FRACTURE ENERGY OF CONCRETE AND SHEAR STRENGTH OF RC BEAMS INTERNALLY CURED USING POROUS CERAMIC-ROOF TILE WASTE AGGREGATE

M. M. MACHARIA*, Y. OGAWA†, K. KAWAI† AND R. SATO†

* Graduate Student, Department of Civil and Environmental Engineering,
Graduate School of Engineering, Hiroshima University
1-4-1, Kagamiyama, Higashi-Hiroshima 739-8527 Japan
E-mail: machangi-machayan@hiroshima-u.ac.jp.

† Assistant Professor, Department of Civil and Environmental Engineering,
Graduate School of Engineering, Hiroshima University
1-4-1, Kagamiyama, Higashi-Hiroshima 739-8527 Japan
E-mail: ogaway@hiroshima-u.ac.jp

† Professor, Department of Civil and Environmental Engineering, Graduate School of Engineering, Hiroshima University
1-4-1, Kagamiyama, Higashi-Hiroshima 739-8527 Japan
E-mail: kkawai@hiroshima-u.ac.jp

† Professor, Department of Civil and Environmental Engineering, Graduate School of Engineering, Hiroshima University
1-4-1, Kagamiyama, Higashi-Hiroshima 739-8527 Japan
E-mail: sator@hiroshima-u.ac.jp

Key words: Porous ceramic-roof material waste aggregate, Portland blast furnace slag cement-type B, Internal curing, Fracture energy, Characteristic length, Shear strength

Abstract: Fracture energy tests were carried out on Portland blast furnace cement-type B (BB) concrete where as an internal curing material, partial replacement of 20% of the total course aggregate volume was carried out with porous ceramic-roof material waste aggregate (PCA). In addition, the effects of PCA on the shear strength of reinforced concrete (RC) beams of effective depth 210mm and 250 mm were also investigated. The results showed that PCA contributed to improved compressive, splitting tensile strengths as well as fracture energies. However, the effect of internal curing with PCA on shear strength of RC beams was not observed.

1 INTRODUCTION

The blast furnace slag cement (BB) concrete usually needs a longer wet curing treatment at the early ages to develop the required performances [1]. If sufficient wet curing is carried out on BB concrete at early age, the strength and durability properties of concrete are improved in the long term.

On the other hand, reduced construction periods and costs may lead to inadequate wet curing of concrete. For this reason, the development of a new and effective curing method is necessary.

In the past, 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 the qualities of BB concrete which requires adequate wet curing at early ages.

Table 1 Material properties

Materials	Type		Properties	Notation
Cement	Portland blast furnace cement-Type B		Density: 3020kg/m^3	BB
			Specific surface area: 3650cm^2/g	
Fine aggregates	Crushed quartz	Sand	Surface-dry Density: 2580kg/m^3	S
			Water absorption: 1.56%, FM=2.98	
		Dry-type crushed sand	Surface-dry density: 2570kg/m^3	DS
			Water absorption: 1.71%, FM=2.86	
Course aggregates	Crushed gravel (Sandstone)		Surface-dry Density: 2620kg/m^3	NCA
			Water absorption: 0.59%	
			Crush rate: 12%, Aggregate size: 5-20mm	
	Porous ceramic coarse aggregate		Surface-dry Density: 2240kg/m^3	PCA
			Water absorption: 9%	
			Crush rate: 21%, Aggregate size: 5-13mm	

Table 2 Mixture proportions

Name of specimen	W/C	Air (%)	s/a	Unit content (kg/m^3)					
				W	BB	Sand		Gravel	
						S	DS	G	PCA
BBC	0.5	4.5	0.45	170	340	503	270	977	-
BBC-G20						503	270	781	170

