CHALLENGES TO INCREASED USE OF COAL COMBUSTION PRODUCTS IN CHINA

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Abstract

Electricity accounts for much of the primary energy used in China, and more than three-quarter of the total electricity is generated by coal combustion. Coal burning combined with flue gas cleaning system generates large quantity of coal combustion products (CCPs), which has caused significant environmental and economic burden to the economy, ecology and society. Of great importance are thus different applications which contribute to the increased use of CCPs. This thesis looks at an overview of CCPs production and utilization all around the world and investigates current CCPs applications as well as potential technically sound and economically justified technologies. Results of this thesis show that CCPs utilization rate in different countries varies widely from 13% to 97%. Worldwide, a significant proportion of CCPs from the main producers, e.g. China, the United States and India, is still being disposed off, resulting in a low-level of overall utilization of these products. It is evident that the amount of CCPs produced substantially exceeds consumptions because of various existing obstacles and limitations. In order to formulate effective approaches, identifying challenges to increased use of CCPs is of great weight. The aim of this thesis is to analyze current and potential utilizations of CCPs and more specifically address factors that inhibit or promote the use of CCPs from coal-fired power plants in China.

Savings of natural resources, energy, emissions of pollutants, GHG emissions and useful land were found as the major incentives for CCPs utilization. In China, a ban of solid clay bricks was also found to be a very powerful measure to stimulate the development of other by-product based wall materials while saving useful land and protecting the environment. However, this strong support from the government has not been fully implemented, which seriously hampered CCPs uses. Results presented in this thesis also show that high transportation cost of low unit-value CCPs, competition from available natural materials and spatial variation in supply-demand poses three of the most important barriers to the increased use of CCPs in China. Industrial organizations with assistances from the government have shown to be of fundamental importance for formulating approaches to take in overcoming the barriers.

This thesis emphasized that transforming laboratory- and pilot-scale technologies into commercial productivity is of the highest priority for increased use of CCPs. A conceptual model of CCPs Eco-Industry Park (EIP) as a potential effective solution was proposed. Mutual economic and environmental benefits can be achieved through the collaboration between different industries in the CCPs EIP. And other feasible recommendations of initiatives from both the government and industries were also discussed.
Acknowledgment

First of all, I would like to extend my sincere gratitude to my supervisor, Dr. Joakim Krook, for his instructive advice and continuous support in this master’s thesis. He showed me different ways to map out a research strategy, identify research questions and the need to be persistent to accomplish objectives. Without his encouragement and constant guidance, I could not have finished this thesis. He has always been so patient to talk my ideas, to proofread, and make comments to help me think through my research problems. My sincere thanks are also given to Pro. Mats Eklund from whose lectures of Eco-Industry I benefited greatly. I would especially like to express my great appreciation to Swedish people who provide me a good opportunity to learn advanced knowledge in energy and environmental engineering.

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<th>Description</th>
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<tr>
<td>ACAA</td>
<td>American Coal Ash Association</td>
</tr>
<tr>
<td>ADAA</td>
<td>Ash Development Association of Australia</td>
</tr>
<tr>
<td>ASTM</td>
<td>American Society for Testing Materials</td>
</tr>
<tr>
<td>CCPs</td>
<td>Coal Combustion Products</td>
</tr>
<tr>
<td>CFB</td>
<td>Circulating Fluidized-Bed</td>
</tr>
<tr>
<td>CGOSC</td>
<td>China’s General Office of the State Council</td>
</tr>
<tr>
<td>CIRCA</td>
<td>Association of Canadian Industries Recycling Coal Ash</td>
</tr>
<tr>
<td>ECOBA</td>
<td>European Coal Combustion Products Association</td>
</tr>
<tr>
<td>EERC</td>
<td>US Energy and Environmental Research Center</td>
</tr>
<tr>
<td>EIP</td>
<td>Eco-Industry Park</td>
</tr>
<tr>
<td>ESP</td>
<td>Electrostatic Precipitator</td>
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<tr>
<td>FBC</td>
<td>Fluidized Bed Combustion</td>
</tr>
<tr>
<td>FF</td>
<td>Fabric Filter</td>
</tr>
<tr>
<td>FGD</td>
<td>Flue Gas Desulphurization</td>
</tr>
<tr>
<td>GB</td>
<td>National Standard of the People’s Republic of China</td>
</tr>
<tr>
<td>GHG</td>
<td>Green House Gas</td>
</tr>
<tr>
<td>HVFAC</td>
<td>High Volume Fly Ash Concrete</td>
</tr>
<tr>
<td>JCOAL</td>
<td>Japan Coal Energy Center</td>
</tr>
<tr>
<td>LOI</td>
<td>Loss of Ignition</td>
</tr>
<tr>
<td>NCASI</td>
<td>US National Council for Air and Stream Improvement</td>
</tr>
<tr>
<td>R&amp;D</td>
<td>Research and development</td>
</tr>
<tr>
<td>SDA</td>
<td>Spray Dryer Absorption</td>
</tr>
<tr>
<td>TFHRC</td>
<td>US Turner-Fairbank Highway Research Center</td>
</tr>
<tr>
<td>TIFAC</td>
<td>Technology Information, Forecasting and Assessment Council</td>
</tr>
<tr>
<td>TPY</td>
<td>Tonne per Year</td>
</tr>
<tr>
<td>USEPA</td>
<td>US Environmental Protection Agency</td>
</tr>
<tr>
<td>VAT</td>
<td>Value-Added Tax</td>
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</table>
1 Introduction

Coal is and continues to be one of the most important primary energy sources for countries all over the world. The worldwide coal reserves are estimated to be $8 \times 10^{12}$ tonnes with annual consumption of $5 \times 10^9$ tonnes (CIRCA, 2010), among which the majority is consumed by electric power utilities. Coal combustion products (CCPs) are the byproducts generated during the combustion of coal, combined with pollution control technologies, for the purpose of electricity generation. The estimates of current worldwide annual production of coal combustion products range from 500 million tonnes (Berg & Feuerborn, 2001) to 600 million tonnes (Ahmaruzzaman, 2010) with fly ash shared 75-80% (Ahmaruzzaman, 2010) of the total CCPs produced. Based on the statistics and forecasts the worldwide CCPs production has been increased steadily over the years and will keep on rise over the next decade.

China has abundant coal reserves and coal will remain the dominating energy source to produce power and steam for the industries in a long run. In 2003, the total power generation capacity in China has reached 391 GW of which coal constituting about 70% (Mukherjee et al., 2008). It is estimated that about 1.1 billion tonnes coal is consumed by the power industries and over 200 million tonnes of fly ash are produced annually in China (Liu, 2009), which makes the country the largest CCPs producer in the world. It is anticipated that this figure will gradually increase in the years to come. The amount of cumulated fly ash by far was about 2.2 billion tonnes, which have covered 300 square kilometer of useful land in China (Mukherjee et al., 2008), and this volume is expected to be 3 billion tonnes by 2020 (Liu, 2009). These large amounts of by-products, which were unable to be recovered for beneficial uses, have become real industrial wastes and pollutants. CCPs as industrial by-products, if inadequately disposed, can produce severe water and air pollution which is likely to cause serious human health risks. In China, CCPs with the gangue and calcium carbide slag has been listed as the top three industrial wastes (Wei, 2009).

The majority of the total CCPs produced worldwide are currently disposed of, which has caused significant environmental and economic burden to the ecology and society. Of great importance are thus different applications which promote the use of CCPs. From the worldwide perspective, growing concern for increased landfill cost and shortage of natural resources has led to the development of a number of CCPs recovery technologies such as fly ash cement, concrete addition, structure fill, mining backfill, etc. Manz (1997) reported that worldwide the major use of fly ash is in cement and concrete industries, which exceeds any other single application. There are several environmental and economic benefits connected with the use of CCPs as saving of natural resources, saving of energy, saving of emissions of pollutants, saving of GHG emissions and saving of useful land (ACAA, 2008). However, the demand for fly ash in the cement and construction industries is limited by various factors in terms of fly ash quality, market development, location affects, season problems (Kikuchi, 1999), etc. In many cases, the market for utilization of fly ash in construction industries is close to being saturated. Regardless of the positive uses, it is obviously that more CCPs are being produced than the current applications can consume (Iyer & Scott, 2001). More laboratory researching and industrialization practices, therefore, need to be conducted in order to find other technically viable and economically justified applications and to promote the efficient utilization of CCPs as
well as decrease the impacts on the environment and economy. Several commercial testing have been attempted in the past, however, often with little success. It has been shown that these attempts failed to commercialization, not for technical reasons, but mainly for economic reasons.

There exist a number of barriers to the increased use of large quantities of CCPs. The principle obstacles are those issues with regard to materials characterization, market abilities, standards, specifications, policies, regulations, demonstration, public perceptions, etc. Hitch (2005) argued that a prerequisite for formulating approaches to take in overcoming the barriers to CCPs uses is the full range of identification of those barriers. Identifying the barriers to, and driving forces for increased use of CCPs is of fundamental importance for going extra miles on the way of CCPs utilization.

1.1 Aim and research questions

To meet the challenges of increased use of CCPs and formulate effective approaches, it is of great importance to identify the incentives and obstacles to CCPs utilization. The aim of this thesis is to analyze present and potential use of CCPs and more specifically address factors that inhibit or promote the utilization of CCPs from coal-fired power plants in China.

In order to make real and steady progress in the face of those challenges, three research questions are formulated and examined based on the aim of the thesis. The research questions are:

1. What are the current and potential utilization of CCPs in China and other developed countries? What are the possible environmental impacts and health risks from coal combustion products?
2. What are the benefits derived from CCPs recovery and the obstacles to the increased use of CCPs in China? What are the most important challenges to the use of CCPs?
3. What kinds of policies, regulations and recommendations can be applied to strengthen the management of CCPs utilization and increase the use of CCPs in China?

1.2 Scope and delimitations

This thesis highlights the utilization of coal combustion products generated from coal-fired power plants in China, especially the obstacles that inhibit the use of CCPs both from a scientific point of view and a societal point of view. Although coal combustion products consist of many different materials, which contain fly ash, boiler slag, bottom ash and flue gas desulphurization (FGD) products, the vast majority of CCPs are fly ash and FGD products. Fly ash clearly accounts for the largest share of CCPs usage. For this reason, how to use fly ash in an optimal and viable way is the key issue for the increased use of CCPs. In China, from the perspective of commercial utilization, generally, bottom ash and boiler slag are embodied in the category of fly ash (Wang & Wu, 2004). The focus of this thesis, therefore, will be on barriers to, and driving forces for the utilization of fly ash and a lesser degree on FGD materials utilization.
Efforts were made to compile the up to date total CCPs production and consumption data in China. However, for details of multiple applications of CCPs only the year of 1997 data were available. There is no specific institution or organization taking charge of CCPs production and utilization statistics in China. Various versions of CCPs statistics can be found, however, some of them often differ widely from each other. The reliability of some statistics of CCPs production and utilization is still open to question.
2 Methods

The research will be carried out mainly based on data collection, literature survey, interviews and questionnaires. Literature for this project was sourced from the internet, library, company reports and other available information. CCPs producers, users and general public were involved in a method of interview and questionnaire investigation. An approach to problem-finding and problem-solving has been mapped out as follows.

2.1 Research process and methodology

The research strategy was based on multiple research methods: literature survey, top-down approach, concept of industrial ecology, previous-case study, questionnaire and interviews. The combination of research methods enables a deep insight into the utilization of CCPs as well as its challenges (Haes & Grembergen, 2008). Each step of research process applied different research method individually or multiply, as shown in Figure 1.

![Figure 1 Framework for research process and methodology. The figure is inspired by Haes & Grembergen (2008).](image_url)

The research process started with exploring the experimental documents and identifying the research questions through a detailed literature review in the field of CCPs utilization. The focus was on finding an initial structure of research process and formulating research objectives (Haes & Grembergen, 2008). After having formulated the objectives, properties of CCPs’ different components, worldwide production and utilization of CCPs were investigated by means of literature survey and studying previous CCPs utilization cases. A top-down approach, which is known as the
breaking down of a system to gain more details about its sub-systems, was also used for analyzing worldwide CCPs uses. In a top-down approach an overview of CCPs production and utilization all around the world was first formulated. And then multiple patterns of CCPs use applications in subsystems – different countries – were specified. The utilization of CCPs in China was further refined in a greater detail. In identifying barriers to, and driving forces for the increased use of CCPs, a method of questionnaires and interviews with CCPs producers, CCPs users and general public was conducted. The following research step was aimed at analyzing the CCPs application challenges from the stand points of different actors involved, and then indicating potential improvements and effective solutions in combing with a concept of industrial ecology.

### 2.2 Research design

A research process of problem-finding is first carried out. A method of questionnaire is designed for the purpose of identifying incentives and barriers to CCPs use from the perspective of different actors involved in CCPs production and utilization.

#### 2.2.1 Identification of research questions

Problem identification is the first and important step in designing and conducting a research. Inspired by IDRC (2010), selection, analysis and statement of research questions were structured in Figure 2.

**RQ1:** What are CCPs? What are worldwide and domestic production and utilization of CCPs? What are the environmental impacts from CCPs disposal?

**RQ2:** What are the barriers to, and driving forces for utilization of CCPs? What are the most important challenges to the increased use of CCPs?

**RQ3:** What kinds of effective solutions can be formulated by the government and industries to overcome the barriers?

*Figure 2 Selection, analysis and statement of research questions*
The first question mainly concerns the current and potential utilization of CCPs in China and other developed countries. The second one concerns obstacles to, and driving forces for the increases use of CCPs. The third question regards the initiatives from the government and industries to strengthen and promote CCPs uses. The focus of this thesis will be on the obstacles of utilization of CCPs and the potential approaches that minimize or overcome the barriers to the increased use of CCPs in China.

