A Sand Drying System Utilizing Latent Heat from Water Vapor Condensation in Exhaust Gases

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Abstract: Asphalt plants, which produce heated asphalt mixtures used in road paving, have actively incorporated energy-saving technologies throughout their development and now achieve thermal efficiencies exceeding 85%. However, this high efficiency also indicates that the potential for further energy efficiency improvements in asphalt plants is approaching its limit. Asphalt mixtures must be applied while still hot to preserve workability, and the time available for transport by dump trucks is restricted. Thus, over 1,000 asphalt plants have been distributed across Japan. This dispersed network lowers the utilization rate of individual plants, reducing overall productivity and posing a barrier to further energy conservation. From another perspective, asphalt plants use fossil fuels as a heat source during the production of the heated asphalt mixture and emit approximately 1.03 million tons of CO_2 annually across the country. The majority of these emissions occur during the drying process to remove moisture from the aggregates. In particular, sand, which has a large specific surface area, retains over 70% of the moisture in the aggregates. If this moisture can be removed in advance by effectively utilizing waste heat, this treatment can be an extremely effective means of both conserving energy and reducing CO_2 emissions.

This paper outlines a sand drying system designed to achieve thermal efficiency exceeding 150% by recovering and utilizing the latent heat of condensation of water vapor in the exhaust gas—which has conventionally been discarded as waste heat and not effectively harnessed in aggregate drying. The system operates within the sand supply chain, which is not affected by the operational constraints of asphalt plants that have extremely low operating rates. This paper also evaluates the potential fuel savings and CO_2 emission reductions that could be realized at asphalt plants through the use of this pre-dried sand at asphalt plants.

Keywords: CO_2 emission reduction, latent heat of condensation of water vapor, sand drying, condensation tower

1. Introduction

The international community has been taking major steps toward the goal of limiting the global temperature rise to less than 1.5°C above pre-industrial levels by the end of this century. COP26 (the 26th Conference of the Parties to the United Nations Framework Convention on Climate Change) was held in November 2021 in Glasgow, UK, with representatives from 194 countries in attendance. The G7 nations, including Japan, declared ambitious targets to achieve net-zero greenhouse gas (GHG) emissions by 2050. Japan, in particular, has pledged to the international community that it will reduce its GHG emissions by 46% by 2030 compared to 2013 levels, with an even more ambitious target of reaching a 50% reduction.

In addition, Japan has declared its greenhouse gas reduction target for 2035—due for submission to the United Nations by February 2025—as a Nationally Determined Contribution (NDC), setting a 60% reduction compared to 2013 levels. To support this commitment, Japan has newly formulated and approved by the Cabinet the 7th Strategic Energy Plan. The core strategy focuses on further increasing the proportion of energy derived from renewable sources and nuclear power—neither of which emits CO_2 or other greenhouse gases—beyond previous levels, and on promoting greater energy conservation than ever before. However, the transition to renewable energy presents challenges, particularly in reducing costs. Due to their significantly lower energy density compared to fossil fuels, renewable energy sources tend to require much larger conversion facilities, such as those for generating electricity. Moreover, because of their high variability and sensitivity to weather conditions, substantial investments in infrastructure, such as battery storage and power transmission and distribution systems, are also necessary.

With regard to nuclear energy, Japan must confront the hurdles of gaining approval from the Nuclear Regulation Authority—known for having the world' s strictest safety standards—and building consensus among local communities for the restart of reactors, all in light of the hard lessons learned from the 2011 Fukushima Daiichi nuclear disaster. Furthermore, Japan also faces challenges in achieving carbon neutrality in 2050, such as replacing aging reactors, constructing new ones, and training engineers and developing human resources to support the nuclear industry.

With regard to energy conservation, Japan, strongly impacted by the two oil crises, has promoted world-leading energy-saving measures across its industrial sector. However, achieving further energy conservation is becoming increasingly difficult, often likened to wringing out a dry towel, indicating that we are approaching the limits of what can be achieved. Nevertheless, energy conservation remains a highly effective means of reducing both CO_2 emissions and associated costs. Moreover, it is effective across all types of energy resources, including renewable and nuclear energy.

Meanwhile, amid these societal trends, if we turn our attention to roads—an essential component of transportation infrastructure—over 38 million tons of hot-mix asphalt (hereinafter referred to as "HMA") are produced annually in Japan as a paving material for new road construction and maintenance.[1] It is estimated that asphalt plants (hereinafter referred to as "APs") that manufacture HMA emit approximately 1.03 million tons of CO_2 per year. Even in APs, energy-saving technologies were proactively adopted early on in response to the two oil crises of the past. As a result, thermal efficiency based on Lower Heating Value (LHV) has now reached over 85%. However, this also suggests that APs are nearing the limits of further energy efficiency improvements.

In addition, since HMA must be transported and applied while still hot to maintain its workability, the time (or distance) it can be transported by dump trucks is limited. To address this constraint, more than 1,000 APs are distributed across the country. However, this distribution reduces the operating rates of individual APs, which in turn hinders productivity and becomes a barrier to further energy efficiency improvements.

Next, focusing on the fossil fuels consumed by APs during the production of HMA, the majority is used in the drying process to remove moisture from the aggregates. In particular, sand, which has a large specific surface area, retains over 70% of the total moisture content in the aggregates. Therefore, if this moisture can be removed in advance by effectively utilizing waste heat or other means, this treatment would make a significant contribution to energy savings, improved fuel efficiency, and reduced CO_2 emissions.

This paper outlines a sand drying system designed to achieve thermal efficiency of over 150% based on LHV by recovering and utilizing the latent heat of condensation of water vapor in the exhaust gas—which has conventionally been discarded as waste heat and not effectively harnessed in aggregate drying. The system is implemented in the sand supply chain, which is not affected by the operational constraints of APs that have extremely low operating rates. The paper also examines the potential fuel savings and CO_2 emission reductions at APs when this pre-dried sand is supplied as aggregate for hot-mix asphalt.

2. Challenges of APs

Chapter 2 begins with "**2.1 Overview of Asphalt Plants,**" providing a general outline of AP characteristics. It then examines the current challenges faced by APs in the context of achieving net-zero GHG emissions by 2050, and interim reduction targets of 46% by 2030 and 60% by 2035. The discussion focuses on "**2.2 Limits of Energy Efficiency Improvements**" and "**2.3 Limits of Operating Rate Improvements.**"

2.1 Overview of Asphalt Plants

An AP is a facility that produces HMA, a paving material for road construction, by drying and heating virgin aggregates (hereinafter referred to as "V-aggregates") such as crushed stone and sand, which make up approximately 90% of the mixture by weight, and adding about 5% asphalt—a residue from crude oil—as a binder, along with approximately 5% filler in the form of stone powder (calcium carbonate) to form the paving mixture.

Photo 1 and **Photo 2** show overall views of a typical AP, and its process flow is illustrated in **Figure 1**[2]. As shown in the figure, the plant includes several components such as a V-aggregate dryer (hereinafter referred to as the "V-dryer") for drying and heating V-aggregates; a screen that separates the heated aggregates by particle size; a weighing system that measures the aggregates stored in hot bins according to the mix design; and a twin-shaft pugmill mixer that combines the measured V-aggregates with specified amounts of asphalt and filler, while maintaining the mixture at high temperature.