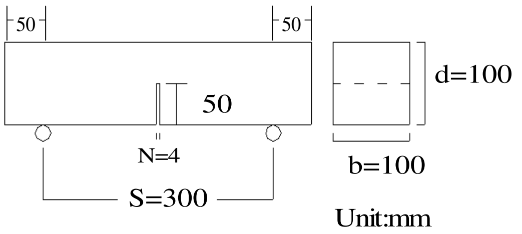


Fig 1 Outline of fracture energy test specimen

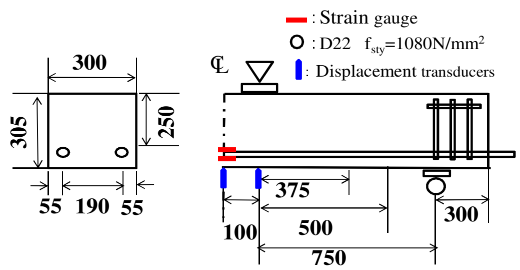


Fig 2 Dimensions and configurations of Series I RC beam

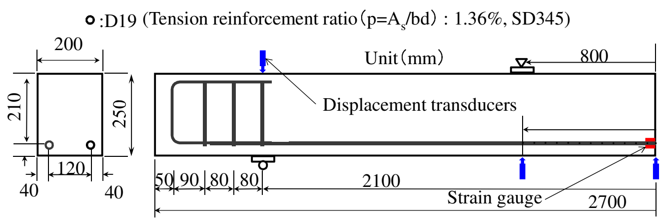


Fig 3 Dimensions and configurations of Series II RC beam

In Chugoku district of Western Japan "Sekishu Kawara", which is a roof material made of clay, about 200,000 tons per year of this material are 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 (PCA) hereafter, 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 PCA has been reported to be effective in improving the performances of BB concrete in drying condition in terms of strength, porosity as well as mitigating chloride penetration [4].

However, in order to utilize PCA as a structural concrete material, there is need to understand its effects on shear properties of reinforced concrete (RC), especially the shear properties of RC beams, due to the disastrous and unpredictable nature of shear failure in concrete.

Based on the above discussions, the present study aims to investigate the effects of 20% volume replacement of natural aggregate with PCA on the fracture energy as well as the shear properties of BB concrete.

2 TEST PROGRAM

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 BBC where part of the course aggregate (NCA) was replaced with PCA. The PCA was 8-9% in water absorption rate after being immersed for 7 days. Crushed sand (quartz) was used as fine aggregate and crushed gravel (NCA) was used as coarse aggregate.

Table 2 tabulates the mixture proportions of the two types of concrete prepared in this study. The water to cement ratio was fixed at 0.5. BBC-G20 denotes BB concrete whose replacement ratios of PCA is 20% of the total volume of course aggregate. The total amounts of water absorbed in PCA was 15.3kg/m^3 for the above mixture proportions. In the case of RC beams, BB concrete beams are denoted as RBBC, while BB concrete beams with PCA are denoted as RBBC-G20.

High strength deformed steel bars ($f_y \geq$ 1080N/mm^2) were used to induce shear failure in Series I RC beams while Series II RC beams were designed such that the flexural capacity was almost equal to the shear capacity.

2.2 Specimens

The size and dimensions of the fracture energy test specimens are shown in **Fig. 1**. For each mixture proportion, 8 specimens were prepared.

In order to investigate the effect of PCA and fracture energy on shear strength of RC beams, 2 types of RC specimens of effective depths 250 mm (Series I) and 210mm (Series II) for each mixture proportion were prepared. For each effective depth, 2 RC beams were prepared. The size and dimensions for these specimens of effective depth 250mm (Series I) are shown in **Fig 2**, while those of 210mm (Series II) are shown in **Fig. 3**.

Cylindrical specimens of φ100×200mm for compressive strength and Young's Modulus, φ150×200mm for splitting tensile stength tests were also prepared.

2.2 Exposure Condition

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 7 days and exposed to air of 7.9℃ and humidity 52.5% on average.

2.2 Loading and measurements

The fracture energy tests were carried out in accordance to Japan Concrete Institute Standard (JCI-S-002-2003) [5]. The tests were carried out at almost the same age as the loading age of the RC beams in both Series.

