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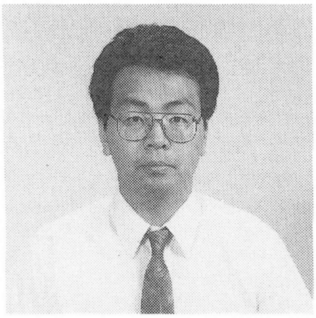
A NEW METHOD OF EVALUATING THE ACTIVITY OF GROUND GRANULATED BLAST-FURNACE SLAG

(Translation from Proceedings of JSCE, No.414/V-12, Feb. 1990)



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SYNOPSIS

Mortar specimens for compressive strength test were prepared using six kinds of ground granulated blast-furnace slags of various Blaine specific surface areas. Water-cement ratio and sand-cement ratio of reference mortar containing no ground slag were fixed at 0.50 and 2.50, respectively. Replacement ratios of cement by ground slag were set at 30, 50 and 70 % by volume. Both the preparation and moist-curing of the specimens were made at a constant temperature; i.e., 5, 10, or 20 C. The results of compressive strength test were analyzed to derive equations, by which the effects of each influential factor could be evaluated quantitatively. New two indices, which are independent on various factors, were proposed for the evaluation of the activity of ground slags.

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1. INTRODUCTION

Ground granulated blast-furnace slag (hereafter, this will be simply called "ground slag") to be used for the improvement of the qualities of concrete has also a role of binding material in concrete. Since the degree of the binding capability of ground slag is mainly dependent on its activity, specifications in many countries for ground slag stipulate its activity, generally in terms of Slag Activity Index (SAI). SAI is the relative compressive strength of mortar made with 50-50 weight combinations (as in U.S.A. and Japan) or volume combinations (as in Canada) of ground slag and ordinary portland cement to that of reference mortar made with the same weight or volume of ordinary portland cement as the total weight or volume of ground slag and cement in the test mortar. If test conditions, both cement and sand to be used, and mix proportions are maintained constant, SAI may be a useful index for evaluating the activity of various ground slags under those conditions. In certain restricted conditions, it may be possible to predict, to some extent, the strength development of concrete containing ground slag [1]. However, many of previous papers clearly showed that the strength development of slag concrete was greatly influenced by many factors; the effects of the replacement ratio of cement by ground slag and curing temperature being particularly significant [2,3]. Therefore, it is hard to state that SAI obtained at a standard temperature (20 C) from specimens of a constant slag replacement rate (50 %) is a general index applicable to other cases where the rate of slag replacement and/or temperature are different.

In the present work, mortar specimens which were prepared using various kinds of ground slags at different replacing rates and cured under three different temperatures were tested for their compressive strength at various ages. The effect of each influential factor on the strength of mortar was, then, analyzed step by step using the test results to derive an evaluation equation with which not only the effect of each factor but also total effects of all factors on the strength of mortar could be evaluated quantitatively. Two coefficients contained in the equation, which are independent of any of the factors, were found to be characteristic values to express the activity of incorporated ground slag. It was proposed to employ these two values for the evaluation of the activity of ground slag.

2. MATERIALS

Two kinds of water-granulated blast-furnace slags KO and B were obtained from different sources, and each was ground to 3 different levels of fineness in order to produce a total of 6 ground slag samples. For grinding the slags, a small-scale jet mill was used for slag KO and industrial ball mill for slag B. The physical properties and chemical compositions of the samples thus prepared are shown in Table 1. In this table, the chemical compositions for KO series are represented by those for the original slag KO, because the jet mill used for this series was cleaned thoroughly before every grinding.

Cement used in this study is ordinary portland cement, the physical properties and chemical compositions of which are shown Table 2. In a part of the study, an inert mineral fine, which was prepared by grinding Toyoura standard sand in a small size ball mill to the fineness of 4310 cm^2/g Blaine surface, was used in place of ground slag. Specific gravity of the mineral fine was measured to be 2.64. For fine aggregate, Kinu River sand (specific gravity: 2.60, absorption: 2.17, fineness modulus: 2.56) was used.

Table 1 Physical properties and chemical compositions of ground slags

Ground Slags	Specific Gravity	Specific Surface*1 (cm^2/g)	Chemical Compositions (%)									Basicity*2	Loss on Ignition (%)
			CaO	SiO_2	Al_2O_3	MgO	SO_3	TiO_2	S	MnO	Fe_2O_3		
KO5	2.90	7000 (5380)	42.9	33.9	13.1	6.5	----	0.75	0.9	0.67	----	1.850	+0.48
KO3	2.90	10110 (8180)											
KO1	2.90	11540 (9820)											
B3	2.90	6260 (3650)	42.49	33.23	15.09	6.00	0.13	1.07	0.70	0.74	0.46	1.913	+0.26
B5	2.90	10040 (6000)	43.03	32.45	14.77	5.85	0.70	1.05	0.73	0.61	0.51	1.961	+0.29
B8	2.90	12530 (7710)	42.75	32.95	15.24	5.89	0.51	1.07	0.73	0.65	0.39	1.939	+0.60

*1 Calculated specific surface area using the particle size distributions analyzed by laser beam method, assuming that particles are spherical.
The values in parentheses are Blaine specific surface areas.
*2 $(CaO+MgO+Al_2O_3)/SiO_2$

Table 2 Physical properties and chemical compositions of cement

Cement	Specific Gravity	Specific Surface* (cm^2/g)	Chemical Compositions (%)								Loss on Ignition (%)
			CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	K_2O	Na_2O	
C	3.16	2820 (3260)	64.7	22.0	5.2	3.0	1.5	2.0	0.53	0.28	1.0

* Calculated specific surface area using the particle size distributions analyzed by laser beam method, assuming that particles are spherical.
The value in parenthesis is Blaine specific surface area.

