- Technical Paper -

Study of Mechanical Properties of Portland Blast Furnace Cement-Type B Concrete with Partial Replacement of Aggregate with Porous Ceramic Course Aggregate

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ABSTRACT

Fracture energy tests were carried out on Portland blast furnace cement-type B (BB) where as an internal curing material, partial replacement of course aggregate was carried out with porous ceramic-roof material waste (PCCA). The results obtained at age 28 days showed that the fracture energy was larger under drying condition than that under sealed condition independent of replacement ratio of PCCA from 0 to 40%, and furthermore, the fracture energy was the largest in case of 10 % replacement ratio independent of exposure condition.

Keywords: Portland blast furnace cement-type B concrete, Porous ceramic-roof material waste, Replacement ratio, Internal curing, Fracture energy

1. INTRODUCTION

It has been known that the hydration reaction of BB is slower than that of ordinary Portland cement concrete (NC). The BB usually needs a longer wet curing treatment at the early ages to develop the required performances [1]. In the last decade, studies on application of artificial light-weight aggregate or super absorbent polymer particle as an internal curing material have been actively carried out for the purpose of reducing early age shrinkage of low water to cement (W/C) ratio concrete [2]. This internal curing technique may be effective in improving BB quality, especially when BB is exposed to the air at early ages.

In Chugoku district “Sekishu Kawara”, which is a roof material made of clay, about 20,000 ton per year of this material is produced, 10% of which is demolished due to thermal cracking induced damage, and expected to be recycled. This waste aggregate designated as porous ceramic course aggregate (PCCA) has a crushing value of 20% which is an intermediate value [3] between artificial light weight aggregate at 40% and natural aggregate at 10%. This PCCA has been reported to be effective in improving the performances of BB in drying condition in terms of strength and porosity [4].

On the other hand, the effect of fracture energy on shear strength of concrete was reported by Gustafsson *et al* [5] for normal strength concrete and Mitani *et al* [6] for ultra high strength concrete beams, where decrease in fracture energy resulted in decreased shear strength at diagonal cracking. Therefore, when PCCA is applied to structural concrete, understanding of the fracture energy of concrete with PCCA concrete should be indispensable

Based on the above discussion, the present study aims to investigate the effects of the replacement of coarse aggregate with PCCA as well as exposure condition on fracture energy of BB concrete.

2. TEST PROGRAMS

2.1 Materials and mixture proportions

Table 1 lists the material properties of the materials used in the present study. Portland blast furnace cement-type B (BB) was used as reference concrete for comparison with BB where part of the course aggregate (NCA) was replaced with PCCA. The PCCA was 8-9% in water absorption rate after being immersed for 7 days. Crushed quartz (QS) mixed with limestone (LS) sand was used as fine aggregate and crushed gravel (NCA) was used as coarse aggregate.

Table 2 tabulates the mixture proportions of the five types of concrete prepared in this study. The water to cement ratio was fixed at 0.5. BB-G10, BB-G20, BB-G30 and BB-G40 denotes BB whose replacement ratios of PCCA are 10%, 20%, 30% and 40% respectively of the total volume of course aggregate. The total amounts of water absorbed in PCCA was 7.7kg/m^3, 15.3kg/m^3, 23.0kg/m^3 and 30.7kg/m^3 for the above mixture proportions respectively.

2.2 Exposure Condition

The exposure conditions are shown in Table 3. The specimens were covered with aluminum adhesive tape and wet fabric immediately after casting to avoid early water loss through evaporation. All the specimens were demolded at age 3 days and sealing of the sealed condition specimen was done using aluminum adhesive tape. The air temperature and humidity conditions were 20±1℃ and 60±5% for all conditions.

