Blue Smoke and Offensive Odor Control Technologies in Asphalt Plants and Their Evolution

AUTHOR

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Abstract

Unlike hazardous air pollutants, offensive odors do not directly cause adverse health effects. However, by inducing discomfort and fatigue, they may indirectly affect human health and emotional well-being, for example by causing loss of appetite. Since the enforcement of the Offensive Odor Control Act in 1971, various industrial sectors have implemented measures to control odor emissions, and more than half a century has now passed since the legislation came into effect. Asphalt plants (hereinafter referred to as APs) are no exception. Blue smoke and odors generated during asphalt production occasionally give rise to complaints from nearby residents. Furthermore, under the Basic Act for Establishing a Sound Material-Cycle Society, the Construction Material Recycling Act, which came into force in 2002, requires asphalt concrete debris generated during pavement rehabilitation to be recycled as a valuable resource. As a result, the recycling rate has now reached approximately 99%, and recycled asphalt mixtures account for more than 70% of total asphalt mixture shipments in Japan. Although these figures indicate that the objectives of the legislation have largely been achieved, they also mean that the production process of recycled asphalt mixtures, a major source of blue smoke and odors, has become routine at the vast majority of APs. Nevertheless, economic and technical challenges associated with odor control remain substantial, and adequate countermeasures have yet to be fully implemented at all APs. This paper first examines the fundamental nature of odor and reviews the regulatory framework governing odor emissions. It then traces the evolution of technologies developed to control odors, particularly blue smoke generated by APs, from the early days of recycling asphalt concrete debris for pavement applications to the present day. Finally, future prospects for odor-control technologies are discussed.

Keywords: asphalt plant, recycling, blue smoke, offensive odor, deodorization.

1. Introduction

The evolution of odor control and deodorization technologies for asphalt plants (APs) has been discussed in the author's previous publications, *NIKKO TECHNICAL REPORT*, Vol. 3, No. 1 (2022), "Transition and Prospects of Carbon Dioxide Emission Reduction Technology in Asphalt Plant,"[1] and *NIKKO TECHNICAL REPORT*, Vol. 6, No. 2 (2025), "Evaluation of Decomposition Performance of Asphalt Odor Components by Direct Combustion and Catalytic Combustion."[2] Readers are encouraged to refer to these publications.

This paper first examines the fundamental nature of odor and reviews the historical development of objective evaluation methods for quantifying odor, which is inherently a sensory perception. It also provides an overview of the background and development of odor-related regulations. Furthermore, this paper reviews the evolution of technologies for mitigating blue smoke and offensive odors associated with reclaimed asphalt pavement (hereinafter referred to as RAP), particularly since RAP began to be recycled as a valuable paving material. Special attention is given to blue smoke and offensive odors generated when processed RAP (hereinafter referred to as R-material), which is produced by crushing and grading reclaimed asphalt pavement, is dried and heated in a recycling dryer (R-dryer). Focusing primarily on findings obtained by the author, this paper discusses the mechanisms responsible for the generation of blue smoke and odor, their chemical constituents, methods for their prevention, and practical odor-control technologies, and finally presents perspectives on the future development of asphalt plants. The remainder of this paper is organized as follows.

Chapter 2, "Background," examines the fundamental characteristics of odor components and human olfaction. From both biological and societal perspectives, it describes the circumstances that led offensive odors to become an environmental issue and ultimately to the establishment of odor-control regulations. Chapter 3, "Offensive Odor Control Act and Odor Measurement," outlines the historical development and framework of Japan's Offensive Odor Control Act. It also explains the transition from instrumental chemical analysis to the Odor Index Regulation, based on the Triangle Odor Bag Method, which utilizes human olfactory perception, together with the establishment of the corresponding measurement methodology.

Chapter 4, "Volatile Organic Compounds (Odor-Causing Components) Derived from Asphalt," first reviews the historical background and compositional characteristics of asphalt. Based on preliminary experiments and previous studies, it then discusses the mechanisms by which blue smoke and odor are generated, volatilized, and subsequently condensed during the heating process in an R-dryer.

Chapter 5, "Offensive Odor Control Technologies for Asphalt Plants," describes the evolution of odor-control technologies from the early countermeasures to today's advanced deodorization technologies, based on the generation mechanisms discussed in Chapter 4. It further examines the principles and applicability to asphalt plants of combustion methods (direct thermal oxidation, catalytic oxidation, and regenerative thermal oxidation), chemical scrubbing, adsorption, biological deodorization, and deodorants and odor neutralizers.

Chapter 6, "Future Perspectives," presents effective deodorization technologies for asphalt plants, based on the foregoing discussions, together with future prospects for reducing environmental impacts.

2. Background

In Japanese, the word *nioi* (“odor”) is often written using different kanji depending on the nature of the odor: 匂い for odors that are beneficial or pleasant to humans, and 臭い for those that are unpleasant. This distinction reflects the common convention that odors perceived favorably are regarded differently from those perceived unfavorably. Like light and sound, odor is a sensory stimulus perceived by humans. Accordingly, the perceived intensity of an odor is not linearly proportional to the concentration of its odorants. Rather, as described by the Weber–Fechner law (**Figure 1**)[3], the relationship is logarithmic rather than linear. This means that the human olfactory system is relatively insensitive to strong odors but becomes increasingly sensitive as odor intensity decreases. Furthermore, when multiple odorants interact simultaneously, not only the perceived intensity but also the qualitative character of the odor may change. This phenomenon forms the scientific basis of perfume blending, a technique that has been particularly refined in Europe, especially in France.

The perceived intensity of an odor also varies considerably among individuals depending on personal preference and emotional state. Consequently, depending on the type of odor, its concentration, temperature, humidity, duration of exposure, surrounding environment, and the psychological state of the individual, an odor that is initially perceived as pleasant may gradually come to be regarded as unpleasant, eventually becoming a malodor that causes discomfort and, in some cases, gives rise to odor pollution. For example, the aroma of grilled meat drifting through the air may stimulate the appetite of a passerby, whereas the same odor may be perceived as an offensive odor by a neighboring resident who is continuously exposed to it[4].

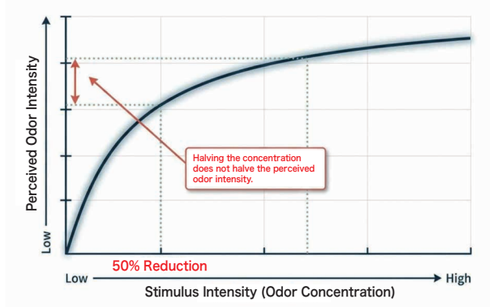


Figure 1: Concept of the Weber–Fechner Law

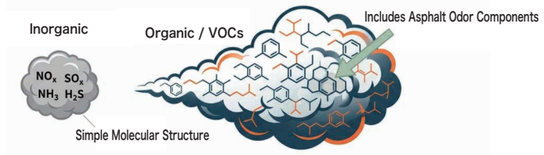


Figure 2: Inorganic and Organic Odor Components

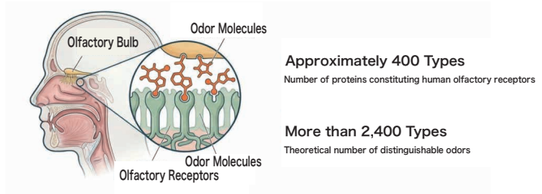


Figure 3: Olfactory Receptors in the Human Nasal Cavity

Unlike hazardous air pollutants, offensive odors do not directly cause adverse effects on human health or deterioration of the natural environment. However, by inducing discomfort and fatigue, they may indirectly affect human health and emotional well-being, for example by causing loss of appetite[5]. For this reason, odor control regulations are implemented by local governments in designated areas pursuant to the Offensive Odor Control Act. (The Offensive Odor Control Act is discussed in detail in Chapter 3.)

It is estimated that more than 400,000 odor-causing substances exist in the atmosphere[6][7]. As shown in **Figure 2**, these substances can be broadly classified into

inorganic and organic compounds. Representative inorganic odorants include nitrogen oxides (NOx) and sulfur oxides (SOx), which are generated during the combustion of fossil fuels such as coal and petroleum, as well as ammonia (NH_3) and hydrogen sulfide (H_2S). In contrast, organic odorants are overwhelmingly more abundant than inorganic odorants. The vast majority consist of volatile organic compounds (VOCs) having hydrocarbon skeletons, such as aliphatic and aromatic hydrocarbons, to which functional groups including hydroxyl (-OH) and carboxyl (-COOH) groups are attached. This remarkable diversity is thought to be closely related to the enormous variety of living organisms on Earth. However, because all living organisms are themselves composed of organic compounds, there is a complexity that cannot be fully captured by a simple distinction between organic and inorganic substances.

