

Experimental Study on Drying Shrinkage Cracking and Flexural Behaviour of PET Fiber Added Red Clay Concrete

Jang-Ho Jay Kim¹, Sung Bae Kim¹, Na Hyun Yi¹ and Hyun Young Kim¹

¹School of Civil and Environmental Engineering, Yonsei University, Seoul, South Korea, Email: jjhkim@yonsei.ac.kr

ABSTRACT: There have been numerous studies to develop eco-friendly concrete. An attempt to reduce the amount of cement used in manufacturing concrete is suggested as one of the solutions for developing eco-friendly concrete. To reduce the amount of cement used in concrete, the pozzolan-reaction materials such as ground granulated blast furnace slag, fly ash, and metakaolin are widely used as the mineral admixture. Red clay deposited broadly in Korean soil is a well known eco-friendly material. Also, activated red clay for increasing pozzolan-reaction can be practically used as a mineral admixture of concrete. Meanwhile, PET fiber made of recycled PET bottle is a type of recycled material and can control micro-cracks in concrete. However, presently, the studies about concrete mixed with recycled PET fiber are insufficient. Moreover, the researches on PET fiber mixed with red clay have been rarely conducted. In this study, drying shrinkage and flexural behaviour of recycled PET fiber added red clay concrete are carried out. To measure drying shrinkage, free shrinkage tests and restrained shrinkage cracking test were performed. To measure flexural behaviour, flexural strength test of reinforced concrete beam was performed. Test results showed that the drying shrinkage is controlled by red clay admixture and PET fiber. Flexural strength of reinforced concrete increased approximately 10% from adding red clay and increased approximately 30% from mixing PET fiber. And, because of reinforcing effect of PET fiber, the ductility of PET fiber added red clay concrete beam increased approximately 3 folds compared to reinforced slag concrete beam.

Keywords: environment friendly material, activated red clay, recycled PET fiber, flexural behaviour

1. INTRODUCTION

Recently, global environmental problems have been a matter of grave concern around the globe due to acceleration of global warming. Since the construction industries produce 42% of the total CO₂ generated by the Korean industries, the engineers' attempt to use eco-friendly material for construction of structures has been increasing. Especially, construction industries, which consume

significant amount of energy and generate superfluous amount of waste, reduction of cement and steel usage became a central issue in an attempt to reduce greenhouse effect. Therefore, in order to maintain eco-friendly construction industries by decreasing usage of environmentally hazardous materials and emission of industrial pollutions, it has been forced to change from the existing development concept of "the development for the sake of

development” to a new paradigm centered on sustainable development using eco-friendly construction technologies including resource reduction, energy saving, service life extension, and waste recycling.

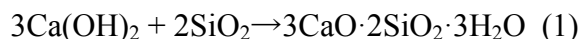
This study evaluates applicability of red clay concrete as a part of efforts to reduce the consumption of cement. And, if mixed with recycled PET fibers made from waste PET (Polyethylene Terephthalate) bottle, it's expected to be effective in the recycling of waste PET bottles as well as improving concrete ductility.

2. MATERIAL PROPERTIES AND MIX PROPORTION

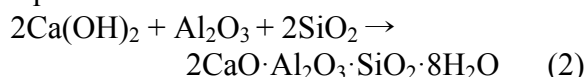
2.1 Activated red clay

Red clay, which is a type of Kaolin, makes up more than 10% of Korean soil. Therefore, the supply of red clay far surpasses the current demand due to abundant resources in Korea. However, untreated red clay is difficult to use as a construction material due to its inherent characteristics of dry shrinkage crack producing and low compressive strength properties. However, when red clay is treated at a high temperature to produce activated red clay, the pozzolan-reactions increase greatly. This activated red clay can be used as an admixture for eco-friendly concrete. The adequate temperature for activation of red clay has been reported to be between 600°C and 1000°C [1]. The red clay used in the present investigation was activated at the temperature of 850°C. The main chemical components in activated red clay are SiO_2 and Al_2O_3 , which form a stable pozzolanic material by slow cohesion with $\text{Ca}(\text{OH})_2$ at an ambient temperature. This reaction is usually classified into the afwilite reaction and the stratlingite reaction, according to the type of pozzolanic material produced [1], [2]. The afwilite reaction indicates that afwilite, CSH gel, which is an elaborate and stable material, is produced by reaction of SiO_2 with $\text{Ca}(\text{OH})_2$. The

equation for this reaction can be written as follows.



