International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 2 Issue 2, February- 2013

Emerging Trends in Greener Pavements

Vignesh H*, Ramesh Babu N.G, Manivasagan V, Suganya S and Eajas Basha M

Department of Biotechnology,

Adhiyamaan College of Engineering (Autonomous),

Hosur-635109, Tamil Nadu, India

*Corresponding Author

Vignesh H

Department of Biotechnology,

Adhiyamaan College of Engineering (Autonomous),

Hosur-635109, Tamil Nadu, India

ISSN: 2278-0181
Vol. 2 Issue 2, February- 2013

Abstract

The traditional, commercial and the most commonly used method for paving roads and pavements is asphalting. Asphalt also known as bitumen is a sticky, black and highly viscous liquid or semi-solid form of petroleum entirely soluble in carbon disulfide, and composed primarily of highly condensed polycyclic aromatic hydrocarbons. It contains toxic, heavy metals including nickel, lead, mercury, vanadium, chromium, mercury, arsenic and selenium. Oxidation can cause deterioration via long-term aging and eventually result in cracking of asphalt pavements. Due to the adverse effects of asphalting, greener method was mandatory. Today's 'green revolution' has brought about an interesting and more environmentally friendly alternative to asphalt known as 'BioAsphalt' which is free from toxic materials. Bioasphalt is an asphalt alternative made from bitumen from non-petroleum based renewable resources. Bioasphalting decreases paving costs by 20%, decreases carbon footprint, diminishes greenhouse gas emissions, and it boasts increased pavement life.

Keywords: asphalt, green revolution, bioasphalt

1. Introduction

The traditional, commercial and the most commonly used method for paving roads and pavements is asphalting. Due to its adverse effects and increase in the rate of global warming, finding a newer method was mandatory. The green revolution paved the way to overcome those adverse effects by the usage of renewable resources and wastes. This biologically modified form of Asphalt is called BioAsphalt. In this review, the effects of traditional pavements, their properties and how to overcome those effects by using eco-friendly methods have been discussed.

2. Asphalt

Asphalt i/ˈæsfɔːlt/ or /ˈæʃfɔːlt/ or /ˈæsʃfɛlt/, also known as bitumen, is a sticky, black and highly viscous liquid or semi-solid form of petroleum entirely soluble in carbon disulfide, and composed primarily of highly condensed polycyclic aromatic hydrocarbons. It may be found in natural deposits or may be a refined product; it is a substance classed as a pitch. Until the 20th century, the term asphaltum was also used [4].

Figure 1. Asphalt

The primary use of asphalt/bitumen is in road construction, where it is used as the glue or binder mixed with aggregate particles to create asphalt concrete. Its other main uses are for bituminous waterproofing products, including production of roofing felt and for sealing flat roofs.

The terms asphalt and bitumen are often used interchangeably to mean both natural and manufactured forms of the substance. In American English, asphalt (or asphalt cement) is the carefully refined residue from the distillation process of selected crude oils. Outside the United States, the product is often called bitumen. The term Bitumen is preferred in geology. Common usage often refers to various forms of asphalt/bitumen as "tar", such as at the La Brea Tar Pits. Another term, mostly archaic, refers to asphalt/bitumen as "pitch". The pitch used in this mixture is sometimes found in natural deposits but usually made by the distillation of crude oil.

Naturally occurring asphalt/bitumen is sometimes specified by the term "crude bitumen"; its viscosity is similar to that of cold molasses. [1] [25] whilst the material obtained from the fractional distillation of crude oil [boiling at 525 °C (977 °F)] is sometimes referred to as "refined bitumen".

3. Sources

Natural deposits of asphalt/bitumen include lakes such as the Pitch Lake in Trinidad and Tobago and Lake Bermudez in Venezuela, Gilsonite, the Dead Sea, asphalt/bitumen-impregnated sandstones known as bituminous rock and the similar "tar sands". Asphalt/bitumen was mined at Ritchie Mines in Macfarlan in Ritchie County, West Virginia in the United States from 1852 to 1873.

Asphalt/bitumen can be separated from the other components in crude oil (such as naphtha, gasoline and diesel) by the process of fractional distillation, usually under vacuum conditions. A better separation can be achieved by further processing of the heavier fractions of the crude oil in a de-asphalting unit, which uses either propane or butane in a supercritical phase to dissolve the lighter molecules which are then separated. Further processing is possible by "blowing" the product: namely reacting the product with oxygen. This makes the product harder and more viscous.