### 2.2.2 Identification of barriers

Based on a study of CCPs utilization barriers identification, which was conducted by US Energy and Environmental Research Center (EERC) in 1999, the barriers to the utilization of CCPs in China were similarly classified into following distinct categories: technical, economic, marketing, regulatory, public perception and attitude. A method of questionnaire and interview investigation in combining with literature survey was embodied in this thesis to examine general barriers existing in China’s CCPs industries.

### 2.2.3 Interview and questionnaire design

A research method of questionnaire and structured telephone interview was used for investigating the present production and utilization of CCPs in some coal-fired power plants and CCPs users. In China, cement and concrete industries play significant roles in the development of CCPs uses because the majority of the recovered fly ash was currently used in construction material manufacturing and civil engineering applications. For this reason, as important actors of CCPs utilization, a cement plant, a construction company and a gypsum manufacturing plant have also been involved in the interviews.

**Table 1 List of companies consulted in the study**

<table>
<thead>
<tr>
<th>Company</th>
<th>Type</th>
<th>Position of interviewee</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baotou No.2 Thermal Power Plant</td>
<td>CCPs Producer</td>
<td>Environmental manager</td>
<td>Questionnaire</td>
</tr>
<tr>
<td>Ningxia Jinyuyuan Thermal Power Plant</td>
<td>CCPs Producer</td>
<td>Environmental manager</td>
<td>Questionnaire and telephone interview</td>
</tr>
<tr>
<td>FAW Thermal Power Plant</td>
<td>CCPs Producer</td>
<td>Environmental manager</td>
<td>Questionnaire</td>
</tr>
<tr>
<td>Taizhou Power Plant</td>
<td>CCPs Producer</td>
<td>Environmental manager</td>
<td>Questionnaire</td>
</tr>
<tr>
<td>Anhui Runji Cement Plant</td>
<td>CCPs user</td>
<td>Sales manager</td>
<td>Telephone interview and Questionnaire</td>
</tr>
<tr>
<td>Zhejiang Jiangong Real Estate Development Group Co., Ltd.</td>
<td>Potential CCPs user</td>
<td>Structural engineer</td>
<td>Telephone interview</td>
</tr>
<tr>
<td>HSLB Gypsum board Manufacturing Plant</td>
<td>CCPs user</td>
<td>Sales manager</td>
<td>Telephone interview</td>
</tr>
</tbody>
</table>
The respondents from power plants and other companies were asked to indicate which barriers to, and driving forces for increased use of CCPs are most relevant to their companies and provide input regarding the importance of incentives and barriers identified. The rank of different barriers and drivers for utilization of CCPs was designed based on a three grade scale where 3 points corresponding to very important, 2 points for moderate and 1 point if the respondent considered the identified factors are weak drivers/barriers. And the results derived from the questionnaires and structured interviews were normalized to avoid biases. For details see Appendix-Questionnaire. The results were translated from Chinese to English and presented in this thesis. The questionnaires were sent out via emails to the respondents and designed to be answered by environmental managers or people in charge of waste handling issues in the power plants. As such people are familiar with the processes of the power plants’ waste handling systems and destabilizing factors that influence the output quality of CCPs. Furthermore, they are the ones who are often in charge of directly contact with the users of the CCPs, which implies that more feedback information from the users could be grasped by these people.

Structured telephone interviews were carried out with the managers from technical and sales department of CCPs use companies. In addition to asking questions about obstacles and driving forces, the interviews also included questions about the respondents’ view of whether there exist weaknesses in the management of CCPs at their companies and related improving measures which had not been undertaken. Questions such as what is the cost for CCPs materials and transportation, whether there is a need for investments on additional facilities, and what kind of preference and support could be obtained from the government to promote the use of CCPs were also asked.

2.2.4 Validity and reliability of research method

The validity and reliability of the scientific method are of great importance (Shuttleworth, 2008). An investigation of questionnaire and structured telephone interview carried out among different actors involved in the CCPs production and utilization is an effective and reliable method to identify incentives and barriers from the economic, environmental and societal perspectives. However, an experiment that uses human judgment, to some extent, is likely to come under question (Shuttleworth, 2008). When drawing conclusions from the questionnaires and in-depth interviews the respondent’s answers may include a degree of bias; and personal opinions, for example, may affect the respondent’s answers to some questions (Thollander, 2008). To make the results derived from the interviews and questionnaire valid enough and minimize biases, a wide range of sample groups including the government, CCPs producers, CCPs users and the general public, should be involved. Furthermore, it must be kept in mind that the number of companies interviewed is limited and they are mainly located in some specific areas. Data or information collected from the interviews and questionnaires, to some extent, may not be very representative from the perspective of the whole country.
3 Coal combustion products

The definition for solid materials generated from coal combustion processes has been evolved from the first used term "coal combustion wastes" to "coal combustion byproducts" and lately to the term "coal combustion products" (Kalyoncu, 2001). From the transition of working definition for CCPs, it is evident that the CCPs from coal combustion power plants has been gaining wide public concern and its environmental and commercial value has also been emphasized due to current interest in "low-carbon economy" and "sustainable development".

3.1 Composition of CCPs

Coal Combustion Products (CCPs) are the solid, inorganic minerals that remain after coal is burned to generated electricity in power plants. The major solid residues included in CCPs are fly ash, bottom ash, boiler slag and FGD materials.

Fly ash is produced from the burning of fine grinded coal in a pulverized coal combustion boiler. It is collected from the coal-fired power plant exhaust gases primarily by electrostatic precipitators (ESP), or fabric filters (FF) and secondary FGD scrubbers. Fly ash is a fine and powdery material, which is composed mainly of non-combustible inorganic materials, such as spherical glassy particles, and some carbon due to incomplete combustion of coal.

Bottom ash is a heavier, coarser and granular material removed from the dry-bottom boiler which is the most common boiler type. When pulverized coal is burned in such type of boiler, about 80% leaves as fly ash and 20% remains as bottom ash which is too large to be carried in the flue gases (The Fly Ash Resource Center, 2010).

Boiler slag is the molten bottom ash drawn from the base of slag-type boiler or cyclone boiler and discharged into a water pit where it is quenched and removed. The proportion of bottom ash generated in these kinds of boilers is higher than that of pulverized coal boilers. The resulting boiler slag is made up of coarse, hard, black,
dense, glassy particles. The boiler slag accounts for a mere fraction, only about 2.5%, of the total amount of CCPs produced from coal-fired power plants (Kalyoncu, 2001).

Flue gas desulphurization material is a product of a process used for the purpose of removing SO$_2$ from a coal-fired boiler exhausted gas. Generally, FGD material consists of fluidized bed combustion (FBC) ash, spray dryer absorption (SDA) products and FGD gypsum. In the European Union of the EU15, the total production of CCPs was 61 Mt in 2007, with fly ash accounts for a major component about 69% of CCPs produced, followed by FGD material which represents about 18% by weight (ECOBA, 2009). Figure 4 shows the typical proportions of different constituents of CCPs produced for 2007 in Europe (EU15).

![Figure 4 Typical compositions of CCPs in Europe (EU15) in 2007; total production 61 million tonne (ECOBA, 2009)](image)

In China, the ash content of electricity coal, which ranges from 15% - 30%, is relatively higher than that in other countries (Chen P., 2007). Consequently, the amount of fly ash contained in CCPs produced from coal-fired power plants accounts for a much higher percentage than normal. Based on the country’s energy structure and economic foundation, it is foreseeable that the framework of primary energy source dominated by coal is hard to be changed in the next five decades. The production of FGD materials, therefore, will be rising rapidly along with the increasing intension on SO$_2$ emission control in China. It is estimated that 8.5 million tonnes of FGD gypsum will be produced in 2010, while the use rate is hard to reach 30% (Tian et al., 2006). Increasing the use of fly ash and FGD materials to the greatest extent, therefore, plays a significant role towards the increased use of CCPs.

The distinct chemical and physical properties of CCPs’ different constituents allow each of them well-suited for particular applications (Kalyoncu, 2001). As these distinct properties of different components are likely to influence the opportunities for CCPs uses, an understanding of characterization of CCPs in terms of physical, mineral, surface chemistry and reactivity, therefore, is of great importance (González et al., 2009). What follows fly ash and FGD materials are mainly discussed.
3.2 Properties of fly ash

Fly ash is an artificial volcanic ash, i.e. a siliceous or siliceous and aluminous material, which has slight or non self-cementing properties. Such materials with pozzolanic properties will react with calcium hydroxide in the presence of water at ambient temperature to produce calcium silicate hydrates (cementitious compounds). The pozzolanic properties of fly ash, including its lime binding capacity allows it to replace Portland cement in concrete products or to be used as raw material for cement clinker (Ahmaruzzaman, 2010). The chemical and physical properties of fly ash vary considerably depending upon the properties of coal, powder preparation equipments, furnace types, ash collection methods, flue gas emission control measures and etc, which influence, to a great extend, the development of various fly ash applications.

3.2.1 Chemical properties

The chemical properties of fly ash, which is nearly identical to volcanic ash, are influenced significantly by the source of coal and the techniques used for storage, preparing and combustion (TFHRC, 2010). Coal consists of inorganic and organic substances. Organic matter is made up of volatile and fixed carbon; mainly consists of carbon, hydrogen and oxygen. Fly ash is the residue generated from the combustion of inorganic matters, which is composed principally of silica, alumina and iron oxide, with smaller percentage of calcium oxide, sulphur oxide, magnesium oxide, unburned carbon and other compounds (TFHRC, 2010; Gu, 2004). Table 2 compares the normal range of the chemical constituents for fly ash generated from burning different ranks of coals.

<table>
<thead>
<tr>
<th>Component</th>
<th>Bituminous</th>
<th>Sub-bituminous</th>
<th>Lignite</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>20-60</td>
<td>40-60</td>
<td>15-45</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>5-35</td>
<td>20-30</td>
<td>10-25</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>10-40</td>
<td>4-10</td>
<td>4-15</td>
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<td>CaO</td>
<td>1-12</td>
<td>5-30</td>
<td>15-40</td>
</tr>
<tr>
<td>MgO</td>
<td>0-5</td>
<td>1-6</td>
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<tr>
<td>SO₃</td>
<td>0-4</td>
<td>0-2</td>
<td>0-6</td>
</tr>
<tr>
<td>Na₂O</td>
<td>0-4</td>
<td>0-2</td>
<td>0-4</td>
</tr>
<tr>
<td>K₂O</td>
<td>0-3</td>
<td>0-4</td>
<td>0-4</td>
</tr>
<tr>
<td>LOI¹</td>
<td>0-15</td>
<td>0-3</td>
<td>0-5</td>
</tr>
</tbody>
</table>

As shown in Table 3, typical fly ash in China is composed primarily silica, alumina and iron oxide, which accounts for about 85% of the total amount of fly ash. The relatively low calcium oxide content makes fly ash presenting non self-cementing in nature (Gu, 2004). Properties of other constituents are not over the standards of

¹ Loss of Ignition.
engineering applications. However, the loss of ignition varies widely and the average value is relatively high than normal, which poses a potential barrier to CCPs used in concrete applications.

Table 3 Typical composition of fly ash in China (Gu, 2004)

<table>
<thead>
<tr>
<th>Component</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>Fe₂O₃</th>
<th>CaO</th>
<th>MgO</th>
<th>SO₃</th>
<th>Na₂O</th>
<th>K₂O</th>
<th>LOI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>50.6</td>
<td>27.2</td>
<td>7.0</td>
<td>2.8</td>
<td>1.2</td>
<td>0.3</td>
<td>0.5</td>
<td>1.3</td>
<td>8.2</td>
</tr>
<tr>
<td>Range</td>
<td>33.9-</td>
<td>16.5-</td>
<td>1.5-</td>
<td>0.8-</td>
<td>0.7-</td>
<td>0-1.1</td>
<td>0.2-</td>
<td>0.7-</td>
<td>1.2-</td>
</tr>
<tr>
<td></td>
<td>59.7</td>
<td>35.4</td>
<td>15.4</td>
<td>4.0</td>
<td>1.9</td>
<td>1.1</td>
<td>2.9</td>
<td>23.5</td>
<td></td>
</tr>
</tbody>
</table>

The chemical make-up of fly ash draws wide concern from power plants and end users. Loss of ignition (LOI) is generally used by power plants for indicating whether the coal is combusted completely. As fly ash is becoming a useful engineering material, LOI, which is a measurement of the amount of unburned carbon remaining in fly ash, can be used as an indicator of suitability for use as a cement replacement in concrete. Fly ash with high carbon content will influence the quality of concrete when using this material as a cement replacement. As a result, LOI is considered as one of the most significant chemical properties of fly ash (TFHRC, 2010). And the chemical composition of fly ash has been widely accepted as a mainly standard for quality classification and grading of fly ash by CCPs marketers and engineering departments (Gu, 2004).

According to the American Society for Testing Materials (ASTM), two categories of fly ash are recognized. The ash containing more than 70 mass percent SiO₂ + Al₂O₃ + Fe₂O₃ are defined as class F, while class C requires a SiO₂+ Al₂O₃ +Fe₂O₃ content at least 50 mass percent (ASTM C618, 2005). In general, Class C fly ash contains higher CaO than Class F fly ash. In China, there is no specific accepted standard for classification of fly ash, but briefly sort into high-calcium and low-calcium fly ash, which are similar to ASTM Class C and Class F fly ash respectively (Gu, 2004). The high-calcium Class C fly ash is normally produced from the burning of low-rank coals (lignite or sub-bituminous coals) and have cementitious properties (self-hardening when reacted with water) (Ahmaruzzaman, 2010). While, the low-calcium Class F fly ash is commonly produced from the burning of higher-rank coals (bituminous coals or anthracites) that are pozzolanic in nature (hardening when reacted with Ca(OH)₂ and water) (ASTM C618, 2005).