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Table 1 Material properties

Materials	Type	Properties	Notation
Cement	Portland blast furnace cement-Type B	Specific gravity: 3.02 Specific surface area: 3650cm^2/g	BB
Fine aggregates	Crushed quartz	Surface-dry Specific gravity: 2.60 Water arbsorption: 1.06%	QS
	Crushed Limestone	Surface-dry Specific gravity: 2.65 Water arbsorption: 1.22%	LS
Course aggregates	Crushed gravel (Sandstone)	Surface-dry Specific gravity: 2.62 Water arbsorption: 0.69% Crushing value: 12%, Aggregate size: 5-20mm	NCA
	Porous ceramic coarse aggregate	Surface-dry Specific gravity: 2.24 Water absorption: 9.0% Crushing value: 21%, Aggregate size: 5-20mm	PCA
Chemical admixtures	Air entraining agent Air entraining and water reducing agent	Polyalkylene glycol derivative Lignin sulfonic acid compound and polycol complex	AD

Table 2 Mixture proportions

Name of specimen	W/C	Air(%)	s/a	Unit weight (kg/m^3)					
				W	BB	S	LS	G	PCCA
BB	0.5	4.5	0.45	165	330	475	323	988	–
BB-G10								889	85
BB-G20								790	170
BB-G30								692	256
BB-G40								593	341

Table 3 Exposure conditions

Exposure condition	Ages (days)		
	3	7	28
Exposed at the age of 3 days	Sealed	→ Drying	
Sealed condition	→ Sealed		

2.1 Loading and measurements

(1) Strength and Young's modulus

Compressive strengths and Young's modulus tests were carried out at ages 3, 7 and 28 days in accordance with JIS A 1108 in which cylindrical specimens with diameter of 100mm and height of 200mm were used. Splitting tensile strength tests were carried out at age 7 and 28 days in accordance with JIS A 1113 in which cylindrical specimens with diameter 150mm and height 200mm were used. In the case of BB-G30 and BB-G40, only the strengths and Young's modulus at the age of 28 days were determined.

(2) Shrinkage

Shrinkage was measured from age 1 day to 28 days on prismatic concrete specimens (100×100×400mm) using a contact strain gage with a minimum graduation of 0.001mm.

(3) Fracture energy

The fracture energy tests were carried out at the age of 28 days in accordance to Japan Concrete Institute Standard (JCI-S-002-2003) [7] and for each mixture proportion, 4 specimens for each condition of dimension 100mm×100mm×400mm were prepared.

In each specimen, a notch at the mid-length to a depth of 50mm, as shown in Fig. 1 was made. In addition, to avoid the effects of shrinkage after making the notch, the maximum time allowed before loading was 3 hours. Loading was carried out using capacity 100kN displacement controlled loading apparatus. In order to eliminate torsional action on the specimen, the loading block and one of the supports were rotatable around their axes in the direction coincidental with the specimen axis. Both supports were hinged with rollers. The crack opening displacement (COD) was measured using a clip gauge of accuracy 1/1000mm.

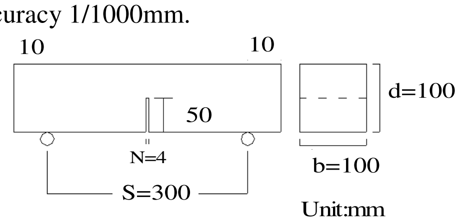


Fig. 1 Outline of the specimen

Characteristic lengths of the specimen were also obtained at the age of 28 days using the Eq. 1 below.

