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Investigating the use of high performance concrete in partially prestressed beams and optimization of partially prestressed ratio

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Abstract

The main objective of this study is to investigate the behaviour of partially prestressed concrete (PPC) beams subjected to pure flexure. The test beams were produced using both high performance concrete (HPC) and traditional concrete (TC). Test beams were compared with each other for strength, strain and cracking cases. The comparison was done by theoretical and experimental methods. Test measurements included failure loads, deflections, strains in concrete and steels, failure moments and service moments, experimental safety coefficients, number of cracks, crack widths, curvatures. Thus, optimum partially prestress ratio was determined for HPC and TC. Advantages of using HPC in partially prestressed beams were brought out. According to the results of the study, optimum partially prestress ratio for PPC beams produced using traditional concrete is ~60%; while it is ~70% when HPC is used. The test results are shown that the usage of HPC in PPC beams is more convenient than the TC under some boundaries and conditions.

Keywords: Beams, High performance concrete, Partially prestressed ratio.

Introduction

Chronologically, construction techniques were revealed as reinforced concrete, prestressed concrete and partially prestressed concrete. None of these techniques are substituted to each other. Each technique is used in its own conditions (Akgün, 2003). As known that, all structures must have stability, a sufficient strength, durability, ductility and stiffness but fully prestressed concrete construction technique is much lower ductility than reinforced concrete construction technique. So, it hasn't any adaptation property. According to this reason, partially prestressed concrete (PPC) construction technique that has adaptation property should be used especially at the active earthquake regions. Because, there are both active (prestressing steels) and passive (reinforcing steels) steels in sections of elements produced with PPC. PPC construction technique is obtained adaptation property by presence of passive reinforcement. Consequently, partially prestressed construction technique is more rational and economical than fully prestressed concrete construction technique under some boundaries and conditions (for buildings that are allowable for occurring crack or protected from bad weather conditions) (Durmuş, 1976, Durmuş *et al*., 1979;1982a).

From other aspect, in terms of strength and durability of concrete, it is clear that concrete components and steels used in structure elements produced by using partially and fully prestressed concrete construction technique have better performance than traditional construction techniques. To improve the performance of concrete, both compressive strength and workable of concrete should be increased. Concretes with high strength, workable and durable are named high performance concretes. Production of these concretes requires decreasing water/cement ratio and using chemical and mineral additives to improve the strength and workability. If failure mechanisms of concrete are considered, the three parameters such as strength of aggregates, quality of cement and adherence of aggregate-cement paste are required to be high for improve strength of concrete (Durmuş & Pul, 1993; Akgun *et al*., 2009).

Research significance

This investigation attracts attention to using of partially prestressed concrete construction technique (because of ductility property) instead of fully prestressed concrete construction technique at the active earthquake regions. Advantages of using high performance concrete in partially prestressed beams are exposed. This study determines optimum partially prestressed ratios for partially prestressed beams produced by using high performance concrete and traditional concrete.

Test program

Properties of test beams

Test beams were produced by using both high performance concrete and traditional concrete. Test beams are compared to each other. There are nine series in total. The sizes of test beams are 100x200x2100 mm. Reinforcement numbers of the test beams are given in Table 1. Reinforcement schemes and active reinforcement eccentricities of the test beams are illustrated in Fig. 1. Passive reinforcements of partially and fully prestressed concrete test beams were put into cross-section with corrosion space. Active reinforcements were put into beams as to theoretical eccentricity (e=h/6) which provides the stresses occurred at top of fibre of beam to be equal to zero. All of the beams, spacing and diameter of stirrups were chosen equal as Ø8/10.

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Fig. 1. Reinforcement schemes of test beams.

