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Flexural behavior of reinforced concrete beams with cementitious repair materials

S. K. Park and D. S. Yang
Department of Civil Engineering, Sungkyunkwan University, 300, Chunchun-Dong, Jangan-Gu, Suwon, Kyonggi-Do 440-746, Korea

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ABSTRACT

There is an urgent need to develop efficient methods for the repairs and rehabilitation of currently existing structures, they are being deteriorated over time, and also the magnitude of loadings keeps rapidly increasing for such structures. Possibly one of the most challenging tasks in the rehabilitation processes is to upgrade the overall capacity of deteriorated concrete structures. Recently, considerable efforts are being directed toward developing new construction materials. This paper presents the experimental study for the flexural behavior of reinforced concrete beams repaired by Polymer Cement Mortar (PCM) and Ordinary Portland Cement Mortar (OPCM) in the tension region. Tests were performed for eight reinforced concrete beams with varying reinforcement ratios, repair materials and repair lengths. Emphasis is given to overall bending capacity, deflection, ductility index, failure mode and crack development of repaired beams. The results are compared with those from the control beam.

RÉSUMÉ

Il est urgent de développer une méthode efficace pour le renforcement et la réparation afin de remettre en état la structure dont le fonctionnement est dégradé en raison de l'accroissement de la charge ou de l'écoulement du temps. Au cours du processus de renforcement, un des paramètres les plus importants est d'améliorer la performance globale des structures en béton endommagées. La tendance d'aujourd'hui est de développer un nouveau matériau. Dans cet article sont menées des études expérimentales sur la flexion de poutres en béton armé réparées ou renforcées avec du mortier de ciment polymère (MCP) et du mortier de ciment portland ordinaire (MCPO) repectivement. Pour des essais, 8 échantillons d'essais ont été fabriqués en variant le rapport d'armature, le matériau de réparation, ainsi que la longueur à réparer, avant de faire les essais. Les résultats confirment : la capacité de la flexion, une flèche, un indice de la ductilité, une rupture apparente, la forme de la fissure des poutres réparées. Et ces résultats ont été comparés avec celui de l'échantillon de référence.

1. INTRODUCTION

Even though the cost associated with the repair and rehabilitation of existing structures is rapidly increasing, vast number of the repaired and rehabilitated structures do not function properly as expected during their remaining service lives. This involves clear economical implications. The development of better materials and methods for repair and rehabilitation would hopefully improve the safety and reliability of the concrete structure, and eventually extend the service life of those existing structures.

Repair materials used in recent rehabilitation projects are generally classified into two types: resinous and cementitious group. Cementitious repair materials are used mainly as grouting chemicals and often as inhibitors and fillers as well. Cementitious repair materials used as grouting chemicals must exhibit high fluidity, good infilling characteristics, segregation resistance, non-shrinkage, high bond strength and durability.

In this study, a series of reinforced concrete beams were manufactured for the test. Those beams were built such that some parts of the beams were under artificial delamination and spalling of the concrete in the tension zone to make the experimental conditions as similar to the actual field conditions as possible.

A flexural test was performed after those beams were repaired using Polymer Cement Mortar (PCM) and Ordinary Portland Cement Mortar (OPCM). Variables used in design of the tests beams include the reinforcement ratio and the repair length of the PCM. From the results of the test, analysis was carried out for the behavior of beams such as crack patterns, the failure mode, the yielding load and the ultimate load. The ductility index of repaired beams is calculated and compared with that of the control beam.

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Table 1- Details and data of tested beams

Variables		Beams	Tension rein.	Compres-sive bar	Stirrup	Remarks
Rein. ratio	0.0106	STD16	2@H16	2@H10	D6	Control Beam
		MTD16				PCM
		ETD16				OPCM
	0.0206	STD22	2@H22			Control Beam
		MTD22				PCM
		ETD22				OPCM
Repair length		MRL160	2@H16			PCM
		MRL120				PCM

OPCM: Ordinary Portland Cement Mortar
PCM: Polymer Cement Mortar

2. EXPERIMENTAL PROGRAM

The main objective of the study is to examine the flexural behavior of reinforced concrete beams repaired with cementitious repair materials by carrying out flexural tests on a damaged beam that has been repaired using OPCM or PCM. In order to set the criteria for the test data, a control beam is prepared. To compare properly OPCM with PCM as the repair materials, each material is mixed such that it has the identical strength each other. Beams are made with rectangular double-reinforcement beams with a section area of 150×250 mm, an effective depth of d = 220 mm, a total length of 2.2 m and a effective span length of 2.0 m. Details and data of tested beams are shown in Table 1.