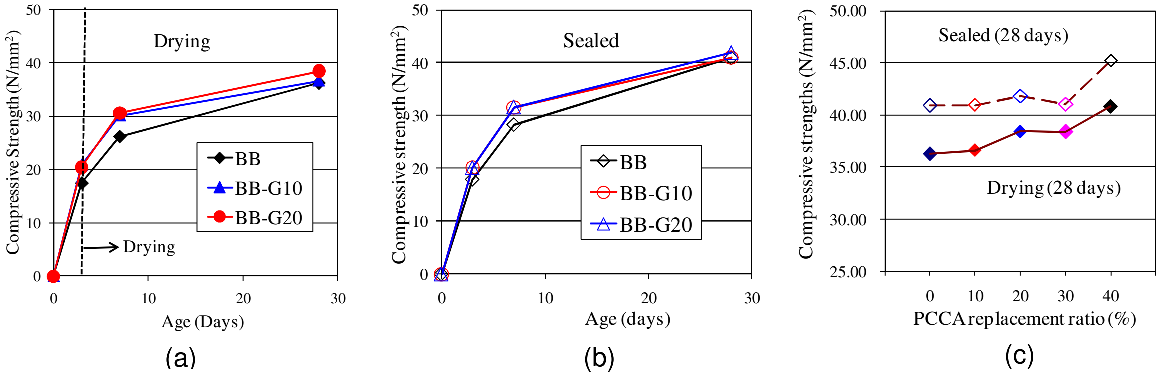


Fig. 2 Effects of internal curing on compressive strength of concretes

$$l_{ch} = \frac{E_c G_f}{f_t^2} \qquad (1)$$

Where,
G_f = Fracture energy (N/mm^2)
E_c = Young's modulus (N/mm^2)
f_t = Tensile strength (N/mm^2)

3. RESULTS AND DISCUSSIONS

3.1 Strengths and Young's modulus

The test results have been summarized in Table 4 below. The effects of internal curing on compressive strengths are shown on Fig. 2. According to Fig.2 (a) and (b), it can be said that both the drying and sealed conditions show similar development in the compressive strengths and no significant effect of the addition of PCCA was observed up to age 7 days. However, after 7 days, the compressive strength of the internally cured mixtures increase slightly compared to that of the reference mixture (BB). This can be attributed to the internal curing effect of PCCA where the water absorbed in the pore system of PCCA supplies additional water to produce further hydration products between 7 and 28 days. Although there is only a slight increase, it shows that replacement of NCA with PCCA did not have negative effects on the compressive strength of the internally cured concretes. From Fig. 2 (c), it is found that regardless of the replacement ratio of PCCA, the compressive strengths of up to 30% replacement ratio increase slightly both in the drying and sealed conditions and those of 40% replacement ratio increase noticeably in both conditions. In addition, the compressive strengths of the sealed condition increase by about 10% compared to those of the drying condition.

The effects of internal curing on splitting tensile strengths of concretes are shown on Fig. 3. From Fig. 3 (a) and (b), in both conditions, regardless of the replacement ratio, there is no significant increase in the splitting tensile strengths up to age 7 days compared to that of BB. Between 7 and 28 days, the splitting tensile strengths of the internally cured mixtures increase beyond those of the BB in both conditions. From Fig. 3 (c), it was found that regardless of the replacement ratio, the splitting tensile strengths in both drying and sealed conditions are higher than those obtained through the formula provided in the JSCE standard [8].

The effects of partial replacement of NCA with PCCA on Young's modulus of concretes are shown on Fig. 4. From Fig. 4 (a), it was found that Young's modulus decreases gradually as the replacement with PCCA increases. Fig 4 (b) shows relationship between Young's modulus and compressive strengths in which the relationship obtained by JSCE Standard [9] is also shown. According to this figure, Young's modulus of concrete with PCCA exposed to the air is smaller than that by JSCE as well as that sealed. This may be due to low density of concrete [10].

