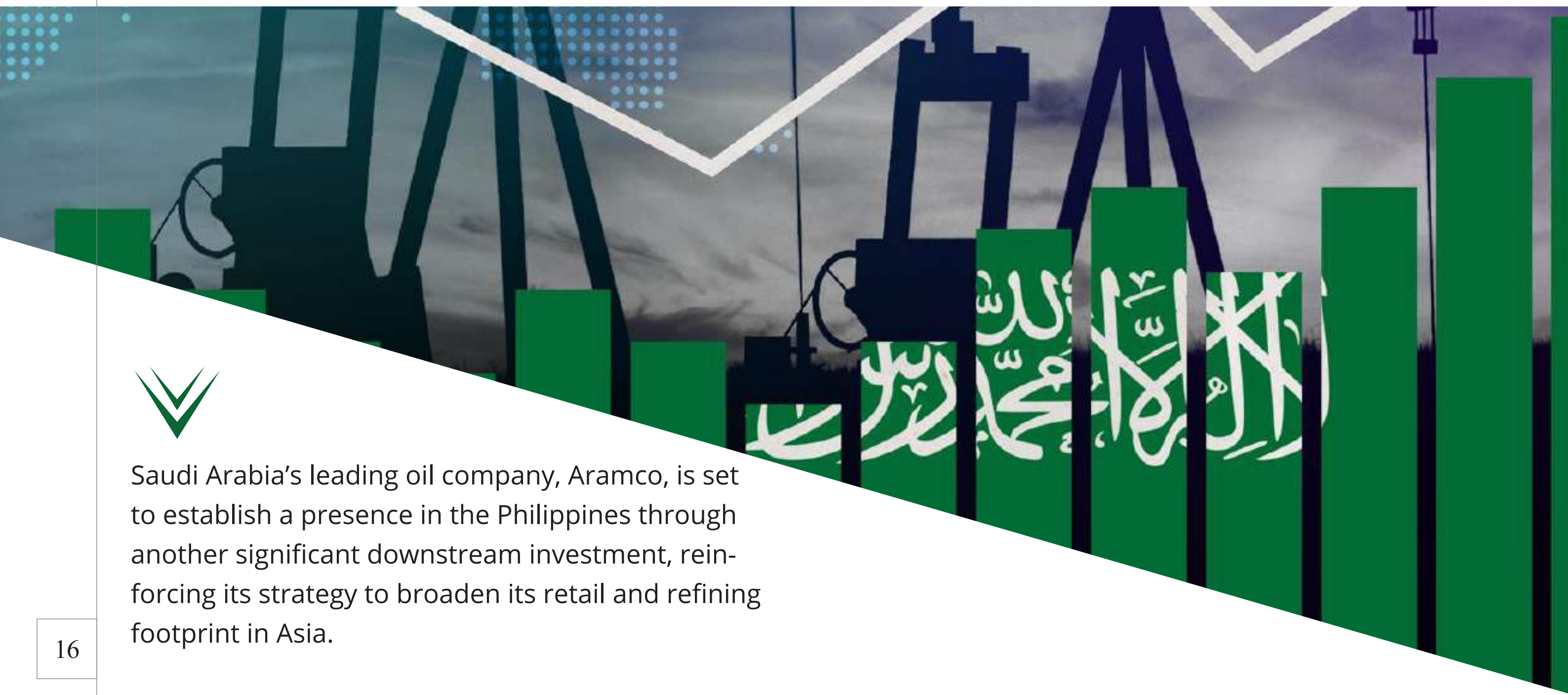
Aramco to Purchase 25% Interest in Unioil Petroleum Philippines



Saudi Arabia's leading oil company, Aramco, is set to establish a presence in the Philippines through another significant downstream investment, reinforcing its strategy to broaden its retail and refining footprint in Asia.

Recently, ownership stake in Unioil Petroleum Philippines, one of the most prominent fuel companies in the country.

By making this investment, Aramco aims to leverage the anticipated expansion of the high-value fuels sector in the Philippines. However, the completion of the acquisition remains contingent on standard closing requirements, including necessary regulatory clearances.

According to Aramco, the transaction represents another step forward in the company's downstream growth strategy and the expansion of its global retail network, which is designed to secure additional distribution channels for its refined petroleum products.

Yasser Mufti, Aramco's Executive Vice President of Products & Customers, emphasized the company's commitment to international expansion, stating,

"Our goal is to unlock further value and strengthen our involvement in dynamic economies by working alongside well-established partners."

This proposed investment in the Philippines—one of Southeast Asia's largest economies—follows Aramco's previous retail acquisitions in Chile and Pakistan.

Over the past few years, the Saudi oil giant has been actively seeking deals to enhance its downstream presence globally, particularly in high-demand regions like Asia.

Mufti had previously mentioned in September 2024 that Aramco remains focused on identifying new acquisition opportunities in the refining sector and the liquefied natural gas (LNG) market.

In 2023, the company entered Pakistan's downstream industry by purchasing a 40% stake in Gas & Oil Pakistan Ltd, a major player in the country's fuel retail and storage sector.

Additionally, early in 2023, Aramco disclosed two significant refinery and petrochemical agreements in China. These deals not only secured the firm's stake in China's refining industry but also provided an extra export outlet for 690,000 barrels per day of Saudi crude oil.

Simultaneously, Aramco is intensifying its collaboration with Chinese petrochemical leaders to strengthen refining and petrochemical operations in both China and Saudi Arabia.

Vietnam Expands Bitumen Imports from the Middle East Due to Competitive Pricing

WPB: Vietnam significantly increased its bitumen imports from the Middle East last year, driven by more attractive pricing compared to shipments from Asian suppliers. The overall volume of imports experienced year-on-year growth, largely supported by rising demand from incomplete infrastructure projects.

As a country that primarily relies on foreign sources for road construction materials, Vietnam imported approximately 1.14 million tons of bitumen in the previous year, marking a 10% increase compared to 1.04 million tons the year before, according to trade data. The volume of bitumen imported specifically from the Middle East reached 382,000 tons, reflecting an impressive 49% rise compared to the prior year.

The expansion in import volumes was closely linked to the surge in ongoing infrastructure projects, particularly highway construction, which intensified in the latter half of the year. However, some industry insiders emphasized that price competitiveness played a crucial role in determining trade flows and sourcing preferences.

"The pricing environment is the primary factor influencing where imports originate," stated a Vietnamese importer.

Throughout the year, bulk bitumen shipments from Iran were consistently priced at a discount of around $131 per ton compared to Singapore's benchmark ABX 1 bitumen prices. The gap became even more pronounced between August and October, when supply shortages caused by production reductions pushed Singapore's seaborne prices higher, leading to Middle East cargoes being traded at discounts ranging from $160 to $180 per ton.

Meanwhile, shipping costs for transporting bitumen from the Middle East to Vietnam were estimated at $120 per ton, according to market sources.

However, Vietnam's prolonged adverse weather conditions suppressed demand during most of the year, particularly until the final quarter, preventing domestic prices from increasing. This situation further encouraged local buyers to seek more affordable Middle Eastern cargoes instead of higher-priced alternatives from other regions.

According to an importer, buyers only turned to suppliers from other Asian countries when specific material specifications were required, otherwise, there was little incentive to import from elsewhere.

Trade data revealed that imports from Singapore totaled 383,000 tons, reflecting a 13% increase from the previous year. In contrast, shipments from China and South Korea experienced sharp declines, falling by 44% and 60%, respectively.

Higher seaborne prices and elevated freight costs from both China and South Korea further discouraged Vietnamese buyers from sourcing bitumen from these markets, industry participants noted.

Looking ahead to 2025, expectations remain optimistic, with bitumen demand projected to remain steady to strong, driven by the continuation of infrastructure development. Import volumes are expected to range between 1 million and 1.3 million tons.

Additionally, the faster allocation of project funds has facilitated a smoother financial flow for contractors, enabling them to accelerate road construction.

U.S. SET TO INTENSIFY RESTRICTIONS ON IRANIAN OIL TRADE

WPB: The Trump Administration is gearing up to enforce U.S. sanctions on Iran's oil sector with greater rigor, U.S. Secretary of Energy Chris Wright stated in an interview with Bloomberg during the CERAWeek conference organized by S&P Global.

Over the past few months, U.S. measures against Iranian oil exports have become increasingly stringent. While the Biden Administration took steps to tighten these sanctions toward the end of 2024, the Trump Administration has already implemented two additional rounds of restrictions. These new measures specifically target the clandestine fleet that facilitates the shipment of Iranian crude to China.

Secretary Wright pointed out that under Biden's leadership, these sanctions were not strictly upheld. As a result, Iran managed to ramp up its oil exports, reaching the highest level in six years by mid-2024. However, the current administration intends to leave no room for leniency. Last month, President Donald Trump instructed the Secretary of State to launch a "strong and ongoing initiative," working in tandem with the Treasury Department and other government agencies, to completely halt Iran's oil exports—including crude shipments to China.

This renewed focus on curbing Iran's oil trade aligns with the U.S. government's broader "maximum pressure" strategy. Wright recalled that Iranian exports were significantly lower during Trump's previous term in office.
"Biden did not revoke the sanctions, but he effectively suspended their enforcement," Wright remarked in his Bloomberg interview at the Houston conference. "That decision allowed Iran to accumulate wealth. And now, we see the consequences—chaos caused by groups like the Houthis, Hezbollah, and Hamas. Is President Trump committed to restoring order and promoting global stability? Absolutely. Can we afford to cut off Iranian oil exports? Without a doubt."

Despite these efforts, analysts tracking global oil shipments report that as of late February, Iranian crude continues to flow to China—its largest buyer, accounting for approximately 90% of its exports. Traders and intermediaries have been adapting by rerouting tankers and increasing ship-to-ship transfers, particularly in offshore areas near Malaysia.

Turkmenistan Innovates in Bitumen Emulsion Production

WPB: ASHGABAT, Turkmenistan (MNTV) — A team of researchers at the International Scientific and Technological Park, operating under the Academy of Sciences of Turkmenistan, has successfully created a novel method for producing bitumen emulsion utilizing domestically sourced materials, according to Business Turkmenistan

.

This breakthrough is part of a broader initiative aimed at minimizing the nation's reliance on imported substances.

The newly formulated bitumen emulsion consists of 40% bitumen, 48.8% water, 10% solvent, 0.6% hydrochloric acid, and 0.6% emulsifier.

This composition significantly enhances its effectiveness in roadwork by strengthening layer adhesion, sealing cracks, restoring potholes, and optimizing asphalt concrete production.

Unlike conventional bitumen, which necessitates high temperatures for application, this emulsion can be used in its cold form, providing a more practical and eco-friendly alternative.

The innovation is anticipated to elevate the durability and performance of roads throughout Turkmenistan while also cutting expenses linked to material imports.

It offers high efficiency in road construction, enhancing layer adhesion, filling cracks, repairing potholes, and improving asphalt concrete production

DEBUNKING THREE COMMON MISCONCEPTIONS IN ASPHALT PAVEMENT DESIGN

WPB: Asphalt pavement design has long been subject to widely accepted yet unverified beliefs. By critically examining these notions through extensive research and field data, it becomes possible to separate fact from misconception. This report addresses three key assumptions related to pavement thickness and perpetual pavements:

1. The coefficients used for pavement layers remain unchanged when incorporating high-polymer-modified (HP) binders.
2. A pavement must be exceptionally thick to qualify as a perpetual pavement.
3. Lean, stiff binder mixtures (intermediate layers) can be effectively used if covered with a durable surface mix.

Impact of High-Polymer-Modified (HP) Binders on Layer Coefficients

HP binders are frequently employed to enhance pavement durability, particularly in scenarios where increasing structural thickness is not feasible. In regions that rely on layer coefficients for pavement design, HP mixtures have demonstrated superior structural performance, often resulting in higher coefficients than traditional mixes.

A study conducted by the Florida Department of Transportation revealed that HP mixes exhibit layer coefficients approximately 23% higher than conventional alternatives. Additionally, research from the National Center for Asphalt Technology (NCAT) (Report 12-10) indicated an even greater increase, with HP layer coefficients being at least 43% higher.

These findings were derived from conservative assumptions, as the test section at NCAT was removed from service despite showing no visible distress after sustaining 20 million equivalent single axle loadings (ESALs).

The actual performance of HP-modified sections suggests the possibility of perpetual pavement with reduced thickness, challenging the long-held belief that greater depth is necessary for long-term durability. Ongoing research continues to refine the exact impact of HP mixes on pavement design. However, the documented advantages of these advanced materials suggest an opportunity to construct highly durable roadways without excessive initial costs. To maximize these benefits, maintaining adequate layer thickness remains crucial, as premature reductions may compromise long-term performance.

Rethinking Perpetual Pavement Thickness Requirements

The concept of perpetual pavement refers to a flexible road structure designed to withstand repeated loading cycles indefinitely, provided that tensile strains at the base of the asphalt layers remain below critical thresholds. Historically, achieving this level of durability has been associated with substantial pavement thickness, often exceeding 12 inches. However, modern evidence challenges the necessity of such extreme depth.

Analysis of the Asphalt Pavement Alliance's Perpetual Pavement Award-winning projects, which have been recognized since 2001, indicates that structural designs typically range between 10 and 14 inches in total asphalt thickness. These designs, which predate the widespread use of performance-modified binders, suggest that previous assumptions about minimum thickness may have been influenced by outdated mix design methodologies.