Photo1
Recent Example of an Asphalt Plant (AP) – Case ①
Source: NIKKO Co., Ltd., NAP News No. 364, July 2024

Photo2
Recent Example of an Asphalt Plant (AP) – Case ②
Source: NIKKO Co., Ltd., NAP News No. 355, April 2022

Furthermore, from the perspective of building a recycling-oriented society, most APs in Japan are equipped with facilities for producing recycled asphalt mixture (hereinafter referred to as "R-mixture") by crushing and adjusting the particle size of asphalt concrete chunks—pavement waste material generated during the replacement of deteriorated asphalt pavement (hereinafter referred to as "Ascon-gara")—to create recycled material (hereinafter referred to as "R-material"), which is then added and mixed at a fixed ratio with virgin aggregates (hereinafter referred to as "V-aggregates") as part of the aggregate composition. The key equipment in this recycling system includes: a recycling dryer (hereinafter referred to as the "R-dryer") for drying and heating the R-material; a surge bin for temporarily storing the heated R-material; a weighing device that feeds the heated R-material from the surge bin into the twin-shaft pugmill mixer at a specified ratio; and a deodorization unit that purifies the odorous exhaust gas generated by the R-dryer.

In addition, asphalt mixture silos that allow for continuous operation of APs without being interrupted by the loading of asphalt mixtures onto dump trucks have become increasingly common. These silos contribute to energy savings and enhanced productivity. Currently, R asphalt mixtures account for nearly 70% of all asphalt mixtures shipped domestically. In contrast, asphalt mixtures that do not contain recycled material are referred to as virgin asphalt mixtures (hereinafter referred to as "V mixtures") for differentiation. Hereinafter, the term "asphalt mixture" refers to both types collectively.

When hot, asphalt mixtures are fluid and workable. Once laid and compacted on a road surface, they cool down, and the asphalt binder hardens, providing the necessary strength for pavement. To produce asphalt mixtures with the required quality, such as workability and compaction, at an AP, the process must include drying and heating aggregates such as crushed stones and sand containing moisture from ambient temperature up to around 170°C. This drying and heating process is the primary source of fuel consumption and CO_2 emissions in asphalt plants.

The drying and heating of aggregates are carried out using hot air (combustion gas) generated by burning fossil fuels such as heavy oil or natural gas in a burner. This hot air serves as the heat medium and is brought into direct contact with the aggregates to facilitate heat exchange (drying and heating). The equipment responsible for this heat exchange process is called a dryer. A full view of a dryer is shown in **Photo 3**[2], and an internal schematic diagram is shown in **Figure 2**[2]. As seen in the photo and diagram, the AP dryer typically includes a cylindrical, rotating drum installed at an angle along the direction of aggregate flow. Aggregates and hot air are continuously fed into this drum, and as the drum rotates, the aggregates are fluidized and dispersed while coming into direct contact with the hot air. In particular, to enhance the heat exchange by increasing the contact surface area between the aggregates and the hot air, many lifters are installed inside the dryer. These lifters are configured to lift the aggregates and evenly distribute them as the drum rotates.

The V-dryer used in the process of producing V-mixtures adopts a counter-flow method, in which the hot air and the aggregates continuously flow in opposite directions. As shown in **Figure 3**, this method allows for the largest possible logarithmic mean temperature difference between the aggregates and the hot air throughout the entire interior of the dryer. As a result, the

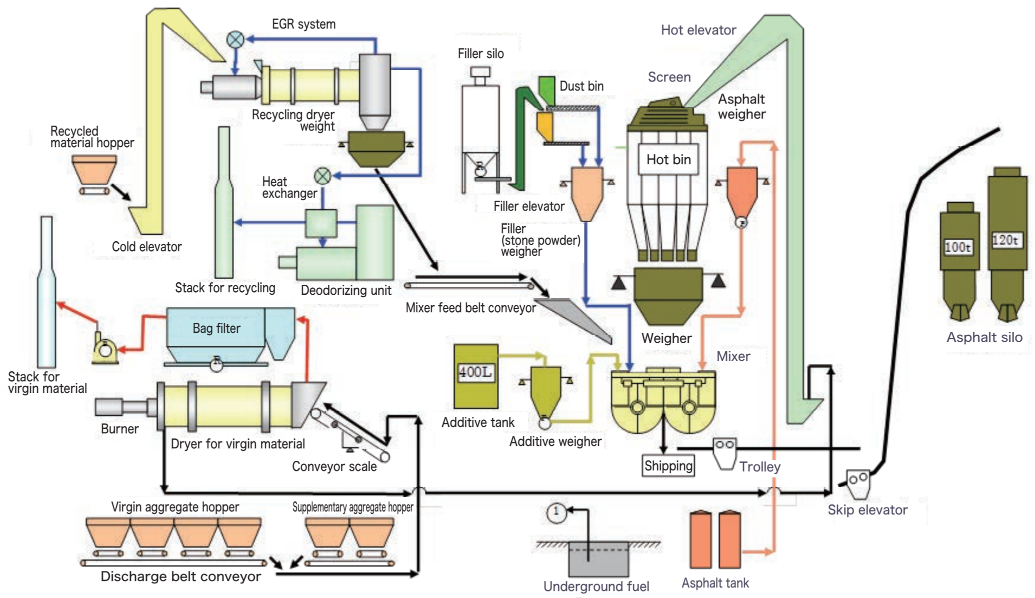

Figure1 Mixture Production Process at General Asphalt Plant (AP)[2]

exhaust gas temperature can be designed to be lower than the heated aggregate temperature, enabling extremely high heat exchange efficiency.

The parallel-flow method, in which the hot air and aggregates flow in the same direction, is primarily used in the process of producing R-mixtures. As shown in **Figure 4**, this method results in a smaller logarithmic mean temperature difference between the hot air and the R-material compared to the V-dryer. This helps decrease the degradation of asphalt contained in the R-material and also allows the heated R-material, which becomes adhesive as the temperature rises, to capture fine particles carried in from upstream. However, because, by design, the exhaust gas temperature cannot be lower than the heated R-material temperature, the heat exchange efficiency is inferior to that of the counter-flow method.

2.2 Limits of Energy Efficiency Improvements

The AP dryer, based on the principles described in the previous section, focuses primarily on drying and heating, similar to typical industrial drying equipment. Accordingly, useful energy is defined as the latent heat of water vapor (drying) and the sensible heat of the aggregates (heating), while waste energy is defined as heat dissipation, sensible heat in the exhaust gas, and other unaccounted heat. As a result, the thermal efficiency (LHV) of the V-dryer, which adopts a counter-flow method, exceeds 85%, making it an exceptionally efficient drying system. This achievement can be attributed to the strong impact of the two past oil shocks, which also affected APs, prompting an early focus on fuel efficiency. In response, energy-saving equipment such as low air ratio burners and high-efficiency dryers has been rapidly developed and introduced into the market[3)–16)]. In particular, APs have made proactive efforts to reduce exhaust gas, which accounts for the majority of waste

Photo3 Overview of the Dryer[2]

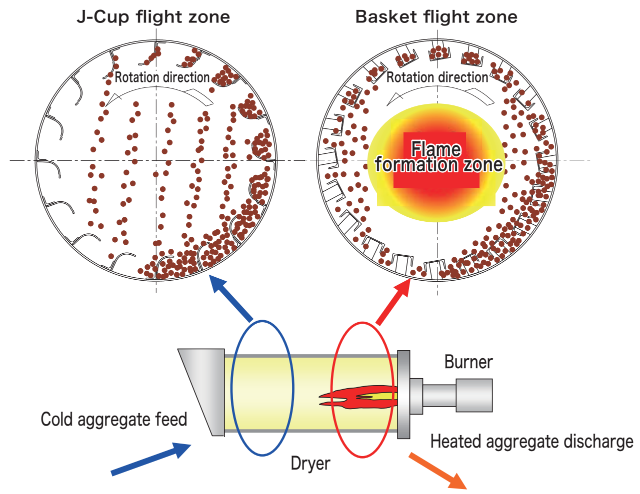

Figure2 Internal Image of the Dryer[2]

energy, and to recover sensible heat from it. As a result, the exhaust gas temperature has already been reduced to below 100°C, and thermal energy is being efficiently utilized for drying and heating the aggregates up to the point where the water vapor in the exhaust gas is nearly saturated. However, this high level of energy recovery has, in some cases, led to undesirable side effects, such as low-temperature corrosion in exhaust gas treatment equipment like dust collectors.