Naturally occurring deposits of asphalt/bitumen are formed from the remains of ancient, microscopic algae (diatoms) and other ancient living beings. These remains were deposited in the mud on the bottom of the ocean or lake where the organisms lived. Due to the heat (above 50 °C) and pressure of being buried deep in the earth, the remains were transformed into materials such as asphalt/bitumen, kerogen, or petroleum. Deposits at the La Brea Tar Pits is an example.

4. Properties

The substance is completely soluble in carbon disulfide, and composed primarily of a mixture of highly condensed polycyclic aromatic hydrocarbons; it is most commonly modelled as a colloid, with asphaltenes as the dispersed phase and maltenes as the continuous phase (though there is some disagreement amongst chemists regarding its structure). One report stated although a "considerable amount of work has been done on the composition of asphalt, it is exceedingly difficult to separate individual hydrocarbon in pure form", [21] and "it is almost impossible to separate and identify all the different molecules of asphalt, because the number of molecules with different chemical structures is extremely large" [21].

Asphalt/bitumen is typically stored and transported at temperatures around 150°C (300°F). Sometimes diesel oil or kerosene are mixed in before shipping to retain liquidity; upon delivery, these lighter materials are separated out of the mixture. This mixture is often called "bitumen feedstock", or BFS.

5. Components

Most natural bitumens contain sulfur and several heavy metals, such as nickel, vanadium, lead, chromium, mercury, arsenic, selenium, and other toxic elements. Bitumens can provide good preservation of plants and animal fossils.

6. Usage

a) Earlier

The Greek fire, whose composition was a military secret of the Byzantine navy, contained asphalt/bitumen as a component among other things.

Among the earlier uses of asphalt/bitumen in the United Kingdom was for etching. William Salmon's Polygraphice (1673) provides a recipe for varnish used in etching, consisting of three ounces of virgin wax, two ounces of mastic, and one ounce of asphaltum [22]. By the time of the fifth edition in 1685, he had included more asphaltum recipes from other sources [23].

The Tongva, Luiseño and Chumash, people collected the naturally occurring asphalt/bitumen that seeped to the surface above underlying petroleum deposits. All three used the substance as an adhesive. It was also used in decorations.

b) Modern

The largest use of asphalt/bitumen is for making asphalt concrete for road surfaces and accounts for approximately 85% of the asphalt consumed in the United States. Asphalt concrete pavement material is commonly composed of 5% asphalt/bitumen cement and 95% aggregates (stone, sand, and gravel).

Mastic asphalt is a type of asphalt which differs from dense graded asphalt (asphalt concrete) in that it has a higher asphalt/bitumen (binder) content, usually around 7–10% of the whole aggregate mix, as opposed to rolled asphalt concrete, which has only around 5% added asphalt/bitumen.

Mixing asphalt with petroleum solvents forms "cutbacks" with reduced melting point, or mixtures with water to turn the asphalt/bitumen into an emulsion. Asphalt emulsions contain up to 70% asphalt/bitumen and typically less than 1.5% chemical additives.

Asphalt/bitumen is used to make Japan black, a lacquer known especially for its use on iron and steel.

7. Environmental impacts of Asphalt pavement

- Unhealthy fumes
- Odors
- Fossil fuels
- Contains toxic, heavy metals including nickel, lead, mercury, vanadium, chromium, mercury, arsenic and selenium.
- Oxidation can cause deterioration via long-term aging and eventually result in cracking.

8. Green Revolution

In the recent past, there’s a lot of movement and thinking when it comes to creating more environmentally friendly and sustainable products. They’re often derived from organic components, or even waste by-products. Today’s ‘green revolution’ has brought about an interesting and more environmentally friendly alternative to Asphalt known as ‘BioAsphalt’ which is free from toxic materials. Bio-oil could potentially serve as an antioxidant additive in asphalt mixtures [24].

9. Bioasphalt

Bioasphalt is an asphalt alternative made from bitumen from non-petroleum based renewable resources. It has been used on a limited basis for some years now, and is part of an ongoing research at Iowa State University. USA in addition to the renewable source of the material, and the potential cost benefits versus standard asphalt, this material can be colored, which has the potential to reduce the heat island effect and energy use impacts associated with hot, dark colored pavements [15]. Companies like United Environment & Energy LLC (Limited Liability Company) and Avello Bioenergy have made great strides into feasibility studies, application testing, and the commercialization of BioAsphalt for commercial and residential use. Avello Bioenergy claims that its BioAsphalt product decreases paving costs by 20%, decreases carbon footprint, diminishes greenhouse gas emissions, and it boasts increased pavement life. [12]

10. Sources

a) Renewable resources

A natural resource is a renewable resource if it is replaced by natural processes at a rate comparable or faster than its rate of consumption by humans. Solar radiation, tides, winds and hydroelectricity are perpetual resources that are in no danger of a lack of long-term availability.