Further supporting this perspective, NCAT's research on advanced binder technologies has demonstrated that perpetual performance can be achieved with significantly thinner asphalt layers. One test section exhibiting perpetual characteristics measured only 5.75 inches in thickness. Nevertheless, the viability of thinner pavements depends on site-specific factors. For example, NCAT's studies in Oklahoma found that a thickness of 14 inches was required under certain conditions.

Pavement design must consider multiple variables, including:

- Traffic load: High truck volumes generally necessitate thicker pavement structures.

- Subgrade quality: Weaker subgrades may require increased asphalt thickness or stabilized base layers.

The Role of Intermediate Layers in Pavement Longevity

• Climate conditions: Extreme heat, cold, and freeze-thaw cycles influence material selection and layer depth.

Ultimately, perpetual pavement can be engineered for various environments. With the integration of advanced materials, achieving long-lasting performance with significantly reduced thickness is now a practical possibility.

The Role of Intermediate Layers in Pavement Longevity
The long-term durability of a pavement depends on selecting appropriate materials for each structural layer, ensuring adequate thickness to prevent deep-seated distress, and implementing effective preservation strategies. While the surface layer receives the most attention due to its visibility, all underlying layers must meet performance requirements to ensure overall pavement integrity.

Intermediate layers, for example, must be designed to minimize deflections through a combination of stiffness and thickness. One method to enhance stiffness is by increasing the percentage of reclaimed asphalt pavement (RAP) in the mix.

While RAP-rich designs are often beneficial, they must be carefully evaluated using balanced mix design (BMD) testing to confirm sufficient binder content and resistance to cracking. This becomes especially important when resurfacing existing pavements with persistent underlying cracks. If an inlaid mix is too lean or contains excessive aged binder, preexisting cracks can rapidly propagate through the new surface.

The widespread use of multi-generational RAP—material that has been recycled multiple times since its original placement—introduces additional considerations. Adjacent pavement layers with

Rethinking Perpetual Pavement Thickness Requirements

significant stiffness differences may experience high interlayer tensile stresses under traffic loading.

Proper tack application at suitable rates is essential to prevent premature delamination when stiffer intermediate mixes are placed above or below more flexible layers.

Agencies responsible for pavement management should also reconsider design air void requirements in BMD-approved mixtures. While traditional volumetric specifications provide insight into binder content quantity, they offer little information about its quality. Maximizing RAP utilization can improve both economic efficiency and environmental sustainability, but only if it does not compromise long-term pavement performance.

Conclusion

Asphalt pavement design continues to evolve, driven by advancements in material science and performance-based engineering. By reassessing long-held assumptions regarding layer coefficients, thickness requirements, and intermediate layer composition, the industry can develop cost-effective, high-performance pavements that offer extended service life. Strategic material selection, appropriate layer thickness, and comprehensive quality control remain fundamental to achieving durable and sustainable roadways.

WPB

U.S. LNG Imports to China Halted

China has not received a single liquefied natural gas (LNG) shipment from the United States in the past 40 days, and currently, no LNG carriers are on route to the country.

Bloomberg, citing data collected from ship-tracking information providers and Kepler, reported that China has halted its LNG purchases from the U.S.

The suspension of purchases is a result of the tariff war initiated by former U.S. President Donald Trump, who imposed an additional 10% tariff on all Chinese imports upon taking office. In response, China imposed a 15% tariff on U.S. LNG imports, along with a lower tariff on U.S. crude oil imports.

According to Bloomberg, Chinese LNG buyers with long-term contracts with U.S. producers have begun reselling their shipments to Europe in response to these tariffs. Additionally, Chinese traders are uncertain about committing to new long-term purchase agreements with the U.S. and are instead seeking long-term contracts with gas producers in the Middle East and Asia-Pacific.

The American news outlet highlighted a new 15-year contract between China Resources Gas International and Woodside Energy, marking the first long-term agreement between a Chinese and an Australian company in years.

According to Oil Price, this situation is generally in Europe's favor, as the arrival of spring signals the end of the high gas demand season. However, demand in the region will remain elevated for some time, as gas reserves need to be replenished. In fact, Kepler predicts that European gas demand will increase in the coming weeks since the continent is emerging from winter with significantly lower reserves.

The Invention of a Fuel That Can Replace Fossil Fuels

The first e-methanol produced in Denmark has the potential to replace fossil fuels in heavy transport and aviation.

A Danish company, European Energy, has successfully produced its first batch of e-methanol.

The company stated that production will now be ramped up, with the facility having the capacity to produce 42,000 tons of electrified methanol annually. This will be achieved using three electrolyzers from Siemens Energy and a methanol loop designed and built by European Energy.

Electrified methanol is a type of synthetic liquid fuel produced by combining green hydrogen—generated from water electrolysis using renewable energy—with carbon dioxide captured from the atmosphere.

Enhancing Efficiency

The electrolyzers have a combined capacity of 52.5 MW, primarily powered by the nearby Kassø Solar Park, which was developed and launched by European Energy.

Vikær Andersen, CEO of the company, expressed excitement over the production of the first batch of electrified methanol at their facility, calling it a major milestone in a journey that began four years ago. He noted that the lessons learned have helped refine the process, improve efficiency, and reduce costs for future projects.

A Practical and Scalable Solution for Industrial Decarbonization

Andersen emphasized that this development proves the feasibility of a practical and scalable solution for decarbonizing industries that cannot be directly electrified.

The Kassø facility, the world's first and largest commercial electrified methanol plant, began producing green hydrogen in January 2025. By combining hydrogen with biogenic carbon dioxide in a reactor, the first batch of methanol was successfully produced.

Designed to supply industries and sectors requiring alternatives to fossil fuels, the facility is set to be fully operational by Q2 2025. It converts renewable energy, water, and carbon dioxide into green fuel and chemicals, offering a viable pathway for industries that cannot rely on direct electrification to reduce their carbon footprint. This innovation supports companies and Europe in achieving net-zero carbon emissions goals.

Electrified Methanol as a Fossil Fuel Alternative

The company revealed that sectors such as shipping, aviation, and the chemical industry must significantly cut their fossil-based CO_2 emissions in the coming years. Since direct electrification is not a feasible solution for these industries in the foreseeable future, green alternatives like electrified methanol are critical for decarbonizing heavy transport and chemical production.

This new solution has the potential to significantly reduce fossil fuel consumption in these sectors. By converting renewable energy from wind and solar into sustainable fuels, the company ensures a fossil-free energy and raw material source for industries where direct electrification is impractical or impossible.

In a statement, the company said:
"We believe electrified methanol will play a crucial role in the green transition. Today, it can replace fossil fuels in heavy transport and serve as a raw material for the chemical industry and plastic production."

Electrified methanol is also essential for the production of sustainable aviation fuel (SAF). The shipping, aviation, and chemical sectors require electrified methanol as a green alternative to cut fossil fuel emissions and achieve climate targets.

Construction of the Largest Municipal Wastewater Treatment Unit at Tehran Refinery

Regarding the Tehran Refinery's fuel oil quality improvement project, he noted that this initiative is in its final stages and will be completed by 2029.

The CEO of Tehran Refinery announced that the largest industrial water treatment unit at Tehran Refinery is under construction.

During a visit to the refinery, Abbas Mohseni-Niko told reporters that the largest industrial water treatment and desalination unit at Tehran Refinery is currently being built. He stated that the first phase of this desalination unit will be operational in May, the second phase in June, and the third phase in September this year.

Emphasizing the importance of this initiative, he noted that once this water treatment section is operational, it will save 1.5% of Tehran's total water consumption. The raw material for this treatment plant will be supplied by Tehran's wastewater system through the Water and Wastewater Company.

The CEO highlighted that the Tehran Refinery's water treatment project has reached 89% completion, with its three phases scheduled for commissioning in May, June, and September of the following year. Once operational, the refinery's industrial wastewater treatment plant will meet the water needs of the refinery's industry and green spaces, reducing the use of Tehran's potable water, equivalent to a 1.5% saving in the city's drinking water consumption.

Mohseni-Niko explained that the initial contract for wastewater supply to this treatment plant was set at 1,000 tomans per cubic meter, but the price has now increased to 25,000 tomans per cubic meter. The Tehran Refinery's industrial wastewater treatment project has a capacity of 52,000 cubic meters, equivalent to 1.5% of Tehran's daily drinking water supply. This means that by launching this treatment plant, 1.5% of Tehran's drinking water consumption will be saved.

He further stated that 8.9 billion tomans and 10 million euros in investment contracts have been signed for the construction of Tehran Refinery's treatment plant.

Mohseni-Niko also mentioned that Tehran Refinery is among the companies listed in the Justice Shares portfolio, with four board seats allocated to Justice Shares. He added that 7 trillion tomans from last year's refinery profits were transferred to the Central Securities Depository Company for distribution to shareholders.

Regarding the Tehran Refinery's fuel oil quality improvement project, he noted that this initiative is in its final stages and will be completed by 2029.

Additionally, the CEO stated that the refinery is implementing another project aimed at reducing the sulfur content of fuel oil from 3.5% to less than 0.5%. The fuel oil quality improvement project, developed in collaboration with research institutions, is in its finalization phase and is set to be operational by 2029. Moreover, extensive planning is underway to comply with new standards that mandate reducing sulfur content to below 0.1%.

THE HIGHEST-GROSSING OIL AND GAS COMPANIES OF 2024

With continuous demand for oil and gas, the leading companies in this sector generate astronomical revenues and play a crucial role in shaping the global energy landscape.

The oil and gas industry has long been the backbone of the global economy, supplying energy for industries, fueling transportation, and sustaining modern life. In a recent report, the website Petrochemical Expert identified the top 10 oil and gas companies by revenue in 2024:

1- Saudi Aramco

Revenue (2024): $510 billion

The state-owned giant Saudi Aramco continues to dominate the oil and gas industry with the highest revenue. Established in 1933, it is not only the world's largest oil company by revenue but also the most profitable.

Saudi Aramco manages the vast oil reserves of Saudi Arabia, among the largest in the world. Its massive scale allows the company to produce over 12 million barrels of oil per day.

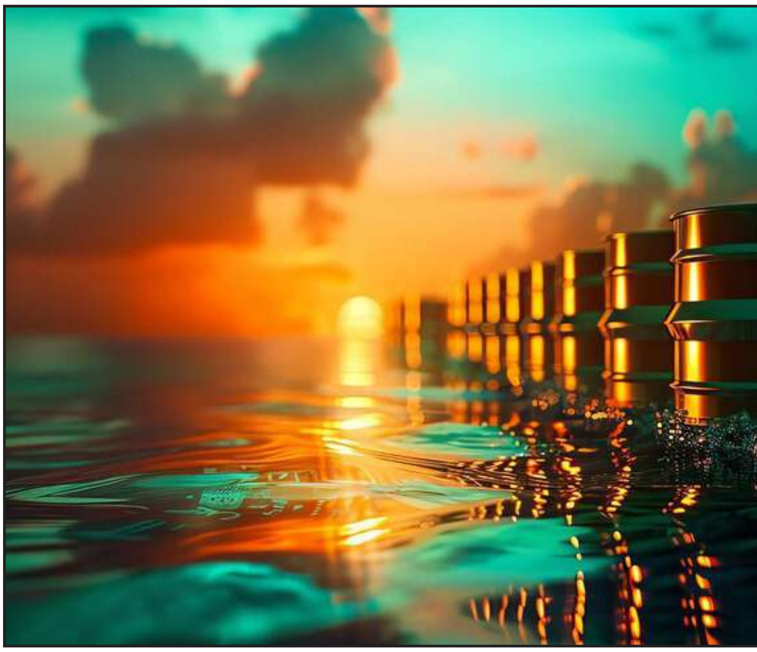
Beyond crude oil production, Aramco operates an extensive refining network, a major petrochemical business, and invests in renewable energy, making it a key player in both traditional and emerging energy markets.

2- ExxonMobil

Revenue (2024): $400 billion

ExxonMobil, one of the world's largest oil and gas companies, is headquartered in Irving, Texas.

Its diverse business portfolio includes exploration and production, refining and marketing, and chemicals. The company's upstream activities span North



America, the Middle East, and Asia.

3- Shell

Revenue (2024): $380 billion

Headquartered in The Hague, Netherlands, Shell is another major player in the global oil and gas industry.

Renowned for its large-scale upstream and downstream operations, Shell is involved in oil and gas exploration, production, refining, and distribution.

With significant investments in renewable energy, electric vehicle charging infrastructure, and low-carbon technologies, Shell is at the forefront of the energy transition. Its extensive refining capacity and dominant position in global liquefied natural gas (LNG) markets help maintain its status as one of the top-earning oil companies.

4- BP (British Petroleum)

Revenue (2024): $300 billion

London-based BP is one of the oldest and most reputable companies in the global oil and gas sector.

In recent years, BP has diversified its operations, increasing its focus on clean energy and carbon neutrality. With major investments in both upstream and downstream sectors worldwide, BP remains a top oil and gas producer.

The company is heavily involved in wind, solar, and bioenergy projects, reflecting its commitment to reshaping its portfolio and contributing to a greener future. Despite market fluctuations, BP's ability to generate substantial revenue solidifies its position as a key industry player.

5- Chevron

Revenue (2024): $290 billion

Chevron, an American company operating in over 180 countries, focuses on a diverse portfolio that includes oil and gas exploration, refining, and chemical production.

Its upstream business is heavily centered on oil exploration, while its downstream segment handles refining and marketing of refined products.