The stratlingite reaction means that stratlingite material, CASH gel, is made from reaction of Al_2O_3 with $\text{Ca}(\text{OH})_2$. The equation for this reaction is



2.2 Recycled PET fiber

Most of PET bottles used as beverage containers are thrown away after its usage, causing environmental waste problems. In order to solve this problem, a method to recycle wasted PET bottles is being presented as an alternative plan [3]. For manufacturing PET fiber, recycled PET sheet produced from collected waste PET bottles is used. Recycled PET sheet are slitted thinly by using slitting machine, transforming them into straight type PET fiber. However, straight type plastic fiber has low bond capacity when mixed with concrete, making them difficult to be used as reinforcing fiber. In order to increase bond strength of PET fibers, surface configuration is performed. Surface configuration is applied by using deforming machine. Various surface configurations can be given to PET fiber according to gear of deforming machine. Fig. 1 shows the manufacturing process of recycled PET fiber. Generally, the types of fiber are crimped, twisted, and embossed types. For this study, embossed type is used due to its superior bond properties. Fig. 2 shows various types of manufactured recycled PET fiber.

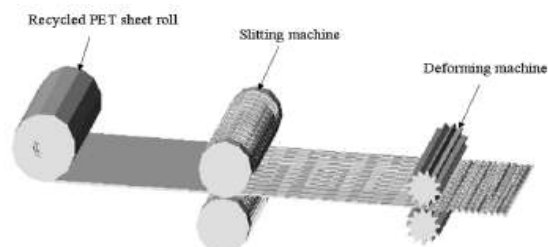


Figure 1: Process used to manufacture fibers from recycled PET sheet

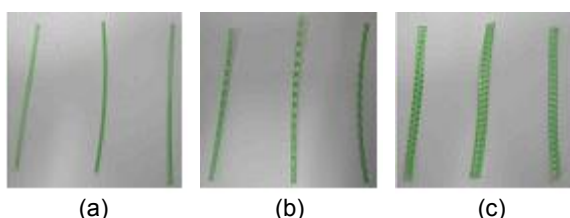


Figure 2: Geometry of the recycled PET fibers; (a) straight type, (b) crimped type, (c) embossed type

2.3 Mixing proportion

The material properties of red clay and recycled PET fiber used for the experiment are shown in Tables I and II. In order to verify the property of recycled PET fiber added red clay concrete, the literature reviews and preliminary experiments are performed. The study results revealed that the capacity of red clay is improved if it is used with slag and the replacement ratio of red clay was 25% of slag cement. Recycled PET fiber was mixed as much as 1% of volume of concrete. Table III show the mixture proportion used in the experiment.

3. EXPERIMENT

3.1 Compression test methods

The number of test specimens for the

Table I: Chemical composition of red clay

Composition	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	CaO	K ₂ O	TiO ₂	Na ₂ O
Rate (%)	42.5	36.6	4.05	0.69	0.57	0.41	0.23	0.18

Table II: Properties of recycled PET fiber

Fiber type	Dimension (mm)	Length (mm)	Density (g/cm ³)	Elastic modulus (MPa)	Tensile strength (MPa)	Ultimate elongation (%)	Bond strength (MPa)
Embossed	0.2×1.3	50	1.38	10,175.4	420.7	11.2	2.54

Table III: Mix proportion of concrete

Specimen	W/B (%)	S/A (%)	Replacement ratio of red clay (%)	W (kg/m ³)	RC (kg/m ³)	SC (kg/m ³)	S (kg/m ³)	A (kg/m ³)	Recycled PET fiber (kg/m ³)
SC			0		-	759.54			-
RCC	43	50	25	323.76	186.58	572.87	708.72	708.72	-
RCPC			25		186.58	572.87			13.8

compression test was 9, as was the case for

the flexural test. The compressive strength test specimen was a cylinder with a diameter of 100 mm and a height of 200 mm. After casting, the specimens were covered with polyethylene films and wet fabrics and stored in a humidity chamber for approximately 24 hours, in which temperature was $20 \pm 1^\circ\text{C}$ and humidity was $60 \pm 5\%$.