Based on these facts, it can be said that there is virtually no room left for further energy savings in APs, and the system has reached the "**limits of energy efficiency improvements.**"

2.3 Limits of Operating Rate Improvements

As previously described, asphalt mixtures must be transported from APs to paving sites while still hot to prevent a decline in construction quality, such as reduced workability or inadequate compaction due to temperature loss. It is generally understood that hot mixtures can be transported by dump truck for up to approximately 1.5 hours without significant cooling. Due to this characteristic of asphalt mixtures, the development of APs in Japan has followed a path in which plants have been distributed nationwide, enabling them to overcome the limitation of transport time. In other words, APs are located so that asphalt mixtures can be delivered to paving sites across the country within 1.5 hours.

On the other hand, according to the latest statistics from the Japan Road Contractors Association, during the economic bubble period of the 1990s, more than 2,000 APs were in operation nationwide, producing over 80 million tons of asphalt mixture annually. However, following the collapse of the bubble economy and the resulting suppression of road construction, the production volume of asphalt mixtures was reduced by half, and, alongside this, the consolidation of APs accelerated, bringing the total number of plants down to around 1,100[1)].

Furthermore, APs have evolved toward larger-scale facilities with greater production capacity in contrast to the halving of asphalt mixture production volume, in response to new demands such as the addition of R-dryers for producing R-mixtures and the reduction of loading time when transferring mixtures to dump trucks (i.e., improving loading efficiency). These developments are considered major factors that have driven down the operating rate of APs to below 40%. Here, the operating rate (%) of APs is defined as:

Annual asphalt mixture production (t/year) ÷ Annual production capacity of APs (t/year) × 100

The annual production capacity (t/year) is calculated as:

Total nominal capacity of all APs (t/hour) × 5 hours/day × 20 days/month × 12 months/year

Based on these definitions, the annual operating time is less than 1,200 hours per year, which is extremely low for a manufacturing facility. In comparison to a typical production facility that operates for 7,200 hours per year, the operating rate of APs falls below one-sixth, at 6.7% (1,200/7,200 × 40%). This figure clearly highlights the unique operational characteristics of APs.

Given this background, it is essential to maintain the current locations of APs to ensure a stable uninterrupted supply of asphalt mixtures to roads across the country even if their operating rates continue to decline. Accordingly, further consolidation of APs to improve operating rates and productivity—while also promoting energy savings and CO_2 reduction—has reached its practical limits due to constraints such as transportation time and loading time into dump trucks. It must be said that APs are now facing the "**Limits of Operating Rate Improvements.**"

3. Overview and Features of Sand Drying System

In Chapter 3, after reviewing the key components of the present sand drying system in **Section 3.1, Major Equipment Configuration**, and **the fundamental principles for improving thermal efficiency in Section 3.2**, Basic Principles for Improving Thermal Efficiency, we then address Section **3.3, Waste Heat Recovery and Sand Drying Mechanism** using a Condensation Tower, which constitutes the core of the system's advanced energy-saving technology. This is followed by an examination of two critical technologies: **Section 3.4, Reduction of Non-Condensable Gases (reduction of infiltration air)**, which raises the steam dew point to increase the recoverable latent heat of condensation; and **Section 3.5, Residual Moisture in Dried Sand**, which ensures that the supplied thermal energy is devoted exclusively to evaporating moisture without raising the sand temperature.

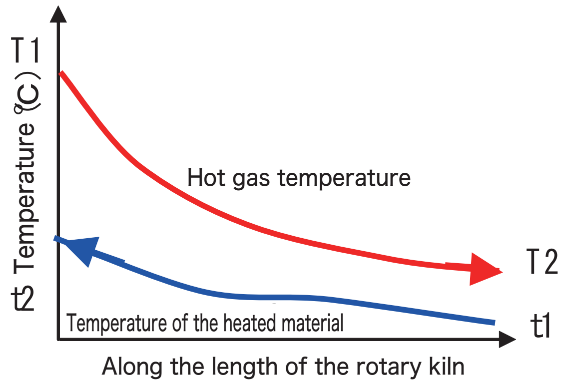

Figure3 Relationship Between Gas Temperature and Aggregate Temperature in Counter-flow

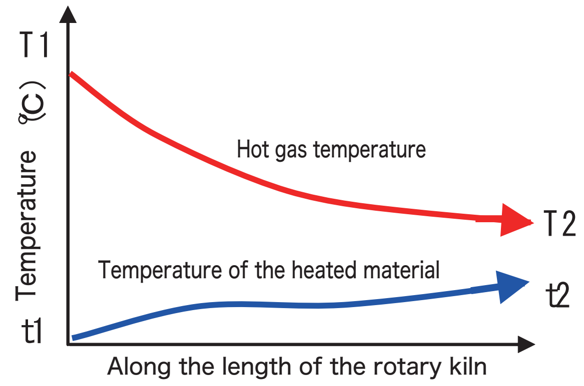

Figure4 Relationship Between Gas Temperature and R Material Temperature in Parallel-flow

3.1 Major Equipment Configuration

To serve as a benchmark for the present sand drying system, **Figure 5** illustrates the flow of a conventional sand drying system (hereinafter referred to as the conventional system), which does not include a device for recovering the latent heat of condensation from the water vapor contained in the exhaust gas (hereinafter referred to as the condensation tower). As shown in the figure, the conventional system includes components such as a sand supply unit, a burner for generating hot air, a parallel-flow (co-current) dryer, a bag filter (dust collector), an exhaust fan, and a chimney. It should be noted that the dryer in the sand drying system deliberately adopts the parallel-flow configuration, the details of which will be discussed later. As described in the previous chapter, the dryer used in the AP (asphalt plant) has already achieved a thermal efficiency of over 85%, resulting in exhaust gas temperatures below 100°C. At this point, the contained water vapor becomes saturated, indicating that the system has already reached the "**limits of energy efficiency improvements.**"

Next, taking the Conventional System as the basic reference, **Figure 6** illustrates the flow of the present sand drying system equipped with a condensation tower. As shown in the figure, the present sand drying system includes two dryers: a Primary sand dryer (hereinafter referred to as the Pr-sand dryer) equipped with a burner for hot air generation, and a Secondary sand dryer (hereinafter referred to as the Se-sand dryer), which is not equipped with a burner. Both dryers adopt the parallel-flow (co-current) method as in the conventional system, and are equipped with a bag filter, an exhaust fan, and other ancillary equipment to remove dust from the exhaust gas. A distinctive feature of this system is the condensation tower installed downstream of the bag filter for the Pr-sand dryer. In this condensation tower, water is sprayed directly into the exhaust gas, causing the water vapor contained in the exhaust gas to condense, and recovering the latent heat released during condensation in the form of hot water.

The recovered hot water is subsequently directed to a heat exchanger for warm air generation, where it exchanges heat with ambient air to produce warm air. This hot air is then used as the heat medium for drying fresh sand in the Se-sand dryer. In other words, the thermal energy supplied to the Se-sand dryer for drying sand is entirely derived from the latent heat of condensation of water vapor that would otherwise have been discharged as waste heat in the conventional system. Accordingly, all the thermal energy used in the Se-sand dryer for drying sand contributes directly to energy conservation and CO_2 reduction.