Chevron has made significant strides in promoting renewable energy and reducing greenhouse gas emissions through investments in low-carbon

Saudi Aramco manages the vast oil reserves of Saudi Arabia, among the largest in the world. Its massive scale allows the company to produce over 12 million barrels of oil per day.

technologies such as hydrogen, carbon capture, and renewable fuels.

6- TotalEnergies

Revenue (2024): $275 billion

Based in Paris, France, TotalEnergies is a multinational energy giant engaged in oil and gas exploration, production, refining, and marketing.

The company generates revenue from its upstream operations and extensive refining and marketing business. Through significant investments in wind, solar, and low-carbon technologies, TotalEnergies is emerging as a leader in the renewable energy sector. Its strategy to diversify away from fossil fuels has proven effective, maintaining its strong position in the global energy market.

7- Gazprom

Revenue (2024): $270 billion

Russia's state-owned energy company, Gazprom, is the world's largest producer of natural gas. While it is primarily known for its gas operations, Gazprom also engages in significant oil production and refining activities. The company operates the world's largest natural gas transmission network.

8- ConocoPhillips

Revenue (2024): $240 billion

ConocoPhillips, a multinational American company, is a major player in the global oil and gas industry.

Focused on exploration and production, ConocoPhillips has seen significant growth in its upstream business, with major operations in North America, the Middle East, and Asia. The company has streamlined its operations by focusing on core oil and gas production while divesting non-core assets.

This strategy has helped ConocoPhillips remain profitable despite oil price volatility.

9- Eni

Revenue (2024): $220 billion

Headquartered in Rome, Italy, Eni is a global energy company engaged in oil, natural gas, and petrochemical sectors.

Its upstream business includes significant exploration and production activities, particularly in Africa, the Mediterranean, and South America. Eni has been investing in renewable energy sources such as solar and wind while advancing hydrogen and bioenergy initiatives.

10- PetroChina

Revenue (2024): $200 billion

A subsidiary of the China National Petroleum Corporation (CNPC), PetroChina is involved in oil and gas exploration, refining, and petrochemical production.

With extensive reserves in China and abroad, the company has major exploration and production activities in countries like Canada, Kazakhstan, and Indonesia. Despite global oil price fluctuations, PetroChina's vast scale and strategic investments in upstream and downstream sectors have enabled it to maintain substantial revenues.

Trade War Becomes a Threat to Oil Demand

The International Energy Agency (IEA) has announced that global oil demand is under pressure due to the intensification of the trade war and the resurgence of OPEC+ production.

According to the latest monthly report by the IEA, slower oil deliveries in recent months have led the agency to lower its forecast for consumption growth this year. Global markets are expected to face an oversupply of 600,000 barrels per day in 2025, and OPEC+'s unexpected decision last week could add another 400,000 barrels per day to this surplus.

The Paris-based agency stated: "The macroeconomic conditions underlying our oil demand forecasts worsened over the past month due to escalating trade tensions between the United States and several other countries. The surge in tariffs has increased downside risks to the global economy."

Following OPEC+'s decision to gradually resume production increases starting in April, and former U.S. President Donald Trump's immediate decision to impose tariffs on imports from China, Europe, Canada, and Mexico, oil was trading close to $71 per barrel in London.

OPEC and its allies in the OPEC+ group surprised oil traders on March 3 by approving a gradual production increase starting next month. Trump had previously urged the group to lower oil prices.

The IEA, which advises major economies, has revised its forecast for global oil consumption growth this year downward by about 100,000 barrels per day, estimating it at approximately 1 million barrels per day. According to the agency's projections, global demand in 2025 will average 103.9 million barrels per day, with Asia accounting for nearly 60% of this year's demand growth.

According to a Bloomberg report, the increase in demand will be lower than the 1.5 million barrels per day growth in oil supply, driven by production from the U.S., Brazil, Canada, and Guyana.

The IEA stated that as a result of rising production in these countries, even if OPEC+ opts to cancel the remainder of its planned production increases, global markets will still be heading toward an oversupply.

HOW FAR HAS THE DEVELOPMENT OF IRAN'S JOINT OIL FIELDS PROGRESSED?

With substantial investments and the adoption of modern technologies, the development of the Azadegan, Yadavaran, Sepehr, and Jofeir oil fields in the West Karun region has been prioritized. According to the latest figures, the South Azadegan oil field's production and processing unit, with a capacity exceeding 320,000 barrels per day, is recognized as the largest oil processing facility in the country. Under large-scale projects, the goal is to increase production to 550,000 barrels per day over an eight-year period.

To achieve the strategic objective of increasing oil production and strengthening Iran's position in the global market, the government and the Ministry of Petroleum are taking significant steps by implementing development plans in West Karun's joint oil fields. According to the latest figures announced by the CEO of the National Iranian Oil Company's Petroleum Engineering and Development Company (PEDEC), key projects in the Azadegan, Yadavaran, Sepehr, and Jofeir fields are being executed using advanced technologies and extensive participation from domestic banks and companies.

Azadegan Field

Located in the Abadan Plain region, approximately 80 kilometers west and southwest of Ahvaz along the Iran-Iraq border, the Azadegan oil field is the largest joint oil field in the country. Estimates suggest that the field contains around 32 billion barrels of oil reserves, with current production at approximately 190,000 barrels per day. The South Azadegan processing unit, with a capacity

of 320,000 barrels per day, is the largest oil processing facility in the country. This unit, which underwent a 24-hour operational test on March 19 (the last day of the Persian year), was launched on a trial basis. However, after project handover, it faced supply shortages. Petropars, the main contractor, has since purchased and fully paid for some of the required equipment.

In this regard, the massive Integrated Azadegan Project, one of the country's key initiatives, has been planned with a $10 billion investment for the second development phase of the North and South Azadegan fields. The project aims to achieve sustainable production of 550,000 barrels per day over an eight-year period. Azadegan Alvand Company, which was established with the participation of several banks, has reported that its organizational structure has been set up, and environmental and engineering studies have begun. The project's execution is expected to commence in early April 2025.

Yadavaran Field

The Yadavaran oil field, located about 70 kilometers southwest of Ahvaz and north of Khorramshahr, is another joint oil field between Iran and Iraq. Over the past years, its development has experienced pauses and resumptions. In the first phase, the field's production capacity was planned to reach 85,000 barrels per day, but with an additional increase of 15,000 barrels per day, it has reached approximately 100,000 barrels per day.

So far, about 65 million barrels of crude oil have been extracted from this field, generating approximately $3.2 billion in revenue for the country. In the next development phases, utilizing advanced monitoring technologies and new drilling operations (such as the drilling of 24 wells), the goal is to gradually increase daily production capacity to 180,000 barrels.

Sepehr and Jofeir Projects

The Sepehr and Jofeir oil fields, located east of Azadegan in the West Karun region, are among the key projects aimed at boosting the country's oil production. Their development plan, which faced delayed decisions in recent months, is now finalized, and the project is currently in the procurement stage for equipment and drilling rigs for the second phase. It is expected that by 2025, production

from this project will increase by 30,000 barrels per day.

According to the latest figures and reports, the development of the Azadegan, Yadavaran, Sepehr, and Jofeir oil fields represents a major transformation in the country's oil industry. These projects, through the application of modern technologies, extensive domestic participation, and integrated contracts, not only significantly enhance oil production capacity but also create employment and fulfill social responsibility obligations in surrounding areas.

Successful outputs from these fields, including the trial operation of the South Azadegan processing unit and the planned second-phase developments of the Yadavaran, Sepehr, and Jofeir fields, indicate progress toward long-term goals aimed at strengthening the national economy and Iran's role in the global oil market.

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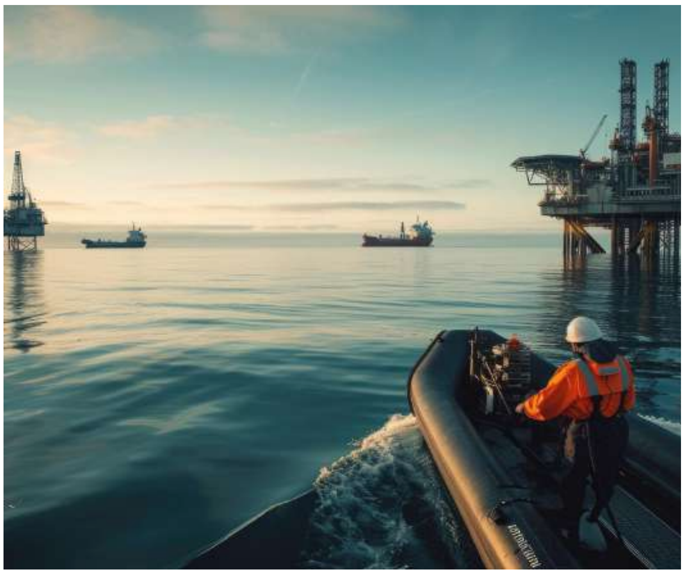


HOW WOULD RUSSIA'S ENERGY TRADE CHANGE IF SANCTIONS ARE EASED?

As negotiations continue to end the war in Ukraine, the potential easing of sanctions imposed on Russia—particularly in its vast energy sector—is a key topic under discussion.

Oil and gas exports are a crucial revenue source for Moscow. This sector has been under Western sanctions since 2014 when Russia annexed Crimea. After Russia's invasion of Ukraine in 2022, these sanctions intensified significantly, with Washington announcing its most severe round on January 10.

Russia's Trade with the U.S. and the EU

Before the war, Russia was one of the largest suppliers of fuel oil to the U.S., exporting around one million tons (240,000 barrels per day) per month. The U.S. also imported some crude oil, mainly from Russia's Far East. If sanctions are eased, these export flows could resume.

Europe was Russia's primary oil and gas buyer before the war. Several rounds of EU sanctions—including the latest package extended until September—along with efforts to reduce reliance on Moscow, have significantly cut these purchases.

According to Eurostat, the volume of oil imported from Russia in Q4 2024 was just 10% of what it was in Q1 2021.

Unless Brussels reviews the current sanctions package, no changes in Russian oil and gas imports to the EU are expected. However, Europe remains cautious toward Russia and has a broad target of stopping Russian oil and gas imports by 2027, making a return to pre-war energy trade unlikely even if sanctions are lifted.

Infrastructure damage, such as the Nord Stream gas pipelines connecting Russia to Germany—three of which were blown up in 2022—also limits future flows.

Payments

The easing of U.S. financial sanctions would have a greater impact on Russia's energy exports and revenues.

U.S. and EU sanctions blocked major Russian banks from accessing the SWIFT global payment system and other financial services, leading to higher transaction fees and months-long payment delays for Russian exporters forced to use alternative payment schemes.

Lifting U.S. sanctions could make dollar transactions easier for Russian companies. While Russian and Chinese banks have found ways to shorten payment processing times, W P B

challenges remain. Payments in currencies other than the U.S. dollar are costly because Russian oil sellers must conduct multiple currency conversions, adding to transaction fees.

Gazprom Neft and Surgutneftegas—the third and fourth largest Russian oil producers by output—were included in the U.S. sanctions announced on January 10, forcing them to rely more on intermediaries.

In November, the U.S. also imposed sanctions on Russia's Gazprombank, which had facilitated payments for European gas customers. Since then, Washington has issued temporary exemptions for Hungary, Slovakia, and Turkey to allow payments through this bank.

Oil Selling Prices

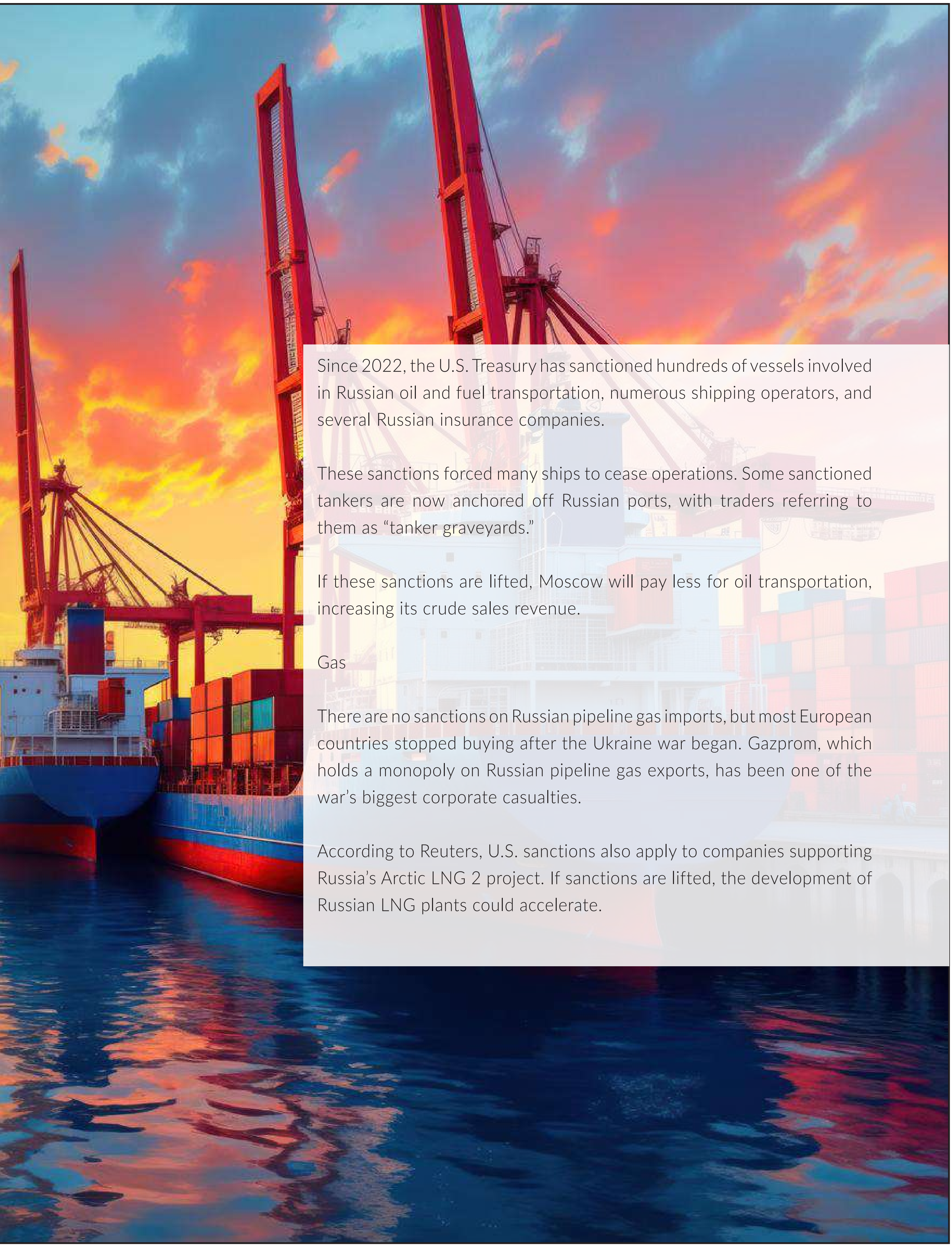
The U.S., EU, and their allies have imposed a $60-per-barrel price cap on Russian oil sales, preventing Western insurers and shippers from facilitating trade above that level. If the U.S. stops enforcing this cap, Russian exporters may find more shipping service providers willing to work with them.

