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Chemically Prestressed Precast Concrete Box Culvert with Expansive Additives

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Abstract

Although portland cement concrete is one of the most universal construction materials, it has some disadvantage such as shrinkage, which is an inherent characteristic. Because of this shrinkage, combined with the low tensile strength of the material, cracks of varying sizes can be found in every reinforced concrete. To prevent this cracking, keeping the concrete in compression by mechanical prestress has been used. This study discusses application of expansive additives for concrete to improve the serviceability of precast concrete box culvert by inducing chemical prestress. For this purpose, both expansive concrete slabs and normal concrete slabs are tested to verify the effect of expansive additives. Then the failure tests of the fullscale precast box culverts were carried out and the critical aspects of the structural behavior were investigated. The result of the material tests shows that the optimal proportion of expansive additives is 13 percent of cement weight, and the properties of expansive concrete are the same as those of normal concrete in that proportion. Both the experimental cracking load and service load of the expansive concrete members are increased in comparison with those of the normal concrete, but the ultimate load is decreased slightly. In addition to the above results, the deformation of expansive concrete member is less than that of normal concrete member, and permanent strain which results from cyclic load is decreased. It can be concluded that the use of expansive additives to induce chemical prestress in precast concrete box culvert greatly improves the serviceability.

keywords : chemical prestress, cracking load, expansive additives, precast box culvert

1. Introduction

Recently, precast concrete box culvert is more popular than cast insitu concrete box culvert in urban areas because the former has many advantages over the latter in view of quality, installation and construction time. Also, most of the precast box culverts which are placed in corrosive environment are required to restrict the development of cracks, and to resist increasing vehicle loads. Thus, there arise conspicuous needs for better durability of precast box culverts.

To improve durability of precast concrete box culverts, it is important to understand the influence of constituents as the properties of concrete.

Portland cement concrete is one of the most universal construction materials, but it has some disadvantages such as shrinkage which is an inherent characteristic. Due to this shrinkage, combined with the low tensile strength of the material, cracks of various sizes can be found in most of the reinforced concrete structures. To prevent cracking, mechanical prestress has been used to keep the concrete in compression. This paper reports the effect of chemical prestress induced by the application of expansive additives under restrained condition.

Under restrained condition, concrete is able to induce compressive stresses while it expands[(2)]. When the restrained expansive strain is greater than the subsequent strain due to shrinkage and creep, permanent compressive stresses will remain in the concrete.

In this study, concrete was produced by mixing expansive additives with type I portland cement. Material test, slab test and full-scale precast concrete box culvert test were carried out in order to examine the effect of expansive additives in the properties of concrete.

2. Test Program

2.1 Material Test

In this test, the difference between normal and expansive concrete on their properties such as compressive strength, modulus of rupture, f_r, and modulus of elasticity was investigated. Table 1 shows the test parameters.

Type I portland cement made in Korea was used in this test. Table 2 shows the chemical composition of the cement used. The fine aggregate was natural sand with a fineness modulus of 2.38 and specific gravity of 2.58. The coarse aggregate was crushed stone having a maximum particle size of 25 mm and specific gravity of 2.68. The expansive additive was K type specified by ACI. Its physical properties and chemical composition are shown in Table 3.

Four types of mixtures were made by changing the proportion of the expansive additives. The amount of the expansive additives in the mixture was expressed as a percentage by weight of cement. The mixture proportions are shown in Table 4 with a target 28-day compressive strength of 33 MPa. Also, the typical mixture proportion without expansive additives is the Same mixture proportion as that of a common precast box culvert manufacturer. The main objective of this material test was to determine the optimal proportion of the expansive additives required for the chemically prestressed precast concrete box culvert.

16-100×100×400 mm specimens were tested to evaluate the unrestrained longitudinal expansion. Strain gages were embedded at the center of the specimens.

Table 1 Test parameter

Test type	Parameters				
	Proportion of expansive additives	Test age	Curing condition		Restrain conditon
			In – water	Steam	
Compressive strength	O	O	O	O	
Modulus of elasticity	O		O	O	
Modulus of rupture	O	O			
Expansive strain	O	O	O	O	O
Slump	O				
Air content	O				

Table 2 Physical properties and chemical composition of cement

Physical properties			Chemical composition of cement (%)					
Specific gravity	Ignition loss (%)	Insoluble residuum (%)	SiO_2	Al_2O_3	Fe_2O	CaO	MgO	SO_3
3.15	1.0	0.9	22.1	5.1	2.9	64.3	1.2	1.7

Table 3 Physical properties and chemical composition of expansive additives

Physical properties			Chemical composition of cement (%)					
Specific gravity	Ignition Loss (%)	Insoluble residuum (%)	SiO_2	Al_2O_3	Fe_2O	CaO	MgO	SO_3
2.93	1.0	1.4	4.0	10.0	1.2	52.5	0.5	28.3

Table 4 Mixture proportion

f_{ck} (kgf/cm^2)	W/C (%)	Proportion of expansive additives (%)	G_{max} (mm)	Air (%)	Slump (cm)	S/a (%)	Unit weight(kg/cm^2)				
							W	C	S	G	Expansive additives
340	35.2	0	25	1.5	8 2	40.4	169	480	629.3	1095.1	0
		11						427.2			52.8
		13						417.6			62.4
		15						408			72

Also, 16-100×100×385 mm specimens with reinforcement ratio of 0.98 percent were used for evaluating restrained expansion.

