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Editorial

Special Issue on Fatigue, Performance, and Damage Assessments of Concrete

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Abstract: This Special Issue covers the latest research on fatigue, performance, and damage assessments of concrete. Concrete fatigue is known as a phenomenon characterized by the repetition of loads. The fatigue-based performance of concrete may be affected by a combination of diverse loads, mechanical strength properties, and environmental changes. These factors eventually lead to poor concrete performance. In this Special Issue, nine papers were accepted, divided into three subgroups: two papers on fatigue, two papers on performance, and five papers on damage assessment. Unlike articles published in past Special Issues, our Special Issue contains papers that address concrete performance in concrete pavement applications. In particular, six of the articles contained in this issue concentrate on pavement performance and damage assessments, especially in terms of the Pavement Condition Index. Together with a brief introduction, the keywords, research significance and potential impacts of each article are summarized in this Editorial.

Keywords: fatigue; performance; high performance; long-term durability; damage assessment; distress; Pavement Condition Index

1. Introduction

Concrete fatigue is a phenomenon brought about by the repetition of loads. When subjected to cyclic loads throughout the life span, high-rise buildings, bridges, and pavements exhibit fatigue failures. The fatigue-based performance of concrete may be affected by a combination of diverse loads, mechanical strength properties, reinforcing properties, environmental changes, and so on. Compared to static loads, concrete strength under fatigue loads is typically low [1].

Concretes under the repetition of loads will be subject to an increase in displacements and cracks, finally causing fatigue failure [2]. The accurate prediction of these time-dependent quantities, as well as many other important considerations, such as serviceability criteria, were discussed in 1983 in ACI Special Publication-75, titled "Fatigue of Concrete Structures" [2]. In ACI SP-75, a total of 18 articles were published: five papers related to different loading conditions; two papers on flexural fatigue; three papers on special structures, such as hollow concrete spheres, offshore concrete, and prestressed concrete; two papers on bond characteristics; two papers on different material conditions related to the air content, water-to-cement ratio, and coarse aggregate type; three papers on deflections and crack width and growth; two papers on bar corrosion and different spliced reinforcements; and one paper on the diverse environmental conditions in chloride solution, in seawater, and in air. In 2022, Kachkouch et al. [3] summarized existing knowledge of concrete fatigue behavior, discussing current standards and the prospects of future experimental research. They provided a timeline of the first relevant fatigue studies with respect to compression, bending, and tension as well as loading frequency as an influencing parameter.

As structures become larger and more complex, the construction materials used will require more stringent standards of performance than those in force today. To meet these

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standards, today's products, often termed high-performance concretes (HPCs), need to be improved in terms of their mechanical strength, durability, dimensional stability, and overall reliability [4]. In particular, the long-term pavement performance (LTPP) was evaluated to collect pavement performance data, this being one of the major research areas in the concrete research field [5]. Thus, concrete performance in the literature has been understood as the durability or long-term performance of concrete products.

Numerous comprehensive studies on HPCs have been conducted over the past 20 years or so. These studies include research on the unhardened paste properties of HPC [6], the effect of incorporating fibers [7], mix designs using supplementary cementitious materials (SCMs) [8], and structural applications in hybrid hollow core structures [9], bridges [10], sleepers [11], and tunnels [12]. For a comprehensive review on pavement performance, refer to Hu et al. [13], who conducted a comprehensive review of empirical methods for pavement performance modeling.

Damage assessments of existing structures are defined as a set of activities performed to verify the reliability of an existing structure for future use [14]. The categories considered in these assessments include the state of structural experience, environmental changes, structural capacity, durability, etc. [15]. Traditionally, concrete damage induced by diverse loads and environmental conditions has been mainly detected by visual assessment and field measurements, including cored specimens. This basic method is very easy and cost-effective, although it is time-consuming and laborious, in addition to many high structures being difficult to reach [16]. Thus, various non-destructive test methods or modern computational and/or analytical methods, alone or in conjunction with experimental techniques, have been adopted for the intelligent damage assessment of concrete materials and structures. In addition, in the context of pavements, the damage assessment is typically interpreted as a pavement condition rating or index.