Renewable resources are sugar, molasses and rice, corn and potato starches, natural tree and gum resins, natural latex rubber and vegetable oils, lignin, cellulose, palm oil waste, coconut waste, peanut oil waste, canola oil waste, dried sewerage effluents, etc.

Bitumen can also be made from waste vacuum tower bottoms produced in the process of cleaning used motor oils, which are normally burnt or dumped into landfills.

11. History and Implementation

Asphalt made with vegetable oil based binders was patented by Colas S.A in France in 2004 [8].

A number of homeowners seeking an environmentally friendly alternative to asphalt for paving have experimented with waste vegetable oil as a binder for driveways and parking areas in single-family applications. The earliest known test occurred in 2002 in Ohio, where the homeowner combined waste vegetable oil with dry aggregate to create a low-cost and less polluting paving material for his 200-foot driveway. After five years, the homeowner reports the driveway is performing as well or better than petroleum-based materials.

HALIK Asphalts Ltd. of Israel has been experimenting with recycled and secondary road building since 2003. The company is using various wastes such as diesel, vegetable oil & fats and wax, and thermoplastic elastomers to build and repair roads.

In Dubai/Nairobi, during 2006 roads made out of sugar, ships powered and propelled by the sun and grease gobbling bacteria were among the environmentally-sound technologies unveiled at an International United Nations Conference.

The technologies, ranging from renewable energies and waste reduction systems to solar powered fridges for storing vaccines, are on show at the Ninth Special Session of the United Nations Governing Council/Global Ministerial Environment Forum.

Klaus Toepfer, United Nations Environment Programme's Executive Director, has said that technology has a vital role to play in delivering a cleaner, healthier and more stable world. In the United Arab Emirates, they are show casing the imaginative, creative and practical ideas of local and international companies. He hopes these technologies, aimed at solving the energy crisis up to reducing water, soil and air pollution, would be beacons of inspiration for governments, civil society and industry meeting. He also said that with proof that, with the right policies, countries can catalyze creative minds to solve some of the pressing and environment and development issues facing this planet while generating new industries and new jobs.

Ecopave GEO 320 is an Australian invention that turns sugars from sugar cane or molasses into material for road paving. It is designed to be a substitute for conventional bitumen from fossil fuels used to pave most roads around the world. The company claims that not only sugars but a wide range of other natural materials can be used to make the paving including tree resins and gums, vegetable oils and potato and rice starches. It also claims the product is environmentally-friendly in others ways. For example negligible levels of fumes are involved during the laying and unlike bitumen, which must be constantly heated at temperatures of 170ºC, the new material can be stored and transported at room temperature. A novel spin off is that the product can be 'pigmented' to reflect heat and thus help to cool hot cities, the company claims.

Shell Oil Company paved two public roads in Norway in 2007 with vegetable-oil-based asphalt. Results of this study are yet to be published [16].

A bicycle path in Des Moines, Iowa, was paved with bio-oil based asphalt through a partnership between Iowa State University, the City of Des Moines, and Avello Bioenergy Inc (2010). A section of the Waveland Bike Trail on the northwest side of Des Moines was selected for a demonstration project. About 900 feet of the 10-foot-wide trail was paved with a 2-inch layer of an asphalt mix containing 3% Bioasphalt [8]. Research is being conducted on the asphalt mixture, derived from plants and trees to replace petroleum-based mixes.

12. Production of Bio-Oil

One of the thermochemical processes used to produce bio-oils is fast pyrolysis.

a) Fast pyrolysis

Fast pyrolysis is the process in which biomass is heated rapidly in a high temperature environment, yielding a mix of liquid fuel (bio oil), combustible gases, and solid char.

The yields from fast pyrolysis vary with the biomass feed stock and the reactor conditions [19]. Generally, this process generates bio-oil, biochar, gases, and moisture. The biochar can be used for carbon sequestration as a soil modifier by improving the soil's ability to retain liquid fertilizers and thus reducing liquid fertilizer application rates. The bio-oil is a liquid fuel containing lignin that can be combusted by some engines or turbines for electricity generation [17].