2.2 Slab Test

Slab specimens were designed to estimate the effect of chemical prestress induced by expansive additives. The optimal proportion of expansive additives in concrete mixture was deter-mined from the results of the previous material test. The slabs were reinforced with deformed mild steel bars (φ 13 mm and φ 16 mm). The major variables were the proportion of expansive additives, the slab height and the amount of bot-tom longitudinal reinforcement. Fig. 1 illus-trates details of the specimen. Individual pa-rameters are summarized in Table 5.

Table 5 Slab Specimen List and Parameter

Specimen		Parameter		
		Height (cm)	Proportion of expansive additives (%)	Rein-forcement (A_s)
20-series	20-0-16	20	0	3D16
	20-13-16		13	
	20-13-13			3D13
15-series	15-0-16	15	0	3D16
	15-13-16		13	
	15-13-13			3D13

Each specimen was instrumented with a load cell, displacement transducers, and strain gages to monitor the applied loads, corresponding dis-placement and the resulting strains. Two roller supports were provided at the ends of the speci-men

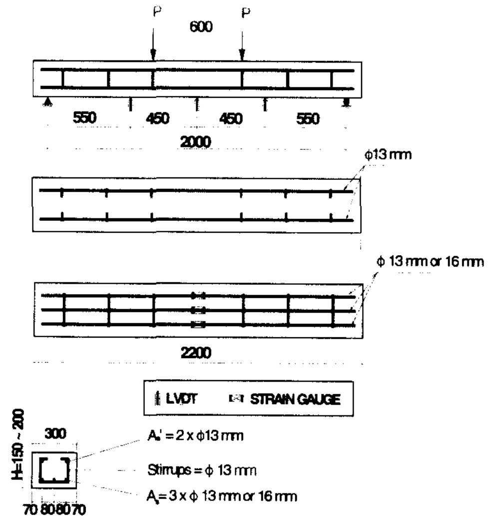


Fig. 1 Detail of slab specimen

The loading system was designed to produce a constant moment region in the middle of the specimen. As one of the objectives of this test is to compare the permanent strains of expansive concrete with those of normal concrete, the process of loading and unloading was repeated on each specimen for each load level of 9.8 kN to 39.2 kN which is about 30 percent of the expected ultimate load. After the process of loading and unloading, load was increased gradually until failure occurred. At each stage, strains of the bottom longitudinal reinforcements and deflection were measured at the midspan of the specimens and flexural cracks were marked.

2.3 Full-Scale Precast Concrete Box Culvert Test

Two types of full-scale precast concrete box culvert specimens were fabricated. One was type-A which was made of expansive concrete and the other was type-B which was made of normal concrete. Both of them were manufactured by steam curing at precast concrete plants. The details of the specimens are shown in Fig. 2.

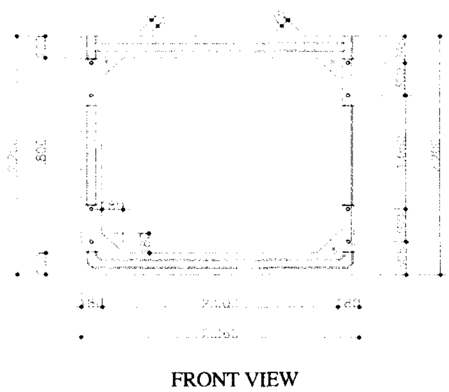


Fig. 2 Box culvert specimen (unit : mm)

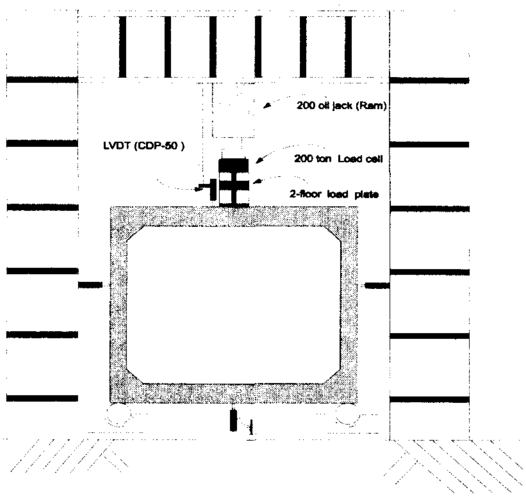


Fig. 3 Test setup of precast box culvert specimen

The concrete mixture was designed from the result of the material tests. The average compressive strength of normal concrete was 34.8 MPa, and that of expansive concrete was 34.3 MPa. Culvert specimens were reinforced by deformed mild steel bars of 13 mm and 16 mm with yield strength of 490.3 MPa and 509.5 MPa respectively.

