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Study of the structural behavior of High-Performance Concrete bridge decks

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ORIGINAL RESEARCH PAPER

ABSTRACT

The manufacture of High-Performance Concrete (HPC) in bridge deck construction is part of an experimental framework that is also developing in the numerical domain to fill the existing gaps in understanding its behavior. However, the numerical modeling of HPC for bridge decks remains largely under-explored. It is precisely this gap that has sparked our interest in this research area, thus giving our work its innovative character.

This study primarily aims to deepen the understanding of the behavior of HPC bridge decks while manufacturing an efficient and economical HPC using local materials possessing very high properties (mechanical, physical, elastic, durability, and implementation) and advanced numerical modeling. This modeling has enabled us to study the behavior of HPC bridge decks in relation to cracking through the Extended Finite Element Method (X-FEM), an innovative solution that enables the modeling of discontinuities without complicating the process. This has been confirmed by the quality of the results, which show an excellent correlation with experimental data, underscoring the accuracy of the modeling. These results also reveal that the use of HPC in bridge construction can significantly reduce degradation risks while enhancing their performance. Consequently, the adoption of HPC stands out as a beneficial strategy, not only to minimize bridge degradation but also to extend their durability.

KEYWORDS

HPC, bridge deck, behavior, modeling, cracking

1. INTRODUCTION

High-performance concrete (HPC) stands out as a superior alternative to traditional concrete, especially in the context of bridge construction. HPC offers a range of benefits that extend beyond its basic mechanical strengths, primarily due to its exceptional resistance to cracking. This quality significantly boosts its structural integrity and durability over traditional concrete.

The inherent properties of HPC, including enhanced durability, mechanical strength, and longevity, address many issues associated with conventional concrete. These characteristics are vital for bridges that face various stressors such as vehicular loads, wind pressures, thermal changes, and seismic activities. The ability of HPC to maintain its structure under such conditions is largely due to its low water permeability, which minimizes the risk of cracks forming.

Additionally, the HPC formulation, which incorporates special materials and construction techniques, not only improves its resistance to environmental and mechanical stress but also elevates the overall quality of road infrastructure. The use of HPC in bridge decks leads to improved performance, resulting in safer, more resilient, and cost-effective structures over their lifetime [1, 2].

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Bridge decks made from high-performance concrete are more resistant to mechanical stress, cycles of freezing and thawing, and chemical attacks, as well as mechanical stress due to the use of specific components and advanced manufacturing processes. They are also more resistant to chemical attacks, such as those caused by de-icing salts used on roads. Further, they are smooth and uniform in appearance, which reduces vehicle wear and enhances safety on roadways [3].

The integration of these innovative decks can significantly increase the lifespan of infrastructure, reduce maintenance expenses, and provide a lasting solution to the ever-increasing demands of urban mobility [2, 4]. Furthermore, their flexible design allows for meticulous adaptation to the specific needs of each project. This allows for the creation of custom structures suited to the most sophisticated or unique bridge configurations.

Moreover, the appearance of cracks is significant in evaluating the performance of decks, especially those intended for bridges. Due to this reality, several techniques have been developed for the numerical modeling of bridges. Among these techniques, the Finite Element Method (FEM) offers numerical solutions adapted to various structures. Several researchers have applied this method to bridge decks, such as Mabsout et al. (2000) [5], Thiagarayan and Roy (2005) [6], Zanjani Zadeh and Patnai (2014) [7], Lantsoght and al. (2019) [8], and Aminu et al. (2020) [9]. Based on these studies and after examining the causes and remedies for deck ruptures, the main findings indicate that subsidence, erosion, and cracks are the most common problems.

Recently, the numerical modeling of concrete decks designed for bridges has been addressed by several researchers, such as Cajka et al. (2020) [10], Zhu et al. (2020) [11], and Yepes-Bellver et al. (2022) [12]; in these studies the FEM is still used to model decks.

In all these research works, the modeling did not take into account the cracking in the decks, which has a very important and critical effect, especially on the bridges. That is why, in this research work, we will use the method of extended finite elements (X-FEM) to model this cracking in the bridge decks. This method is widely used in various fields, such as geomechanics for modeling slope stability and also in the field of civil engineering, such as the modeling of road cracks, which is detailed in Nehar et al. [13].

The purpose of this research is to conduct an experimental study to determine how HPC can be manufactured both efficiently and economically using local materials and to model and evaluate the behavior of bridge decks using extended finite element methods (X-FEM). The modeling takes into account cracks that present one of the most dangerous modes of degradation in bridges. This allowed us to propose using HPC to minimize this degradation since HPC has excellent strength and durability, which therefore reduces maintenance costs; it can also provide better conditions for bridge decks, and this indicates our originality.

