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Estimation of Compressive Strength of Reinforced Concrete Structure Using Impact Testing Method and Rebound Hardness Method

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Abstract The nondestructive test is widely used in the field of diagnosis and maintenance to evaluate the degree of damaging of structures caused by aging, and the demand for this test method is expected to continue increasing. However, there is a lack of standards related to the nondestructive test, and South Korea is relying heavily on developed nations for original technologies related to diagnosis. It is an urgent task to establish a nondestructive test method appropriate for the circumstance of South Korea. The purpose of this study is to compare and analyze estimated error of compressive strength in single-story structures comprised of vertical and horizontal reinforced concrete members using the impact testing method and rebound hardness method, which are nondestructive test methods, and to review on-site applicability of these methods. Based on compressive strength of the structures estimated, overall mean error was 21.2% for the impact testing method and 15.6% for the rebound hardness method. The necessity of a reliable diagnostic method based on compound nondestructive test methods to increase accuracy of estimation was confirmed.

Keywords: Estimation, Compressive Strength, Reinforced Concrete Structure, Impact Testing Method, Rebound Hardness Method

1. INTRODUCTION

A large quantity of buildings in South Korea was constructed in 1990s, and the 30-year cycle is approaching soon. Diagnosis and maintenance of structures have become primary concerns. The nondestructive test is widely used in the field of diagnosis and maintenance to evaluate the degree of damaging of structures caused by aging, and the demand for this test method is expected to continue increasing. However, there is a lack of standards related to the nondestructive test, and South Korea is relying heavily on developed nations (ACI (2003); ACI (1998)) for original technologies related to diagnosis. It is an urgent task to establish a nondestructive test method appropriate for the circumstance of South Korea.

The purpose of this study is to compare and analyze estimated error of compressive strength in single-story structures comprised of vertical and horizontal reinforced concrete members using the impact testing method and rebound hardness method, which are non-destructive test methods, and to review on-site applicability of these methods.

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2. IMPACT TESTING METHOD

The theory applied to the impact testing method (NDIS (2017)) is as described by T. Sakai et al. (2010). A concrete structure is regarded as an ideal elastic body, and mass (M) of a hammer collides with the concrete surface with initial velocity (V) and spring constant (K). In this case, elastic deformation of the concrete surface is caused by kinetic energy of the hammer. Displacement on the concrete surface caused by collision of the hammer is defined as x, and Eq. (1) can be expressed as below according to the law of energy balance.

$$1/2MV_0{}^2 = 1/2Kx_{max}{}^2 \quad (1)$$

According to Hooke's law, force F can be expressed as Eq. (2).

$$F_{max} = Kx_{max} \quad (2)$$

x_{max} is determined by Eq. (2) and can be substituted into Eq. (1) to derive Eq. (3).

$$\sqrt{MK} = F_{max}/V_0 \quad (3)$$

$\sqrt{MK}$ indicates mechanical impedance, which is calculated by dividing maximum force into initial velocity that occurs upon hammer impact. Spring constant (K) corresponds to elastic modulus of the concrete surface. The correlation between elastic modulus and compressive strength is known. IN fact, since maximum impact force of hammering is proportional to 1.2th power of impact velocity, impact velocity can be compensated as shown in Eq. (4) when calculating mechanical impedance.

$$\sqrt{MK} = F_{max}/V_0{}^{1.2} \quad (4)$$

In relation to estimation of compressive strength of concrete, the relationship between mechanical impedance index of concrete and elastic modulus is as expressed by Eq. (5).

$$E = aZ^N \quad (5)$$

Here, Z is impedance value, is a constant and varies with the reduction rate of elastic modulus. N is 4 if strain does not change and 3 in the case of ordinary concrete. The constant (a) changes according to maximum strain of concrete.

3. REBOUND HARDNESS METHOD

The rebound hardness method (KS (2008)) is one of impact methods and a nondestructive test method that estimates compressive strength of concrete by measuring rebound of the concrete surface. There are many rebound hardness methods including the dropping hammer method, spring hammer method, rotating hammer method and Schmidt hammer method. The Schmidt hammer method is used widely. The Schmidt is a simple and internationally standardized test method based on the fact that rebound hardness changes according to strength of concrete (S. U. Hong and Y. S. Cho (2011)). However, it needs to be compensated to resolve the problem of errors, where strike angle, age and surface conditions are taken into account. Accordingly, rebound (R) is compensated and substituted into Eq. (6) to estimate compressive strength.

$$F_c = 12R - 184 \quad (6)$$

4. EXPERIMENTS

In this study, reliability of estimated compressive strength of reinforced concrete structures was evaluated by manufacturing single-story reinforced concrete structures comprised of vertical members (column, wall) and horizontal members (girder, slab) as shown in Fig. 1, with height of 2,400mm, width of 2,400mm and height of 1,600mm. Two structures were made according to size of members, divided into 24MPa and 30MPa according to design compressive strength presented in Table 1.