In each specimen, a notch at the mid-length to a depth of 50mm, as shown in **Fig. 1** was made. 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. The fracture energies of the specimens were obtained using Eq. (1), while the characteristic lengths were also obtained using the Eq. (2) below.

$$G_f = \frac{0.75W_0 + W_1}{A_{lig}} \quad (1)$$

Where,

G_f: Fracture energy (N/mm^2)

W_0: Area below COD curve up to rupture of specimen (Nmm)

W_I: Work done by deadweight of specimen and loading jig (Nmm)

A_{lig}: Area of broken ligament (mm^2)

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

Where,

G_f = Fracture energy (N/mm^2)

E_c = Young's modulus (N/mm^2)

f_t = Tensile strength (N/mm^2)

All the RC beams were loaded symmetrically with two concentrated loads, as shown in **Fig. 2** and **Fig. 3.** The shear span length to effective depth ratio (a/d) was fixed to 3.0 for Series I RC beams and 3.1 for Series II beams.

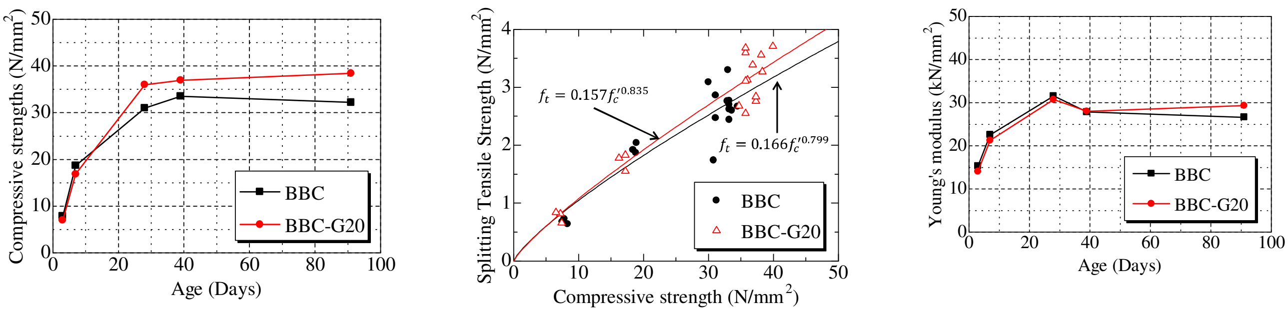
Deflection at the center section of the RC beams was measured using displacement transducers with minimum graduations ranging from 0.001 mm to 0.005 mm.

3. RESULTS AND DISCUSSIONS

3.1 Strengths and Young's Modulus

The effects of internal curing on the compressive strengths are shown in **Fig. 4(a).** From this figure, the strengths of the internally cured BBC-G20 were observed to be slightly lower at early ages, but after the age of 7 days, the strengths increased significantly compared to those of reference mixture BB. This increase in strengths can be attributed to the internal curing effect of PCA.

The relationship between splitting tensile strengths and compressive strengths for both the internally cured BBC-G20 and reference mixture BBC are shown in **Fig. 4**(b). The regression curves of both mixtures obtained

