Research Article

Performance Evaluation of JPCP with Changes of Pavement Mix Design Using Pavement Management Data

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This study aimed to analyze long-term performance of JPCP (jointed plain concrete pavement) according to changes in standard mix design using evaluation of concrete properties based on Korea HPMS (highway pavement management system) and Korea LTPP (long-term pavement performance) data accumulated for over 15 years. The concrete pavements built in the 2010s by the specification of a durability-based mix design adopted in 2010 were found to have better performance with much fewer surface distresses than the concrete pavements built before 2010 by the specification of a classical strength-based mix design. Also, in order to realize long-life concrete pavement, experimental construction was carried out for high-durability concrete mix design. The performance monitoring data for the construction site implied that the high-durability mix design can make it possible to lead a long-life concrete pavement.

1. Introduction

Since the first application of concrete pavement to the Namhae Expressway in 1982, concrete pavement has grown rapidly in quantitative terms to account for 65% (9,194.6 km/lane) of Korea Expressway in 2016. In this quantitative growth process, the concrete pavement construction technology has led to the qualitative growth of the concrete mix design technology while experiencing many early-age deteriorations.

This study was conducted to analyze the improvement effects applying advanced technologies in the process of overcoming the early-age deteriorations based on field data, and includes standard mix design criteria for achieving long-life concrete pavement. The field data used in this study were collected from Korea HPMS (highway pavement management system) and Korea LTPP (long-term pavement performance).

The strategies such as pavement design, construction, repair, rehabilitation, maintenance, preservation, and management were determined by using HPMS and LTPP

database of analysis of the pavements materials, types, and so on. Wang and Tsai and Ker et al. used LTPP data to develop a reliable faulting prediction model [1, 2]. Also, Selezneva et al. conducted a study to investigate spatial characteristics of transverse cracking occurring in CRCP and to develop a theoretical model [3]. Zhou et al. [4] and Lu and Denver [5] used LTPP data to improve the IRI model for design of flexible pavement. It is also used for the verification and the comparability analysis of the developed model using LTPP data. Hall et al. used LTPP data for k -value verification of concrete pavement [6]. Jamal Khattak and Peddapati analyzed the relationship between the actual performance of the flexible pavements and its relationship with the in situ mechanistic and volumetric properties using LTPP data [7]. Mamlouk and Dosa performed validation of chip seal for preventive maintenance [8]. Hwang and Lee, and Dong and Huang performed the evaluation of effectiveness of each rehabilitation method using LTPP data [9, 10]. LTPP data were also used to analyze the performance of skid resistance as well as the structural performance of the various pavement types [11, 12]. In other words, the use of LTPP data is

essential for design and verification to improve pavement performance.

The Korea HPMS was put in place since 2003 to manage pavements at a network level. From 2003, pavement condition surveys were conducted using the automatic pavement condition survey equipment every two to four years depending on traffic volume and years of service. Since 2008, pavement condition surveys have been performed for the entire highway networks every two years, and pavement condition evaluation data from 6 to 7 network level surveys are stored in a database now. Also, in order to analyze pavement performance and effects of construction methods at a project level, Korea LTPP research has continued since 2005, and analyses on pavement performance for a broad range of materials and construction methods are underway.

The performance evaluation of the concrete pavement according to the standard mix design change is performed for the concrete pavement sections constructed in the 2000s and 2010s at the network level. To this end, for about 10 years, accumulated HPMS database and LTPP research methodology were used.

2. Mix Design Changes in Concrete Pavement in Korea

2.1. Early-Age Deteriorations of JPCP in Korea. In the 2000s, concrete pavement faced two big problems as shown in Figure 1: one is cracking by ASR (alkali-silica reaction) and the other is widespread spalling and scaling of joints caused by wet deicing operations in winter in the form of early stage distress. This is considered due to poor concrete durability [13–16]. In 2010, to solve these issues, a new mix design was used, whereby fly ash is added to the binder to prevent ASR-causing distress and durability management indexes are put in place to mitigate distress due to freeze-thaw effects and air void spacing factors are intensively managed [17–20].