For terrestrial organisms, the sense of smell plays an essential role as an innate biological capability in behaviors such as hunting, self-defense, and courtship for reproduction[8)9)]. Since organisms first colonized land approximately 500 million years ago, olfaction has undergone repeated processes of evolutionary development and regression. Among terrestrial animals, mammals have evolved the most highly developed olfactory systems, and their olfactory receptors are highly sensitive to VOCs. Even among mammals, the African elephant possesses the largest known repertoire of olfactory receptor genes, whereas dolphins, which returned from terrestrial to aquatic habitats during evolution, have experienced a marked regression of their olfactory system[10)11)].

As shown in **Figure 3**, the human nasal cavity contains approximately 400 different types of olfactory receptor proteins. Through the combinatorial activation of these receptors, humans are theoretically capable of discriminating more than 2,400 distinct odors. Furthermore, as odors are dispersed through the atmosphere, their sphere of influence is generally spatially limited. It is also well established that the repertoire of olfactory receptors in the nasal cavity varies among individuals as a result of genetic differences[12)13)].

Whereas terrestrial organisms detect odorants transmitted through the atmosphere, aquatic organisms such as fish possess olfactory systems that respond to water-soluble substances. Genomic analyses of olfaction are gradually elucidating the evolution and diversification of olfactory systems. In addition, recent studies have reported that plants emit specific volatile compounds in response to herbivore attack, thereby repelling herbivorous insects that are highly sensitive to these compounds through their olfactory receptors[14)].

Meanwhile, in Japan, where economic prosperity has

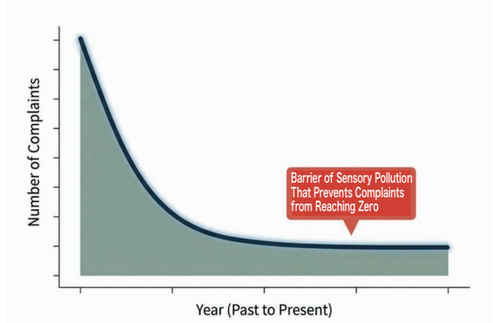


Figure 4: Asymptotic Trend in the Number of Odor Complaints

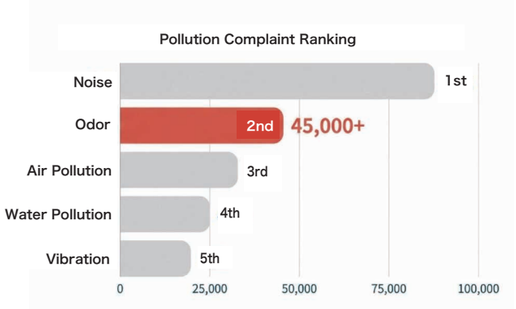


Figure 5: Odor Complaints Rank Second Only to Noise Complaints



Photo 1: Blue Smoke Emitted from the Stack of an Asphalt Plant

long been enjoyed, growing public awareness of the quality of the living environment, increasing concern for global environmental issues, changing dietary habits, diversification of odor preferences, heightened awareness of the sense of smell, and a growing pursuit of amenity have become increasingly evident. Against this background, regulations on offensive odors have been strengthened. As shown in **Figure 4**, the number of odor-related complaints has gradually declined in recent years. As shown in **Figure 5**, odor-related complaints remain at a level second only to noise-related complaints among the seven major types of environmental pollution in Japan—air pollution, water pollution, dust, noise and vibration, offensive odors, soil contamination, and land subsidence. Because offensive odors constitute a form of sensory pollution, it has been suggested that complete elimination of odor complaints is impossible, regardless of how stringent the regulations become.

Against this social background, odor concentration regulations have been implemented under the guidance of local government authorities. It is anticipated that an increasing number of regions will require APs, particularly recycling plants that heat and recycle R-material (hereinafter referred to as "RPs"), to comply with regulations governing the odor concentration of their exhaust gases.

In particular, blue smoke and other odors emitted from APs, as shown in **Photo 1**, have long been the subject of odor complaints from nearby residents, and considerable time has elapsed since odor control measures based on the Offensive Odor Control Act were first required. Furthermore, these offensive odors, which originate from asphalt, a residue of petroleum refining through distillation, are considered to consist of a diverse mixture of organic odor-causing compounds.

Following the enactment of the Basic Act for Establishing a Sound Material-Cycle Society in 2000, the Construction Material Recycling Act came into force in 2002. As a result, the recycling rate of reclaimed asphalt pavement generated during road resurfacing has exceeded 99%, indicating that a certain degree of progress has been achieved. However, because of economic and technical challenges associated with controlling blue smoke and odors generated during the heating process for recycling, deodorization equipment has not yet been installed at all APs. Meanwhile, odor regulations under the Offensive Odor Control Act are established by individual local governments, each of which specifies its own regulatory limits.

3. Offensive Odor Control Act and Odor Measurement

This chapter provides a comprehensive analysis of the historical development of offensive odor control in Japan, including the legal framework, measurement techniques, accumulation of odor data, and the development of professional expertise, based on major previous studies. It traces the evolution of Japan's odor management system, beginning with the enactment of the Offensive Odor Control Act in 1971, followed by the introduction of the Odor Index Regulation in 1995, the establishment of the Certified Odor Assessor System in 2000, and the development of the Triangle Odor Bag Method together with the accumulation of olfactory threshold data. These achievements have contributed to effective odor-control policies that reflect residents' sensory perceptions and have gained international recognition. Further advances in odor management are expected through improvements in measurement technologies, quality control of odor data, and continued training and development of specialized personnel.

The following sections systematically examine the historical background of the Offensive Odor Control Act, the development of the Triangle Odor Bag Method, and the accumulation of olfactory threshold data, thereby clarifying the key elements that form the foundation of modern odor management, together with the remaining challenges and future prospects.

3.1 Historical Background of the Offensive Odor Control Act

In response to the increasingly serious environmental pollution that accompanied Japan's period of rapid economic growth, the Basic Act for Environmental Pollution Control was enacted in 1967 as a comprehensive legal framework through which the national government could implement pollution control measures (this Act was subsequently replaced by the Basic Environment Act in 1993). Under economic policies aimed at catching up with and surpassing the Western industrialized nations, Japan underwent rapid industrialization, bringing unprecedented convenience and prosperity that became deeply embedded in society. However, this progress came at a cost. The seven major categories of pollution—air pollution, water pollution, soil contamination, noise, vibration, land subsidence, and offensive odors—emerged as serious social problems, directly degrading the living environment and causing widespread adverse effects on public health. Among these, air pollution and water pollution left a particularly profound mark on Japan's history through pollution-related diseases such as Yokkaichi asthma and Itai-itai disease.

Offensive odors do not directly cause adverse health effects. However, they can give rise to indirect health problems, such as feelings of discomfort and loss of appetite. Consequently, offensive odors developed into a social issue in the form of odor pollution, ultimately leading to deliberations in the National Diet on legislation for odor control.

The Offensive Odor Control Act, enacted in 1971, was intended to preserve the living environment and protect public health by establishing the necessary regulations governing offensive odors emitted from factories and other business establishments located within designated regulatory areas. Accordingly, the Act is regarded as the starting point of odor control in Japan. At the time of its enactment, the Act regulated offensive odors by measuring the concentrations of designated offensive odor substances using instrumental analytical methods. However, as complaints increasingly involved complex

odors and odors arising from everyday activities, it became difficult to adequately address these issues using the conventional regulatory approach[15].

The Offensive Odor Control Act has subsequently been amended in response to changing social needs and technological advances. In particular, the introduction of odor index regulation in 1995 made it possible to address complex odors and subjective odor complaints that had been difficult to manage using conventional instrumental analytical methods, and the system was gradually adopted by local governments throughout Japan. Under odor index regulation, a sensory evaluation method based on the human sense of smell—the Triangle Odor Bag Method—was adopted as the official measurement method[16]. This method subsequently became the basis for odor index regulation implemented by local governments nationwide. It enabled odor conditions to be assessed in a manner more closely reflecting residents' actual perceptions, thereby considerably enhancing the ability to address complex odors and individual differences in odor perception[17].

Furthermore, in 2000, the Certified Odor Assessor System was formally established, further strengthening the training of qualified professionals and improving the reliability of odor measurements. The Certified Odor Assessor System is a professional certification system designed to ensure the expertise required to conduct sensory evaluation tests and to maintain the consistency and accuracy of measurement results. Through rigorous examinations and educational programs, certified odor assessors are trained to make significant contributions to improving the living environment of local residents and promoting odor control measures by business operators. Under this system, certified odor assessors are expected to make complementary use of both sensory evaluation methods and instrumental analytical methods to contribute to improvements in the living environment of local communities.

Challenges that remain include variability associated with measurement methods and panel characteristics, as well as differences in the purity and preparation of reagents. To address these issues, quality control of data across multiple organizations and the complementary use of sensory evaluation methods and instrumental analytical methods are required.