3. EXPERIMENTAL WORKS

Water-cement ratio and sand-cement ratio of reference mortar with no ground slag were fixed at 0.50 and 2.50, respectively. This mix proportion represents that of the portion of mortar in concrete generally in use and is the same as that of reference mortar specified in the JSCE Standard "Ground Granulated Blast-Furnace Slag for Concrete." When ground slag or mineral fine is used, 30, 50 or 70 % of the cement in the reference mortar was replaced by the same volume of ground slag or mineral fine as the volume of the replaced cement; i.e., the volume ratios of cement plus ground slag or mineral fine to water and fine aggregate were kept constant for all mortars.

Test temperatures were set at 5, 10 and 20 C, and the storage of materials, mixing of mortar, and preparation and curing of specimens were all conducted at respective test temperature. In the case of mortars with inert mineral fine, however, their tests were made only at 5 and 20 C. When ground slag or mineral fine was used, its required quantity was premixed sufficiently with weighed cement in a plastic bag. A mortar mixer conforming to JIS R 5201 (5 liter capacity) was used to mix 1.2-2.3 liters of mortar.

Three cylindrical mortar specimens (5 cm diameter. x 10cm) were prepared from 2 batches of mortar for their compressive strength test at each test age. Their capping by cement paste and demolding were made when their maturities reached 15 and 30 DD, respectively. Demolded specimens were immediately placed in water controlled at the test temperature and cured until their test ages. The compressive strength test was made at 3, 7, 28 and 91 days.

4. TEST RESULTS AND THEIR ANALYSIS

Table 3 summarizes the results of compressive strength test of slag mortars, and Fig. 1 shows examples of the strength development of slag mortars drawn using

Table 3 Compressive strength test data of mortar

Unit : kgf/cm^2

Ground Slags			20°C				10°C				5°C			
Name	Specific Surface (cm^2/g)	Replacing Rate[*3] (%)	Testing Age of Mortar (days)											
			1	7	28	91	1	7	28	91	1	7	28	91
None[*1]	2820[*2]	0	202	327	459	542	117	258	436	526	77	204	414	505
KO5	7000	50	97	199	448	570	38	123	327	473	21	79	282	459
		70	85	220	405	-	-	-	-	-	13	67	266	-
KO3	10110	30	-	308	529	-	-	212	459	-	-	147	421	-
		50	153	313	533	642	58	190	476	571	33	127	403	571
		70	156	325	542	-	-	180	419	-	24	110	382	-
KO1	11540	30	-	327	533	-	-	218	453	-	-	150	427	-
		50	176	353	546	640	65	221	473	571	32	137	440	586
		70	-	369	562	-	-	217	459	-	-	130	435	-
B3	6260	30	-	212	396	-	-	155	331	-	-	112	303	-
		50	87	159	377	508	38	107	265	383	23	76	225	364
B5	10040	50	124	250	438	544	53	163	399	525	28	109	370	513
B8	12530	50	164	364	559	598	67	220	487	533	34	139	460	569
		70	-	343	509	-	-	213	458	-	-	128	431	-

Note: Each compressive strength in this table is the mean of three values obtained from three specimens.

*1 Reference mortar: Water-cement ratio = 0.50, Sand-cement ratio = 2.50
*2 Specific surface area of cement
*3 Replacing rate of cement in reference mortar by ground slags on volume basis.

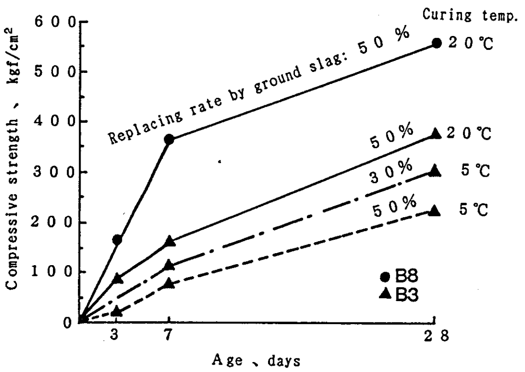

Fig. 1 Examples of the strength development of slag mortars

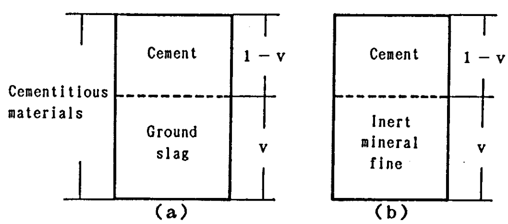

Fig. 2 Schematical diagram of cementious materials in mortar

representative results in Table 3. As can be seen in the figure, it was also confirmed in this study that the strengths of slag mortars differed greatly depending on the fineness and replacing rate of ground slags, ages, curing temperature, and so forth. These differences in strength are considered to be caused by the differences in the hydration reaction of binding materials or hardening properties of paste portion influenced by many factors as mentioned above. Paying attention to this point, an attempt was made to analyze step by step the test results for the effects of influential factors in the following sections. It may be noted that water-cement ratio of reference mortar is assumed to be constant, say, 50 % in the analysis, since the mix proportions of mortars were so determined as mentioned in the previous chapter.