Specimens were simply supported and concen-trated loads were applied at the midspan of the upper slab. Midspan deflections of the upper slab were measured and the flexural crack width was measured using a microscope of fifteen magnifications. Strain gages were mounted on the tensile reinforcements and on the surface of the concrete.

3. Test Result and Discussion

3.1 Material Test

Half of the specimens were demolded after 12-hour steam curing and they were placed in ambient environment of 20 ℃ until tested. The others were demolded 24 hours after the place-ment of concrete and then cured in water.

3.1.1 Compressive Strength

2-standard cylinders(ϕ10x20cm) were tested at various ages - right after demolding (0.5 day for steam curing, 1 day for standard curing), 3, 7, 14, and 28 days. Total numbers of tested specimens are 80.

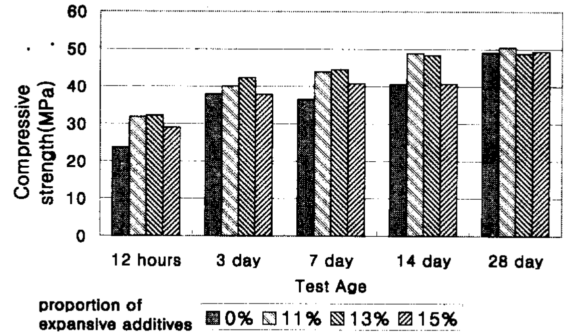
The relationship between the compressive strength and the proportion of the expansive add-itives based on different curing methods is shown in Fig. 4. The compressive strengths of expansive concrete specimens were much higher than those of normal concrete specimens right after demolding in all curing cases. However, the difference of strength between expansive concrete specimens and normal concrete speci-mens was decreased at 28 days.

3.1.2 Modulus of Elasticity

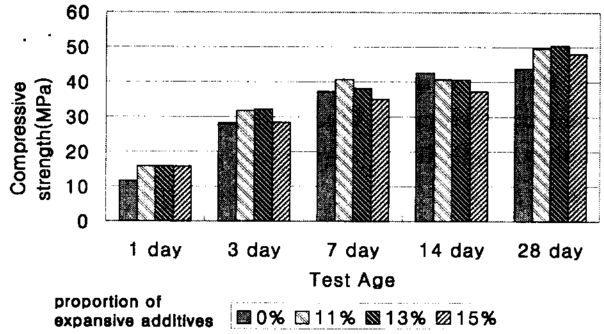
Fig. 5 shows modulus of elasticity of both expansive concrete and normal concrete. The secant modulus of elasticity, using half point of maximum strength, were used for the measure-ment of modulus of elasticity. As shown in Fig. 5, there is no significant difference between them.

3.1.3 Modulus of Rupture

This test consists of 16 specimens; 4 specimens (steam cured; 2, in-water cured; 2) at every age.



(a) Steam curing



(b) Standard curing

Fig. 4 Compressive strength

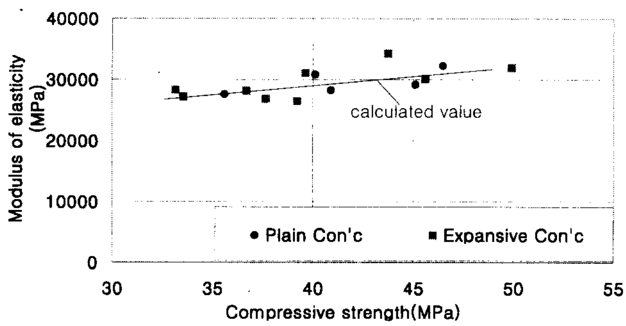


Fig. 5 Modulus of elasticity

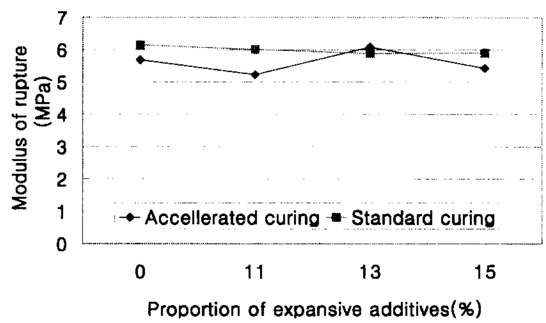
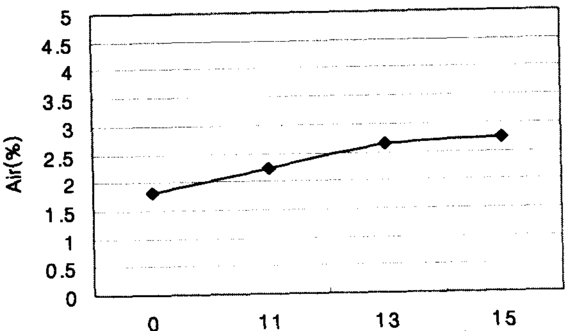