Stirrups are arranged with 6 mm diameter reinforcing bars at an interval of 100 mm. In particular, for the beams MTD16, MTD22, ETD16, ETD22, MRL120 and MRL160, OPCM or PCM is placed up to 8 cm above the bottom of the tension zone to simulate the actual repair conditions in the field subjected to delamination by crack and spalling. The shapes of beams are shown in Fig. 1.

2.1 Materials

The type of concrete used in this test is ready-mixed concrete that has been aged for 28 days. Its specified concrete strength is 24.5 MPa, its compressive strength is 30.1 MPa and its slump value is 120 mm. The design yield stress of the reinforcing bars of 6 mm diameter used for the arrangement of beams is 357.1 MPa and for the main reinforcing bars of 10 mm, 16 mm, and 22 mm diameters, the yield stress is all 408.2 MPa.

The repair materials used in this test are categorized into OPCM and PCM. PCM used in this test is a high-strength mortar that strengthens the low-density polymer. It tends to harden rapidly, and therefore it can be effectively used for the structural repair of a void. This property also enables the use of trowels on the concrete structures as well as the rendering and profiling of the horizontal and vertical areas. The mechanical properties of PCM are shown in Table 2.

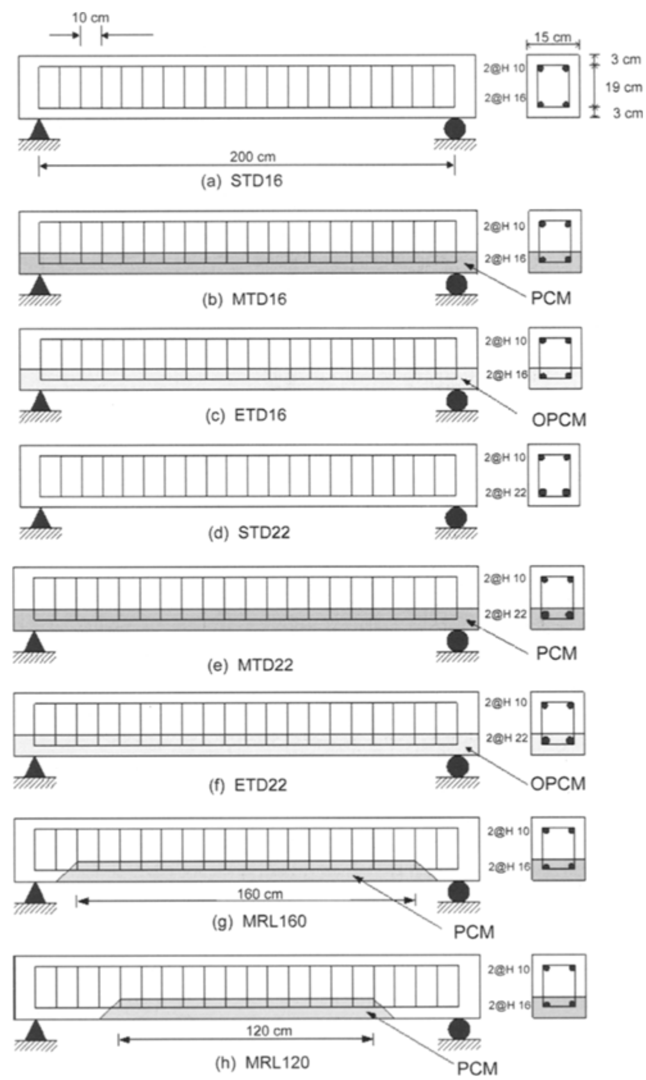


Fig. 1 - Shape of beams.

2.2 Loading and measurement

The reinforced concrete beams are loaded for the flexural test at 4 points on the frame with Universal Test Machine (UTM). Linear Variable Differential Transformer (LVDT) is installed on the center area to measure the displacement of the beam. As shown in Fig. 2, strain gauges are installed on the tension reinforcement, the compressive bar and the stirrup before the placement of the concrete, and strain gauge are also installed on the span of the beam to measure the strain. The measurements from this sensor are transferred to the data acquisition system (EDX-1500A) and the computer that processes data. The strength of the specimens of concrete, PCM and the OPCM are shown in Table 3.