3.2.2 Physical properties

Fly ash consists of fine, powdery particles that are generally largely spherical in shape, either solid or hollow, and mostly glassy (amorphous) in nature. Because of the different constituents and contents of fly ash, the color can vary widely from tan to gray to black, depending on the amount of unburned carbon in the ash (TFHRC, 2010). Generally, the variation of fly ash properties and the composition of fly ash can be identified and reflected briefly based on the changes of ash colour (Shen & Wu, 2004). The particle size distribution of coal fly ash collected generally ranges from 0.5-300µm, which is close to the variation range of cement particle size, but majority of the fly ash particles are smaller than those in cement (Shen & Wu, 2004). The fineness of fly ash particles is considered as one of the most important parameters that
influence the fly ash quality for applications in cement and concrete industries. Based on National Standard of the People’s Republic of China Fly Ash used for cement and concrete GB1596-1991, the percentage of material passing the 45µm (No. 325) sieve is applied as an indicator for fly ash fineness. In China, coal ash captured from particles collection systems seldom fulfills the GB standard of fly ash used in reinforced concrete without further classifying and grading treatment. Shen and Wu (2004) has pointed out that large fluctuation in fly ash physical properties makes the use of CCPs more difficult. The specific gravity of fly ash usually ranges from 2.1 to 3.0, while its specific surface area may vary from 170 to 1000 m²/kg (ASTM C204, 1994). Molten minerals such as clay, quartz, and feldspar, solidify in the flue gas, giving approximately 60% of the fly ash particles a spherical shape (TFHRC, 2010).

The particular cementitious properties of fly ash with its unique spherical shape, particle size distribution, and alkalinity offer CCPs additional value for a variety of beneficial use options (NCASI, 2003). As fly ash is a mixture compounded by various particles with different properties, it is of great importance to understand clearly about the particle components and contents in the ash in order to develop and explore the use of CCPs in broader range.

3.3 Properties of bottom ash/boiler slag

Coal bottom ash and boiler slag are the heavier and coarser coal combustion by-products that are collected from the bottom of furnaces. The type of bottom ash and boiler slag produced depends on the type of boiler furnace (dry-bottom boiler, wet-bottom boiler and cyclone furnace) used to burn the coal (TFHRC, 2010).

When coal is burned in a most common dry-bottom boiler, 20% remains in the furnace as bottom ash and 80% leaves as fly ash. Bottom ash is gray to brown, coarse-grained, granular, incombustible material that is collected in a water-filled hopper at the bottom of the furnace (The Fly Ash Resource Center, 2010). Bottom ash is predominantly sand-sized particles, usually with 50 to 90 percent passing a 4.75 mm (No. 4) sieve and a top size usually ranging from 19 mm to 38.1 mm (TFHRC, 2010).

Boiler slag is vitrified bottom ash generated from a wet-bottom boiler. The bottom ash in wet-bottom boiler is kept in a molten state and tapped off as a liquid which is cooled by quenching water contained in the ash hopper in wet-bottom furnace. In this type of furnace, the molten slag is fractured instantly, and thus the resulting product is often a coarse, hard, black, angular, and glassy material (NCASI, 2003). Boiler slag is essentially a coarse to medium sand, predominately single sized with 90-100 percent passing a 4.75 mm (No. 4) sieve (TFHRC, 2010).

The particular particle size of bottom ash and boiler slag and the durability of boiler slag are considered as the primary and additional value of these materials. These advantages of the particle size of bottom ash and boiler slag and the durability of the slag are taken by various lucrative applications such as fine aggregate in asphalt paving, structure fill and etc (NCASI, 2003).
3.4 Properties of FGD materials

FGD material is a product of a process typically used for reducing SO$_2$ emissions from the exhaust gas system of a coal-fired boiler, which mainly contains three categories of products: fluidized bed combustion (FBC) ash, spray dryer absorption (SDA) products and FGD gypsum (ECOBA, 2010). The physical nature of these materials varies from a wet sludge to a dry powdered material depending on the process.

FBC ash is produced in fluidized bed combustion boilers which introduce ground limestone (or lime) into the combustion furnace that burns the finely pulverized coal at temperatures of 800 to 900°C (ECOBA, 2010) to minimize the emission of pollutants such as SO$_2$ and NO$_x$ from the exhaust gas. Because of the incomplete combustion of coal, this process intends to result in "weaker fuel mineral decomposition", "lower novel mineral formation intensity" and a significant increase in the LOI of fly ash, which makes the ash unsuitable for cement and concrete applications (Kalyoncu, 2001). The FBC ash chemical composition is directly influenced by coal characteristics resulting from the chemical composition of inorganic fraction of coal, the sulfur content of coal and the SO$_2$ removal rate (Lecuyer, Gueraud, & Bursi, 2001). Depending on coal sulfur content and the sorbent reactivity for desulphurization, FBC ashes may rich in lime and sulphur and this chemical composition of FBC ash usually results in a high alkaline and high content of SiO$_2$+Al$_2$O$_3$+Fe$_2$O$_3$ (Lecuyer, Gueraud, & Bursi, 2001). In this case, FBC ash does not meet the ASTM C618 and GB1596-1991 requirements for conventional civil engineering and concrete applications.

SDA product is a fine grained material resulting from dry flue gas desulphurization with quick lime or slaked lime acting as the react reagent. The dry material from dry scrubbers or reactors that is captured in an ESP or FF mainly consists of fly ash, CaSO$_3$ and Ca(OH)$_2$, with some impurities such as CaSO$_4$, CaCO$_3$ and CaCl$_2$. Although fly ash accounts for about 50% of the SDA product, the chemical and physical properties of SDA product have become very different from normal fly ash because of the introduced De-SO$_x$ end products (Xu Q., 2003). The chemical activity of SDA product has been significant impacted by higher content of sulphur and lower content of SiO$_2$+Al$_2$O$_3$+Fe$_2$O$_3$ compared with normal fly ash. The beneficial use of SDA product in construction materials and civil engineering applications is, therefore, restricted and limited significantly by its relatively inactive properties (Cui et al., 2008).

FGD gypsum is natural gypsum like solid residue generated from the wet desulphurization of flue gas from coal-fired power plants. It is estimated that the wet limestone (or lime) FGD system accounts about 80% of all of the FGD systems which have been extensively installed in coal-fired power plants (Wang & Wu, 2004). Because the wet FGD systems are designed to introduce primarily lime or limestone as reagent sorbent and generally combined with fly ash removal facilities, the obtained end product is usually a mixture of gypsum, calcium sulfite (CaSO$_3$), fly ash, and un-reacted lime or limestone (TFHRC, 2010). FGD gypsum is generally characteristic of yellowy color and consists of small, fine particles with 10% - 15% moisture content. The wet product from limestone based reagent wet scrubbing processes is predominantly calcium sulfite. Generally, calcium sulfite is converted to
calcium sulfate (CaSO₄) by forced oxidation and the moisture and other impurities in FGD gypsum are reduced by appropriate measures, such as vacuum dewatering and physical processing, to satisfy the requirements for industrial applications (Kalyoncu, 2001). The primary value of FGD gypsum is the higher calcium sulfate content renders it suitable for a variety of beneficial use applications in the construction and agricultural industry (NCASI, 2003). Calcium sulfate, once it has been dewatered, is a material similar as natural gypsum, can be used in wallboard manufacturing and in place of gypsum for the production of cement. The impurities, such as CaSO₃ and carbon, contained in the FGD gypsum tends to have negative impacts on applications in cement manufacturing; while for gypsum board production, the detrimental impurities are those water soluble organic or inorganic substances, such as potassium, sodium, iron, magnesium and etc (Wang & Wu, 2004).
4 CCPs utilization

The utilization of CCPs began with Roman times; some 2000 years ago - long before the invention of Portland cement - the Romans used volcanic ash in the construction of aqueducts and coliseums that are still standing today (Kalyoncu, 2001; NCASI, 2003). The history of CCPs in China began from the late Ming Dynasty - about 400 years ago - with the use of lime and volcanic ash mixed concrete in hydraulic engineering (Shen & Wu, 2004). The first research on applying fly ash to concrete was reported by America scientist R. E. Davis in 1935 (Kalyoncu, 2001; Shen & Wu, 2004). One of the milestones of large scale CCPs applications is the project carried by the U.S. Bureau of Reclamation who used more than 100,000 tonnes of fly ash in the construction of the Hungry Horse Dam in Montana from 1948 to 1953 (Kalyoncu, 2001; Shen & Wu, 2004; Chang & Xu, 2007). The patterns of CCPs utilization and corresponding use rate vary due to the differences of individual countries in terms of economic and technology level of development.

4.1 Worldwide utilization of CCPs

Berg and Feuerborn reported in 2001 that about 500 million tonnes of CCPs were generated worldwide. However, only mere fraction of the total CCPs produced was beneficially used. The untreated disposal of such vast sum of products can have significant economic and environmental problems. The current utilization of CCPs on worldwide basis varied widely from a minimum of 13% to a maximum of 97% as showing in Table 4. While the world average utilization rate of CCPs is still keeping low.

Table 4 Overview of coal combustion products production and use in different countries

<table>
<thead>
<tr>
<th>Country/Region</th>
<th>CCPs Production (Mt)</th>
<th>CCPs Utilization (Mt)</th>
<th>Utilization Rate</th>
<th>Year</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>USA</td>
<td>136.1</td>
<td>60.6</td>
<td>44.5%</td>
<td>2008</td>
<td>(ACAA, 2009)</td>
</tr>
<tr>
<td>China</td>
<td>120.0</td>
<td>69.6</td>
<td>58.0%</td>
<td>2000</td>
<td>(Wang &amp; Wu, 2004)</td>
</tr>
<tr>
<td>India</td>
<td>90.0</td>
<td>11.7</td>
<td>13.0%</td>
<td>2000</td>
<td>(Kalyoncu, 2001)</td>
</tr>
<tr>
<td>EU15</td>
<td>61.2</td>
<td>55.4</td>
<td>89.3%</td>
<td>2007</td>
<td>(ECOBA, 2009)</td>
</tr>
<tr>
<td>Australia</td>
<td>14.6</td>
<td>4.6</td>
<td>31.0%</td>
<td>2008</td>
<td>(ADAA, 2009)</td>
</tr>
<tr>
<td>Japan</td>
<td>11.0</td>
<td>10.7</td>
<td>97.2%</td>
<td>2006</td>
<td>(JCOAL, 2010)</td>
</tr>
<tr>
<td>Canada</td>
<td>6.8</td>
<td>2.3</td>
<td>33.0%</td>
<td>2004</td>
<td>(CIRCA, 2005)</td>
</tr>
</tbody>
</table>

Based on the statistics issued by European Coal Combustion Products Association (ECOBA) in 2009, the overall CCP production for 2007 in the European Union of the EU 15 was about 61 Mt with a utilization rate of 89.3% as shown in Figure 5. About 52.7% of the CCPs produced were used in construction industries (concrete, cement,

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2 This figure includes only the production of coal ash based on the data available. With new figures also on FGD products the total amount of CCPs produced in China will be much higher.
gypsum panel, etc.) and civil engineering (road base, embankment, flowable fill, etc.) and 36.5% were used in restoration of open cast mines with 2.5% were temporary stockpiled for future use and 8.3% were disposed of. ECOBA member countries are Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, the Netherlands, Poland, Portugal, Romania, Russia, Spain and the United Kingdom. In the larger EU of 27 member states the total production in 2007 is estimated to be about 100 million tonnes (ECOBA, 2010). That is to say ECOBA members account for over 60% of CCP production in Europe.

![Figure 5 Utilization and disposal of CCPs in Europe (EU15); total amount 61 million tonnes (based on ECOBA, 2009)](image)

Below Figure 6 shows the CCPs applications and related distribution rate for 2008 in the United States. The America Coal Ash Association (ACAA) reported in 2009 that the overall CCP production for 2008 is estimated at 136.1 million tons, while 60.6 million tons, which represents a 44.5% of total CCPs generation, are beneficially used compared with about 89.3% use in the EU15. As in Europe (EU15), the United States used CCPs in a number of applications, with construction industries and civil engineering leading the way at 32.1%, followed by mining applications with 7.7% and other applications with 4.7%. The remained 75.5 million tons were still being stockpiled or disposed in landfills and/or lagoons, which accounts up to 55.5% of total CCPs produced (ACAA, 2009).

![Figure 6 U.S.A CCPs utilization and disposal in 2008; total amount 136.1 million tonnes (based on ACAA, 2009)](image)
Table 5 summarizes profitably utilization rate of different components of CCPs in the EU15 and the United States. Over 20 million tonnes of the 42 million tonnes of fly ash produced in the EU15 was beneficially used (47% use rate) with a slightly smaller fraction (44%) of bottom ash, 88% of boiler slag, and 81% of synthetic gypsum produced found beneficial uses. As in the EU15, the United States has almost same profitably utilization rate of fly ash (40%), bottom ash (44%) and boiler slag (83%). Almost all of the FBC ash produced from the EU15 and the United States was not used in value-added applications and the utilization rate of SDA products in the United States is only 17% compared with that of the EU15 (61%).