2.2. Changes in Concrete Pavement Mix Design. After massive research on various performance requirements for concrete pavement, the standard mix design for cement concrete pavement has been modified through six revisions from 1986 to 2010 as listed in Table 1. In Korea, the initial mix design for concrete pavement was established in 1986 for the construction of the Jungbu Expressway with design flexural strength of 4.5 MPa and the first standard concrete pavement mix design was presented in 1996. Afterwards, according to the strength mix design, the standard mix continued to change until the mix design in 2002 in which compared to the initial mix design (cement content: 356–378 kg/m³), the cement content of the mix design in 2002 (cement content: 326 kg/m³) fell around 10–16%. However, major changes in the recent standard mix (2010) for enhanced durability of cement concrete included the introduction of AE (air-entrained) and WR (water-reducing) admixtures and replacement of 20% unit binder with fly ash as an alternative to cement in order to address ASR, spalling, and joint distress due to freeze-thaw effects, which were representative types of distresses of concrete pavement in the 2000s.

2.3. Paradigm Conversion of Concrete Pavement Mix Design. As described above, expressway concrete pavements in Korea were constructed using cement-only binder according to the strength-based mix design standard. In the 2000s, however, prewetted sodium deicers and difficulty in supplying quality aggregates resulted in a sharp increase in ASR distress, spalling at joints, and freeze-thaw distress, raising the need for strategies to solve this. A series of root-cause analyses indicated that durability of concrete mix should be enhanced, and as a result of this, the Comprehensive Plan to Improve Concrete Pavement Quality was established in 2010 as in Table 2. The major improvements under the 2010 plan included the introduction of AE and WR admixtures, reduction of unit cement content, and application of fly ash as a replacement of cement, which aimed at enhanced cement concrete constructability and durability indexes. At the core of the comprehensive plan were the adoption of air void spacing factor and change of mix design. More specifically, air void spacing factor standard (0.2 mm or less) was added to air voids among the durability. And, in the case of mixing, the unit binder weight was increased (326 → 350 kg/m³) with 20-percent fly ash. On top of this, the standard for entrained air voids was increased (4–6% → 5–7%), and management of AE and WR admixtures was strengthened. This represents a paradigm shift from the existing strength-based mix design to a mix design focusing on concrete durability in Korea [21–25].

Despite major concrete pavement mix design improvements such as the introduction of AE admixture and water-reducing admixtures and the application of cement containing fly ash admixtures, further quantitative studies are still in need for the analysis of strength, durability, and performance according to changes in concrete pavement mix design.

Consequently, this study performed a performance evaluation according to major changes in the standard mix design of concrete pavement and examined how the mix design characteristics for concrete pavement affect its performance. In particular, beyond the existing strength-based mix design, a durability-based mix design was used to conduct a pavement condition survey and evaluation of properties of concrete pavement materials for comparison.

3. Pavement Performance Evaluation and Survey Sections

3.1. Pavement Performance Evaluation. The performance evaluation for concrete pavement depending on changes in the standard mix design was based on the HPMS data at a network level and data on properties from in situ core specimens.

HPMS is expressed as HPCI (highway pavement condition index) and calculated for concrete pavement using IRI (International Roughness Index) and SD (surface distress area) as in equation (1). Pavement condition surveys were conducted using an automatic pavement condition survey vehicle that can travel up to 80 km/h and collect data such as road profiles and pavement surface photo for SD analysis every 10 m distance and generated HPCI:

FIGURE 1: Typical distresses of JPCP in Korea. (a) ASR distresses. (b) Joint freeze-thawing distress.

TABLE 1: Mix design changes of expressway concrete pavement in Korea.

Year	Slump (mm)	Air (%)	Water/binder ratio	Unit weight (kg/m ³)					Admixtures	
				Water	Binder		Sand	Gravel	AE (%)	WR (%)
					Cement	Fly ash				
1986	30–50	3–6		153–170	356–378	—	595–694	1135–1272	0.03	—
1996	40–60	4–6	0.45	151	336	—	678	1162	0.15	—
2002	40–60	4–6		147	326	—	692	1122	0.3	—
2010	40–60	5–7	0.43	150	280	70	630	1150	0.02	0.3

TABLE 2: Summary of Comprehensive Plan to Improve Concrete Pavement Quality (2010).