To protect each piece of equipment from low-temperature corrosion, the burner is assumed to use fuels free of sulfur compounds that can form acidic gases such as sulfur oxides. Suitable fuels include white kerosene, city gas, and liquefied natural gas (LNG).

3.2 Basic Principles for Improving Thermal Efficiency

As described in Chapter 2, the definition of thermal efficiency in APs, which focus primarily on the drying and heating process of aggregates, considers useful energy to be the sensible heat of the aggregates (heating) and the latent heat of moisture (evaporation). In contrast, waste energy cannot be utilized for drying and heating the aggregates and includes heat dissipation, sensible heat of the exhaust gas containing water vapor, and unaccounted heat. The majority

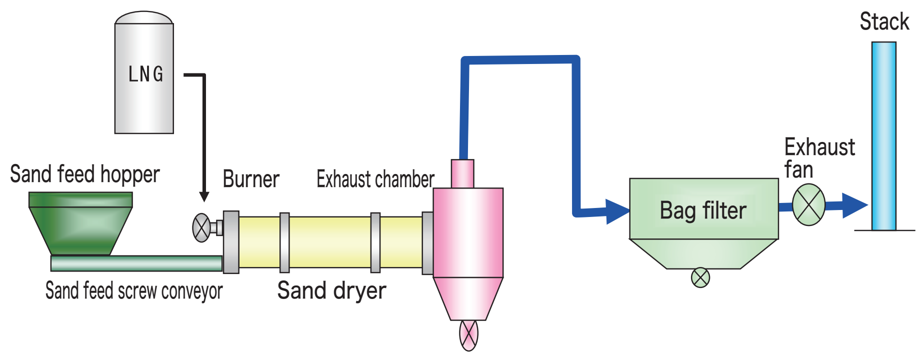

Figure5 Overall Flow of the Conventional Sand Drying System

of waste energy is attributable to the sensible heat of exhaust gases. In any case, since the total amount of useful energy defined in APs accounts for more than 85% of the total input energy (i.e., combustion heat), the system can be evaluated as a highly efficient drying system under the definition of thermal efficiency.

The above description can be expressed using the following equations:

Input heat = (Useful heat) + (Waste heat)

Thermal efficiency = (Useful heat) / (Input heat)

where:

Useful heat = (Sensible heat of aggregates) + (Latent heat of moisture)

Waste heat = (Heat dissipation) + (Sensible heat of exhaust gas) + (Unaccounted heat)

However, when shifting the perspective to the state after the aggregates have been dried, the useful energy retained in the aggregates as sensible heat accounts for only about 38% of the total input energy. The remaining 47% or more, in the form of latent heat, is discharged as the enthalpy of water vapor accompanying the exhaust gas. Given that the law of conservation of energy holds, exhaust gas containing a large amount of water vapor still retains a significant amount of latent thermal energy, despite the low exergy (i.e., low-quality energy) and therefore limited usability. Accordingly, when evaluating the exhaust gas only by its sensible heat, the waste energy appears to be no more than 10–15% of the total input energy. However, if the enthalpy of water vapor (both sensible and latent heat) is considered, it becomes evident that more than 60% of the input energy is actually discharged as exhaust gas.

As previously mentioned, the counter-flow V-dryer has already reached the "**Limits of Energy Efficiency Improvements,**" where the exhaust gas temperature falls below 100°C and condensation of water vapor occurs. However, the temperature difference between aggregates at ambient temperature (10°C) and the exhaust gas slightly below 100°C is nearly 90°C. Thus, there remains considerable potential for heat exchange. Nevertheless, in the case of direct heat exchange between exhaust gas below 100°C containing a large amount of saturated steam and aggregates at ambient temperature, both heat transfer and mass transfer (condensation of water vapor) occur simultaneously in the same space, which hinders heat exchange, particularly the drying of moisture. In other words, as soon as heat transfer begins from the exhaust gas to the cold aggregates, condensation of water vapor begins. This situation causes the moisture content of the aggregates to increase, which is a major obstacle to improving thermal efficiency and is a key reason why APs have reached the "**Limits of Energy Efficiency Improvements.**"

The increase in the moisture content of the aggregates occurs locally near the aggregate feed point in the counter-flow V-dryer. In actual AP operations, a problematic phenomenon has been observed: when the partial pressure of water vapor in the exhaust gas is high and its dew point temperature exceeds the aggregate temperature, fine particles such as silt and clay, which have large specific surface areas and are attached to the aggregates, become moistened by condensate. These moistened particles then adhere to and grow by adhesion on the inner walls of the dryer. As a countermeasure to this adhesion, contrary to the goal of energy saving, it is effective to raise the exhaust gas temperature, thereby increasing the inner wall temperature of the dryer. This is because adhesion will not develop as long as the wall temperature remains above the dew point and the surface does not become wet with condensate.

As a thought experiment, consider a counter-flow dryer whose length is extended infinitely. In this scenario, it can be reasonably assumed that at some point along the dryer's

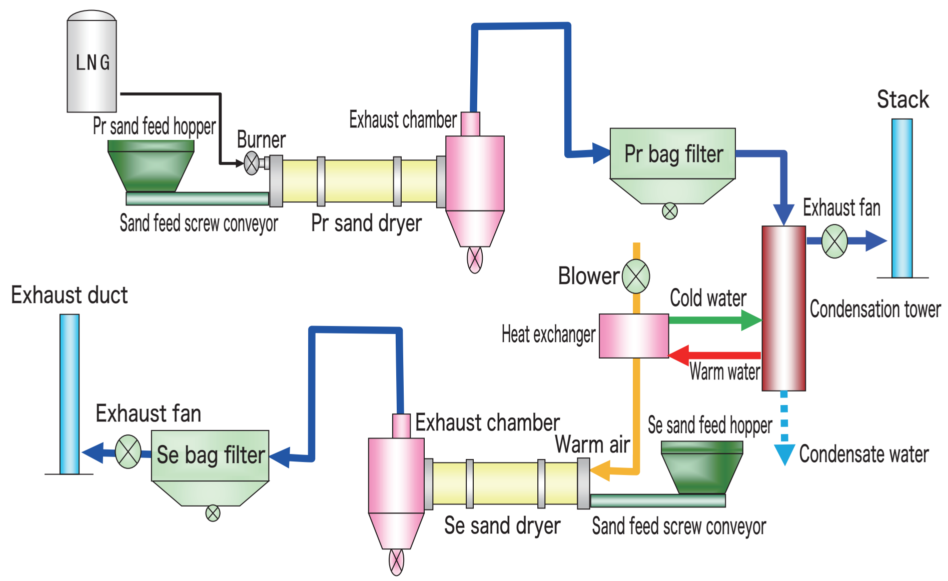

Figure6 Overall Flow of the Present Sand Drying System

longitudinal axis, a thermal equilibrium will be reached where the temperatures of the exhaust gas, aggregates, dryer wall, and dew point all become equal. This equilibrium temperature would approach the saturation temperature corresponding to the partial pressure of the water vapor (100°C or lower at atmospheric pressure). This illustrates the fundamental reason why further drying cannot proceed due to the influence of water vapor condensation, even though a temperature difference of nearly 90°C can be obtained between the exhaust gas and the aggregates.

The thought experiment suggests that the key principle of the present sand drying system lies in separating heat (sensible heat + latent heat of condensation) from mass transfer (condensation of water vapor) so that they do not occur simultaneously in the same space. In other words, to improve thermal efficiency, it is essential to utilize the latent heat of condensation of water vapor to heat the aggregates while preventing any increase in their moisture content by separating the condensate from the aggregates.