3.2 Flexural test methods

All specimens were tested for flexural strength after 28 days. All of the beams were reinforced with three D10 bars (diameter of 10mm) in the tension zone. The beams were provided with 10mm diameter shear reinforcements, with 300mm spacing. They were all designed to prevent shear failure. Fig. 3 shows the dimensions and details of the beam specimens. The flexural members were tested using a three point bending test as shown in Fig. 4. To obtain an accurate deflection reading, a Linear Variable Differential Transducer (LVDT) was also mounted at the mid-span. Crack initiation and propagation were monitored by visual inspection during testing, and the crack patterns were marked.

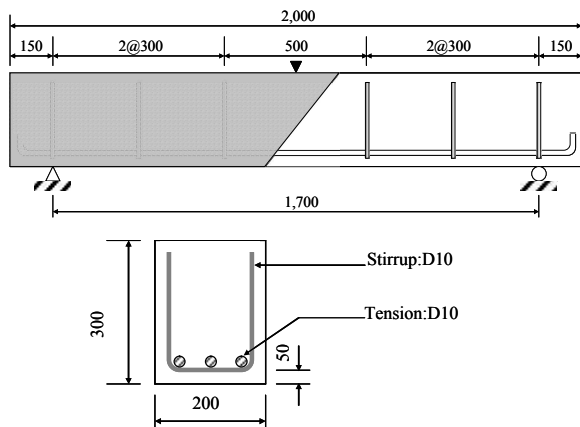
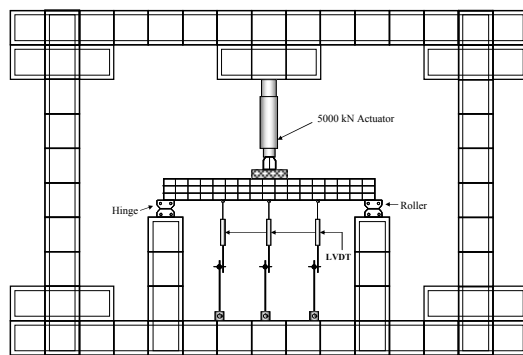
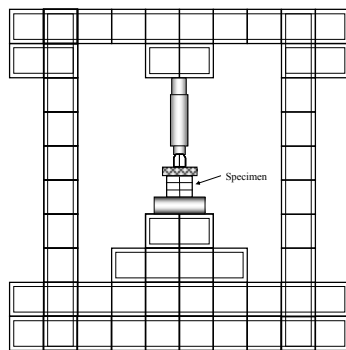


Figure 3: Dimensions and details of test beam (unit: mm)



(a) Front view



(b) Section view

Figure 4: Setup of test specimen

3.3 Drying shrinkage cracking test methods

To analyze the effect of red clay and recycled PET fiber on drying shrinkage cracking of concrete, free drying shrinkage strain and restrained drying shrinkage strain experiments were performed according to Korean Standard 2595 test method for

drying shrinkage cracking of restrained concrete [4].

The specimens were manufactured from each mixture and wet cured until testing. The curing temperature was $20 \pm 1^\circ\text{C}$ and humidity was $60 \pm 5\%$. Removal of form was performed 7 days after casting. In order to measure restrained drying shrinkage strain after removal from formwork, concrete strain was measured by attaching the concrete strain gauge to the central part of upper and lower surface of specimen, and strain gauge was attached to the central part of restrained plate to measure strain of restrained plate. The crack of specimens was checked every day, and cracking point and cracking time of each specimen were recorded. The size and shape of the specimen to measure the restrained drying shrinkage strain are shown in Fig 5.