Urals crude prices collapsed in early 2022 when European refiners halted Russian imports. The grade, which is priced relative to Brent (the global oil market benchmark), now trades at a $10-per-barrel discount—compared to a $1–2 discount before the war.

If U.S. sanctions are eased, Urals crude prices may rise, but they are unlikely to return to pre-war highs unless European sanctions are lifted. Until then, Russia will continue selling more oil to India and China, which became its largest buyers after European refiners stopped purchases.

Shipping

WPB



Since 2022, the U.S. Treasury has sanctioned hundreds of vessels involved in Russian oil and fuel transportation, numerous shipping operators, and several Russian insurance companies.

These sanctions forced many ships to cease operations. Some sanctioned tankers are now anchored off Russian ports, with traders referring to them as "tanker graveyards."

If these sanctions are lifted, Moscow will pay less for oil transportation, increasing its crude sales revenue.

Gas

There are no sanctions on Russian pipeline gas imports, but most European countries stopped buying after the Ukraine war began. Gazprom, which holds a monopoly on Russian pipeline gas exports, has been one of the war's biggest corporate casualties.

According to Reuters, U.S. sanctions also apply to companies supporting Russia's Arctic LNG 2 project. If sanctions are lifted, the development of Russian LNG plants could accelerate.

CHEVRON PAID MILLIONS TO VENEZUELA

Despite a license explicitly prohibiting payments to the Venezuelan government, the Biden administration secretly allowed Chevron to send hundreds of millions of dollars to the South American country.

According to Bloomberg sources, an addendum to Chevron's November 2022 sanctions waiver allowed the U.S. energy giant to pay oil-related taxes and royalties to the government of Venezuelan President Nicolás Maduro without violating U.S. laws.

The Office of Foreign Assets Control (OFAC) initially granted Chevron a waiver to conduct limited operations in Venezuela.

Under former U.S. President Donald Trump, this waiver was revoked, forcing the oil major to halt its activities in Venezuela.

Chevron stated:

"The company operates globally in full compliance with all laws and regulations, including U.S. government sanctions frameworks."

The sanctions waiver—known as a general license—permitted Chevron to produce and export Venezuelan crude oil but explicitly barred payments of taxes, royalties, or dividends to the Venezuelan government or any state-controlled entity. However, sources familiar with the matter revealed that an undisclosed addendum to the waiver allowed Chevron to make certain payments necessary to sustain its business

THE COMPANY OPERATES GLOBALLY IN FULL COMPLIANCE WITH ALL LAWS AND REGULATIONS, INCLUDING U.S. GOVERNMENT SANCTIONS FRAMEWORKS

operations.

Chevron is the only major U.S. oil company still operating in Venezuela after nationalization policies under late President Hugo Chávez in the 2000s forced many foreign producers to exit or seek compensation. The company's operations were halted under Trump-era sanctions but resumed in 2022 when Biden officials brokered a deal allowing Chevron to return in exchange for Maduro agreeing to democratic elections.

According to Bloomberg, Chevron's dealings in Venezuela have come under intense scrutiny from former President Trump in recent weeks. Earlier this month, he issued a 30-day deadline for Chevron to end its joint venture with Venezuela's state oil company, PDVSA.

Iranian Oil Shipments to China Persist Despite Intensified U.S. Sanctions

The U.S. government has ramped up its pressure campaign against Iran's oil exports under the Trump Administration, tightening sanctions in an effort to disrupt crude flows to China, Iran's largest oil customer. Despite these intensified restrictions, Iranian crude continues to reach Chinese buyers as traders and intermediaries adjust supply routes, increasing ship-to-ship transfers—particularly off the coast of Malaysia, according to vessel-tracking analysts.

Although recent U.S. sanctions have complicated trade by reducing the number of available tankers that are not blacklisted, Iranian oil exports to China have maintained a steady pace in recent months. China remains the primary destination for Iranian crude, a trend that has persisted since 2018, when former President Donald Trump withdrew from the Iranian nuclear agreement and reinstated sanctions.

Independent Chinese refineries have played a key role in purchasing Iranian crude, benefiting from deep discounts. This trade dynamic is mutually advantageous: Iran secures a market for its oil, which many other buyers avoid due to sanctions, while Chinese refiners gain access to inexpensive crude.

As part of the renewed "maximum pressure" campaign, President Trump instructed the Secretary of State to execute an aggressive strategy—working alongside the Treasury and other agencies—to bring Iran's oil exports, including shipments to China, down to zero. However, Beijing does not acknowledge U.S. sanctions and continues to devise alternative methods to sustain imports.

Efforts to bypass restrictions have been particularly evident in February, when China's independent oil terminals at ports outside Shandong—including Dalian, Shanghai, Zhoushan, and Huizhou—started accepting sanctioned oil, including shipments delivered by blacklisted tankers, according to Emma Li, a senior market analyst at Vortexa. Iranian oil that was stranded offshore has been redirected to Shandong, the primary hub for China's independent refiners, often via ship-to-ship transfers.

Additionally, at least eight supertankers—either recently added to the so-called "dark fleet" or previously inactive—have emerged to facilitate transfers between Malaysia and China, according to Vortexa's data. This maneuvering allowed China's Iranian crude imports to bounce back in February, with shipments to Shandong exceeding the 2024 average, reaching approximately 1.1 million barrels per day (bpd) from February 1 to 20.

Looking ahead, analysts note that the growing number of U.S.-sanctioned oil tankers is limiting Iran's ability to transport crude. Tehran is now facing increased competition from Russia and Venezuela for vessels that have not yet been blacklisted by the U.S. Treasury. Although China has successfully adjusted to the early-February restrictions, Washington responded by sanctioning additional tankers and traders later that month, vowing to intensify efforts to block Iranian oil trade.

"The U.S. will leverage every available tool to target all components of Iran's oil supply chain. Anyone engaging in transactions involving Iranian crude risks severe sanctions," Treasury Secretary Scott Bessent stated.

Despite these measures, Iranian oil exports have not plummeted, as traders continue to seek alternative shipping methods, including more ship-to-ship transfers. Complete elimination of Iranian oil sales remains unlikely.

"There will always be some level of circumvention with any sanction regime," said Ja Ian Chong, a political science professor at the National University of Singapore. He explained that sanctions typically aim to make trade so financially unfeasible that buyers and sellers are forced to shift their behavior. However, achieving "zero Iranian oil exports" is not a realistic expectation.

Nonetheless, the Trump Administration remains committed to aggressively reducing Iran's crude exports—currently estimated at 1.5 to 1.6 million bpd—by tightening restrictions on financial networks and regional entities that facilitate Iran's oil trade and revenue collection.

"We will sever Iran's access to the global financial system by targeting regional actors that assist in transferring its oil revenues," Bessent declared. "Our objective is to dismantle Iran's oil industry and its drone production capabilities."

CHINA'S GASOLINE EXPORTS PLUNGE TO LOWEST LEVEL IN 12 YEARS

China's gasoline exports in February fell to their lowest level since August 2012 due to reduced refinery production and lower profit margins.

Data from China's General Administration of Customs showed that gasoline exports saw the steepest decline, dropping 73% year-on-year to 200,000 tons (1.69 million barrels) in February. Diesel and jet fuel exports also weakened during the same period.

Emma Li, a senior market analyst at Vortexa, stated that China's gasoline exports in February were constrained by lower production, particularly from private refineries, as well as strong domestic demand during the Chinese New Year travel season. Weak Asian profit margins, an export tax imposed in January, and limited export quotas further restricted any potential increase in exports.

Gasoline exports in January and February totaled 700,000 tons, marking a 56% decline compared to the same period last year. Diesel exports in the first two months of this year fell 42% year-on-year to 710,000 tons, while jet fuel exports dropped 5% to 2.67 million tons.

According to a Reuters report, total exports of China's refined petroleum products—including diesel, gasoline, jet fuel, and marine fuel—declined 18% year-on-year to 7.21 million tons. The data also revealed that China's liquefied natural gas (LNG) imports fell 19% annually to 10.6 million tons in January and February.

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CHINA'S NEW REGULATIONS AGAINST FOREIGN SANCTIONS COME INTO EFFECT

Chinese Premier Li Qiang has signed an order to implement new regulations aimed at strengthening the country's countermeasures against foreign sanctions.

These regulations pertain to the enforcement of China's Anti-Foreign Sanctions Law, which was passed in 2021. The law states that individuals or entities involved in imposing or enforcing discriminatory measures against Chinese citizens or entities can be placed on China's counter-sanctions list.

Those on this list may be barred from entering China or expelled from the country. Their assets in China could be seized or frozen, and they may be prohibited from conducting business with Chinese individuals or entities.

The new regulations clarify which sectors may have restrictions on foreign individuals and organizations. These sectors include education, science and technology, legal services, environmental protection, economy and trade, culture, tourism, healthcare, and sports.

The regulations also outline the measures the Chinese government can take in response, including banning or restricting individuals and organizations from importing or exporting relevant goods and technologies.

In recent years, China has faced trade and investment restrictions in major Western markets. Since February, U.S. President Donald Trump has imposed an additional 20% tariff on Chinese goods and is expected to introduce further tariffs in early April.

In response, China has imposed counter-tariffs, restricted exports of certain resources—including rare earth elements—and launched investigations into foreign companies.

According to a Reuters report, the Anti-Foreign Sanctions Law provides China with another tool to push back against foreign governments that it sees as infringing on its right to economic development.

Aramco in Talks to Invest in Indian Oil Refineries

Saudi Arabia's state-owned oil company, Aramco, is in talks to invest in two planned refinery projects in India, according to multiple informed Indian sources.

India, the world's third-largest oil consumer and importer, aims to become a global oil refining hub as Western companies reduce crude refining capacity in the transition to cleaner fuels. Meanwhile, Aramco—the world's largest oil exporter—is looking for stable crude oil sales markets in this growing market.

...time, Saudi Arabia's share of India's oil imports has declined ...ies, which have invested billions of dollars in upgrading ... diversified their crude oil supply sources and tur- ...lternatives, including Russian oil.

According to sources, Aramco is separately negotiating investments in Bharat Petroleum Corporation's planned refinery in the southern state of Andhra Pradesh and a proposed refinery by India's state-controlled Oil and Natural Gas Corporation (ONGC) in the western state of Gujarat.

While ONGC's Gujarat refinery project is still in its early stages, Bharat Petroleum's chairman stated in December that the company plans to invest $11 billion in the Andhra Pradesh refinery and petrochemical project.

Two refinery sources separately confirmed that these projects will proceed regardless of Aramco's investment. One of them noted, "Everything depends on the proposal Aramco puts forward."

According to informed sources, Aramco has proposed supplying crude oil equivalent to three times its stake in each project and intends to either sell its share of production in India or export it.

A second refinery source said, "We want flexibility in crude purchases. If we give them a 30% stake, they'll want to supply 90% of the refinery's crude capacity, which isn't feasible."

Details on the potential investment amount and the configuration of the planned refineries are currently unavailable.

A third source familiar with the matter stated that Indian Prime Minister Narendra Modi plans to visit Saudi Arabia in the second quarter of this year, and both countries are working to reach an agreement before the visit.

Aramco has long sought to expand its refining presence in India. In 2018, the company joined a consortium of Indian firms to build a 1.2 million-barrel-per-day refinery and petrochemical complex in western India. In 2019, it signed a non-binding agreement to acquire a 20% stake in Reliance Industries. However, the massive refinery project was delayed due to land acquisition issues, and the deal with Reliance was canceled due to valuation disagreements.

