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a cura di Marina Mistretta, Bruno Mussari, Adolfo Santini

Tecnologie e materiali innovativi per infrastrutture di trasporto più sostenibili

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Le tecnologie e i materiali innovativi possono favorire gli obiettivi contenuti nella risoluzione A/RES/70/1 delle Nazioni Unite.
Le pavimentazioni stradali a bassa rumorosità (ad esempio le pavimentazioni porose, le miscele bituminose con gomma e le pavimentazioni con tessitura ottimizzata) hanno proprietà volumetriche, superficiali (quali drenabilità, tessitura, aderenza e prestazioni acustiche) e proprietà meccaniche che decadono nel tempo. Ciò dipende dalla particolare tecnologia utilizzata e da molteplici variabili. Molti processi e fenomeni sono coinvolti, con conseguenze in termini di sicurezza, rumorosità e budget. Alla luce di questi problemi, gli obiettivi di questo studio riguardano la messa a punto di una metodologia volta a migliorare la progettazione delle principali proprietà di una pavimentazione stradale e in particolare di quelle relative alla superficie. Le proprietà superficiali e volumetriche sono state monitorate, analizzate, in laboratorio e in situ. I risultati mostrano che l'uso di superfici stradali "speciali" (aventi, ad esempio, bassa emissione di rumore) può aumentare la durata complessiva della pavimentazione e che il metodo messo a punto può migliorare notevolmente la sostenibilità complessiva delle infrastrutture di trasporto, raggiungendo alcuni degli obiettivi indicati nella risoluzione A/RES/70/1.

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Innovative Technologies and Materials for More Sustainable Transportation Infrastructures

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The United Nations Resolution, A/RES/70/1[1], 21 October 2015, adopted by the General Assembly on 25 September 2015, includes seventeen main "Sustainable Development Goals". Furthermore, innovative technologies and materials for more sustainable transportation infrastructures include low-noise road pavements (for example porous asphalt concretes, asphalt rubberised mixtures, and texture-optimised pavements) and innovative technologies for the transportation infrastructures for the future. The above-mentioned innovations can lead to improvements by referring to the following A/RES/70/1 Goals (tab. 1).

Discussion of Several Prospective Developments

Hot mix asphalts (HMA) (including Open-Graded Friction Courses (OGFC), Stone Matrix Asphalt (SMA), and fine- and coarse graded dense mixes, etc.) are expected to perform over extended periods of time under a variety of traffic and environmental conditions, but their properties decay

1. Un General Assembly 2015.

A/RES/70/1 goals	Innovative technologies and materials contribution
Goal 3. Ensure healthy lives and promote well-being for all at all ages.	Reducing noise through porous asphalt concrete, and reducing Particulate Matters (PMs) through better pavements and vehicles.
Goal 9. Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation. Goal 11. Make cities and human settlements inclusive, safe, resilient and sustainable. Goal 12. Ensure sustainable consumption and production patterns.	Reducing the consequences deriving from flash floods though high-permeable friction courses and improving the resilience of transportation infrastructures.
Goal 11. Make cities and human settlements inclusive, safe, resilient and sustainable.	Reducing vulnerability acting on the minimization of water runoff through high-permeable friction courses.
Goal 13. Take urgent action to combat climate change and its impacts.	Reducing the urban heath island effect through the use of permeable pavements.

Table 1. How Innovative technologies and materials match 2030 agenda United Nations A/RES/70/1 (Author's own compilation).

over time affecting safety, quietness, and budget[2]. One of the possible solutions, the porous asphalt, was developed in 1967 in Great Britain to solve the hydroplaning problem. Porous pavements are used throughout the world, most commonly in Europe and the United States[3]. They are commonly referred to as Porous Asphalt (PA), Porous Concrete (PC), Open-Graded Friction Course (OGFC), or permeable friction course (PFC), and their performance is influenced by the high Air Void content

2. Praticò, Ammendola, Moro 2010.

3. Charbeneau, Barret 2008.

(AV). Porous asphalt mixtures have an air voids content (18-24% for wearing layer, and 24-28% for bonding layer), which is greater than typical mineral-asphalt mixtures (3-8%)[4]. This result is obtained because of the aggregate gradation. This has many advantages and benefits such as improving the surface drainability and wet skid resistance, minimizing hydroplaning, reducing splash and spray, improving visibility (wet conditions) and, finally reducing noise levels between the tyre and the road surface[5].