3. TEST RESULTS

3.1 Results

The results of the flexural tests for the repaired reinforced concrete beams are presented in Table 4. The test results show that the ultimate load of the control beam is 101kN with the reinforcement ratio of 0.0106. The ultimate load of the beam repaired with PCM is 96kN, which is 95% of the ultimate load of the control beam, and the ultimate load of the beam repaired with OPCM is 91% of the ultimate load of the control beam. This indicates that PCM has better repair effects than OPCM. Although both the tension reinforcement and the compressive bars of the control beam yielded, in beams MTD16 and ETD16, only the tension reinforcement bars yielded.

The ultimate load of the beams with reinforcement ratio of 0.0206 is lower than expected due to the bearing failure of the supporting point. Only the tension reinforcements of the STD22 beam yielded due to bearing failure, whereas the tension reinforcement and the compressive bars of the MTD22 beam and the ETD22 beam did not yield.

The deflection of STD16 was measured at 4.4 mm under the service load. The deflection values for the beams MTD16, ETD16, MRL160 and MRL120 were 5.3 mm, 5.4 mm, 4.8 mm and 5.2 mm, respectively. Also, the deflections of beams STD22, MTD22 and ETD22, were 6.5 mm, 6.6 mm and 12.3 mm, respectively. These results indicate that the beams repaired with OPCM are less stiff compared with the control beams and the PCM beams.

Beams MRL160 and MRL120, repaired using PCM with different repair lengths, were prepared and subject to conditions similar to those in the field. Those beams carried loads that are equal to or greater than the ultimate load of the control beam STD16, and load-deflection curves that are almost identical. For beams MTD16, MRL160 and MRL120, with different repair lengths, only the tension reinforcements yielded and not the compressive bar. Relation of load-deflection and load-steel strain of the beam are shown in Figs. 3 and 4.

3.2 Failure mode

The results of the test presented in this paper indicate that the STD16 beam with reinforcement ratio of 0.0106 exhibits typical flexural failure. Beam MTD16, repaired with PCM, developed a horizontal crack under 45 kN and a splitting crack that progressed. Consequently, both flexural failure and delamination failure occurred. For beam ETD16, however, a horizontal crack occurred at approximately 51 kN and damage occurred due to delamination. Beams STD22, MTD22 and ETD22, all with reinforcement ratios of 0.0206, were finally broken down due to bearing failure on the supporting point.

Beams MRL160 and MRL120 differ in the repair length, and they have flexural failure similar to the failure occurred in the control beam. For those two beams, the horizontal crack loads are 52 kN and 51 kN, respectively. These values are higher than that of beam MTD16, which was repaired for the whole span length. In general, the number of cracks in the beams that were repaired with PCM decreased by approximately 50% compared to the number of cracks in the beams that were repaired with OPCM. It is clear from this result that the composite fiber included

Table 2 - Mechanical properties of PCM

Density	Bending strength	Modulus of elasticity	Permeability coefficient	Oxygen diffusion coefficient
kg/m^3	MPa	MPa	m/sec	cm^2/sec
1700~1750	44.9	2.04×10^4	9.65×10^{-15}	2.72×10^{-4}

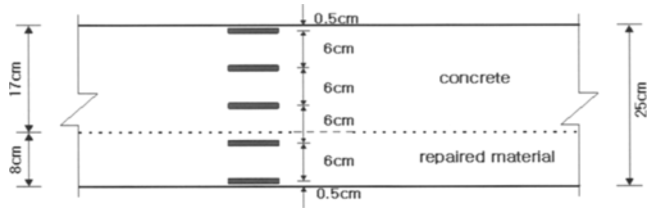


Fig. 2 - Location of concrete strain gauge.

Table 3 - Strength of specimens

	Concrete (MPa)	PCM (MPa)	OPCM (MPa)
Compressive strength	36.2	49.9	49.6
Splitting strength	1.63	1.9	1.5
Modulus of rupture	4.95	5.2	4.48

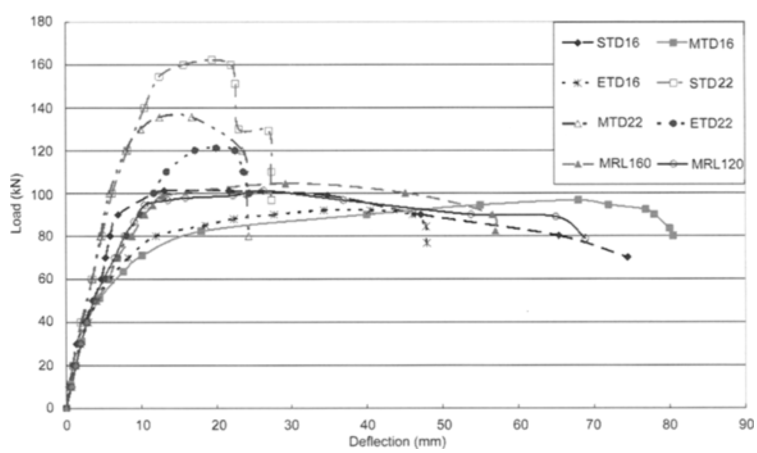


Fig. 3 - Relation of load and deflection.