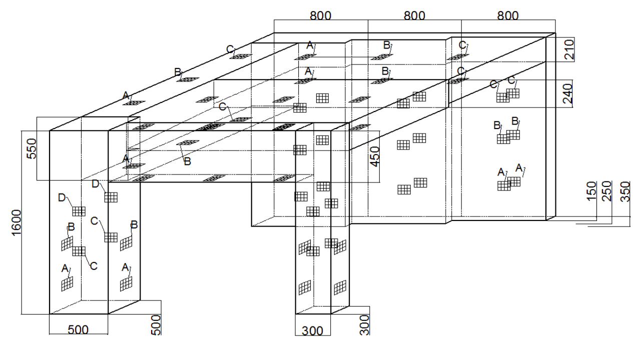

Figure 1. Shape of specimen

Two structures were made for each strength as shown in Table 2 and Fig. 1. One of the structures had column thickness of 250x250mm and 400x400mm, girder thickness of 250mm and 350mm, wall thickness of 100mm, 200mm and 300mm, and slab thickness of 150mm and 180mm. The other structure had column thickness of 300x300mm and 500x500mm, girder thickness of 450mm and 550mm, wall thickness of 150mm, 250mm and 350mm, and slab thickness of 210mm and 240mm.

To estimate compressive strength of the single-story reinforced concrete structures using the impact testing method and rebound hardness method, the concrete core specimens were taken from the slab member in accordance with KS F 2422 and the compressive strength test was performed in accordance with KS F 2405. Estimation of compressive strength using the impact testing method was performed in accordance with NDIS 3434, and estimation of compressive strength using the rebound hardness method was performed in accordance with KS F 2730. Measuring devices used were CTS-02V4 of Nitto and HT225A

Table 1. Mix ratio of concrete

Designed Strength 24 MPa: Unit weight (kg/m^3)					
Cement	Water	Fine aggregate	Crushed Sand	Coarse aggregate	High performance AE reducing agent
314	166	619	267	931	2.51
W/B	52.9%		S/a		49%
Designed Strength 30 MPa: Unit weight (kg/m^3)					
383	170	557	240	948	3.06
W/B	44.4%		S/a		45.9%

Table 2. List of specimens

Specimen		Designed size	Measured size	Specimen		Designed size	Measured size
		(mm)				(mm)	
1	RC24C250	250x250	249x248	5	RC30C250	250x250	249x250
2	RC24C300	300x300	299x297	6	RC30C300	300x300	300x296
3	RC24C400	400x400	390x395	7	RC30C400	400x400	398x400
4	RC24C500	500x500	495x498	8	RC30C500	500x500	488x498
9	RC24W100	100	96.0	15	RC30W100	100	96.3
10	RC24W150	150	152.0	16	RC30W150	150	152.0
11	RC24W200	200	195.3	17	RC30W200	200	198.0
12	RC24W250	250	248.3	18	RC30W250	250	248.3
13	RC24W300	300	300.0	19	RC30W300	300	300.0
14	RC24W350	350	343.3	20	RC30W350	350	343.3
21	RC24G250	250	256.0	25	RC30G250	250	242.0
22	RC24G350	350	364.0	26	RC30G350	350	365.0
23	RC24G450	450	434.0	27	RC30G450	450	430.0
24	RC24G550	550	542.0	28	RC30G550	550	554.0
29	RC24S150	150	174.3	33	RC30S150	150	178.3
30	RC24S180	180	202.3	34	RC30S180	180	195.0
31	RC24S210	210	210.0	35	RC30S210	210	211.0
32	RC24S240	240	241.7	36	RC30S240	240	242.3

RC: Reinforced concrete
Design strength of concrete: 24MPa, 30MPa
Type of member: Column (C), Wall (W), Girder (G), Slab (S)
Size of member: Column (250, 300, 400),
Wall (100, 150, 200, 250, 300, 350mm),
Girder (250, 350, 450, 550),
Slab (150, 180, 210, 240)

of Sadt. As for positions of compressive strength estimation, 3~4 spots at 200mm, 550mm and 900mm from the ground for the column, at 250mm, 650mm and 1,050mm for the wall, and at 350mm, 950mm and 1,550mm from the tip of the member for the girder and slab were measured 20 times to find the mean value.

5. EXPERIMENT RESULTS

(1) Results of compressive strength test

The results of the compressive strength test performed on 6 core specimens with 2 design compressive strengths of 24MPa and 30MPa are presented in Table 3. Mean compressive strength of the core specimen with design strength of 24MPa was 30.5MPa, which is 127% of design strength. Mean compressive strength of the specimen with design strength of 30MPa was 36.2MPa, which is 121% of design strength.

