

Comprehensive Utilization of Coal Ash in China

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Abstract From the perspective of environmental protection and sustainable energy development, this paper seeks to introduce the output of coal ash, its physical and chemical characteristics, new techniques and methods of comprehensive utilization in China. Coal ash is mainly used in the fields of building materials, road engineering, construction engineering, agricultural application, environmental protection, fine chemical engineering, resources recycling, etc.

Key words coal ash; comprehensive utilization; China

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中国粉煤灰的综合利用

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摘要: 从环境保护和能源可持续发展的角度, 介绍了中国粉煤灰的产量、物理性质和化学性质、综合利用的新技术和新方法。粉煤灰主要被用于建筑材料、道路工程、建设工程、农业应用、环境保护、精细化工、资源回收等方面。

关键词: 粉煤灰; 综合利用; 中国

1 Preface

China is a developing country dependent upon coal for its main energy resource. Coal constitutes 76% among the primary energy consumption, which makes up twice higher than that of the world average consumption level. By statistics, the generation of thermoelectricity and the related production in China consumes annually about 600 million tons of raw coal, which constitutes one third of its raw coal yield. The quantity of coal ash, as a by-product, exhausted coal-fired electric power plant amounts to 180 million tons^[1]. To generate electricity with coal is still the trend of electric industry in China in the long period. The ratio of utilization of coal ash is very low. The utilization ratio of coal ash most areas is only about 30%, and in a few areas, such as Shanghai, it can amount to 60%^[2]. The accumulation of coal ash has reached more than 1 250 million tons by the end of 2000. These coal ash occupies a room of about 500-625 thousand mu^[3]. Every ten thousand tons coal ash requires 4-5 mu on average. The coal ash not only takes up a great deal of farmlands, but also will fly into the air with the wind and flow into the river with the rain. As a result, it will pollute the environment and do harm to the health of human being. Therefore, the comprehensive utilization and valid management of coal ash is of great social and economic significance.

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2 Chemical and physical characteristics of coal ash

2.1 Chemical Characteristics

Coal ash is a kind of clay volcanic ash material exhausted in the process of the combustion of coal. Observed under microscope, coal ash is a mixture with complex structure, which is made up of crystallate vitreous materials and small amount carbon which is not fully burned. Its chemical compositions have relation to such factors as the types of coal, producing area and the structure of furnace. The main oxides contained in coal ash are SiO_2 , Al_2O_3 , $\text{Fe}_2\text{O}_3 + \text{FeO}$, CaO , MgO , SO_3 , Na_2O , K_2O , TiO_2 , MnO , P_2O_5 , and others are also found^[4]. Among them SiO_2 , Al_2O_3 and TiO_2 come from the clay and shale; Fe_2O_3 and FeO mainly comes from pyrite; CaO and MgO come from the carbonate and vitriol. Its main chemical compositions are listed in Tab 1^[5].

It can be seen from the table that the main compositions of the coal ash are silicon oxide, aluminum oxide and iron oxide, which amount to 85% of the coal ash. The percentage of the calcium oxide is low in low calcium coal, thus the coal ash from low calcium coal has no self-hardening on the whole. But in China, what is increasingly

exhausted is high calcium ash. High calcium ash contains some self-hardening mineral and helps enhance the strength of coal ash products. Moreover, with the continuous raise of the capacity of boiler, coal combustion inside the stove tends to be complete, which means that the loss on ignition will become lower and lower. So the coal ash is a kind of very pure building material after it is burned at a high temperature.

2.2 Physical Characteristics

The inorganic matters of coal powder goes through the four processes of resolving, fritting, diatexis and cooling when it is burned in a boiler. Cooling grains of the coal ash consist mainly of silica-alumina vitreous materials and a little amount of carbon grains. The vitreous materials are composed of single beads, continuous beads and irregular spongy aggregate. The quality of coal ash is mainly decided by the size of the grains and the proportion of the grains with different shape. By statistics, the basic physical properties of coal ash from 68 thermal power plants in China are listed in Tab 2^[6].