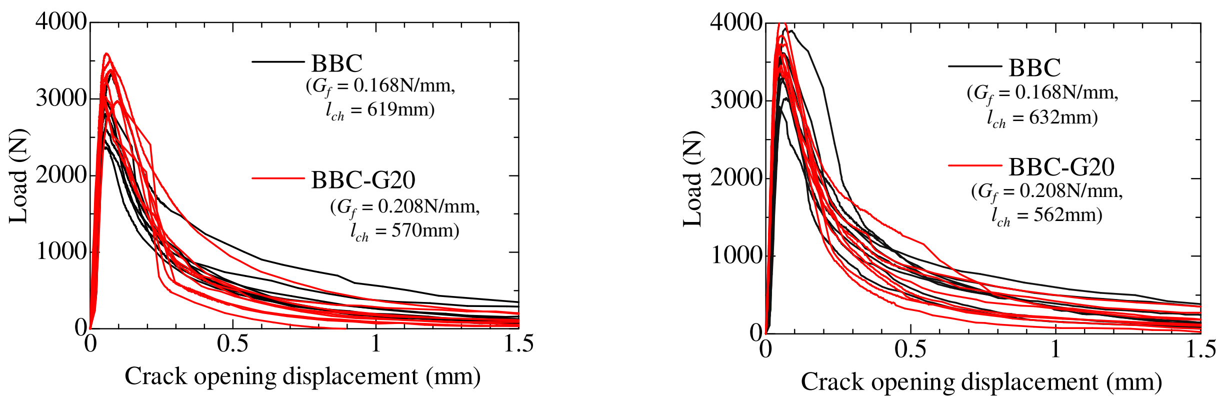


(a) Relationship between compressive strengths and age

(b) Relationship between splitting tensile strength and compressive strength

(c) Relationship between Young's modulus and age

Fig. 4 Effects of internal curing of PCA on the strengths and Young's modulus of concretes



(a) Relationship between load and crack opening diplacement (Series I)

(b) Relationship between load and crack opening diplacement (Series II)

Fig 5 Effects of internal curing on fracture energies of concretes using the method of least squares are also shown. Due to variation of the experimental values of both mixtures, the splitting tensile strengths were obtained from the regression curves.

The effect of internal curing on the Young's modulus of concrete is shown in **Fig. 4 (c).** From this figure, there was no observable effect of PCA on the Young's moduli of the internally cured concretes compared to those of BBC.

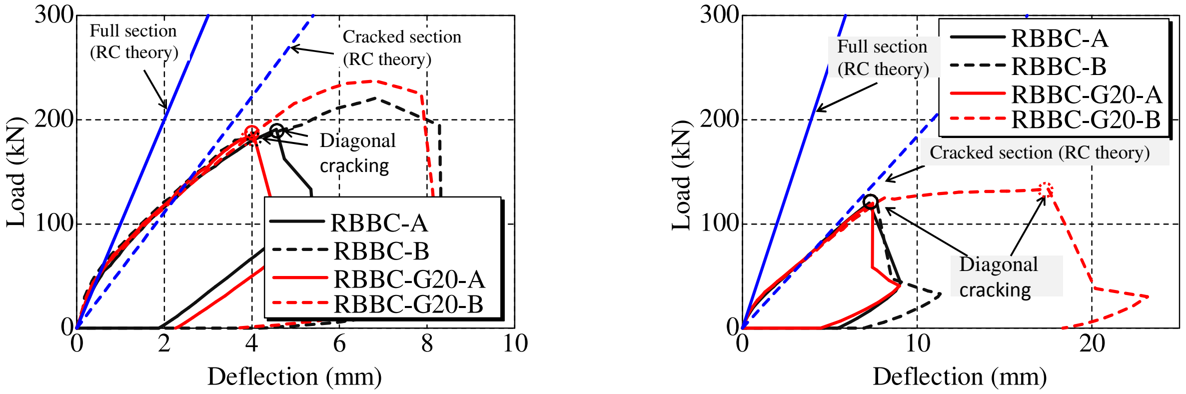
3.2 Fracture energy

The effects of internal curing on the fracture energies of concretes in series I and II are shown in **Fig 5 (a)** and **(b)**. The average fracture energies and characteristic lengths of the internally cured BBC-G20 as well as those of BBC are shown in the legend. The values of fracture energies and characteristic lengths that varied widely were considered as experimental errors and were not included in the average values. The fracture energies of the BBC-G20 increased by approximately 20% compared to those of BBC. From the figures, it can be observed that the fracture energies of BBC-G20 increase in the micro cracking zone and reduce slightly in the bridging zone compared to those of BBC, in the case of Series I while in Series II, there is only a slight increase in the micro cracking zone and no significant change in the bridging zone. This shows the possibility of