The Pavement Condition Index (PCI) ranges from 0 to 100, which indicates the general condition of a pavement system. This index was originally proposed by the United States Army Corps of Engineers as a rating system for airport pavements [17]. The PCI is widely applied to road pavements and airport pavements and used in asset management. Various distress/severity combinations result in values being deducted from an initial value of 100. The PCI is a complex index covering all forms of general pavement distress related to functional pavement performance as well as structural pavement performance.

In airport pavements, certain forms of pavement distress, originating from patching or alligator cracking, can cause loose pieces, which may result in potential damage to aircraft engines and tires. This type of damage to an aircraft engine is defined as foreign object damage (FOD). Thus, road and airport agencies typically use three pavement condition indices: the Pavement Condition Index (PCI), the Structural Condition Index (SCI), and the FOD Index (FOD) [18]. The main differences between the PCI, SCI, and FOD are the pavement distress types factored into their index calculations. The PCI counts around 16 concrete pavement distress types, while the FOD does not count types of pavement distress that have no risk of causing loose foreign objects [18]. On the other hand, a limited group of types of structural pavement distress (e.g., cracking, corner breaks, pumping, spalling) are categorized in the SCI [18].

Recently, a few Special Issues (SIs) related to concrete fatigue, performance, or damage assessment have been published in scientific journals. Table 1 lists those SIs published after 2019. "Fatigue" [19] was published as an SI in *Structural Concrete* by FIP in 2019; it contains 10 papers on fatigue and cyclic loading of high-strength and high-performance concrete. Another SI, "Fatigue and Fracture of Non-Metallic Materials and Structures" [20], was published by *Applied Sciences* in 2019. Ten out of a total of thirty-four papers in this SI address fatigue on bridges, fiber-reinforced concrete (FRC), and other applications, such as asphalt and rocks. The third SI, titled "Cyclic Deterioration of Concrete", was published by *Materials* in 2021 [21]; this SI focused on fatigue, damage evolution, and cyclic loading of high-strength and high-performance concrete.

Table 1. Special publications related to fatigue, performance, and damage identification in concrete area since 2019.

No.	SI Title	Specialty	Papers	Year
1	Fatigue [19]	Fatigue and cyclic loading of high-strength or high-performance concrete	10	2019
2	Fatigue and Fracture of Non-Metallic Materials and Structures [20]	Fatigue of bridges, FRC, and other applications such as asphalt and rocks.	10(34) [1]	2019
3	Cyclic Deterioration of Concrete [21]	Fatigue, damage evolution, and cyclic loading of high-strength and high-performance concrete	12	2021

[1] The Special Issue contains a total of 34 papers; papers related to fatigue number 10, while those related to fracture number 24.

This Special Issue introduces recent achievements in the synthesis, performance, damage characteristics, as well as fatigue of concrete. Unlike articles published in the past, as introduced in Table 1, our Special Issue contains papers that include research findings on concrete pavement.

2. Main Keywords, Significance, and Potential Impact

Table 2 summarizes the research significance and potential impact of the nine published articles. Table 3 tabulates the main keywords for each article. Table 4 subcategorizes each article into 'Fatigue', 'Performance', and 'Damage Assessment' categories. Contributions 1, 3, and 8 belong to both the 'Performance' and 'Damage Assessment' categories. These papers deal more with the Pavement Condition Index (PCI), and thus they were finally grouped into 'Damage Assessment' in the subsequent section. For example, the article from contribution 5 is related to the Fatigue subcategory entirely (denoted by the bullseye symbol '◎') while that from contribution 9 is related mainly to the Fatigue subcategory and a little to the Performance subcategory (denoted by the white circle '○').

Table 2. Research significance and potential impact from articles published in this Special Issue.