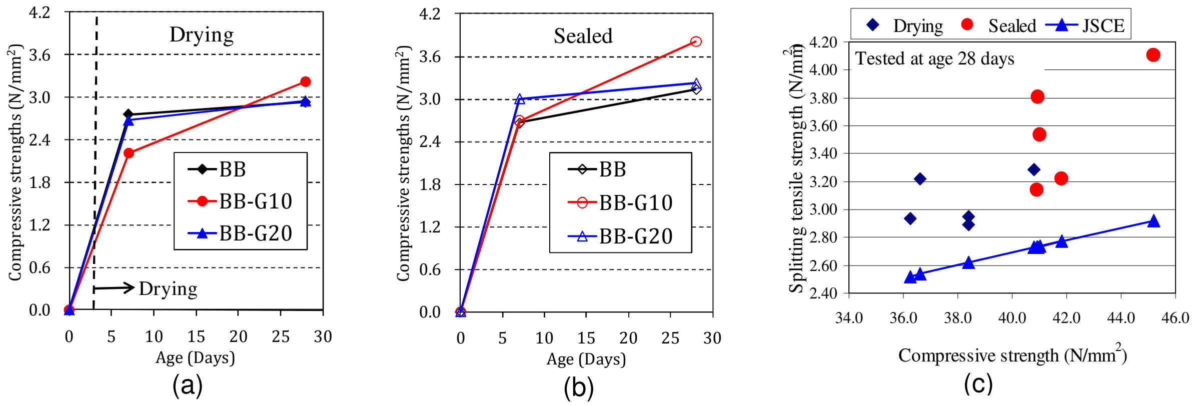
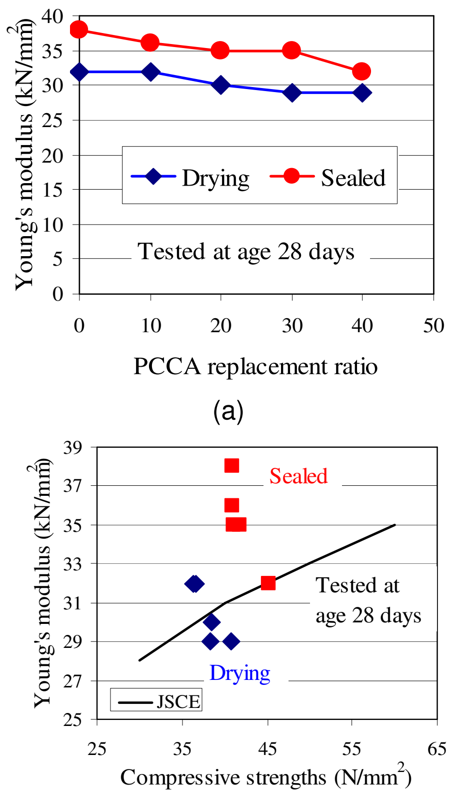


Fig. 3 Effects of internal curing on splitting tensile strength of concrete

Table 4 Test results

Name of specimen	Compressive Strength		Splitting Tensile Strength		Young's Modulus		No.	Fracture Energy				Characteristic Length	
	f'_c (N/mm^2)		f_t (N/mm^2)		E_c (kN/mm^2)			G_f (N/mm)				l_{ch} (mm)	
	Drying	Sealed	Drying	Sealed	Drying	Sealed		Drying	Average	Sealed	Average	Drying	Sealed
BB	36.27	40.89	2.93	3.14	32	38	1	0.147	0.155	0.133	0.117	577.7	440.2
							2	0.170		0.104			
							3	0.155		0.113			
							4	0.148		0.118			
BB-G10	36.62	40.93	3.22	3.81	32	36	1	0.223	0.211	0.160	0.150	549.4	279.6
							2	0.222		0.144			
							3	0.202		0.155			
							4	0.197		0.142			
BB-G20	38.42	41.83	2.95	3.22	30	35	1	0.188	0.189	0.137	0.143	549.2	347.4
							2	0.202		0.178			
							3	0.189		0.127			
							4	0.176		0.129			
BB-G30	38.40	41.00	2.89	3.53	29	35	1	0.179	0.156	0.132	0.135	541.8	352.8
							2	0.149		0.141			
							3	0.217		0.131			
							4	0.139		0.098			
BB-G40	40.80	45.20	3.29	4.11	29	32	1	0.155	0.138	0.103	0.124	391.1	219.1
							2	0.136		0.137			
							3	0.124		0.131			
							4	0.170		0.092			



(b)