According to a Reuters report, Indian Oil Minister Hardeep Singh Puri stated in January that India is planning to launch three refineries, each with a capacity of 400,000 barrels per day.

AHMAD REZA YOUSEFI - RAZIEH GILANI

BITUMEN PRICES IN 2025

Ahmad Reza Yousefi, CEO of Infinity Galaxy and a Ph.D. candidate in International Entrepreneurship, has over ten years of experience in bitumen and petrochemical exports. Leading a young and dynamic team, he is committed to serving his country through exports. He believes that when customers trust his company, providing exceptional service is essential. Over the past five years, he has actively informed customers of the latest market changes, trends, and insights to help them maximize their business.

Razieh Gilani, Export Manager at Infinity Galaxy, is a bitumen market analyst and consultant with over seven years of experience in export, trade, and shipping, focusing on bitumen and petrochemical exports, particularly in markets such as China, India, East Asia, and Africa. For over 200 weeks, she has produced detailed market analyses to help industry stakeholders make informed decisions based on the latest trends and developments.

POTENTIAL SCENARIOS FOR BITUMEN PRICES IN 2025 BASED ON THE MAIN COMPONENT OF OIL PRICES

Introduction:

Bitumen, a vital, widely used material derived from crude oil, plays a crucial role in the world's modern infrastructure, from roads and highways to building insulation. Therefore, fluctuations in bitumen prices not only affect dependent industries but also indirectly impact the macroeconomy. Bitumen prices are inherently linked to the pulse of the crude oil market, and any change in the oil market is quickly reflected in bitumen prices.

Analysts envision various scenarios for oil prices in 2025. On one hand, signs of improving global demand, especially from China as the largest energy consumer, have raised hopes. On the other hand, the heavy shadow of geopolitical developments, changes in US shale oil production, and Federal Reserve monetary policies continue to loom as deterrents and concerns.

In this article, we will examine the potential scenarios for bitumen prices in 2025 in detail. By focusing on key components such as China's role in global demand, geopolitical developments, US shale oil production, Federal Reserve monetary policies, and key trends of 2024, we will try to paint a clearer picture of the future of bitumen prices. Finally, by analyzing the interplay between oil and bitumen, we will arrive at two potential scenarios for bitumen prices in 2025: an optimistic scenario with oil prices above $80 and a cautious scenario with oil prices around $70.

1. China's Key Role in Global Oil and Bitumen Demand:

China, as the world's second-largest economy and the largest oil importer, has a decisive impact on global oil prices and, consequently, on bitumen prices. Chinese President Xi Jinping's remarks at the beginning of 2025 about implementing active policies to stimulate economic growth in the year have increased hopes for improved energy demand. However, there are conflicting data on the country's economic situation:

- The Caixin/S&P Global report shows that China's factory activity in December 2024 grew slower than expected.

- Challenges such as slowing economic growth, the risk of US trade tariffs, and analysts' concerns about the impact of these factors on oil demand have caused market fluctuations.

In general, the improvement or weakening of China's economy in 2025 will act as a key driver in determining the path of oil prices and petroleum products such as bitumen.

2. Geopolitical Developments and US Shale Oil Production:

a) Regional Tensions:

The continuation of peace in the Middle East and the achievement of peace between Russia and Ukraine have blurred the amount of risk and concern about disruptions in the oil and gas supply chain. These tensions can put upward or downward pressure on crude oil prices (including WTI) in the short term, thereby increasing the cost of bitumen production.

b) The United States' Position as a Major Player:

- US oil demand reached 21.01 million barrels per day in October 2024 (the highest level since the pandemic).

- The country's shale oil production has also increased to a record 13.46 million barrels per day.

This simultaneous growth in demand and supply strengthens the US position as an indirect regulator of global prices. Increased shale oil production increases the likelihood of market saturation and lower oil prices in the long term, which could also lower bitumen prices. Of course, it should be noted that after Trump's election as president, his pressure on the large oil cartel OPEC to increase production and lower oil prices has begun. Also, Trump has forced Iraq to produce and export oil from the Kurdistan Region. This issue is in line with attracting the satisfaction of voters.

3. Federal Reserve Monetary Policies and Impact on the

Energy Market:

The US Federal Reserve is expected to cautiously pursue interest rate cuts in 2025 due to relatively high inflation. High interest rates can reduce demand for oil as a dollar-denominated commodity and also increase borrowing costs for infrastructure projects (major bitumen consumers), limiting bitumen demand.

4. Key Trends in 2024 and Outlook for 2025:

In 2024, the average decline in oil prices due to increased global supply and weak demand caused investor caution on the eve of 2025.

In 2025, oil prices are expected to remain in the $70 per barrel range. The main factors in this price range are:

- High supply: Increased US shale oil production and efforts by non-OPEC+ countries to compensate for budget deficits.

- Uncertain demand: Slowing economic growth in China and relative stagnation in Europe.

Conclusion: The Link Between Oil and Bitumen: Analyzing Interplay Effects

Bitumen, as a heavy petroleum product, is directly affected by crude oil price fluctuations. In 2025, two scenarios are likely:

1. Optimistic Scenario (Oil Prices Above $80):

If shale oil production decreases or geopolitical tensions intensify, bitumen prices will trend upward due to increased production costs, and without considering many basic components, the trend of packed bitumen prices in Iran can be predicted in the range of 400 to 450 dollars per ton.

2. Cautious Scenario (Oil Prices Near $70):

With continued high supply and weak demand, bitumen prices may remain relatively stable or even decline, and as in the optimistic scenario, and without considering other basic components, including: inflation, production costs; dollar rate; energy imbalance in production and other major issues, and in general, only based on the oil price component, the trend of packed bitumen prices in Iran can be predicted in the range of 350 to 400 dollars per ton.

It is worth mentioning that other major issues such as energy imbalance, the continuation of Trump's pressure on Iran, inflation, complex regional issues; the exchange rate and other issues are not seen in this forecast and cannot be measured in the current situation and only based on oil prices and previous trends in bitumen pricing; this range has been considered.

ENGINEERING BITUMEN FOR FUTURE ASPHALT PAVEMENTS: A REVIEW OF CHEMISTRY,

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ABSTRACT

Bitumen, a product mostly used as a binder in road construction, has been subject of numerous scientific investigations with the goal to optimise its function as an engineering material. Although a lot of research has been devoted to the three main pillars of bitumen characterisation, chemistry, structure and rheology, less attention has been paid to addressing their respective interrelationship. This critical review revisits modern theories, research advancements and methods, with a primary focus on how techniques like spectroscopy, chemical separation, rheology and microscopy can help to identify issues related to processes like modification and ageing of bitumen. Finally, an overview of current advancements of trying to correlate and interrelate these different schools is given. These individual studies highlight that a considerable amount of research is still required to understand the link between chemistry, mechanical behavior and structure of bitumen which can be related to its complex nature that depends on factors like crude oil origin and refinement process. In addition to that, more advanced characterisation tools and statistical methods, via the developing field of bitumen chemomechanics, can also help to solve modern issues related to future questions. Obtaining the required knowledge will ultimately help design and engineer future paving materials.

Keywords: Bitumen ,Asphalt binder, Chemistry, Rheology, Structure

UV	Ultraviolet	LDA	Linear Discriminant Analysis
ROS	Reactive Oxygen Species	THF	Tetrahydrofuran
SBS	Styrene Butadiene Styrene	SEE	Synchronous Excitation Emission
SARA	Saturates Aromatic Resins Asphaltenes	FEEM	Fluorescence Excitation-Emission Mapping
MD	Molecular Dynamics	NMR	Nuclear Magnetic Resonance
GPC	Gel Permeation Chromatography	EPR	Electron Paramagnetic Resonance
HPLC	High-Pressure Liquid Chromatography	TOF-SIMS	Time-of-Flight Secondary Ion Mass Spectrometry
ATR-FTIR	Attenuated Total Reflectance - Fourier TransformInfrared		
SNV	Standard Normal Variant		
PCA	Principal Component Analysis		

(continued)

SANS	Small-Angle Neutron Scattering	DSR	Dynamic Shear Rheometer
SAXS	Small-Angle X-Ray Scattering	TTSP	Time-Temperature Superposition Principle
WAXD	Wide-Angle X-Ray Diffraction	LAS	Linear Amplitude Sweep
AFM	Atomic Force Microscopy	MSCR	Multiple Stress Creep Recovery
CLSM	Confocal Laser Scanning Microscopy	VBA	Viennese Binder Ageing
ESEM	Environmental Scanning Electron Microscopy	PAV	Pressure Ageing Vessel
STEM	Scanning Transmission Electron Microscopy	PTR	Proton Transfer Reaction
		2D-FFT	Two-dimensional Fast-Fourier Transformation

1. Introduction

Bitumen, at ambient temperature, is a sticky, highly viscous, black or dark-coloured material, also commonly known as asphalt (Southeast Asia) or asphalt binder (North America). Chemically, bitumen is a complex blend of hydrocarbons and other heteroatoms such as oxygen, sulfur and nitrogen that are acquired through the distillation process of crude oil [1].

It is most used in road construction as a binder or adhesive for asphalt concrete, but it is also used to a limited extent for the production of roofing membranes, waterproofing materials, and some types of sealants. During the process of refining crude oil through distillation, a range of hydrocarbon products such as gasoline, kerosene, diesel, and lubricating oil are generated. These are typically recognised as highvalue refined products. The remaining material, often referred to as short residue, is commonly identified as straight-run bitumen.

Here, it is crucial to highlight that the characteristics of high-value distillation products, such as gasoline, undergo stringent control measures. As a result, the variations in chemical composition among sources of crude oil are significantly accentuated in the resultant short residue or straight-run distilled bitumen. To this end, the original property of each bitumen is greatly influenced by the methods used to produce and process it as well as the properties of the crude oil from which it is derived [2]. Generally, heavier crude oil tends to yield higher quantities of bitumen and hence, selecting the right crude oil and refining it using appropriate techniques is an important consideration for bitumen producers [3].

Nevertheless, it should be noted that bitumen is often not the main product of the refining operation. Currently, the majority of the bitumen produced worldwide is used predominantly as a binder in the asphalt paving industry [4]. This involves mixing bitumen with aggregates to create asphalt concrete mixes, typically through a hot mixing process at temperatures over 150 C.

Although other techniques exist, such as using foamed bitumen, warm mix and cold mix technology, they are not commonly used, accounting for a small percentage of the total asphalt mix production [5–7]. In situations where straight-run bitumen does not meet the specifications for pavement applications, producers resort to additional processing methods. This involves the manipulation of key variables, including the proportional blending of various binders, the selection of specific techniques and chemical catalysts (such as air blowing or half air blowing), and the incorporation of additives to modify properties [1]. Refineries employ optimisation strategies for these variables to engineer a bitumen that adheres to consumer requirements while minimising overall production costs. One of the most important characteristics of bitumen is that it exhibits a temperature-dependent viscoelastic behaviour, indicating its physical response as an engineering material falls within the continuum between a viscous fluid

and an elastic solid. This distinctive property highlights their inherent time-dependent nature, wherein their mechanical response evolves over time. More specifically, bitumen as an organic material is prone to oxidise or "age" during its service life.
During this ageing process, the material is exposed to environmental factors such as elevated temperatures, UV and visible sunlight, moisture or water as well as reactive oxygen species (ROS) present in the atmosphere [8–12]. Moreover, as a road paving material, it shows different behaviour depending on the service temperature and loading time.

At high temperatures and under slow-moving loads, it behaves as a purely viscous material and is prone to plastic deformations and rutting. At low temperatures and high rates of loading, it behaves as an elastic and eventually brittle material, leading to low-temperature cracking [13]. Hence, depending on the climatic region, bitumen with different properties is used in paving applications to meet performance requirements.
It is also common nowadays to modify bitumen with modifiers such as polymers at various percentages to improve its service properties [14–17]. The incorporation of modifiers in bitumen is undertaken to enhance its rheological and functional characteristics and widen the temperature window of application in asphalt pavements. The selection of an appropriate modifier is pivotal from both engineering and economic perspectives to achieve desired properties for paving applications.

Extensive research has explored materials such as polyolefins, natural rubber, thermoplastic elastomers, and crumb rubber as potential modifiers [18,19]. However, only a limited number of these have proven to be satisfactory in terms of both performance and cost-effectiveness. Out of these, styrene butadiene styrene (SBS) is a commonly used modifier, well recognised for improving the overall rheological properties of bitumen [20].

Such modification primarily targets the enhancement of fundamental properties, including rigidity, elasticity, brittleness, storage stability, durability, and resistance to accumulated damage. Other types of modification reported include recycled polymers, thiourea, isocyanate-functionalised prepolymers and phosphogypsum waste [21–24].
Lastly, another important class of additives are rejuvenators, which are used commonly to regenerate the rheological properties of bitumen after extended ageing in-situ. The main purpose of rejuvenation is to increase the recycling rate of the aged asphalt materials by recovering their properties [25–27]. However, issues such as phase discontinuity, poor dispersion, and instability with the use of such additives can complicate the production and application of modified materials in practice [28–31].

Overall, the engineering of bituminous materials to meet design requirements, especially in the face of increased traffic loads and the onset of climate change is an ongoing challenge for practitioners and engineers [32].