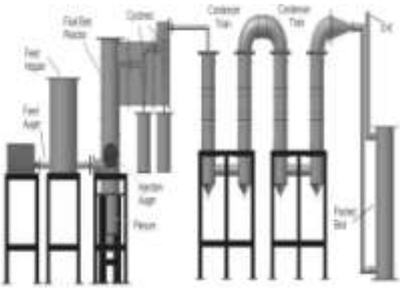
Fast pyrolysis is a thermal decomposition process that requires a high heat transfer rate to the biomass particles and a short vapor residence time in the reaction zone [7]. In other words, fast pyrolysis is the rapid decomposition of organic matter (biomass) in the absence of oxygen to produce solids such as char, pyrolysis liquid or oil (bio-oils), and gas [20] [2].

Generally, fast pyrolysis is used to obtain high-grade bio-oil. Organic biomass consists of biopolymers, such as cellulose, hemicelluloses, and lignin. Because of the different sources of biomass, the amount of production of the liquid bio-oils, solid char, and non-condensable gases varies. For example, fast pyrolysis processes produce about 60 to 75 wt% of liquid bio-oil, 15 to 25 wt% of solid char, and 10 to 20 wt% of non-condensable gases [18].

Figure 2 shows the 25 kWt fast pyrolysis system developed at Iowa State University by the Center for Sustainable Environmental Technology where bio-oils are produced from different biomass materials.

ISSN: 2278-0181
Vol. 2 Issue 2, February- 2013

Figure 2. Bio-oil mass pyrolysis pilot plant (Source: Iowa State University)



The pilot unit consists of a 16.2-cm diameter fluidized bed reactor, a burner to externally heat the reactor, a two-stage auger to feed the solid, two cyclones to remove particulate matter, and a vapor-condensing system consisting of four condensers and an electrostatic precipitator.

The system can process 6 to 10 kg/h of solid feed. The separation of bio-oils into multiple fractions was conducted using a fractionation condenser system which facilitated the selection of bio-oil fractions that would be optimal for being used as a pavement binder. However, bio-oils cannot be used as biobinders–pavement materials without any heat pre-treatment, since an upgrading procedure is required [5].

Raouf also found that the biobinders developed from oakwood, switchgrass, and corn stover bio-oils cannot be treated at temperatures higher than 120°C because of the volatilization of some bio-oil compounds [5]. Raouf further found considerable differences between the properties of the bio-oils and asphalt at the same temperatures, and thus the Superpave test criterion should be modified to comply with the biobinders properties, namely the Superpave specifications for the rolling thin film oven test (RTFOT) and the pressure aging vessel (PAV) procedures [5]. Longer *in-situ* aging studies would need to be done to understand the aging mechanisms of biobinders such that simulative laboratory criteria can be established.

The essential features of the fast pyrolysis process can be summarized [3]

- Heating to approximately 500 ^{o}C at a high heat transfer rate,
- Carefully controlled reaction temperature with short vapor residence times less than two seconds, and
- Rapid cooling of the pyrolysis vapors.

Figure 3. Process carried out by Avello Bioenergy Inc. [10]

13. Bioasphalt from Urban Yard Waste Carbonization [9]

Urban yard waste poses solid waste management difficulties for many communities. In many areas, municipal solid waste is disposed off in sanitary landfills. However, yard waste may not be landfilled. For this, communities must collect and dispose off this separately. With the increasing cost of fuel, separate yard waste collection is an increasing financial burden on these communities. Furthermore, there are few waste management alternatives for yard wastes.

Most communities compost yard waste but this is not an ideal solution.

1. Composting takes time, energy, and a large amount of space.
2. Yard waste compost is not in high demand as a consumer product.
3. Yard waste composting can lead to aesthetic problems such as concerns about odor.
4. Yard waste composting can lead to concerns about plant and animal pathogens that are not deactivated in compost piles and
5. Composting yard waste releases all of the CO_2 potential of this organic waste.