Item	Detail
Introduction of spacing factor	(i) Add standard air void spacing factor to durability indexes (0.2 mm or less)
	(ii) Increase unit binder weight (326 → 350 kg/m ³ , fly ash 20%)
Change of concrete pavement mix design standard	(iii) Adjust air voids content (4–6% → 5–7%)
	(iv) Strictly manage admixtures (air-entrained, water-reducing, etc.)

$$\text{for HPMS : HPCI} = 5 - 0.8 \times \text{IRI}^{0.7} - 0.85 \times \log(1 + 2.5 \times \text{SD}), \quad (1)$$

where HPCI = calculated with SD₀, IRI = International Roughness Index (m/km), and SD = unified surface distress area excluding patched section (m²).

The SD means an unified surface distress which can be obtained by the summation of the deteriorated areas with line cracks (crack length (m) × 0.3 m), spalls, surface deteriorations, and exclusion of patched areas with partial or full depth repair. The reason for excluding the repair section from the SD calculation is that the pavement condition is considered to be improved through the maintenance budget input when the maintenance method is applied.

For HPMS, HPCI of 5.0 represents the best pavement performance, and depending on HPCI₀, IRI, and SD values, seven classifications for management are established as in Table 3.

However, in case of LTPP, because it is the purpose of analysis of performance life cycle of the pavement, it is desirable to regard the repair section as a damaged area. The

patched area is included in the SD calculation, and HPCI is calculated as shown in equation (2) [26]. Therefore, in this study, HPCI₁ and SD₁ were used to analyze the performance of JPCP depending on concrete mix design change:

$$\text{for LTPP : HPCI}_1 = 5 - 0.8 \times \text{IRI}^{0.7} - 0.85 \times \log(1 + 2.5 \times \text{SD}_1), \quad (2)$$

where HPCI₁ = calculated with SD₁, IRI = International Roughness Index (m/km), and SD₁ = unified surface distress area including patched section (m²).

Also, the analysis of concrete properties using in situ core specimens resulted in the measurement of converted flexural strength using compressive strength and split tensile strength as concrete strength management factors and that of air void spacing factor as a factor of durability management. As the Korean highway bridge design codes (limit state design) require that the converted flexural strength via split tensile strength be determined approximately [27], this study measured the split tensile strength using in situ core specimens and then calculated the flexural strength.

TABLE 3: Grade of pavement performance index of HPCI component for HPMS.

Grade	HPCI	IRI	SD (m^2)	SD (%)*	Action
1	4.0 or more	Below 1.5	0	0	Do nothing
2	4.0–3.5	1.5–2.0	Less 1.0	0.3	Preventive maintenance
3	3.5–3.25	2.0–2.5	1.0–18	0.3–5	Maintenance and repair if necessary
4	3.25–3.0	2.5–3.0	18–36	5–10	Maintenance and repair
5	3.0–2.5	3.0–3.5	36–52	10–15	Rehabilitation, if necessary
6	2.5–2.0	3.5–4.0	52–72	15–20	Rehabilitation
7	Below 2.0	4.0 or more	72 or more	20 or more	Preferred rehabilitation

*SD (%): unified surface distress per unit area of pavement surface.

3.2. Survey Sections. If the paradigm conversion of mix design makes an effect on the quality improvement on concrete pavement of performance, a meaningful difference of the concrete pavement should be made between the concrete pavement sections built in 2000s and 2010s. In order to identify the difference, the data analysis for the comparison of the pavement performance was conducted using HPMS data. Two data groups from the concrete pavement sections built in 2000s and 2010s, respectively, were divided and separately analyzed. Then, the concrete pavement performance data of these groups were compared.