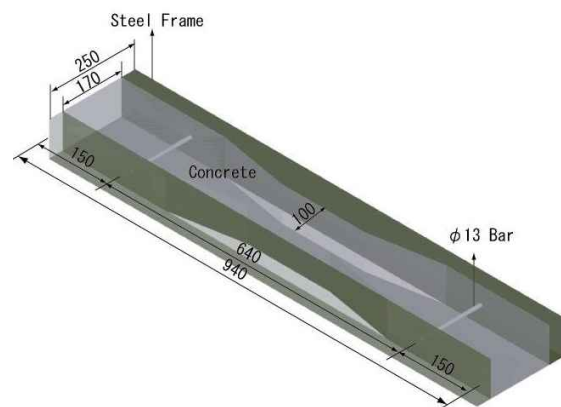


Figure 5: Restrained frame (unit: mm)

4. RESULTS AND DISCUSSION

4.1 Compression test

In the early age, compression strength of slag concrete (SC) was higher than that of red clay concrete (RCC) and red clay concrete mixed with recycled PET fiber (RCPC). However, as specimens aged, compression strength of RCC became higher. This result can be explained by compression strength of red clay concrete becoming larger over time by pozzolan-reaction of activated red clay. Compressive

strength of recycled PET fiber added RCC increased by pozzolan-reaction of activated red clay. However, recycled PET fiber reduced compressive strength of concrete. The reduction of strength can be explained by PET fibers acting similar to air void within concrete where effective sectional area of concrete is reduced. Fig. 6 shows the result of compressive strength test.

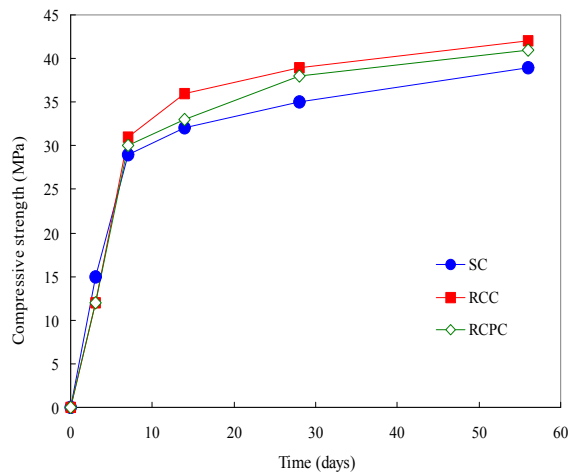


Figure 6: Compressive strength test result

4.2 Flexural test

4.2.1 Load-deflection

Table IV summarizes the results of the flexural tests of all of the beam specimens. Fig. 7 shows the load-deflection relation of specimen. From the flexural tests, the load capacity of the RCC and RCPC were 10% and 30% higher than that of the SC,

respectively. This result can be explained by PET fiber providing abridgement across cracks within cement matrix thereby controlling flexural crack extension and increasing flexural capacity.

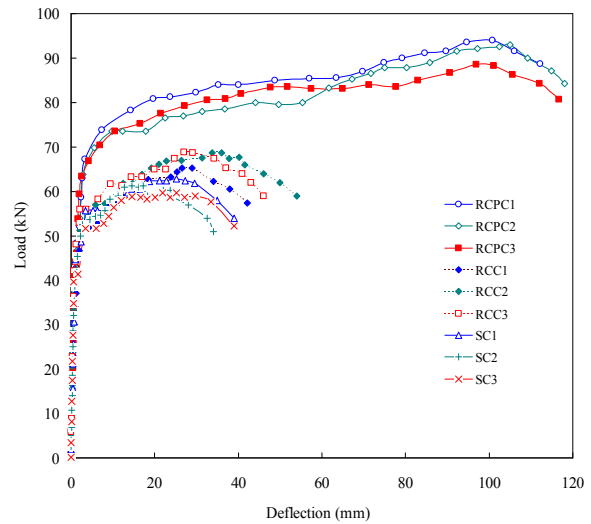


Figure 7: Comparison of load-deflection

4.2.2 Cracking modes for the beams

In order to grasp failure behaviours by mixing red clay and PET fibers, crack growth and distribution for each load step was inspected until failure, which is shown in Fig. 8. SC specimens showed typical tensile failure with yielding of tension reinforcement during loading. As loading increased gradually until the failure, flexural tensile failure occurred rapidly at an ultimate load. RCC specimen showed a similar behaviour as SC specimen. However,