Table 5 Profitably utilization rate of CCPs in Europe (EU15) and USA³

<table>
<thead>
<tr>
<th>Country/Region</th>
<th>FA</th>
<th>BA</th>
<th>BS</th>
<th>FBC</th>
<th>SDA</th>
<th>FGD</th>
<th>Year</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>EU15</td>
<td>47%</td>
<td>44%</td>
<td>88%</td>
<td>15%</td>
<td>61%</td>
<td>81%</td>
<td>2007</td>
<td>(ECOBA, 2009)</td>
</tr>
<tr>
<td>USA</td>
<td>40%</td>
<td>44%</td>
<td>83%</td>
<td>2.3%</td>
<td>17%</td>
<td>60%</td>
<td>2008</td>
<td>(ACAA, 2009)</td>
</tr>
</tbody>
</table>

FA = fly ash; BA = bottom ash; BS = boiler slag; FBC = fluidized bed combustion residues; SDA = spray dryer absorption product; FGD = flue gas desulphurization gypsum

Among the other individual countries investigated, India used only 11.7 million tonnes (13%) of 90 million tonnes fly ash produced in 1999, the remainder was disposed of. Approximately 14.6 million tonnes of CCPs were produced within Australia, and some 4.6 million tonnes (or 31%) of CCPs have been effectively utilized in various applications. Whereas, Canada generated 6.8 million tonnes CCPs in 2004, of which about 33% (2.3 million tonnes) was used. In Japan, the total generated coal ash was 11 million tonnes in 2006, among which 10.6 million tonnes was effectively used, equivalent to 97.2% use rate of the total production. The high disposal cost of CCPs in Japan ($100.00 per metric ton) (Kalyoncu, 2001) and scarcity in natural resources makes alternative uses economically viable.

4.2 CCPs utilization in China

The use of CCPs in China has become an increasing concern in recent years due to increasing costs of landfill space and current interest in sustainable development. China is the biggest coal output country all around the world and coal is and will be the main driver for economic development. In response to the growth in coal and electricity demand, the amount of CCPs produced in China continues to increase. The total fly ash produced from coal-fired power plants was increased from 37.7 Mt (million tonnes) in 1985 to 120 Mt in 2000 with an average annual production of 55 Mt (Wang & Wu, 2004). It is estimated that about 1.1 billion tonnes coal is consumed by the power industries and over 200 million tonnes of fly ash are produced during 2006 in China (Liu, 2009), which makes the country the largest CCPs producer in the world. The predicted amounts of fly ash in 2010 and 2020 will be 320 - 380 Mt and 570 - 610 Mt, respectively (Cao et al., 2008).

Utilization of CCPs has attracted much attention from the government over the years.

³ Restoration and mining applications are not counted as beneficial uses in the statistics.
Fly ash has been used as a mineral admixture material in concrete and grout for construction applications, especially for dam constructions, from the early 1950s in China (Wang & Wu, 2004). While only few amounts of total generated fly ash were beneficially utilized at that time. Along with the increasing pace of the economic development, coupled with great demand from the construction industries, making the pattern of fly ash applications more diverse. Since 1970s, several advanced production lines have been imported to produce novel wall materials, such as fly ash blocks, wall board and fly ash fused ceramics. However, for a variety of reasons these technologies have not been widely spread across the country, which had led to a lower utilization rate of fly ash, only 14% in 1980 (Wang & Wu, 2004). Until 1990s, the government promulgated series preference policies and incentive measures to develop other high volume applications, such as road base pavement, structural fill, backfill and agriculture fertilizer, outside cement and concrete industries. Simultaneously, researches on high levels applications have also been listed in the government research and development agenda, which had CCPs utilization to be promoted to a quite new stage.

The domestic fly ash production and utilization trend from 1979 to 2000 is presented in Figure 7. From late 1970s, the utilization rate has been hanging around at 20% for many years, however, with the increased interested in the value of CCPs and the reinforced policies the use rate grew rapidly in recent years and this figure reached up to 58% in 2000 (Wang & Wu, 2004). It is anticipated that this rate continues to grow for the years to come.

![Fly ash production and utilization trend from 1979 to 2000 in China (Wang & Wu, 2004)](image)

Presently, in China, fly ash is used extensively in construction, road-building, backfill, agriculture applications and mineral extraction, among which the first three applications share more than 90% of the total recovered fly ash. The distribution of
different applications of fly ash is summarized in Figure 8. More than 56.8% of total fly ash produced in 1997 was disposed of. Use in construction industries and civil engineering tops the list of leading fly ash applications with about 32.8%, followed by restoration (6.7%) and agriculture (1.8%) (Wang & Wu, 2004).

![Figure 8 China fly ash utilization and disposal in 1997; total production 106 million tonnes (based on Wang & Wu, 2004)](image)

A number of fly ash utilization projects have been carried out from 1960s in China. However, the current development level of fly ash utilization in China is still lower than that of in developed countries. Because of the unbalanced development levels of region economy, the utilization rate varies widely from a minimum of 10% to a maximum of 100% (Chang & Xu, 2007). Moreover, most of the fly ash generated from coal-fired power plants was used for low value added applications such as road pavement and mine restoration. Only 5% of the total fly ash produced was used in novel construction materials manufactures (Chang & Xu, 2007). Nevertheless, China has scored substantial achievements on fly ash treatment and utilization in recent years. A massive amount of fly ash based concrete has been used in the Great Three Gorges dam project known as the largest hydroelectric project in the world. The total amount of concrete used is estimated about 27 million m³ and fly ash as an admixture to the normal concrete accounts for about 50 percent (Chang & Xu, 2007). In some developed areas, Shanghai, Nanjing and Nantong of Jiangsu Province and Nanchang of Jiangxi Province, the utilization rate of produced fly ash was 100% in the past five years and used extensively in geotechnical engineering of road construction and wallboard materials (Cao et al., 2008).

While the situation in some less developed areas is not so optimistic, substantial amount of CCPs is currently unable to be used in gainful applications, but only to be land filled or stockpiled on site. Most of the fly ash produced in China’s Western areas is stockpiling in open fields without any treatment, which has produced serious environmental contaminations. A significant proportion of electricity produced from power plants in these economic underdeveloped areas is being sent to the developed coastal regions of East China; however, the produced fly ash as a combustion by-product is difficult to find beneficial use applications because of the market limitations, such as relatively high cost of transportation and lack of local market.

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demand of CCPs. It can be predicted that this situation is getting much worse by increasing production of electricity and expansion of power plants in these areas.

4.3 CCPs use applications

Growing concern for increased landfill costs, shortage of natural resources, negative impacts to the environment and threaten to public health has led to significant interest in developing other CCPs recovery technologies. Because of the substantial amounts of CCPs generated, the focus has primarily been on high volume utilization applications, generally in the engineering and construction areas. Such current CCPs utilization efforts have so far met with much success in many countries. However, despite the large scale and positive uses, the amount of CCPs produced clearly far exceeds consumptions currently (Iyer & Scott, 2001), which leads to continued efforts are still needed to achieve high levels utilization of CCPs.

4.3.1 Current CCPs applications

Among the most common applications of CCPs is the substitution of fly ash for Portland cement in concrete or the use of fly ash as a mineral additive in concrete and as a raw feed for cement clinker (ACAA, 2008; ECOBA, 2009), because of the advantages in particular geotechnical properties, e.g. specific gravity, permeability, internal angular friction, and consolidation characteristics (Ahmaruzzaman, 2010). Coal ash can be considered as the world’s fifth largest raw material resource with its large amount and particular cementitious properties (Ahmaruzzaman, 2010). As Manz (1997) writes: “worldwide the major use of coal ash is in concrete, which exceeds any other single application…The state of the art is well established with respect to coal ash as a cement raw material, for use in blended cement and as a partial replacement for cement” (Manz, 1997). Using fly ash concrete can improve the performance of concrete and quality of construction while saving cement and concrete cost. Fly ash has a successful history of use in concrete around the world for over 50 years (Cao et al., 2008). In the United States of America about 16 million tonnes (ACAA, 2009) fly ash, and in Europe of the EU15 more than 14 million tonnes (ECOBA, 2009) fly ash are used annually in cement and concrete industries.

And the second most common use of CCPs is the replacement of FGD gypsum for natural gypsum, which is a hydrated form of calcium sulfate, in wallboard (ACAA, 2008; USEPA, 2010). The FGD gypsum utilization progress is better in developed countries and most of FGD gypsum produced are extensively used in construction material industries. Apart from wallboard manufacturing, there exist other applications such as gypsum grout, gypsum powder, cement retarder, etc. The primary value of FGD material is its chemical composition (NCASI, 2003), which makes FGD gypsum that is rich in calcium sulfate content well-suited for replacing the natural gypsum in cement retarder as well as wallboard. In China, the total amount of cement produced in 2000 has reached to 300 million tonnes and the requirement of natural gypsum as cement retarder was 12 million tonnes based on the calculations in accordance with retarder agent makes up 4% of cement; and the production of natural gypsum in 2000 was 13.7 million tonnes, it can be seen that approximately 88% of natural gypsum produced was used in cement industries (Wang & Wu, 2004). Using FGD gypsum as cement retarder agent, therefore, possesses a large market potential. By proper treatment, the quality of FGD gypsum can superior to natural gypsum
making FGD gypsum in replacement of natural gypsum as cement retarder agent more feasible.

In addition to the cementitious properties, the unique spherical shape, particle size distribution, and alkalinity of fly ash provide value for a variety of beneficial use options (NCASI, 2003). These processes and applications include, but are not limited to mining restoration, embankments, pavement, underground void filling, lightweight aggregate, brick and ceramic, cenospheres, mineral filler, soil modification and waste stabilization. Wang and Wu (2005) showed the possible multiple fly ash utilization patterns in different sectors based on the natural advantages of this resource (Figure 9).

4.3.2 Potential CCPs applications

Currently, CCPs are mainly used in civil construction industries and these applications have scored substantial achievements, however, such efforts are not adequate for increased use of CCPs as is obvious from the low level of utilization, e.g. low utilization rate and low value added (Kikuchi, 1999). Moreover, in many cases the markets for CCPs as an ingredient in cementitious and other construction process are close to saturation (Iyer & Scott, 2001). As a consequence, alternative uses of CCPs other than the conventional cement and construction industry are, therefore, needed to be developed and industrialized. Efforts have been directed to developments of other commercially viable products, which may yield high value addition to its manufacturers (TIFAC, 2009) and help to save other dwindling
resources (Iyer & Scott, 2001). Potential high value added fly ash applications listed as shown below in Table 6.

Table 6 Potential fly ash high value added applications (based on TIFAC, 2009 and Wang & Wu, 2004)

<table>
<thead>
<tr>
<th>Category</th>
<th>High value-added applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mineral extraction</td>
<td>Alumina</td>
</tr>
<tr>
<td></td>
<td>Magnetite</td>
</tr>
<tr>
<td></td>
<td>Iron</td>
</tr>
<tr>
<td></td>
<td>Carbon</td>
</tr>
<tr>
<td></td>
<td>Cenospheres</td>
</tr>
<tr>
<td></td>
<td>Other mineral and trace items</td>
</tr>
<tr>
<td>Construction and engineering</td>
<td>Enhanced Pozzolana cement</td>
</tr>
<tr>
<td></td>
<td>Oil Well Cement</td>
</tr>
<tr>
<td></td>
<td>Decorative glass</td>
</tr>
<tr>
<td></td>
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<td>Glazed floor and wall tiles</td>
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<td>Potassium silicate fertilizer</td>
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Fly ash is a mixture which is mainly constituted by hollow glass beads, solid glass beads, iron-rich glass beads, porous spherical carbon grains, fragmental carbon grains and other spongy substances (Wang & Wu, 2004). The components, density and shape are quite different in different particles, thus the utilization and value of those particles are also distinct. Through a certain physical or chemical processing, various microspheres can be selected and obtained from the ash. These kinds of high value added products consume lower volume of fly ash than that of construction, back fill and road pavement applications. However, they have the potential in generating considerable sales revenues for power plants and manufacturers, which helps to prompt the development of different high level CCPs technologies.
A conceptual commercial scale design and financial estimate for a plant to recover high value added products from fly ash using a direct acid leaching process, with the rate of return exceeding 20% of the investment, was developed by the US Department of Energy during 1983-1984 (Golden & Wilder, 1985). It was estimated that by processing 1180 000 tons/year (TPY) of fly ash, 158 000 TPY of alumina, 102 000 TPY of ferric oxide, 46 000 TPY of gypsum, 81 000 TPY of alkali sulfate salts and 866 000 TPY of spent fly ash would be obtained. An excess cogeneration of 1940 MWh of energy from a commercial scale plant was also included.

The main component of fly ash are SiO$_2$ (40–65 wt %) and Al$_2$O$_3$ (25–40 wt %), with small quantities of Fe$_2$O$_3$, Mg, Ca, P, and Ti (Kikuchi, 1999). Fly ash therefore can be considered to be an aluminum silicate compound containing some impurities, which enables its use for the synthesis of zeolite (Kikuchi, 1999) and alum (Park et al., 2004). The zeolite has an ability to exchange one cation for another, known as “cation exchange capacity” or CEC (Liu, 2009). Synthetic zeolite is, therefore, accepted wildly as a drying agent, deodorant, freshness-holding agent, water-softening agent, soil conditioner, fertilizer additive, and feed additive (Kikuchi, 1999). The synthesis of artificial zeolite from coal ash on a semi-industrial scale has been conducted. Kikuchi (1999) has pointed out that natural zeolite is not widely distributed but is localized in certain regions of the world, which means synthetic zeolite will be in a highly competitive position outside of the natural ore field. It is anticipated that the zeolite converted from coal ash has a big potential for commercialization in terms of quality, localization of natural zeolite mines, and commercial price (Kikuchi, 1999).