Three sections among concrete pavements built in 2010s (durability-based mix) were selected as shown in Table 4, and five sections among concrete pavements built in 2000s (strength-based mix) were selected as shown in Table 5. For all lanes of these selected sections, the pavement performance data stored in HPMS database were extracted and analyzed [28–41]. Two- or three-cored specimens were obtained for each section. Properties of cored specimens from the selected sections were evaluated.

4. Performance Evaluation of JPCP

4.1. HPMS Data: HPCI₁, IRI, and SD₁. Figure 2 illustrates results from pavement condition surveys according to changes in the standard mix design for concrete pavement. The routes constructed in the 2010s are represented by a solid line and those built in the 2000s in dotted line, with indications of both-direction averages for the outermost lanes (design lane) of each route. Since changes in pavement performance are more apparent in the inside lane (2nd lane) than in the passing lane (1st lane) for reasons such as heavy traffic, the data of inside lane were used for analysis.

Figure 2(a) shows HPCI₁ changes over service life. Although initial measurements of each have slight differences, all routes were found to exhibit good condition of 3.5 or over at HPCI₁ for a service life of 10 years or so without a noticeable change and the routes built in the 2000s were a bit higher in their HPCI₁ than those built in the 2010s. There are no data available for 10 years later for the routes constructed in the 2010s as they have been in service for seven to eight years, but HPCI₁ values for those constructed in the 2000s sharply fall from around 12 years of service. In addition, HPCI₁ levels of some of the routes constructed in the 2000s appear to fall and then rise again. The increase of HPCI₁ can be explained by the fact that sections with low HPCI₁ were excluded from the analysis by applying asphalt overlays on

the sections suffering from severe pavement distress as a concrete pavement maintenance solution, and the survey was conducted only on the concrete pavements showing relatively better performance.

Figure 2(b) describes IRI changes depending on years of service. All routes repeat increase and decrease in IRI and eventually increase to some degree over the service period, but they still remain in good condition without clear change. It is considered that IRI decreased because diamond grinding was widely used across the concrete pavement to enhance the ride quality along the expressways and to manage pavement condition. In addition, the routes constructed in the 2000s with a service life of 10 years or less were found to have lower IRI and exhibit better roughness, compared to those built in the 2010s.

Figure 2(c) shows SD₁ (%) changes by service life. Recent surveys revealed that there is no apparent increase in surface distress of the routes constructed in the 2010s. In contrast, those built in the 2000 displayed widespread surface distress from the service lives of 6 to 8 years. Like IRI, increase and decrease in SD₁ occurred in the routes built in the 2000s. If SD₁ increased, ASR, joint spalling, and freeze-thaw distress happened as major damages of JPCPs laid in the 2000s as described earlier. The decrease in SD₁ was thought to be due to the fact that surface distress was removed with diamond grinding to raise IRI or AP overlays were applied to severely damaged sections, which were then excluded from the analysis.

Two major factors affecting HPCI₁ of concrete pavement, IRI and SD₁, were found to be directly influenced by maintenance activities like diamond grinding and AP overlay intended to maintain serviceability grades for expressways. HPCI₁ for the routes built in the 2000s apparently decreased in ten years of service, but IRI showed no apparent change over the service life by applying roughness improvement strategies such as diamond grinding. This indicates that it would be appropriate to analyze changes in SD₁ for performance evaluation according to changes in the standard mix design for concrete pavement.

The HPCI₁, IRI, and SD₁ results in the maximum distress occurrence year by route are presented in Table 6 and Figure 3. For the routes built in the 2010s (#65, #27, #45-1), the last survey results refer to the maximum distress occurrence year and the routes built in the 2000s (#45-2, #45-3, #15, #35, #55) represent sections having the highest SD₁ during the survey.

The average HPCI₁ of the sections built in the 2010s was 3.88, representing better performance, compared to the

TABLE 4: Summary of concrete pavement sections built in 2010s for performance data analysis.