As described above, Japan's approach to odor control has made remarkable progress in terms of its legal framework, technological development, data accumulation, and the training of specialized professionals, as offensive odor problems have become an important social issue as a form of sensory pollution[18].

On the other hand, the Offensive Odor Control Act adopts a designated regulatory area system in view of the characteristics of damage caused by offensive odors. This approach is based on the understanding that the principal impact of offensive odors is to cause discomfort and unpleasantness to people. Accordingly, there is no need to regulate odor emissions in areas where offensive odors are not perceived. Furthermore, because the effects of offensive odors are temporary and do not accumulate in food or other materials to subsequently affect human health through ingestion, it is considered sufficient to apply regulations only in areas where odor control is actually required.

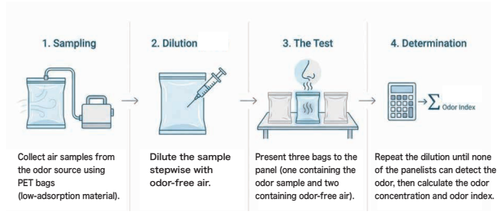


Figure 6: Analytical Procedure of the Triangle Odor Bag Method

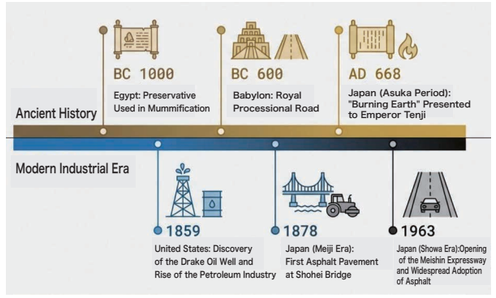


Figure 7: History of Asphalt

In addition, the Governor of a prefecture or the mayor of a municipality is responsible for designating the regulatory areas and establishing regulatory standards for those areas, taking into account their natural and social conditions, within the scope prescribed by the Ordinance of the Ministry of the Environment. Furthermore, the regulations apply to factories and other business establishments located within the designated regulatory areas. Regardless of their industry, size, or type of ownership, all offensive odors generated by business activities at such facilities are subject to regulation[19].

It should be noted that the Act regulates offensive odors emitted from factories and other business establishments as stationary sources. Mobile sources, such as automobiles, ships, and aircraft, and temporary or individual sources, such as construction sites, private residences, and open burning, are therefore not subject to regulation. In recent years, complaints concerning these unregulated sources have accounted for approximately half of all odor complaints, with complaints related particularly to open burning and private residences showing an increasing trend[20].

3.2 Introduction of Odor Index Regulation and the Triangle Odor Bag Method

Under the current Offensive Odor Control Act, 22 substances are designated as offensive odor substances, and regulations are imposed on their emission concentrations. With recent advances in analytical technology, odor-causing compounds can be identified and their concentrations quantified with sufficient accuracy using instrumental analytical methods. However, regulating only the concentrations of designated offensive odor substances is insufficient as an odor-control measure; it is also necessary to address the fundamental nature of odor itself[21].

The relationship between the concentration of odorants and odor intensity, which is a sensory quantity, is not linear. Rather, as described by the Weber–Fechner law[3], the relationship is logarithmic rather than linear. Specifically, reducing the odor intensity perceived by the human sense of smell by half generally requires a reduction of approximately 90% or more in the concentration of odor-causing compounds. Furthermore, because odor perception varies depending on odor quality and the combination of odorants present, it is extremely difficult to correlate the sensory quantity of odor intensity perceived by humans with the concentrations of odor-causing compounds determined by instrumental analysis[22].

To overcome these limitations, the odor index regulation system introduced in the previous section was established. In particular, the Triangle Odor Bag Method, a sensory evaluation method based on the human sense of smell that was first implemented under a Tokyo Metropolitan Government ordinance, came to be adopted by an increasing number of local governments as an official measurement method complementary to instrumental analytical methods.

As a result, this approach not only enabled odor conditions to be evaluated in a manner more consistent with residents' actual perceptions, which had been difficult to achieve using conventional instrumental analytical methods, but also considerably improved the ability to address complex odors and subjective complaints arising from individual differences in odor perception. These developments ultimately established the foundation for odor index regulation[23].

3.3 Accumulation of Olfactory Threshold Data and Overview of the Measurement Method

Olfactory threshold data for 223 odorants, determined using the Triangle Odor Bag Method, have been accumulated in a database. Olfactory thresholds provide the fundamental data linking instrumental analytical methods with sensory evaluation methods by indicating the threshold concentration at which an odor becomes

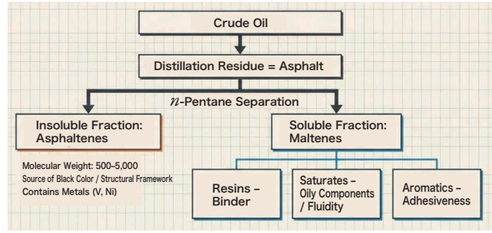


Figure 8: Composition of Asphalt

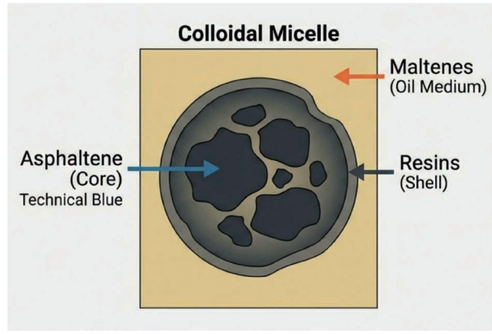


Figure 9: Colloidal Structure of Asphalt

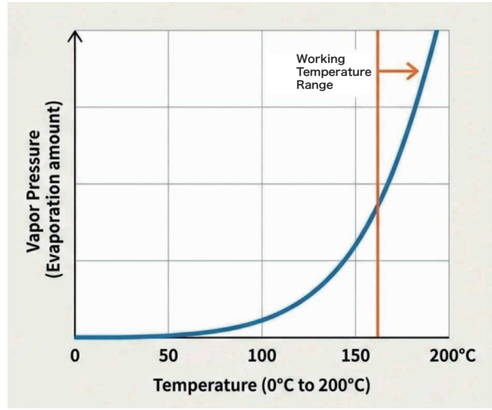


Figure 10: Vapor Pressure of Asphalt

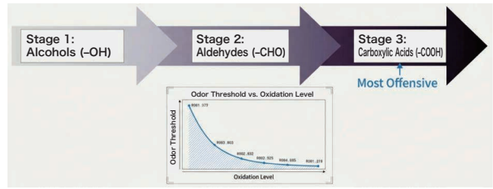


Figure 11: Changes in Odor Components during VOC Oxidation

perceptible to the human sense of smell. Today, this database is widely used in diverse fields, including odor control, occupational hygiene, and health impact assessment. Moreover, it provides the scientific basis for odor index regulation and has gained widespread international recognition[24].

The syringe method, which had traditionally been used for sensory odor evaluation, suffered from several limitations, including insufficient sample volume, odor loss due to adsorption, and inadequate measurement objectivity. To overcome these issues, the Triangle Odor Bag Method was developed as a scientifically sound and practical measurement method[25][26].

Figure 6 illustrates the analytical procedure of the Triangle Odor Bag Method. As illustrated, it begins by collecting an air sample from the odor source into an odor sampling bag. The sampling bag should be made of polyethylene terephthalate (PET) or another material that minimizes odor adsorption. A panel consisting of at least six participants who have passed an olfactory screening test is then selected. The purpose of the screening test is to exclude individuals with olfactory dysfunction, who are estimated to account for approximately 5% of the population. Panelists are not required to possess exceptional olfactory sensitivity; normal human olfactory function is sufficient.

The collected odor sample is then diluted stepwise with odor-free air until the odor is no longer perceptible. Following the Triangle Odor Bag Method, panelists are presented with three bags, one containing the diluted odor sample and two containing odor-free air, and are asked to identify the bag containing the odor. This dilution procedure is repeated until none of the panelists can detect the odor. The dilution factor at this endpoint is used to determine the odor concentration, which is subsequently converted to the odor index by logarithmic transformation. In this manner, the Triangle Odor Bag Method is founded on scientifically established principles, including the selection of appropriate bag materials, determination of the required panel size, and probabilistic definition of the olfactory threshold.

The entire series of odor measurement and evaluation procedures described above is carried out by certified odor assessors, who hold a national qualification in Japan.