2. USED MATERIALS

2.1. Cement

The cement used is CPJ-CEM II/42.5A (Algerian).

2.2. Aggregates

The gravels used are crushed limestone. They belong to classes 3/8 and 8/15 and have a specific weight of 2.65, an impurity level of 3.70%, and a moisture content of 0.3% with a Los Angeles coefficient of 19%. The sand has a specific weight of 2.70 and a fineness modulus of 3.2.

2.3. Additive

The additive used is a local superplasticizer named “MEDAFLOW30”. It is a solution of polycarboxylates with a 30% dry extract, is yellowish in color, and has a pH of 6–6.5.

2.4. Fillers

Three fillers were used:

2.4.1. Limestone. The limestone used is a crushed rock in the form of pebbles with a granularity of 20/100 mm, a SSA of 11,000 $cm^2\ g^{-1}$ (after grinding), and is mainly composed of calcite ($CaCO_3$).

2.4.2. Tile polishing waste. We have reused this waste as a filler in order to recycle this polluting waste. This material consists of grey cement (23%), and crushed limestone (77%). This filler is characterized by a very low presence of harmful elements and a SSA of around 9,000 $cm^2\ g^{-1}$.

2.4.3. Crushed dune sand. This is dune sand, characterized by its real bulk density of 2.43 and a SSA of 8,230 $cm^2\ g^{-1}$. Chemical analysis shows that its nature is siliceous (94.51% silica “SiO_2”).

3. EXPERIMENTAL STUDY OF HPC SAMPLES

3.1. Concrete composition

The development of the concretes aimed to achieve a two-phase mixture: a concrete resembling, as closely as possible, a massive rock with the lowest porosity, composed of the inert skeleton (gravel and sand) determined by the Dreux-Gorisse method, while optimizing the maximum diameter of the coarse aggregates [14]. Meanwhile, the second phase consists of the binding paste (cement, superplasticizer, water, and additions). This was optimized through experimental grouts [15].

The final compositions of the four concrete mixtures used after optimization are reported in Table 1.

The test specimens were manufactured in accordance with current standards, including mixing and compaction processes. They have various geometries suitable for the specific tests to be conducted, with dimensions of 10 × 10 × 10 cm^3

Table 1. Final compositions of the used concretes

Components	Concrete			
	RC	LCC	TPWCC	DSCC
Superplasticizer (1.5%)	0	25	25	25
Water/Binder	0.50	0.26	0.26	0.26
Cement (kg m^{-3})	450	404.5	382.5	382.5
Sand (0/5) (kg m^{-3})	670	670	670	670
Gravel (3/8) (kg m^{-3})	200	200	200	200
Gravel (8/15) (kg m^{-3})	905	905	905	905
CPJ42.5 + 10% Limestone (kg m^{-3})	–	45.5	–	–
CPJ42.5 + 15% Tile Polishing Waste (kg m^{-3})	–	–	67.5	–
CPJ42.5 + 15% Dune Sand (kg m^{-3})	–	–	–	67.5

and $10 \times 10 \times 40\,cm^3$. After demolding, they are stored in water at 20 °C.

The following abbreviations are used:

HPC: High-Performance Concrete
RC: Reference Concrete
LCC: Limestone-Crushed Concrete
TPWCC: Tile Polishing Waste Crushed Concrete
DSCC: Dune Sand Crushed Concrete
SSA: Specific Surface Area (Blaine)

4. RESULTS AND DISCUSSION

4.1. Compressive mechanical strength

Figure 1 illustrates the results obtained at room temperature for concrete aged 28, 90, and 270 days. It appears that for a Water/Binder (W/B) ratio of 0.26, concretes made with CPJ 42.5 cement incorporating 10% limestone fines, 15% tile polishing waste, and 15% dune sand exhibit remarkable mechanical properties.

The compressive strength of the concrete with these additions is approximately twice that of ordinary concrete.

The compressive strength of concrete is primarily influenced by three key factors. Firstly, the choice of additives plays a crucial role, especially in terms of type and quality. Secondly, the use of very fine additions also contributes to this increase in strength. Thirdly, and perhaps most importantly, is the reduction of the water-to-cement ratio (W/C). This last factor promotes the formation of internal hydration products characterized by an extremely fine texture, resembling a compact phase of an amorphous nature.

It is interesting to note that the increase in strength appears to follow an almost linear trend. This means that over periods of 28, 90, and 270 days, the hydration process continues with almost the same intensity as observed in the initial days. This consistency could be attributed to the curing method applied to the concrete, which seems to play an essential role in maintaining hydration activity over long periods.