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3 Main uses of coal ash and the applying technology

In China, the study of comprehensive utilization of coal ash started in 1950s. Those studies focused mainly on the application and development of cement and concrete, which have been widely applied in construction engineering. China has accumulated a great many of experiences through decades' practice, and construction engineering has become a big market of coal ash consumption. For example, it is estimated that the amount of coal

Tab 1 Chemical composition of coal ash

Composition	Contents/%	composition	Contents/%
SiO_2	38-54	MgO	0.5-4
Al_2O_3	23-38	SO_3	0.1-1.2
Fe_2O_3	4-6	Na_2O	0.3-0.6
CaO	3-10	K_2O	1-1.3

Tab 2 Basic physical properties of coal ash in China

Item	Mean value
Density	2.1 g/cm ³
Stacking density	780 g/cm ³
Compactedness	36.5 g/cm ³
Specific surface area	Oxygen adsorptive process 34 000 cm ² /g
	3 300 cm ² /g
Standard consistence of raw ash	Ventilated method 48.0%
Compression strength ratio (28 d)	66%
Fineness	> 80 mm
	23.9%
	45-80 mm
	< 45 mm
Need the amount of water	106%

ash consume the Sanxia project amount to 1338 thousand tons. Coal ash was also widely used in the construction of the highways of Hu-Ning, Jing-Shen and Jing-Ji. It has been proved that a great deal of energy will be saved if coal ash resources are reasonably used. The energy departments of many countries therefore encourage and support the circularly application of coal ash resources and give impetus to the research and application of coal ash. In the recent years with the development of the advocacy of environmental protection, the treatment and utilization of coal ash is related closely to environmental protection. As a solid waste, coal ash should be reduced in quantity in the process of production, and be recycled in the process of waste treatment. According to the quantity recycled and the level of technique applied, comprehensive utilization of coal ash falls into three divisions: (1) large quantity and low level of technique utilization, including backfill, dam construction, building filling, grouting, road construction and soil improving, etc; (2) medium quantity and medium level of technique utilization, which refers mainly to the uses of coal ash as building material, including being used as cement substitute, concrete admixture in brickwork, brick and wallboard, and also as plastics and rubber filler, floccules, asphalt mixture filler, etc; (3) small quantity and high technique utilization, wherein high-new techniques which will produce high profit are applied, such as being used in separating metals and minerals and in the production of heat preservation and heat-resistant materials, etc. In China, the current study of the application of coal ash covers the following fields:

3.1 Used as concrete admixture

Coal ash used as concrete mixture can economize the cement, lower the production cost and construction costs, enhance final-period strength of the concrete, the anti-permeability and the ability of anti-chemistry erosion, improve the mixing of concrete so as to let it easy to be carried through pump-poured and vibrated, can reduce the negative influence of alkali aggregate reaction, lower heat of hydration of the cement and repress the occurrence and development of temperature crack, and enhance the stability of the cement by combining with the free calcium oxide in the cement^[7].

Coal ash is mainly used in various concrete in construction project. Many researches about coal ash mixed in concrete of large volume have been done. Sun Jiashun et al. have launched the research about the optimization and application of coal ash of different quality in San Xia construction project^[8]. Shumao Gui based on the constructions of the box foundation of Henan International Trade Center and the pile foundation of Henan Insurance Building has studied influence that coal ash produces on the internal temperature in the base of construction wherein concrete is used in large volume. A law has been found that the temperature rises quickly but declines slowly, and the temperature rises and drops irregularly after the concrete is filled into the mold, which continues for 3.5-5.0 days. In this period, the temperature keeps changing for many times before it becomes stable, and then it will not change irregularly but decline slowly until it reaches the common degree. Compared with that of pure concrete, the temperature of concrete mixed with coal ash rises less. According to the temperature in pure concrete, it is estimated that the temperature in these construction will reach more than 50 degree centigrade, but it is actually 39-40 degrees centigrade, it is lowered by 10-20 degree centigrade.