Table 3. Results of compressive strength test

Designed Strength (MPa)	Compressive strength (MPa)			
	Specimen			Average of compressive strength
	1	2	3	
	4	5	6	
24	33.3	29.6	25.8	30.5
	33.3	26.8	34.1	
30	35.0	36.1	35.3	36.2
	30.6	42.4	37.5	

(2) Results of impact testing method

The results of estimating compressive strength of the single-story reinforced concrete structures using the impact testing method were summarized in the order of the vertical members (column and wall) and the horizontal members (girder and slab).

Among the vertical members, estimated compressive strength of the column member for design strength of 24MPa is 25.0MPa for thickness of 250mm as shown in Table 4, showing mean error of 17.95% compared to the compressive strength test results for the core specimen. Mean estimated compressive strength for thickness of 300mm is 27.7MPa, showing mean error of 9.10% compared to the compressive strength test results for the core specimen. Mean estimated compressive strength for thickness of 400mm is 25.1MPa, showing mean error of 17.62% compared to the compressive strength test results for the core specimen. Mean estimated compressive strength for thickness of 500mm is 27.9MPa, showing mean error of 8.44% compared to the compressive strength test results for the core specimen.

Table 4. Test results of column member

No.	Location	Compressive Strength (MPa)		Error ratio (%)	
		Estimation	Test		
1A	200	25.6	30.5	16.07	17.95
1B	550	21.3		30.16	
1C	550	24.8		18.69	
1D	900	28.4		6.89	
2A	200	29.9		1.97	9.10
2B	550	26.7		12.46	
2C	550	24.2		20.66	
2D	900	30.1		1.31	
3A	200	28.2		7.54	17.62
3B	550	24.5		19.67	
3C	550	26.1		14.43	
3D	900	21.7		28.85	
4A	200	27.9		8.52	8.44
4B	550	27.8		8.85	
4C	550	26.4		13.44	
4D	900	29.6		2.95	
5A	200	25.6	36.2	29.28	33.15
5B	550	23.2		35.91	
5C	550	25.2		30.39	
5D	900	22.8		37.02	
6A	200	24.7		31.77	32.67
6B	550	26.5		26.8	
6C	550	24.9		31.22	
6D	900	21.4		40.88	
7A	200	24.2		33.15	36.12
7B	550	21.6		40.33	
7C	550	22.9		36.74	
7D	900	23.8		34.25	
8A	200	25.6		29.28	26.31
8B	550	27.5		24.03	
8C	550	27.2		24.86	
8D	900	26.4		27.07	

Measurement location: A, B, C, D

For design strength of 30MPa, estimated compressive strength for thickness of 250mm is 24.20MPa as shown in Table 4, showing mean error of 33.15% compared to the compressive strength test results. Estimated compressive strength for thickness of 300mm is 24.4MPa, showing mean error of 32.67% compared to the compressive strength test results. Estimated compressive strength for thickness of 400mm is 23.1MPa, showing mean error of 36.12% compared to the compressive strength test results. Estimated compressive strength for thickness of 500mm is 26.7MPa, showing mean error of 26.31% compared to the compressive strength test results.

Table 5. Test results of wall member

No.	Location	Compressive Strength (MPa)		Error ratio (%)	
		Estimation	Test		
9A	250	25.5	30.5	16.39	14.43
9B	650	25.9		15.08	
9C	1050	26.9		11.80	
10A	250	27		11.48	10.71
10B	650	25.9		15.08	
10C	1050	28.8		5.57	
11A	250	26.8		12.13	10.71
11B	650	28.5		6.56	
11C	1050	26.4		13.44	
12A	250	29		4.92	7.65
12B	650	26.1		14.43	
12C	1050	29.4		3.61	
13A	250	27.8		8.85	15.85
13B	650	25.6		16.07	
13C	1050	23.6		22.62	
14A	250	28.2		7.54	15.19
14B	650	25.4		16.72	
14C	1050	24		21.31	
15A	250	23.4	36.2	35.36	38.49
15B	650	23.5		35.08	
15C	1050	19.9		45.03	
16A	250	25.8		28.73	31.86
16B	650	19.5		46.13	
16C	1050	28.7		20.72	
17A	250	29.9		17.40	24.95
17B	650	27.2		24.86	
17C	1050	24.4		32.60	
18A	250	21.5		40.61	29.38
18B	650	25.7		29.01	
18C	1050	29.5		18.51	
19A	250	27.7		23.48	30.11
19B	650	25.6		29.28	
19C	1050	22.6		37.57	
20A	250	23.3		35.64	33.61
20B	650	26.7		26.24	
20C	1050	22.1		38.95	