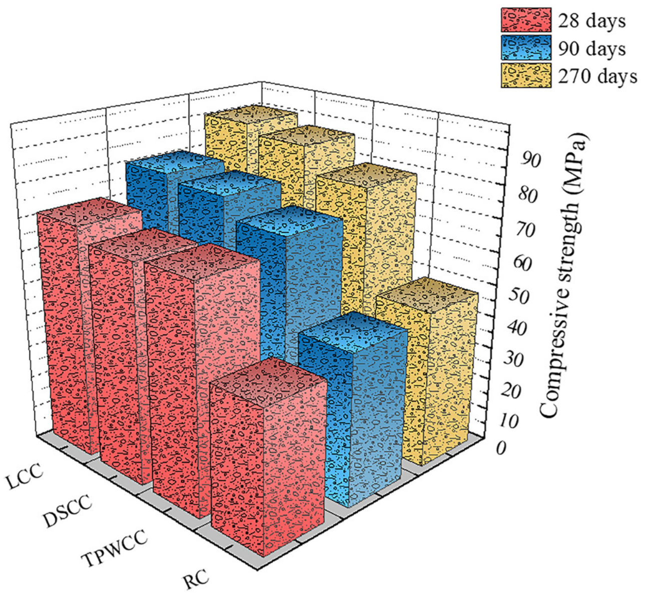

Fig. 1. The compressive strength of concrete

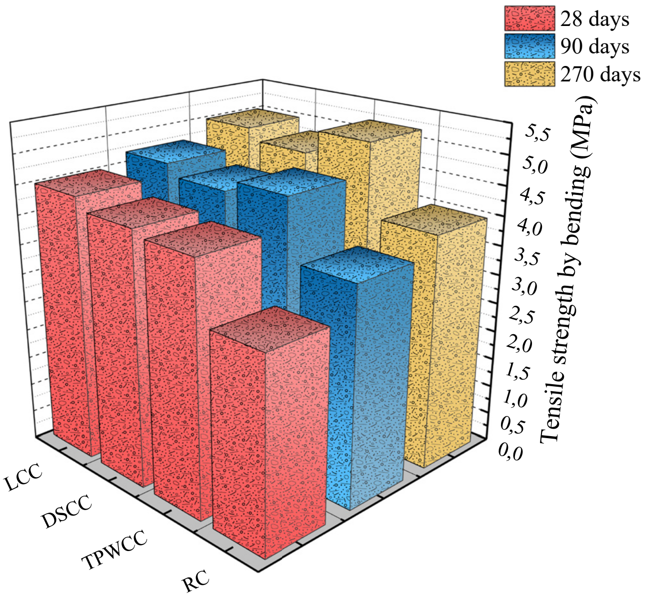

Fig. 2. Flexural strength of concretes

4.2. Flexural strength

The method used to determine flexural strength is bending traction. The specimens, measuring 10 × 10 × 40 cm^3, were stored in water at a controlled temperature of 20 ± 2 °C in the laboratory until the age designated for testing. The results obtained are illustrated in the Fig. 2.

The data indicates that achieving a strength threshold of 5.3 MPa in 28 days is challenging, even with the presence of a superplasticizer. The highest tensile strength at this age was observed in limestone concrete (LCC + 10%), reaching 5.3 MPa. This represents an improvement of 27% compared to the reference concrete (RC/0.5). For DSCC concrete, an increase of 15% was recorded, and 19% for TPWCC concrete.

It is also observed that the trend in the variation of flexural strength is similar to that of compressive strength. Over a period of 2 years, the strength of concrete with additives proved to be higher than that of the control concrete.

Note: Data collected revealed that the addition of limestone filler significantly increased strength after 28 days. Consequently, this value has been specifically chosen to be integrated into our future studies, due to its positive impact on the properties of materials.