Table IV: Summary of test results

Specimen	Pcr (kN)	Δ_{cr} (mm)	Py (kN)	Δ_y (mm)	Pu (kN)	Δ_u (mm)	Ductility index (Δ_u / Δ_y)	Relative ductility
SC	44.6	1.08	55.6	8.8	62.8	26.72	3.03	1
	40.2	0.78	53.7	4.24	61.2	23.2	5.47	
	41.2	0.7	52.4	4.14	59.6	21.94	5.30	
RCC	36.4	0.65	52.8	6.28	65.3	29.01	4.62	1.34
	42.6	0.58	56.8	5.32	68.4	35.93	6.75	
	42	0.63	56.0	3.8	68.8	27.02	7.11	
RCPC	46.8	1.03	76.6	11.56	94	100.8	8.72	3.3
	43.6	0.81	69.8	5.54	93	105	18.95	
	46	1.32	69.0	5.42	88.5	96.85	17.87	

its flexural capacity was a slightly higher than that of SC specimen. General flexural behaviour was similar with that of SC specimen, where flexural tensile failure occurred rapidly shortly after reaching an ultimate load. Also, RCPC specimens' flexural crack pattern was studied. It showed ductile behaviour after reaching ultimate load, unlike SC and RCC specimens, thereby confirming the increased safety of the member. In addition, the time of initial crack formation was almost similar with that of SC and RCC specimens. However, crack growth rate was much slower by PET fiber restraining crack growth and extending the time needed to reach an ultimate load after initial cracking. The results showed that recycled PET fiber mixed with concrete has superior bond strength with cement matrix, effectively restraining crack growth of concrete.

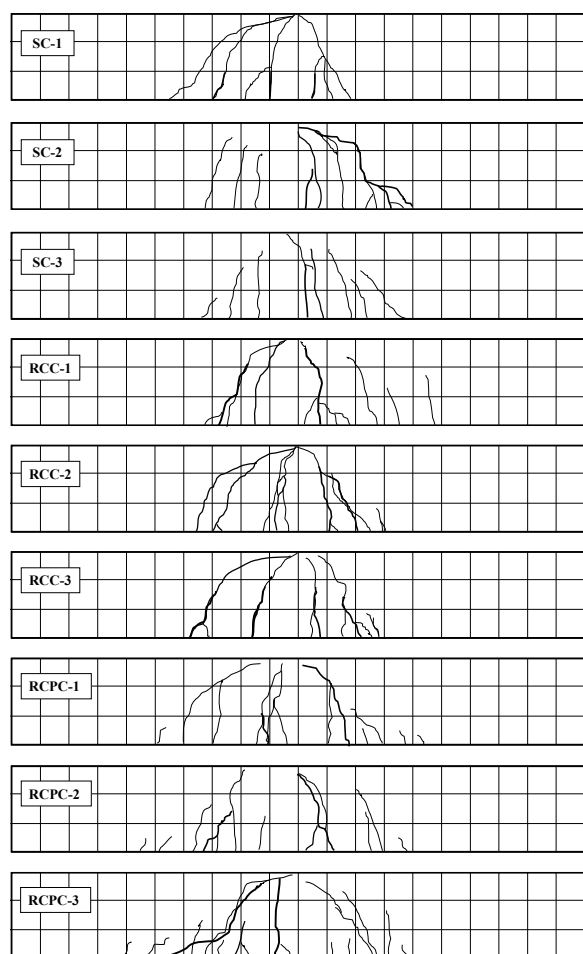


Figure 8: Crack patterns of each specimen

4.2.3 Estimation of ductility

The safety of the members is assessed by using ductility indices, which are expressed as the ratio of the deflections at ultimate and yield loads.