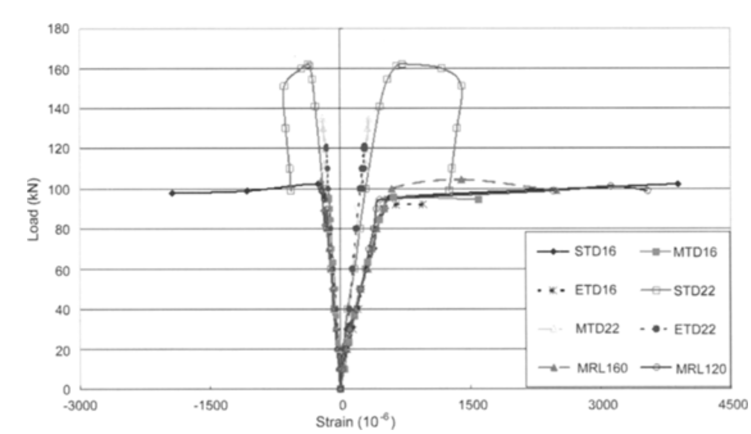
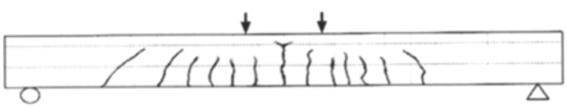


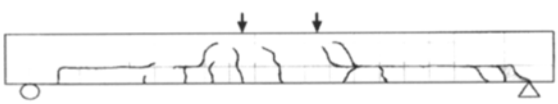
Fig. 4 - Relation of load and steel strain.

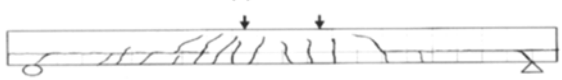
Table 4 - Results of tested beams

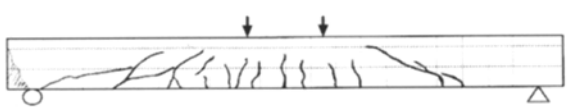
Beams	Cracking load			Yield load			Ultimate load	Failure mode
	Theory (a) (kN)	Test (b) (kN)	(a)/(b)	Theory (a) (kN)	Test (b) (kN)	(c)/(d)	Test (kN)	
STD16	21.6	27	1.25	94.8	91	0.96	101	F
MTD16	-	30	1.39	-	87	0.92	96	F + D
ETD16	-	28	1.30	-	80	0.84	92	D
STD22	24.7	37	1.50	173.0	125	0.72	162	B
MTD22	-	38	1.54	-	121	0.70	135	B
ETD22	-	32	1.30	-	111	0.64	121	B
MRL160	-	26	1.20	-	95	1.00	101	F
MRL120	-	24	1.11	-	95	1.00	104	F

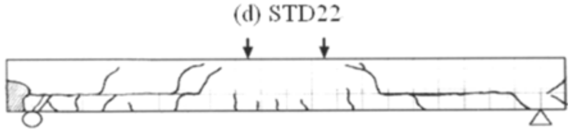
* F: flexural failure D: delamination B: bearing failure

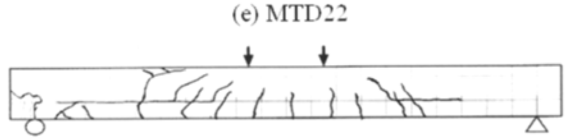

(a) STD16

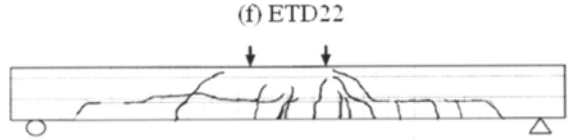

(b) MTD16


(c) ETD16


(d) STD22


(e) MTD22


(f) ETD22


(g) MRL160

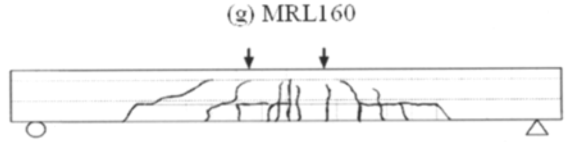

(h) MRL120

Fig. 5 - Failure mode of beams.

in the repaired materials can play a major role in the reduction and prevention of the cracks. The failure mode of the beams is shown in Fig. 5.