Paper No.	Research Significance	Potential Impact
1	Construction Analysis for Pavement Rehabilitation Strategies (CA4PRS) software was used to examine the application of pavement overlays via life cycle cost (LCC) analysis applying user costs, construction costs, and overlay life cycles.	To achieve beneficial economic effects, the LCC analysis results can be used in pavement overlay constructions as primary decision criteria.
2	Concerning the current Pavement Condition Index (PCI) ratings for airport pavement, an adjusted deduction value curve for multiple forms of distress due to different airport conditions is proposed.	Prediction of long-term pavement performance can be more reasonably estimated using the so-called "K−PCI", which adjusts for multiple distress types.
3	Future pavement performance is evaluated with the concrete Pavement Condition Index using machine learning concepts.	Prediction of long-term pavement conditions can be more precisely estimated using machine learning concepts than by using conventional regression modeling.
4	FEM analysis, field investigation, and indoor evaluations were used to evaluate lateral vibrations for different types of longitudinal texture tining specifications on concrete pavement.	Based on FEM analysis, field and indoor driving simulation tests, field applications, and panel ratings, a longitudinal texture specification (3 mm × 3 mm × 16 mm) that minimizes lateral vibrations can be practically applied to the road pavement.

Table 2. *Cont.*

Paper No.	Research Significance	Potential Impact
5	Diverse machine learning models were adopted to predict the concrete fatigue life subjected to compressive loads.	Non-precision data processing using outlier detection methods can be expanded to the software area.
6	Damaged spalling depth can be estimated using ultrasonic velocity measurement from the concrete pavement, and its sound rating can be graded accordingly.	The test results may be directly applied in the concrete pavement field to determine whether the existing concrete pavement is sound.
7	Concrete properties containing wool fiber waste were evaluated in terms of their mechanical strength properties, along with durability properties such as freeze–thaw resistance and chloride penetration resistance.	Based on the test results, which show an increase in tensile strength, a significant increase in freeze–thaw resistance, and an equivalent chloride penetration resistance, and compared to the control specimen, glass wool waste with a range from 0.5 to 2% by cementweight can be used as a fiber-reinforcing material.
8	Significant types of distress in pavement propped up on a mechanically stabilized earth-retaining wall were systematically evaluated via visual inspections, cored specimens, Falling Weight Deflectometery (FWD) tests, etc.	After conducting a systematic evaluation of the pavement of a mechanically stabilized earth-retaining wall, an appropriate repair strategy can be adopted, with insights into the potential distress mechanism.
9	The bond behavior of carbon-fiber-reinforced polymer (CFRP) rods and UHP-FRC subjected to fatigue stress is determined by adopting an interface element of FEM analysis.	The new analytical interface element adopted in this study significantly improves the performance prediction of the CFRP−UHP−FRC bond subjected to fatigue loads.

Table 3. Main keywords from published articles in this Special Issue.

Paper No.	Keywords
1	Pavement, Overlay, Rehabilitation, Traffic volume, LCC
2	Pavement, Airport, Panel rating, Deduct volume, Pavement condition index
3	Pavement, Condition predicting, PCI, Particle filtering, Machine learning
4	Pavement, Tining, Lateral vibration, Panel survey, FEM
5	Structure, Fatigue, Stress level, Outliers, Machine learning
6	Pavement, Soundness, Spalling, NDT, Ultrasonic velocity,
7	Structure, Waste wool, Fiber RC, Mechanical properties, Durability
8	Pavement, MSE wall, FWD, DCP, CPTs
9	Structure, CFRP rod, UHP-FRC, Bonding, FEM

Table 4. Subcategories for each published article.

SI Contributed Paper No.	Fatigue	Performance	Damage Assessment
Contribution 5	◎		
Contribution 9	◎	○	
Contribution 4		◎	
Contribution 7		◎	
Contribution 1		○	◎
Contribution 2			◎
Contribution 3		○	◎
Contribution 6			◎
Contribution 8		○	◎

3. Overviews of the Articles Published in the Special Issue

As categorized in the previous section, the articles from Son and Yang (contribution 5) and Azarkerdar and Hejazi (contribution 9) belong to the Fatigue subcategory, while those from Rye et al. (contribution 4) and Lim et al. (contribution 7) belong to the Performance subcategory. Other articles from Jung et al. (contribution 1), Cho et al. (contribution 2), Lee et al. (contribution 3), Yeon et al. (contribution 6), and Lee et al. (contribution 8) were categorized in the Damage Assessment category.