Route name (#no.)	IC./Jct. to IC./Jct. length (km)	Construction year	Length of concrete pavement section (km/line)	Data survey year
Donghae (#65)	Hajodae-Yangyang (9.7)	2013	31.7	2014, 2015*, 2017
Suncheon Wanjū (#27)	Namwon-Wanjū (59.5)	2010	204.0	2012, 2014, 2016*
Jungbu Naeryuk (#45-1)	Namyeeju-Yangpyeong (34.5)	2010	117.8	2012, 2014, 2015*, 2017

*Evaluation of concrete properties using in situ core specimens.

TABLE 5: Summary of concrete pavement sections built in 2000s for performance data analysis.

Route name (#no.)	IC/JC to IC/JC length (km)	Construction year	Length of concrete pavement section (km/line)	Data survey year
Jungbu Naeryuk (#45-2)	Gimcheon-Nakdong (24.8)	2001	84.64	2005, 2009, 2011, 2013, 2015*, 2017
Jungbu Naeryuk (#45-3)	Goisan-Yeojū (55.9)	2002	174.4	2005, 2006, 2009, 2011, 2013, 2014, 2015*
Seohaean (#15)	Dongseocheon-Dangjin (103.1)	2001	334.9	2004, 2007, 2009, 2011, 2013, 2015, 2017
Daejeon Tongyoung (#35)	Jangsu-Sanae (72.3)	2001	218.0	2006, 2008, 2010, 2012, 2014, 2016*
Jungang (#55)	Danyang-Chuncheon (139.1)	2000	432.7	2005, 2007, 2009, 2011, 2013, 2015*, 2016

*Evaluation of concrete properties using in situ core specimens.

FIGURE 2: Pavement condition change according to the whole performance period. (a) HPCI₁. (b) IRI (m/km). (c) SD₁ (%).

average of those built in the 2000s at 3.30. The standard deviation of the sections built in the 2010s was 0.42, lower than 0.76 of those built in the 2000s ($p = 0.001$). IRI values showed that all sections were in good condition for service, which suggests that resurfacing applications like diamond grinding enhanced IRI across the expressways nationwide. As far as SD_1 was concerned, the average cracking ratio of the sections constructed in the 2010s hit 0.09%, remarkably lower than 1.87% of those constructed in the 2000s, and the standard deviation of 0.63 for the sections built in the 2010s was profoundly lower than 3.73 of those built in the 2000s ($p = 0.012$). Statistical comparisons between 2010s and 2000s were made using Student's t -test; $p < 0.05$ was used to establish statistical significance.

4.2. Properties of Concrete: Strengths and Spacing Factor. In situ core specimens were collected from every route in order to assess surface distress using pavement condition survey data and to carry out property evaluation of concrete pavement according to changes in the standard mix. The compressive strength and split tensile strength of concrete pavement were measured, and flexural tensile strength was estimated from the split tensile strength. Moreover, spacing factor as one of the key changes in the 2010 mix in terms of durability was measured by ASTM C457 [42], and the evaluation results are shown in Table 7.

The compressive strength evaluation showed that all the sections displayed a compressive strength of 30 MPa or over and compressive strengths of the routes built in the 2000s were higher than those built in the 2010s. In addition, the evaluation of converted flexural tensile strength found that the results were similar in magnitude between the routes built in the 2010s and 2000s but failed to meet the design flexural strength of 4.5 MPa to some degree. In concrete strength, the sections built in the 2000s were found to have higher compressive strengths than those built in the 2010s and similar flexural tensile strengths, which is, however, considered inappropriate to be accepted as the differences according to changes of concrete mix design because these results came from the difference in years of service.

The air void spacing factor as a durability management item for concrete pavement was significantly higher in the sections constructed in the 2000s at $343 \mu\text{m}$, while that of the routes built in the 2010s appeared to be fair at $206 \mu\text{m}$. The concrete pavements placed before the Comprehensive Plan to Improve Concrete Pavement Quality in 2010 adhered to the strength-based mix design and appeared to exhibit somewhat disadvantageous levels of spacing factor that affects concrete durability, despite high concrete strengths.

In contrast, the sections built in the 2010s followed the durability-based mix design, not the existing strength-based design concept, which resulted in concrete strengths such as compressive strength and split tensile strength that were good enough even though lower than the sections built in the 2000s, and the air void spacing factor affecting concrete durability was considerably enhanced.