3.3 Waste Heat Recovery and Sand Drying Mechanism via a Condensation Tower

This sand drying system is equipped with a condensation tower that utilizes water as the direct medium for heat recovery. In the condensation tower, water is atomized to create an extremely large heat exchange surface area, which is brought into direct contact with the exhaust gas so that the latent heat of condensation of the water vapor contained in the exhaust gas is recovered as hot water.

Specifically, exhaust gas containing saturated water vapor at temperatures below 100°C is introduced into the condensation tower. This exhaust gas, collected from the Pr-sand dryer shown in **Figure 6**, has been treated by a dust collection system. The system adopts an updraft method in which the exhaust gas is introduced into the central upper part of the condensation tower, redirected at the lower part to the outer periphery to flow upward. Against the upward-flowing exhaust gas, cold water at around 15°C is sprayed downwards. This creates a cross counter—flow between the rising exhaust gas and the falling water droplets.

Inside the condensation tower, water vapor in the exhaust gas condenses onto the sprayed water droplets, which act as nuclei, similar to the mechanism by which rain forms. As condensation progresses, the water vapor in the exhaust gas condenses onto the droplets, causing them to grow larger while their temperature increases. To increase the heat exchange surface area, the smaller the droplet size, the greater the specific surface area becomes. However, if the droplets are too small, a larger proportion of them will scatter along with the exhaust gas. Therefore, there exists an optimal range of droplet sizes depending on the density, temperature, and velocity of the exhaust gas. With this mechanism, water is used as the medium for heat exchange, and the system avoids the simultaneous occurrence of heat transfer and mass transfer (condensation of water vapor) in the same space—an issue that posed a challenge in conventional systems.

Next, the hot water recovered at approximately 80°C in the condensation tower is supplied to a heat exchanger used for generating hot air, where the air at 15°C and 50% relative humidity (RH) is heated to 70°C. As a result, the relative

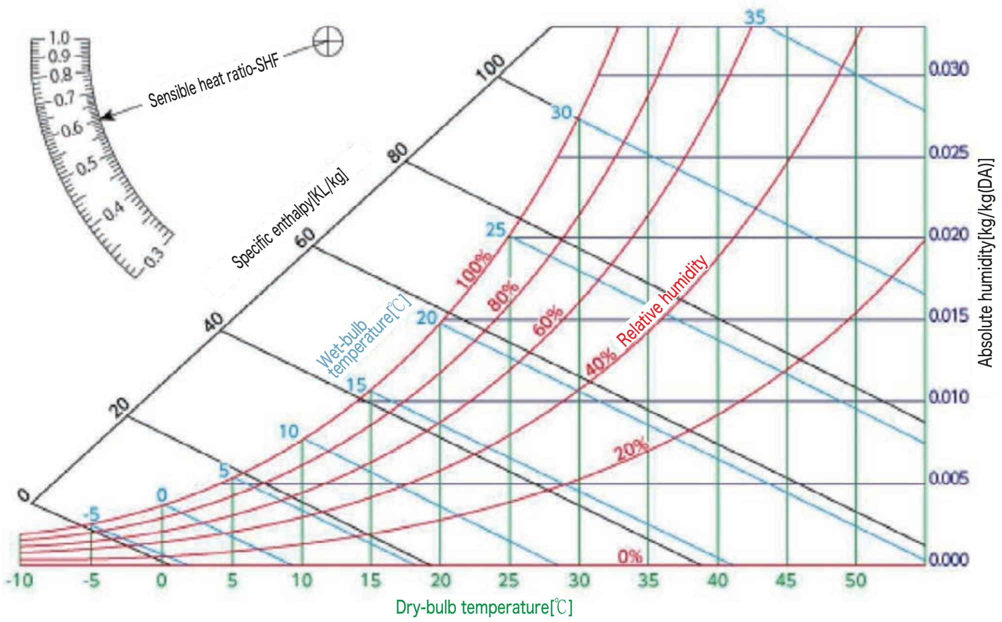

Figure7 Psychrometric Chart[17)]

humidity of the hot air decreases to 2.7% RH, thus achieving drying performance comparable to that of a hair dryer or clothes dryer.

As an illustrative example to convey the scale of the system, 30 metric tons of wet sand are fed into the Pr-sand dryer per hour. The latent heat of condensation recovered from the exhaust gas is then used in the Se-sand dryer to dry 20 metric tons per hour of wet sand. In this context, the thermal energy available from 1 Nm^3 of 70°C hot air at 2.7% RH is only sufficient to evaporate about 20 grams of water when exchanged with the sand and cooled to 30°C with a temperature drop of 40°C. Based on this, if the Se-sand dryer has a drying capacity of 20 tons per hour and is designed to reduce the moisture content by 10%, hot air capable of evaporating 2,000kg of water per hour (33.3kg/min) is required, which corresponds to 100,000Nm^3/h (1,667Nm^3/min) of hot air.

As described above, the sand drying system is designed to recover and utilize the latent heat of condensation of water vapor, which could not be effectively used in the conventional AP process due to the simultaneous occurrence of heat and mass transfer. As a result, it becomes possible to construct a sand drying system with 1.67 times the drying capacity per unit of energy input compared to conventional systems.

3.4 Reduction of Non-Condensable Gases (Reduction of Infiltration air)

When recovering the latent heat of condensation of water vapor as hot water in the condensation tower, the dew point temperature is determined by the dry-bulb temperature (horizontal axis) at the point where the water vapor partial pressure in the exhaust gas (right vertical axis: absolute humidity) intersects with the 100% relative humidity line, as shown in **Figure 7**[17)]. In other words, the exhaust gas contains non-condensable gases such as nitrogen (N_2), oxygen (O_2), and carbon dioxide (CO_2). Under atmospheric pressure, the dew point temperature of water vapor at atmospheric pressure is determined by the balance between the partial pressure of water vapor and the partial pressures of these non-condensable gases. Thus, the higher the partial pressure of water vapor, the higher the dew point temperature becomes, allowing hotter water to be recovered and improving the efficiency of latent heat recovery.

If no non-condensable gases were present, the dew point temperature of water vapor at atmospheric pressure would rise to 100°C, allowing the latent heat of condensation to be recovered with high efficiency. For reference, in thermal power plants, the steam used to drive turbines is 100% pure steam free of non-condensable gases. When this steam is cooled to 100°C or lower in a condenser, the pressure drops below atmospheric pressure (creating a vacuum), which reduces the back pressure on the steam turbine and is effectively utilized to improve power generation efficiency.

Based on the above, to raise the dew point temperature, it is essential to thoroughly reduce both the amount of infiltration air into the Pr-sand dryer, as shown in **Fig. 4**, and the excess air used for burner combustion, so that the partial pressures of non-condensable gases such as N_2, O_2, and CO_2 are lowered. Furthermore, it is a critical technical requirement that thermal energy be consumed solely for the evaporation of moisture in the sand, as will be discussed in detail in the next section, "**3.5 Residual Moisture in Dried Sand,**"

Regarding the reduction of burner combustion air, it is important to control the amount of combustion air according to the fuel combustion rate, taking into account temperature and pressure corrections, as air density fluctuates depending on these conditions. In this sand drying system, optimal low excess-air combustion by the burner is achieved through continuous feedback control of both fuel flow rate and combustion air flow rate. In conventional burners, it is common practice to adjust the air-to-fuel ratio based on summer conditions where the ambient temperature can vary by over 30°C between summer and winter. As a result, when ambient temperatures drop in winter, air density increases, leading to combustion under excess-air condition. A temperature difference of 30°C between summer and winter results in approximately a 10% increase in air density during winter, thereby increasing the amount of excess air by about 10%. As a result, the volume of exhaust gas increases, leading to a decrease in both thermal efficiency and the partial pressure of water vapor. Furthermore, utilizing preheated air for burner combustion, which raises the combustion temperature and reduces the volume of exhaust gases, is also an effective method for improving thermal efficiency and increasing the partial pressure of water vapor.