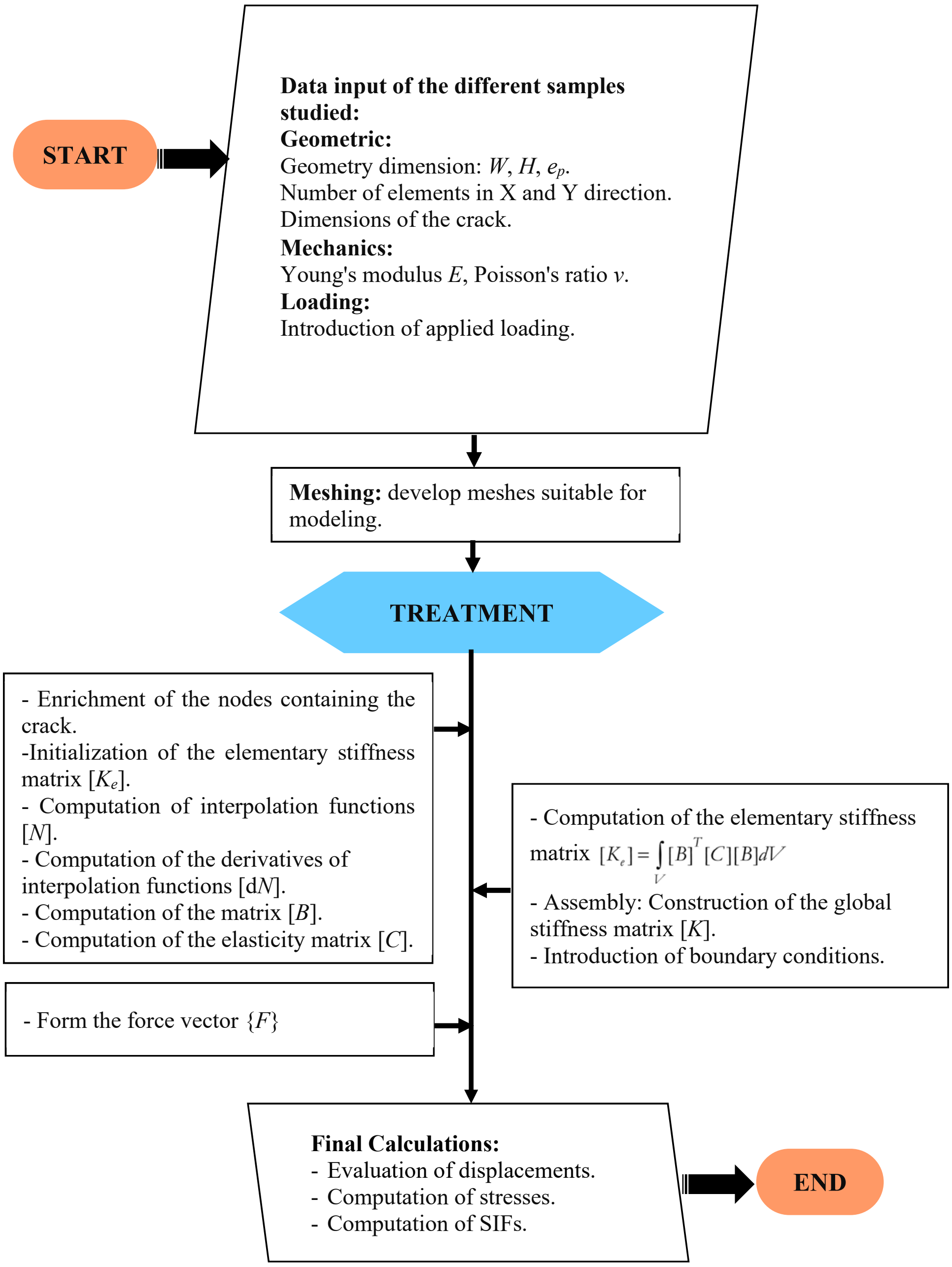

Fig. 3. Flowchart of numerical modeling

5. NUMERICAL STUDY OF HPC SAMPLES

5.1. Finite element modeling

The HPC samples were modeled using the FEM method, which aimed to determine their maximum compressive and flexural tensile strength at 28 days. The modeling of these samples is inspired by the work of Nehar et al. [16, 17].

As for the modeling of cracks observed on these samples, the extended finite element method (X-FEM) was preferred. The key steps of this method are detailed in the work of Nehar et al. [16], which can be summarized as follows:

Introduction of data: integration of the geometric and mechanical properties of the different samples studied.

Crack type: identifies the type of crack, whether edge, central, or other.

Crack characterization: accurately defines crack dimensions, including crack length and inclination angle.

Load: a specification of the nature and value of an applied load.

Meshing: develop meshes suitable for modeling.

Enrichment: specific enrichment of the nodes affected by the presence of cracks.

Elementary stiffness matrix: computation of this matrix, which is crucial for modeling.

Assembly: a combination of components to obtain the global stiffness matrix.

Boundary conditions: integration of restrictive or specific conditions.

Force vector: development of the vector that represents the forces in play.

Final calculations: evaluation of displacements, stresses, deformations, and the stress intensity factor.