1.1. Importance of bitumen in pavement engineering
Globally, asphalt pavement is predominantly favored for its exceptional performance on roads, its straightforward rehabilitative processes, and the comfort it provides for driving conditions. As mentioned, the mechanical properties of asphalt mixtures are inherited from the bitumen and dependent on time, temperature, and age [33]. Bitumen generally constitutes a mere 4–8 % of the asphalt mixture by weight, whereas from a volumetric perspective, typical compositions feature 9–18 % bitumen, 78–85 % mineral aggregates, and 3–6 % air voids.

Despite its modest mass or volume fraction, bitumen commands a substantial portion of the material costs in asphalt mixture production [34].
This emphasises the considerable influence of bitumen prices, often linked to crude oil costs, on the overall economic dynamics of asphalt mixtures.

In essence, understanding the behaviour and performance of asphalt mixtures requires comprehension of the characteristics and performance of bitumen. Specifically in terms of rheological properties, the resistance to plastic deformation and rutting in asphalt mixtures is provided by both the aggregate structure as well as the bitumen, with the contribution of the bitumen being significant and crucial for predicting and understanding rutting [35].

Similarly, the failure of asphalt mixtures is also often caused by the displacement of bitumen from the aggregate particle surface, known as stripping, due to moisture. The ability of the interface between bitumen and aggregate to withstand such damage is determined by the physical and chemical surface characteristics of the bitumen as well as the aggregate [36].

Lastly, an essential characteristic of asphalt pavements is their resistance to cracking induced by thermal shrinkage during temperature reductions or by repeated action of traffic loads, typically exacerbated by ageing. Decreasing air and pavement temperatures lead to the development of tensile stresses within the asphalt mixture. Owing to bitumen's intrinsic viscoelastic properties, it possesses the ability to relax and thereby reduce these tensile stresses over time.

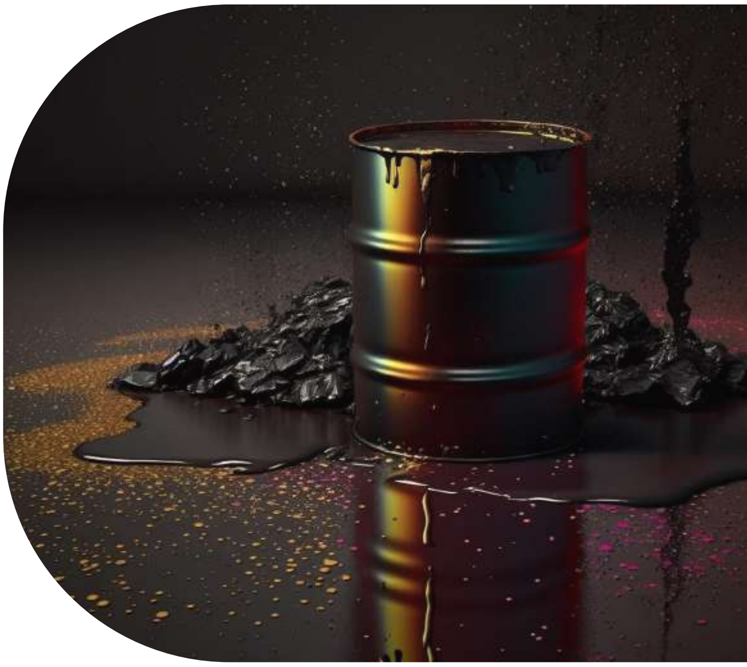
This phenomenon ensures that the cumulative tensile stresses remain within the bitumen's strength threshold, highlighting the material's ability to mitigate thermal-induced cracking [13].

1.2. Need for this review

There is wide consensus in the pavement engineering community that the behaviour and performance of bitumen are fundamental in predicting the performance of asphalt mixtures and pavements. However, it can be also contended that in mixtures, bitumen is used exclusively with aggregates and the behaviour of asphalt mixtures as a whole is naturally consequential when considering it as a structural entity.

Although such statements hold partial merit, it is crucial to emphasise that the durability of the asphalt mixtures heavily depends on the quality of the bitumen, and it is essential to choose one that is wellsuited for the prevailing climatic and traffic conditions. This ensures adequate performance as a first step towards designing a wellperforming asphalt mix. Developing and manufacturing bitumen with enhanced qualities can lead to significant enhancements in the longevity and lifecycle expenses of asphalt mixtures and pavements [37,38].

This is still a challenging prospect as the chemistry of the bitumen is complicated and many of its chemical



characteristics that eventually dictate rheological performance are topics of ongoing research. In that regard, the comprehension of bitumen chemistry is critical to appreciate and engineer its properties during all its life stages i.e., the production stage, service life and end of life. Such knowledge is important to appreciate several critical characteristics of bitumen such as modifications, extensions, bitumen ageing and eventual recycling with possible utilisation of rejuvenation.

When designing asphalt mixtures for high-end pavement applications, it would be practical to screen and engineer bitumen with superior mechanical properties. Additionally, the rise in traffic speed and load and unpredicted climatic events have resulted in decreasing the life of asphalt pavements [39,40].

This leads to higher maintenance costs and an increased risk to users. One of the ways that practitioners are looking to address this issue is through bitumen enhancement and the incorporation of various additives to improve its performance properties.
However, the eclectic nature of bitumen and complicated chemistry makes it a difficult material to comprehend and engineer for pavement practitioners. One of the main knowledge gaps that exists as of this review's writing is understanding the relationship between the chemistry, rheology and morphological structure or microstructure of bitumen. It has long been speculated that the links between these three pillars may be the key to fully understanding

the material and engineering its performance to the best possible extent. Moreover, current studies and research efforts do not employ the full potential of existing experimental tools for bitumen research, while the sample preparation and standardisation of these techniques need to be also carefully considered.

Thus, the purpose of this review article is to disseminate the current state of the art in bitumen with an emphasis on the latest developments and comprehension in chemistry, rheology, and microstructure. Based on this, the future direction and required research to achieve superior levels of understanding and engineering performance of the material is deliberated. The three pillars of relevance in this review are depicted schematically in Fig. 1 together with the direct relationships represented by the given arrows.

1.3. Scope and outline of this review

This review article presents the current state of the art in relation to bitumen as a binder material for asphalt pavements. It is important to note that this critical review is aimed at providing a succinct overview of the subject matter and is not an exhaustive review of all available literature, for which the reader is referred elsewhere [12,41]. In view of that, the article is mainly divided into five distinct sections. In the first three sections, the chemistry, structure and rheology of bitumen are deliberated.

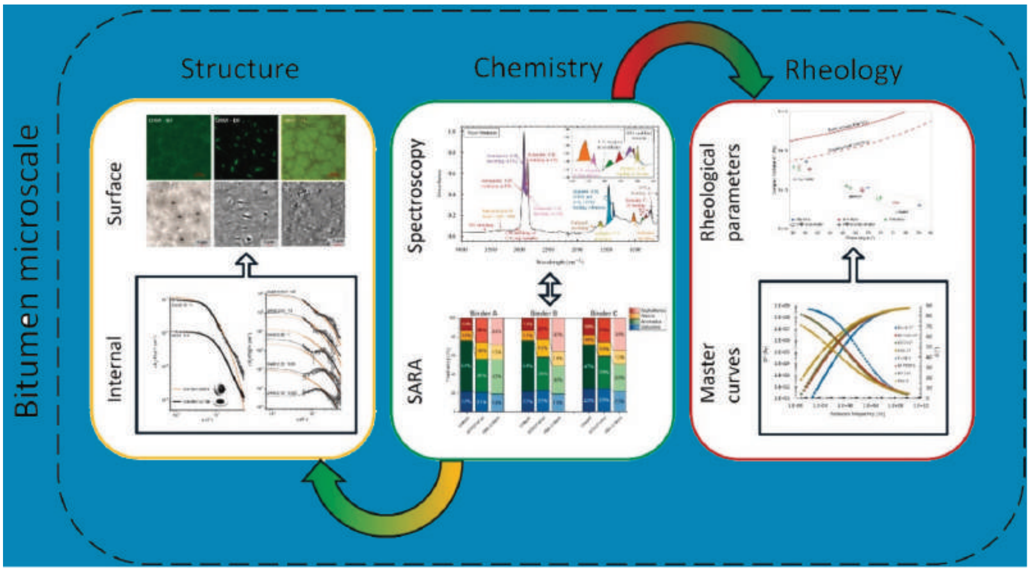


Fig. 1. The three pillars of bitumen focus of this review article.

Each section provides a synopsis of the current state of knowledge in these areas including the latest research advancements over the past years. Next, the interrelationship between the properties is contemplated with an emphasis on bitumen characterisation, ageing and modifications. Lastly, based on the critical evaluation of existing literature, the future directions of research including vital knowledge gaps that need to be addressed are discussed. Overall, this critical review article is expected to be helpful for researchers, engineers, and policymakers as a reference guide to understand the current information on this topic and identify key areas for impactful future research.

2. The chemistry

This section focuses on the chemistry of bitumen and illustrates various analytical methods that can be used for its characterisation.

These techniques include separation techniques as well as a broad variety of spectroscopic analysis tools that can give valuable insight into the chemical nature of the material.

2.1. Identification and simplification of bitumen chemistry by separation techniques

2.1.1. SARA fractionation

Bitumen is a complex engineering material consisting of a multitude of different molecules. To simplify its study, the characterisation and identification of bitumen including its chemical composition has been a topic of interest for more than 50 years [42–46]. In 1957 Stewart used chromatographic separation techniques and infrared spectroscopy to identify the chemical composition of unaged and field-aged fractions of roofing bitumen. A separation of asphaltenes and maltenes was achieved by using n-pentane as a solvent [42]. Roughly 10 years later, Corbett proposed elution-adsorption chromatography to separate bitumen into four fractions the saturates, naphthene aromatics, polar aromatics and asphaltenes [44]. This separation has since been further developed with slight adaptations to the solvents or different names of the fractions.

For example, the proprietary method of SARA-AD of the Western Research Institute (WRI) provides even further subfractions of the four main SARA fractions [47]. However, the overall concept of separating the material into polarity-based fractions, the SARA (Saturates, Aromatics, Resins and Asphaltenes) has remained the same. This led to the standardisation in the ASTM D41 24–01 [48], where the binders get separated into saturates, naphthenic aromatics (renamed aromatics), polar aromatics (renamed resins) and asphaltenes. It is worth noting that this separation is not a strict separation into a precise set of molecules but rather a separation along a polarity gradient. This indicates that saturates, resins or asphaltenes can also contain small or large aromatic structures.

Typically, such a polarity-based separation is a tedious and timeconsuming procedure. Thus, modern adaptations have led to new methods that utilise automatised separation or fast, small-scale approaches.

One example is the approach developed by Sakib et al. [49], where solid phase extraction was used to separate 400 mg of binder, yielding the four desired SARA fractions with quick execution and excellent repeatability. This method has already been implemented in other international research groups [50–53] and the miniature apparatus can be seen in Fig. 2. Mirwald et al [50,51] looked at the spectroscopic information of these SARA fractions and their respective changes during ageing. Guo et al. characterised the effect of rejuvenators on the SARA fractions [53] and attempted to link the SARA fractions to molecular dynamic (MD) simulations [52].

Work by Schettmann et al. [54] used a similar solid phase extraction and compared it to column chromatography. Their work investigated virgin and aged bitumen via gravimetric determination and also analysed the fractions chemically.

Thus, all these separation methods mostly served the same purpose i.e. to evaluate the polarity distribution of these fractions and determine their composition. It should be noted that the exact chemical constituents of the SARA fractions such as carbon, oxygen, sulfur and nitrogen can only be revealed via elemental analysis [55]. However, this method only provides an elemental overview of the material and does not provide any insight to how these elements are linked to each other.

Thus, their insight needs to correlated to a specific chemical question.

2.1.2. Gel permeation chromatography (GPC)

Another important chromatographic technique used to characterise bitumen is gel permeation chromatography (GPC), which provides information on the molecular weight distribution of bitumen [56–58].

Larger molecules require less time to travel through the column compared to smaller ones. Thus, the resulting chromatogram shows the molecular weight distribution in correlation to elution time. In 1979, Such et al [45] used GPC and high-pressure liquid chromatography (HPLC) to characterise bitumen. The SHRP report from 1993 also reports results from GPC of the SHRP binders AAA-AAG [59] indicating that the method can account also for the interaction between their molecules.

Thus, GPC is used to address differences in bitumen ageing [60–63], impact of additives such as polymers like SBS [64–66], crumb rubber [67,68], alternative materials such as bio-based binders [69], the effect of recycling and rejuvenation agents [63] or the usage of antioxidants [70]. A drawback of the method is that it requires specific equipment and dissolved samples, which leads to a more

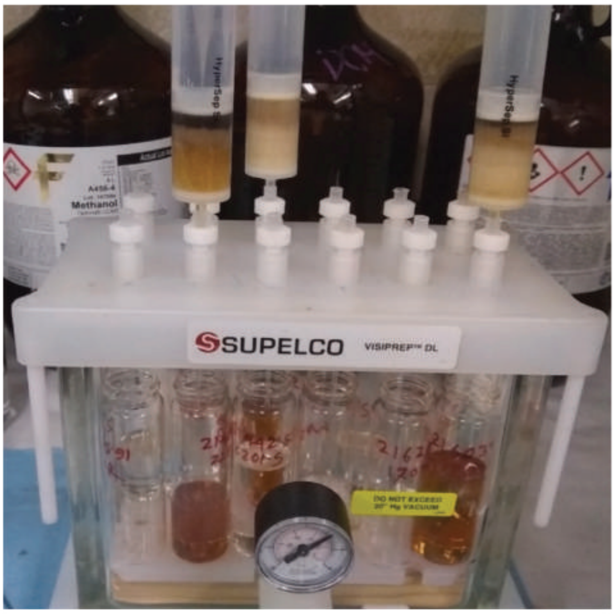


Fig. 2. The small-scale apparatus developed for SARA fractionation (reprinted from [49].

complicated sample preparation procedure. The obtained results also are slightly dependent on other characteristics of the test setup. Therefore, it is not a commonly used chemical characterisation technique in bitumen and asphalt research.