Many researches on the compound of high strength concrete with coal ash. Jing Yang et al. have systematically studied the influence that coal ash produces on the strength of high-performance concrete.^[9] The study indicates that: First, coal ash has little influence on the strength of concrete when the glue ratio is low; when the glue ratio is less than 0.35, the strength ratio of sand-cement mixed with 30% coal ash (compared with its strength when there is no coal ash mixed under the same condition) can reach 0.95 or more; the processing property and the structure density of the concrete can be greatly improved, and the heat of hydration can also be lowered. Second, coal ashes of different kinds have different influence on the strength of high performance concrete, but the influence is not obvious between the high-quality coal ash and the senior grade coal ash. Third,

the strength of the concrete somewhat descends with the increase of the quantity of coal ash mixed when the quantity of coal ash ranges from 30% to 50%, but the influence of the water-cement ratio is obvious. When the water-cement ratio is properly declined on the premise that the mobility is guaranteed, even if second class coal ash is added to 50%, the 60 days strength of the concrete can also attain more than 60 MPa. Finally, the strength of high performance concrete mixed with coal ash tends to increase with time.

3.2 Application of coal ash in the production of cement

The main chemical composition of coal ash is similar to that of clay, therefore, coal ash can take the place of clay to be used to compound the raw material of cement. With cement adopts coal ash as raw material, it can make use of the carbon which is not entirely exhausted. It is proved that to replace clay with coal ash as raw material can increase the yield of cement kiln. At the same time, it can also lower fuel consumption by 16% - 17%. According to the statistics, it can economize 120 thousand tons fuels when 1 million ton coal ash is added.

Although coal ash itself doesn't harden after water is added, it can cause chemical reaction with alkaline exciting agents, such as lime and clinker of cement, and generate compound which has water hardening and getting property. Therefore, coal ash can be used to as active mixed material of cement.

The chemical and mineral composition of some coal ash is fit to produce special cement, such as shale ash which has higher calcium oxide. Shale cement can be produced when 30% or so shale ash is added to clinker of cement. The property of shale cement is similar to that of portland slag cement.

3.3 Application of coal ash in road construction

The main composition of coal ash is basically the same as that of the main materials of cement, but its cost is lower. To substitute coal ash for part of the cement in the construction of cement concrete pavement, can not only lower the cost, but also help to lower the initial collapse degree of the concrete, to prolong the initial setting time, and reduce the collapse loss in the process of transportation. It can also lower heat of hydration and the temperature of concrete, reduce the constringency crack of the pavement, improve the compression strength and bending strength of the pavement, and enhance the abrasability of the pavement^[10].

It is more advantageous to use lime and coal ash stable soil (two dusts soil) than to use traditional material in the construction of Subcrust. The research which Yingxin Yang has done based on the construction of subcrust of Zhong-Chuan highways in Gansu Province indicates that: First, the strength of two dusts soil of coal ash and lime compound increases with time, and the long-term strength grows quickly. When the ratio of lime is 8%, coal ash 24%, compactedness 93%, the compression strength of 7 days is 0.685 MPa, but the compression strength of 28 days is 5.75 times of that of 7 days, and 180 days is 9.32 times of 7 days. Second, the strength of two dusts soil increases with the increase of the quantity of lime and coal ash, and also with time. Third, different compactedness have more influence to the strength of two dusts soil, and the strength will increase or decrease when compactedness increases or decreases. Finally, strength of roadbed is high as a whole, the stability of the water is good, the compressibility is small, the ability scattering load is strong, and to a certain extent, the desiccation fissures and lukewarm shrinkage fissures that appear in the initial period can self-coalesce.

The process is simple to use coal ash to build road and the cost is small, and the technique is mature. In the recent years, the scope of the application of coal ash has grown been continuously wide in the construction of municipal facilities. Coal ash is used in the construction of highway, as well as in the building of bridge, slope protection, leading road and airport runway, including Shanghai Cui song and Hu jia highways, the fifth highways around Beijing city, Yellow Sea Bridge in Xiamen, Huangpu River tunnel and the like. Coal ash is used in all of these projects. The technique is getting more and more mature, and the economic benefit is good^[11].

To fill the humpback of the structure with some second-level or third-level coal ash, on the one hand, can reduce the pressure of the embankment on the ground and the bridge abutment. On the other hand, second-

– level or third– level coal ash has certain strength themselves. Therefore, it will not contract and settle under the upper load and dead– weight, preventing the bridgehead embankment from settlement.