Fig. 6 Modulus of rupture

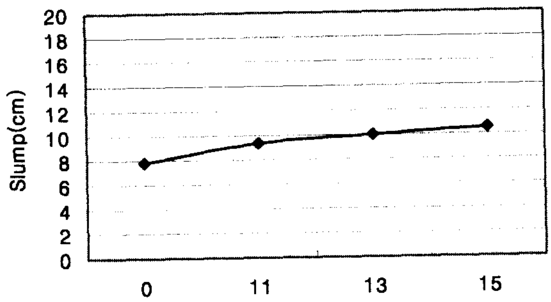
Since the tensile strength of concrete, unlike the compressive strength, is determined mainly by bonding of cement paste, tensile strength of expansive concrete tends to be decreased as some of the cement are replaced by expansive additives. However, in this test, as shown in Fig. 6, the reduction of tensile strength is in-sig-nificant.

3.1.4 Slump and Air Content

Workability was not affected although slump and air content were slightly increased as the proportion of the expansive additives was in-creased. Fig. 7 shows slump and air content according to the proportion of expansive add-itives.



(a) Proportion of Expansive additives(%)



(b) Proportion of Expansive additives(%)

Fig. 7 Air content and slump

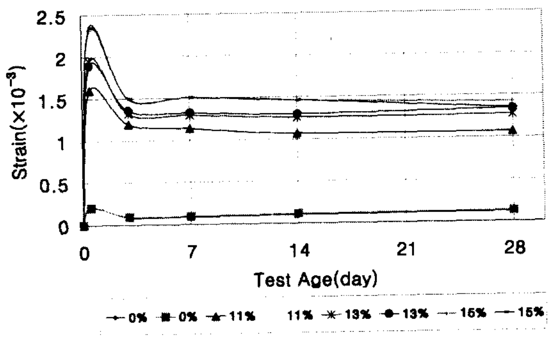
3.1.5 Expansive Longitudinal Strains

32-specimens were tested: unrestrained 16(standard cured; 8, steam cured; 8), restrained 16 (standard cured;8, steam cured ;8).

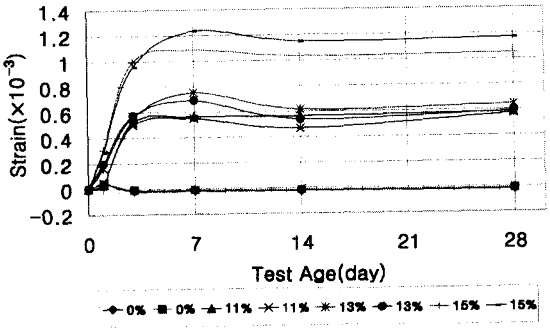
Fig. 8-(a) shows the expansive longitudinal strains of the unrestrained specimens which were cured in water after demolding, and Figure 8-(b) shows the result of the unrestrained specimens which were conditioned in ambient environment after steam curing. As shown in Fig. 8, the expansive longitudinal strains of the unrestrained specimens continuously occurred to about 90 percent of the highest expansive longitudinal strains for 7 days after demolding in water whereas those of the unrestrained specimens, which were cured in ambient environment, began shrinkage right after steam curing. Therefore, in order to acquire the sufficient expansive strains for chemical prestress, plentiful water, which is required for hydration of expansive additives, should be provided to specimens at least for 7 days after demolding [(3)].

Fig. 9-(a) shows the expansive longitudinal strains of the restrained specimens which were cured in water after demolding, and Fig. 9-(b) shows results of the restrained specimens which were cured in ambient environment after steam curing. The trends of the expansive longitudi-nal strains of the restrained specimens are similar to those of the unrestrained specimens in all cases of curing methods. But the amounts of strains were about one third of those of the unrestrained specimens. This means that the chemical prestresses by expansive additives were developed from the difference of strains between unrestrained specimens and restrained specimens.

In particular, as shown in Fig. 9-(a), the expan-sive longitudinal strains of the restrained speci-mens with mixture proportion of 15 % exceed 1×10^{-3} at which tensile crack would occur in reinforced concrete. During this test, there were no cracks in expansive strain specimens. Therefore, it could be said that the optimal proportion of the expansive additives is 13 % of the unit cement weight in this test.