2.2. Spectroscopic techniques

2.2.1. Fourier Transform infrared (FTIR) spectroscopy

The most common analytical technique used in the field of bitumen research is Fourier Transform Infrared (FTIR) spectroscopy [71]. A material can be characterized by FTIR if it contains IR active functional groups that absorb infrared light. IR light absorption leads to a change in dipole momentum and the molecules start to rotate or vibrate, which creates a characteristic band for a specific functional group. Fig. 3

summarises most of the functional groups found in bitumen documented by Petersen et al. [72]. The ketones and sulphoxides are particularly relevant in bitumen analysis as they are formed during the ageing process and can thus be traced with FTIR spectroscopy in a semiquantitative way.

A typical FTIR spectrum of an unmodified (blue) and a polymermodified bitumen (green) is shown in Fig. 4. The respective functional group and assigned vibration of the bands shown in Fig. 3 are listed in Table 1 (hydrocarbons), Table 2 (oxygen-containing functional groups) and Table 3 (sulphur-containing functional groups).

In order to determine the significance of these functional groups, the changes of their respective intensities upon chemical processes such as ageing need to be considered. Starting with the hydrocarbon-containing functional groups, it can be said that the alkyl bands listed in Table 1 remain mostly unaffected by ageing.

Thus, these functional groups often act as a reference band. The aromatic bands at 1600, 850, 810 and 750 cm 1 increase slightly, which can be attributed to the dehydrogenation of perhydro-aromatics such as 9.10-dihydroantracenes, which are assumed to be the initial molecules reacting with oxygen, starting a chain oxidation mechanism [9]. For bitumen ageing quantification, the ketone and sulphoxide functional groups at 1700 and 1030 cm 1 are mainly of interest, as they change significantly with ageing. Other groups such as 2-quinolones, carboxylic acids [9,50] or esters are mostly found in the resins fraction or are formed during ageing [46,73,74].

Looking back at the early stages of bitumen characterisation, Stewart was one of the first to report the infrared spectra of roofing binders [42].

During the first FTIR trials with bitumen, the binders had to be prepared and measured in transmission mode [46,75,76]. Since bitumen in its solid-state lack's transparency, and it needs to be dissolved and applied onto a compatible substrate, such as a KBr, CsI, or NaCl crystal window [77].

This was a tedious process and consumed a lot of time, which diminished the methods practicality. After the implementation of the attenuated total reflection (ATR) geometry, where the solid bitumen sample can be placed directly onto the ATR crystal, the method's usability increased significantly. Most ATR crystals are made of diamond, germanium, or zinc selenide.

While the applicability of ATR-FTIR increased the method's popularity significantly, it led to questions regarding routine measurement and universal applicability. Since there is currently no standard for measuring bitumen with FTIR spectroscopy, various measurement routines and approaches for spectral evaluation have been developed. Typical spectral evaluation involves normalisation and integration of regions of interest, such as the region of carbonyl around 1700 cm^{-1} or sulphoxides at 1030 cm^{-1}. Lamontagne et al., the Belgian Road Research Centre (BRRC), Laboratoire central des ponts et chaus´ees (LCPC) and participants from the MURE evaluated FTIR spectra using the valley-tovalley or tangential integration method [75,78–81]. Work by Hofko et al.

[82] tackled the topic of repeatability and sensitivity regarding the effects on oxidation comparing raw data and normalised spectra as well as full-baseline and tangential (valley-to-valley) integration methods.

Follow-up work by Mirwald et al. investigated the impact of sample preparation and the impact of thermal history (heating time and temperature).

They furthermore reported the influence of storage time and storage conditioning of different unmodified and modified bitumen with ATR-FTIR spectroscopy [73,83]. A more sophisticated spectral data evaluation approach was investigated by Weigel et al. [77,84] who applied standard normal variant (SNV) transformation and coupled it with multivariance analysis to detect differences in binder origins to predict its properties. Ma et al.

[85] also utilised principal component analysis (PCA) and linear discriminant analysis (LDA) models to investigate the effects of ageing via FTIR spectroscopy and correlated specific bands or wavenumber regions to bitumen source, type, and ageing state. Primerano et al.

[86] also utilised multivariance analysis to find differences in FTIR spectra of various laboratory and field long-term aged bitumen and highlighted the influence of different ageinginducing factors. FTIR spectroscopy can also be used to characterise prominent bitumen modifiers such as SBS. Since both styrene and butadiene are IRactive functional groups, they can be tracked with infrared spectroscopy [87–89].

In the FTIR spectra, the band assigned to the polybutadiene

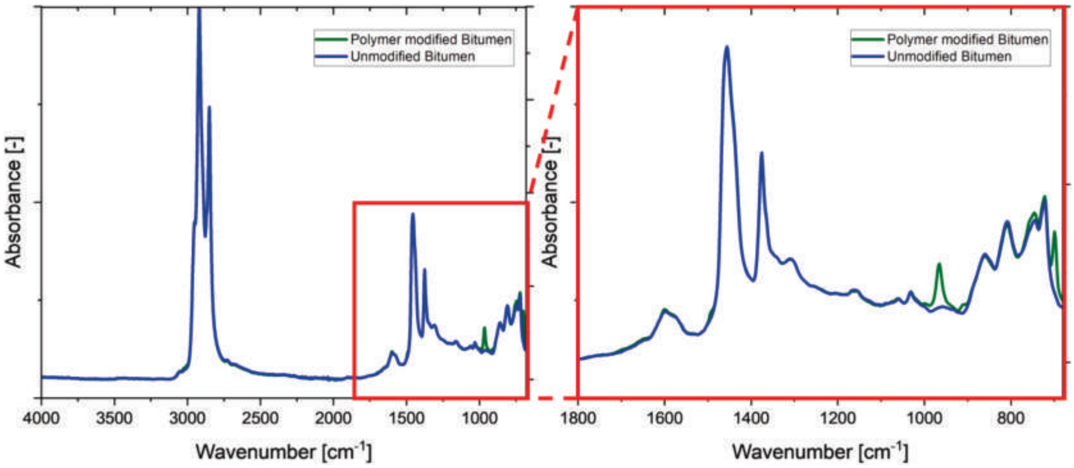


Fig. 4. Exemplary FTIR spectra of an unmodified (blue) and polymer-modified bitumen (green) shown at full spectral range (left) and in the fingerprint regio (right). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Hydrocarbon functional groups found in bitumen (taken from [50]).

Functional Group	Assigned Vibration	Appearing Band [cm^{-1}]
Alkyls	ν_{as} CH_2/CH_3	2920
Alkyls	ν_s CH_2/CH_3	2850
Alkyls	δ_{as} CH_2/CH_3	1455
Alkyls	δ_s CH_2/CH_3	1380
Alkyls	ρ (CH_{2n})	720
Aromatic	ν C=C	1600
Aromatic	γ CH_{aro}	860
Aromatic	γ CH_{aro}	810
Aromatic	γ CH_{aro}	750
Alkene	δ (CH)	960

Table 2
Possible oxygen-containing functional groups found in bitumen (taken from [50]).

Functional Group	Assigned Vibration	Appearing Band [cm^{-1}]
Ketone	ν C=O	1700
2-Quinolone	ν C=O	1655
Carboxylic Acids	ν C=O	1730

Table 3
Possible Sulphur-containing functional groups found in bitumen (taken from [50]).

Functional Group	Assigned Vibration	Appearing Band [cm^{-1}]
Sulphoxides	ν S=O	1030
Sulphones	ν SO_2 (out-of-phase)	1310
Sulphones	ν SO_2 (in-phase)	1160
Sulphate Ester	ν_{as} SO_3	1260
Sulphate Ester	ν_s SO_3	1080
Sulphate Ester	ν S-O-C	810

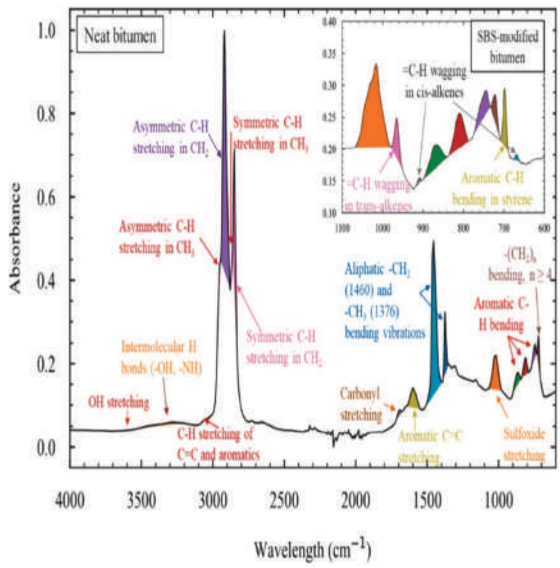


Fig. 5. Possible functional groups in FTIR spectra of conventional and polymer-modified bitumen (reprinted from [85]).

can be seen at 966 cm^{-1} and the polystyrene at 699 cm^{-1}. These bands can either be used to identify whether bitumen contains SBS or if the polymer is changing upon phenomena like ageing. As an example, Sun et al. used FTIR spectroscopy to quantify the amount of SBS polymer contained in different bitumen, ranging from 2 to 6 % [88]. On the other hand, Mouillet et al. used FTIR spectroscopy to quantify the degradation of SBS polymer upon UV ageing via the evolution of the butadiene double bond band at 966 cm^{-1} [90]. The same principle applies to other additives such as rejuvenators or other extenders, where FTIR can be used as a characterisation tool if the materials contain IR active functional groups. A representative FTIR spectrum, including information about all possible functional groups in conventional and polymermodified bitumen, is shown in Fig. 5.

2.2.2. UV Vis and fluorescence spectroscopy

Light in the visible and ultraviolet domain can also be used to obtain characteristic information of the chemical composition of bitumen. Soenen et al. [91] studied laboratory aged bitumen dissolved in tetrahydrofuran (THF) with UV–vis absorption spectrophotometry and showed changes in absorption at longer wavelengths around 600 nm which increased upon ageing.

Hou et al. [92] and Hung et al. [93] have also obtained similar results, where ageing causes an increase in the wavelength domain of 700 – 900 nm, which was linked to the increase in asphaltene content.

Buisine et al. [59] studied different bitumen samples using synchronous excitation emission (SEE) fluorescence spectroscopy, revealing a strong fluorescence signal in the range between 250 – 600 nm. These can be assigned to aromatic rings of different sizes, where an increase in wavelength corresponds to an increased aromatic ring size. Handle et al.[94] and Grossegger et al. [95] conducted similar fluorescence spectroscopic measurements on unmodified, solid bitumen and its SARA fractions.

Excitation scans, emission scans and fluorescence excitationemission mapping (FEEM) revealed an overall strong loss in fluorescence intensity, that can be linked to the decrease in aromatic content during ageing. The analysis of the SARA fractions revealed that most of the intensity comes from the aromatic fraction as its fluorescence intensity is two orders of magnitude higher compared to the rest of the fractions.

The overall intensity loss upon ageing can be explained by the fact that the aromatic fraction decays the most. Mirwald et al. [96] coupled fluorescence spectroscopy with optical fluorescence and darkfield microscopy to investigate the differences between various long-term ageing procedures. FEEM results showed that besides the overall decrease in the fluorescence intensity, a shift towards a higher emission wavelength and possible quenching effects were observed. Recent work by Werkovits et al. [97,98] combined fluorescence spectroscopy with FTIR spectroscopy and Nuclear Magnetic Resonance (NMR) spectroscopy to investigate the ageing effects on bitumen and its SARA fractions (Fig. 6).

Emission scans and FEEM maps confirmed a shift towards higher wavelengths upon long-term ageing. These trends were also highlighted in differential FEEMs, where the loss of small aromatics was observed in the saturates and aromatics, which reappeared in the fractions with higher polarity.

Similar to FTIR spectroscopy, fluorescence spectroscopy can also be used to identify SBS polymers within polymer-modified bitumen. This can be explained by the fact that SBS exhibits autofluorescence on a significantly higher level than the bitumen itself.

A study by Mirwald et al. was able to identify the contribution of SBS in fluorescence spectroscopy, revealing a strong signal around 350 nm when measured in excitation mode. Surfaces containing different amounts of SBS show different intensities of the respective signal around 350 nm [99,100].

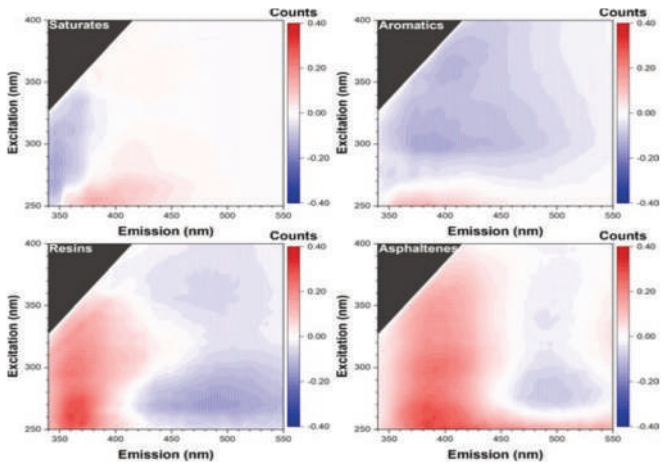


Fig. 6. Typical FEEM of the SARA fractions (reprinted from [98]).