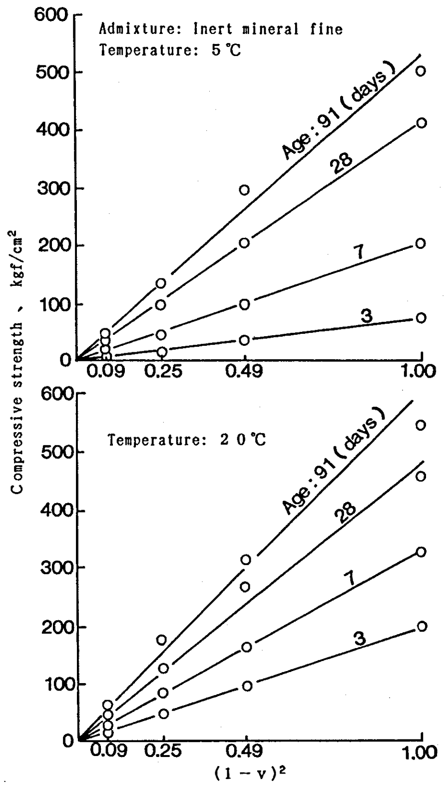

Fig. 3 $(1\text{-}v)^2$ vs. compressive strength

(1) Formulation of Effect of Replacing Rate of Ground Slag

The portion of cementitious materials in slag mortar or slag concrete, in which a part of its cement is replaced by ground slag of the same volume as that of the replaced cement, can be schematically expressed as Fig. 2 (a), where v is the replacing rate by ground slag on volume basis. The strength development of mortar or concrete containing these cementitious materials would be brought about as a total effect of the contribution by each cementitious material to the gain of strength. However, neither the extent of the contribution by each cementitious material nor the means to evaluate the total effect has been clarified yet. Therefore, as the first step, the effect of the portion of cement only in Fig. 2(a) on the strength development of mortar was examined by conducting a series of experiment in which inert siliceous fine was incorporated in place of ground slag as shown in Fig. 2 (b).

Fig. 3 shows the results of compressive strength test of mortars with cement and inert siliceous fine as cementitious materials. In this figure, compressive strength was plotted against the square of the volume proportion of cement in the portion of cementitious materials, i.e., $(1\text{-}v)^2$. It is seen from this figure that, for both temperature conditions of 5 and 20 C, the relation between the two quantities for each test age may be approximated by a straight line which passes through the origin, although the test results at later ages lie a little apart from the lines. From these results, the compressive strength (f_0) of mortar containing inert siliceous fine in place of ground slag was assumed to be expressed by Eq.(1) using the parameter (1-v).

$$f_0 = \{K_c(1-v)\}^2 \qquad (1)$$

where, K_c : coefficient representing the effectiveness of the contribution of cement to the strength gain. (The value varies with curing temperature and age.)

It may be noted here that the role of inert fine particles to help develop the strength by providing additional space for hydration products in flocks of cement particles as proposed by Yamazaki [4] is included in Eq.(1).

If we set v=0 in Eq.(1), f_0 is considered to be the strength of reference mortar (f_b) and, therefore, K_c can be expressed as:

$$K_c = \sqrt{f_b} \tag{2}$$

It is expected that the compressive strength of slag mortar may be expressed by adding in the parenthesis { } in Eq.(1) a proper term or terms, which will be also a function of the replacing rate (v). With this expectation, Eq.(3) was assumed to express the compressive strength of slag mortar where K_{sv} denotes the term or terms for the strength increase due to the use of ground slag. Eq.(4) is a transformed form of Eq.(3),

$$f_m = \{K_c(1-v) + K_{sv}\}^2 \tag{3}$$

$$K_{sv} = \sqrt{f_m} - K_c(1-v) \tag{4}$$

where, f_m : compressive strength of slag mortar
1-v : volume proportion of cement in cementitious materials

In order to examine the functional form of K_{sv}, the values of K_{sv} at all replacing rates for all the ground slags were, then, calculated by substituting both the values of K_c read from Fig. 3 or calculated by Eq.(2) and the compressive strengths of slag mortar (f_m) in Table 3 into Eq.(4), and the results were plotted against the replacing rate (v) by ground slag.