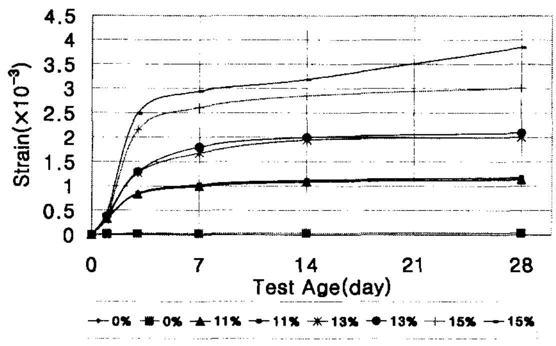


(a) Standard curing

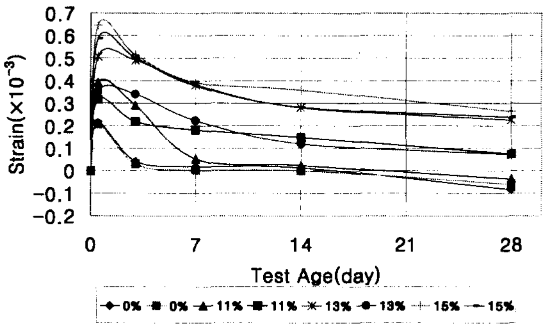


(b) Steam curing

Fig. 8 Strains of unrestrained specimen



(a) Standard curing



(b) Steam curing

Fig. 9 Strains of restrained specimen

3.2 Slabs Test

3.2.1 Cracking Load and Ultimate Load

Cracking is one of the major characteristics of concrete that affects design procedure. The load vs. deflection responses are plotted in Fig. 10. As shown in Fig.10, the cracking loads of expan-sive concrete slabs were higher than those of normal concrete slabs.

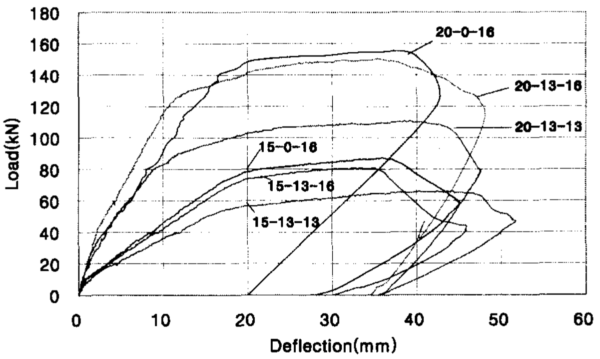


Fig. 10 Load vs. deflection response of slab specimen

Table 6 gives the cracking load (Pcr) and ulti-mate load (Pu) of each specimen. As shown in Table 6, the cracking load of the specimen 20-13-16 (which has the same reinforcement ratio and was mixed with 13 per-cent expansive addi-tives) was approximately 1.4 times higher than that of the control specimen 20-0-16. Moreover, the cracking load of the specimen 20-13-13, al-though reinforcement amount was 76 percent of that of 20-0-16, was increased by about 10 per-cent when compared with 20-0-16. Also, in the cases of 15-series specimens (of which the height was decreased by 5 cm when compared with 20-series specimens), the cracking load of specimen 15-13-13 higher than that of the specimen 15-0-16.

Table 6 Cracking load and ultimate load of slab specimen (kN)

Soecimen	P_{cr}		P_u	
	P_{cr}	r_{cr}	P_u	r_u
20-0-16	**27.978**	**1.000**	**154.553**	**1.000**
20-13-16	38.834	1.388	150.434	0.973
20-13-13	30.989	1.107	109.933	0.711
15-0-16	**10.297**	**1.000**	**87.181**	**1.000**
15-13-16	12.062	1.171	80.905	0.928
15-13-13	10.983	1.070	65.901	0.756

r_{cr} : ratio of P_{cr} to normal specimens.
r_u : ratio of P_u to normal specimens

Therefore, it could be said that the effect of the chemical prestress induced by expansive addi-tives is very significant in the case of same size and reinforce-ment amount. However, the effect is reduced with a decrease in height of the concrete member.

3.2.2 Deflection

The deflections are shown in Fig. 10. Table 7 shows the deflections according to each step. As shown in Ta-ble 7, the deflection of the speci-men 20-13-16 is lower than that of the specimen 20-0-16. and the deflection of the specimen 20-13-13 is similar to that of the specimen 20-0-16. This clearly demonstrates the positive effect of expansive additives.

Table 7 Deflection of slab specimen (mm)

Specimen	Load step (kN)				
	9.8	19.6	39.2	58.84	78.45
20-0-16	0.4	1.0	3.1	6.2	7.9
20-13-16	0.4	1.0	2.2	4.3	6.3
20-13-13	0.4	1.0	3.2	5.9	8.7
15-0-16	1.4	3.5	8.4	13.3	-
15-13-16	0.8	3.7	9.0	14.8	-
15-13-13	0.9	4.5	11.5	-	-

3.2.3 Permanent Strains and Restoring Force

In general, restoring force can be estimated from the amount of permanent strain when load is completely removed. Load vs. strain re-sponses of tensile reinforcement are illustrated in Fig. 11. The permanent strains are noted in Table 8. As shown in Table 8, the permanent strains of expansive concrete specimens were lower than those of the normal concrete. Thus it can be said that the restoring power was in-creased by chemical prestress.