4. Volatile Organic Compounds (Odor-Causing Components) Derived from Asphalt

4.1 Asphalt

4.1.1 History

As shown in **Figure 7**, the use of asphalt dates back to ancient civilizations, reaching as far back as ancient Egypt. Evidence has been found that natural asphalt was used as a preservative in the mummification of Tutankhamun and other individuals around 1000 BC. Furthermore, historical records indicate that asphalt pavement was first used on the royal processional road in the ancient city of Babylon during the Mesopotamian civilization around 600 BC. These natural asphalts are believed to have formed when crude oil exposed at the Earth's surface underwent thermal alteration associated with volcanic activity, after which low-molecular-weight components volatilized under the influence of atmospheric oxygen and sunlight (ultraviolet radiation), while the heavier fractions underwent polymerization and condensation reactions, resulting in the formation and accumulation of high-molecular-weight materials.

Much later, in 1859, Edwin Drake discovered an oil field in Pennsylvania, marking the beginning of the mechanized petroleum industry. John D. Rockefeller subsequently founded Standard Oil and famously came to dominate petroleum distribution throughout the United States. The subsequent invention of the gasoline engine by Nikolaus Otto in 1877 and the diesel engine by Rudolf Diesel in 1893 further accelerated the widespread adoption of automobiles.

As fuel demand increased, crude oil production also expanded, and asphalt produced as a by-product became established as an inexpensive binder for road paving. Economic growth was accompanied by increasing motorization, which further accelerated the construction of asphalt-paved roads.

In Japan, by contrast, the *Nihon Shoki* (*Chronicles of Japan*) records that, in 668 AD during the Asuka period, natural asphalt from Koshi Province (present-day Niigata Prefecture), referred to as *moetsuchi* ("burning earth"), was presented at the enthronement ceremony of Emperor Tenji. During the Edo period, natural asphalt from Akita Prefecture began to be used in the production of lampblack, the raw material for traditional Japanese ink. In 1878 (Meiji 11), asphalt from the same prefecture was used to construct Japan's first asphalt pavement on Shohei Bridge in Tokyo. In the early Showa period, the production of petroleum asphalt from imported crude oil began, and its widespread use accelerated during Japan's postwar period of rapid economic growth, particularly following the opening of the Meishin Expressway in 1963.

4.1.2 Overview

Asphalt used as a binder for pavement has appropriate fluidity and adhesiveness, and its flow characteristics can be adjusted by changes in temperature. It is also highly water-resistant and has a density greater than that of water. At ambient temperature, it is solid, physically and chemically stable, and harmless to humans and animals.

Asphalt is broadly classified into three categories: natural asphalt, petroleum asphalt, and modified asphalt. Natural asphalt occurs naturally, whereas petroleum asphalt is produced as the residual fraction remaining after crude oil refining. Modified asphalt is produced by incorporating rubber, resins, or other additives into petroleum asphalt to improve its performance.

In recent years, policies such as the Act on Sophisticated Methods of Energy Supply Structures have promoted higher yields of high-value light petroleum products during crude oil refining. As a result, the residual oil used for asphalt production has increasingly been subjected to vacuum cracking and other upgrading processes, leading to reduced asphalt production, higher prices, and changes in asphalt properties.

4.1.3 Constituents

Petroleum asphalt is the residue remaining after the distillation and refining of crude oil. During the refining process, crude oil is separated into fractions such as naphtha, gasoline, kerosene, diesel fuel, and heavy fuel oil according to their boiling points, with asphalt remaining as the final residue. The principal constituents of crude oil are hydrocarbons, which are classified into paraffinic, naphthenic, and aromatic hydrocarbons[27]. In general, their boiling points tend to increase in the following order: paraffinic < naphthenic < aromatic.

Asphalt is a high-molecular-weight mixture of diverse hydrocarbons and contains many thermally unstable components; consequently, its composition is subject to continual variation. For convenience, as shown in **Figure 8**, asphalt is broadly classified into two fractions: asphaltenes, which are insoluble in *n*-pentane, and maltenes, which are soluble in *n*-pentane.

Asphaltenes have molecular weights ranging from approximately 500 to 5,000 and contain porphyrin compounds incorporating metals such as vanadium and nickel. They are characterized by a twisted two-dimensional molecular structure. The black color of asphalt is attributed to the absorption of visible light by these high-molecular-weight polycyclic aromatic compounds.

In contrast, maltenes have relatively lower molecular weights, typically ranging from approximately 200 to 1,500, and are further classified into oils, which are soluble in propane, and resins, which are insoluble in propane. These fractions consist primarily of hydrocarbons containing approximately C5–C20 carbon atoms and are responsible for the flow properties of asphalt. As shown in **Figure 9**, asphalt is generally considered to have a colloidal structure in which asphaltene micelles are dispersed throughout the maltene phase.

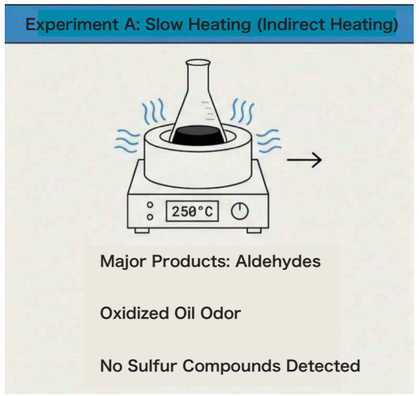


Figure 12: Experiment A

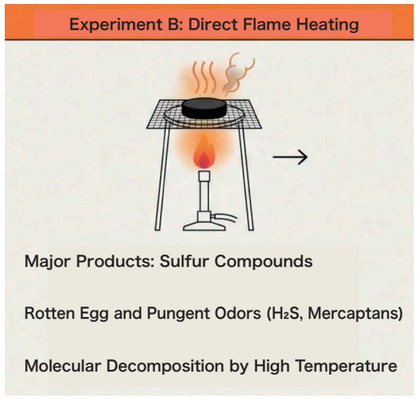


Figure 13: Experiment B

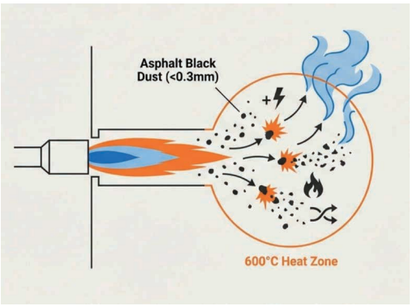


Figure 14: Dispersion of Fine R-Material Particles and Incomplete Combustion (Dryer Inlet)

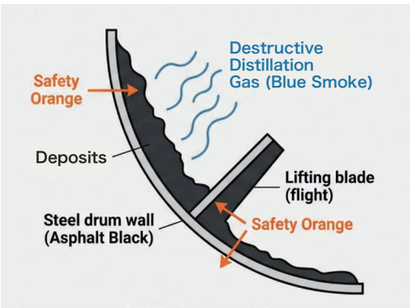


Figure 15: Destructive Distillation of Deposits inside the Dryer

4.2 Mechanism of VOC (Odor-Causing Component) Generation

4.2.1 Vapor Pressure of Asphalt (VOC Emission)

The emission of VOCs (volatile organic compounds) from asphalt depends largely on its vapor pressure. Asphalt is solid at ambient temperature. However, heating it above its pour point (65–70°C) increases the vapor pressures of lower-boiling paraffinic, naphthenic, and aromatic hydrocarbons, causing them to volatilize sequentially. In particular, the viscosity of paraffinic hydrocarbons decreases with increasing temperature, promoting convective flow and thereby accelerating evaporation.

In addition, the Japanese Industrial Standards (JIS) specify that the rate of mass change of an asphalt thin film after heating at 163°C for 5 hours must not exceed 0.6%. This requirement indicates that asphalt contains small amounts of volatile components. Furthermore, oxidation by atmospheric oxygen promotes the decomposition of high-molecular-weight components, resulting in the formation of highly volatile, low-molecular-weight VOCs.

Figure 10 shows the vapor pressure of straight-run asphalt (80–100 penetration grade), measured under oxygen-free conditions (a reducing atmosphere), at approximately 160°C, the typical shipping temperature. The results confirm that substantial amounts of low-boiling components remain even in asphalt, the residual fraction obtained during crude oil refining. In an actual asphalt plant, as oxygen is present, oxidative decomposition is presumed to further increase the vapor pressure. As shown in **Figure 11**, many of the VOCs generated as oxidation proceeds are aromatic compounds or compounds containing functional groups such as aldehyde (–CHO), carboxyl (–COOH), and carbonyl (>C=O) groups. These compounds are considered to act as the substances responsible for the characteristic offensive odor of asphalt.

4.2.2 Preliminary Experiments

The following experiments were conducted to examine how differences in the heating process affect the composition of odor-causing components.

4.2.2.1 Experiment A

As shown in **Figure 12**, asphalt was heated to approximately 250°C in a sealed vessel, and air was introduced into the vessel. The resulting odor-causing components were analyzed by gas chromatography (GC). These conditions were intended to simulate those in the downstream section of the R-dryer, where the material temperature is approximately 160°C, as well as those during mixing and silo storage.