These steps are also presented in this flowchart (Fig. 3):

5.2. Application example

As part of our study, HPC bridge decks were modeled using our computational code. Initially, HPC samples were designed to evaluate the maximum compressive strength. These samples have dimensions of $W \times H \times e_p = (10 \times 10 \times 10)\ \text{cm}^3$. They were subjected to compression simulating experimental conditions. The mesh chosen for these samples is quadrangular, with a density of 100 × 100 elements. It should be noted that plane strain conditions were assumed, as shown in Fig. 4.

Subsequently, we modeled HPC beams to estimate their tensile strength induced by bending. These beams have dimensions of $W \times H \times e_p = (40 \times 10 \times 10)\ \text{cm}^3$ and were tested under four-point bending, as illustrated in Fig. 5. A similar quadrangular mesh with a density of 400 × 100 was employed.

Table 2 summarizes the mechanical properties of the material studied:

During this section, we have taken into consideration two distinct case studies. The first aims to compare the compressive and flexural tensile strengths after 28 days with the results obtained experimentally. The second aims to examine the cracking behavior of HPC decks, specially designed for infrastructure like bridges. The studied bridge decks have precise dimensions of $W \times H \times e_p = (160 \times 20 \times 45)\ \text{cm}^3$, as illustrated in Fig. 6(a). It is important to emphasize that these dimensions are drawn from the literature [19].

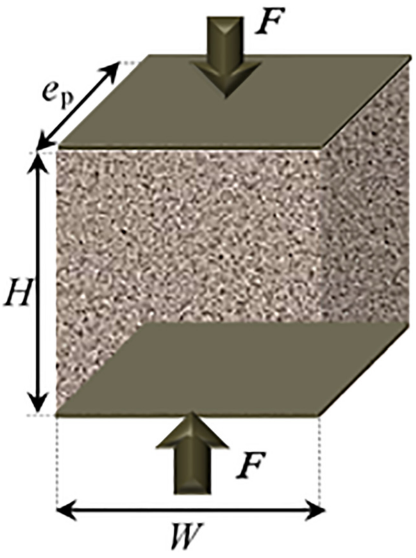

Fig. 4. Geometry of the studied HPC samples

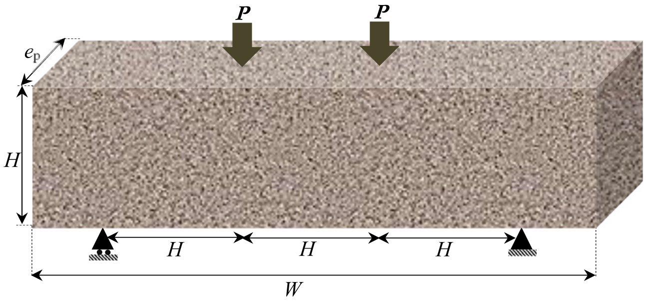

Fig. 5. Geometry of the studied HPC beams

Table 2. Mechanical characteristics of the concretes used during this study [18]

	Elastic Modulus E (MPa)	Poisson Ratio ν
Reference Concrete (RC)	35×10^3	0.20
High-Performance Concrete (HPC)	45×10^3	0.24

In the context of crack analysis, a crack of length "c" has been artificially introduced into the decks. In one of the scenarios, this crack is located at the edge, while in the other, it is located at the center, as illustrated in Fig. 6(b).

5.3. Results and discussion

The HPC samples were numerically modeled using our calculation code. In order to verify the relevance of our program, a comparison was made with results from experimental studies.

5.3.1. 28-day compressive strength. Figure 7 shows a comparison of the 28-day compressive strengths, from both the experimental perspective and the numerical prediction via the finite element method, for samples of concrete commonly used in bridges and HPC incorporating limestone filler (LCC).

It is worth noting that, similarly to the findings of Nehar et al. [16] regarding the 28-day compressive strength, the results generated by our calculation code are in remarkable agreement with the experimental measurements.

5.3.2. 28-day flexural tensile strength. A comparative analysis was conducted between the flexural tensile strengths obtained experimentally and the numerical estimations provided by FEM. Figure 8 depicts this comparison for all the beams studied.

Following this comparative analysis, it is evident that the results derived from our calculation code closely match the experimental results for all the beams examined.

5.3.3. Study of the behavior of HPC bridge decks. The behavior of HPC bridge decks is fundamentally linked to understanding the initiation of cracks within these decks, which reduces their mechanical strengths to the point of causing premature failure, potentially leading to serious consequences. To prevent such outcomes, it has become necessary to consider the phenomenon of cracking during the design of structural elements. For this reason, a study on the presence of cracks is proposed for the same previous application. This study was mainly carried out to suggest the use of a new type of concrete to minimize the cracking of bridge decks.