Measurement location: A, B, C

Among the vertical members, estimated compressive strength of the column member for design strength of 24MPa is 26.1MPa for thickness of 100mm as shown in Table 5, showing mean error of 14.42% compared to the compressive strength test results. Estimated compressive strength for thickness of 150mm is 27.2MPa, showing mean error of 10.71% compared to the compressive strength test results. Estimated compressive strength for thickness of 200mm is 27.2MPa, showing mean error of 10.7% compared to the compressive strength test results. Estimated compressive strength for thickness of 250mm is 28.2MPa, showing mean error of 7.65% compared to the compressive strength test results. Estimated compressive strength for thickness of 300mm is 25.7MPa, showing mean error of 15.85% compared to the compressive strength test results. Estimated compressive strength for thickness of 350mm is 25.9MPa, showing mean error of 15.19% compared to the compressive strength test results of 30.5MPa.

Table 6. Test results of girder member

No.	Location	Compressive Strength (MPa)		Error ratio (%)	
		Estimation	Test		
21A	350	32.1	30.5	5.25	12.90
21B	950	27.9		8.52	
21C	1550	22.9		24.92	
22A	300	22.9		24.92	14.86
22B	800	28.4		6.89	
22C	1300	34.4		12.79	
23A	350	23.2		23.93	15.52
23B	950	25.2		17.38	
23C	1550	28.9		5.25	
24A	300	28.6		6.23	4.04
24B	800	31.8		4.26	
24C	1300	30.0		1.64	
25A	350	26.9	36.2	25.69	30.57
25B	950	24.8		31.49	
25C	1550	23.7		34.53	
26A	300	27.7		23.48	28.64
26B	800	25.4		29.83	
26C	1300	24.4		32.60	
27A	350	29.4		18.78	27.62
27B	950	24.5		32.32	
27C	1550	24.7		31.77	
28A	300	19.4		46.41	41.07
28B	800	22.1		38.95	
28C	1300	22.5		37.85	

Measurement location: A, B, C

For design strength of 30MPa, estimated compressive strength for thickness of 100mm is 22.3MPa as shown in Table 5, showing error of 38.4% compared to the compressive strength test results. Estimated compressive strength for thickness of 150mm is 24.7MPa, showing error of 31.86% compared to the compressive strength test results. Estimated compressive strength for thickness of 200mm is 27.2MPa, showing error of 24.95% compared to the compressive strength test results. Estimated compressive strength for thickness of 250mm is 25.6MPa, showing error of 29.38% compared to the compressive strength test results. Estimated compressive strength for thickness of 300mm is 25.3MPa, showing error of 30.11% compared to the compressive strength test results. Estimated compressive strength for thickness of 350mm is 24.0MPa, showing error of 33.61% compared to the compressive strength test results.

Among the horizontal members, estimated compressive strength of the girder member for design strength of 24MPa is 27.6MPa for thickness of 250mm as shown in Table 6, showing error of 14.86% compared to the compressive strength test results. Estimated compressive strength for thickness of 350mm is 28.6MPa, showing error of 14.86% compared to the compressive strength test results. Estimated compressive strength for thickness of 450mm is 25.8MPa, showing error of 15.52% compared to the compressive strength test results. Estimated compressive strength for thickness of 550mm is 30.1MPa, showing error of 4.04% compared to the compressive strength test results of 22.2MPa.

For design strength of 30MPa, estimated compressive strength for thickness of 250mm is 25.1MPa as shown in Table 6, showing error of 30.57% compared to the compressive strength test results. Estimated compressive strength for thickness of 350mm is 25.8MPa, showing error of 28.64% compared to the compressive strength test results. Estimated compressive strength for thickness of 450mm is 26.2MPa, showing error of 27.62% compared to the compressive strength test results. Estimated compressive strength for thickness of 550mm is 21.3MPa, showing error of 41.07% compared to the compressive strength test results of 36.2MPa.

Among the horizontal members, estimated compressive strength of the slab member for design strength of 24MPa is 28.2MPa for thickness of 150mm as shown in Table 7, showing error of 7.65% compared to the compressive strength test results. Estimated compressive strength for thickness of 180mm is 25.2MPa, showing error of 17.49% compared to the compressive strength test results. Estimated compressive strength for thickness of 210mm is 27.9MPa, showing error of 9.51%