The findings from the pavement condition surveys and evaluation of properties using in situ core specimens showed

that the concrete pavement sections built in the 2010s after the standard mix improvement had strikingly less surface distress as a major type of damage of the concrete pavements laid in the 2000s and enhanced durability. As a result, concrete pavements placed in the 2010s are expected to show better performance than those in the 2000s.

5. Experimental Construction to Improve Standard Mix Design for Long-Life Concrete Pavement

5.1. Experimental Construction for Long-Life and High-Durability Concrete Mix Design. The changes in the durability-based concrete pavement standard mix in 2010 have led to preventing major types of distress of the existing concrete pavement and ensuring excellent pavement performance. Another improvement of the standard mix including increase of unit binder weight and enhanced design flexural strength was made for long-life concrete pavement [43–48]. For this purpose, experimental constructions by mix design were put in place by enhancing the design flexural strength from 4.5 MPa to 5.0 MPa.

A high-durability concrete mix design for long-life concrete pavement was established by increasing unit binder weight as shown in Table 8 on the basis of the current standard mix with a design flexural strength of 4.5 MPa (2010 mix design). The applied concrete mix design had three variables in total: two types of mix that increased unit binder weight from the existing 20% fly ash content and one OPC (ordinary Portland cement) mix that increased unit cement content only. The experimental constructions were located on a new construction expressway in June 2016. In order to investigate the effect of such increased design flexural strength on concrete pavement performance, concrete durability was evaluated for around one year of construction, using in situ core specimens by concrete pavement age.

5.2. Properties of Concrete. In order to evaluate concrete durability of the experimental constructions using high-strength concrete pavement, flexural strength, scaling resistance, freeze-thaw resistance, and RCPT (resistance concrete penetration test) were conducted on in situ core specimens by the age of concrete pavement. Results of such durability evaluation by concrete age are shown in Table 9.

Compared to the existing standard mix (FAC 350) for concrete pavement, the high-strength concrete pavement (FAC 408, FAC 390) mix showed enhanced durability properties such as freeze-thaw resistance and chlorine ion penetration resistance by 40–60% or over. When compared to the existing mix (FAC 350), the OPC 388 mix that increased unit cement content only showed a bit lower chlorine ion penetration resistance. Considering the road management practices in Korea where deicers are widely used in winter, the OPC mix seems inappropriate as its RCPT is still disadvantageous even after around one year of construction although it provides extremely high flexural strength. On top of that, from the fact that the primary

TABLE 6: HPMS data at the time of maximum distresses occurrence.

Route (#)	Construction year	Age of maximum distresses occurrence (year)	SD ₁		IRI		HPCI ₁	
			Mean	Stdev	Mean	Stdev	Mean	Stdev
#65	2013	5 (2017)	0.08	0.62	1.39	0.58	3.91	0.39
#27	2010	7 (2016)	0.08	0.56	1.39	0.58	3.90	0.43
#45-1	2010	8 (2017)	0.11	0.63	1.44	0.54	3.83	0.44
		2010s average	0.09	0.60	1.41	0.57	3.88	0.42
#45-2	2001	12 (2013)	2.77	5.57	1.34	0.54	3.42	0.68
#45-3	2002	13 (2015)	1.21	1.98	1.27	0.54	3.36	0.82
#15	2001	12 (2013)	1.55	4.93	1.21	0.54	3.67	0.73
#35	2001	15 (2016)	2.33	4.13	1.43	0.58	3.07	0.83
#55	2000	16 (2016)	1.50	2.06	1.56	0.63	3.00	0.75
		2000s average	1.87	3.73	1.36	0.57	3.30	0.76

FIGURE 3: Pavement condition according to maximum distresses occurrence year. (a) HPCI₁. (b) IRI (m/km). (c) SD₁ (%).

TABLE 7: Test result of concrete properties using in situ core specimens.