3.3 Neutral axis

In this paper, all the beams, excluding the control beams, were subjected to the artificial damage on the tension zone of their section due to delamination and spalling of concrete, and the tests were carried out after they are repaired with repair materials.

As the repaired beams consist of two materials, a high repair effect is indicated only if there is perfect bonding between the interface of the materials. Therefore, variations in the neutral axis of the central section of the span were measured during the each loading stage to evaluate the bonding performance.

In Fig. 6, the beams repaired with OPCM have two neutral axes caused by delamination of the interface between the concrete and the repair materials, and they do not appear to behave accordingly. However, for those repaired with PCM (beams MTD16, MRL160 and MRL120), variations of strain caused by the difference in strength of PCM and concrete on the interface decreased evenly. This is due to the fact that, unlike OPCM, the concrete and PCM move together because the bonding force on the interface between concrete and PCM is strong enough.

3.4 Ductility index

Ductility is a qualitative concept representing inelastic deformation of materials, sections, members or structures just before they collapse without serious damage on segregation resistance. Ductility may be a very important safety coefficient that delays local failure by redistributing redundant stress in the critical section of a statically indeterminate structure. The ductility index or ductility factor is used to measure ductility. It is defined as ratios of curvature, rotation and deflection at the ultimate load to the yielding as shown in Equations (1)~(3).

$$\mu_\phi = \frac{\phi_u}{\phi_y} \quad (1)$$

$$\mu_\theta = \frac{\theta_u}{\theta_y} \quad (2)$$

$$\mu_\Delta = \frac{\Delta_u}{\Delta_y} \quad (3)$$

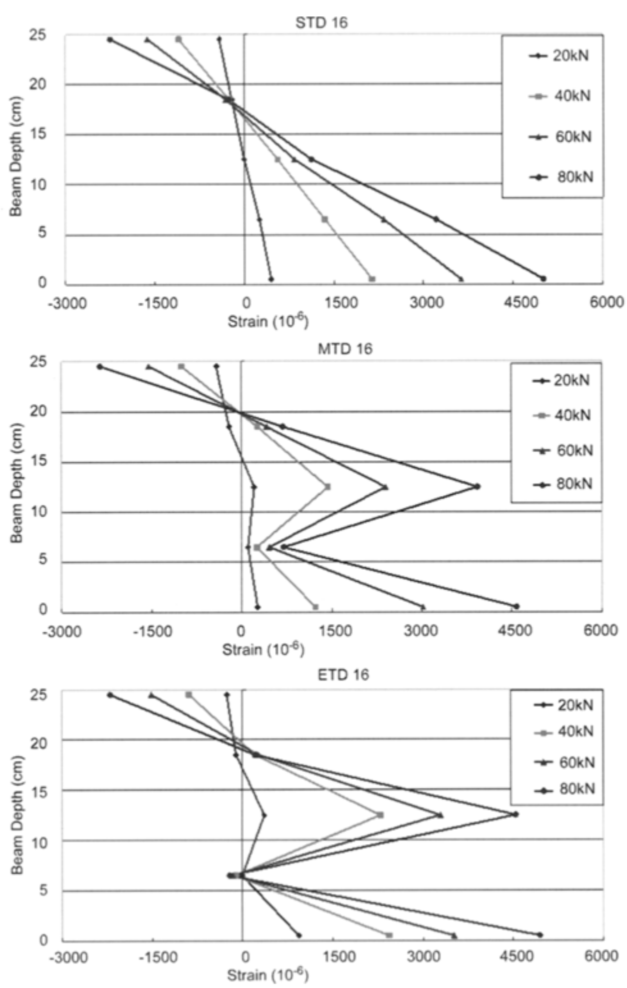
where μ is index of ductility and ϕ, θ, and Δ are Rotation, Curvature and Deflection.

In this test, the safety of members is evaluated by the ductility index. The ductility indices are expressed as the ratio of the deflection at the ultimate load to the yielding deflection in this study.