Table 8 Permanent strain of tensile reinforcement of slab specimen ($x10^{-3}$)

Speci-men	Load step (kN)					
	9.8		19.6		39.2	
	Strain	r	Strain	r	strain	r
20-0-16	**0.033**	**1.000**	**0.120**	**1.000**	**0.260**	**1.000**
20-13-16	0.008	0.242	0.049	0.408	0.072	0.277
20-13-13	0.011	0.333	0.081	0.675	0.103	0.396
15-0-16	**0.152**	**1.000**	**0.318**	**1.000**	**0.388**	**1.000**
15-13-16	0.147	0.967	0.259	0.914	0.287	0.797
15-13-13	0.038	0.250	0.327	1.169	0.485	1.250

3.2.4 Service Load and Safety Factor

Regarding the service load (Pw) as the load at the allowable deflection of slabs (L/360 = 200/360 = 0.55 cm), the service load of the specimen 20-13-16 would be 1.25 times higher than that of the control specimen 20-0-16 and that of the specimen 20-13-13 almost the same. Table 9 shows the service load and ultimate load of the slab specimens.

3.3 Full-Scale Precast Concrete Box Culvert Test

3.3.1 Phases of Cracking

The crack patterns of the bottom face of upper slabs of the precast box culverts after test are illustrated in Fig. 12. Flexural cracks initially formed near the load point. As the load in-creased, these cracks grew, while more cracks developed away from the load point. As shown in Fig. 12, fewer cracks were observed in type-A.

Table 9 Service load and safety factor of slab specimens (kN)

Speci-men	P_w	r_w	P_u	r_u	P_u / P_w
20-0-16	56.437	1.000	154.553	1.000	2.738
20-13-16	71.098	1.230	150.434	0.973	2.116
20-13-13	58.055	1.027	109.933	0.713	1.894
15-0-16	23.536	0.417	87.181	0.564	3.704
15-13-16	25.301	0.448	80.905	0.523	3.197
15-13-13	22.751	0.403	67.901	0.426	2.896

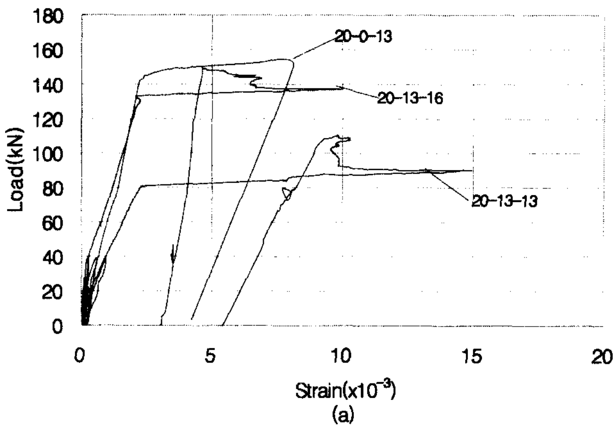


Fig. 11 Load vs. Strain response of reinforcements at midspan of slab specimens

3.3.2 Crack Width

The crack width vs. applied load response is illustrated in Fig. 13. Crack width was measured at one point of the first occurring crack on top slab soffit with every load step. As shown in Fig. 13, the crack widths of type-A are smaller than those of type-B. Also, the difference between them increased as the load was increased.