As alumina is widely used as high performance raw material for many applications and fly ash primary consists of fine inorganic particles SiO$_2$ and Al$_2$O$_3$, the synthesis of Al$_2$O$_3$ powder from the ash, is of great commercial interest (Park et al., 2004). The process applying coal fly ash for alumina powder synthesis and using spent fly ash as raw material for cement production was shown to be technically viable, and this technology has been semi-industrialized successfully in Poland (Wang & Wu, 2004). China has also obtained a number of achievements in this field. However, the research on alumina synthesized from fly ash is still of laboratory-scale. Experiences from the semi-industrialized project in Poland showed that the quality of alumina produced from fly ash based on a limestone-sintering process is far superior to that of other conventional alumina extraction processes, which makes the commercial price of fly ash alumina several times higher than that of conventional one (Wang & Wu, 2004). Along with the development of alumina synthesis technology, it is foreseeable that the alumina extracted from fly ash may have a big market potential.

Coal fly ash can also be used to produce a cheap and environmentally-friendly absorbent for dry-type flue gas desulphurization and this process has been successfully commercialized (Wang & Wu, 2006) (refer to Figure 10). The adsorbent used in dry-type FGD processes are high reactivity pellets produced from fly ash and slaked lime spent absorbent (could be FGD gypsum). These pellets have favorably large pore volume making it possible to achieve a high De-SO$_x$ efficiency (Kikuchi, 1999). This process, to a certain extent, is superior to other traditional FGD processes, e.g. Dry-type, Semi-dry and Wet-type FGD. Because the adsorbent is made of recycled waste materials and no drainage and gas re-heater are required. Wet FGD can achieve high De-SO$_x$ efficiency and is easy for operation. However, it has drawbacks such as a large consumption of water and the need for waste water
treatment. Although dry-type and semi-dry FGD do not have drainage, in order to obtain a same high DeSO$_3$ efficiency as wet-type FGD, a larger amount of adsorbent are needed because a higher molar ratio of calcium to sulfur is required, compared with wet-type FGD (Kikuchi, 1999).

Some industrial plants using active-treated fly ash as FGD absorbent have achieved DeSO$_3$ efficiencies of over 90%, such as the Ebetsu power station (50 000 Nm$^3$/h) and the Tohtoh Atsuma power station (644 000 Nm$^3$/h) under a high molar ratio of calcium to sulfur (1.0–1.2) (Kikuchi, 1999). As Kikuchi (1999) writes: During operation, there is no need for wastewater treatment or gas reheating, and so this process is considered to be an ideal choice for controlling the emission of sulfur dioxide and an environmentally-friendly method for reuse of coal ash...but this FGD process has not yet spread worldwide (Kikuchi, 1999). This technology of activating coal ash as FGD adsorbent with double benefits of environmental and economic should be widely spread in China, where there exits a large demand of FGD adsorbents to increase the reduction of SO$_2$ emissions. Although the FGD process using coal ash as adsorbent has been industrialized and achieved a good success in some developed countries, few researches in this field have been done in China (Chang & Xu, 2007).

A number of researches on high value added applications, such as waste water treatment, anti-corrosion materials, glass ceramics and reflective materials, have also been carried out in China (Wang & Wu, 2004). Several researches have achieved abundant accomplishment. However, a number of projects on high value added fly ash applications reported work to date are still of laboratory- or pilot- scale, even some of the technologies have been commercialized in other developed countries for many years. Thus, further development work in this area is needed.
5 Driving forces for the use of CCPs

CCPs from coal combustion power plants have been gaining wide public concern and its environmental and commercial value has also been highlighted under the worldwide background of "low-carbon economy" and "sustainable development". Based on the normalized results derived from questionnaires and interviews, different kinds of incentives and corresponding degree of importance have been identified from the standpoint of both CCPs producers and users, as shown in Figure 11 and 12. The preference policies, such as tax exemption, "green" subsidies and low interest loan, made by the government were identified by the power plants as policy drivers for CCPs use. Investment savings from reduced maintenance and operation cost, financial rewards from the sales of CCPs and land saving were also considered as main economic incentives. Reduction of environmental impacts, such as air pollution, water contamination and GHG emission, were regarded as driving forces for CCPs utilization.

Figure 11 Identified incentives from the perspective of CCPs producers

The four power plants interviewed as CCPs producers considered land saving is the most important driving force followed by the incentive of environmental impacts reduction. Using CCPs helps to save disposal cost while releasing useful land occupied by CCPs stockpiling. For this reason, all of the consulted power plants input the highest grade on the category of land saving. The power plants also considered reducing impacts on the environment as important driver for utilization of CCPs. Investment on storage facilities and maintenance or operation costs could also be reduced by using CCPs. As the amount of revenues provided by the sale of CCPs and subsidy from the government are insignificant in relation to the profits generated from the sale of electricity, therefore, financial rewards and preference policies were likely to be considered less important.
Figure 12 Identified incentives from the perspective of CCPs users

While from the point view of CCPs users, economic factors were considered as the overriding incentive for using CCPs. Fly ash as the principle component of CCPs, generally costs less than other available raw materials for cement and concrete industries. It helps to reduce the cost of raw materials while maintaining or improving the quality of end products. Policy supports and subsidies provided by the government also play a significant role in increasing use of CCPs in those companies. Land saving was not a significant factor that promotes the use of CCPs in those CCPs users.

The identified driving forces for the use of CCPs were briefly grouped into three categories: environmental incentives, economic incentives and legislations.

5.1 Environmental incentives

Reduction of environmental impacts plays a significant role in promoting use of CCPs. Water contamination and air pollution from the disposed and stockpiled CCPs will be prevented by CCPs utilization.

5.1.1 Water pollution prevention

A greater proportion of CCPs produced in China is still disposed of in landfills and impoundments or stockpiled for future use, which has caused significant burden to the environment. As those substantial amounts of CCPs are sometimes disposed on unlined landfills, water from rainfall can potentially dissolve elements in the CCPs and then mix with surrounding water system. Coal fly ash, bottom ash, and boiler slag are primarily aluminum and silica and FGD materials composition is dominated by calcium and sulfur, while all CCPs contain metals in trace amounts (Murarka et al., 1992). A potential surface and ground water contamination can be caused by the leaching of dissolved toxic elements and heavy metals such as lead, mercury, cadmium, copper and zinc in fly ash if inadequately deposited (Polie et al., 2006). Hung et al. (2009) indicated that Pb leaching from large scale fly ash landfills may induce serious human health risks.

Murarka (2003) reported that the increasing use of low NOx emission combustion technologies at coal-fired power plant is expected to result in elevated concentrations
of ammonium in coal ash. The ammonium leached from landfills is likely to convert to nitrate that could migrate in groundwater and resulting in water pollution thereby.

5.1.2 Air pollution prevention

Fly ash is a fine and powdery material, the particle size distribution of coal fly ash collected generally ranges from 0.5-300 µm. The toxic trace elements are generally concentrated in the fine particles with a grain diameter of 2 µm, which can be inhaled and retained in human bronchus, is likely to pose significant human health risks (Tang et al., 2004). For the dry stockpile fields, the dust escaped from fly ash would aggravate the air quality on a regional basis. The residents in the vicinity of power plants, where dry stockpile fields are constructed, will under high risk of exposure into harmful fugitive dust in air.

5.1.3 GHG emissions reduction

The pozzolanic properties of coal fly ash make it suitable for replacing a portion of the Portland cement used in making concrete. Portland cement manufacture accounts for about 80% of green house gas (GHG) emissions embodied in concrete (Flower & Sanjayan, 2007). The average CO$_2$ emission is approximately 0.8 kg/kg cement (Josa et al., 2004), using 1 tonne of fly ash in cement results in about 0.8 tonne reduction of CO$_2$ emission. Using CCPs in place of virgin materials by reducing the energy-intensive mining operations and mining energy use needed to generate virgin materials can also lead to reduction in GHG emissions.

5.2 Economic incentives

Various economic benefits can be obtained from reduced quantities of disposed CCPs and increased use of those products. Using CCPs helps to reduce disposal cost and save natural resources while releasing useful land.

5.2.1 Land saving

Land saving was identified as the most important driving forces by the power plants interviewed. The disposal of CCPs will result in a significant cost to the power plants and utilizing companies in terms of operation, maintenance, transportation and on-site storage investment. On the other hand, high disposal cost of CCPs makes alternative uses economically viable (Kalyoncu, 2001). In China, the amount of cumulated fly ash has reached to about 2.2 billion tonnes. Based on the current CCPs annual amount of production, the requirements for ash-sluicing water and land for storage will be increased to about 10 billion tonnes and 300 square kilometers, respectively (Wang & Wu, 2004).

China is scarce in water resource and land per capita, such significant amount of water and land requirement for CCPs disposal will cause huge economic burden to the country. Power plants located in urban areas, especially for those in prosperous coastal regions, may no longer have adequate on-site storage space, which necessitates the CCPs produced to be transported to remote areas for disposal. The cost for disposal will increase dramatically due to the long distance for transportation. Some China’s lager power plants, e.g. Tuhe Power Plant, Shijingshan Power Plant
and Jianbi Power Plants, have to invest more than 100 million ¥ each on the construction of on-site storage silos or stockpile fields (Wang & Wu, 2004).

5.2.2 Natural resources conservation

Fly ash can typically replace between 15 to 30 percent of the cement in concrete with even higher percentages used for mass concrete placements (USEPA, 2010). CCPs, therefore, have a big potential for natural resources and energy conservation. Proper use of CCPs in construction applications makes good economic sense.

The interviewed CCPs use companies considered economic factors as the overriding incentive for using CCPs. Fly ash as the principle component of CCPs has been widely applied as cement replacement in concrete industries in China. It generally costs less than other available raw materials and helps to reduce the cost of raw materials while maintaining or improving the quality of end products. Fly ash concrete is technically superior to conventional concrete. Combining fly ash with Portland cement mixtures can produce for higher performance and longer-lasting buildings than conventional constructions (ACAA, 2008). Economic gains are significant from both technical and sustainability perspectives, as well as from aesthetic point of view (ACAA, 2008).

Moreover, FGD synthetic gypsum material has a potential for replacing about 10% of total wall bricks consumed currently by the construction industries in China, which is likely to help saving about 2.5 million tonnes of standard coal annually (Wang & Wu, 2004). CCPs are often considered as more cost-effective materials, they are less costly than the materials they replace. Economic benefits from CCPs utilization can include reduced costs from landfill disposal, increased revenue from the sale of CCPs as well as savings from using CCPs in place of other, more costly materials (USEPA, 2010).

5.3 Legislations

Tightened regulations on landfill of CCPs and strong policy support provided by the government are also of great importance for promoting CCPs uses.

5.3.1 Heightened regulations for landfill

The heightened regulations are making the disposal of CCPs an undesirable option. When the CCPs disposal locations are filled, new land and facilities must be found for storage. The extensive environmental impact evaluations and regulatory hurdles make obtaining the required permits and authorizations for those new disposal facilities increasingly difficult (Hall & Livingston, 2002).

5.3.2 Ban of solid clay bricks

In 2005, China’s General Office of the State Council (CGOSC) promulgated "Advices to further speed up wall materials innovation and to promote building energy efficiency." China’s wall construction material market is currently dominated by solid clay bricks, which consumed more than 1 billion m³ clay resources, equivalent to 330 square kilometer useful land, and 70 million tonnes standard coal annually (CGOSC, 2005). This advice aims to speed up moves to ban the use of solid clay bricks in all
construction industries and promote the utilization of "green" wall materials, which is a significant control means to protect limited land resources and the environment. Studies show that using other new building materials, e.g. fly ash based construction products, instead of solid clay bricks can save 47 percent of the energy in producing wall materials and 30 to 50 percent of the heating energy of dwellings (Xinhua, 2004).

The production and use of solid clay bricks in all municipalities, large and mid-sized cities in coastal areas, and cities in provinces where capita farmland is scarce have to be banned from 2000 (Xinhua, 2004). And the ban of using solid clay bricks in construction has to be mandatory implemented in all municipalities by the end of 2010 (CGOSC, 2005). The government also imposes mineral resource tax and re-imposes 17% value-added tax (VAT) on solid clay brick manufacturers, which makes the solid clay brick manufacturers less competitive in the construction material markets (Chen E., 2008). Under this regulation background, moving to use CCPs based construction materials in place of traditional solid clay bricks will be accelerated dramatically in China.

5.3.3 Preferential policies for CCPs applications

Besides the regulations on the ban of solid clay bricks, China Central Government and local authorities also unveiled fresh policies for encouraging the use of CCPs in different applications, which was also acknowledged by the interviewed CCPs users as important incentives. Representatives of Baotou No.2 thermal power plant, Inner Mongolia, and Jinyuyuan thermal power plant, Ningxia Province, stated that when using CCPs as raw materials to produce other industry products, the company or personnel will receive a tax exemption of 0.5 ¥/tonne of CCPs (BTTPP, 2010) and the industry enterprises also have the right for 5-year income tax exemption from the business began (JYYTPP, 2010).
6 Barriers to the increased use of CCPs in China

The use of CCPs in China has steadily increased in recent years however only a portion of the products were beneficially used. Obviously, there is quite a bit room to grow the CCPs market, the CCPs industry has to step up the effort to find additional beneficial uses or increase the amount used in the present applications (Hitch, 2005). It is predictable that new problems will emerge in endlessly during the practice progress of CCPs applications (Wei, 2009). Examining and minimizing the barriers to CCPs use is of great importance in the quest for increased use of CCPs. Based on the normalized results derived from questionnaires and interviews, various barriers have been identified from the different point view of CCPs producers and users, as shown in Figure 13 and 14. The identified principle barriers to CCPs uses are those issues related to materials characterization, market abilities, standards, specifications, policies, regulations, demonstration and public perceptions.

![Bar Chart](image)

**Figure 13 Identified barriers from the perspective of CCPs producers**

Difficulties in using FGD materials were identified by the power plants as one of the most important challenges to the increased use of CCPs. The utilization of FBC ash and SDA products was largely restricted to the special characteristics of high-calcium, high-sulphur, and high-carbon content; because these materials do not meet the standards of coal ash applications in cement and concrete, making them unsuitable for replacement of cement in concrete. The power plants have to dispose of these products as real industrial wastes. Outdated facilities and techniques in using CCPs were considered as factors that are likely to result in low quality of end products, making the expansion of CCPs market more difficult.