Table 7. Test results of slab member

No.	Location	Compressive Strength (MPa)		Error ratio (%)	
		Estimation	Test		
29A	350	30.0		1.64	
29B	1000	29.4		3.61	7.65
29C	1650	25.1		17.70	
30A	350	26.8		12.13	
30B	1000	26.2		14.10	17.49
30C	1650	22.5	30.5	26.23	
31A	350	24.9		18.36	
31B	1000	30.9		1.31	9.51
31C	1650	27.8		8.85	
32A	350	26.5		13.11	
32B	1000	29.1		4.59	7.98
32C	1650	28.6		6.23	
33A	350	28.3		21.82	
33B	1000	29.1		19.61	23.48
33C	1650	25.7		29.01	
34A	350	24.4		32.60	
34B	1000	31.6		12.71	28.45
34C	1650	21.7	36.2	40.06	
35A	350	25.4		29.83	
35B	1000	24.3		32.87	29.74
35C	1650	26.6		26.52	
36A	350	26.8		25.97	
36B	1000	29.6		18.23	20.26
36C	1650	30.2		16.57	

Table 8. Test results of column member

No.	Location	Average of R	Compressive Strength (MPa)		Error ratio (%)	
			Estimation	Test		
1A	200	43	37.5		22.95	
1B	550	39	32.3		5.9	11.48
1C	550	39	32.3		5.9	
1D	900	35	27.1		11.15	
2A	200	41	34.9		14.43	
2B	550	42	36.2		18.69	9.10
2C	550	38	31.0		1.64	
2D	900	38	31.0	30.5	1.64	
3A	200	43	37.5		22.95	
3B	550	41	34.9		14.43	17.63
3C	550	42	36.2		18.69	
3D	900	41	34.9		14.43	
4A	200	38	31.0		1.64	
4B	550	38	31.0		1.64	10.17
4C	550	42	36.2		18.69	
4D	900	42	36.2		18.69	
5A	200	43	37.5		3.59	
5B	550	42	36.2		0	2.69
5C	550	44	38.8		7.18	
5D	900	42	36.2		0	
6A	200	48	44.0		21.55	
6B	550	46	41.4		14.36	13.47
6C	550	46	41.4		14.36	
6D	900	43	37.5	36.2	3.59	
7A	200	45	40.1		10.77	
7B	550	44	38.8		7.18	6.28
7C	550	43	37.5		3.59	
7D	900	43	37.5		3.59	
8A	200	50	46.6		28.73	
8B	550	48	44.0		21.55	20.65
8C	550	46	41.4		14.36	
8D	900	47	42.7		17.96	

Measurement location: A, B, C, D

compared to the compressive strength test results. Estimated compressive strength for thickness of 240mm is 28.1MPa, showing error of 7.98% compared to the compressive strength test results.

For design strength of 30MPa, estimated compressive strength for thickness of 150mm is 27.7MPa as shown in Table 7, showing error of 23.48% compared to the compressive strength test results. Estimated compressive strength for thickness of 180mm is 25.9MPa, showing error of 28.45% compared to the compressive strength test results. Estimated compressive strength for thickness of 210mm is 25.4MPa, showing error of 29.74% compared to the compressive strength test results. Estimated compressive strength for thickness of 240mm is 28.9MPa, showing error of 20.26% compared to the compressive strength test results.

(3) Results of rebound hardness method

The results of estimating compressive strength of the single-story reinforced concrete structures using the rebound hardness method were summarized in the order of the vertical members (column and wall) and the horizontal members (girder and slab).

Among the vertical members, mean rebound and mean estimated compressive strength of the column member for design strength of 24MPa are 39 and 32.3MPa for thickness of 250mm as shown in Table 8, showing mean error of 11.48% compared to the compressive strength test results for the core specimen. Mean rebound and mean estimated compressive strength for thickness of 300mm are 40 and 33.3MPa, showing mean error of 9.10% compared to the compressive strength test results for the core specimen. Mean rebound and mean estimated compressive strength for thickness of 400mm are 42 and 35.9MPa, showing mean error of 17.63% compared to the compressive strength test results for the core specimen. Mean rebound and mean estimated compressive strength for thickness of 500mm are 40 and 33.6MPa, showing mean error of 10.17% compared to the compressive strength test results for the core specimen.

For design strength of 30MPa, mean rebound and mean estimated compressive strength for thickness of 250mm are 43 and 37.2MPa as shown in Table 8, showing error of 2.69% compared to the compressive strength test results for the core specimen. Mean rebound and mean estimated compressive strength for thickness of 300mm are 46 and 41.1MPa, showing error of 13.47% compared the compressive strength test results for the core specimen. Mean rebound and mean estimated compressive strength for thickness of 400mm are 44 and 38.5MPa, showing error of 6.28% compared the compressive strength test results for the core specimen. Mean rebound and mean estimated compressive strength for thickness of 500mm are 48 and 43.7MPa, showing error of 20.65% compared the compressive strength test results for the core specimen.