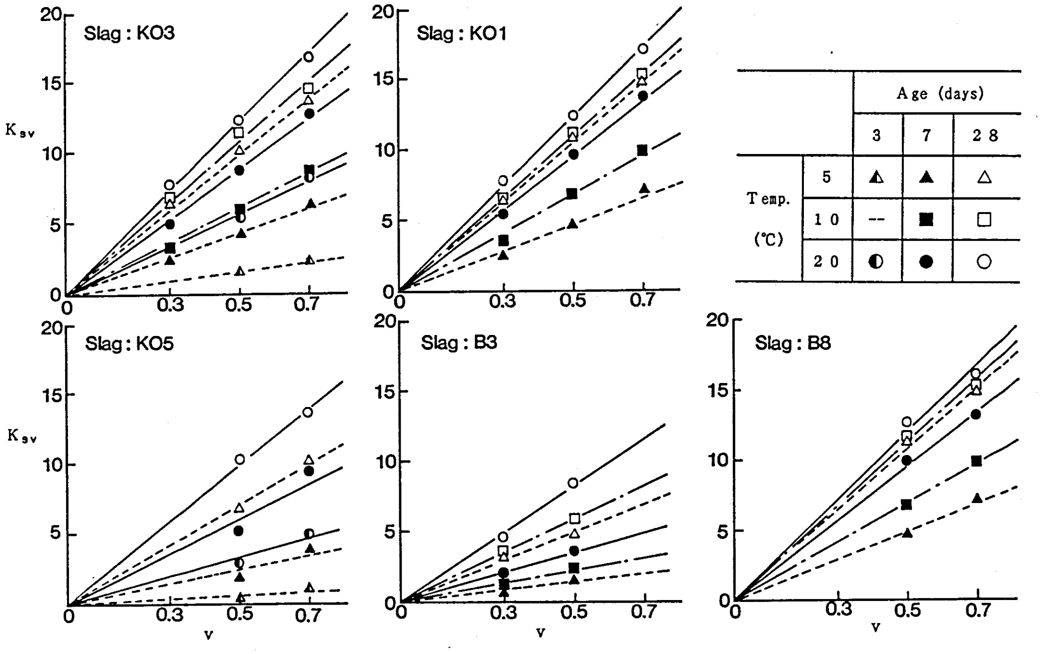

Fig. 4 Relation between v and K_{sv} (unit of K_{sv}: $\sqrt{kgf/cm^2}$)

Fig. 4 shows the relation between the replacing rate (v) and calculated K_{sv}. It is seen in this figure that, when both the curing temperature and test age of slag mortar are fixed, the relations for all the ground slags can be represented by straight lines which pass through the origin. That is,

$$K_{sv} = K_s v \qquad (5)$$

where, K_s : coefficient representing the effectiveness of the contribution of ground slag to the strength gain. (The value varies with curing temperature and age.)

Substitution of Eq.(5) into Eq.(3) results in,

$$f_m = \{K_c(1-v) + K_s v\}^2 \qquad (6)$$

Eq.(6) thus obtained can be regarded as a general equation which shows the relation between the replacing rate by ground slag and the compressive strength of slag mortar, and the effects of curing temperatures and ages on the strength development are taken into account in the values of K_c and K_s. The two coefficients, K_c and K_s, which respectively represent the effectiveness of the contribution of cement and ground slag to the strength gain of slag mortar, can be also regarded as quantities which are related to the activity of respective cementitious materials.

(2) Formulation of Effects of Curing Temperature and Age

Table 4 lists all values of K_c and K_s determined for all cementitious materials in the present work following the above-mentioned procedures. As a matter of course, the values are greatly differ each other depending on the kinds of cementitious materials, curing temperatures and ages. In the next place, therefore, the effects of curing temperature and age on the values of K_c and K_s were examined by applying the concept of maturity. Maturity (M) is a quantity which is often employed for the evaluation of the combined effects of temperature and age on the strength development of concrete, and Eq.(7) is often employed for its calculation.

$$M = \sum t(T + 10) \qquad (7)$$

where, t : age (days)
T : curing temperature (C)

Table 4 Values of K_c for cement and K_s for ground slags

Unit: $\sqrt{kgf/cm^2}$

K	Cementitious Materials	20℃				10℃				5℃			
		3 days	7 days	28days	91days	3 days	7 days	28days	91days	3 days	7 days	28days	91days
K_c	C	14.21	18.16	21.91	23.90	10.82	16.06	20.88	22.93	8.64	14.21	20.35	22.96
K_s	KO5	6.56*	12.27*	19.72*	23.85	1.49	6.12	15.29	20.57	1.13*	4.91*	14.12*	19.89
	KO3	11.34*	17.55*	24.17*	26.78	4.42	11.92*	21.30*	24.86	3.10*	8.55*	19.57*	24.83
	KO1	12.32	19.40*	24.72*	26.70	5.32	13.75*	22.01*	24.86	2.62	9.62*	21.27*	25.45
	B3	4.40	6.82*	16.46*	21.18	1.44	4.46*	11.75*	16.21	0.95	2.93*	9.88*	15.20
	B5	8.06	13.46	19.95	22.75	3.77	9.47	19.07	22.90	1.91	6.67	18.12	22.34
	B8	11.40	19.12*	23.70*	25.01	5.51	13.85*	22.18*	23.24	3.04	9.83*	21.48*	24.75

* Values obtained by applying the least square method to v-K_{sv} relations.

Fig. 5 shows the values of K_c in Table 4 plotted against the respective maturity values which were calculated by Eq.(7) using the values of curing temperatures and ages shown in the same table. Fig. 6 shows the relation between K_s and maturity obtained in the same way as Fig. 5 for each ground slag. It is seen in Fig. 5 that the relation between the two quantities can be expressed by a single curve irrespective of curing temperature, and that the K_c value increases greatly in the region of low maturity, whereas the rate of its increase decreases gradually with the increase in maturity. On the other hand, the relation between K_s and maturity for each ground slag differs a little depending on curing temperature as seen in Fig. 6, although their relation can be well approximated by a similar curve to the curve in Fig. 5 if curing temperature is fixed. Further close observation of Fig. 6 reveals that, in all the cases of ground slags, the curves for lower temperatures than 10 C tend to intercept the maturity axis at a point a little sifted to the right of the origin, whereas the curves for 20 C pass through the origin. These differences of the curves caused by temperature difference may imply that the activity of ground slag is more sensitive to temperature compared with that of cement.