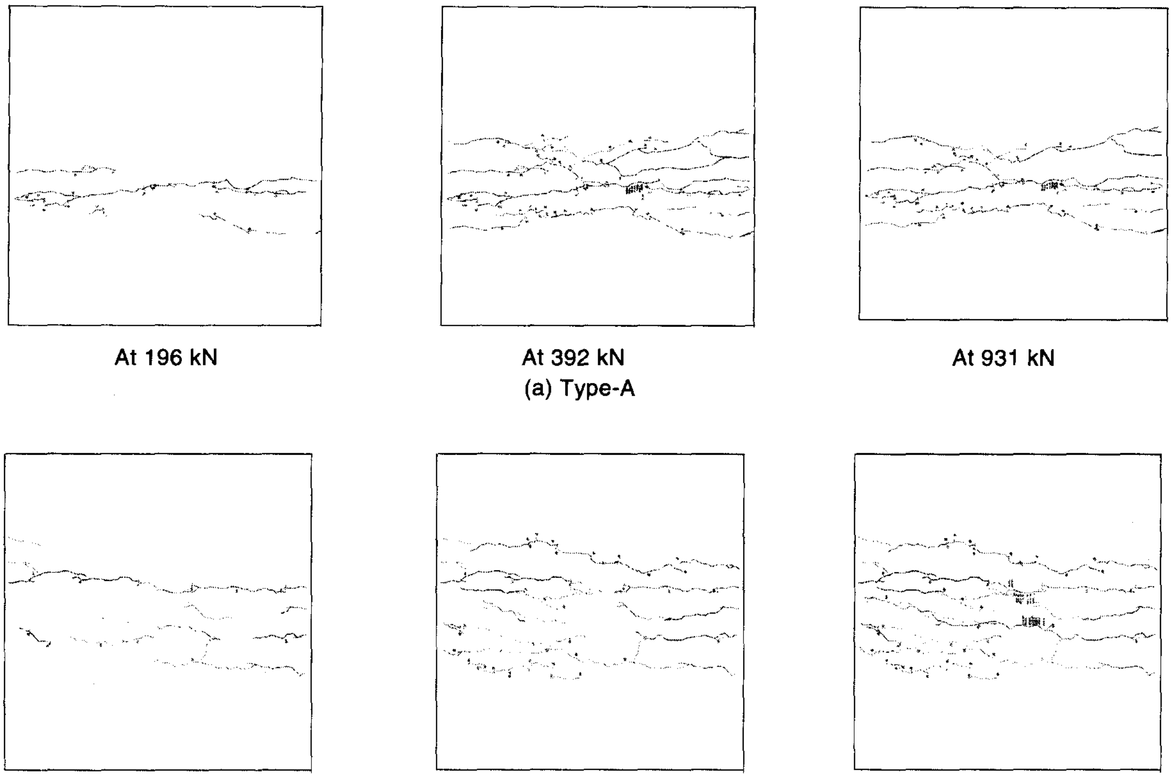
As shown in Fig. 12, there were some differences between crack patterns of both specimens: It could be thought that crack distributed area of type-B was larger than that of type-B due to induced prestress while numbers of cracks are same. It means that the crack spacings of type-A are narrower than those of type-B. Also, initial cracking load of chemically prestressed type-A specimen was less than that of non-prestressed type-B specimen and tensile stress in steel of the former was less than that of the latter up to service load level. Hence, it resulted in smaller crack widths in type-A specimen at the same load level.

3.3.3 Load vs. Deflection Response

Load vs. deflection response is illustrated in Fig. 14. The deflections of type-A were lower than those of type-B. Also, the permanent deflections of type-A, when the loads were removed, is lower.

3.3.4 Cracking Load and Service Load

The cracking load of type-A specimen was 392.2 kN and that of type-B specimen was 313.8 kN(See Fig. 14). Also, Regarding the service load as the load which causes the allowable crack width (0.2 mm - Standard Specification for Con-crete, Ministry of Construction and Transportation of Korea (4)) of the concrete members installed in corrosive environment, the service load of type-A was 333.4 kN and that of type-B was 235.3 kN.



At 196 kN | At 392 kN | At 931 kN

(a) Type-A

At 196 kN | At 392kN | At 833 kN

(b) Type-B

Fig. 12 Crack patterns of upper slab of precast box culvert specimens

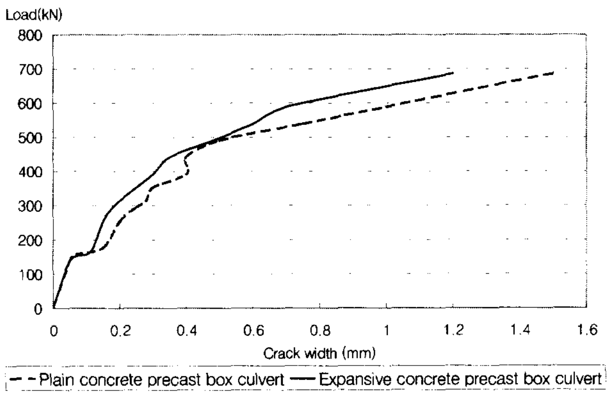


Fig. 13 Load vs. crack width response of upper slab of precast box culvert

3.3.5 Ultimate Load and Safety Factor

Ultimate load and the corresponding safety fac-tor, which is the ratio of the service load to ulti-mate load, are noted in Table 10. As shown in

3.3.6 Permanent Strains and Restoring Force

Load vs. strain responses of reinforcement of the upper slab are illustrated in Fig. 15. The permanent strains of both specimens are noted in Table 11. Similar to the results of the slab test, the permanent strains of type-A is decreased by chemical prestress when compared with type-B.