Among the vertical members, mean rebound and mean estimated compressive strength of the wall member for design strength of 24MPa are 40 and 33.6MPa for thickness of 100mm as shown in Table 9, showing error of 10.16% compared to the compressive strength test results for the core specimen. Mean rebound and mean estimated compressive strength for thickness of 150mm are 40 and 33.6MPa, showing error of 11.91% compared the compressive strength test results for the core specimen. Mean rebound and mean estimated compressive strength for thickness of 200mm are 41 and 34.5MPa, showing error of 13.00% compared the compressive strength test results for the core specimen. Mean rebound and mean estimated compressive strength for thickness of 250mm are 40 and 33.2MPa, showing error of 8.74% compared the compressive strength test results for the core specimen. Mean rebound and mean estimated compressive strength for thickness of 300mm are 41 and 34.5MPa, showing error of 13.00% compared the compressive strength test results for the core specimen. Mean rebound and mean estimated compressive strength for thickness of 350mm are 43 and 37.1MPa, showing error of 21.53% compared the compressive strength test results of 37.1MPa.

Table 9. Test results of wall member

No.	Location	Average of R	Compressive Strength (MPa)		Error ratio (%)	
			Estimation	Test		
9A	250	43	37.5	30.5	22.95	
9B	650	39	32.3		5.90	10.16
9C	1050	38	31.0		1.64	
10A	250	43	37.5		22.95	
10B	650	37	29.7		2.62	11.91
10C	1050	40	33.6		10.16	
11A	250	42	36.2		18.69	
11B	650	40	33.6		10.16	13.00
11C	1050	40	33.6		10.16	
12A	250	40	33.6		10.16	
12B	650	39	32.3		5.90	8.74
12C	1050	40	33.6		10.16	
13A	250	42	36.2		18.69	
13B	650	40	33.6		10.16	13.00
13C	1050	40	33.6		10.16	
14A	250	44	38.8		27.21	
14B	650	42	36.2		18.69	21.53
14C	1050	42	36.2		18.69	
15A	250	43	37.5	36.2	3.59	
15B	650	42	36.2		0.00	2.39
15C	1050	41	34.9		3.59	
16A	250	43	37.5		3.59	
16B	650	43	37.5		3.59	3.59
16C	1050	43	37.5		3.59	
17A	250	46	41.4		14.36	
17B	650	41	34.9		3.59	7.18
17C	1050	43	37.5		3.59	
18A	250	44	38.8		7.18	
18B	650	45	40.1		10.77	7.18
18C	1050	41	34.9		3.59	
19A	250	45	40.1		10.77	
19B	650	44	38.8		7.18	7.18
19C	1050	43	37.5		3.59	
20A	250	46	41.4		14.36	
20B	650	45	40.1		10.77	8.38
20C	1050	42	36.2		0.00	

Measurement location: A, B, C

For design strength of 30MPa, mean rebound and mean estimated compressive strength for thickness of 100mm are 42 and 36.2MPa as shown in Table 9, showing error of 2.39% compared to the compressive strength test results. Mean rebound and mean estimated compressive strength for thickness of 150mm are 43 and 37.5MPa, showing error of 3.59% compared the compressive strength test results. Mean rebound and mean estimated compressive strength for thickness of 200mm are 43 and 37.9MPa, showing error of 7.18% compared the compressive strength test results. Mean rebound and mean estimated compressive strength for thickness of 250mm are 43 and 37.9MPa, showing error of 7.18% compared the compressive strength test results. Mean rebound and mean estimated compressive strength for thickness of 300mm are 44 and 38.8MPa, showing error of 7.18% compared the compressive strength test results. Mean rebound and mean estimated compressive strength for thickness of 350mm are 44 and 39.2MPa, showing error of 8.38% compared the compressive strength test results.

Table 10. Test results of girder member

No.	Location	Average of R	Compressive Strength (MPa)		Error ratio (%)	
			Estimation	Test		
21A	350	41	35.0		14.75	
21B	950	44	38.9		27.54	17.59
21C	1550	40	33.7		10.49	
22A	300	44	38.9		27.54	
22B	800	42	36.3		19.02	20.44
22C	1300	41	35.0	30.5	14.75	
23A	350	47	42.6		39.67	
23B	950	44	38.9		27.54	30.16
23C	1550	43	37.6		23.28	
24A	300	43	37.6		23.28	
24B	800	44	38.9		27.54	27.54
24C	1300	45	40.2		31.80	
25A	350	43	37.6		3.87	
25B	950	45	40.2		11.05	12.06
25C	1550	48	43.9		21.27	
26A	300	41	35.0		3.31	
26B	800	43	37.6		3.87	4.88
26C	1300	44	38.9	36.2	7.46	
27A	350	47	42.6		17.68	
27B	950	47	42.6		17.68	18.88
27C	1550	48	43.9		21.27	
28A	300	48	43.9		21.27	
28B	800	43	37.6		3.87	14.27
28C	1300	47	42.6		17.68	