3.4 Application of coal ash in ceramic production

Ceramic is made of clay or mixture containing clay through the process of molding, drying and roasting. The ceramic products made of coal ash include clay and coal ash brick, coal ash ceramics tile, coal ash wall brick and floor tile. Among them, clay and coal ash brick is made with coal ash and clay as raw material in which coal ash takes up 30% – 70%. The SO_2 in the coal ash used to make such brick is allowed no more than 70%, otherwise both the plasticity and the anti– break strength will turn lower. Moreover, as far as the strength and the range of roasting temperature are concerned, the proper percentage of Al_2O_3 is 15% – 25%, Fe_2O_3 5% – 10%, and MgO and sulfide are the less the better. Coal ash ceramics tile is a kind of light aggregate made with coal ash as raw material, mixed with certain amount of cementitious material and water through the process of balling and firing. It is a kind of artificial light aggregate with good properties. It needs a large quantity of coal ash and the coal ash used can amount to 80%. Moreover, it can make full use of the heat in coal ash. Currently, dry pressing is the method widely used in the production of coal ash wall brick and floor tile, in which coal ash takes about 30% – 50%. The size of the productions is small, seldom bigger than $300\text{mm} \times 300\text{mm}$. To produce pottery with the substitute of coal ash for clay can economize energy and soil. Besides, its property is better than that of those which made of pure clay. Therefore, the prospect of making pottery with coal ash added is good^[12].

3.5 Application of coal ash in agriculture

The application of coal ash in agriculture is distinguished for low investment, large quantity, stable needs and great potential. It is a comprehensive application that is important and appropriate in China under the contemporary condition. The studies on the application of coal ash in agriculture focus on its effect on improving and fertilizing the soil. Although the silicon in coal ash can't be absorbed directly by crops, SO_2 , $Mg(OH)_2$ and KOH can turn into compound by heating at a temperature of 900°C . The elements in this compound, such as silicon, magnesium, potassium etc., can be easily absorbed by the crops, so coal ash can be made into fertilizer through some process. Coal ash is mainly made up of fine breeze which takes about 80%. Therefore, coal ash can be used to improve the property of soil. Moreover, coal ash magnetic fertilizer has an obvious function of increasing the yield of crops. With coal ash as a carrier and mixing valid nutrient, coal ash magnetic fertilizer has a special magnetic effect. This fertilizer has abundant nutrition which is easy to be absorbed by crops. It raises the utilization effect of chemical fertilizer.

The main grain of coal ash is thick grain ($0.25 - 0.01\text{mm}$) and fine grain ($0.005 - 0.001\text{mm}$). In fact, coal ash is similar to sandy ban, and they are the same in their performance of holding water. Moisture is held not only in the capillary of between the grains, but also in the holes of the tattered grains and in the alveolate pores. With the decisive structure of grain, compared with the water held in soil, the water held in coal ash is easier to be absorbed by crops. So, by adding coal ash, the quality of the soil can be improved, and its physical and chemical property, such as unit weight, density, porosity, air permeability, penetration coefficient and PH value (potential of hydrogen) also get improvement, which leads to the increase of yield of crops. The effect is obvious if coal ash is used to improve cohesive soil and acid soil. The output increases by 10% – 20% if each mu farmland has 15– 30 tons coal ash added.

3.6 Application of coal ash in the waste water treatment

The aluminum and iron in coal ash are disassociated to inorganic coagulant under an acid condition. When coal ash is mixed with water, the aluminum ion and iron ion will flocculate suspended particles in the water and subside together as combination. As a result, it completes the separation of the pollutant and the suspended matter from the water, which makes water become clear and transparent in the end. At the same time, as having been

produced through burning at high temperature, coal ash has activity and the process of forming coal ash is similar to forming active carbon. Therefore, their specific surface area is of the same size, which amounts to 2700–3500 m^2/g . So the coal ash has the same function as that of active carbon to adsorb suspended matter, take off the colored matter, lower the chrominance, and adsorb and remove the consuming oxygen substance in the waste water. Lisheng Zheng et al. have done a research and found out that when coal ash is used to purify the water containing chromium, the Cr^{3+} are reduce by 99%^[13]. At the same time, some experts have found out that coal ash can produce good effect in the treatment of domestic sewage, wastewater from paper mill and tannery. It is obvious that coal ash can be used to treat sewage, treating waste with waste. Thus we can use the resources comprehensively. It is a valid method to utilize coal ash, the technique is simple and the cost is low.