3.1. Fatigue

Son and Yang [Contribution 5] used various machine learning models, including artificial neural networks, random forest, and boosting models, to predict the concrete fatigue life when subjected to compression. Three data files were extracted from the original data: the original data, the data after removing outliers, and the average data after removing outliers. After removing the sustained concrete strength, which was considered as the seventh independent parameter in the original data, the use of six input parameters only (concrete compressive strength, ratio of height to width, shape, maximum stress level, stress ratio, frequency) resulted in the improvement of the determination coefficient in the boosting models. Finally, the results of the Permutation Feature Importance tests demonstrated that the maximum stress level and frequency are the most critical independent parameters, while the ratio of height to width and shape are very weak influencing parameters.

Azarkerdar and Hejazi [Contribution 9] set out with a focus on assessing the bonding of carbon-fiber-reinforced polymer (CFRP) rods in ordinary concrete, as well as ultra-high-performance fiber-reinforced concrete (UHPFRC) under cyclic loads. This study aimed to develop an interface model between the CFRP rods and concrete matrix. It sought to clarify the bonding mechanism of CFRP rods in concrete structures. After fabricating two rectangular specimens which were connected through the CRFP rod, dynamic actuation tests subjecting the specimens to cyclic loads were simulated using the finite element program ABAQUS. Moreover, a constitutive model of the CFRP-concrete interface was formulated from the analytical results. Compared to the non-analytical interface element, the new analytical interface element resulted in a 10% improvement in displacement and a 42% improvement in pull-out force for the UHPFRC. Using their analytical model, the interaction between the CRRP rod and the concrete matrix can be more accurately predicted under cyclic loading.

3.2. Performance

Rye et al. [Contribution 4] analyzed the main cause behind the lateral vibration problem in longitudinal tining sections, and proposed a specification of longitudinal texture that can shed light on lateral vibration. The longitudinal tining of concrete pavements is very important to reduce noise and improve skid resistance. However, lateral vibration in longitudinal tining sections threatens driver safety. In this paper, several methods were conducted to determine the optimal longitudinal texturing specification, including panel rating, FEM analysis, field tests, indoor driving simulation tests, and field applications. The results show that the texture denoted as 2 mm $\times$ 3 mm $\times$ 19 mm is the optimal longitudinal texture on aged concrete pavement. However, since this criterion is difficult to apply to concrete pavement at an early age, 3 mm $\times$ 3 mm $\times$ 16 mm is recommended as the optimal longitudinal texture, achieving the best performance from the panel ratings as well as in the numerical analysis. Based on these findings, lateral vibration in longitudinal tining sections on the studied expressway will be reduced.

Lim et al. [Contribution 7] studied the application of mineral and glass wool waste for fiber-reinforced concrete. By adding mineral and glass wool waste in a range from 0.5 to 2% by cement weight, the study aimed to determine the material properties in the areas of unhardened concrete, as well as its durability and mechanical strength properties. The air content was not affected to a significant extent by adding waster fibers. However, by adding more waste fibers, the slump loss is ascribed to the high absorption characteristics of the fibers. Furthermore, the test results demonstrated that by adding fibers, the compressive strength was decreased compared to the control specimen. In contrast, the increase in tensile strength is ascribed to the load-bearing characteristics of the waste fibers. The improvement in freeze–thaw resistance was confirmed in all the glass wool waste specimens. The test results for chloride penetration resistance were found to be equivalent to those of the control specimen. However, it was found that a 2% or higher fiber addition rate was needed to secure freeze–thaw resistance in the case of mineral wool waste. With the increase in the addition rate, a significant increase in permeability was observed.

3.3. Damage Assessment by the PCI

Jung et al. [Contribution 1] examined the applicability of pavement overlays using life cycle cost (LCC) analysis. Firstly, they analyzed the number of lanes, traffic volume, and shoulder availability on South Korean highways. Then, the Construction Analysis for Pavement Rehabilitation Strategies (CA4PRS) software was used to convert the value per vehicle on roads with traffic blockages due to overlay construction into user cost. There was a reduction in the user cost when the shoulder was installed. The pavement construction costs were determined, and all of the overlay methods were identified from the existing literature. Lastly, LCC analysis was conducted by applying the user costs, construction costs, and life cycles of pavement overlays.

