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Durability of Fly Ash Concrete in Salt-laden Environment

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ABSTRACT

Present paper covers some statistics regarding fly ash production and its utilization for concrete. It is shown that the production amount of coal ash in Japan exceeded over 10 million tonne. However, the relative amount of fly ash in use for concrete is low as compared with the case used for raw material in cement manufacturing process. In this way it is necessary to increase the use of fly ash as a mineral admixture for concrete. In addition it is shown that the application of fly ash concrete in marine environments is effective. This is because of a number of experiments that show significant reduction of the penetration of chloride ions in real marine structures with fly ash concretes. The calculation of apparent chloride diffusion coefficient which was proposed for fly ash concrete in the JSCE is introduced.

Keywords. Fly ash, Concrete, Statistics, Chloride ions, Diffusion coefficient

INTRODUCTION

For securing stable energy supply coal-burning power generation has played an important role in Japan. This demand will continue in future. Accordingly large amount of coal ash will be continuously produced. Disposal of coal ash is costly and carries a negative environmental impact. It is obvious for sustainable development that the utilization of coal ash is strongly encouraged (Malhotra, V.M. and Mehta P.K. 2002). Coal ash is normally divided to either fly ash or clinker ash where the relative ratio of each production amount is about 90% for fly ash and 10% for clinker ash. It has been largely recognized that fly ash has been utilized for the partial replacement of ordinary Portland cement. The use of fly ash can improve the properties of fresh concrete such as fluidity and other workability (Concrete library, 1999). In addition hardened concrete with fly ash exhibits beneficial performance as a result of the pozzolanic reaction. The primary constituent in fly ash is silica and alumina and hence can react with calcium hydroxide. Recently fly ash is extended to the use as fine aggregate. This is due to the fact that the supply of fine aggregate with a given quality suitable to concrete is not always possible in some regions of Japan. With fly ash used for the supplement of fine aggregate no reduction of cement content is necessary. This mix design concept is considered acceptable for the application of fly ash concrete in marine environments. However, compared with foreign countries the use of fly ash in concrete is still limited in Japan. In order to improve this situation the Concrete Committee in the Japan Society of Civil Engineers organized a research committee. As a result “New Utilization Technology of Fly Ash Concrete Suitable for Recycled Oriented Society” has been

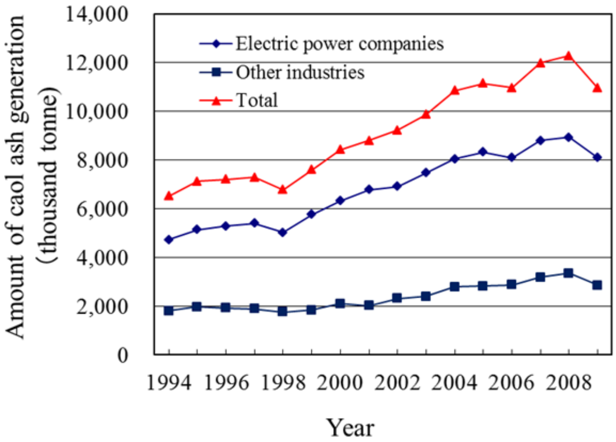
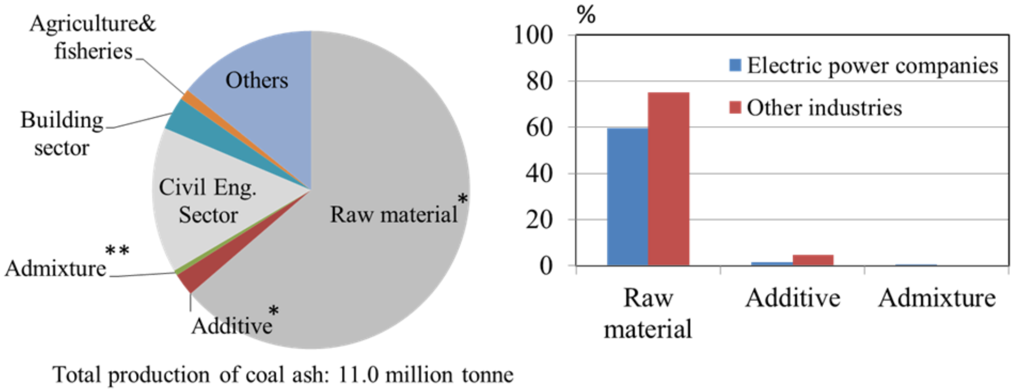