Table 3 Mechanical properties and strain and stress before loading

Name of specimens		Loading age	Mechanical properties at the age of loading					Strain and stress before loading	
			f'_c	f_t	E_c	G_f	l_{ch}	$\varepsilon_{s,def}$	$\sigma_{c,def}$
		Days	N/mm^2	N/mm2	kN/mm^2	N/mm	mm	×10^{-6}	N/mm^2
Series I (d = 250mm)	RBBC-A	43	33.5	2.75	27.8	0.17	619	-91.0	0.33
	RBBC-B	46						-104.0	0.37
	Average	-	-	-	-	-	-	-97.5	0.35
	RBBC-G20-A	43	37.5	3.20	28.0	0.21	570	-87.0	0.31
	RBBC-G20-B	45						-81.0	0.29
	Average	-	-	-	-	-	-	-84.0	0.30
Series II (d = 210mm)	RBBC-A	85	32.2	2.66	26.6	0.17	632	-116.0	0.83
	RBBC-B	89						-133.0	0.95
	Average	-	-	-	-	-	-	-124.5	0.89
	RBBC-G20-A	88	38.4	3.30	29.4	0.21	562	-139.0	1.00
	RBBC-G20-B	89						-134.0	0.96
	Average	-	-	-	-	-	-	-136.5	0.98

f'_c : Compressive strength of concrete
f_t : Splitting tensile strength of concrete
E_c : Young's modulus of concrete
G_f : Fracture energy of concrete
l_{ch} : Characteristic length of concrete
$\varepsilon_{s,def}$: Tension reinforcement strain induced by shrinkage of concrete
$\sigma_{c,def}$: Stress in concrete at the bottom of RC beams



(a) Relationship between load and deflection of RC beams in Series I

(b) Relationship between load and deflection of RC beams in Series II

Fig 6 Effects of internal curing on deflection of RC beams improvement of fracture energies due to internal curing with PCA. In the case of the characteristic length, contrary to what was observed in the case of fracture energies, the characteristic lengths of BBC-G20 in both series decreased by approximately 10% compared to those of BBC. This decrease is due to the increased splitting tensile strengths, which as shown in Eq. (2), the characteristic lengths are inversely proportional to the square of their values.

3.3 Shear properties of RC beam

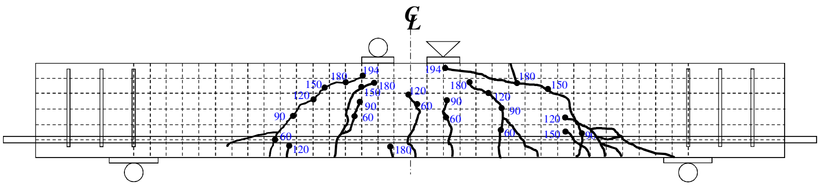
Table 3 shows the mechanical properties of concrete as well as the strain in the reinforcing bars and stress in concrete before loading of the RC beams in both series.

The effects of PCA on the deflection of all the RC beams are shown in **Fig. 6 (a)** and **(b)**. The deflections of RC beams in the case of full and cracked sections calculated in accordance with conventional RC theory are also illustrated in the figure. From the two figures, in both series, there was no observable effect of PCA on the deflection of RC beams.

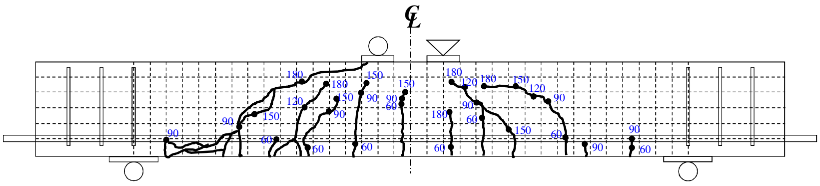
An example of the effects of PCA on the crack patterns of RC beams in both series are shown in **Fig 7**. From this figure, it was observed that the cracks on the internally cured RBBC-G20 slightly increased in number compared to those of RBBC.