The relation between the values of K_c or K_s (hereafter, these values will be called "K value" when they are named generically) and maturity observable in Fig. 5 or Fig. 6 will be generally represented by such a model curve as shown in Fig. 7. In the present work, an attempt was made to use Eq.(8) to formulate the model curve. This equation was originally used by Carino and Lew [5] to express the strength-maturity relation of concrete.

$$K = \frac{M - M_0}{\dfrac{1}{a} + \dfrac{M - M_0}{b}} \qquad (8)$$

Eq.(8) is a hyperbola which can be determined by its initial tangent (:a), the asymptotically approaching maximum value of K (:b), and the intercept of the curve with M axis (:M_0). (See Fig. 7) These features of the equation are considered to be conveniently used for the evaluation of the activity of cementitious materials, provided its application to the test results is proved to be appropriate. That is, if the equation is adaptable, the value "a" can be a characteristic value of cementitious materials which expresses the degree of their contribution to the strength development of mortar at initial stages, since it is the rate of increase in K with maturity at the beginning of the curve. The value "b" can be another characteristic value which expresses the degree of contribution of cementitious materials to the gain of the finally attainable strength of mortar, because it is the asymptotically approaching maximum value of K at the infinite maturity.

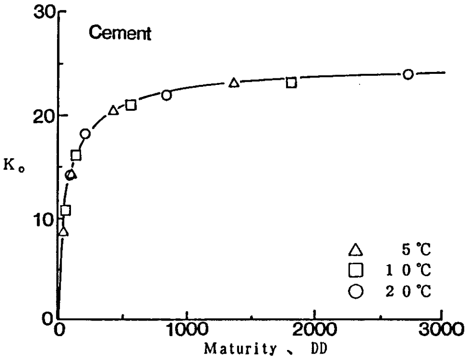

Fig. 5 Maturity vs. Kc

(unit of Kc: $\sqrt{kgf/cm^2}$)

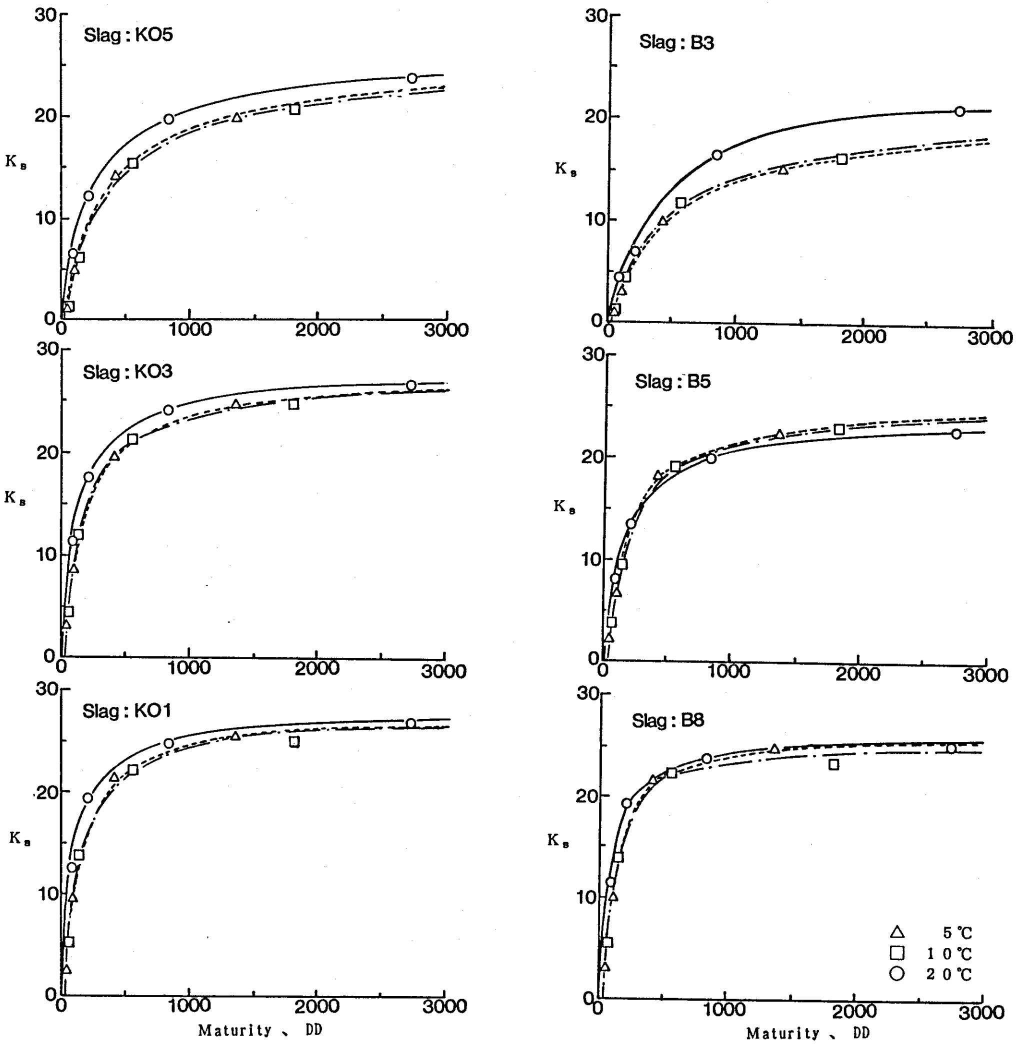

Fig. 6 Maturity vs. K_s (unit of K_s: $\sqrt{kgf/cm^2}$)