$$\mu_{\phi} = \frac{\phi_u}{\phi_y}, \quad \mu_{\theta} = \frac{\theta_u}{\theta_y}, \quad \mu_{\Delta} = \frac{\Delta_u}{\Delta_y} \quad (3)$$

where, μ is ductility index of a member; ϕ is moment factor of a member; θ is curvature of a member; and Δ is the deflection of a member

The ductility index for each beam is shown in Table IV. As shown from the results of the experiments, RCC specimen has a relative ductility index of 1.34, which is approximately 1.3 times greater than that of SC specimen. This reveals that red clay is effective in increasing ductility of concrete. Furthermore, RCPC specimen showed a relative ductility index of 3.3, which is approximately 2 and 3 times higher than that of RCC and SC specimens, respectively. This showed that RCPC has the best ductility capacity. The greatly increased surface energy of the recycled PET fibers in RCPC enhanced the friction resistance during pullout of the fibers bonded to the beams.

4.3 Drying shrinkage cracking test methods

4.3.1 Free drying shrinkage strain

The result of free dry shrinkage strain in SC, RCC, RCPC specimens are shown in Fig. 9. The experimental results of free dry shrinkage strain shows that SC specimen has over 40% higher drying shrinkage strain than RCC and RCPC specimens. For RCC specimen, the amount of cement used decreased due to usage of red clay as admixture. Therefore, initial hydrates decreased, thereby decreasing dry shrinkage strain. Furthermore, in RCPC specimen, red clay having higher fineness compared to cement has the effect of reducing air voids

on bonded surface between recycled PET fiber and cement matrix. Also, with an interaction between cement matrix and recycled PET fiber, drying shrinkage is resisted, resulting in the lowest free drying shrinkage strain among the three types of materials.

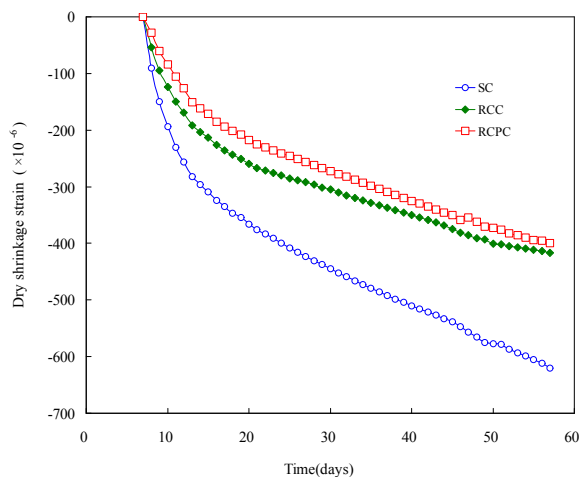


Figure 9: Free dry shrinkage results

4.3.2 Restrained drying shrinkage strain

In restrained drying shrinkage strain test, the cracking time from the time of casting for each mixture is shown in Table V. The order of time required to create the fully-through cracking was in the order of SC, RCC, RCPC specimens. Generally, as the time required for cracking increases, the dry shrinkage strain decreases. According to the experimental result of restrained drying shrinkage strain, cracking of RCC specimen occurred about 20 days later than that of SC specimen. This result reveals that the reduction of the amount of cement from red clay replacement as admixture decreased drying shrinkage strain. Comparing to the previously reported research results, this study result corresponds well with the reported results where drying shrinkage strain decreases if red clay with slag cement mixture is used as cement replacement [5]. Comparing RCC and RCPC specimens using the same mixture design, cracking of RCPC specimen occurred approximately 10 days later than RCC. This result reveals that mixed recycled PET fiber increases tensile

resistance of concrete and controls drying shrinkage cracking.