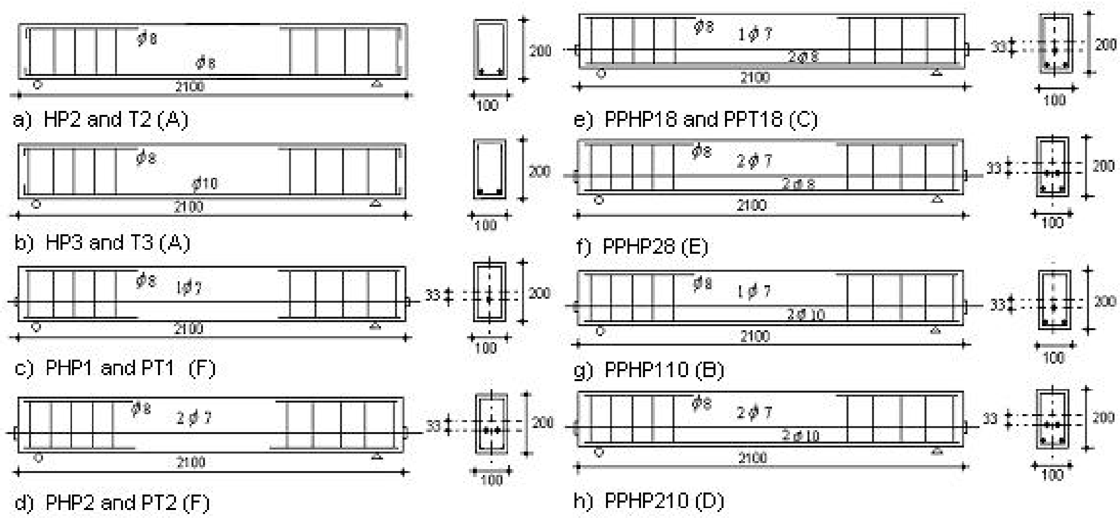
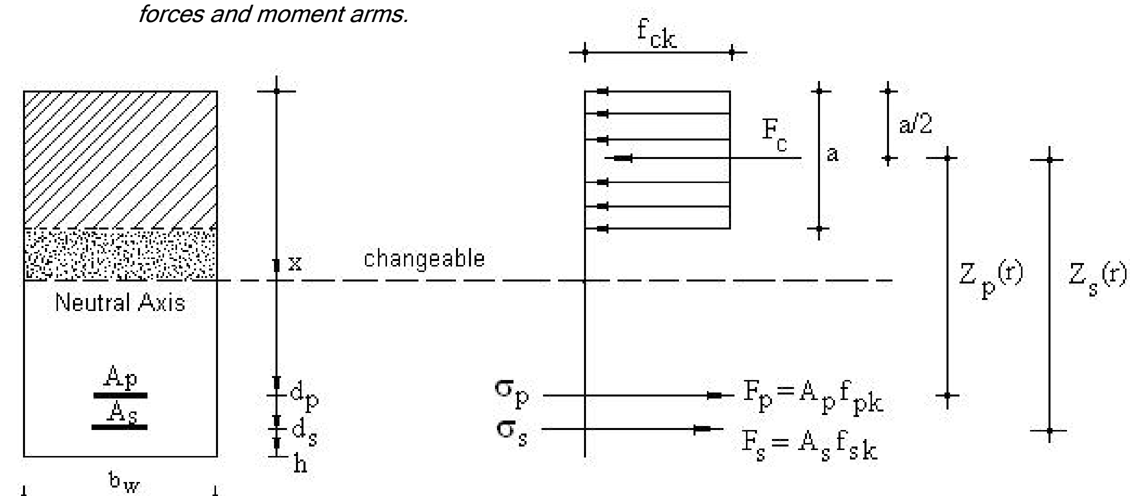


Fig. 2. Cross section of PPC beams, stresses, internal forces and moment arms.



b) Stresses, internal forces and moment arms.

a) Cross section

Fig. 3. HP2-T2 Load-Strain.

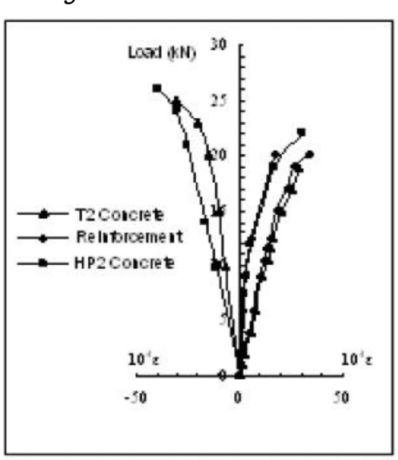


Fig. 4. HP3-T3 Load-Strain.

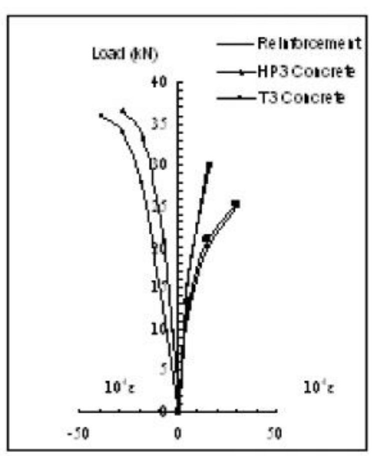


Fig. 5. PPHP110 Load-Strain.