Case Western Reserve University (CWRU) has been evaluating an alternative method of managing yard waste. Research is evaluating the potential of managing yard waste by carbonization. This offers the possibility of allowing for co-collection of yard waste with conventional solid waste (i.e. in one truck instead of two), yard waste management at landfill sites rather than at separate composting facilities, production of soil amendment products that permanently sequester CO_2 (carbon added to soil has been shown to increase crop productivity), and the production of valuable byproducts during the carbonization process. This proposed research will explore the possibility of recovering bioasphalt bitumen from yard waste carbonization processes. This will produce a non-petroleum based product of value to the transportation industry that results from a "carbon negative" process that sequesters more CO_2 than it releases. The amount of bitumen that can be produced from yard waste, the physical and chemical properties of this bitumen, and the carbonization operating conditions under which the production of this material is optimized are all unknown, but the potential advantages of this yard waste management strategy are compelling. The objective of "Bioasphalt from Urban Yard Waste Carbonization" is to conduct groundbreaking research to answer fundamental questions about the potential of yard waste carbonization (YWC) to produce a practical bitumen product that could be used to produce bioasphalt.

14. Applications of BioAsphalt [15]

Due to concerns over dependence on foreign oil, high energy consumption, high asphalt price, air pollution, and climate change, a non-petroleum based bioasphalt technology from recycled and renewable sources has been developed by United Environment & Energy LLC (Limited Liability Company).

a) Roofing applications

United Environment & Energy (UEE) has successfully invented, developed, and scaled up a bioasphalt production technology to make bioasphalt to replace or serve as an additive for asphalt, sealant, and polymers in the manufacture of sustainable roofing materials. The UEE roofing bioasphalt has been evaluated extensively for a variety of applications in different roofing materials and it showed significant advantages over traditional petroleum based asphalt, including improved thermal durability, improved cold weather performance, elimination of stain, high resistance to UV light, and low production costs. Additionally, it is a non-hazardous material.

b) Paving applications

The United Environment & Energy bioasphalt technology, invented and developed for roofing applications, could also be used for paving. In their study, a technical feasibility study on using the roofing bioasphalt technology for paving application has been conducted and demonstrated that with bioasphalt production conditions change, a paving bioasphalt with the required properties could be produced. A detailed evaluation of the UEE bioasphalt and a comparison with petroleum-based asphalt for paving applications has been performed. The bioasphalt has the required performance to substitute petroleum-based asphalt in pavements. Bioasphalt can be blended with traditional asphalt and can be used for hot mix asphalt production. The tests conducted at Washington State University on blended bioasphalt/asphalt and hot mix bioasphalt/asphalt concrete indicated that blending bioasphalt can be both technically and economically competitive. In addition, the base asphalt and percentage of bioasphalt can be adjusted to produce a product for different application conditions.

15. Benefits of using BioAsphalt [13]

The benefits of Bioasphalt binder include

- Renewable - Bioasphalt binder is produced from domestic non-food resources such as agricultural and wood residues. Using biomass derived Bioasphalt binder decreases the demand for imported petroleum.
- Immediate - Extensive research at Iowa State University has shown that bio-oil fractions can be a direct replacement for petroleum based liquid asphalt as an additive, modifier or extender, in existing paving and roofing applications.
- Reduced carbon footprint - Bioasphalt binder can lower the production temperature of hot mix asphalt, which may decrease paving costs by 20% and reduce greenhouse gas emissions up to 30% because less energy input is required. Bioasphalt binder may also provide an anti-oxidant effect which could increase the service life of pavements. The grade range of asphalt may be extended with the addition of Bioasphalt binder.
- Cost competitive - Proforma economic analysis indicates Bioasphalt binder can be priced competitively below today's asphalt prices without subsidies.

16. Issues with BioAsphalt [6]

- Compatibility with petroleum based asphalt
- Cost/benefits
- Production
- Mixture performance

17. Conclusion

Thus, it is possible to conclude that the Green Revolution

ISSN: 2278-0181
Vol. 2 Issue 2, February- 2013

brings up a highly useful and eco-friendly pavement which is low cost and reduces several environmental risks compared to the traditional pavements. Usage of BioAsphalt as an alternative to asphalt to make pavements in all countries will lead to a greener world and reduce the risk of global warming. Though BioAsphalt has its issues, the advantages are so vast that it makes the issues look very minor.

18. Acknowledgement

We sincerely thank Dr.G. Ranganath, Principal, Adhiyamaan College of Engineering, Hosur for his constant support and encouragement.