The representatives from power plants have also pointed out that high transportation cost for low unit-value of CCPs poses a significant barrier to the sales of CCPs. Some of the power plants are located in remote areas and tends to increase the unit transportation cost significantly, making the produced CCPs less competitive in relation to other local available materials. Market limitation is another vital factor which inhibited the use of CCPs. The interviewed power plants are mainly located in northern China, where demand of CCPs from construction industries is limited to a
great extend by season problems, they are usually unable to find outlet with the incremental CCPs produced during wintertime. The interviewees also pointed out that the qualities of CCPs are also influenced by several factors, such as source of coal, coal handling system and combustion techniques. The inconsistent qualities of CCPs are likely to hinder the expansion of CCPs in various applications.

![Bar chart showing identified barriers from the perspective of CCPs users](image)

**Figure 14 Identified barriers from the perspective of CCPs users**

While from the point view of CCPs users interviewed, competition from other materials and high cost for transportation pose two of the most important barriers to the use of CCPs. The market ability of CCPs is influenced significantly by the competition from local available resources, such as natural gypsum and minerals, especially from solid clay bricks. The market price of CCPs varied greatly depending on the grade of materials, season problems and transportation cost. Because of the undersupply of CCPs in some areas and increased transportation cost, the price tends to be increased dramatically, which makes the CCPs based end products less competitive. And unbalanced supply-demand of CCPs in some areas was also indentified as a factor that limits the development of CCPs market.

There are also some quality problems in relation to the CCPs end products because of the outmoded production capacity, which is likely to influence the sales of those products. The general public concerned that they may be exposed to a high risk of failed projects if the quality of CCPs materials is unguaranteed. The interviewed representative from cement plant pointed out that investment in additional fly ash storage facilities is also likely to impede the increased use of CCPs in their company. And the construction company interviewed as a potential CCPs user was not willing to take unnecessary risks in using CCPs because of the inconsistent qualities of CCPs and lack of perfect technical specifications and standards. When using CCPs in many potential applications, there are usually few technical standards available to allow...
their uses, which is likely to impede CCPs uses.

6.1 Technical barriers

The technical barriers included issues related to CCPs production, specifications and standards, product commercialization, and user-related factors.

6.1.1 Lower rate of high-grade fly ash

In China, the rate of fly ash which can be used directly in the cement industries is not high and the number of power plants that can produce high-grade (Class I) fly ash is even small (Cong, 2009). The chemical and physical properties of fly ash vary considerably depending upon the sources of coal, powder preparation equipments, furnace types, ash collection methods as well as types of ash discharge system. Consequence upon the various coal sources and different types of coal mills, the pulverized coal tend to be coarse and can not be combusted completely in the furnace, which lead to a great amount of coarse particles and unburned carbon remaining in the ash. The fineness and loss of ignition (LOI) of fly ash are defined as two key indicators by GB standard for the direct utilization of fly ash in cement industries (Huang H., 2010). The coarse and high-carbon content fly ash, which is over GB standard, therefore, is unable to be used in cement industries.


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<th>No.</th>
<th>Indicator</th>
<th>Class</th>
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<td>I</td>
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<tr>
<td>1</td>
<td>Fineness (amount retained on 0.045mm sieve, %) ≤</td>
<td>12</td>
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<tr>
<td>2</td>
<td>Water requirement ratio, % ≤</td>
<td>95</td>
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<tr>
<td>3</td>
<td>LOI, % ≤</td>
<td>5</td>
</tr>
<tr>
<td>4</td>
<td>Moisture, % ≤</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>SO₃, % ≤</td>
<td>3</td>
</tr>
</tbody>
</table>

Approximately 95% of fly ash produced from coal-fired power plants in China is Class III or off-grade fly ash (Wang et al., 2004). The viability of fly ash quality and the scarcity of high-grade fly ash have been wildly acknowledged by the international cement industries as barriers to the development of fly ash cement (Shen & Wu, 2004). Moreover, high efficiency dust collectors have been installed successively in the large scale power plants in China since 1980s; however, many of those plants are still using wet sluicing system to transform fly ash, or even mixed with bottom ash, to storage impoundments (Cong, 2009). Large amount of high-grade fly ash was also flushed into the impoundments, which has quelled the activities of the fly ash making it difficult to be used.

6.1.2 Difficulties in using FGD materials

Difficulties in using FGD materials have been identified by the interviewed power plants as an important challenge to increased use of CCPs. The utilization of FBC ash and SDA products was largely restricted to the special characteristics of those FGD
materials, such as high-calcium, high-sulphur, and high-carbon content. In China, coal-fired power plants must comply with the acid rain provisions and reduce SO$_2$ and NO$_x$ emissions. Until clean coal technologies emerged, the flue gas scrubber was the only commercial technology capable of achieving the SO$_2$ reduction (Manz, 1998). The conventional FGD processes, wet-type and dry-type, both remove only SO$_2$; neither reduces NO$_x$ emissions. In complying with the current China’s emission regulations, emission control systems for both SO$_2$ and NO$_x$ have to be installed in the coal-fired power plants, which have led to the widespread use of low-NO$_x$ burning technologies combined with the SO$_2$ removing processes.

The low-NO$_x$ burning technologies have been extensively applied by most coal-fired power plants in China into circulating fluidized-bed (CFB) coal combustion system for power and steam generation (Wang & Wu, 2004). Within a CFB boiler, coal is burned at 800 to 900°C (ECOBA, 2010), while limestone is added in the boiler to minimize the emission of SO$_2$ and NO$_x$ from the exhaust gas. Spray dryer absorption (SDA) products resulting from dry FGD scrubbers or reactors take quick lime or slaked lime as an FGD adsorbent to reduce the SO$_2$ emission before it goes into the atmosphere. These NO$_x$ and SO$_2$ emission control technologies impair complete coal combustion (Manz, 1998) and produce high-carbon, high-calcium, and high-sulphur fly ash (ECOBA, 2010), which is unsuitable for using in cement industries. GB1596-1991 (refer to Table 7) requires Class I fly ash used for cement and concrete the LOI and SO$_3$ must be lower than 5% and 3%, respectively. Fly ash carbons and un-reacted FGD sorbent are left in the ash after the incomplete combustion of coal in the furnace, rendering the ash above specification for GB1596-1991 applications for cement and concrete. The stability of concrete products will be affected by higher LOI and calcium oxide remained in the fly ash. This kind of coal ash has lower biding ability with other components in the concrete, which impacts the setting process, causes high alkalinity (Huang H., 2010), air entrainment problems, and reduces the material’s strength and durability, especially during freeze-thaw conditions (Manz, 1998). Manz (1998) also indicated that the increasing use of NO$_x$ control technologies at power plants is also expected to result in increased concentration of ammonium in coal ash. Consequently, this kind of CCPs will become a real industry waste (Wei, 2009). It is evident that fly ash marketability at those specific coal-fired units was reduced due to the introduction of NO$_x$ and SO$_2$ reduction systems.

Moreover, along with the development of clean coal technologies, changing from high-sulfur coal into low-sulfur coal may require the addition of SO$_3$ to the flue gas to facilitate particle collecting efficiency of ESP systems. The addition of SO$_3$ may impact the properties of the fly ash, making it less suitable for use in cement replacement applications (EERC, 1999).

6.1.3 Engineering specifications and standards barriers

Before a new material is able to be used in manufacturing or engineering applications, specifications and standards of materials and products should be well established by industrial institutions to ensure this kind of new material meet with the specific requirements. While CCPs utilization standards are not developed very well in many industries, making many companies or contractors are reluctant to consider using CCPs in their projects when a standard material has been shown to meet project requirements. In addition, when using CCPs in many potential applications, there are
usually few technical standards available to allow their uses, which is likely to present a huge obstacle for their industrialization.

Even current CCPs utilizations standards also need to be further perfected and improved. There exist imperfections in current specification of using fly ash as cement replacement in concrete. Li Y. (2010) has pointed out that when applying fly ash Class I into concrete there is only one specification available, which specifies a same substitution rate of cement in concrete no matter what kind of project and location, or whether there are some special technical requirements. In addition, a test of compressive strength after 28 days standard curing is generally applied as acceptance criteria for fly ash concrete products (Li Y. , 2010). However, because less cement is used in the fly ash concrete, which renders the setting time of the concrete extended, and the initial strength of fly ash concrete is lower compared with the later strength. The fly ash concrete may, therefore, unable to pass the compressive strength test after 28d standard curing, which has limited the amount of admixture-grade fly ash in concrete.

EERC (1999) has argued that "various ashes that pass ASTM C618 may perform quite differently: one may be sulfate-resistant while another is not, or one may be a good water reducer or unaffected by alkali expansion while others do not share these properties." This argument is also applicable in China’s national standards for fly ash as cement replacement in concrete (GB1596-1991). As has already pointed out by EERC (1999), the fly ash classification system should take these performance factors into account and engineering properties should also be specified. The Class I, Class II and Class III distinction in GB1596-1991 is inadequate.

### 6.1.4 Changes in manufacturing processes or facilities

Changes in manufacturing processes or facilities may be required for CCPs to be used in cement and concrete industries, gypsum wallboard manufacturing, and other applications (EERC, 1999). Based on the interview with the representative of Anhui Runji Cement Plant, it was told that additional storage facilities, tank trucks and necessary technical transformations are required for applying fly ash into cement industries (Huang H. , 2010). Because of the relatively high cost of such additional facilities, making the fly ash application may not be advantageous or economically feasible for small operators who may intend to use CCPs as raw materials in their production processes. The changes in normal manufacturing processes may raise the cost of the end products and limit the use of CCPs, such as longer curing times and increased operation procedures for fly ash concrete bricks or other preformed concrete products. As EERC writes: "A necessary incentive to implement changes in procedures must include an equal- or higher-quality end product at an equal or lower cost" (EERC, 1999). Numerous small cement industries are, therefore, not likely to invest on additional facilities and modify their production processes because of the comparatively low profits (Huang H. , 2010).

### 6.1.5 Lack of practical experiences

The scarcity of practical experiences and skilled analysts is a big bottleneck for the increased use of fly ash in construction material industries (Wei, 2009). In China, more than 70 million tonnes fly ash is generated annually, of which 25% is applied
into construction material industries (Wang & Wu, 2004). As mentioned above, the physical and chemical character of CCPs is very individual and varies widely in terms of different coal sources and operation conditions. In construction material industries, there is no universal process formulation which can match all types of fly ash. Consequence upon the variety of fly ash characters, the formulation of raw materials in production lines will be adjusted accordingly after technical analysis. Therefore, a technical analyst plays a significant role in producing high performance fly ash end products. The end product quality will not be guaranteed and the cost of products would be very high, even the whole production lines will break down, without an appropriate formulation of ingredients (Wei, 2009).

6.2 Economic barriers

Economic barriers to increased CCPs utilization are widely accepted as the most important elements among all other factors that affecting by-product use (EERC, 1999). Once the economic incentives for CCPs uses are in place, the necessary resources needed to overcome other barriers will be available (EERC, 1999).

6.2.1 Large variation in CCPs price

The market price of CCPs varied greatly depending on the material (fly ash or FGD gypsum), the grade of fly ash, season and transportation cost. Representatives of two power plants interviewed indicated that the average price of untreated original fly ash from their power plants is about 15 Yuan per tonne, without transportation cost. After further classification, the price of high grade fly ash Class I and Class II will be much higher than that of original ash. The transportation cost is of great importance in influencing the market price of fly ash. For those cement industries that near the interviewed power plants, the transportation cost takes equal weight to the material cost of original fly ash. For longer distance transportation, fly ash price will be increased dramatically, which makes CCPs less competitive.

The price of fly ash is also impacted by season factors, power load and construction work periods. Larger amount of CCPs is emitted in the winter months when power plants are operating at full load. However, the fly ash produced in winter time is very difficult to be used because of lower demands from local construction industries (BTTPP, 2010). There may be no market available for CCPs in this case, especially in North China. On the other hand, the construction industry often needs most of the fly ash during the other seasons especially in the summer. The price of fly ash tends to be higher than usual accordingly. The primary barrier for marketers is economics. Therefore, there must be a profit available when marketing CCPs as a particular commodity (EERC, 1999).

6.2.2 Competition from other materials

The economics of CCPs utilization are influenced by the cost and availability of competing materials. The best example is traditional wall materials, such as solid clay brick with its lower price and easy availability has been widely used in China for thousands of years. Fly ash based wall materials can not pose competition with solid clay bricks from the economic point of view. Without explicitly forbidden of solid clay bricks, the development of other novel wall materials will be seriously hindered.
Another example is FGD gypsum, which can be used for replacing the natural gypsum in wallboard. As has already pointed by EERC (1999), a necessary incentive to market CCPs must include an equal- or higher-quality raw material at an equal or lower cost. As China has substantial natural gypsum reserves, FGD gypsum produced from power plants in mine sections does not have so many advantages in quality and price compared with natural gypsum, which makes the CCPs users preference for natural gypsum rather than taking FGD gypsum as their raw materials for wallboard production. As EERC writes: "Cost savings and end product quality were of key importance to most industries, and anything that would improve or at least maintain product quality while maintaining or reducing the cost would be favorably considered" (EERC, 1999).