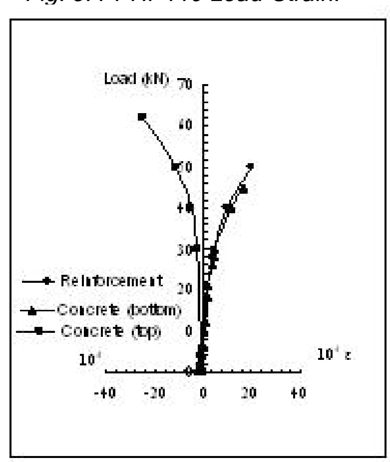


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Table 1. Reinforcement numbers of the test beams

Beam series	Codes of Beams and Types	Reinforcement		Stirrups	(%PPR)	Reinforcement Ratio		
		Active	Passive			Totally ρ_{top}	Active ρ_p	Passive ρ_s
1	HP1, T1	-	-	-	-	-	-	-
2	HP2,T2(A)	-	2 Ø 8	Ø8/10	0	0,0050	-	0,0050
3	HP3,T3(A)	-	2 Ø 10	Ø8/10	0	0,0079	-	0,0079
4	PPHP110(B)	1Ø7	2 Ø 10	Ø8/10	40	0,0098	0,0019	0,0079
5	PPHP18(C)	1Ø7	2 Ø 8	Ø8/10	50	0,0069	0,0019	0,0050
6	PPT18 (C)	1Ø7	2 Ø 8	Ø8/10	50	0,0069	0,0019	0,0050
7	PPHP210(D)	2Ø7	2 Ø 10	Ø8/10	60	0,0117	0,0038	0,0079
8	PPHP28(E)	2Ø7	2 Ø 8	Ø8/10	70	0,0088	0,0038	0,0050
9	PHP1,PT1(F)	1Ø7	-	Ø8/10	100	0,0019	0,0019	-
9	PHP2,PT2(F)	2Ø7	-	Ø8/10	100	0,0038	0,0038	-

Notes: 1) HP_i; High Performance Reinforced Concrete Beam, 2) T_i; Traditional Reinforced Concrete Beam, 3) PPHPab; Partially Prestressed Beam with High Performance Concrete, 4) PPTab; Partially Prestressed Beam with Traditional Concrete a: Active Reinforcemnet Number 1Ø7, 2Ø7 were coded as 1 and 2, b: Passive Reinforcement Diameter Ø8, Ø10 were coded as 8 and 10, 5) PHPa; Prestressed Beam with High Performance Concrete, a: Active Reinforcement Number 1Ø7, 2Ø7 were coded as 1 and 2, 6) PTa; Prestressed Beam with Traditional Concrete, a: Active Reinforcement Number 1Ø7, 2Ø7 were coded as 1 and 2.

Material properties

The aggregate used in production of high performance concrete and traditional concrete was obtained from limestone rock that is provided from Trabzon, Meryemana region. The maximum aggregate size used is 16mm. To compare two different concretes, the granulometry of aggregates used in production of high performance concrete and traditional concrete are similar. This granulometry is given in Table 2.

Table 2. The granulometry of aggregates used in production of concretes

Granulometric class	0-0,5 (mm)	0,5-1,0 (mm)	1,0-2,0 (mm)	2,0-4,0 (mm)	4,0-8,0 (mm)	8,0-16,0 (mm)
Total Weight (%)	15	7	10	15	23	30

Cements used in production of concretes were derived from Unye Cement Factory. Cements used in production of high performance concrete and traditional concrete are respectively PÇ42.5 (PC: Portland cement) and KÇ52.5 (KÇ: Blended Cement). The number 32.5 and 52.5 denotes its characteristic compressive strenght in MPa. Drinking water is used in the mixing.

High performance concrete composition is different from traditional concrete composition. There are silica fume that is in the proportion by 10% of cement mass and superfludifier additive named Sikament FF that is in the proportion by 3% of cement mass + silica fume mass as different from traditional concrete composition in the high performance concrete composition. The mix design of concretes is made by Absolute Volumetric Method (TS802). The mix design results are given in Table 3. Physical and mechanical properties of concretes are given in Table 4. In productions of test beams were used Ø8 and Ø10 diameter ribbed passive reinforcing steels and Ø7 diameter with low relaxation active reinforcing steels.