Table 4 shows the measured and calculated values of shear strength as well as the failure modes of the RC beams. The calculated values of shear tension force were obtained using Eq. (3) below proposed by Niwa *et al* [6] for normal strength concrete.

$$V_c = 0.2{f'_c}^{1/3}(d/1000)^{-1/4}(100p_s)^{1/3}(0.75 + 1.4/(a/d))bd \qquad (3)$$

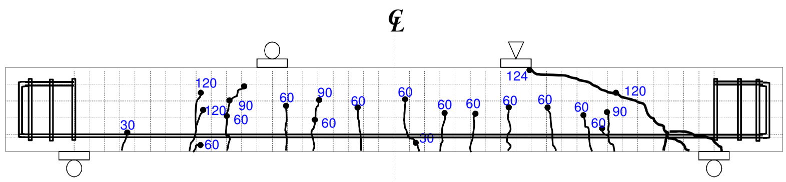


(a) RBBC-A

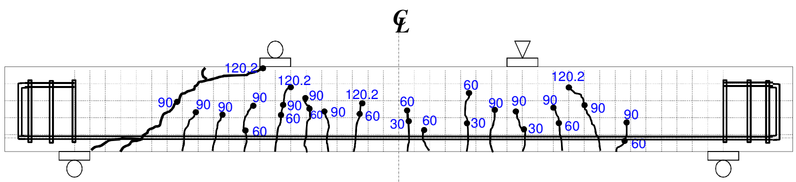


(b) RBBC-G20-A

Crack patterns of RC beams in Series I



(a) RBBC-A



(b) RBBC-G20-A

Crack patterns of RC beams in Series II

Fig 7 Crack patterns

Where,

V_c: Shear force at shear tension failure of RC beams without shear reinforcement

f'_c: Concrete compressive strength

d: Effective depth

p_s: Tension reinforcement ratio

a: Shear span length

b: Width of beam

The ultimate shear strength of the RC beams that failed in shear tension was assumed to be equal to the shear tension force, while in the case where the beams failed in shear compression, the ultimate shear strength was obtained using the following Eq. (4) also proposed by Niwa et al. [6]

$$V_u = \frac{0.244 f_c'^{2/3}\{1+(100p_w)^{1/2}\}\left(1+3.33\frac{r}{d}\right)bd}{1+\left(\frac{a}{d}\right)^2} \quad (4)$$

Where,

r: Width of steel plate in contact with concrete during loading.

Fig. 8 (a) and **(b)** shows the values of $\tau_{c,exp}$ and $\tau_{c,calc}$ for RBBC-G20 normalized by those of RBBC for series I and II respectively. From this figure, a comparison of $\tau_{c,exp}$ between both beams shows that in the case of series I, there was a slight decrease in the measured values of RBBC-G20 compared to those of RBBC, while

Table 4 Shear strength

Name of specimen		Diagonal cracking strength: Experimental values $V_{c,exp}$ (kN)	$\tau_{c,exp}$ (N/mm^2)	Calculated values $V_{c,cal}$ (kN)	$\tau_{c,cal}$ (N/mm^2)	$V_{c,exp}/V_{c,cal}$	Ultimate shear strength: Experimental values $V_{u,exp}$ (kN)	$\tau_{u,exp}$ (N/mm^2)	Calculated values $V_{u,cal}$ (kN)	$\tau_{u,cal}$ (N/mm^2)	$V_{u,exp}/V_{u,cal}$	Failure mode
Series I (d = 250mm)	RBBC-A	96.0	1.28	84.1	1.12	1.14	96.0	1.28	84.1	1.12	1.14	STF
	RBBC-B	90.0	1.20			1.07	110.0	1.47	89.4	1.19	1.23	SCF
	Average	93.0	1.24	-	-	1.11	-	-	-	-	-	-
	RBBC-G20-A	93.0	1.24	87.0	1.16	1.07	93.0	1.24	87.0	1.16	1.07	STF
	RBBC-G20-B	90.0	1.20			1.03	119.0	1.59	96.4	1.29	1.23	SCF
	Average	91.5	1.22	-	-	1.05	-	-	-	-	-	-
Series II (d = 210mm)	RBBC-A	60.0	1.43	52.5	1.25	1.14	60.0	1.43	52.5	1.25	1.14	STF
	RBBC-B	60.0	1.43			1.14	60.0	1.43			1.14	STF
	Average	60.0	1.43	-	-	1.14	60.0	1.43	–	-	1.14	-
	RBBC-G20-A	60.0	1.43	56.0	1.33	1.07	60.0	1.43	56.0	1.33	1.07	STF
	RBBC-G20-B	66.5	1.58			1.19	66.5	1.58			1.19	STFY
	Average	63.3	1.51	-	-	1.13	63.3	1.51	-	-	1.13	-