Fig. 4 Effects of partial replacement of NCA with PCCA on Young's modulus

3.2 Shrinkage

Fig.5 shows the effect of PCCA on autogenous and drying shrinkages of BB, BB-G10 and BB-G20. The solid lines indicate autogenous shrinkage and the dashed lines indicate shrinkage after exposure at the age of 3 days (drying shrinkage). From this figure, it is found that autogenous shrinkage of both BB-G10 and BB-G20 compared to BB is slightly reduced through internal curing effect of PCCA. In addition, a comparison of the drying shrinkages shows that the drying shrinkage of BB-G20 is lower than that of BB and BB-G10. This could be explained by the contribution of internal curing ever under exposure to drying.

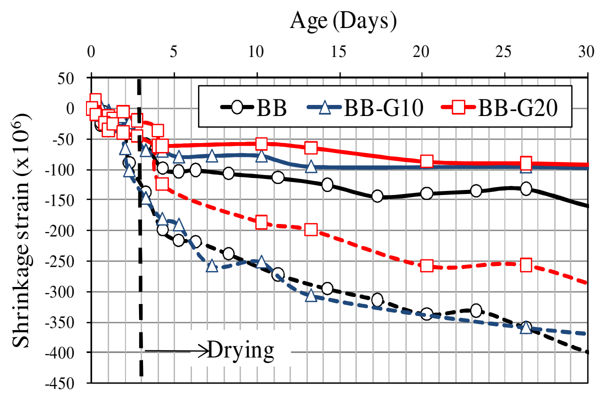
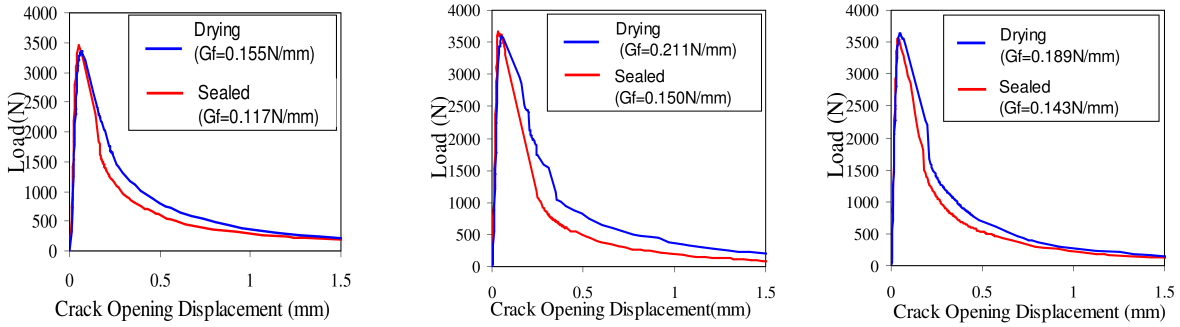


Fig. 5 Effects of PCCA on Shrinkage

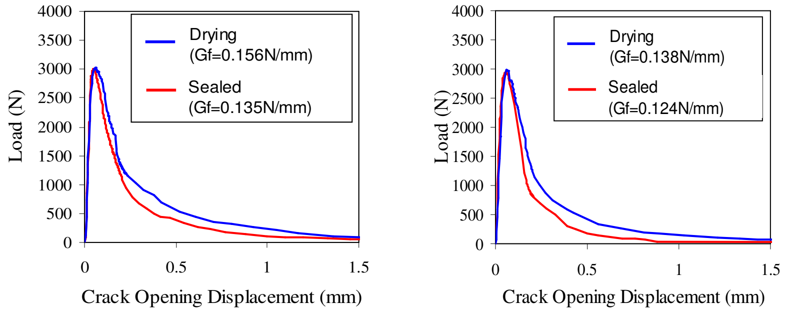
3.3 Fracture energy

The Load-Crack Opening Displacement (COD) curves are shown in Fig 6-1 and Fig 6-2. The legends indicate the exposure condition and the respective average values of fracture energy. . From the figure, it can be seen that independent of the replacement ratio and the exposure condition, the fracture energy in micro cracking zone and the bridging zone increases in all cases. In addition, the effects of the high crushing value of PCCA were not observed.