Reducing Noise and Particulate Matters (PMs) through Porous Asphalt Concretes

At a constant vehicle speed, quiet asphalt pavements contribute to reducing the noise of 3-6 dB compared to a conventional pavement (3 dB roughly corresponds to halving the traffic volume). For instance, Olszacki[6]found that at a speed of 80 km/h, the noise from a passenger car on Hot Mix Asphalt (HMA) and Stone Mastic Asphalt (SMA) pavements was comparable (about 75 dB), while on porous asphalt it was about 70 dB, which is about 5 dB less. Low-noise road pavements can be obtained acting on: i) air void content (> 15%, reduction of air pumping mechanisms and air resonance, reduction of the horn effect, and resonance mechanisms); ii) thickness of the layers; iii) shape, interconnection and size of the air voids (related to maximum aggregates' size and degree of compaction).

The main disadvantage of porous pavement refers to the "clogging" effect due to sand and dust that obstruct the air voids[7] and cause the long-term loss of sound absorption. Possible solutions are: 1) periodic cleaning; 2) the improvment of the mixture design (gradation); 3) the use of two-layer asphalt mixtures or gap-graded thin overlay. In the gap-graded thin overlay (15-25 mm), discontinuous gradation (gap-grade) aggregates guarantee the porosity necessary to properly convey water and dust[8].

In recent decades, Asphalt Rubber (AR) has been proposed as a material for "silent" pavements. AR is a type of asphalt mixture containing rubber from recycled tires. AR can be produced using two methods: i) the"dry" method (rubber used as aggregates); ii) the "wet" method (rubber melted in the bitumen, a.k.a. asphalt rubber).

4. Andrès-Valeri *et alii* 2016.
5. Koshy, Sachdeva, Sreedevi 2015; Bichajło, Kołodziej 2018.
6. Olszacki 2006.
7. Tan, Fwa, Han 2003.
8. Canestrari 2019.

Poro-Elastic Road Surfaces (PERS) are made with rubber granules (40-95% by weight), mixed with a bituminous or synthetic binder, obtaining 25-40% of residual voids. PERS allow for the reduction of traffic noise because they are mechanically "elastic" and acoustically porous. Despite these advantages, some problems related to flammability and adhesion to the substrate have to be solved. Another example of a "quiet" material is the bituminous mixture containing expanded clay (i.e, a light and artificial aggregate in the form of spherical rough granules having a cellular type structure). The expanded clay is introduced as an aggregate with dosages of about 15% in weight, which produces a better sound absorption, a possible reduction of the vibrations, the improvement of the skid resistance because of a finer texture[9], and the reduction of virgin resources.

Porous asphalt pavements are linked to environmental protection. They recharge groundwater and improve runoff water quality by significantly decreasing heavy metals, mineral oils, nutrients, and other soluble and anthropogenic pollutants[10]. It is important to note that the contact between the tyre and the road surface causes shears in the tyre[11] and this results in the generation of wear particles. The amount and size of the particles released depends on the climate (temperature), the composition and the structure of the tyre, the road surface, the driving speed and style, and the nature of the contact (e.g., rolling versus slipping). Among traffic-related particles, a part is generated from non-exhaust traffic related sources such as brake, tyre, and clutch. Road surface wear already exists in the environment as deposited material and becomes re-suspended due to traffic induced turbulence[12]. On average, the Road Wear contribution to $PM_{2.5}$ is about 45% (8.8 $\mu g/m^3$) while it is about 54% (16.8 $\mu g/m^3$) for PM10[13].

The problems related to the PMs can be partly faced using the Permeable Friction Courses above (PFC)[14]. During storms, the rainfall infiltrates into a PFC pavement, it is filtered (especially suspended solids and other pollutants associated with particles), and it is conveyed along the boundary with the underlying conventional pavement to the edge of the road (the hard shoulder). To be more precise, filtering occurs when pollutants become attached to the PFC matrix by straining, collision, and other processes. Literature shows that concentrations of total suspended solids from PFC (i.e. total

9. Masad *et alii* 2007; Praticò, Vaiana 2015.

10. Yao, Chen 2012.

11. Kole *et alii* 2017.

12. Grigoratos, Martini 2014.

13. Denby *et alii* 2013; Amato *et alii* 2014; Weinbruch *et alii* 2014, Panko *et alii* 2019.

14. Eck *et alii* 2012.

suspended solids (TSS), total Kjeldahl nitrogen (TKN), chemical oxygen demand (COD), and total metals like copper, lead, and zinc) are approximately 90% lower than in runoff from conventional pavements[15].