According to Table 5, the control beam with reinforcement ratio of 0.0106 has a ductility index of 4.57, which is higher than with OPCM but lower than with PCM. However, ductility in repair materials is still considered high with the ductility index of above 3. The ductility indices in the beams with reinforcement ratio of 0.0206 are below 3 due to brittle failure caused by bearing failure of the supporting point. In the beams arranged according to the repair length of PCM, the ductility index is lower than in the control beam STD16, but performance concerning ductility is still acceptable since the ductility index is above 3. The ductility index for each beam is shown in Table 5.

Table 5 - Ductility index

Beams	Yield load		Ultimate load		Ductility Index
	Load (kN)	Deflection (mm)	Load (kN)	Deflection (mm)	
STD16	91	7.2	101	32.9	4.57
MTD16	87	11.0	96	68.0	6.18
ETD16	80	12.0	92	40.4	3.37
STD22	125	8.5	162	22.0	2.59
MTD22	121	8.0	135	16.8	2.10
ETD22	111	13.2	121	22.5	1.72
MRL160	95	11.0	101	35.4	3.22
MRL120	95	10.0	104	31.0	3.10



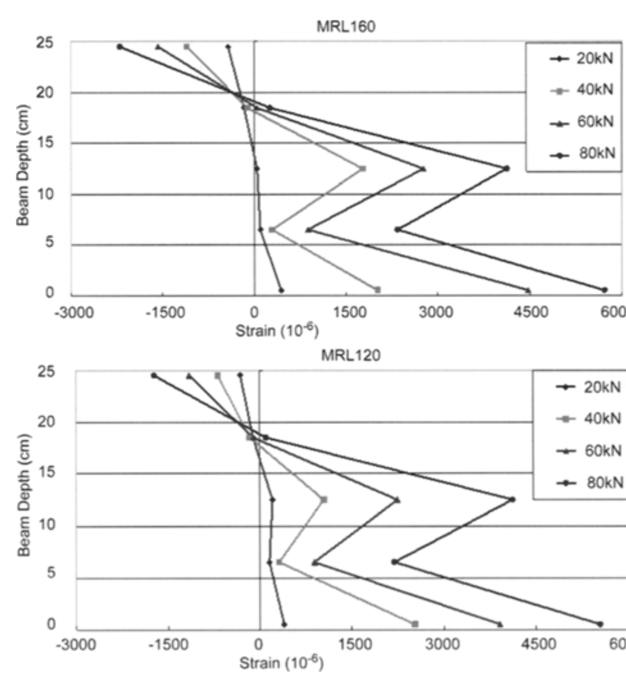


Fig. 6 - Neutral axis of beams

4. CONCLUSIONS

In this paper, a flexural test is carried out to evaluate the structural resisting force of a concrete beam reinforced with PCM versus one reinforced with OPCM. The following are the results of the tests:

1) The test shows that the beams repaired with PCM can carry about 83~103% of the ultimate load of the control beam. This indicates the effect of the repair using PCM is very good. On the other hand, the ultimate load of the beams repaired with OPCM are 75~91% of the ultimate load of the control beam, which is still acceptable. The beams of OPCM have less repair quality compared with the control beams and the PCM beams.

2) It is found that the OPCM beams displayed the major failure modes as the delamination on the adherence surface of the repair materials and the concrete. For beams repaired with PCM, the main failure mode is found to be a flexural failure similar to the control beam, although the repair materials do not behave perfectly together with the remaining sections considering the changes in the neutral axis.

3) Although ductility is low in all beams with reinforcement ratio of 0.0206 due to brittleness caused by bearing failure on the supporting point, the beams repaired with PCM has higher ductility index (above 3) than OPCM beams.

4) In the reinforced concrete beam where more than two

kinds of materials are used, it is found that the performance of the structures depends mainly on the bonding strength on the interface between the materials as splitting strength and modulus of rupture, rather than on the compressive strength of the repair materials. Therefore, more research on the bonding of interfaces between repair materials should be carried out thereby maximizing the repair effect on the structures.

NOTATIONS

A = the cross-sectional area (cm^2)

A_s = the cross-sectional area of reinforcement (cm^2)

d = the effective depth (cm)

ρ = the reinforcement ratio

μ_ϕ = the ductility index of rotation

μ_θ = the ductility index of curvature

μ_Δ = the ductility index of deflection

ϕ_y = the rotation of yield load

ϕ_u = the rotation of ultimate load

θ_y = the curvature of yield load

θ_u = the curvature of ultimate load

Δ_y = the deflection of yield load

Δ_u = the deflection of ultimate load

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