4.2.2.2 Experiment B

As shown in **Figure 13**, R-material was heated by direct flame, and the resulting odor-causing components were analyzed by GC. These conditions were intended to simulate the overheating of fine particles of the R-material and deposits adhering to the dryer when exposed to radiant heat from high-temperature hot gas in the upstream section of the R-dryer.

4.2.2.3 Discussion

In Experiment A, no sulfur compounds were detected, and a marked increase in aldehydes resulting from oxidation reactions was observed. In contrast, Experiment B detected not only aldehydes but also substantial amounts of sulfur-containing compounds, including hydrogen sulfide, sulfur dioxide, and mercaptans.

These results indicate that the composition of odor-causing components varies significantly depending on the heating conditions. In particular, severe offensive odors originating from sulfur-containing compounds were confirmed to be generated under high-temperature conditions. In addition, it was suggested that the volatilized VOCs become supersaturated upon rapid cooling by the ambient air, subsequently condensing to form blue smoke.

4.2.3 Proposed Mechanism of VOC (Odor-Causing Component) Generation in the R-Dryer

Based on the findings described above, the proposed mechanism of VOC generation within the R-dryer is discussed in terms of the following four processes.

4.2.3.1 Dispersion of Fine R-Material Particles and Incomplete Combustion (Dryer Inlet)

Fine particles smaller than 0.3 mm contained in the R-material have a large specific surface area and contain relatively high amounts of asphalt. As shown in **Figure 14**, these particles are dispersed when the R-material is fed into the dryer and are instantaneously heated (combusted) upon direct contact with hot gas at temperatures exceeding 600°C. During this process, thermal decomposition and oxidative decomposition proceed rapidly, generating highly odorous compounds, including sulfur-containing compounds such as methyl mercaptan.

4.2.3.2 Destructive Distillation of Deposits (Inside the Dryer)

As shown in **Figure 15**, fine particles smaller than 0.6 mm readily adhere to the inner surfaces of the dryer, particularly to the walls and lifters (flights) in the vicinity of the burner. In the initial stage, these particles adhere to the surfaces with moisture acting as the binding medium. As the temperature increases and the moisture evaporates, the molten asphalt serves as a binder, causing the deposits to become firmly attached. These deposits are subsequently heated (destructively distilled) by radiant heat and heat transfer from the hot gas, resulting in the volatilization of high concentrations of blue smoke and odor-causing components including sulfur-containing compounds.

4.2.3.3 Volatilization from Heated R-Material (Dryer Outlet)

As illustrated in **Figure 16**, this process involves the volatilization of compounds from the R-material after it has traveled through the dryer and been heated to the target temperature of approximately 160°C. Because the temperature in this region is relatively low, the VOCs generated consist primarily of low-boiling compounds with boiling points below approximately 160°C, together with organic compounds such as aldehydes formed through oxidation. Sulfur-containing compounds are present only in small amounts. However, oxidation continues to proceed in the presence of oxygen in the exhaust gas.

4.2.3.4 Condensation and Particle Growth

The exhaust gas discharged from the R-dryer contains a mixture of gases, mists, and dust and has a temperature of approximately 200°C near the dryer outlet. At this stage, most of the VOCs are present in the gaseous state. However, oxidative decomposition proceeds at an oxygen concentration of approximately 16%, converting the VOCs into lower-molecular-weight compounds such as aldehydes and ketones, as illustrated in **Figure 17**.

Subsequently, as the exhaust gas cools while passing through the dust collector and stack before being released into the atmosphere, the saturation vapor pressure decreases, causing the VOCs to condense into liquid droplets on dust and mist particles that act as condensation nuclei. After the exhaust gas is discharged from the stack and undergoes further cooling by the ambient air, condensation accelerates, producing fine particles that scatter sunlight and appear visually as blue smoke. This phenomenon results from Rayleigh scattering, also known as the Tyndall blue phenomenon, which occurs when the particle diameter is smaller than the wavelength of light, as illustrated in **Figure 18**. It should be noted that, as the particle diameter increases, the emissions become visible as white smoke owing to Mie scattering.

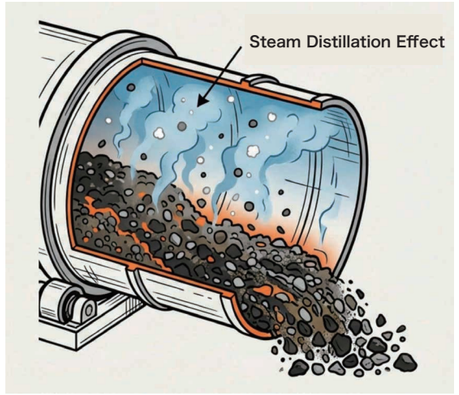


Figure 16: Volatilization from Heated R-Material at the R-Dryer Outlet

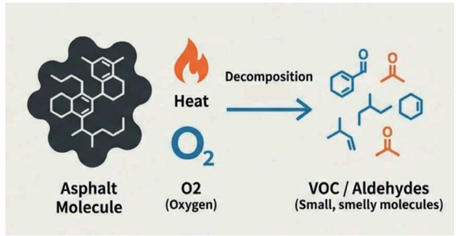


Figure 17: Oxidative Decomposition of VOCs (Odor Components)

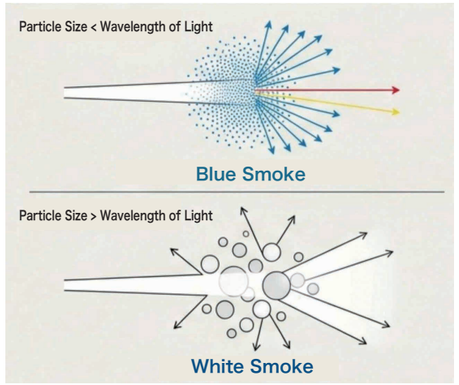


Figure 18: Tyndall Blue Phenomenon

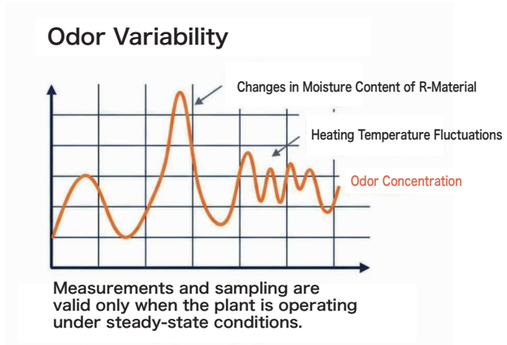


Figure 19: Odor Variability Caused by Multiple Factors

5. Offensive Odor Control Technologies for Asphalt Plants

5.1 Overview

Offensive odors originating from volatile organic compounds (VOCs) emitted from asphalt plants (APs), particularly from R-dryers used for recycling R-material, have remained a persistent issue since the early development of recycled asphalt mixture production. This chapter reviews the technological evolution of odor-control measures developed by the author and provides an overview of the principles of the various deodorization technologies and their applicability to APs[28].

5.2 Sources of Odor Emissions

During the operation of an RP, there are numerous sources of odor emissions that must be considered when implementing odor-control measures, and the intensity and location of these emissions fluctuate continuously, as illustrated in **Figure 19**. Eliminating odor generation at its source is the ideal approach. However, it is difficult to completely prevent odor emissions while maintaining the economically viable process of drying and heating R-material. In principle, electromagnetic heating methods, such as microwave heating and induction heating, do not generate combustion exhaust gas and therefore can reduce the size of downstream exhaust-gas treatment equipment. However, these technologies have not yet been widely adopted because of their high capital cost and limited energy efficiency. Consequently, odor-control strategies have primarily focused on mitigating odor generation within conventional combustion-based heating processes.

5.2.1 Fuel Selection and Combustion Management

Sulfur contained in the fuel is oxidized during combustion to form sulfur oxides (SOx), which are a source of pungent odors. Accordingly, replacing heavy fuel oil (Grade A) with low-sulfur kerosene or gaseous fuels such as liquefied natural gas (LNG) is an effective odor-control measure. In addition, incomplete combustion resulting from inadequate burner maintenance increases the unburned hydrocarbons in the exhaust gas. These hydrocarbons subsequently undergo

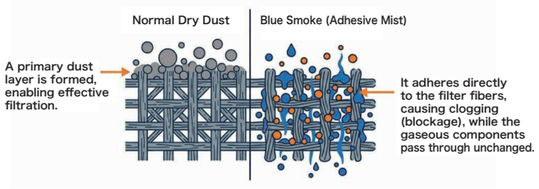


Figure 20: Bag Filter Clogging Caused by Adhesive Mist

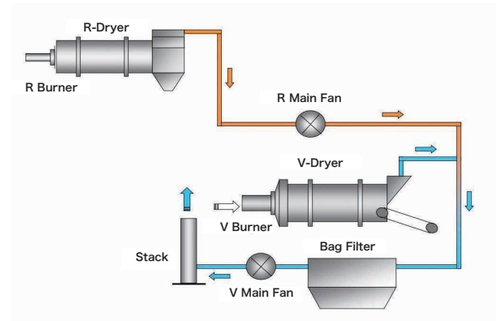


Figure 21: Combined V+R Bag Filter Dust Collection System Using Dust from the V-Dryer as a Filter Aid



Photo 2: Mist Filter (Dust Collector) for the Recycling Dryer

oxidation reactions to form strongly odorous compounds, including aldehydes and ketones.