(a) BB (b) BB-G10 (c) BB-G20

Fig. 6-1 Load-Crack opening displacement curves



(d) BB-G30 (e) BB-G40

Fig. 6-2 Load-Crack opening displacement curves

Fig. 7 shows the effects of replacement of NCA with PCCA and exposure conditions on fracture energy of the concrete mixtures. The parenthesized values in the figure indicate the ratio of fracture energies of internally cured concretes to that of the reference mixture BB. As shown in this figure, increase in fracture energy is highest in the case of BB-G10 independent of the exposure condition, and thereafter shows a decreasing trend as the replacement ratio of PCCA increases above 20%.This could be explained by the assumptions that 10% replacement of PCCA is sufficient to effectively cure concrete with W/C of 0.5 and, the smaller the amount of replacement with PCCA with a crushing value higher than that of natural aggregate is, the greater fracture energy becomes. Contrary to what has been reported in the case where PCCA is used in ultra high strength concrete where 20% replacement in mass of NCA was carried out[6], there is an increase in fracture energy of BB-G10, BB-G20 and BB-G30 in drying condition where it is 1.36, 1.22 and 1.01 times, respectively, higher than that of BB. In the case of BB-G40 a decrease by 11% (0.89 times) is observed. In the case of sealed condition, fracture energy was 1.28, 1.22, 1.15 and 1.06 times, respectively, higher than that of BB. This increase can be attributed to the internal curing effects of PCCA on BB while as mentioned before, the fracture energy decreases as the replacement ratio increases.

A comparison of the two exposure conditions shows that there was a difference in fracture energy where the drying condition showed higher values than the sealed condition in all cases. For the case of BB, BB-G10, BB-G20, BB-G30 and BB-G40 there was a decrease by 32%, 40%, 32% 15% and 11%, respectively.

Although there is no clear explanation for this phenomenon, considering the results in Fig.6 that fracture energies of all specimens under drying are increased by bridging effect of coarse aggregate, and furthermore, fracture energies are also increased in the stage of micro cracking in case of BB-G10 and BB-G20, one of the reasons of the increase could be due to compressive stresses acting on the cement paste-aggregate interface caused by drying shrinkage in cement paste In addition, the internal curing effect of an appropriate replacement with PCCA where it promotes hydration may contribute to enhancing bond strength at interface between mortar and course aggregate as well as tensile strength of mortar.

Another reason could be the high surface energy in the specimens under drying condition compared with that of sealed concrete. Surface energy has been reported to increase, resulting in the increase of strengths of concrete as the moisture content in concrete decreases [11]. Assuming that this concept can be applied to the fracture energy, larger fracture energy under drying condition may be due to the larger surface energy

The above reasons are only assumptions as to why the difference in fracture energy between the two conditions occurs. More work in this area is required to find out the reliability of the above assumptions.

Fig. 8 shows the relationship between characteristic length and PCCA replacement ratio. From this figure, with increase in the replacement ratio, slight decrease in characteristic length within the replacement ratio of 30% is observed in both exposure conditions, which is a different tendency from that observed in Fig. 7.