Determination of prestressed ratios

In this study, the ratio of carrying moment of beams in the case of to be only active reinforcing steel in beam section (M_p) to total carrying moment ın the case of to be both active and passive reinforcing steel in beam section (M_p+M_s) is defined as partially prestressed ratio (PPR=M_p/M_p+M_s). According to Fig. 2. A_p and A_s are respectively cross sectional areas of active and passive reinforcements. f_{pk} ve f_{sk} are respectively charactarestic yield strength of active and passive reinforcements. $Z_p(r)$ ve $Z_s(r)$ are respectively moment arms of resultant force of active and passive reinforcements. Partially prestressed ratio is calculated using Eq. (1) (Akgün, 2003; Durmuş & Pul, 1993; Naaman, 1992). Partially prestressed ratios of test beams which is calculated using Eq. (1) are given in Table 5.

$$PPR = \frac{M_p}{M_p + M_s} = \frac{A_p . f_{pk} . Z_p(r)}{A_p . f_{pk} . Z_p(r) + A_s . f_{sk} . Z_s(r)} \qquad (1)$$

Production of test beams and storing

Test beams are produced using high performance concrete (HPC) and traditional concrete (TC). Beams which are reinforced concrete, partially prestressed concrete and fully prestressed concrete have partially prestressed ratios that are varied in the range of 0 to100. Prestressed force to active reinforcement of test beams was applied by using pre- tension method. Prestressed force on active reinforcement (P=55kN) was transferred to beams 14 days later from concrete dump. Beams are held under wet sack during 21 days. In order to obtain better adhesion when are glued strain gauges to beams before testing, they were kept in a room with a temperature of 20^0 C ± 5^0C and humidity of 70 %± 5%. Flexure testing was performed at the end of 28 day period.

Failure analysis of beams

Table 3. Mix design of concretes

Components	High Performance Concrete	Traditional Concrete
Total Aggregate (kg/m^3)	1794	1849
Absorbed Water (kg/m^3)	11.74	12.10
Water (kg/m^3)	150	175
Cement (kg/m^3)	500	350
Silica Fume (kg/m^3)	50	-
Fludifier (kg/m^3)	16.5	-

Load-strain and load-deflection diagrams of test beams obtained from flexure test are illustrated from Fig. 3 to Fig. 12. According to the results of experimental

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Fig. 6. PPHP18 Load-Strain.

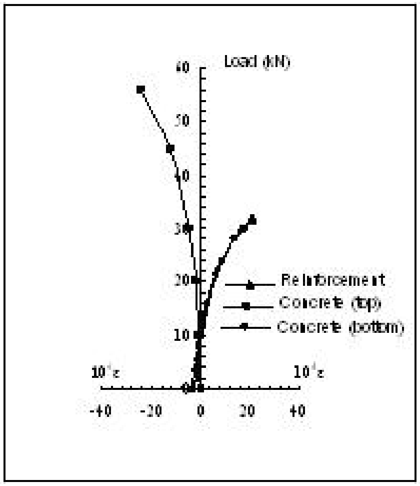

Fig. 7. PPT18 Load-Strain

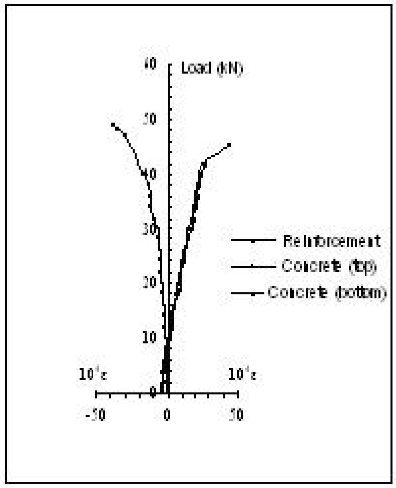

Fig. 8. PPHP210 Load-Strain

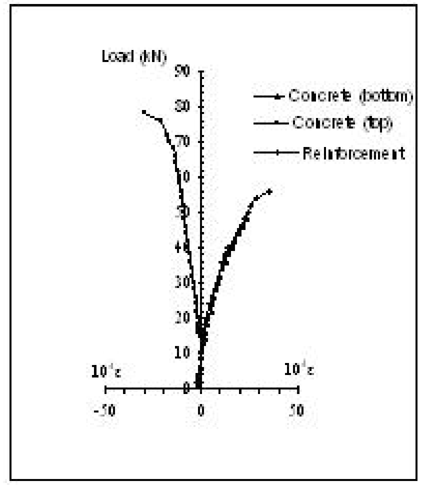

Fig. 9. PPHP28 Load-Strain.