3.7 Application of coal ash in building industry

The new technology about coal ash is now applied in the building industry in China in three divisions: to make slab foundation, to make small hollow brick and used in “frame and concrete” construction^[14].

3.7.1 Coal ash slab foundation

Coal ash slab foundation is a kind of stiffness mat foundation. It is applicable on uniform soft base and is used to replace reinforced concrete slab foundation and pile foundation. One of its characteristics is that it has high rigidity and can pass evenly the load from upper wall and pillar to the base. Second, its density is small and it can enhance bearing capacity. Third, it has solidification and is not easy to be wet. Fourth, its cost is lower than reinforced concrete slab foundation. Finally, its strength can enhance with chemical reaction between coal ash and water. Therefore, the durability of coal ash slab foundation is good.

3.7.2 Small-sized hollow block

Small-sized hollow block is made of the aggregate which include coal ash, cement, cohesive material, excimer and water etc. It is made through the process where in these substances are mixed in a puddle maker to be hard and dry clinker, which is carried by a belt conveyer to the make-up machine, and the block comes into being. This kind of block is light and hard, and can needs a lot of dust, which takes 80% of the whole. The block can be cut and chiseled easily.

3.7.3 Frame and concrete construction

A frame and concrete construction is a compound structure where in homeotic pillar frame is the main bearing structure, and walls are built with coal ash small-sized hollow brick, working together with the homeotic pillar frame as a support against the force of quake. With such system, we make good use of the ductility of the frame and the ability of the wall to work against earthquake. Thus the earthquake resistant behavior of building is well improved. Besides, the flexibility to reshape and decorate a house is improved, too. It reduces the possibility of the settlement of buildings. This construction has been in use for several years in China, and problems and faultiness have never been found.

3.7.4 Other applications in building industry

Coal ash is also used to make the following construction materials. First, coal ash is used to make micro-lite glass. Compared with common micro-lite glass, this kind of micro-lite glass has not only high strength and hardness, but also is able to bear corrosion of 99.8% H_2SO_4 and 35% NaOH , and its abrasion resistance is several times higher than that of common micro-lite glass. Second, coal ash is used to make mineral cotton. When coal ash is mixed with limestone and other substances, we can make mineral cotton which is a wide-used building material. Third, coal ash can be used to prolong the life of glass fiber cement. When 40% coal ash is added to the cement, coal ash will consume the $\text{Ca}(\text{OH})_2$ produced in the hydration process of cement, so the erosion that the $\text{Ca}(\text{OH})_2$ produces on the glass fiber is reduced. Fourth, coal ash can be used as filler of gypsum products. Coal ash is substitute for part of gypsum, and can work as setting accelerator of gypsum. The waterproof property

of the gypsum products can be improved too. Finally, coal ash can be used as asphalt filling material to make waterproof asphalt felt. In 1987, waterproof asphalt felt was made with coal ash as a substitute for talcum powder in China. All quality indexes have reached the national standard. The outward appearance and the physical property of the new waterproof asphalt felt are the same as that of the traditional felt with talcum powder, but the cost is low^[15].

3.8 Application of coal ash as filling materials in mine

In China, the coal ash was initially used to fill mines in 1920s to prevent the possible underground fire. When the dry ash is used as goaf filling of coal mine, at the beginning, it is not so hard. But several weeks later, it becomes harder in a wet environment. Sixteen months later, even an explosion nearby can neither shake the filling body nor change the contractility. The filling body has held the roof hard. Later people mix coal ash with cobblestone to fill the goaf. It is not only hard, but also with good water-proof and sound-proof effect. With the further research on the property of coal ash, it is found out that it can also serve as a low-standard cement under the process of alkaline accelerator. Therefore, it can be used to replace a part of cement as gelling agent. From late 1980s, Jingchuan Company in China has made some research and come to the following conclusion. First, the way to add the coal ash and the quantity needed are determined by the aim and requirement itself. Coal ash can substitute for some cement and some fine aggregate if it is added to the filling materials. Second, coal ash added to filling slurry can be 50 times of the cement in datum slurry. Thus a good social and economic benefit can be obtained. For example, coal ash was successfully used to fill the collapse area of coal mine in Anhui province. Otherwise, more coal ash can be used to fill the hollow left by the brickfield after the brick clay is used^[16].

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