The infiltration air into the dryer is reduced by enhancing the sealing mechanisms at the sliding sections located before and after the dryer, thereby improving airtightness. In addition, the pressure difference between the internal pressure (static pressure) of the dryer and the ambient atmospheric pressure is minimized by static pressure control. A differential pressure gauge is installed on the bulkhead of the Pr-sand dryer, and the exhaust fan suction is feedback-controlled so that the pressure difference between the inside of the dryer and the outside air approaches zero.

By adopting the above technologies, the Pr-sand dryer in this sand drying system achieves a water vapor partial pressure of approximately 50% or higher in the exhaust gas, enabling the recovery of hot water at around 80°C in the condensation tower. In contrast, the water vapor partial pressure in the exhaust gas of a typical AP system is as low as 10 - 15%. This is because, in addition to air infiltration into the dryer, excess combustion air, and the evaporation of moisture, thermal energy is also required to heat the aggregates, and thereby combusting additional fuel to supply the required heat increases the volume of exhaust gases and lowers the water vapor partial pressure. In other words, during the drying and heating process of the aggregates, once moisture evaporation is complete, any further heating of the dried aggregates produces combustion exhaust gas with a constant amount of water vapor, while only the proportion of non-condensable gases such as N_2, O_2, and CO_2 continues to increase.

Specifically, when the amount of infiltration air into the dryer, the air-to-fuel ratio of the burner, and the water vapor released from the sand remain constant, the heating of dried aggregates (i.e., sensible heating without moisture evaporation) means that water vapor is present in the combustion exhaust gas solely as a result of the hydrogen content in the fossil fuel. Combustion air consists of approximately 79% nitrogen (N_2), which does not participate in the combustion reaction. When 1Nm^3 of methane (CH_4) is burned, it consumes 2Nm^3 of oxygen (O_2) from the air and produces 1Nm^3 of carbon dioxide (CO_2) and 2Nm^3 of water vapor (H_2O). In addition, 7.5Nm^3 of nitrogen (N_2), which remains unreacted, is included in the exhaust. As a result, the total volume of theoretical combustion exhaust gas is 10.5Nm^3, with CO_2 accounting for approximately 9.5% and water vapor for about 19%. Furthermore, when excess combustion air or infiltration air is added to this theoretical exhaust gas, the water vapor concentration (i.e., partial pressure) decreases even further.

3.5 Residual Moisture in Dried Sand

To improve the efficiency of latent heat recovery, it is essential to maximize the partial pressure of water vapor in the exhaust gas. As mentioned in the previous section, this requires reducing the concentration (partial pressure) of non-condensable gases by minimizing air infiltration and excess combustion air. Building on that, retaining some moisture in the sand during the drying process of this sand drying system plays a significant role in enhancing energy efficiency and improving operational performance. Specifically, instead of heating the sand above 100 °C to achieve a completely dry state as in AP systems, this system intentionally maintains a residual moisture content of approximately 5% in the dried sand discharged from the dryer. This approach is intended to achieve the following three effects, which are discussed below.

The first point, as mentioned in the previous section, is utilizing thermal energy solely for the evaporation of moisture. The partial pressure of water vapor in the exhaust gas increases as the water vapor evaporated from the sand becomes part of the exhaust gas. By retaining some moisture in the sand, the thermal energy supplied to the sand is balanced with the energy consumed for evaporation in the dryer, resulting in a constant-rate drying state without significant temperature change in the sand. In this way, by utilizing all the supplied thermal energy exclusively for moisture evaporation, the water vapor partial pressure in the exhaust gas can be raised.

However, when thermal energy is consumed to heat dry sand without any accompanying moisture evaporation, the water vapor partial pressure in the combustion gas depends on the type of fuel and the air-to-fuel ratio, and the resulting value is relatively low. This is because the water vapor partial pressure in the combustion gas generated by the burner is determined not by the amount of fuel burned, but by the type of fuel and the air ratio (i.e., the amount of excess combustion air). The type of fuel determines the water vapor partial pressure based on its carbon-to-hydrogen ratio, with natural gas which is composed primarily of methane producing the highest water vapor partial pressure among common fuels.

As mentioned in Section 3.1, both the Pr and Se sand dryers intentionally adopt a parallel-flow configuration, even though it offers lower thermal efficiency than the counter-flow method. This design choice is made to retain moisture in the sand at the discharge end of both dryers. At the discharge end, the temperature difference between the sand and the exhaust gas is smallest, and the humidity of the exhaust gas is highest. Accordingly, the evaporation of moisture from the sand becomes slower, and controlling the residual moisture becomes easier compared to the counter-flow configuration.

The second point is exposure of the sand discharged from the dryer to ambient air, which leads to evaporation of the residual moisture and lowering the sand temperature to the wet-bulb temperature lower than the ambient air temperature. For example, assuming the specific heat of sand is 0.837 kJ/kg·°C and the latent heat of water evaporation is 2.629 MJ/kg, the thermal energy corresponding to a 30°C change in the sensible heat of the sand (30°C × 0.837 kJ/kg·°C = 25.116 kJ/kg) is roughly equivalent to the latent heat required to evaporate 1% moisture content (0.01 × 2.629 MJ/kg = 26.288 kJ/kg). This means that even if the sand temperature inside the dryer is higher than the ambient air temperature under constant-rate drying, exposing it to dry ambient air allows the residual moisture to evaporate quickly. The latent heat consumed in this evaporation process leads to a reduction in moisture content and simultaneously cools the sand down to the ambient wet-bulb temperature. For instance, if the ambient air is at 15°C with 50% relative humidity, the wet-bulb temperature is approximately 10°C. Thus, the sand can use its stored sensible heat to evaporate moisture and lower its own temperature accordingly. In contrast, if dry sand is discharged from the dryer at a temperature higher than the ambient air and no moisture remains, it will simply dissipate heat until it reaches ambient temperature, resulting in wasted thermal energy.

The third point is controlling the residual moisture content of sand to around 5%, which is effective as a dust control measure. Aggregates that include sand used as a raw material for asphalt mixtures are commonly transported using equipment such as wheel loaders, dump trucks, and belt conveyors. Dust is often generated during loading onto dump trucks or at transfer points of belt conveyors. Therefore, retaining some moisture in the sand helps reduce environmental impact, including improving the workplace environment.

As described above, by controlling the residual moisture in sand discharged from the dryer to around 5%, several benefits can be expected: increasing the partial pressure of water vapor in the exhaust gas, reducing residual moisture by consuming the sensible heat of the sand for evaporation, and achieving effective dust control. Furthermore, although rain protection is required, dried sand can be stored for long periods, enabling continuous operation of the sand drying system without being constrained by the operation schedule of APs.