		Compressive strength (MPa)	Calibrated flexural strength (MPa)	Spacing factor (μm)
2010s	Average	40.73	4.39	205.9
	Stdev	6.53	0.66	24.0
2000s	Average	47.36	4.34	343.0
	Stdev	4.31	0.36	31.6

pavement damage is freeze-thaw distress at joint in Korea, the FAC 390 and FAC 408 mixes offering excellent freeze-thaw resistance are considered more adequate for long-life concrete pavement rather than the existing FAC 350 mixture.

Therefore, in this study performed experimental constructions for high-strength concrete mix that meets design high-durability mix design for long-life concrete pavement and assessed concrete durability. As a result, the concrete pavement mix containing a 20% fly ash and increased unit

TABLE 8: Experimental constructions to improve standard mix design of concrete pavement.

Classification	Fly ash 20% blended cement (FAC)			Ordinary Portland cement (OPC)
	FAC 350*	FAC 408	FAC 390	OPC 388
Unit binder content (kg/m ³)	350	408	390	388
Unit water content (kg/m ³)	150	155	148	152
Water/Binder ratio	0.43	0.38	0.38	0.40
Design flexural strength (MPa)	4.5	5.0	5.0	5.0

*The 2010 concrete pavement standard mix design as in Table 2.

TABLE 9: Results of durability evaluation to improve standard mix design of concrete pavement.

Type	Flexural strength (MPa)	Scaling (kg/m ³)	Freezing-thawing (%)	RCPT (C)		
Test method	ASTM C78 [49]	ASTM C672 [50]	ASTM C666 [51]	ASTM C1202 [52]		
Core specimen collection (days)	28	190	330	28	190	449
FAC 350	4.70	0.223	83.2	4,719	1,146	902
FAC 408	5.12	0.130	97.9	5,513	1,398	817
FAC 390	5.83	0.067	97.8	3,260	2,511	915
OPC 388	6.10	0.425	97.4	11,417	3,938	3,245

binder weight with the enhanced design flexural strength can provide higher durability and realize long-life concrete pavement.

6. Conclusions

This study investigated the applicability of the durability-based standard mix design in order to mitigate distresses caused by surface cracking by ASR, joint spalling, and freeze-thaw effects, which were major types of damages occurred in the 2000s along the concrete pavement network across Korea. To this end, performance changes in concrete pavement were analyzed by carrying out evaluations of properties using in situ core specimens and HPMS data accumulated for more than 15 years for five sections built in the 2000s and three sections built in the 2010s since the improvements in the standard mix design in 2010 that worked towards the durability-based mix from the strength-based mix. The findings from the analysis confirmed the appropriateness of the durability-based standard mix improvements, on the basis of which experimental constructions for long-life concrete pavement were conducted, producing an improved standard mix. The following conclusions were drawn from this study.

It was found that an analysis of changes in SD_1 is more appropriate than $HPCI_1$ and IRI for performance evaluation according to changes in standard mix design of concrete pavement with statistical significance. In the routes constructed under the durability-based standard mix design in the 2010s, occurrence and increase of SD_1 was significantly slow until seven years of service, but SD_1 increased rapidly in the routes built in the 2000s from six years of service.

By applying the durability-based mix design, instead of the existing strength-based design concept, the sections constructed in the 2010s appeared to display highly enhanced air spacing factor that affects concrete durability even though concrete strengths such as compressive strength and flexural strength were a bit lower than the pavements

laid in the 2000s. As a consequence, the concrete pavement sections incorporating improvements in the durability-based standard mix design was found to achieve enhanced durability, which is expected to help ensure long-term performance of concrete pavement.

This study conducted the experimental construction and concrete durability evaluation for high-strength concrete mix design that meets design flexural strength of 5.0 MPa for long-life concrete pavement. The findings from this study revealed that the concrete pavement mix containing 20% fly ash and increased unit binder weight with the enhanced design flexural strength will be able to provide better durability and realize long-life concrete pavement, resulting in the proposal of an improved standard mix design for better concrete pavement quality and performance.

Data Availability

The HPMS and concrete properties data used to support the findings of this study have not been made available because the data were supplied by Korea Expressway Corporation under license.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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