5.2.2 Aggregate Characteristics

With respect to virgin aggregates, if the aggregates contain sulfur or organic matter, heating may generate sulfur oxides and burnt odors resulting from the thermal decomposition of proteinaceous materials.

In the case of R-material, the asphalt it contains is the primary source of offensive odors. When the moisture content of the R-material is low, fine particles are readily dispersed in the upstream section of the dryer, where they undergo rapid heating (destructive distillation), leading to increased odor emissions. Conversely, when the moisture content is high, the R-material tends to adhere to the interior surfaces of the R-dryer, reducing thermal efficiency. In addition, when the particle size is fine, the increased amount of entrained dust makes odor problems more pronounced.

5.2.3 Effects of Operating Conditions

The higher the temperature of the hot gas generated by burner combustion, the greater the thermal efficiency of the dryer. However, higher hot-gas temperatures also promote the thermal decomposition and oxidative decomposition of the asphalt contained in the R-material, thereby increasing the generation of VOCs (odor-causing components). To decrease these odor emissions, the hot-gas temperature in our RPs has been progressively reduced from the conventional 1,000°C to 800°C and subsequently to 600°C. To compensate for the reduction in thermal efficiency (fuel economy) associated with lowering the hot-gas temperature, energy performance has been maintained through the introduction of exhaust gas recirculation (EGR) and optimization of the capacity of the R-dryer.

5.3 Odor-Control Technologies in Early Asphalt Plants

In the early generations of APs, odor-control measures primarily relied on increasing stack height to enhance atmospheric dispersion and on removing particulate matter using dust collectors (bag filters).

5.3.1 Filtration Mechanism of Bag Filters

The use of a filter aid is essential for effective operation of bag filters. In the three-dimensional filtration process using felt filter media, the “primary dust layer” formed on the surface of the filter media performs the actual filtration function. However, when adhesive mist, such as the blue smoke generated from the R-dryer, is deposited directly onto the filter media, clogging occurs and the pressure loss increases, as illustrated in **Figure 20**. To prevent this problem, the system shown in **Figure 21** uses virgin dust from the V-dryer, which is free of adhesive components, as a filter aid to form the “primary dust layer.” Subsequently, a “secondary dust layer” including a mixture of adhesive mist and virgin dust is formed on top of the primary dust layer, allowing the accumulated dust to be periodically removed and the filtration layer renewed by pulse-air cleaning.



Photo 3: Combustion Chamber of the Direct Thermal Oxidation System

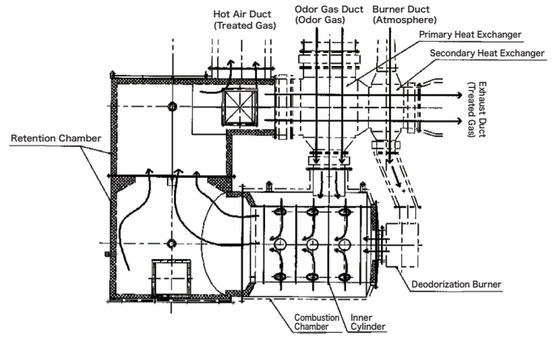


Figure 22: Internal Structure of a Direct Thermal Oxidation System

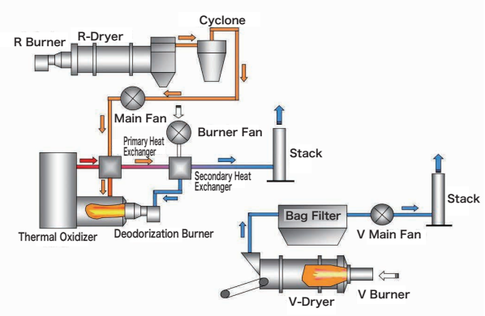


Figure 23: Flow Diagram of the Deodorization System Installed in an Asphalt Plant

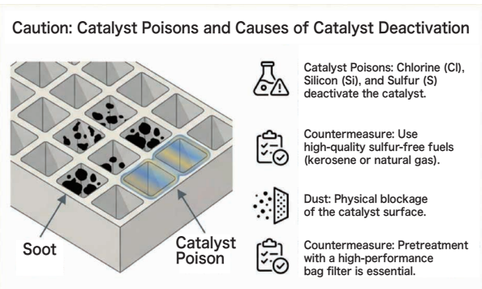


Figure 24: Limitations of Catalytic Oxidation for Deodorization

In addition, mist filters capable of capturing blue smoke and adhesive mist emitted from the R-dryer, as shown in **Photo 2**, were also introduced for practical use. However, because these systems employed disposable filter media, mist components gradually accumulated within the filter material, limiting their effectiveness as an odor-control measure.

5.3.2 Strengthened Regulations and the Need for Advanced Deodorization Systems

The approaches described above were effective to some extent in reducing ground-level odor concentrations. However, following the enforcement of the Offensive Odor Control Act and the expansion of designated regulatory areas, "odor index regulations (Type 2 regulations)" based on human olfactory perception were introduced. As a result, odor control could no longer be achieved solely through atmospheric dispersion or physical filtration, making it necessary to introduce advanced deodorization systems based on physicochemical and biochemical treatment technologies.

5.4 Deodorization Methods and Their Applicability to Asphalt Plants

Deodorization methods widely used in industrial applications include combustion, chemical scrubbing, and activated-carbon adsorption, all of which have well-established track records. When applying these methods to APs, it is necessary to select a system that does not adversely affect production while comprehensively evaluating not only deodorization efficiency but also economic feasibility, safety, and ease of maintenance. The following sections discuss the characteristics and applicability of each method for treating exhaust gas from APs, particularly exhaust gas from the R-dryer.

5.4.1 Combustion

Combustion is a highly effective method for controlling offensive odors (combustible organic compounds) generated by APs. In this method, odor-causing substances are oxidatively decomposed at high temperatures and converted into odorless carbon dioxide (CO_2) and water (H_2O).

5.4.1.1 Direct Thermal Oxidation

In this method, odor-causing compounds are retained



Photo 4: Overall View of the Regenerative Thermal Oxidation (RTO) System

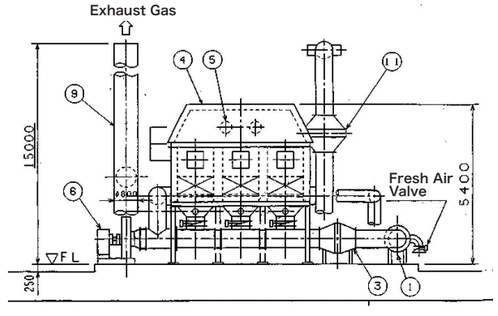


Figure 25: Overall Configuration of a Regenerative Thermal Oxidation (RTO) System

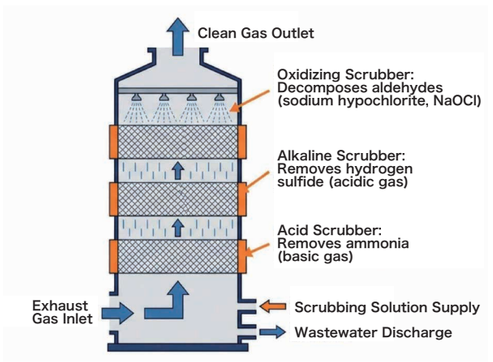


Figure 26: Schematic of Chemical Scrubbing

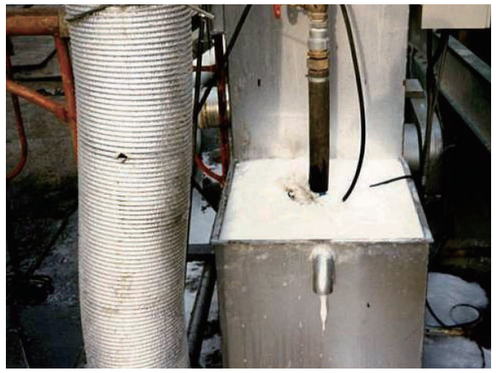


Photo 5: Field Testing of the Chemical Scrubbing System

for a prescribed residence time in a high-temperature, oxygen-rich atmosphere at 600–800°C (typically 750–800°C), where they undergo complete oxidation. **Photo 3** shows an overall view of a combustion chamber of a direct thermal oxidation system, **Figure 22** illustrates its internal structure, and **Figure 23** presents the corresponding process flow. Characteristics: The system has a simple structure and is suited for treating high concentrations of complex odors, including blue smoke. It provides a deodorization efficiency exceeding 95%.

