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Editorial

Advances in Road Engineering: Innovation in Road Pavements and Materials

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The road pavement sector is currently gaining more and more attractivity as a peculiar field of civil engineering. This takes effect considering the high extent of roads in the urban and non-urban texture, as well as the high importance of road systems as a distinctive part of an infrastructure's network that is improving in terms of competitiveness, adaptivity, functionality and global interconnection. Thus, higher and higher investments are going to be allocated towards the pavement engineering field by governments, public and private agencies, contractors, etc. Not least, the related sector became of actual interest in view of the present perspectives related to sustainability, the targets of which aspire towards innovative technical, societal, economic, and environmental frames for smart and integrated mobility and management, climate-neutral policies, and solutions. Within them, the topic of eco-friendly materials and structures promptly emerges, considering the well-known themes about recycling, since environmental and economic benefits due to low-impact materials, waste reuse, saving of finite natural resources, disposal reduction, and pollution mitigation are widely documented. In turn, innovation in pavement engineering is progressing towards a sustainable circular economy apprising certain energy and climate advantages. In this context, the significant research efforts that have been and are still spent by academies, authorities, agencies, etc. (see the huge investments often allocated to R&D departments of certain institutions), are promoting progressive advances and innovations in civil and pavement engineering. This regards improvements about a wide range of applications in road pavements, such as for instance the materials' design, optimization and testing, the structures' design, construction operations and practices, the utilization of innovative/recycled materials, the maintenance optimization and the increase in the durability, the management of investments and the intervention plans, the pavement management systems, and many more. Given this trend, the present Special Issue aims at collecting high-value scientific contributions while spreading advanced technical knowledge about all the mentioned areas by dealing with innovative, smart, eco-friendly road pavements addressed to the general sustainability of the road construction industry.

Based on the current state-of-the-art, countless articles about the presented arguments can be cited in the scientific productions of the last years and decades. However, given the current speed of technological progress (materials and technologies, laboratory and real-scale tests, analysis methods, investigation techniques, data science, etc.), further advancements for high-value scientific production must be actually promoted: this is the principal objective of the present Special Issue. As conceived, this Special Issue takes charge of digging out the majority of the above-discussed topics. This is developed through multiple investigation approaches that, from the strictly scientific point of view, couple more conventional applications (laboratory and field testing) with innovative smart assessment techniques (artificial intelligence, machine learning, digital image processing, etc.).

Innovation in materials for paving can be in regard to several technical improvements; e.g., related to the upgrade of binder performance, the enhancement of lithic skeleton

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properties for the aggregate portion of mixture, the design and implementation of new additives and modifiers, the optimization of the mixture constituents to obtain satisfactory structural characteristics of the pavement layers, etc. A multi-scale analysis approach (evaluating the responses of binders and other constituents, mastics, mortars, and mixtures) is advised to comprehensively investigate the rheological properties and the mechanical behaviors of modified bituminous mixtures for the manufacturing of flexible pavements, studying the materials at different scales with overall consideration of performance under several environmental in-service conditions (temperature, weather, climate, etc.). In this sense, based on the SI content, the viscosity concerns of asphalt concretes are discussed thanks to advanced laboratory testing regarding high- and low-temperature performance of high-viscosity modified asphalt binders [1]. These are studied since the higher viscosity is beneficial to bonding force and adhesion to aggregates, allowing an efficient binder to be adopted in several innovative asphalt mixture types (porous asphalt, stress absorption layers, overlays, etc.), included recycled ones. Specific recommendations are given in terms of binder testing details (rheological indexes for performance evaluation) to identify suitable high-viscosity modified bitumen. Other modifiers for asphalt pavements are investigated in this SI, proposing the integration of epoxy resin and crumb rubber powder in polymer-modified asphalt binders. Here, a styrene–butadiene–styrene bitumen (inclusion of synthetic polymers to confer elastomeric and thermoplastic properties, produced through sequential polymerization operations) is modified to reduce the conventional binder and promote the recycling of waste materials. Epoxy resin is primarily used in the pavement industry to improve the flow and permanent deformation resistance thanks to the crosslinked structures formed during the manufacturing process. When using diluents, fillers, curing and toughening agents in combination with the polymeric structure of epoxy resin, great resistance to fatigue, moisture and oxidation aging can be conferred to the mixture also. The use of crumb rubber powder allows tires which have reached their end-of-life to be recycled for productive outcomes, rather than sent to landfill where they are often burned. Crumb rubber within asphalts enhances their durability, promotes noise absorption while improving the driving comfort, increases resistance to weather-related stress and confers flexibility and skid resistance to upper pavement layers. Based on research included in this SI, conventional asphalt concrete pavements are deteriorating rapidly due to the current increased traffic and extreme climate impacts. In addition to the upgrading in the construction quality, there is an urgent need to expand the utilization of modified asphalt binders to improve road capacity and traffic safety. This study envisions the incorporation of such modifiers to improve the road capacity with traffic safety purposes, being pushed by the current increase in traffic and the extreme climate impacts [2]. The analysis provides various laboratory rheological tests to measures the performance of modified mixtures, which are furtherly assessed via bearing capacity field trials. The strain accumulated by the control reference mix can be strongly reduced when adding modifiers thanks to improved stiffness and resistance to permanent deformations.