One more example is high value added CCPs application, extraction of alumina from fly ash. Wang & Wu (2004) argued that when producing one tonne of alumina from fly ash, an additional consumption of 11 tonnes of limestone, 100 kg of sodium carbonate, 450 kWh of electricity and 1.6 tonne of coal is required compared to conventional alumina extraction from bauxite. And the current reserves of bauxite in China is abundant, therefore, from the standpoint of economics, the process of extracting alumina from fly ash is unable to compete with conventional process. Many other concepts of high value added fly ash application, such as recovery of magnetic material from fly ash (Groppo & Honaker, 2009), have been attempted at the commercial scale numerous times in the past, however most of the attempts were unsuccessful, not for technical reasons, but for economic reasons.

### 6.3 Marketing barriers

Spatial variation in supply-demand of high grade fly ash and high transportation cost for low unit-value CCPs are likely to impede the expansion of CCPs market.

#### 6.3.1 Unbalanced development of CCPs market

China Flying Ash Website CEO Wei (2009) has pointed out that the development of use of CCPs in China’s different regions is extremely unbalanced. There are not so many coal-fired power plants in southern China, therefore, the demand of CCPs exceeds the supply, which makes the utilization of CCPs in this area is relatively successful. Fly ash is widely used as cement replacement and raw material for concrete products in the south region. However, in northern China where coal-fired power plants are centralized and CCPs produced have been excessively accumulated. The power plants in this area have to spend huge sums of money to establish CCPs storage silos or stockpile fields. Consequently, large amount of high quality CCPs is accumulated in the north area without any profitable applications, while the short supply of CCPs in southern China has left a broad market gap in this area (Wei, 2009).

#### 6.3.2 Market limitation

Market limitation is another crucial factor that impedes promoting CCPs utilization. China’s economy has developed rapidly over the years, however, the rate of economic growth is quiet different between China’s and eastern area. The western area is an economically backward area where building material industries are not developed very well and the needs of such materials in this area are relatively less. In the western
interior area, such as Inner Mongolia, Shanxi, Yunnan, and Guizhou, the majority of CCPs produced from power plants are being directly disposed of as industry wastes (Li L., 2008).

In addition, this economically underdeveloped region is usually remote from large economically developed cities and villages located in China’s eastern region where CCPs is widely used in construction applications. Based on Wei’s (2009) research, for low value added fly ash applications, when a demand of building materials exceeds the range of 50 kilometers in distance the cost of fly ash end products will be much higher than market price because of the additional transportation cost. There will be no market demand for CCPs and the use of CCPs will lose its meaning if the haul distance exceeds the limitation.

Fly ash application in road-building has been made a great contribution to the increased use of CCPs in China since 1990s, which has led to the use rate of fly ash increased dramatically from 10% in 1980 to 42% in 1997 (Cong, 2009). However, currently the number of road-building projects near the power plants is decreasing in some areas, and the markets for CCPs used in these projects are close to saturation (Cong, 2009). On the part of a power plant or an area which is near the plant or within the area, after a road-building project has been done the demand for CCPs produced from this area will be declined rapidly.

6.4 Regulatory barriers

The widespread use of CCPs in construction material manufacturing is likely to be inhibited, to a great extent, by poor execution of regulations and weak market supervision.

6.4.1 Poor execution of regulations

The ban of solid clay bricks is a great boost to the development of CCPs based construction materials. However, the power of execution of this regulation is very weak. Motivated by the economic benefits, a number of manufacturers are still producing solid clay bricks instead of completely closing down the production lines. Solid bricks are still used widely in many areas, even in provincial capitals where solid bricks should be radically restricted (Wei, 2009). And the development of CCPs based construction materials is significantly inhibited by the halfway implementation of solid clay bricks ban, dealt a blow to the confidence of novel construction material market.

6.4.2 Weakness in market supervision

Along with the fly ash changes from a waste to a resource, imperfect regulatory system for CCPs utilization management has led to illegal marketers had a chance to hoard high quality fly ash for speculation and monopolization of the market (Wei, 2009). The local market price of admixture-grade fly ash will be increased extraordinarily because of the monopoly of marketing; CCPs producers are, therefore, concerned that they may be exposed to a high financial risk if their end products become markedly less competitive because of the high cost of raw materials. Market monopoly becomes a strong deterrent to those novel construction material producers.
who are willing to use CCPs.

6.5 Public perception and attitude barriers

Many barriers of CCPs use are from the definition of CCPs as industry wastes and the general public lack of familiarity and negative perception on CCPs.

6.5.1 Lack of familiarity with CCPs

A number of leaders of government and managers of companies are generally unfamiliar with CCPs utilization technologies and policies. Many incentive policies can not be executed very well. Because of the ignorance towards CCPs utilization policies and unfamiliarity with the potential applications for CCPs materials, the government authorities and company managers are frequently described as a key barrier to increased utilization of CCPs (Cong, 2009). It was widely indicated that many industries has missed opportunities to enjoy the incentive policies to develop CCPs use applications, which is responsible for the slow commercialization of CCPs in those industries. Lack of adequate understandings on the advantages of fly ash based construction materials among the general public and end users is also influencing the expansion of CCPs market (Ahmaruzzaman, 2010).

6.5.2 Unwillingness to change

As Hitch (2005) writes: "Humans are hesitant to change as it is often uncomfortable. A definition for change is to ‘undergo a loss or modification’. Sometimes it is very hard emotionally for human to undergo that loss, or modification, without knowing what will be put in its place. Acceptance of the unknown may be difficult for some people. Often moving into the unknown creates risks and some people may not be willing to take them. The higher the risk, the more difficult the decision to change becomes” (Hitch, 2005). In many cases, CCPs is regarded as a certain new material, private companies and engineers are lack of willingness to change or experiment with this material in their projects. The representative from construction company interviewed stated that there is no specific engineering standard available in the company for using CCPs products and using of an unproven material in replacing older and more established material is considered as an unnecessary risk (Huang L., 2010). CCPs industries are generally concerned that they may be exposed to a high risk of failed projects if the quality of CCPs materials is unguaranteed and the products later found to cause environmental contamination or engineering structures damage (EERC, 1999).

6.5.3 Negative perception on CCPs utilization

The perception of CCPs as waste is of itself a barrier to increased use of CCPs (EERC, 1999) and CCPs utilization is hindered where it is regarded as a waste rather than a product. CCPs are generally mistaken for hazardous wastes because of inadequate engineering and environmental information available for the public. Recognition of the nonhazardous properties of these materials is not accepted widely. Users and the general public lack of familiarity and negative perceptions are likely to hamper the use of CCPs (EERC, 1999). It is also important to note that lower quality of some CCPs end products often contribute to the negative perception on CCPs. In China, the size of construction material manufactures, which use CCPs as raw materials for
production, is generally small and often equipped with laggard production lines (Wei, 2009). Some illegal manufacturers even use untreated off-grade fly ash or FBC ash for construction materials production to reap fabulous profits. It is evident that the quality of end products produced from these individual workshops is often not guaranteed, which is likely to lead to failed CCPs demonstration projects and the end users and general public will lose confidence to CCPs utilization.
7 Discussion

Though the government has unveiled multiple preference policies to encourage the use of CCPs in different applications and other incentives have also helped to promote the rate of utilization, the demand for CCPs is limited by various factors associated with characterization, market ability, location, transportation, seasons, etc. Identifying the barriers to the increased use of CCPs is of fundamental importance to formulate effective approaches to take in overcoming those obstacles. Based on the results from the literature survey, questionnaires and interviews, an overview of identified barriers in terms of different actors involved in CCPs utilization is shown in below (Figure 15).

Various barriers are identified from the perspective of different actors, such as producers, users, the government and general public. High transportation cost of low unit-value CCPs, competition from available natural materials and spatial variation in supply-demand of CCPs are recognized as the most critical challenges to the increased use of CCPs. High transportation cost tends to increase the CCPs price dramatically, which makes it less competitive in relation to other available materials. For this reason, some potential CCPs users will prefer to select other materials, rather than taking CCPs as feed stocks, for their products. The economics of CCPs utilization are greatly influenced by the cost and availability of competing materials. As a result, fly ash based novel wall materials would be unable to compete with traditional solid clay bricks on price. Without explicitly banning of solid clay bricks, the development of using CCPs in construction materials will be seriously hindered.
Spatial variation in level of economic development and power plants distribution has caused unbalanced supply-demand of CCPs. The utilization of CCPs in the most developed economic areas of southern China is relatively successful, and often the demand exceeds supply in this region. While in western and northern China, large amount of CCPs is still being accumulated without any profitable applications because of the oversupply of CCPs in markets. Although a large number of researches have been conducted and some pilot-scale plants have also been built, many of the projects failed to be commercialized because of the insufficient R&D funds and lower priority of support from the government. Industries have also responded to the interviews that standards and specification of CCPs utilization are comparatively imperfect that have yet to be fully developed to satisfy the demands of practical applications.

Judging from the nationwide situation, it is obviously that more CCPs are being produced than the current applications can consume. There is quite a bit room to grow the current CCPs market in China. The government regulators and CCPs industries have to step up the effort to strengthen the management of CCPs utilization and find potential applications that is likely to minimize or overcome the barriers. The government authorities and industrial association are promising to be the great enablers for the increased use of CCPs. Following are action recommendations for industrial organizations and the government with regard to eliminating obstacles on increased use of CCPs.

### 7.1 CCPs Eco-Industry Park

The concept of industrial ecology "requires that an industrial system be viewed not in isolation from its surrounding systems, but in concert with them. It is a system view in which one seeks to optimize the total materials cycle, from virgin materials, to finished material, to component, to product, to obsolete product, and to ultimate disposal. Factors to be optimized include resources, energy, and capital" (Graedel & Allenby, 1995). As an element of industrial ecology, industrial symbiosis engages traditionally separate entities in a collective approach to competitive advantage involving share of resources and physical exchange of materials (Chertow, 2000). A conceptual CCPs Eco-Industry Park (EIP) derived from the idea of industry symbiosis could be realized to optimize and maximize the use of CCPs (refer to Figure 16).

Power plant that produces CCPs plays a key role, or "anchor tenant", in this CCPs EIP. CCPs generated from the power plants are used as feed stocks for various applications and the produced electricity is supplied to those plants as primary energy source. FGD gypsum is applied as a raw material by gypsum board manufacturer for producing gypsum board which is widely used in construction projects. Fly ash serves as a valuable resource for several applications. Various high value added products, such as alumina, carbon, magnetite and cenospheres, are extracted from fly ash and FBC ash in an integrated mineral extraction plant. And the spent fly ash from the process is used for cement production. Various industries take alumina extracted from the ash as a valuable engineering raw material. Magnetite recovered is used as dense medium for coal cleaning by which high rank of coal is obtained for further clean burning in the power plant. The Selected carbon is used as fuel for combustion and as activated absorbent agent for power plant waste water treatment. Cenospheres extracted from the ash is used as fillers in building painting and coating. Fly ash is also synthesized.
in a zeolite synthesis plant as effective absorbent for waste water treatment. FGD adsorption agent, which is applied to reduce the SO\textsubscript{2} emission from exhausted flue gas, is synthesized from fly ash. Large quantity of off-grade fly ash is firstly classified and grinded; the refined high-grade fly ash is used as raw material for producing high performance cement and the remainder coarse ash is used as an aggregate in concrete. Collaboration between different industries for mutual economic and environmental benefits, known as a "win-win situation", can be achieved through the closing of material and energy flows in EIP (Eklund, 2009).

*Figure 16 Conceptual CCPs Eco-Industrial Park*
Some marketing and economic barriers could be overcome through collaboration between the different actors within the CCPs EIP. As one of the most important economic barriers, high cost of transportation of low unit-value CCPs can be minimized by the geographic proximity of synergistic industries in the CCPs EIP. CCPs storage can be optimized to offer maximum capacity with minimum footprint to allow different users to purchase and stockpile of sufficient CCPs over seasons when they are least expensive to when they are most in demand (Smith, 2005). The high fluctuation of fly ash price can also be inhibited by accurate forecasting of seasonal demand and integration of ash marketing with appropriate coal procurement and handling functions within the CCPs EIP (Smith, 2005).

As has already mentioned numerous attempts of extracting high value minerals from CCPs were failed to be commercialized not for technical reasons, but for economic reasons. One recovery process may not be economically feasible for each of mineral product individually (Groppo & Honaker, 2009). For this reason, Groppo and Honaker (2009) from the University of Kentucky have proposed a process that recovers several products, such as magnetite, aggregate material, carbon fuel, pozzolan for cement replacement, cenospheres and mineral-grade filler, simultaneously has been shown to be economically justified and technically viable. Using spent fly ash from the alumina synthesis process as raw material for cement production is also shown to be technically viable (Wang & Wu, 2004). This integrated mineral extraction process can play a significant important role in realizing the conceptual CCPs EIP. A number of practices on zeolite synthesized from fly ash have been attempted and this process is anticipated to have a large potential to be industrialized. The process produces FGD adsorption agent from fly ash has already been successfully commercialized in Japan (Kikuchi, 1999). However, researches on this area have not been given as much attention in China.

**7.2 Recommendations for industry initiatives**

To satisfy practical application of CCPs in different domains, completing standards and specification need to be further developed. Some potential CCPs users are not willing to take unnecessary risks in using CCPs because of the lack of perfect technical standards. Continuing development of current standards and specification of fly ash used for cement and concrete should be expedited by industrial organizations and universities collaborative technology-based researches (EERC, 1999). Additional engineering specifications are needed for high-volume and high value-added fly ash applications. Industrial standards institute should also shine light on changes in fly ash classifications and wider ranges on LOI, moisture, alkali, and fineness to promote the use of fly ash in broader areas.