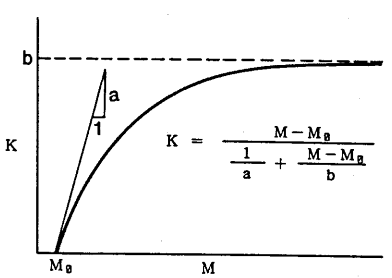

Fig. 7 Model for M-K relation

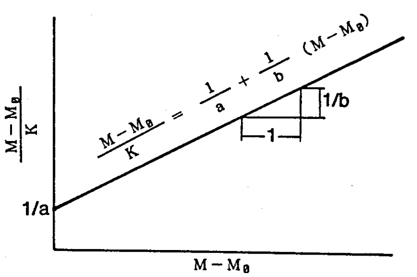

Fig. 8 $(M\text{-}M_0)$ vs. $(M\text{-}M_0)/K$

On the other hand, M_0 is considered to be a maturity after which cementitious materials start to contribute substantially to the strength development of mortar. The approximate values of M_0 can be read from Figs. 5 and 6. The values of M_0 were, however, determined for all the cases in the figures by applying the method of least squares to Eq.(8) for fitting the data, because the applicability of the equation was under study in the present work. The results indicated that all values of M_0 for cement were 0 DD irrespective of curing temperature. On the other hand, the values of M_0 were 0 DD for 20 C curing, and about 30 DD when cured at lower temperatures (5 and 10 C), for all kinds of ground slags. Taking these results into account, Eq.(8) was rewritten as Eqs.(9) and (10) to give K values for cement and ground slags, respectively.

$$K_c = \frac{M}{\dfrac{1}{a_c} + \dfrac{M}{b_c}} \tag{9}$$

$$K_s = \frac{M - M_0}{\dfrac{1}{a_s} + \dfrac{M - M_0}{b_s}} \tag{10}$$

where a_c: characteristic value of cement which expresses the degree of its contribution to the strength development at initial stages

a_s: characteristic value of ground slag which expresses the degree of its contribution to the strength development at initial stages

b_c: characteristic value of cement which expresses the degree of its contribution to the gain of the finally attainable strength

b_s: characteristic value of ground slag which expresses the degree of its contribution to the gain of the finally attainable strength

M_0: 0 (DD) ....for curing at 20 C

30 (DD) ....for curing at 5 C and 10 C

Eq.(8) for the model curve in Fig. 7 can be transformed into Eq.(11). Then, it is apparent that there exists a linear relation between $(M-M_0)/K$ and $(M-M_0)$ as shown in Fig. 8, and that "a" and "b" can be easily determined from the intercept with the longitudinal axis and gradient of the line, respectively.

$$\frac{M - M_0}{K} = \frac{1}{a} + \frac{M - M_0}{b} \tag{11}$$

In order to examine both the applicability of Eq.(8) to the test results and appropriateness of the above-mentioned values of M_0, Eqs.(9) and (10) were transformed into the same form as that of Eq.(11), and the previous M-K relations for all the cementitious materials were changed into new relationships between M and (M/K) or $(M-M_0)$ and $(M-M_0)/K$. The new relations are shown in Figs. 9 and 10. Observation of these figures reveals that the relation between the new quantities is not influenced by curing temperature and can be expressed by a straight line for each cementitious material. Furthermore, all the plotted points are in excellent agreement with the straight lines which were obtained by applying the least square method to the plots. These results are considered to certify that Eq.(8) can be applied quite successfully to the model for the test results of the current study, and that Eqs.(9) and (10) can be employed for the accurate calculation of the values of K_c and K_s.

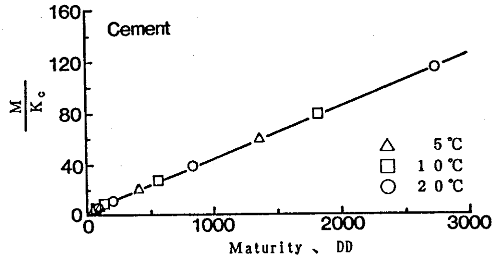

Fig. 9 Relation between maturity(M) and M/K_c
(unit of M/K_c: $DD/\sqrt{kgf/cm^2}$)

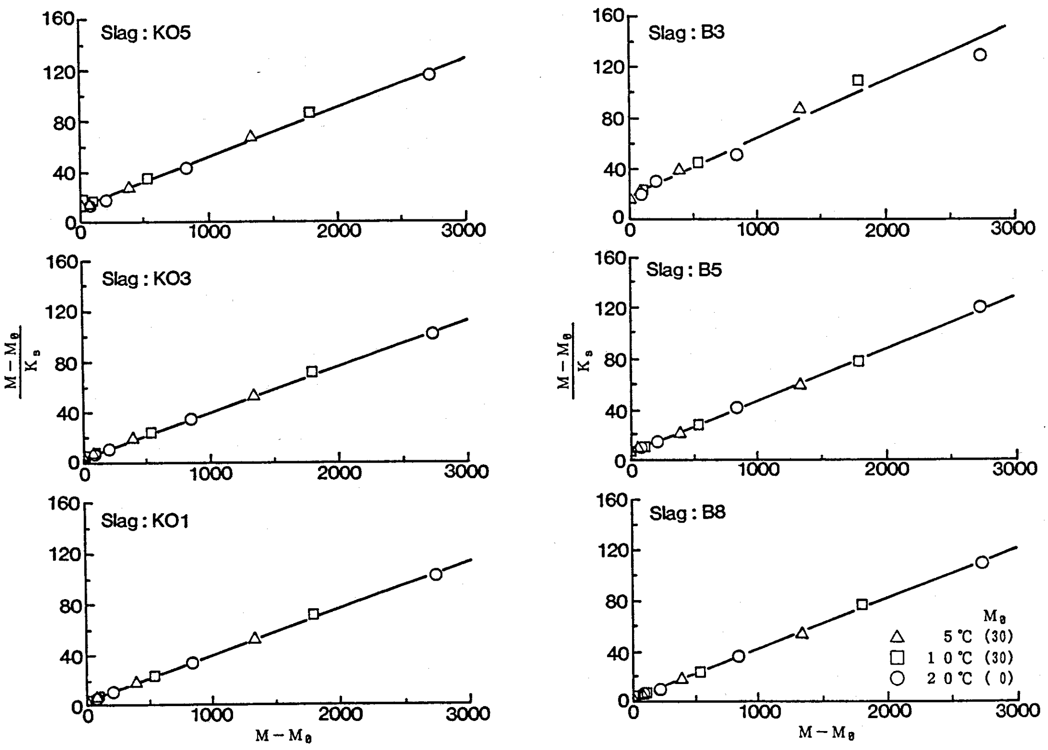

Fig. 10 Relation between $(M-M_0)$ and $(M-M_0)/K_s$ (unit of $(M-M_0)/K_s$: $DD/\sqrt{kgf/cm^2}$)