Fig. 1 Change of production amount of coal ash in Japan (Data based on JCOAL 2011)



(a) Fractions of utilization in different sectors (*: Cement sector, **:Concrete sector)

(b) Utilization of coal ash for cement and concrete sectors

Fig. 2 Utilization of coal ash in Japan (Data based on JCOAL 2011)

published in 2009 (Concrete library, 2009). Not only practical applications but also up-dated research outcomes have been provided to encourage the use of fly ash for concrete.

This paper discusses the result of recent survey regarding the production and use of coal ash in Japan. In addition the resistance to chloride penetration in fly ash concrete is discussed.

RECENT FLY ASH IN JAPAN

According to the recent survey which has been conducted by the Japan Coal Energy Center (JCOAL, 2011) the amount of coal ash (fly ash and clinker ash) production exceeds 10 million tonnes in Japan. This amount includes coal ash produced by electric power companies as well as other industries who are equipped with private power-generation facilities. Fig.1 shows the steady increase of the coal ash production until year of 2008. Approximately 80 % of the total production is attributed to electric power companies. The production amount of coal ash decreased in 2009 after continuous increase until 2008. The reason is not yet clarified for now unless similar data on the version as of 2010 is available.

Fig.2 (a) provides the comparison with the amount of the utilization of coal ash in different sectors in 2009. Cement sector contributes to its utilization by as much as 66 %. In this sector coal ash is used as a raw material and additive in cement manufacturing process. Fly ash is partially used for clay to supplement SiO_2 which is one of the primary compositions in cement clinker. Consequently the amount of fly ash used for the raw material in cement manufacturing process is the largest. This is true regardless of the supply sources of fly ash by either electric power companies or other industries (Fig.2 (b)). Other industries provide the largest percentage of fly ash for the raw material while no admixture is supplied by these industries. In concrete sector fly ash is normally used as a mineral admixture for the partial replacement of ordinary Portland cement and considered as a binder. A number of research have reported the improvement of the properties of concrete due to fly ash used as the admixture while it is recognized that the strength is relatively low at early age. It may be true that the past research was limited to phenomenological discussion showing the benefits of using fly ash in concrete. Recently quantitative evaluation of fly ash used as the admixture has been made to enable the design of fly ash concrete in a practical manner (Concrete library 1999 and 2009). Then it is encouraged to use fly ash as the admixture by partial replacement of ordinary Portland cement as well as fine aggregate. This can bring out the beneficial effect of using fly ash on the improvement of the concrete properties.

The Japan Industrial Standard (JIS) modified the specification - JIS A 6201: Fly ash for use in concrete in 1999. Four types of fly ash, namely Type I, Type II, Type III and Type IV are specified according primarily to the relative percentage of unburned carbon content and the specific surface area. For example, the Type II fly ash must meet the percentage of unburned carbon content less than or equal to 5.0% as well as the specific surface area greater than or equal to $2500cm^2/g$. However the amount of fly ash that is adapted to meet the one of four Types of specified fly ash is only 10%. In order to up-grade coal ash to meet the specification quality control and other investments are necessary on the production side. This appears to be partially the reason why coal ash for use in concrete is little to none in electric power companies and general industries. In addition, the property of fly ash varies as a result of the import of foreign coals with varied quality. From view points of the users varied properties of fly ash may not be acceptable since more quality control and additional facility to accommodate will become necessary.