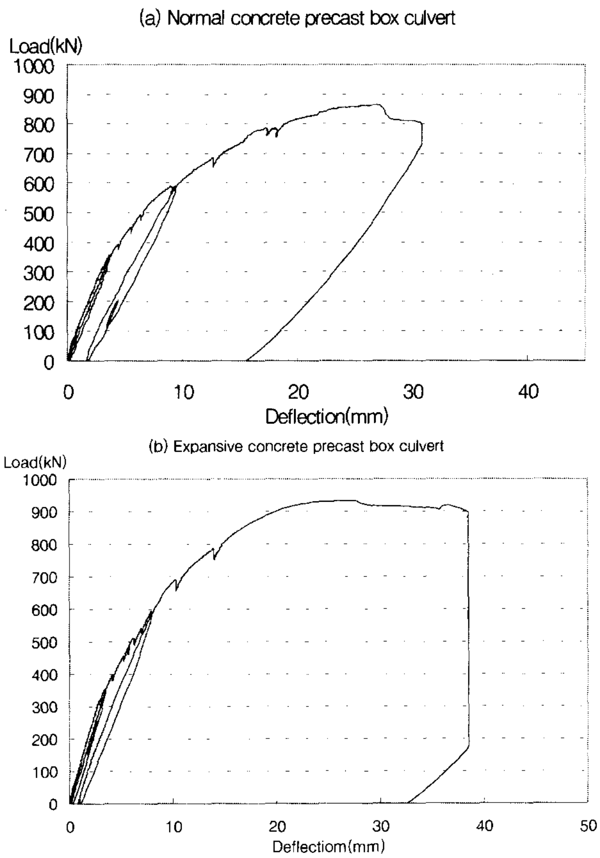
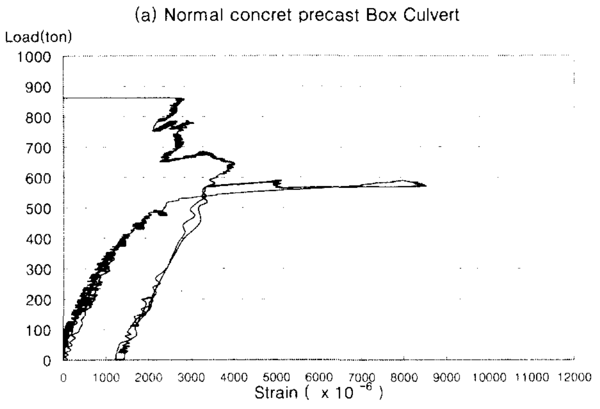


Fig. 14 Load vs. deflection response at the midspan of upper slab of PC box culvert specimen

Therefore, it can be said that the restoring power of type-A is higher than that of the normal one.

Table 10 Service load, ultimate load and safety factor of PC box culvert specimen

Specimen	P_w(kN)	r_w	P_u(kN)	r_u	P_u / P_w
Normal con'c	235.539	1.000	867.889	1.000	3.688
Expansive con'c	333.426	1.427	931.632	1.073	2.790



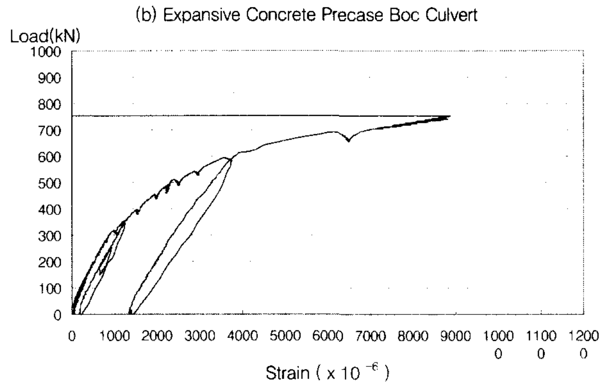


Fig. 15 Load vs. strain response of reinforcement responses at midspan of upper slab of precast box culvert specimens

3. Conclusions

In this study, three kinds of tests were performed to determine the effect of expansive additives on the properties of precast concrete box culvert. Conclusions are as follow

1) As the results of the material test, the physical properties such as compressive strength, modulus of elasticity and modulus of rupture were not affected by mixing expansive additives from 11 percent of unit cement weight to 15 %. Also, workability was not affected althought slump and air content were slightly increased as the amount of the expansive additives was increased from 11% to 15%. However, the expansive longitudinal strains under the restrained condition exceeded the tensile strain $1x10^{-3}$ that could crack on the specimens when 15% of unit cement weight was replaced with expansive additives. Therefore, the optimal proportion of expansive additives in this test mixture proportion is 13% of unit cement weight.
2) The hydration of expansive additives, when sufficient moisture is provided, continue to occur for 7 days after demolding. Thus, the expansive concrete should be moist-cured for at least 7 days after demolding in order to acquire the necessary chemical prestress induced by expansion of concrete.
3) The cracking loads of both slabs and precast box culverts made of expansive concrete are 25 to 40 percent greater than those of both slabs and precast box culvert made of the normal concrete in the same size and reinforcement ratio. Also, the crack widths of the former are smaller than those of the latter and the difference between them is increased as the load is increased.
4) The permanent strains as well as the deflections were significantly decreased when slabs and precast concrete box culvert were made of expansive concrete. This implies that the restoring power of expansive reinforced concrete member is higher than that of the nor-mal concrete one.

Therefore, it can be concluded that the durability of the precast concrete box culverts is improved by the chemical prestress induced by expansive additives. Furthermore, the application of expansive additives for reinforced concrete is very efficient to improve the serviceability related to cracking and service load under proper controls over the curing method and the amount of expansive additives.

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