Applicability to APs: Although the high combustion temperature results in relatively high fuel consumption, operating costs can be reduced by recovering waste heat through a heat exchanger, as shown in **Figure 23**. Accordingly, this method is considered the most suitable deodorization technology for APs.

5.4.1.2 Catalytic Oxidation

This method utilizes catalysts, such as platinum, to promote oxidative decomposition at temperatures lower than those required for direct thermal oxidation (200–400°C, typically 300–350°C).

Characteristics: Because oxidation proceeds at relatively low temperatures, this method offers excellent energy efficiency.

Applicability to APs: As shown in **Figure 24**, exhaust gas from APs contains sulfur compounds, which act as catalyst poisons, as well as fine dust and mist that can foul the catalyst surface. Consequently, the catalyst is susceptible to deactivation. Therefore, reliable pretreatment, such as a bag filter, together with the use of high-quality, sulfur-free fuel, is essential, making operation and maintenance relatively demanding.

Table 1: Major Types and Characteristics of Deodorants and Odor Neutralizers

Type of Agent	Main Characteristics and Applications
Plant Essential Oil-Based Type	This type contains a wide variety of constituents, including phytoncides, and provides a combination of masking, chemical reaction, and odor-neutralizing action. It is highly safe and suitable for spraying in both outdoor and indoor environments.
Chemically Reactive Type	This type chemically converts odor-causing compounds through neutralization, oxidation-reduction, condensation, and related reactions. It is mainly used as an additive to the circulating solution in chemical scrubbers.
Biological and Other Types	This category includes products that utilize microorganisms or enzymes, as well as products that primarily rely on fragrance-based masking.

5.4.1.3 Regenerative Thermal Oxidation (RTO)

This method employs ceramic heat-storage media to recover heat by periodically reversing the flow of exhaust gas.

Characteristics: It provides an exceptionally high heat-recovery efficiency exceeding 90%, resulting in low operating costs.

Applicability to APs: Although the energy-saving performance is excellent, reliable pretreatment equipment is required, as in catalytic oxidation, to prevent dust deposition and blockage of the heat-storage media[29]. **Photo 4** shows an overall view of a regenerative thermal oxidizer (RTO), and **Figure 25** illustrates its overall configuration.

5.4.2 Chemical Scrubbing

In this method, odor-causing compounds are brought into gas–liquid contact with water or chemical solutions (e.g., acids, alkalis, or oxidizing agents), where they are absorbed and chemically decomposed. **Figure 26** illustrates the principle of chemical scrubbing, and **Photo 5** shows a field test of a chemical scrubbing system conducted at an operating AP.

Characteristics: The scrubbing solution is selected according to the properties of the target odor-causing compounds (e.g., acidic or basic compounds).

Applicability to APs: Efficient absorption requires the exhaust gas to be cooled to below 70°C, making large cooling facilities such as cooling towers necessary. In addition, because the exhaust gas from APs contains a wide variety of odor-causing compounds, a single scrubbing solution is generally insufficient to treat all components, and the deodorization efficiency is often limited to approximately 70%. Consequently, secondary treatment, such as activated-carbon adsorption, is frequently required to achieve satisfactory deodorization[30].

5.4.3 Activated-Carbon Adsorption

Activated-carbon adsorption is a method in which odor-causing compounds are physically removed by adsorption onto porous materials such as activated carbon.

Characteristics: This method is effective as a polishing treatment for low-concentration odors.

Applicability to APs: Because the adsorption capacity is highly temperature dependent, the exhaust gas must be cooled to below 40°C to maintain high removal efficiency. In addition, blue smoke (adhesive mist) and dust, which are characteristic of AP exhaust gas, readily accumulate on the surface of the activated carbon, significantly reducing its adsorption capacity. Therefore, highly effective pretreatment is essential. Furthermore, the costs and labor associated with replacing or regenerating saturated activated carbon present additional challenges[31].

5.4.4 Biological Deodorization

Biological deodorization is a method that utilizes the metabolic activity of microorganisms to decompose odor-causing compounds. Representative systems include soil biofiltration and packed-bed biological deodorization. **Figure 27** illustrates the principle of biological deodorization.

Characteristics: This method has low operating costs and is suited for treating low-concentration odors.

Applicability to APs: Because the treatment rate is relatively slow, processing the large volumes of exhaust gas generated by APs requires either a large installation area (in the case of soil biofiltration) or large-scale treatment equipment. In addition, maintaining suitable environmental conditions for microbial growth, including adequate moisture and temperature, is essential. Consequently, the applicability of this method to APs, which are often operated intermittently, is limited[32].

5.4.5 Deodorants and Odor Neutralizers

This method reduces odors by spraying or introducing plant essential oils or chemical agents into the exhaust gas, thereby suppressing odors through masking, neutralization, or chemical reactions.

Characteristics: The required equipment is relatively simple, and the installation cost is low.

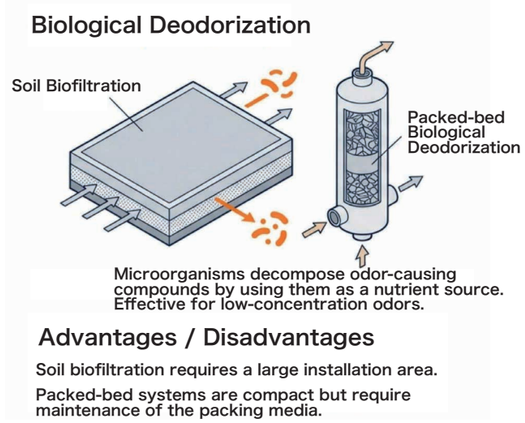


Figure 27: Schematic of Biological Deodorization

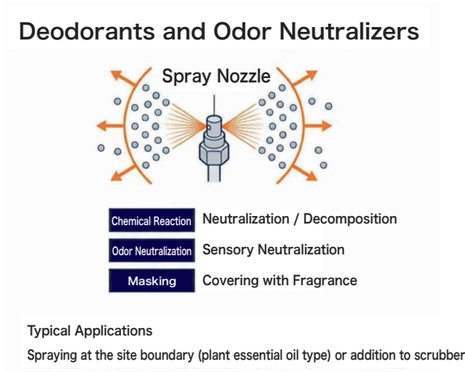


Figure 28: Schematic of Deodorants and Odor Neutralizers

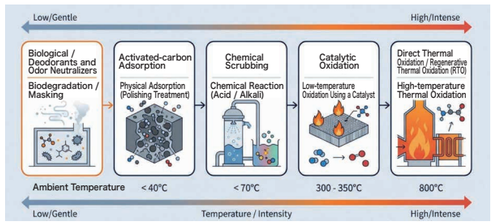


Figure 29: Conceptual Comparison of Deodorization Methods

Method	Deodorization Efficiency	Initial Cost	Operating Cost	Maintenance	Installation Space
Direct Thermal Oxidation	High (◎)	Low (○)	High (×)	Easy (◎)	Med (△)
Regenerative Thermal Oxidation (RTO)	High (◎)	High (×)	Low (◎)	Med (○)	Large (×)
Catalytic Oxidation	Med/High (○)	High (×)	Med (○)	Hard (× - Poison Risk)	Compact (◎)
Chemical Scrubbing	Low (△ - ~70%)	Med (△)	High (× - Wastewater)	Hard (×)	Large (×)
Activated-carbon Adsorption	High (◎ - Finish)	Med (△)	High (× - Replacement)	Med (△)	Large (× - Cooling)

◎ Excellent, ○ Good, △ Average, × Poor/High Cost

Figure 30: Performance Comparison of Deodorization Methods

Applicability to APs: Rather than fundamentally eliminating odor-causing compounds through decomposition or removal, this method primarily modifies or reduces the perceived intensity of odors. It is therefore commonly employed as a supplementary measure, such as by spraying deodorants and odor neutralizers into exhaust ducts or around the facility boundary. Because the effectiveness varies depending on the type of deodorizing agent (e.g., plant essential oil-based or chemically reactive formulations), the appropriate agent should be selected according to the characteristics of the odor at the site[33)34)]. **Figure 28** illustrates the concept of deodorants and odor neutralizers, and **Table 1** summarizes their principal types and characteristics.

5.4.6 Summary of Deodorization Methods

Figure 29 provides a conceptual comparison of the characteristics of direct thermal oxidation, regenerative thermal oxidation, catalytic oxidation, chemical scrubbing, and activated-carbon adsorption, while **Figure 30** compares their performance.