Measurement location: A, B, C

Among the horizontal members, mean rebound and mean estimated compressive strength for design strength of 24MPa are 42 and 35.9MPa for thickness of 250mm as shown in Table 10, showing error of 17.59% compared to the compressive strength test results. Mean rebound and mean estimated compressive strength for thickness of 350mm are 42 and 36.7MPa, showing error of 20.44% compared the compressive strength test results. Mean rebound and mean estimated compressive strength for thickness of 450mm are 45 and 39.7MPa, showing error of 30.16% compared the compressive strength test results. Mean rebound and mean estimated compressive strength for thickness of 550mm are 44 and 38.9MPa, showing error of 27.54% compared the compressive strength test results.

For design strength of 30MPa, mean rebound and mean estimated compressive strength for thickness of 250mm are 45 and 40.6MPa as shown in Table 10, showing error of 12.06% compared to the compressive strength test results. Mean rebound and mean estimated compressive strength for thickness of 350mm are 43 and 37.2MPa, showing error of 4.88% compared the compressive strength test results. Mean rebound and mean estimated compressive strength for thickness of 450mm are 47 and 43MPa, showing error of 18.88% compared the compressive strength test results. Mean rebound and mean estimated compressive strength for thickness of 550mm are 46 and 41.4MPa, showing error of 14.27% compared the compressive strength test results of 36.2MPa.

Table 11. Test results of slab member

No.	Location	Average of R	Compressive Strength (MPa)		Error ratio (%)	
			Estimation	Test		
29A	350	41	35.0		14.75	
29B	1000	49	45.2		48.2	31.58
29C	1650	45	40.2		31.8	
30A	350	41	35.0		14.75	
30B	1000	42	36.3		19.02	17.60
30C	1650	42	36.3	30.5	19.02	
31A	350	47	42.6		39.67	
31B	1000	45	40.2		31.8	41.31
31C	1650	50	46.5		52.46	
32A	350	43	37.6		23.28	
32B	1000	45	40.2		31.8	28.96
32C	1650	45	40.2		31.8	
33A	350	49	45.2		24.86	
33B	1000	51	47.8		32.04	26.06
33C	1650	48	43.9		21.27	
34A	350	47	42.6		17.68	
34B	1000	47	42.6		17.68	12.89
34C	1650	41	35.0	36.2	3.31	
35A	350	45	40.2		11.05	
35B	1000	50	46.5		28.45	15.65
35C	1650	44	38.9		7.46	
36A	350	45	40.2		11.05	
36B	1000	45	40.2		11.05	9.85
36C	1650	44	38.9		7.46	

Measurement location: A, B, C

For design strength of 30MPa, mean rebound and mean estimated compressive strength for thickness of 150mm are 49 and 45.6MPa as shown in Table 11, showing error of 26.06% compared to the compressive strength test results. Mean rebound and mean estimated compressive strength for thickness of 180mm are 45 and 40.1MPa, showing error of 12.89% compared the compressive strength test results. Mean rebound and mean estimated compressive strength for thickness of 210mm are 46 and 41.9MPa, showing error of 15.65% compared the compressive strength test results. Mean rebound and mean estimated compressive strength for thickness of 240mm are 45 and 39.8MPa, showing error of 9.85% compared the compressive strength test results.

6. DISCUSSION

Based on compressive strength estimated using the impact testing method, the specimen with the column member and design strength of 24MPa does not show change of estimated compressive strength according to thickness as shown in Fig. 2. Mean error between estimated compressive strength and compressive strength of the core specimen is 13.3%. The specimen with design strength of 30MPa does not show change of estimated compressive strength according to thickness. Mean error between estimated compressive strength and compressive strength of the core specimen is 32.1%. The specimen with the wall member and design strength of 24MPa does show change of estimated compressive strength according to thickness. Mean error between estimated compressive strength and compressive strength of the core specimen is 12.4%. The specimen with design strength of 30MPa does not show change of estimated compressive strength according to thickness as shown in Fig. 3. Mean error between estimated compressive strength and compressive strength of the core specimen is 31.4%. Overall mean error of estimated compressive strength is 22.7% for the column member and 21.9% for the wall member. Overall mean error for the vertical members is 22.3%.