This SI also makes high-value contributions to the topic of reclaimed asphalt pavement recycling (RAP). This technique is used in asphalt pavement reconstruction and rehabilitation with several maintenance techniques (hot, warm, or cold recycling, in-site and in-plant recycling, etc.). RAP permits to achieve sustainable pavements thanks to cheaper alternatives to virgin bituminous binder and natural aggregates, while reutilizing end-of-life material that is not discharged to landfills. In general, since the asphalt industry is currently encouraging best practices to maximize the RAP percentage recycling, various technical challenges are arising to counterbalance the difficulties involved in the use of RAP as it is (large degree of aging and oxidizing, high stiffness, brittleness, etc.). The presence of these difficulties can compromise efficient production of good performance asphalt concretes. In this perspective, the refined separation method (set of plant procedures and equipment to integrate the RAP in the asphalt concrete) is deeply analyzed and discussed to evaluate the various effects of the mixing ratio of RAP that reflect on the recycled mixture performance. The related study examines the various technical and operational details of the treatment, assessing the variability of aggregate gradation, the asphalt content, the mix properties and the maximum mixing percentage of the coarse fraction [3]. The outcomes showed that the variability of several parameters is often considerable, but a refined separation process can definitely reduce the gradation variance. Another SI publication dealing with RAP proposes a novel approach to enhance the final performance of recycled asphalt concrete [4]. This consists of integrating an innovative kind of rejuvenator agent into the bituminous mixture, composed of constituents of multiple origins (wax, oil, chemical additive, and water). Based on the abovementioned multi-scale approach, various asphalt concretes are assessed at the small binder-scale and the laboratory mixture-scale (multiple stress creep recovery test, analysis of stiffness and visco-elasticity, study of water resistance and adhesion performance, resistance to cracking and rutting). Thanks to the designed rejuvenator, it is demonstrated how it is possible to obtain superior performance for the modified mixture with respect to common RAP-recycling mixture, while also obtaining a general cost convenience.

With respect to in-site testing, this SI also provides some experiences based on specific case studies in particular field conditions. This is the case of a research dealing with prefabricated prestressed concrete pavements (structural layer manufactured in the factory and transported to the construction site for assembly) [5]. Such a construction technique involves the installation of the prefabricated rigid layers and the following treatment of the joints, achieving fast times for construction or pavement maintenance, low material consumption and carbon emissions, high reusability, and long structural lifespan. It is often preferred for low-speed traffic roads in the urban context, as well as for sidewalk paving. Traditionally, the joint bars (dilatation and expansion) are recognized as a weakness domain of the rigid concrete pavements; these metallic bars must transmit the loads through their own shear and bending stiffness, but they are subjected to rust deterioration and can damage the surrounding concrete portions, leading to cracking, water seepage, and vertical misalignments threatening the driving comfort or the adequate bearing capacity of the whole rigid pavement. The proposed research regards the selection of an innovative joint material that is able to improve the bonding effects between the transfer bars and the prefabricated panels, as well as to prevent the water infiltration and the damage of the layers. The material consists of a steel fiber-reinforced self-stressing concrete. In this case, a preliminary laboratory testing is coupled with a real-time monitoring of the rigid pavement installed at a real intersection open to traffic (long-term outcomes are also provided). Results show that the innovative material can lead to long-term high stability at the joints, overcoming the brittle fracture characteristics of the ordinary concrete. The included steel fibers primarily limit the development of self-stress in the early stage, enabling higher self-stress to be retained in the concrete over the long period to improve the cracking resistance of pavement. Another SI research experience related to in-service conditions regards the ice-melting characteristics of a flexible asphalt pavement treated with slow-release deicing agents [6]. Ice and snow occurring during winter weather lay on carriage surfaces and form a thin film that is dangerous for driving safety, and can also be a primary cause of pavement distress. Various practices are usually employed to clean the surfaces (mechanical plowing, manual sweeping, salt spreading, etc.). However, these methods involve specialized machinery and labor costs and may cause traffic congestion. Thus, a slow-release deicing agent formula is designed as a filler replacement and is tested in the lab, assessing its effectiveness and durability on an asphalt pavement (high-temperature stability, cracking resistance and water sensitivity). The experimental findings indicate a slight reduction in such performance when increasing the deicing agent content (a 50% replacement of conventional filler with deicing agent is identified as the optimum concentration for the purpose). In turn, the modified asphalt mixture limits the interface adhesion between the surface and the ice film, with a maximum release concentration within two hours under rain and snow. The predicted durability of such an asphalt mixture is estimated to be around 5–8 years after paving. An additional in-field case study concerns a composite pavement constituted of a roller compacted cement base layer, over which a two-layered bituminous surface treatment is realized. The proposed structure is designed in Cambodia as a solution for the construction and rehabilitation of rural roads [7]. The research is aimed at gauging the bad status of such local roads, which are often unpaved or distressed, also considering the massive rainfalls that occur locally and, in general, the extraordinary growth in the national light and heavy transportation sector experienced by the country in a recent economical evolution. Several in-place trials (visual inspection of surface conditions, deflectometer for bearing capacity, sand patch test for roughness, noise level) were organized to evaluate the performance of the pavement. Effectively, the proposed composite structure showed superior performance to the existing surfaces, also in the presence of heavy truck vehicles and severe climatic conditions. Advanced analysis techniques in the field are presented in another SI article that deals with the crystallization mechanisms of asphalt mixture in a bridge deck pavement [8]. This research focuses on unknown crystal precipitates and is developed through innovative investigation methods employed in a bridge after paving, during ad hoc closures to traffic (fluorescence spectroscopy, infiltration, porosity and splitting tests, multi-wheel rutting, nuclear-free densitometry, ground-penetrating radar). The precipitation areas are analyzed to explain the influence of crystals on the performance of the asphalt pavement, studying the whole section to understand the crystal formation process. It was found that the main components of crystals are water molecules and machine-made sand, and no significant difference in pavement performance in the areas where crystals precipitated were detected.