CHLORIDE PENETRATION IN FLY ASH CONCRETE

Reduction of chloride penetration in real concrete structure. It has been recognized that chloride penetration in fly ash concrete is reduced (Sugiyama et al. 2002). This is often

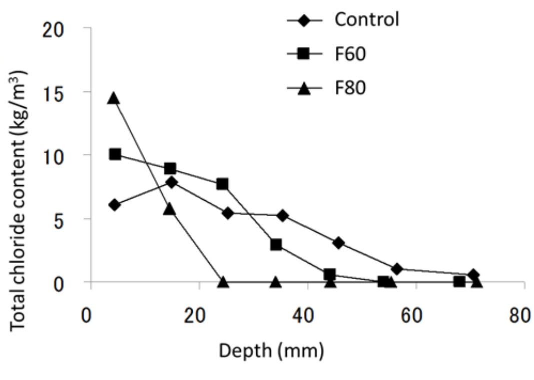


Fig. 3 Profiles of chloride penetration in fly ash concretes

explained by the resultant dense microstructure due to the pozzolanic reaction between fly ash and calcium hydroxide in concrete. To verify this favourable effect chloride penetration in real concrete structure has been investigated. Fig.3 shows the result of the chloride profiles in real concrete structures after 6.75 years under intermittent exposure to seawater in tropical weather (Suzuki et al. 2008). Type III fly ash according to JIS A 6201 was used. Two mix proportions of fly ash concretes were tested for the construction of shore protection structure while normal concrete without fly ash was prepared for control. Mix proportions were determined based on the results of several trial mixings using a concrete mixer which was planned for actual use. Unit content of fly ash was increased to 60 and 80 kg/m^3. They are labelled as F60 and F80, respectively in Fig.3. Water to cement ratio was 70% and 59%, for F60 and F80, respectively. The unit cement content for F60 was 245kg/m^3 and fly ash was used for its partial replacement. On the other hand the cement content was 295kg/m^3 for F80 in which the fly ash was used as fine aggregate for partial replacement of sand.

As shown in Fig.3 it is apparent that F80 exhibits the greatest resistance against the chloride penetration. Although the chloride content in near surface zone was the highest the depth of chloride penetration was less than 30mm from the exposure surface. F60 shows better resistance to chloride penetration as compared with the case of normal concrete (Control). Consequently the fly ash concrete could provide the significant reduction in the chloride penetration. In this verification fly ash replacement of sand exhibited better performance than the cement replacement.

Apparent chloride diffusion coefficient of fly ash concrete. Chloride penetration in fly ash concrete is controlled by its age. Fig. 4 shows the comparison of the apparent chloride diffusion coefficients of fly ash concretes with different exposure periods (Iguchi et al. 2009). It is found that the apparent chloride diffusion coefficient is reduced with elapsed periods in salt-laden environment. The diffusion coefficients of fly ash concrete with the exposure periods of 5 or longer years were the lowest as compared with the cases with exposure periods shorter than 5 years. The pozzolanic reaction of fly ash is a time dependent reaction. Therefore full potential of beneficial effects provided by the addition of fly ash is manifested at later ages.

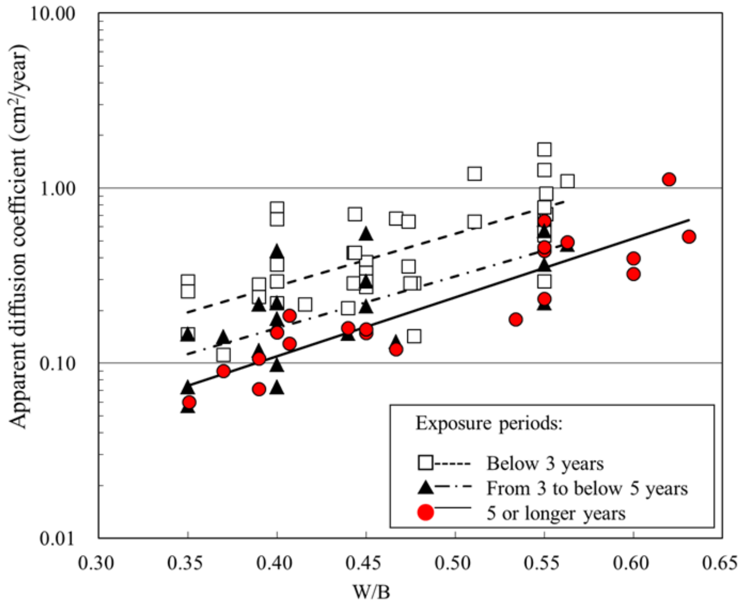


Fig. 4 Time dependent chloride diffusion coefficients of fly ash concretes

Fig.4 also exhibits that increased W/B (Water to binder ratio) results in larger diffusion coefficient. The binder in this study is fly ash regardless of the replacement method, i.e. replacement of either cement or sand as defined in Eq.(1).