Figures 9 and 10 illustrate the values of Stress Intensity Factors (SIF) obtained for a bridge deck presenting a crack. These SIFs are evaluated for either an edge crack or a central crack, considering different lengths (c = 4 cm, c = 8 cm, c = 12 cm, c = 16 cm).

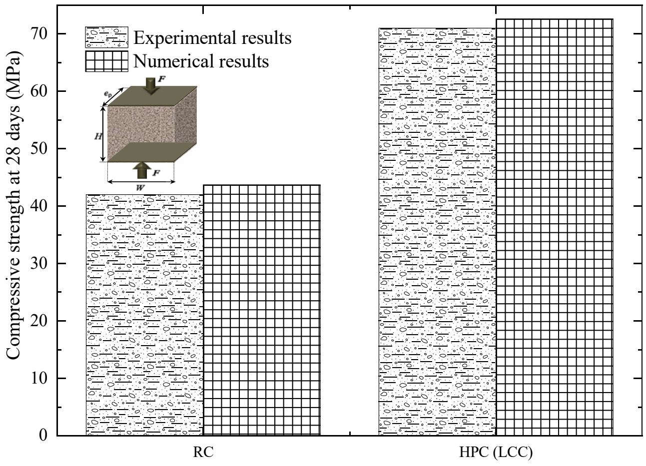

Fig. 7. Comparison of 28-day compressive strengths between experimental and numerical studies of samples

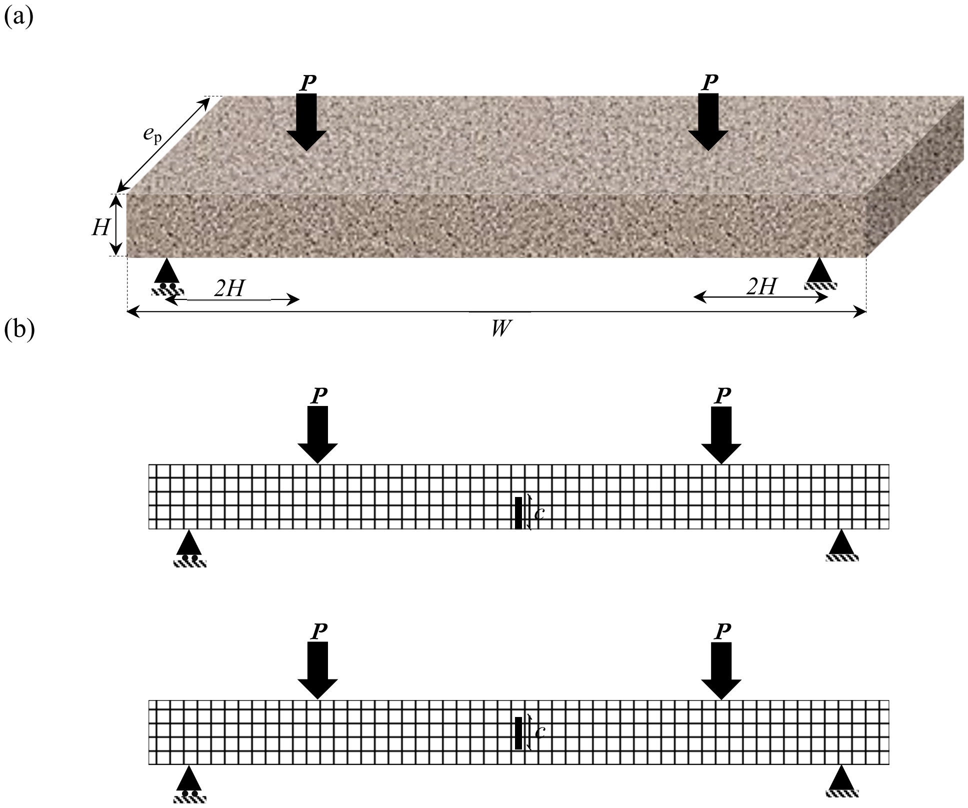

Fig. 6. (a) Geometry of the analyzed bridge deck; (b) Modeling of the deck presenting a crack