In case of RCC specimen, cracking occurred relatively later than SC specimen and behaved almost similarly. However, for the case of RCPC, as shown in Figs. 9 and 10, it shows different behavior from general concrete. In initial behavior of RCPC specimen, it shows almost similar behavior as general concrete. However, it shows definitely different behavior at the point of initial cracking. This confirms that cracking time is delayed due to reinforcing effect of recycled PET fiber (the area shown by the dotted circle) where recycled PET fiber resists formation of cracking, resulting in tensile strength increase.

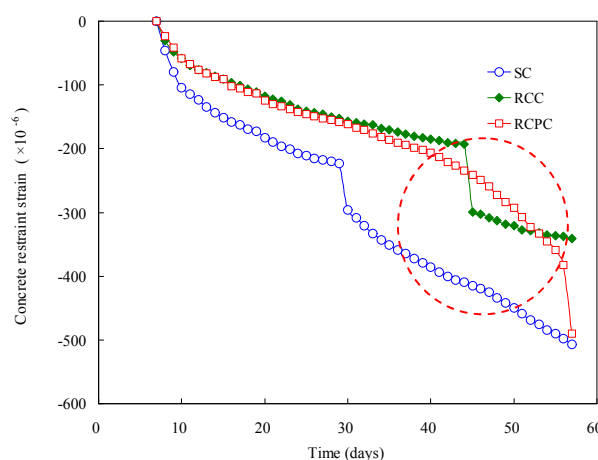


Figure 10: Concrete restraint strain of specimens

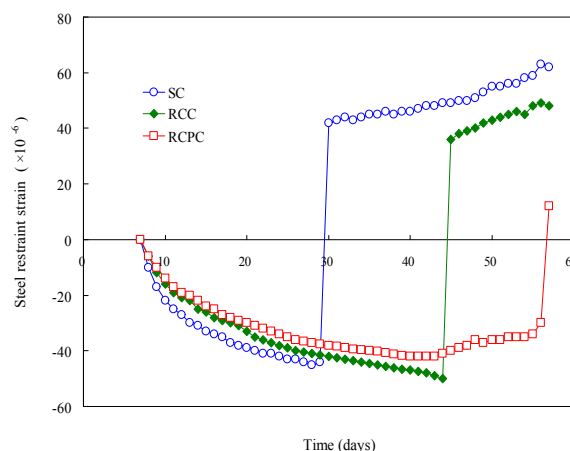


Figure 11: Steel restraint strain of specimens

As the summary of the test results of free drying shrinkage strain and restrained drying shrinkage cracking, red clay decreases drying shrinkage strain of concrete and recycled PET fiber effectively decreases drying shrinkage strain and controls drying shrinkage cracking.

Table V: Result of drying shrinkage cracking test.

Specimens	Shrinkage cracking time (day)	Shrinkage racking averaging time (day)
SC	1	11
	2	27
	3	30
RCC	1	40
	2	45
	3	46
RCPC	1	56
	2	53
	3	46

5. CONCLUSION

The conclusions are as follows.

- (1) In the early age, compression strength of SC was higher than that of RCC and RCPC specimens. However, as specimens aged, compression strength of RCC became higher.
- (2) From the flexural tests, the load capacity of the RCC and RCPC specimens were 10% and 30% higher than that of the SC, respectively. Also, failure pattern of all of the specimens showed typical tensile failure.
- (3) From the results of flexural experiment of beam specimens, relative ductility index of concrete replaced with red clay and concrete beam using red clay with PET fiber was 1.34 and 3.30, respectively.
- (4) The experimental result of free dry shrinkage strain shows that SC specimen has over 40% higher drying shrinkage strain than RCC and RCPC specimens.

(5) The order of time required to create the fully-through cracking was in the order of SC (23day), RCC (44day), and RCPC (52day) specimens.

(6) From the results of flexural and drying shrinkage cracking tests, advantage of using red clay as an admixture was confirmed. Also, it was identified that flexural capacity and drying shrinkage cracking resistance can be significantly improved if used together with recycled PET fibers

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