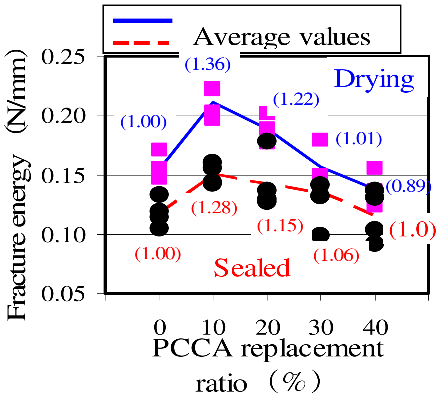


Fig. 7 Effects of replacement ratio of PCCA on fracture energy

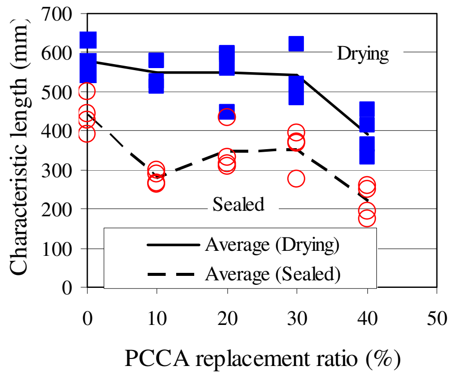


Fig. 8 Relationship between characteristic length and PCCA replacement ratio

4. CONCLUSIONS

The present study aims at investigating the fracture energy properties of BB with partial replacement of NCA with PCCA. Based on the experimental results, the following conclusions can be drawn within the limit of the present study:

(1) The internal curing effect of PCCA on compressive strength and splitting tensile strengths of BB is not noticeable at early ages.
(2) There is only a slight decrease in Young's modulus with increase in PCCA replacement ratio
(3) The internal curing effect of PCCA was effective in mitigating the autogenous shrinkage of both BB-G10 and BB-G20 but in the case of drying shrinkage, it was effective in reducing that of BB-G20, and not effective in BB-G10.
(4) There was a decrease in fracture energies of the sealed specimens compared to the specimens exposed to drying independent of the exposure condition.
(5) The increase in fracture energy was largest in the case of BB-G10 independent of exposure conditions. The fracture energy increased at a range of 0.6~36.2% up to replacement ratio 30% compared to BB in the drying condition, while a decrease by 11% was observed in the case of BB-G40 in the same condition. In the sealed condition, the range of increase was 5.7%~28.4% for all the mixture proportions compared to BB. This shows that the high crushing value of PCCA had very minimal effects on fracture energy.
(6) A slight decrease in the characteristic length up to replacement ratio 30% was observed in both exposure conditions.

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REFERENCES

[1] JSCE (1996), Recommendation for Construction of Concrete Containing Blast-Furnace Slag as a Mineral Admixture, Concrete Engineering Series, 86
[2] Weber, S. and Reinhaldt, H.W.(1996) A Blend of Aggregate to Support Curing of Concrete, Proc. of International Symposium on Structural Lightweight Concrete, Eds. I. Holand, T.A. Hammer and F. Fluge, Sandefjord, Norway, pp. 662-671.
[3] Hirotaka Tobita et al, Research on the applicability of crushed roof tile materials as concrete aggregates, JCI, Vol 28, No. 1, pp1577~1582, 2006. (In Japanese)
[4] Akira Shigematsu et al, Improvement of Properties of Portland Blast Furnace Cement-Type B concrete by Internal Curing Using Ceramic Roof Material Waste, JCI, Vol 31, No. 1, pp205~210, 2009. (In Japanese)
[5] Gustafsson, P. J. et al, Sensitivity in Shear Strength of Longitudinally Reinforced Concrete Beams to Fracture Energy of Concrete, ACI Structural Journal, May-June, pp.286-294,1988.
[6] Takahiro Mitani et al, Evaluation of Shrinkage and Size Effects on the Diagonal Cracking Strength of Ultra High Strength RC Beams, JCI, Vol 32, No 2, pp667~672, 2010. (In Japanese)
[7] Japan Concrete Institute, Method of Test for Fracture Energy of Concrete by Use of Notched Beam, 2003
[8] JSCE (2007), Standard Specifications for Concrete Structures, Design, pp34 (In Japanese)
[9] JSCE (2007), Standard Specifications for Concrete Structures, Design, pp44 (In Japanese)
[10] A. M. Neville, "Properties of Concrete" Fourth edition, 1995, pp418~419.
[11] T. Okajima, Effect of moisture on mechanical properties of concrete, Japan Cement Association, Cement & concrete, No. 464, pp18~26, 1985 (In Japanese)