19. References

1. "Oil Sands - Glossary", Oil Sands Royalty Guidelines, Government of Alberta. 2008.
2. A.M. Barnes, K. D. Bartle, and V. R. A. Thibon, "A Review of Zinc Dialkyldithiophosphates (ZDDPS): Characterization and Role in the Lubricating Oil" Tribology International, Vol. 34, 2001, pp. 389–395.
3. A.V. Bridgwater, "Principles and Practice of Biomass Pyrolysis Processes for Liquids", Journal of Analytical and Applied Pyrolysis, 1999, V.51, pp. 3-22.
4. Abraham and Herbert, "Asphalts and Allied Substances: Their Occurrence, Modes of Production, Uses in the Arts, and Methods of Testing", New York: D. Van Nostrand Co., 4th ed., 1938.
5. Arnold, T. S., J. Rozario, and J. Youtcheff, "New Lime Test for Hot-Mix Asphalt Unveiled", Public Roads, Vol. 70, No. 5, 2007.
6. Baoshan Huang Ph.D., P.E., "Asphalt Goes Green – Environmentally Friendly Asphalt Technology", ASCEC, 14-1-2011
7. C. J. Pedersen, "Mechanism of Antioxidant Action in Gasoline", Additives in Fuels, Vol. 48, No. 10, 1956, pp. 1881–1884.
8. Chris Williams, Scott Schram, and Dennis Banasiak, "Technology News", oct-dec 2011, pp. 5-6.
9. Daniel R. Hill, and Aaron A. Jennings, "Bioasphalt from Urban Yard Waste Carbonization A Student Study", Ohio Department of Transportation, June 2011.
10. Dennis S. Banasiak, "Avello Bioenergy-Leveraging Resources and Relationships to Commercial Viability", Renewable chemicals live, April 2, 2012.
11. http://answers.com/topic/colas-s-a?cat=biz-fin
12. http://thegreenenergyblog.com/uncategorized/bioasphalt-renewable-construction-material-2
13. http://www.avellobioenergy.com/en/products/bioasphalt_binder/
14. http://www.myspace.com/nomoretarroofs/blog/429898936
15. http://www.unitedee.com/BioasphaltTechnology.html

ISSN: 2278-0181
Vol. 2 Issue 2, February- 2013

16. http://wwwstatic.shell.com/static/bitumen/downloads/technical_papers_0507.pdf
17. I. Yut, and A. Zofka, "Attenuated Total Reflection (ATR) Fourier Transform Infrared (FT-IR) Spectroscopy of Oxidized Polymer-Modified Bitumens", Applied Spectroscopy, 2011, Vol. 65, No. 7, pp. 765–770.
18. J. C. Petersen, and P. M. Harnsberger, "Asphalt Aging: Dual Oxidation Mechanism and Its Interrelationships with Asphalt Composition and Oxidative Age Hardening", In Transportation Research Record 1638, TRB, National Research Council, Washington, D.C., 1998, pp. 47–55.
19. Jemison H., B. Burr, R. R. Davison, J. A. Bullin, and C. J. Glover, "Application and Use of the ATR FTIR Method to Asphalt Aging Studies", Petroleum Science and Technology, Vol. 10, No. 4, 1992, pp. 795–808.
20. L. R. Mahoney, S. Korcek, S. Hoffman, and P. A. Willermet, "Determination of the Antioxidant Capacity of New and Used Lubricants: Methods and Applications", Industrial Engineering Chemistry Product Research and Development, Vol. 17, No. 3, 1978, pp. 250–255
21. Muhammad Abdul Quddus (1992). "Catalytic Oxidation of Asphalt", thesis submitted to Department of Applied Chemistry; University of Karachi. Pakistan: Higher Education Commission Pakistan: Pakistan Research Repository. p. 6, in ch.2 pdf.
22. Salmon, and William, "Polygraphice; Or, The Arts of Drawing, Engraving, Etching, Limning, Painting, Washing, Varnishing, Gilding, Colouring, Dying, Beautifying and Perfuming" (Second ed.). London: R. Jones, 1673, pp. 81.
23. Salmon, and William, "Polygraphice; Or, The Arts of Drawing, Engraving, Etching, Limning, Painting, Washing, Varnishing, Gilding, Colouring, Dying, Beautifying and Perfuming", (5th ed.), London: R. Jones, 1685, pp. 76–77
24. Tang, and Sheng, "Asphalt modification by utilizing bio-oil ESP and tall oil additive", Graduate Theses and Dissertations, 2010, pp. 11569.
25. Walker, C. Ian, "Marketing Challenges for Canadian Bitumen, Tulsa, OK", International Centre for Heavy Hydrocarbons, 1998.