From the above discussions, it is evident now that K_c and K_s, which represent the effectiveness of the contribution of cement and ground slag, respectively, to the strength gain of mortar, can be adequately evaluated by introducing the maturity function (M), and Eqs.(9) and (10) can be employed for their calculation. It may be added here that the values of M_0 for other temperatures than those studied at the present study are uncertain, because no test result is available. However, it would be reasonable to assume that the value is 0 DD for higher temperatures than 20 C. In addition, no significant difference will be observed in the results of data analysis, even if a linear approximation is made for its value at a temperature (T) between 10 and 20 C using $M_0 = 60-3T$.

(3) Indices for Evaluating Activity of Ground Slag

The numerical values of a_c, b_c, a_s and b_s do change if the water-cement ratio of reference mortar is altered. However, even when the water-cement ratio is altered, they will still remain to be characteristic values of cementitious materials at the altered water-cement ratio and express the degrees of contribution of cementitious materials to the strength development of mortar at both initial and late ages. Their another feature is that they are independent on such factors as the replacing rate of cement by ground slag, ages and curing temperature. Furthermore, they are such quantities as to make it possible to calculate the strength of mortar at any age for arbitrary curing temperature and/or replacing rate of cement by ground slag through the use of Eq.(6), once K values are determined by substituting them into Eqs.(9) and (10). Consideration of these characteristics would lead to an expectation that the numerical values might be such quantities as to express the degrees of activity inherent in respective cementitious materials at a fixed water-cement ratio. Table 5 summarizes these values obtained for all the cementitious materials used in the present work.

If one assumes that the values of a_c, b_c, a_s and b_s are inherent in respective cementitious materials as mentioned above, the values of a_s of a group of ground slags that were made from the same water-granulated slag will be in proportion to their specific surface areas. In order to examine this point, both the values of a_s and specific surface areas per unit volume of ground slags (S_{VS}) were converted to their ratios to those of cement and the relation between the two quantities was plotted in Fig. 11. In this examination, specific surface areas which were calculated from particle size distributions obtained by laser method were employed. This is based on the authors' study that laser method gave more realistic and accurate information on specific surface area than Blaine method, when specific surface areas were quite large or when fines were produced from different raw materials or by different grinding methods [6]. It is seen in Fig. 11 that a_s/a_c increases linearly with the increase of S_{VS}/S_{VC} as expected. It may be interesting to noted that all the values of a_s/a_c is smaller than 1.0 and ground slags must have a specific surface area about 4.5 times larger than that of cement in order to contribute to the strength development of mortar at initial stages to the same extent as cement.

On the other hand, it is natural to expect that the values of b_s for ground slags made from the same raw material will be constant regardless of their

Table 5 Characteristic values of cementitious materials

unit of a: $\sqrt{kgf/cm^2}/DD$
unit of b: $\sqrt{kgf/cm^2}$

Cement	a_c	b_c
C	0.308	24.33

Ground Slags	a_s	b_s
KO5	0.076	26.04
KO3	0.188	27.78
KO1	0.228	27.55
B3	0.049	22.88
B5	0.145	24.51
B8	0.266	25.71

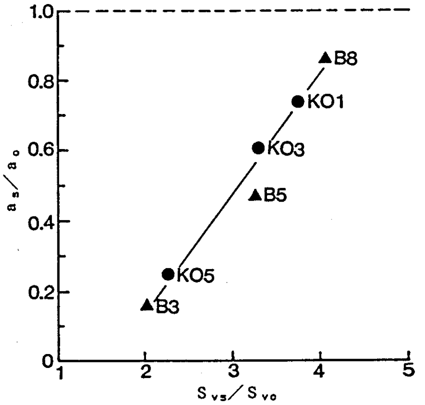

Fig. 11 S_{VS}/S_{VC} vs. a_s/a_c

specific surface area, if their nature as mentioned before is taken into consideration. Referring to Table 5, the values of b_s for ground slags within respective series (K0 and B) are nearly equal each other as were expected to be. Also observable in Table 5 is that the values of b_s are generally larger than b_c. This would support the general test results that the use of ground slags increases the long term strength of concrete. These results are considered to indicate that a_s and b_s are not only the values inherent in respective ground slags, but also rational and superior indices with which the activity of ground slags can be expressed.

Such useful characteristic values as mentioned above can be easily obtained by performing the strength test on both reference mortar and slag mortar at 3 to 4 ages and, then, drawing such linear relationships as indicated in Fig. 10. In this case, test ages and temperatures may be arbitrarily selected provided that the strengths of both reference mortar and slag mortar are tested at the same maturity (M), although it is desirable to select them in such a way that the values of $(M-M_0)$ distribute in a wide range. The replacing rate by ground slag can be also arbitrarily selected, although it may be desirable to set it at about 50 %. Considering these convenience of testing procedures and the previously mentioned rational characteristics of the values, the authors propose to name a_s and b_s coefficient of initial activity and coefficient of long-time activity, respectively, and to use them or their relative values to the corresponding values of cement as new indices for evaluating the activity of ground slags. It may be added here that these coefficients varies depending on cement to be used together. However, this is also true for the case of slag activity index which is currently employed in many countries.