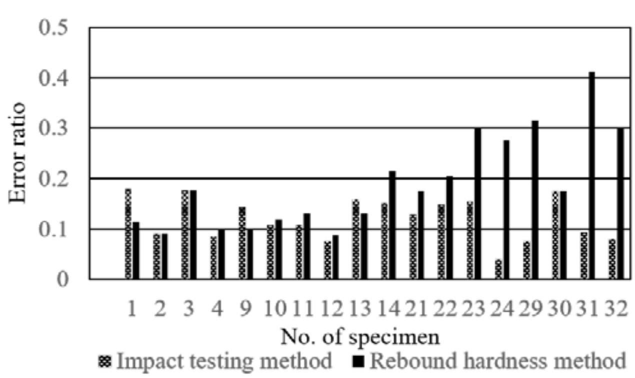

Figure 2. Comparison of experiment results (24MPa)

The specimen with the girder member and design strength of 24MPa does not show change of estimated compressive strength according to thickness. Mean error between estimated compressive strength and compressive strength of the core specimen is 11.8%. The specimen with design strength of 30MPa does not show change of estimated compressive strength according to thickness. Mean error between estimated compressive strength and compressive strength of the core specimen is 32.0%. The specimen with the slab member and design strength of 24MPa does not show change of estimated compressive strength according to thickness. Mean error between estimated compressive strength and compressive strength of the core specimen is 10.7%. The specimen with design strength of 30MPa does not show change of estimated compressive strength according to thickness. Mean error between estimated compressive strength and compressive strength of the core specimen is 25.5%. Overall mean error of estimated compressive strength is 21.9% for the girder member, 18.1% for the slab member, and 20.0% for the horizontal members. Overall mean error of estimated compressive strength for all structures is 21.2%.

Based on compressive strength estimated using the rebound hardness method, the specimen with the column member and design strength of 24MPa does not show change of estimated compressive strength according to thickness as shown in Fig. 2. Mean error between estimated compressive strength and compressive strength of the core specimen is 12.1%. The specimen with design strength of 30MPa does not show change of estimated compressive strength according to thickness. Mean error between estimated compressive strength and compressive strength of the core specimen is 10.8%. The specimen with the wall member and design strength of 24MPa does not show change of estimated compressive strength according to thickness. Mean error between estimated compressive strength and compressive strength of the core specimen is 13.1%. The specimen with design strength of 30MPa does not show change of estimated compressive strength according to thickness. Mean error between estimated compressive strength and compressive strength of the core specimen is 6.0%. Overall mean error of estimated compressive strength is 11.5% the column member and 9.6% for the wall member. Overall mean error for the vertical members is 10.6%.

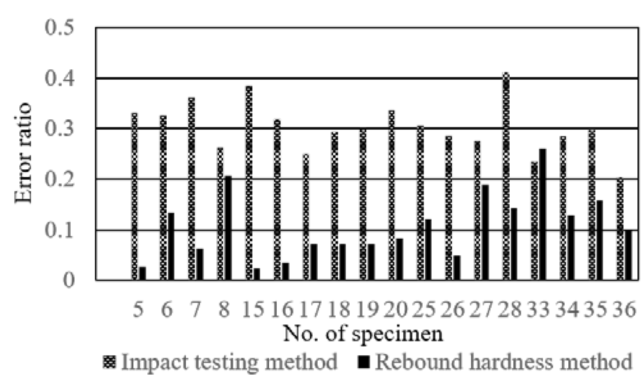

Figure 3. Comparison of experiment results (30MPa)

The specimen with the girder member and design strength of 24MPa does not show change of estimated compressive strength according to thickness. Mean error between estimated compressive strength and compressive strength of the core specimen is 23.9%. The specimen with design strength of 30MPa does not show change of estimated compressive strength according to thickness as shown in Fig. 3. Mean error between estimated compressive strength and compressive strength of the core specimen is 12.5%. The specimen with the slab member and design strength of 24MPa does not show change of estimated compressive strength according to thickness. Mean error between estimated compressive strength and compressive strength of the core specimen is 29.9%. The specimen with design strength of 30MPa does not show change of estimated compressive strength according to thickness. Mean error between estimated compressive strength and compressive strength of the core specimen is 16.1%. Overall mean error of estimated compressive strength is 18.2% for the girder member, 23.0% for the slab member, and 20.6% for the horizontal members. Overall mean error of estimated compressive strength for all structures is 15.6%.

The results of the compressive strength estimation using the impact testing method showed that the mean error rate is 12.1% for the specimens with the design strength of 24 MPa and 30.3% for the specimens with the design strength of 30 MPa. The results of compressive strength estimation using rebound hardness method showed that the mean error rate is 19.8% for specimens with a design strength of 24 MPa and 11.4% for specimens with a design compressive strength of 30 MPa.

7. CONCLUSION

Compressive strength of the single-story reinforced concrete structures comprised of vertical and horizontal members was estimated using the impact testing method and rebound hardness method of nondestructive test methods in this study, and the following conclusions were drawn.

1) Based on compressive strength of the structures estimated, overall mean error was 21.2% for the impact testing method and 15.6% for the rebound hardness method.
2) The necessity of a reliable diagnostic method based on compound nondestructive test methods to increase accuracy of estimation was confirmed.

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