4. Business Model of the Sand Drying System and Effects

4.1 Macroscopic Perspective

As mentioned in Chapter 1, according to statistics from the Japan Asphalt Mixture Association (a general incorporated association), the national production volume

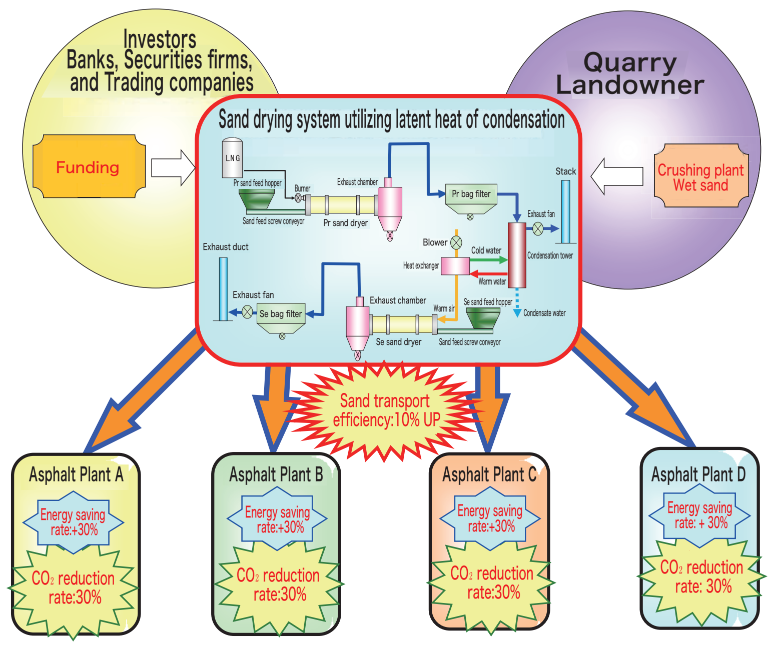

Figure8 Sand Drying Business Model[1)]

of asphalt mixture has decreased by half from its peak during the economic bubble period and has since remained around 38 million tons annually[1)]. On the other hand, in road replacement projects, waste asphalt concrete—commonly referred to in Japan as Ascon-gara—generated from the removal of deteriorated asphalt pavement is designated as a specified construction waste under the Construction Recycling Act. Moreover, Ascon-gara that meets certain criteria is required to be recycled under this law. According to fiscal year 2022 statistics from the Ministry of Land, Infrastructure, Transport and Tourism (MLIT), the total annual generation of Ascon-gara amounts to approximately 21.28 million tons. Of this amount, about 15 million tons, which is roughly 70%, is reused as recycled asphalt mixture (R-mixture), while the remaining 6.3 million tons are effectively used as roadbed material. In this way, the recycling rate of Ascon-gara has remained stable over 99.5% in recent years, making it one of the construction resources most consistent with effective resource utilization and the realization of a recycling-oriented society[18)].

Accordingly, R-mixture can be estimated to account for just over 39% of the total asphalt mixture production (15 million tons out of 38 million tons). Assuming this estimate, if we shift our focus to virgin aggregates, it is inferred that approximately 23 million tons, or 61% of the annual asphalt mixture production of 38 million tons, account for virgin aggregates. Of this amount, about 30% is estimated to be fine aggregate, i.e., sand, which totals approximately 6.9 million tons.

According to statistical data from the Ministry of Economy, Trade and Industry, there are approximately 2,400 crushed stone plants nationwide, supplying aggregates for concrete and asphalt mixtures. The total production volume reaches 160 million tons[19)]. In particular, natural river sand and sea sand have become extremely difficult to procure due to environmental protection concerns, and crushed sand artificially produced at these plants has become the mainstream. These sands have a large specific surface area and therefore retain a high moisture content. In addition, the primary reason for the high moisture content is that silt and clay are removed by washing to ensure the required quality. As the moisture content of these sands is between 12 and 15%, it is estimated that APs consume fossil fuels to remove 828,000 to 1,035,000 tons of water on a macro scale. Furthermore, assuming a thermal efficiency of 80% for APs, about 0.1 liters of A fuel oil (heavy oil A) is consumed and 0.25 kg of CO_2 is emitted to evaporate every 1 kg of water. Thus, it is calculated that, on a macro scale, 828,00 to 103,500 kiloliters of heavy oil A are consumed, resulting in CO_2 emissions of 207,000 to 259,000 tons.

4.2 Business Model

As a means to overcome the barriers to energy conservation and CO_2 reduction at APs, that is, the "**limits**

Table1 Comparison of Energy Saving and CO_2 Reduction Effects

Method	Conventional System	New Sand Drying System
Sand drying capacity – Primary dryer	50.0 t/h	30.0 t/t
Sand drying capacity – Secondary dryer	-	20.0 t/h
Total sand drying capacity *with 10% moisture reduction	50.0 t/h	50.0 t/h
Fuel consumption	471.3 Nm³/h	250.8 Nm³/h
Overall thermal efficiency *based on LHV	80.0 %	150.6 %
Energy-saving rate *compared to benchmark	0 %	88 %
CO_2 emissions from fuel	923.7 kg/h	491.6 kg/h
CO_2 emissions from electricity	35.0 kg/h	80.0 kg/h
Total CO_2 emissions	958.7 kg/h	571.6 kg/h
CO_2 reduction rate *compared to benchmark	0 %	40 %

of energy efficiency improvements" and the "**limits of operating rate improvements,**" a new business model is being considered. This model involves introducing the previously discussed sand drying system into crushed stone plants, which are part of the sand supply chain, to produce dried sand and supply it to multiple APs.

For example, as shown in **Figure 8**[1], installing the sand drying system within a crushed stone plant allows for stable and continuous operation unaffected by the intermittent operation of APs, thereby improving productivity. Furthermore, as described above, effectively utilizing the latent heat of condensation of water vapor in the exhaust gases for sand drying allows for significant energy savings and CO_2 reduction. In addition, with respect to the transportation efficiency of supplying dried sand from crushed stone plants to multiple APs, removing 10% moisture directly improves dump truck transport efficiency by 10%, which is expected to synergistically contribute to both productivity and CO_2 reduction.

As a concrete business model for the sand drying system, the systems capable of producing 300,000 tons of dried sand annually can be installed at 10 crushed stone plants nationwide. Each system would be configured to reduce the moisture content by 10%, operate 6,000 hours per year, have a drying capacity of 50 tons per hour, achieve a CO_2 reduction of 4,000 tons per year, reach a thermal efficiency of 150% (LHV basis), and reduce fuel consumption equivalent to 1,400 kiloliters of heavy oil. Through this initiative, the total annual production of dried sand would reach 3 million tons, resulting in a CO_2 reduction of 40,000 tons per year and a fuel savings of 14,000 kiloliters (economic viability) due to improved energy efficiency, thereby achieving economic viability.

Furthermore, by producing 3 million tons of dried sand with a 10% reduction in moisture content per year with this sand drying system, it is expected that the transport efficiency of the approximately 300,000 dump trucks involved in delivering the sand can be improved by 10%. In other words, conventionally, the equivalent of 30,000 dump trucks (300,000 tons) were being used to transport excess water. With the moisture removed, an additional 300,000 tons of sand can be transported instead. Assuming a dump truck fuel efficiency of 3.0 liters per kilometer and an average transport distance of 20 km per truck, the diesel fuel saved would be: 3.0 L/km × 20 km/truck × 30,000 trucks/year = 1,800 kiloliters/year. Using a CO_2 emission factor of 2.6 kg-CO_2 per liter of diesel, the annual CO_2 reduction is estimated at: 1,800 kL/year × 2.6 kg-CO_2/L = 4,680 tons-CO_2/year. Technically, this sand drying system can be installed at individual APs to pre-dry the aggregates. However, it is extremely difficult to achieve economic viability in such configurations due to the low partial pressure of water vapor (10–15%) in exhaust gas at APs, the low dew point (around 50–60°C), and warm air of about 40–50°C after heat exchange with ambient air. In addition, the annual operating hours of APs are extremely low (approximately 1,000–1,500 hours/year) and often involve intermittent operation.

Therefore, instead of installing the sand drying system at each AP, a configuration could optimize both economic viability and environmental compatibility, where the sand drying system is installed at a quarry located upstream in the aggregate supply chain to operate for up to 6,000 hours per year.