Cho et al. [Contribution 2] introduced the existing PCI procedure and used the findings to redefine the main types of distress found from airport pavements in S. Korea. Airports mainly use pavement management indices such as the FOD index, using the PCI for safety issues. These indices are utilized in decision-making systems for ordinary pavement maintenance and repair. However, since the most significant airports in S. Korea are mid-sized or large and commercial, the authors pointed out problems related to the direct applications of the deduction value of the existing PCI. In addition, a deduction value curve considering the severity level of the main distress types and a corrected deduction value curve for multiple distress types regarding the standard pavement form were prepared using panel rating. Lastly, a new KPCI was recommended with the proposed curves, and the test field results were compared with the current PCI values to investigate the applicability of the KPCI.

Lee et al. [Contribution 3] presented a new methodology that can aid in decision making related to management strategies through a more efficient and systematic analysis of the vast annual pavement condition database. The traditional method, polynomial regression analysis, which is calculated through relatively complex formulae, is applicable only at the network level of pavement management. The new approach introduced in this study employs "particle filtering," a machine learning method, to allow for a hybrid-style application at the network and project levels. Additionally, this method aims to capture the characteristics of time series data more accurately. For training, this study utilized time series pavement condition data from 469 individual unit segments (10 m) at various ages of (19, 20, 21, 23, 25, 27, 29, and 30) years. The minimum conditions required to ensure at least 90% prediction accuracy were determined as follows: (1) determining the initial pavement condition index—deciding the basic model form; (2) determining the appropriate number of particles—15,000; and (3) determining the minimum number of time series points—five consecutive pavement condition survey data points for the same segment.

Yeon et al. [Contribution 6] evaluated the level of functional damage on the pavement surface using the UV method, which is one of the NDT techniques. The findings were used to suggest a method to determine the depth of the pavement damage. It was observed that the currently used management method does not adequately detect the deteriorated pavement area at early ages. From the UV test results, the sound rating of the concrete pavement was graded. Also, a decreasing tendency of UV penetration was confirmed as the propagation depth of the deteriorated areas increases.

Lee et al. [Contribution 8] presented an extensive case study of the evaluation of distress observed in pavement propped up on a mechanically stabilized earth (MSE) wall that showed a significant degree of distress. Extensive testing, including visual observations, FWD tests, coring operations, and various field tests, revealed the primary causes of distress. A critical insight derived from this study is the role of backfill soils in embankment stability. The use of poor-quality backfill soils with high plasticity, combined with challenges like water penetration, accelerated distress. Soil can shrink and swell with changes in moisture, affecting the MSE wall and causing pavement distress. Additionally, it was found that the soil under the pavement structure had been washed away, creating voids. Given these findings, a detailed analysis of the data provided valuable insights into potential distress mechanisms. The repair strategy adopted was to replace weak areas with stronger material up to specific elevations above the base of the wall.

4. Conclusions

This Special Issue covers the latest research on fatigue, performance, and damage assessments of concrete. There were 15 papers submitted to this Special Issue, out of which 9 papers were accepted. This Special Issue was divided into three subgroups: two papers on fatigue, two papers on performance, and five papers on damage assessment. Unlike the articles published in past Special Issue, our Special Issue contains papers that address other structural applications, such as concrete pavement. In particular, six of the articles contained in this Special Issue concentrate on pavement performance and damage assessments, especially in terms of the Pavement Condition Index. In this Editorial, each article was summarized with a brief introduction and a presentation of their keywords, research significance, and potential impacts. The findings presented in this SI will be useful in future efforts to enhance the structural integrity, durability, and performance of concrete materials and structures. As Guest Editor, I would like to acknowledge all the authors for their valuable contributions to this Special Issue.

Conflicts of Interest: The author declares no conflicts of interest.

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