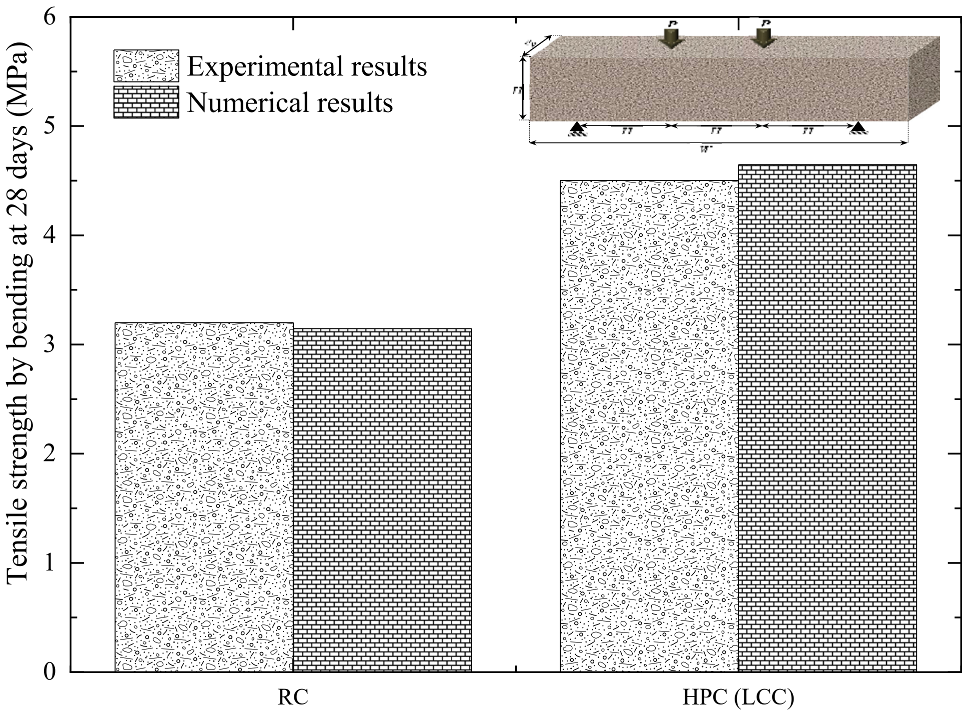

Fig. 8. Results of the 28-day flexural tensile strength from experimental and numerical studies of the beams studied

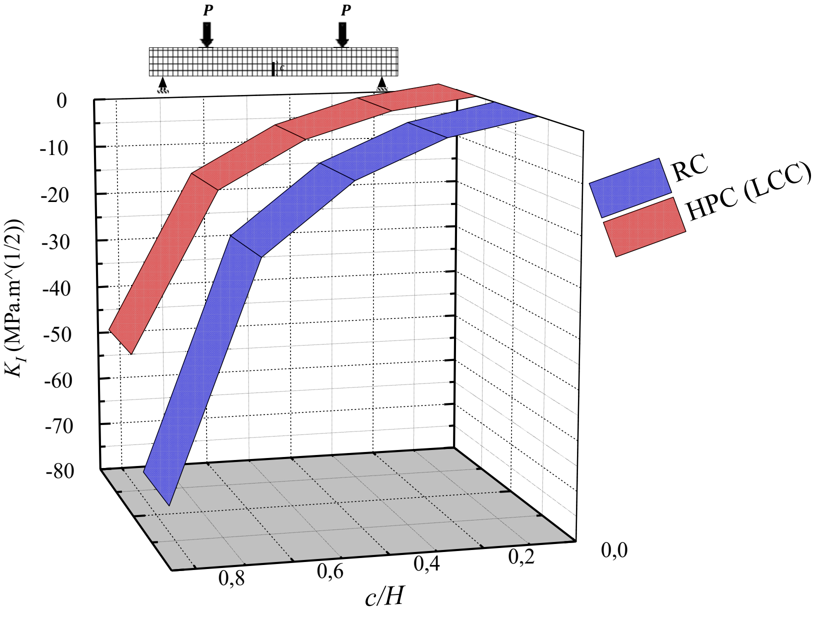

Fig. 9. SIFs in Mode I as a function of *c/H* for a concrete bridge deck with an edge crack

The examination of the data illustrated in Figs 9 and 10 highlights that the stress intensity factor (SIF) for concrete decks commonly used in bridge construction exceeds that of high-performance concrete decks. To illustrate, consider a central crack with a *c/H* ratio of 0.20: the SIF for Reference Concrete (RC) is estimated at $(-1.9664\,\mathrm{MPa}\sqrt{\mathrm{m}})$, whereas it stands at $(-1.3765\,\mathrm{MPa}\sqrt{\mathrm{m}})$ for High-Performance Concrete (HPC) incorporating limestone filler (LCC) under the same conditions. In fracture mechanics, a lower SIF suggests a reduced material tendency for crack propagation under an equivalent load, a highly desirable trait for materials used in bridge construction. The lower SIFs observed for HPC thus indicate its superiority in terms of resistance to crack propagation, a property undoubtedly related to its specific composition, which fosters a more compact and uniform internal structure, thereby strengthening its capacity to withstand tensile forces and cracking. These results underscore the effectiveness of HPC, which seems to