$V_{c,exp}$: Shear force at diagonal cracking $V_{u,exp}$: Ultimate shear force $V_{u,cal}$: Calculated ultimate shear force

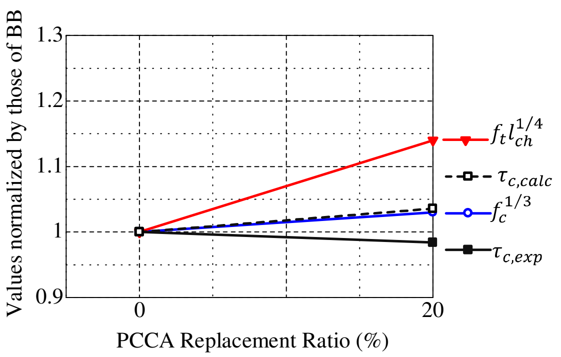
$\tau_{c,exp}$: Shear strength at diagonal cracking $\tau_{u,exp}$: Ultimate shear strength $\tau_{u,cal}$: Calculated ultimate shear strength

$V_{c,cal}$: Calculated shear tension force

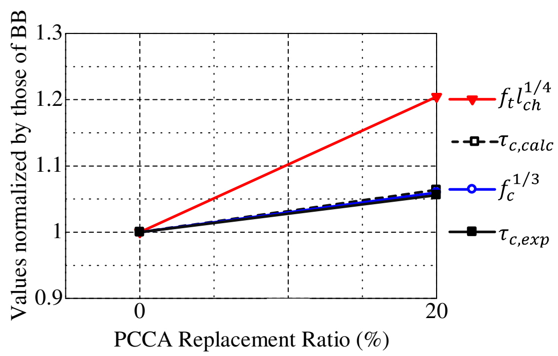
$\tau_{c,cal}$: Calculated shear tension strengh

STF: Shear tension failure SCF: Shear compression failure

STFY: Shear tension failure after yielding of tension reinforcement



(a) Series I



(b) Series II

Fig.8 Effect of f'_c, f_t and l_{ch}

in the case of series II, a slight increase was observed. This shows that there was no considerable effect of internal curing with PCA on the shear strength of RC beams.

From **Table 4**, In the case of Series I, it was observed that the $\tau_{c,calc}$ values of RBBC and RBBC-G20 were lower than $\tau_{c,exp}$ by approximately 10% and 5% respectively on average, while in series II, the difference was approximately 13% for both mixtures. In addition the values $\tau_{c,calc}$ were larger in the case of RBBC-G20 compared to RBBC in both series.

Eq. (3), which was used to obtain the values of $\tau_{c,calc}$, expresses the shear resistance of concrete as $f'_c{}^{1/3}$, which includes the contribution of compression concrete, the shear transfer along cracks as well as dowel action. In this study the internal curing effect of PCA contributed to increasing f'_c, which resulted in the increase in $\tau_{c,calc}$ of RBBC-G20 in both series.

From **Fig.8**, although the difference is not significantly large, it is observed that in the case of series I, the values of $\tau_{c,exp}$ decrease slightly in the case of RBBC-G20, which is a trend different from that observed in the case of $\tau_{c,calc}$, which directly depends on $f'_c{}^{1/3}$. However, in the case of series II, it is observed that the shear strength can be effectively evaluated using $\tau_{c,calc}$. Although the trends are different in both series, the differences are relatively small, therefore showing the possibility of estimation of shear tension strength of RC beams with PCA using Eq. (3).

On the other hand, Gustafson and Hillerborg proposed Eq. (5) below, based on FEM analysis, where the increase in f_t and l_{ch} results in increased shear strength. Based on this equation, the effects of f_t and l_{ch} were investigated and are also shown in **Fig 8**.

$$\tau_c/f_t \propto \left(d/l_{ch}\right)^{-1/4} \tag{5}$$

Where,

τ_c: Shear strength of concrete

f_t: Tensile strength of concrete.

