論 文 の 要 旨

題 目 EVALUATION OF THE CEMENTING EFFICIENCY FACTOR OF LOW-CALCIUM FLY ASH FOR STRENGTH DEVELOPMENT AND CHLORIDE-PENETRATION RESISTANCE OF CONCRETES
(コンクリートの強度発現性および塩分浸透抵抗性に関するフライアッシュのセメント有効係数の評価)

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Fly ash is known as a pozzolanic material, which possesses a little or no cementitious value. In order that fly ash is effectively used to replace part of the cement in the concrete, its cementing efficiency factor (*k*-value) that indicates its contribution to the mechanical and durability properties of concretes has been investigated by several studies. The quantity of the fly ash in concrete can be multiplied by the *k*-value to estimate the equivalent cement content, which can be added to the existing cement content for the determination of the water-to-cement ratio in the mixture. This leads to the more effective design of concrete mixture proportion that contains the fly ash as a supplementary cementitious material.

Most of the proposed methods for determining the *k*-value of fly ash are for the compressive strength of concretes due to the simplicity and reliability of compression tests. Only a few studies have evaluated the *k*-value of fly ash for the durability of concretes, especially for the chloride-penetration resistances. Additionally, the effects of cement type and water-to-binder (W/B) ratio on the *k*-value of fly ash for strength development of concretes have not been evaluated in a chemical approach yet. Namely, there is a lack of research evaluating the effect of fly ash reaction degree on its *k*-value, and the correlation between the *k*-value of fly ash for strength development and that for chloride-penetration resistance of concretes has not been discussed in previous studies. The three objectives of this research are the following: (1) evaluation of the effect of cement type and W/B ratio on the *k*-value of fly ash for the concrete-strength development for a long period, (2) investigation in a simple approach the *k*-value of fly ash for the chloride-penetration resistance of concretes using the chloride-penetration depth as a concrete-durability property (3) experimental evaluation of the effect of fly ash reactions on its *k*-value for the concrete-strength development and chloride-penetration resistance of concretes. In addition to these, the correlation between the *k*-value of fly ash for the strength and durability of the concrete is obtained. The discussion on these evaluations would be shown by using the results of chemical analysis and/or pore structure analysis. To achieve these objectives, this dissertation is organized as follows:

Chapter 1 provides the background and motivation of this study.

Chapter 2 presents a brief review on fly ash and its *k*-value for the concrete-strength development and chloride-penetration resistance of concretes.

Chapter 3 describes the experimental program consisting of materials and mixture proportions, the mixing, casting, and curing condition for the paste and concrete specimens. This study uses a low-calcium fly ash which is one of the most popular fly ashes as mineral admixtures in Japan. Control concrete samples with W/B ratios of 0.30, 0.40, 0.50, and 0.60 by mass were prepared to experimentally evaluate the *k*-value of fly ash. Cement was partially replaced with fly ash at ratios of 20% to 40% by mass for the paste and concrete specimens with a W/B ratio of 0.50. To evaluate the *k*-value of fly ash for the strength development of

concretes, two types of cement, namely, ordinary Portland cement (OPC) and high-early-strength Portland cement (HSPC) were used for making paste and concrete specimens. In addition, a W/B ratio of 0.30 was further used for making OPC specimens to investigate effect of W/B ratio on the *k*-value of fly ash for the concrete-strength development. All the paste and concrete specimens were sealed and stored at 20 ºC until the designated ages. For evaluation of the *k*-value of fly ash for the chloride-penetration resistance of concretes, only the OPC and two fly ash replacement ratios of 20% (F20) and 40% (F40) by mass for the paste and concrete specimens with a W/B ratio of 0.50 were investigated. The specimens cured for 91 days were immersed in a sodium chloride solution (10% NaCl).

Chapter 4 investigates the effects of cement type and W/B ratio on the *k*-value of low-calcium fly ash for the concrete-strength development. The obtained results indicate that the cement type strongly affects the *k*-value of fly ash for concrete-strength development because of the significant difference in the Blaine fineness between cement and fly ash as well as the difference in the relationships between cement-to-water ratio and compressive strength of the control concretes. For OPC concrete, a lower W/B ratio has a higher *k*-value at the early ages mainly because of cement-hydration-enhancement effect of fly ash, and all the *k*-values increased significantly after 28 days due to the pozzolanic reaction of fly ash. Further, a modified equation of the CH consumption taking the cement-hydration-enhancement effect into account was firstly proposed to evaluate precisely the CH consumption in fly-ash cement paste. This result is consistent well with the result of the degree of fly ash reaction, especially for OPC paste with a low W/B ratio of 0.30.

Chapter 5 aims at simply evaluating the *k*-value of low-calcium fly ash for the chloride-penetration resistance of concretes using the chloride-penetration depth (x_d). The chloride concentration profile and the x_d are examined, whereas the *k*-value of fly ash for the chloride-penetration resistance of concretes is evaluated by using the apparent diffusion coefficient (D_{app}) of chloride ion as well as the x_d. Additionally, the results of pore size distribution in pastes are presented in this chapter. The results indicate that x_d could be used as a concrete-durability property to obtain the *k*-value of fly ash in a simple approach compared to the D_{app}. The *k*-values of fly ash based on the x_d of the concrete after the immersion periods of 13, 26, and 39 weeks ranged from 2.75 to 3.94 and from 1.96 to 2.69 for F20 and F40 samples, respectively. The replacement of 40% or less cement by fly ash in the concretes with a W/B ratio of 0.50 yielded chloride-penetration resistance that is as good as that of plain cement concrete with a W/B ratio of 0.30 after 39 weeks of exposure to a 10% NaCl solution with regard to the chloride-diffusion coefficient.

Chapter 6 discusses (1) the relationship between the *k*-value of fly ash for concrete-strength development and the degree of fly ash reaction, (2) the effect of the degree of fly ash reaction on the *k*-value for the chloride-penetration resistance of concretes, and (3) the difference between the *k*-value for the compressive strength and that for the chloride-penetration resistance. Briefly, the *k*-value of fly ash for the strength development of concretes increased linearly with an increase in the degree of fly ash reaction regardless of cement type and W/B ratio. Also, the *k*-value of fly ash based on the x_d of concretes increased linearly with the increment in the degree of fly ash reaction subsequent to the start of immersion. For OPC concretes with a W/B ratio of 0.50, the *k*-value of fly ash for the chloride-penetration resistance of the concrete was approximately 2.5 higher than that for the concrete-strength development at each corresponding time.

Chapter 7 summaries the conclusions of this study. Recommendations for the future research are suggested as well. This study indicated that the *k*-value of fly ash for the strength of concretes was strongly affected by the cement type and W/B ratio. In addition, the x_d could be used as a concrete-durability property to obtain the *k*-value of fly ash for the durability of concretes in a simple approach compared to the D_{app}.