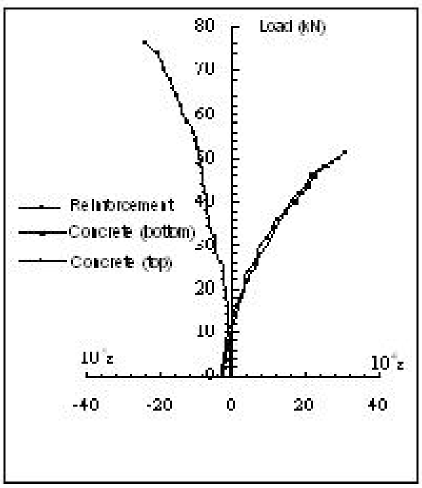

Fig. 10. HP2-HP3-T2-T3 Load-Deflection.

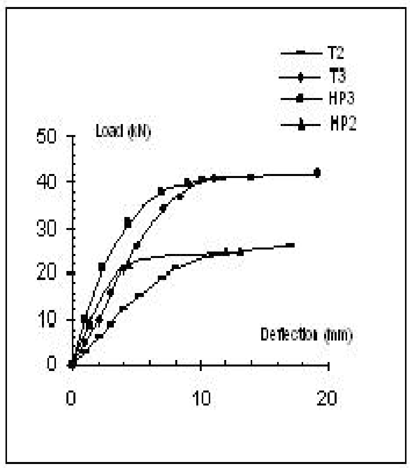

Fig. 11.Load-Deflection.

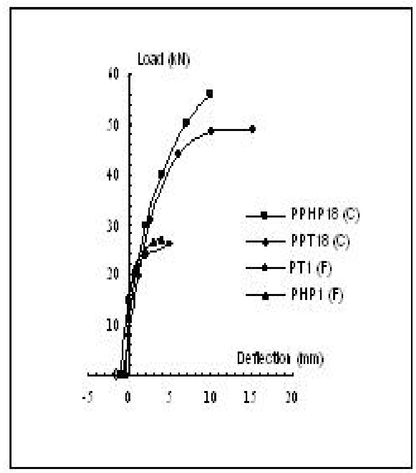

Fig. 12. Load-Deflection

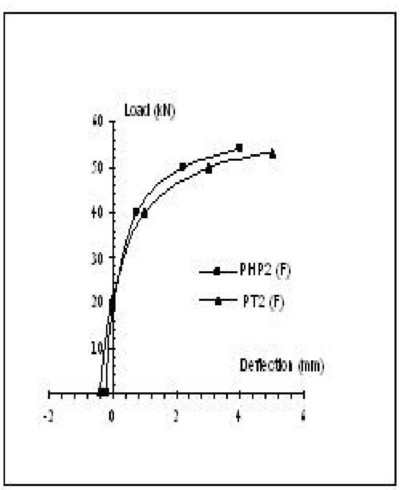

Fig. 13. Rigidity variations of test beams as to partially prestressed ratio.