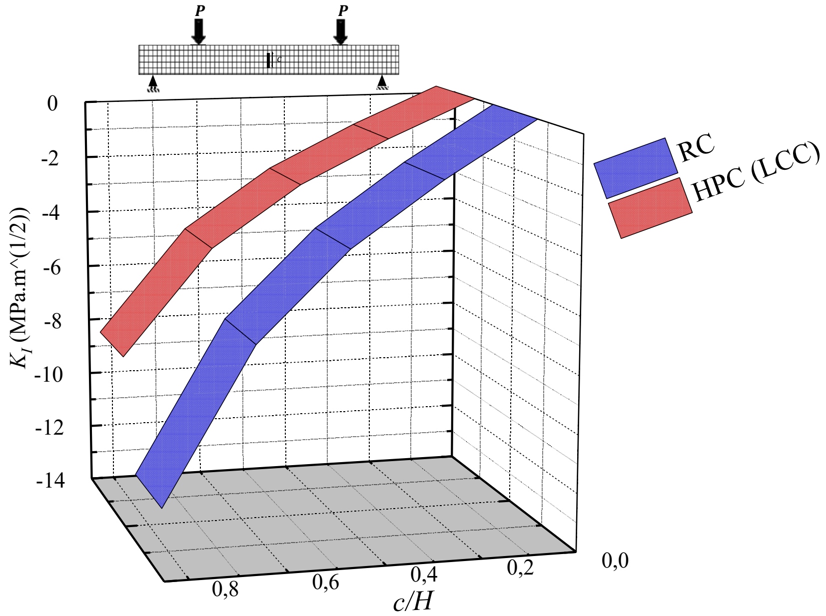

Fig. 10. SIFs in Mode I as a function of *c/H* for a concrete bridge deck with a central crack

promote the better performance of bridge decks against cracking.

It is also important to emphasize that the SIFs associated with an edge crack are consistently higher than those from a central crack. Take for example, the HPC where the SIF reaches ($-1.3765\,\mathrm{MPa}\sqrt{\mathrm{m}}$) for a central crack and ($-2.6041\,\mathrm{MPa}\sqrt{\mathrm{m}}$) for an edge crack, as demonstrated in Figs 9 and 10. Indeed, an edge crack affects two surfaces of the material, thus posing a greater threat to structural stability compared to a central crack that only partially propagates through the material. The higher SIFs for edge cracks signal a greater potential for energy release if the crack propagates, meaning that these pose a higher risk and should be more rigorously monitored.

6. CONCLUSION

The work presented in this article delves into the analysis of the behavior, both experimental and numerical, of bridge decks made of high-performance concrete (HPC). The conclusions drawn from this study are summarized as follows:

1. There is a possibility to manufacture HPC using simple means, which can achieve strengths exceeding 80 MPa at 28 days with adequate plasticity.
2. The production of HPC with high strengths and low complexity can be emphasized as an important step in the process of making building materials.
3. The limestone concrete has demonstrated excellent mechanical properties due to its very high compactness.
4. The superplasticizer used in the production of concrete plays a crucial role in improving the mechanical strength as it reduces the porosity of the concrete.
5. The focus on the beneficial effects of specific materials, including as superplasticizers and limestone additions, on the mechanical characteristics of HPC provides valuable data for improving concrete mixtures in order to increase the strength and durability of structures.
6. From the perspective of numerical modeling, a significant correlation has been observed between the 28-day compressive and flexural tensile strength results obtained from our computational model and those derived from experimental tests, especially for HPC incorporating limestone filler (LCC).
7. Regarding the cracking of HPC bridge decks, it was demonstrated that the SIF is lower than that of decks made of traditional concrete, suggesting that HPC is potentially less susceptible to hazards and could enhance bridge performance, particularly in the context of crack appearance.
8. The study proved the utility of numerical models in developing more robust structures by establishing an excellent relationship between experimental and numerical results, in addition to confirming the validity of these models in predicting the performance of HPC.
9. The integration of HPC in the construction of bridge decks proves to be a beneficial strategy for reducing their degradation and extending their durability.
10. Evaluating the susceptibility of HPC to cracking and its potential to improve bridge performance and durability constitutes a significant practical contribution, offering practical methods for material selection in crucial applications.
11. It is essential to select appropriate materials when designing structures subjected to repetitive loads or adverse environmental conditions that can induce cracking. HPC thus stands out as a wise choice in such applications.

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