6. Future Perspectives

This paper has discussed the mechanisms responsible for the generation of offensive odors and blue smoke in asphalt plants (APs), as well as the evolution of technologies developed to control these emissions. The effective utilization of R-material is indispensable for the realization of a circular economy; however, the associated odor problems remain an unavoidable challenge. Building on the discussions presented thus far and taking into account the growing demand for a decarbonized society, the future direction of deodorization technologies for APs is discussed from the following three perspectives.

6.1 Establishing the Most Suitable Deodorization Method for Asphalt Plants

As discussed in Chapter 5 and confirmed by the decomposition performance evaluation experiments conducted separately, the exhaust gas emitted from APs, particularly from the R-dryer, is characterized by the presence of moisture, fine dust, adhesive mist (blue smoke), and sulfur compounds that act as catalyst poisons. Although catalytic oxidation offers advantages in terms of energy efficiency, minimizing the risk of catalyst deactivation caused by dust and catalyst poisons characteristic of AP exhaust gas requires rigorous pretreatment and careful maintenance. In contrast, direct thermal oxidation is capable of reliably oxidizing and decomposing high concentrations of complex odors, including blue smoke, by maintaining temperatures of 800°C or higher and providing a sufficient gas residence time. Moreover, because it is less susceptible to operational problems caused by dust accumulation and blockage, it can presently be regarded as the most robust deodorization technology for APs. In the future, direct thermal oxidation is expected to remain the principal deodorization method, while being integrated with the energy-efficiency improvements discussed in the next section as the preferred approach.

6.2 Reconciling Advanced Deodorization with Decarbonization (Energy Efficiency)

Direct thermal oxidation provides excellent deodorization performance. However, it requires the consumption of fossil fuels to maintain high operating temperatures, creating an environmental trade-off in the form of increased CO_2 emissions. At a time when carbon neutrality is receiving increasing emphasis, simply incinerating odor-causing compounds is no longer considered sufficient. Accordingly, future asphalt plants will require the following technological approaches to effectively utilize the thermal energy generated by deodorization processes throughout the overall process.

6.2.1 Cascade Utilization of Thermal Energy (RAV System)

As shown in **Photo 6** and **Figure 31**, the high-temperature hot gas (800–1200°C) generated by the thermal oxidizer can be utilized not only for waste-heat recovery but also as a heat source for the virgin aggregate dryer (V-dryer) and the R-dryer through a cascade heat utilization system. This approach improves the overall thermal efficiency of the plant, making it possible to offset—or even exceed—the additional fuel consumption associated with the deodorization process. **Figure 32** illustrates an advanced RAV system in which the heat distribution is optimized by incorporating additional heat exchangers. This configuration enables operation with an R-material content of up to 70%.

6.2.2 Latent Heat Recovery and Process Separation

The potential for further improving the energy efficiency of APs is often considered to be approaching its practical limit. However, considerable room remains for recovering the latent heat released by the condensation of water vapor contained in the exhaust gas. For example, as illustrated in **Figure 33**, an effective approach is to introduce a sand drying system in which the drying process for sand, which accounts for most of the moisture contained in the aggregates, is separated from the main AP process and carried out in advance using hot air generated through latent heat recovery from the exhaust gas. This approach dramatically reduces the thermal load on the main AP process, allowing the resulting surplus thermal energy to be allocated to advanced deodorization by direct thermal oxidation. As a result, both advanced deodorization and decarbonization can be achieved simultaneously on an overall process basis[35].

6.3 Addressing Sensory Pollution and Promoting Community Coexistence

The regulatory framework under the Offensive Odor Control Act is gradually shifting from substance concentration limits based on instrumental analysis to odor index regulations based on human olfactory perception, specifically the Triangle Odor Bag Method. This represents a paradigm shift from the conventional criterion that emissions are acceptable as long as they contain no harmful substances to one based on whether local residents experience discomfort. One of the challenges of sensory pollution is that odor complaints may arise because of the nature of the odor itself, even when emission concentrations remain below the applicable regulatory limits. Future asphalt plants will therefore be required not only to install deodorization equipment but also to implement flexible operational management in response to meteorological conditions and the types of mixtures being produced, thereby establishing odor management that is responsive to the perceptions of local residents. Ultimately, advanced thermal oxidation technologies should be integrated with thorough thermal energy utilization technologies, including latent heat recovery, with the aim of realizing odor-free, zero-emission asphalt plants capable of coexisting harmoniously with local communities.



Photo 6: In-House Trial Assembly of the RAV System

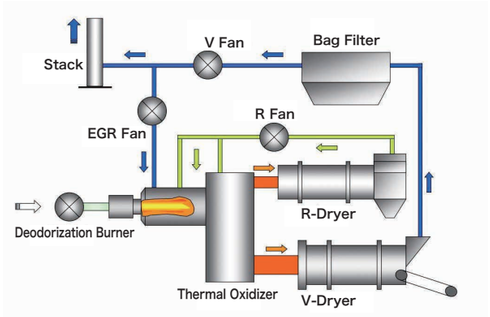


Figure 31: Flow Diagram of the RAV System

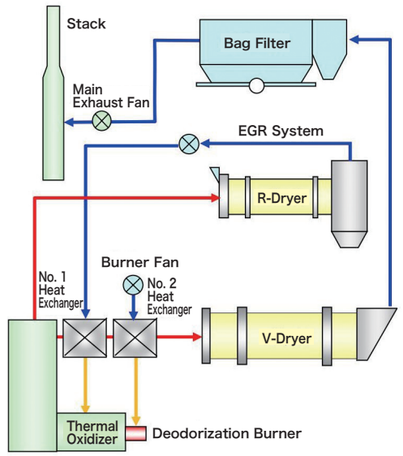


Figure 32: Advanced RAV System

7. Conclusions

This paper has examined the issue of odor emissions from asphalt plants (APs) from multiple perspectives, including human olfactory perception, the evolution of odor-control regulations, and the development of engineering countermeasures.

The recycling of reclaimed asphalt pavement (RAP) is indispensable for the realization of a circular economy. However, the blue smoke and offensive odors generated during the heating of R-material constitute a form of sensory pollution that directly affects the living environment of nearby residents. Without effectively addressing this issue, the long-term sustainability of plant operations cannot be ensured.

The principal findings of this study may be summarized as follows.

First, the odor-causing components (VOCs) emitted from APs, particularly from the R-dryer, consist of complex mixtures of hydrocarbons accompanied by fine dust and adhesive mist, forming a highly complex odor. Consequently, rather than targeting individual compounds, deodorization technologies capable of comprehensively oxidizing and decomposing these emissions are required. Among the technologies currently available, direct thermal oxidation provides the most reliable and robust solution.

Second, the advancement of deodorization technology is inevitably accompanied by the challenge of energy consumption. High-temperature thermal oxidation ensures highly effective deodorization. However, it also requires the consumption of fossil fuels, resulting in increased CO_2 emissions. As discussed in Chapter 6, however, this trade-off can be mitigated by integrating technologies such as cascade utilization of thermal energy (e.g., the RAV system), which reuses waste heat from the thermal oxidizer as a heat source for the dryers, and latent heat recovery, which utilizes the latent heat released by the condensation of water vapor in the exhaust gas for aggregate drying. In other words, advanced deodorization and decarbonization can be achieved simultaneously through optimization of the overall process.

Third, the transition in regulatory philosophy from concentration-based standards for specific odor-causing substances to odor index regulations based on human olfactory perception has important implications. Even

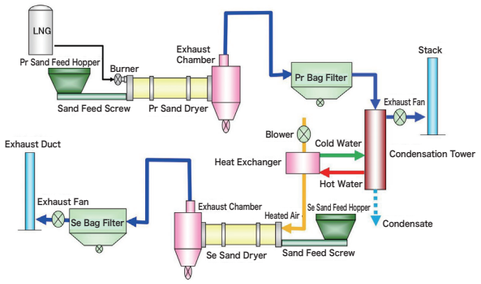


Figure 33: Concept of Latent Heat Recovery Technology from Water Vapor

when measured concentrations satisfy regulatory limits, odors may still give rise to complaints if they are perceived as unpleasant by nearby residents. Future APs must therefore go beyond simply installing deodorization equipment and instead implement odor management practices that incorporate flexible operational control according to meteorological conditions and plant operating status while taking into account the perceptions of surrounding communities.

The era in which visible black or white smoke was regarded as evidence of productive industrial activity has long since passed. Looking ahead, continued technological innovation and the wider implementation of advanced combustion technologies integrated with highly efficient thermal energy utilization technologies will be essential for realizing odor-free, zero-emission asphalt plants that coexist harmoniously with local communities while minimizing environmental impacts.

It is hoped that this paper will contribute to these efforts.

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