2.2.3. Nuclear Magnetic Resonance (NMR) spectroscopy
NMR is a spectroscopic technique which is used for materials that contain elements with an odd number of protons, such as hydrogen, carbon or phosphorous. Since organic materials like bitumen mostly consist of these elements, it would be an ideal candidate for NMR spectroscopy.

However, since bitumen contains millions of different molecules [37], the resulting outcome can show overlapping signals and lead to unclear results. Nonetheless, researchers have investigated binders with 1H and 13C NMR spectroscopy, typically regarding changes induced by laboratory ageing [101–107]. Most of these studies showed many overlapping bands, making it difficult to come to a precise answer.

Thus, the post-separation spectral analysis becomes a necessary step. On the bitumen level, Woods et al. [108], Guo et al. [52] and Huang [109] investigated the SARA fractions with 1H and 13C NMR spectroscopy.

Results showed an increase in aromatic carbon ratio as well as a cycloalkane carbon decrease with rising polarity (Saturates < Aromatics < Resins < Asphaltenes). Furthermore, poly-condensed aromatic rings were found in the aromatics, resins and asphaltenes.
However, the necessity for separation also makes this method quite inconvenient and unpractical.

Thus, another possible approach to tackle the issue of overlapping signals was addressed by the combination of different NMR techniques. Such a combination was mostly conducted on crude oil fractions [110], from feeds in the refinery process [111] or on heavy fuel oils [112]. However, recently Werkovits et al. [97] applied different NMR techniques, such as HSQC and 31P NMR, on various bitumen and its SARA fractions, which provided insight into the H/C ratio, aromatic systems and average molecular size of binder and fractions. A typical HSQC NMR spectrum of bitumen can be found in Fig. 7.

Notable conclusions were that the fractions contain varying chain lengths of aliphatic substituents. Functional groups such as esters or amides are found in the resins, which was indicated by a characteristic shift. 31P NMR revealed the presence of minor amounts of alcohols and carboxylic
acids. Overall, it can be inferred that the utilisation of NMR spectroscopy has risen in recent times, but fundamental knowledge at the chemical fractions level as well as a its use as a combination with other techniques is required to come to meaningful conclusions.

2.2.4. Electron paramagnetic resonance (EPR) spectroscopy

Analogous to the principle of NMR spectroscopy, where the electromagnetic field is used to analyse nuclei of the molecules, electron paramagnetic resonance (EPR) spectroscopy makes use of the electromagnetic field but investigates the unpaired electrons or their spins.

Pipintakos et al. [102,113] investigated the oxidation mechanism of bitumen using EPR spectroscopy and combined it with FTIR spectroscopy, 1H NMR and Time-of-flight secondary ion mass spectrometry (TOF-SIMS). The EPR analysis revealed that carbon-centred radicals form upon oxidation, while vanadyl-porphyrins remain mostly unchanged. Rossi et al. [114] also analysed the effect of antioxidants on the ageing process by investigating asphaltenes and maltenes via EPR and combined it with rheological investigations. EPR results showed the effectiveness of the antioxidants, as a lower content of radicals was determined for the fractions containing the antioxidants.

2.2.5. Time-of-Flight secondary ion mass spectrometry (ToF-SIMS)

Mass spectrometry can also be used to determine the chemical composition of the surface of the material. An ion beam (primary ions) bombards the surface of the material, emitting secondary ions. These ions are then separated according to their different masses using a timeof- flight analyser. Not a lot of literature and research has been conducted using this method, which can mainly be attributed to the fact that it is an expensive device and that the information gained from a complex material like bitumen is limited. On top of that, most mass spectrometers work under vacuum, which requires special attention during preparation and measurement. Nonetheless, various researchers have studied different binders using ToF-SIMS [101,115–118]. Results mainly indicate that hydrocarbon ions CxHy+ dominate the positive ion spectra, while the negative ion spectra show peaks from heteroatom-containing ions.

3. The structure

The previous section on chemistry reviewed the use of techniques, such as chromatography and spectroscopy, to examine the variety of molecular species in bitumen based on polarity, molecular size and functional groups. However, most of these spectroscopic techniques fail to realise the structure of the material i.e. the spatial distribution of the different molecular species. Thus, microscopic and other characterisation techniques are required to resolve the morphology and structure of the material.

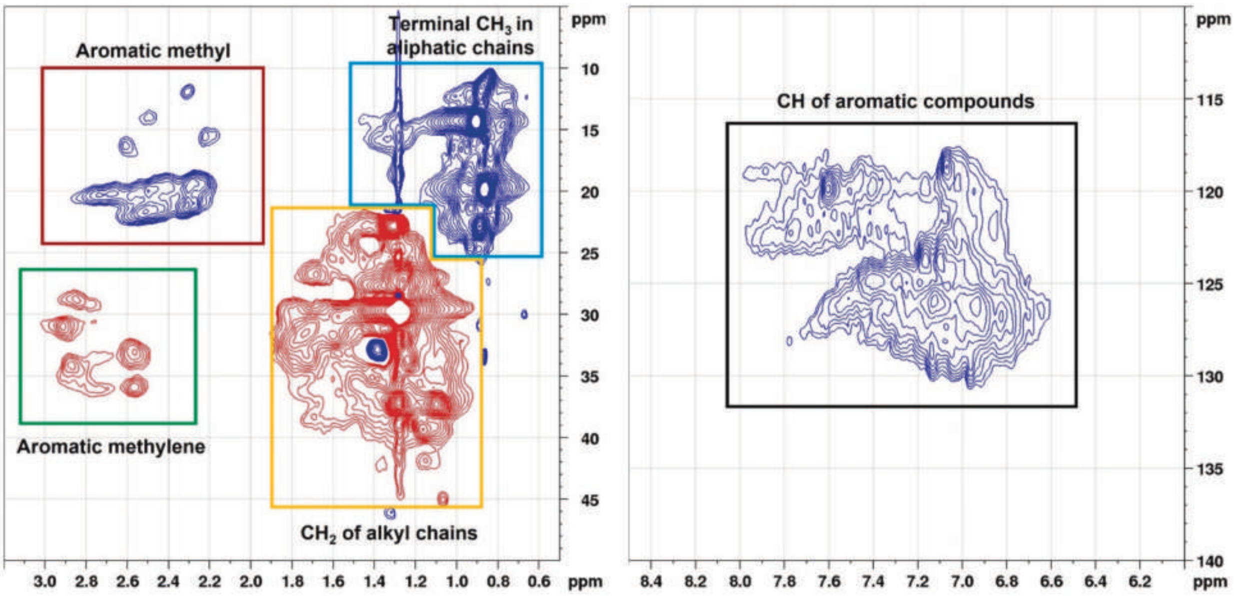


Fig. 7. HSQC NMR spectrum of bitumen depicting the aliphatic and aromatic regions (reprinted from [97]).

3.1. Modern theories of bitumen's structure

The internal structure of bitumen has long been of interest to researchers, in part because of the possible connection to its viscoelastic performance. Theories about the structure of bitumen are rooted back to 1914 when Rosinger shaped the idea of the colloidal structure [119].

This model was adopted and further discussed by Nellensteyn, describing bitumen as a colloidal suspension of asphaltenes and maltenes,in which resins surround the asphaltenes contributing to a stabilising effect in this suspension [120]. This idea was widely accepted by the scientific community for many years as it found basis as an explanation of the sol–gel behaviour of bitumen [121,122]. More specifically, bitumen can behave as a Newtonian or non-Newtonian fluid-like material, depending on the aggregation and interaction potential of the asphaltenes inside the oily maltene medium [123].

Another theory put forward for the structure of bitumen is widely known as dispersed polar fluid [124–126]. It was speculated that since an elastic plateau cannot exist for a gel bitumen [127], then it should be a purely homogeneous fluid of all the SARA fractions in a mutual solution.

The SARA fractions do have different solubilities in this solution, while a phase separation could be explained by a reduction in the system's entropy and by successive enthalpy compensation. Based on contemporaneous theories from colloids science, Yen initially hypothesised bitumen structure in a hierarchical way forming cores, micelles and aggregates consisting of asphaltenes [128]. Mullins further developed this idea by classifying the structure of bitumen based on the propensity of asphaltenes to form nanoaggregates and clusters [129,130]. This theory is known as the Yen-Mullins model (Fig. 8) and various sophisticated spectroscopic and scattering techniques have partially validated its rationale [131,132].

3.2. Modern theories of bitumen's surface microstructure

It appears that bitumen has a strong tendency to form peculiar surface microstructural patterns, as observed by different modes of microscopy. To explain these surface features, theories have been developed over the years in the scientific community. It has long been a matter of debate which one could explain their formation supporting also a reasonable thermodynamical balance. As expected, each school of thought has its merits and deficiencies.

On the one hand, the 'wax theory' has its basis on the paraffinic wax that can exist in bitumen's composition [133–135] whereas the 'asphaltene theory' attributes these microstructures to the most polar of the SARA fractions [136]. The former supports that the crystallisable components that exist by means of paraffinic or microcrystalline waxes can crystallise in large, thin flat plates or small crystals of a few micrometres respectively [137–139]. When crystallised the waxes are considered responsible for the formation of the surface microstructures

in bitumen [140].

The 'asphaltene theory' is built around the premise that the polar asphaltene micelles can be stabilised in the maltene matrix. The association of the hierarchically structured agglomerations of asphaltenes and the various sizes of the surface microstructures is considered the most sound argument of this theory [141–143]. It is worth mentioning that the asphaltene theory put forward attempts to bridge the gap between bulk and surface microstructure as well as its chemical composition.

3.3. Internal and surface structure

3.3.1. Small-Angle Neutron (SANS), x-ray scattering (SAXS) and Wide- Angle X-ray Diffraction (WAXD) To elucidate the internal structure of bitumen in the scale of nanoobservations, scholars have utilised scattering techniques such as SANS, SAXS and WAXD. The advantage of these techniques is the investigation of the bulk of bitumen.

It additionally provides information regarding the orientation and composition of the captured units, assumed to be asphaltene nanoaggregation, as shown in Fig. 9 [144,145]. The basic working principle of these techniques is based on the different reflections at varying scattering angles that the various bitumen molecules experience. It can provide an estimation for the type and organisation of these agglomerations when compared with standard probe materials [134,146].
SANS is particularly used to study isolated asphaltenes nanoaggregation in dissolutions whereas SAXS and WAXD are more applicable to study the parent bitumen. The morphology and size of aggregation are made possible via these techniques. Moreover, paraffins, when present in bitumen, are found to be typically organised in orthorhombic unit cells [131,147].
Several studies report that the asphaltene nanoaggregation ranges between 60 and 300 \AA whereas their shape varies somewhere between disk and spherical [148–150]. Asphaltenes aggregate in 'islands' in low concentrations while in higher concentrations they form 'clusters'.

3.3.2. Atomic Force Microscopy (AFM)

Several microscopic techniques have been applied to study the surface microstructure of bitumen. To name some of them, Environmental Scanning Electron Microscopy (ESEM) [151], Scanning Transmission Electron Microscopy (STEM) [139], Confocal Laser Scanning Microscopy (CLSM) [152], Brightfield and Darkfield Microscopy [153,154] have been successfully applied to bitumen applications. Out of these, the technique that has been used largely is Atomic Force Microscopy (AFM).

An example of microscopic images of the same bitumen in different modes is shown in Fig. 10.
AFM has been used to study the topography, adhesion, stiffness and phase contrast at the microscale level [155,156]. Sample preparation for AFM plays a crucial role in the surface-driven patterns that can be captured and is conducted either via spin or heat casting [157,158].
Operation of a typical AFM can be performed in near-contact, tapping and non-contact mode, while recent developments provide also a coupling with peak force and nanomechanical or chemical mapping [159].
It should be noted that bitumen modification, like SBS, cannot be

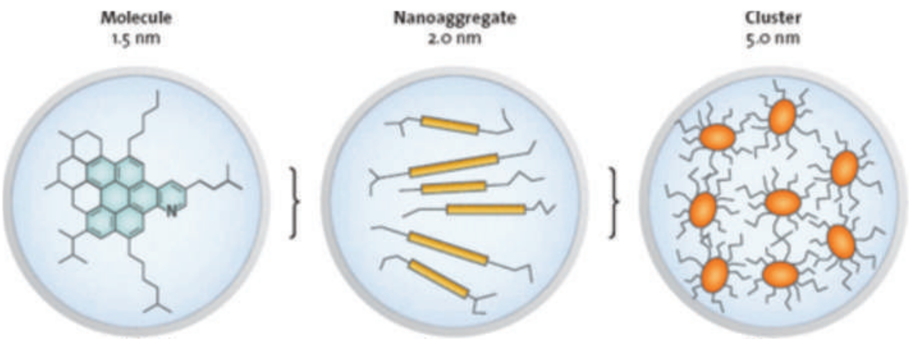


Fig. 8. Simplified representation of the Yen-Mullins model (reprinted from [129]).

This article continues, and you can read the rest of it in the April issue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