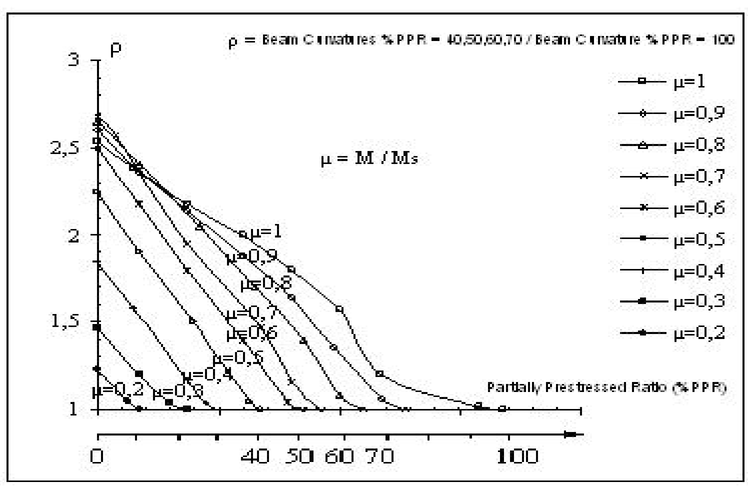

Table 4. Physical and mechanical properties of concrete specimens

Properties	High Performance Concrete	Traditional Concrete
Physical Properties		
Dry Unit Weight (kg/m^3)	2350	2300
Saturated Unit Weight (kg/m^3)	2465	2415
Mechanical Properties		
Average compressive strength(MPa)	66	35
Characteristic compressive strength (MPa)	61	33.60
Elasticity modules (MPa)	31000	27000
Poisson' s Ratio	0.22	0.20
$10^3£_{co}$	2.42	2.30

diagrams experimental failure load and deflections determined from experimental diagrams and theoretical moment (M_{rt}), average moment (M_{rm}), characteristic moment (M_{rk}) and design moment (M_{rd}) ultimate and ve service moments (M_s), experimental ultimate moments (M_{re}) calculated from test results and the ratio of experimental ultimate moment to service moment is defined to be experimental safety coefficient $¥_s = M_{re}/M_s$, $¥_r = M_{re}/M_{rt}$, $¥_r^* = M_{re}/M_{rm}$, $¥_r^{**} = M_{re}/M_{rk}$ and $¥_r^{***} = M_{re}/M_{rd}$ are given in Table 6.

Table 5. Partially prestressed ratios (%PPR)

Type of beam	A	B	C	D	E	F
Partially Prestressed Ratio (%PPR)	0	40	50	60	70	100

A: Reinforced Concrete, B,C,D and E: Partially Prestressed Concrete, F: Fully Prestressed Concrete

Analysis of cracking state of beams

Crack number, average crack spacing, experimental, theoretical and characteristic crack width, experimental and theoretical first cracking moments, maximum unit elongations cause to first crack determined at instant failure and constant moment region of produced by using both high performance and traditional concrete reinforced, partially prestressed and fully prestressed concrete test beams are given Table 7.

Rigidity variations of beams

In this study, rigidity variations of beams depending on partially prestressed ratio are investigated. The aim of this investigation is to determine the optimum partially prestressed ratio which does not completely lose conditions of adaptation properties of beams. Accordingly, ratio of partially prestressed produced by using high performance concrete beam curvature to fully prestressed produced by using high performance concrete beam curvature is defined as rigidity (ρ). In determination of beam curvatures, the followings are used: applied moment to beam, elasticity module, inertia moment, and strain at the top and bottom fibres of beam, height of beam. PPR is defined as partially prestressed ratio. Applied moments ratio to beams is defined as ($\mu = M/M_s$). Variations of the three parameters are illustrated in Fig. 13. As seen from this figure, rigidities under service loads of beams increase rapidly until 70% values of partially prestressed ratio. Whereas, increasing the amount of rigidity is very slow for larger values of prestressed ratio. It is understood here that optimum partially prestressed ratio of partially prestressed concrete beams produced by using high performance concrete is approximately 70% in terms limitation of strain.

Conclusion

When investigation of cracking and failure state of unreinforced concrete beams (HP1, T1) and fully prestressed concrete beams is made (see Table 3 & Table 4) although load carrying capacities of fully prestressed concrete beams increase, their cracking number doesn't change and a sudden and brittle failure occurs with a single crack as unreinforced concrete beams at under failure load and moment constant regions. It is understood that, there isn't adaptation property of fully prestressed concrete beams. But, behaviour of partially prestressed concrete beams with various partially prestressed ratios and sufficient passive reinforcement likes reinforced concrete beams. It is clear that, adaptation ability (ductility) is recovered in partially prestressed concrete beams because of passive reinforcement. In fact, this ability is expected from all structural elements and is especially very important at the active earthquake regions.

In this study, it was made comparisons on type of beams (C). According to this, experimental failure moments and safety coefficients of partially prestressed beams produced by using high performance concrete (PPHP) are higher than partially prestressed beams produced by using traditional concrete (PPT) but their average deflections are lower than PPT. Cracking numbers of PPHP are higher than PPT. Crack spacing and width of PPHP are lower than PPT. Experimental first cracking moments of PPHP are higher than PPT's. Unit elongations of PPHP are lower than PPT's. These indicators are shown that, bending behaviours of beams used high performance concrete improve from in many aspects. So, high performance concrete is preferred to traditional concrete in production of partially prestressed concrete beams.