The method of evaluating the activity of ground slags as described above is considered to be also applicable to other various mineral fines such as fly ash and silica fume and various kinds of cement as a useful means for the evaluation of their relative activity. If the contents of the current study is advanced, it may become possible to establish a method with which the strength of mortar or concrete under arbitrary conditions can be estimated. These points will be investigated further in future work.

5. CONCLUSIONS

Within the limits of current study, the following conclusions may be drawn.

(1) The compressive strength of slag mortar, which is made by replacing a part of cement in the reference mortar with ground slag of equal volume to the volume of the replaced cement, can be generally expressed by the following equation.

$$f_m = \{K_c(1-v)) + K_s v\}^2$$

where, f_m: compressive strength of slag mortar
K_c: coefficient representing the effectiveness of the contribution of cement to the strength gain
K_s: coefficient representing the effectiveness of the contribution of ground slag to the strength gain
v: replacing rate of cement by ground slag on volume basis

(2) The above coefficients, K_c and K_s, can be expressed by the following equations for arbitrary curing temperatures (T) and ages (t).

$$K_c = \frac{M}{\frac{1}{a_c} + \frac{M}{b_c}} \tag{9}$$

$$K_s = \frac{M - M_0}{\frac{1}{a_s} + \frac{M - M_0}{b_s}} \tag{10}$$

$$M = \sum t(T + 10)$$

where a_c: characteristic value of cement which expresses the degree of its contribution to the strength development at initial stages

a_s: characteristic value of ground slag which expresses the degree of its contribution to the strength development at initial stages

b_c: characteristic value of cement which expresses the degree of its contribution to the gain of the finally attainable strength

b_s: characteristic value of ground slag which expresses the degree of its contribution to the gain of the finally attainable strength

M_0: 0 (DD) ....for curing at higher temperature than 20 C

60-3T (DD) ....for curing at 10 and 20 C

30 (DD) ....for curing at 5 to 10 C

(3) If water-cement ratio of reference mortar is fixed and a part of its cement is replaced by the same volume of ground slag as the replaced cement, such characteristic values as a_c, b_c, a_s and b_s can be easily determined as follows.

Firstly, the compressive strengths of reference mortar and slag mortar are tested at 3 to 4 ages. The ages shall be so selected that they are common to both kinds of mortars and the values of maturity (M) distribute in a wide range. Secondly, K_c and K_s for each age are calculated using the equations shown below. Then, the values of M/K_c and M, or $(M-M_0)/K_s$ and $(M-M_0)$ are calculated for each age, and the results are plotted in a rectangular co-ordinate system with the former quantity in ordinate and the latter in abscissa. The reciprocals of both the intercept with the ordinate and gradient of the linear equation which is obtained by applying the least square method to the plots are a_c or a_s, and b_c or b_s, respectively.

$$K_c = \sqrt{f_b}$$

$$K_s = \{\sqrt{f_m} - K_c(1-v)\}/v$$

where, f_b: compressive strength of reference mortar

(4) Such characteristic values as a_c, b_c, a_s and b_s have a feature of being independent of the replacing rate of cement by ground slag, test age and test temperature, and are quantities with which the activity inherent in respective ground slag can be represented. The authors propose to name a_s and b_s coefficient of initial activity and coefficient of long-time activity, respectively, and to use them or their relative values as new indices for the evaluation of the activity of ground slag in place of SAI currently employed in many countries.

ACKNOWLEDGEMENTS

A grant was received from Sumitomo Metal Industries Ltd. in carrying out the present work. Grinding of slag and measurement of particle size distribution of ground slags by laser method were conducted through the kind offices of persons at Seisin Enterprises Inc. The assistance of Mr. M. Iidaka, Technical Staff of Inst. of Engineering Mechanics, Univ. of Tsukuba, was received in the experimental part of the study. The authors wish to express sincere thanks to all of these parties.

REFERENCES

[1] Yamamoto, Y.: "Commentary on the JSCE specification of ground granulated blast-furnace slag", Concrete Library, No. 63, JSCE, 1988.
[2] For example, Endo, Y., Kodama, K., Nakagawa, O. and Takada, M.: "Effects of the use of ground granulated blast-furnace slags on the mixing proportions and strength of concrete", Proc. of Symp. on the Application of Ground Granulated Blast-Furnace Slag in Concrete (AGSC), JSCE, 1987.
[3] For example, Imai, M., Oh-hashi, T. and Saito, A.: "Properties of concrete incorporating ground granulated blast-furnace slags", Proc. of Symp. on AGSC, JSCE, 1987.
[4] Yamazaki, K.: "Fundamental studies of the effects of mineral fines on the workability and strength of concrete", Concrete Library, No. 8, JSCE, 1963.
[5] Carino, N. J. and Lew, H. S.: "Temperature effect on strength-maturity relations of mortar", Journal of ACI, Vol.80, No. 3, ACI, 1983.
[6] Chikamatsu, R. and Yamamoto, Y.: "A study on the methods of evaluating the fineness of ground granulated blast-furnace slag", Proc. of JSCE, Vol. 420 (V-3), JSCE, 1990.