A further set of SI publications also involve the adoption of innovative smart analysis techniques applied to several fields of study. This is typically referred to as the machine learning approach, i.e., a branch of artificial intelligence and computer science focused on the managing of data and algorithms to imitate the way that humans learn, ingesting a large amount of unstructured raw data to automatically determine a set of distinguishable features and categories. This method can be leveraged as a cutting-edge technology to address challenges in pavement infrastructure management, ultimately supporting the sustainability and longevity of transportation networks. More specifically, machine learning is used in combination with advanced image detection techniques to predict and detect the reflective cracking phenomenon in some pavement infrastructures [9]. The target of this study concerns the improvement in the predictive capabilities of pavement management systems, seeking to integrate advanced image processing to support real-time monitoring and assessment of pavement conditions. The developed machine learning model is characterized by a high predictive accuracy that can be further incremented through a mask region-based convolutional neural network for image detection. Thus, it can be implemented to reliably detect and monitor the reflective cracking, even across different pavement types and weather conditions. This SI also collects a contribution in which the machine learning technique is used to predict the bearing capacity of the soil (expressed in terms of CBR value) starting from known soil index properties. A model based on the natural gradient boosting algorithm is coupled with artificial intelligence to gap the current lack of reliable probabilistic estimations of soaked CBR values (conventional CBR predictions provide only deterministic results, without accounting for aleatoric uncertainty) [10]. A database of more than two thousand CBR results of different types of subgrade soils is used to instruct the algorithms, obtaining robust predictive indications of the soaked CBR performance with reliable confidence intervals. The method improvement is considered of extreme importance since the bearing properties of the subgrade layers are used as common input parameters for all the dimensioning methods of flexible or rigid road pavements. An algorithm for a finite element analysis is also discussed in a SI publication that investigates the stress–strain transmission and the cracking mechanisms in joints for rigid concrete pavement [11]. Transverse joints are constructed in plain concrete pavements to mitigate the cracking risk caused by shrinkage and temperature dilatations. However, the structural behavior of this kind of rigid pavement can be deeply influenced by the characteristics of the transverse joints that generate discontinuity through cement slabs. For these reasons, steel dowel bars can be installed in the traffic direction to improve the load transfer in the joint proximity (loaded vs. unloaded sides), relieving the slabs from common distresses. The research furnishes a three-dimensional pavement model able to simulate the pavement structural response and the flexural stress concentration in the slab by considering different dowel bar characteristics and configurations (positions and depth, size, bonding properties, etc.). Based on the results, it is possible to establish an optimum configuration for the joint design in the rigid pavement.

In conclusion, it is believed that the contributions given in this Special Issue could be able to move specific and narrow applications to the broader pavement engineering context by exploring many in-depth aspects of materials, structures, construction, and climate. Additionally, it is conceived that the published contents could drive technical future applications, further advancing the actual state of the art and knowledge, laying the foundations for future high-level scientific production regarding road engineering.

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