In many cases, the market for fly ash used in cement and concrete applications is tending to be saturated based on current replacing rate. For this reason, developing high volume fly ash concrete technology (HV FAC) and increasing the amount of CCPs used in the present cement and concrete applications is likely to be a foremost measure for increased use of CCPs. Among the most common applications of CCPs is the substitution of fly ash for Portland cement in concrete or the use of fly ash as a mineral additive in concrete (ACAA, 2008). In 1997, about 46 million tonnes fly ash was beneficially used in China, of which 27.6% was used in concrete industries. However, the use of fly ash in cement and concrete is limited by the maximum
blended rate, normally is about 30% (Wang & Wu, 2004). If the replacement rate could be increased to technically viable level of 50%, which means larger amount of fly ash can be utilized beneficially in concrete industries.

As has been shown, many barriers to increased use of CCPs are from the general public and end users who may have negative perception on CCPs. For this reason, public education on benefits and methods of CCPs utilization is of significant importance. Industry association with assistances from the government should support for publicizing annual survey of CCP production, utilization, and GHG reductions by using CCPs. Educational programs can be implemented with engineering and science departments at universities, government’s propaganda and communication media. Action on promoting the education on the value of life-cycle analysis of CCPs applications can be initiated through the collaboration with private owners and groups (EERC, 1999). The government should sponsor high-volume and high value added CCPs utilization commercial-scale demonstration projects and valuate the viability and environmental acceptability of these applications. The demonstration project can shine light on road-building, bridge, dam, and industrial symbiosis networks.

The quality problems in relation to CCPs end products have also led to some negative perceptions on CCPs. The end users and general public are generally concerned that they may be exposed to a high risk of failed projects if the quality of CCPs materials is unguaranteed. To improve the quality of CCPs products, actions that can be taken by CCPs industries include enhancement of quality control, operator training and laboratory analysis, modification of equipments and operating methods, and investment in advanced facilities. CCPs industry association should increase research and data assessment to track engineering and environmental performance of CCPs projects and report the value of CCPs uses versus virgin materials. Quality control department should enhance source certification of CCPs, development and standardization of sampling and analysis protocol, and support for development of other quality control instruments (EERC, 1999).

7.3 Recommendations for government initiatives

Governmental incentives should be targeted to achieve technical innovation and to extend CCPs applications in other areas, e.g. high-value added fly ash applications, outside of the cement and concrete industries. Monetary incentives such as funding preferences should be offered by the government to encourage the research and development of such high-tech applications and to promote the transformation from patent technologies into commercial productivity. A number of researches on high value added applications, such as waste water treatment, anti-corrosion materials, glass ceramics and reflective materials, have been carried out in China (Wang & Wu, 2004). Several researches have achieved abundant accomplishment. However, because of the lack of research funds and strong support from the government, a number of projects reported work to date are still of laboratory- scale or failed to commercialization. Making policies to encourage the innovative CCPs use technologies and streamlining approval for CCPs beneficially utilization projects are required for the government.

Policy and economic incentives, including tax exemption, "green" subsidies, regulatory preferences and low interest loan, should be offered by the government to
prompt the use of CCPs that are long-term interest of the public (EERC, 1999). Eliminating regulatory barriers are also required for industries improvements that increase the commercial viability of CCPs. And those preferential policies should be well-established as long-range policies instead of annually policy determination. For government bidding construction projects, contractors or companies that use CCPs with enhanced quality and durability shall have the priority to receive bid preferences from the government. Newly built or rebuilt or extended coal-fired power plants without any ancillary CCPs utilization projects simultaneously operated should not get approval from the government. Monetary incentives for creating optimized logistical solutions to increased CCPs beneficial use should also be provided.

The widespread use of novel "green" wall materials, such as fly ash hollow blocks and aerated concrete, can be realized only when the ban of using solid clay bricks is mandatory implemented. For this reason, the government should strengthen the execution of regulations to speed up moves to ban the production and utilization of solid clay bricks in all municipalities, especially cities in coastal areas where capita farmland is scarce.

7.4 Actors’ role in overcoming the barriers to increased use of CCPs

Various barriers were identified from the perspectives of different actors involved in CCPs production and utilization. Corresponding solutions can be formulated by the initiatives from the government and industries. Actors’ role in overcoming and minimizing the barriers to increased use of CCPs is summarized in Table 8 as shown in below.

Table 8 Actors’ role in overcoming barriers to CCPs uses

<table>
<thead>
<tr>
<th>Barriers</th>
<th>Solutions</th>
<th>Actors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower rate of high-grade fly ash</td>
<td>Developing ash handling system</td>
<td>CCPs producer</td>
</tr>
<tr>
<td>Inconsistent qualities of CCPs</td>
<td>Applying classification and grinding technology</td>
<td>CCPs producer</td>
</tr>
<tr>
<td>Difficulties in using FGD materials</td>
<td>Developing mineral extraction process</td>
<td>CCPs user</td>
</tr>
<tr>
<td>Market limitation</td>
<td>CCPs Eco-Industry Park, high volume fly ash concrete technology</td>
<td>Government, CCPs producer and CCPs user</td>
</tr>
<tr>
<td>High cost for transportation</td>
<td>CCPs Eco-Industry Park</td>
<td>Government, CCPs producer and CCPs user</td>
</tr>
<tr>
<td>Spatial variation in supply-demand</td>
<td>CCPs Eco-Industry Park</td>
<td>Government, CCPs producer and CCPs user</td>
</tr>
<tr>
<td>Lack of perfect technical standards</td>
<td>Developing CCPs use technical standards and specification</td>
<td>Government and industrial institutes</td>
</tr>
<tr>
<td>Lack of practical experiences</td>
<td>Employee training and education</td>
<td>CCPs user</td>
</tr>
<tr>
<td>Weakness in using techniques</td>
<td>Applying advanced technologies, enhancing end products quality control</td>
<td>CCPs user</td>
</tr>
<tr>
<td>Challenge</td>
<td>Solution</td>
<td>Responsible Party</td>
</tr>
<tr>
<td>--------------------------------------------------------------------------</td>
<td>-------------------------------------------------</td>
<td>------------------------------------</td>
</tr>
<tr>
<td>Competition from other materials</td>
<td>Strengthening execution of solid clay bricks, providing monetary incentives and policy support</td>
<td>Government</td>
</tr>
<tr>
<td>Large variation in high grade fly ash price</td>
<td>Tightening market supervision</td>
<td>Government</td>
</tr>
<tr>
<td>Insufficient R&amp;D funds</td>
<td>Providing sufficient funds</td>
<td>Government</td>
</tr>
<tr>
<td>Unwillingness to change and negative perception on CCPs</td>
<td>Public education</td>
<td>Government, general public</td>
</tr>
<tr>
<td>Lack of familiarity with CCPs</td>
<td>Demonstration projects</td>
<td>CCPs users</td>
</tr>
</tbody>
</table>
8 Conclusions

Coal burning combined with flue gas cleaning system generates large quantity of coal combustion products, which has caused significant environmental and economic burden to the economy, ecology and society. Growing concern for scarce in useful land, shortage of natural sources and negative impacts to the environment has led to significant interests in utilization of CCPs. China as the world’s largest CCPs producer, influenced greatly by the increased environmental and economic burden resulting from the disposed and stockpiled CCPs.

Incentives

Savings of natural resources, energy, emissions of pollutants, GHG emissions and useful land were found as the major incentives for CCPs utilization. Increased use of CCPs, which can be an environmental and economic palliative, is of significant importance for achieving sustainable development.

Utilization of CCPs

The value of CCPs has been well established by researches and industrialized practices carried out all over the world. As valuable engineering materials, these products have led to the emerging of considerable utilization technologies for the purpose of saving costs while protecting the environment. Because of the substantial amounts of CCPs generated - most of which is fly ash - the focus of CCPs utilization has primarily been on high volume applications, generally as pozzolan cement replacement in civil engineering and construction areas. Such efforts have so far met with much success in China as well as other developed countries. CCPs utilization rate in different countries varies widely from 13% to 97%. The utilization rate of CCPs in the Europe Union of EU 15 has reached to a high level of 89% in 2007, and Japan used almost all of the coal ash (97%) produced in 2006. In China, from the late 1970s, the utilization rate has been hanging around at 20% for many years. Along with the increasing interested in the value of CCPs and the reinforced policies, the use rate grew rapidly and reached up to 58% in 2000. Worldwide, a significant proportion of CCPs from the main producers, e.g. China, the United States and India, however, is still being disposed off, resulting in a low-level of overall utilization of these coal combustion products. Current efforts to increase use of CCPs are not adequate as is obvious from the low level of utilization, e.g. low use rate and low value added. In many cases, the markets for CCPs as an ingredient in cementitious applications are tending to be saturated. Therefore, alternatives for CCPs utilization, such as mineral extraction, zeolite synthesis, fly ash FGD absorbent, etc., other than traditional cement and construction applications are needed to be developed and industrialized. Some of those high-value added applications have been commercialized in other developed countries while few relevant researches have been done in China. Further work in developing alternative applications of CCPs is urgently needed.

Barriers to increased use of CCPs

The role of policy makers in China over the past years has added more weight to the issue of promoting CCPs utilization. However, despite the large-scale and positive uses, more CCPs are being produced than the current applications can consume because of numerous limitations and various barriers existed in CCPs industries and domestic markets. Identification of barriers to CCPs uses is one of the foremost steps in developing CCPs utilization. Economic barriers to increased use of CCPs are
widely accepted as the most important elements among all other factors that affecting CCPs uses. The high cost of transportation of low unit-value CCPs, competition from available natural materials and spatial variation in supply-demand poses three of the most important barriers to the increased use of CCPs in China. CCPs markets in northern areas and economic backward regions are limited, to a large degree, by high transportation cost and oversupply of fly ash especially in winter months. On the other hand, the short supply of fly ash in southern area and the most economic developed costal regions has led to an unreasonable high CCPs price, which is also likely to encourage illegal speculations and inhibit the spread of different CCPs applications. More regulatory measures from the government are required for stabilizing the CCPs market. A ban of solid clay bricks was also found to be a very powerful measure to stimulate the development of other by-product based wall materials while saving useful land and protecting the environment. However, this strong policy support from the government has not been well executed, which seriously limited new initiatives and market potential.

**Corresponding solutions**

There should be a greater emphasis on eliminating and overcoming those barriers to the increased use of CCPs. Industrial organizations with assistances from the government have shown to be of fundamental importance for formulating approaches to take in overcoming the barriers. A conceptual model of CCPs Eco-Industry Park was proposed as a potential effective solution. Some marketing and economic barriers, such as transportation cost and unbalanced supply-demand, could be overcome through share of information and resources between different actors. Mutual economic and environmental benefits can be achieved through the collaboration between different industries in the CCPs EIP. It has been shown that a number of high value-added CCPs commercial applications have been attempted for several times, but few of them succeed mainly due to economic reasons. An integrated process in CCPs EIP for simultaneously extracting different high value materials from CCPs was shown to be one of the potential feasible options. The ban of solid clay bricks as another large propellant for increasing CCPs use in China aims at encouraging the use of novel construction materials produced from industrial by-products. However, the widespread use of those novel construction materials can be realized only when the ban of using solid clay bricks is mandatory executed. For this reason, strengthened execution of regulations to speed up moves to ban the production and utilization of solid clay bricks is urgently needed. The government should enhance the power of execution and provide additional economic funds and preferences to encourage the development of novel CCPs based construction materials in place of solid clay bricks.

In conclusion, there is a need for concerted effort to promote the "technically sound", "environmentally safe", and "economically justified" utilization of CCPs. A number of researches and projects on high levels utilization of CCPs have been carried out in China, however, the majority of which have not yet been commercialized. It should be emphasized that transforming such laboratory- or pilot-scale technologies into industrial productivity is of the highest priority for increased use of CCPs.
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Appendix

Questionnaire for CCPs production and utilization

1. Name of Power Plant: ______________________________

2. Capacity of the Power Plant: ________________________ MW

3. Annual CCPs production: ___________________________ tonnes

4. Applications of CCPs:
   Identified (mark: ×)
   - Concrete / Concrete Products / Grout
   - Structural Fills / Embankments
   - Mining Applications
   - Gypsum Panel Products
   - Blended Cement/ Raw Feed for Clinker
   - Waste Stabilization/Solidification
   - Burning-free Bricks
   - Road Base/Sub-base
   - Soil Modification/Stabilization
   - Aggregate
   - Grinding / Sorting
   - Agriculture
   - Mineral extraction
   - Miscellaneous / Other (if any) ________________

5. CCPs qualities: __________________________ (e.g. comply with which industrial standards)

6. CCPs price: ________________________________ ¥/tonne

7. Transport charge for CCPs: ________________________ ¥/tonne

8. Driving forces for CCPs utilization:
   Identify   Rank*
   - Landfill space release
   - Financial rewards
   - Reduction of hazardous exposure to flying ash
   - Ground water contaminant prevention
   - Investment savings
   - Other driving forces (if any) ____________________
9. Barriers to CCPs utilization:

<table>
<thead>
<tr>
<th>Identify</th>
<th>Rank*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unstable qualities of CCPs</td>
<td>☐</td>
</tr>
<tr>
<td>Low added-value</td>
<td>☐</td>
</tr>
<tr>
<td>Market limitation</td>
<td>☐</td>
</tr>
<tr>
<td>High transportation charge</td>
<td>☐</td>
</tr>
<tr>
<td>Business fraud</td>
<td>☐</td>
</tr>
<tr>
<td>Weakness in utilization technologies</td>
<td>☐</td>
</tr>
<tr>
<td>Imperfect legal system for CCPs commercial utilization</td>
<td>☐</td>
</tr>
<tr>
<td>Imperfect standard system for CCPs industrial application</td>
<td>☐</td>
</tr>
<tr>
<td>Other barriers (if any)</td>
<td>☐</td>
</tr>
</tbody>
</table>

* Identified (×); Rank (High-3; Medium-2; Low-1)

10. Is there any preference policy applied to the use of CCPs?