As described above, by supplying dried sand produced by the sand drying system to APs that have extremely low operating rates and offer little room for further energy efficiency improvements, it becomes possible to greatly enhance the effects of energy savings and CO_2 reduction—by nearly 30%—without the need for additional facility investments to improve the operating rates or energy efficiency of the APs.

4.3 Improving Operating Rates

APs often operate intermittently due to mismatches between their production capacity and the volume or timing of asphalt mixture shipments. A significant amount of thermal energy is consumed during startup preheating, resulting in substantial CO_2 emissions. Preheating is an essential process to prevent the condensation of water vapor inside components such as the dryer, flue, and bag filter, suppress corrosion, and promote the rapid stabilization of the heated aggregate temperature. As this intermittent operation of APs is carried out repeatedly, it is undeniable that the thermal energy stored in the dryer and bag filter is released unnecessarily into the atmosphere. Intermittent operation at APs is largely attributed to the need to complete paving work within the limited time during which the temperature of the asphalt mixture does not drop. To support this requirement, APs have been distributed throughout the country. Furthermore, in response to demand for shorter loading times into dump trucks, APs have been scaled up to increase production capacity and provide instantaneous output capacity. As noted in **Chapter 2**, these factors have significantly contributed to lowering the operating rates of APs.

Accordingly, even in the drying of sand, which has the highest moisture content among aggregates and consumes the most energy, the process is being carried out at APs that operate at extremely low rates under conventional systems. No matter how high the thermal efficiency may be during steady-state operation (exceeding 85%), the frequent use of intermittent operation inevitably leads to significant energy loss, substantially impairing the overall thermal efficiency.

To break away from this situation, the focus has shifted to separating the drying of high-moisture-content sand from the APs and instead drying the sand independently within the supply chain. By producing dried sand that retains a small amount of moisture, the sensible heat of the sand is used to evaporate the remaining moisture, causing the sand temperature to drop to the wet-bulb temperature, which is lower than the outside air temperature. Based on this principle, energy loss due to the dissipation of sensible heat is reduced, and although protection from rain is necessary, long-term storage and long-distance transportation of the dried sand become feasible.

As described above, by removing the factors that hinder improved operating rates, continuous operation of the sand drying system becomes possible. As a result, the sand drying process, which consumes the most energy, can be carried out without being affected by the intermittent operation of APs, thereby avoiding energy losses and productivity declines associated with such intermittent use.

Furthermore, supplying the dried sand produced by the sand drying system to multiple APs allows for indirectly achieving energy savings and CO_2 reductions even during off-peak seasons when asphalt production volume is low and APs frequently operate intermittently.

4.4 Energy Saving and CO_2 Reduction

As previously mentioned, it is necessary to incorporate the sand drying system into the sand supply chain in order to confront the "**limits of energy efficiency improvements**" and "**limits of operating rate improvements**" at APs.

Regarding energy saving, the approach focuses on recovering the latent heat of water vapor from exhaust gases. This is an area that conventional AP technologies have not addressed due to constraints such as economic viability, legal regulations, social norms, and conventional thinking. As stated earlier, to increase the partial pressure of water vapor in the exhaust gas and enhance the efficiency of latent heat recovery, the system specializes in drying sand with high moisture content while strictly managing combustion air and infiltration air to reduce the partial pressure of non-condensable gases. Furthermore, to eliminate energy loss from heat dissipation of the dried sand, the system dries the sand while leaving a small amount of residual moisture. As a result, most of the thermal energy supplied to the sand is consumed for water evaporation. The recovered latent heat of the water vapor is then transferred to ambient air, which serves as a new heat medium, to generate warm air that is reused for subsequent sand drying.

Table 1 presents a comparison between the conventional system (used as a benchmark) and the sand drying system. In this comparison, the sand drying capacity is set at 50 tons per hour, a reduction in moisture content of 10%, and the benchmark thermal efficiency at 80%. According to the table, in terms of energy savings, the sand drying system achieves a thermal efficiency of 150% (LHV), which is a 70% increase over the benchmark. This improvement is attributed to the recovery of water vapor generated in the Pr-sand dryer, which is used to produce warm air for drying incoming sand in the Se sand dryer. In other words, the system is able to dry 20 tons of sand per hour using the amount of fuel (thermal energy) that would be required to reduce the moisture content of 30 tons of sand per hour by 10%.

Next, regarding the CO_2 reduction effect of the sand drying system, it achieves a 40% CO_2 reduction relative to the benchmark system. Additionally, **Table 1** shows the CO_2 emissions for all systems when LNG is used as the fuel. When comparing emissions using heavy oil A, which is most commonly used at APs, the benchmark system achieves a 19% CO_2 reduction, while the sand drying system achieves an impressive 52% reduction.

5. Conclusion

Until the Industrial Revolution, which began in Britain around 1750 in the mid-18th century, humanity primarily used biomass fuels such as firewood. The productivity was not high compared to today's standards. However, human activity remained in harmony with nature, following a localized, self-sufficient production model that used only the necessary amount of resources when needed. Consequently, it is known that the atmospheric CO_2 concentration remained balanced at around 280 ppm.

Eventually, following the Industrial Revolution and the widespread adoption of steam engines, humanity depleted domestic forest resources used as fuel and developed technologies to efficiently utilize fossil fuels such as coal, which had previously been difficult to mine and burn. Compared to firewood, coal has a significantly higher energy density, and its use as a fuel led to a rapid acceleration of industrial activity, accompanied by a sharp increase in CO_2 emissions. Furthermore, the start of industrial ammonia production through the Haber-Bosch process in 1906 enabled a significant rise in the production of chemical fertilizers, and the global food supply conditions were greatly improved. The resulting population explosion from less than 1 billion in 1800 to 8 billion by the year 2000 can also be cited as a factor contributing to the increase in atmospheric CO_2 concentration.

Furthermore, compounding the situation, the two World Wars from 1914 to 1918 and from 1939 to 1945 accelerated the exploration and development of oil fields by major oil companies in pursuit of petroleum—a more convenient, high-energy-density, and inexpensive liquid fuel. As the development of petroleum-based products and petrochemicals advanced, they came to be used in great quantities, like water, as people in a handful of developed countries pursued increasingly prosperous lifestyles. They continued to embrace an era of mass production, mass consumption, and mass disposal, which ultimately drove atmospheric CO_2 concentration up to 420 ppm. As a result, we are facing the harmful effects of global warming, including extreme weather events and the extinction of species due to ecological disruptions. The Intergovernmental Panel on Climate Change (IPCC) has warned that if humanity continues to consume fossil fuels at the current pace and pursue economic growth without change, the atmospheric CO_2 concentration could exceed 800 ppm by the end of this century, and the Earth's average temperature could rise by 4.8°C. In addition, plastic waste—a petroleum-derived product—has begun to flow into the oceans and break down into microplastics, which are affecting ecosystems and becoming a global environmental issue.

Japan, lacking domestic energy resources, experienced two oil crises following its period of rapid economic growth, in 1973 and 1979. These oil crises triggered a sweeping wave of energy conservation efforts aimed at mitigating the impact of crude oil prices, which had surged more than tenfold. Notably, the progress made in energy efficiency within the industrial sector was remarkable. In industries such as steel and glass, productivity has increased without a corresponding rise in energy consumption. Such nationwide efforts to promote energy conservation have led Japan to achieve the lowest level of energy consumption relative to GDP among developed countries.

Similarly, asphalt plants (APs) are also actively adopting new energy-saving technologies in pursuit of both economic efficiency and the reduction of CO_2 emissions. As a manufacturer of AP systems, our company aims to remain responsive to changes in the global environment, social trends, and economic conditions, while also committing to the timely development of new technologies and fostering a culture and mindset that enable us to proactively make proposals to our customers.

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