In this study, comparisons were made on rigidities of partially and fully prestressed concrete beams. As results of these comparisons, optimum prestressed ratios are determined by improve the rigidity. These ratios for high performance concrete and traditional concrete are respectively 70% and 60%.

Using high performance concrete in production of partially prestressed concrete structural elements

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Table 6. Analysis of failure of beams

Experimental failure loads, deflections, failure and service moments

Type of beam	Failure Load (kN)(F_r)	Deflection (mm) (0,75F_r)	M_{re} (kNm)	M_{rt} (kNm)	M_{rm} (kNm)	M_{rk} (kNm)	M_{rd} (kNm)	M_s (kNm)
HP1	12,50	-	4,19	-	-	-	-	-
HP2 (A)	25,00	4,82	8,38	7,90	6,57	6,33	5,48	3,65
HP3 (A)	41,00	7,40	13,74	12,50	10,17	9,79	8,45	5,63
T1	7,00	-	2,35	-	-	-	-	-
T2 (A)	26,00	4,90	8,71	8,06	6,47	6,24	5,38	3,59
T3 (A)	42,00	6,90	14,07	12,56	9,93	9,57	8,20	5,47
PPHP110(B)	62,00	12,00	20,77	18,33	16,53	16,50	14,01	9,34
PPHP18 (C)	56,00	10,00	18,76	16,14	13,24	13,19	11,24	7,49
PPT18 (C)	49,00	15,00	16,42	13,89	12,47	12,43	10,38	6,92
PPHP210(D)	80,00	8,00	27,47	24,20	22,39	22,18	18,50	12,33
PPHP28 (E)	77,00	7,00	25,80	22,90	19,30	19,09	15,96	10,64
PHP2 (F)	54,00	4,00	18,10	16,16	13,92	13,71	11,75	7,84
PT2 (F)	53,00	5,00	17,80	15,90	14,02	13,91	11,63	7,74

Experimental safety coefficient.

Type of Beam	¥$_s$	¥$_r$	¥$_r^*$	¥$_r^{**}$	¥$_r^{***}$
HP2 (A)	2,30	1,06	1,28	1,32	1,53
HP3 (A)	2,44	1,10	1,35	1,40	1,63
T2 (A)	2,43	1,08	1,35	1,40	1,62
T3 (A)	2,57	1,12	1,42	1,47	1,72
PPHP110 (B)	2,22	1,13	1,26	1,25	1,48
PPHP18 (C)	2,50	1,16	1,42	1,48	1,67
PPT18 (C)	2,37	1,18	1,33	1,32	1,58
PPHP210 (D)	2,23	1,14	1,23	1,24	1,48
PPHP28 (E)	2,42	1,13	1,34	1,35	1,62
PHP2 (F)	2,31	1,12	1,30	1,32	1,54
PT2 (F)	2,30	1,12	1,27	1,28	1,53

decreases size of element. So, larger openness is passed by compensation of constant load. In addition to, Time dependent prestress losses which occur from shrinkage and creep will reduced by using high performance concrete.

At active earthquake regions, PPHP which has optimum partially prestressed ratio (PPR) is more convenient than fully prestressed concrete in monolithic and prefabric buildings.

Table 7. Analysis of cracking state of beams

Type of beam	Crack number	Crack spacing (mm)	Crack Width (mm)	Experimental moment (kNm)	Theoretical moment (kNm)	Unit elongation (10^6£$_{ct}$)
HP1	-	-	-	2,68	2,37	100
HP2 (A)	10	80	1,00	3,48	2,51	105
HP3 (A)	13	76	0,90	4,22	2,62	105
T1	-	-	-	2,01	1,76	100
T2 (A)	7	98	0,90	2,81	1,89	110
T3 (A)	9	85	0,80	3,08	1,97	115
PPHP110(B)	16	50	0,30	6,53	6,17	115
PPHP18(C)	15	60	0,35	6,70	6,27	100
PPT18 (C)	5	90	0,80	5,51	5,03	110
PPHP210(D)	13	68	0,40	6,80	6,28	115
PPHP28 (E)	10	75	0,45	7,04	6,38	110
PHP2(F)	1	-	-	6,32	5,98	100
PT2 (F)	1	-	-	5,69	5,35	105

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