Based on Eq. 5, it was found that the effect of improved f_t and decreased l_{ch} results in overestimation of the shear strength, as shown in **Fig. 8**. This shows that the increased f_t had a larger effect than the decreased l_{ch}.

The characteristic of l_{ch} of BBC-G20 is similar to what was observed in high strength concrete (HSC). When Sato and Kawakane [8] applied the Gustafson and Hillerborg proposal in evaluating the shear strength of HSC while considering the effect of early age deformation, they were successfully able to apply Eq. 5 in the case of high shrinkage and low shrinkage as $\tau_c/f_t\alpha(d/l_{ch})^{-1/2}$, and $\tau_c/f_t\alpha(d/l_{ch})^{-2/5}$ respectively.

In this study, although it would be hard to make an evaluation due to the small number of RC beams tested, it was found that when evaluating the shear strength of RC members with PCA whose crushing value is twice that of natural aggregate, based on the fracture mechanics approach, there is need for an evaluation method that incorporates the effects of increased f_t as well as those of decreased l_{ch}.

4 CONCLUSIONS AND RECOMENDATIONS

The following conclusions can be drawn within the limits of the present study:

(1) The internal curing effect of 20% replacement of course aggregate with PCA resulted in increased compressive and splitting tensile strengths. However, there was no observable effect of PCA on Young's modulus of concrete.

(2) The internal curing effect of PCA resulted in increased fracture energies by about 24%. However, the effect was no observed in the case of characteristic length.

(3) There was no observable change in the deflection of RC beams internally cured with PCA, compared to those made using the reference concrete.

(4) There was no significant effect of internal curing with PCA on the shear tension strength of concrete. However, it was possible to estimate the shear strength of RC beams with PCA.

(5) The internal curing effect of PCA was observed to improve the mechanical properties of BB, while the effect was no observed in improving the properties

of RC beams.

(6) Although it is important to carry out more research in order to fully understand the internal curing effect of PCA on RC members, when evaluating the shear strength of RC beams with PCA based on the fracture mechanics approach, there is need for investigation on an evaluation method that incorporates the effects of increased splitting tensile strength as well as those of decreased characteristic lengths.

REFERENCES

[1] Japan Society of Civil Engineers 8JSCE)., 1996. Recommendation for Construction of Concrete Containing Blast-Furnace Slag as a Mineral Admixture, *Concrete Engineering Series*, 86.

[2] RILEM., 2007. Technical committee *"Internal Curing of Concrete"* TC 196-ICC-N45

[3] Tobita, H., Uehara T., Umehara, H. and Tomotake, H., 2006. Research on the applicability of crushed roof tile materials as concrete aggregates, *JCI*, Vol. 28, No. 1, pp1577~1582 (In Japanese)

[4] Sato, R., Shigematsu A., Nukushina T. and Kimura M., 2011 Improvement of Properties of Portland Blast Furnace Cement Type B Concrete by Internal Curing Using Ceramic Roof Material Waste、 *JMCE*、 ASCE、 Vol. 23、 Issue 6、 June 2011、 pp. 777-782

[5] Japan Concrete Institute, 2003. Method of Test for Fracture Energy of Concrete by Use of Notched Beam

[6] Niwa, J., Yamada, K., Yokozawa, K. and Okamura, H., 1986. Reevaluation of the equation for shear strength of reinforced concrete beams without web reinforcement, *Concrete Library of JSCE*, No. 9, pp65-84, June 1987.

[7] Gustafson, P. J., Hillerborg, A., 1988. Sensitivity in Shear Strength of Longitudinally Reinforced Concrete Beams to Fracture Energy of Concrete, ACI *Structural Journal*, May-June, pp.286-294, 1988

[8] Sato, R. and Kawakane H., 1988. A New Concept for the Early Age Shrinkage Effect on Diagonal Cracking Strength of Reinforced HSC Beams, Journal of Advanced Concrete Technology, JCI, Vol. 6, No. 1, pp. 45-67.