$$W/B = W/\left(C + FA1 + FA2\right) \tag{1}$$

Where *W* is the unit water content, B is the binder, *C* is the unit cement content, *FA1* is the amount of fly ash for partial replacement of cement and *FA2* is the fly ash for partial replacement of fine aggregate.

Fig. 5 The IRABU GREAT Bridge under construction. Courtesy by Prof. Tomiyama

Apparent chloride diffusion coefficient of fly ash concrete has been proposed based on the data given in Fig.4 (Concrete library, 2009). The proposed equation is shown in Eq.(2).

$$\log D_p = 3.0(W/B) - 1.9 \tag{2}$$

Where D_p is apparent chloride diffusion coefficient (cm^2/year)

CONSTRUCTION OF FLY ASH CONCRETE IN MARINE ENVIRONMENT

Fly ash concrete was used for the substructure of the IRABU GREAT Bridge in Okinawa prefecture. This bridge which has a total span length of 3540 m, will be expected to start its service in 2013. The bridge was designed in such way as to provide adequate durability for as long as 100 years under harsh marine environment. Benefits of using fly ash for the bridge columns are expected as follows:

(a) Resistance to chloride penetration
(b) Reduction of Alkali Silica Reaction
(c) Reduction of thermal cracking

The utilized fly ash was Type II, which was available from local electric power company who has produced coal ash yearly by approximately 10 thousands tonne. It was anticipated that approximately 50 tonnes of fly ash was consumed monthly through the construction of this bridge. Therefore this project contributes largely to the Zero-Emission Plan for Okinawa Island (Kazama, 2010). In this regard the fly ash was planned to use from environmental points of view.

Past research has demonstrated that the total amount of fly ash should be limited below 100kg/m^3. Use of fly ash with over 100kg/m^3 showed too much viscosity resulting in decreased workability. In addition, by considering strength development and pumpability of fly ash concrete the replacement ratio of cement was set at 20%. After numerous discussions and trial mixings the mix proportion given in Table 1 as FAC was proposed for use (Kazama, 2010). OPC is the base mix proportion without fly ash. The amount of fly ash for the cement replacement (F1) was 65kg/m^3 while fly ash was replaced by 25kg/m^3 for fine aggregates (F2). Design strength was 27N/mm^2 and target slump was initially 8cm and increased later to 12.5 cm with the range of 10.0 to 15.0cm. This increase was made by controlling the amount of chemical admixture. The air content was not specified for fly ash concrete because no frost damage is expected under tropical marine environment on the construction site.

Table 1 Mix proportion of fly ash concrete

Mix No.	W/(C+F1) (%)	s/a (%)	Unit Content (kg/m^3)						Chemical[*4]
			W	C	F1	F2	S	G	(C+F1)%
FAC	49.5	38.6[*1]	156	250	65	25	672 [*2]	1145 [*3]	0.475
OPC	49.5	38.0	156	315	0	0	703	1173	0.3-0.5[*5]

*1: s=Volume of F2 and S, *2: 399kg for sea sand and 273kg for crashed sand, *3: 458kg for 5 to 40mm size and 687kg for 5 to 20mm size, *4: air entrained water reducer, *5: unit in kg/m^3

Fig.5 The IRABU GREAT bridge under construction. Courtesy by Prof. Tomiyama

CONCLUSIONS

It was shown that the amount of coal ash (fly ash and clinker ash) production exceeds 10 million tonne in Japan. Cement sector contributes to its utilization by as large as 66 % in use for a raw material and additive in cement manufacturing process. In order to have beneficial effects of fly ash the amount of utilization for admixture in concrete needs to increase. Fly ash concrete used for real concrete structure in salt laden environment demonstrated the reduction of chloride penetration. Apparent chloride diffusion coefficient proposed for fly ash concrete was introduced.

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