Improving Resilience and Reducing the Consequences Deriving from Flash Floods though High-Permeable Friction Courses

Unbridled urbanization, demographic growth and climate changes have been identified as the main causes of the significant rise in flood event risk. Poorly maintained drains may concur to minimize the drainability of the infrastructures and produce, during storms, an instantaneous runoff and flash flooding[16]. Anyhow, in extreme weather events, traditional rainwater management systems and existing defence structures for flooding have been proven to be ineffective, and unable to mitigate the problem[17].

In contrast, in terms of risk management, a certain resilience is requested. The latter is defined as a system's ability to continue to function at an acceptable level of efficiency in the face of disruptive or unexpected conditions. This means the ability for people to get around in the face of one or more major obstacles to normality. Indeed, these obstacles can include extreme weather events like the ones above.

To limit flash floods risks in developed areas (where the storm water risk is frequent) permeable pavement systems (PPS) can be used[18].

Literature[19] shows that the hydrological effects of permeable pavements on flood mitigation are highly dependent on pavement type, the clogging rate and the initial water content of the pavement. Permeable pavements reduce surface runoff by 1-40%, and peak flow by 7-43% in a 12-h storm event with rainfall of about 114 mm. Permeable friction courses can be applied also to low-traffic streets, driveways, patios, bike paths, parking lots, plazas and sidewalks, obtaining a decrease in the storm water runoff volume of up to 70-90%[20]. The size of the air voids influences the lifespan of porous pavements. Oxidation and lower durability can be noted[21].

15. Barret, Keafott, Malina 2006.
16. Zaw Htoo Oo 2018.
17. Sayama *et alii* 2012.
18. Imrana, Akiba, Karim 2013.
19. Hu *et alii* 2018.
20. Cruijsen 2015.
21. Kumar Das, Das Saikia 2018.

Reducing Vulnerability Acting on the Minimization of Water Run Off through High Permeable Friction Course

Risk, resilience and vulnerability are interconnected. Vulnerability analysis refers to the susceptibility to extreme strains for a dynamic system[22]. It is noted that open-graded friction courses (PFC, OGFC, PAC)reduce vulnerability[23].

Reducing the Urban Heat Island (UHI) Effect through the Use of Permeable Pavements

The United States Environmental Protection Agency (US EPA) defines the Urban Heat Island (UHI) effect as «the phenomenon whereby urban regions experience warmer temperatures than their rural surroundings»[24]. In fact, the replacement of land and vegetation (permeable and humid sites) with structures and infrastructures (impermeable and dry) leads to an increase in the sun's energy absorption and storage (i.e., the heat is transferred downwards and stored in the subsurface, then it is released during the night, affecting also the quality of the waterways).

For cities with one or more than one million people, this leads to the fact that the annual mean air temperature can be 1-3°C and 7-12°C warmer than the surroundings, during the day and the night, respectively. Furthermore, if the surface temperature of developed and rural areas is considered, the ranges above become 10-15°C and 5-10°C, respectively. It is important to note that, during the summertime: i) conventionally paved areas can reach 48–67°C; ii) an increase in 0.6°C leads to an increase in 1.5-2% of the peak urban electricity demand; iii) over recent decades, to compensate for the UHI effect, 5-10% of the community's demand for electricity is used.

Different approaches have been proposed to mitigate the UHI effect: the use of trees and vegetation, green and cool roofs and cool pavements (e.g., reflective or permeable pavements).

Ii is important to note that if pavement surface temperatures are reduced, in turn, it is possible to reduce the risk of rutting (premature depressions) due to heavy vehicles and to slow down the rate of aging that is responsible for other types of distress. Stempiharshowed that porous asphalt has higher day-time surface temperatures than other pavements, but lower night-time temperatures

22. Reggiani, Nijkamp, Lanzi 2015.

23. Barret, Keafott, Malina 2006; Cooley *et alii* 2009; Braga, Connolly 2010.

24. United States Environmental Protection Agency 2008.

compared to other materials with a similar or higher albedo[25]. Mohajerani found that the UHI effect can be further mitigated if recycled materials are used to build these types of pavement[26]. Ibrahimmeasured the highest temperature for traditional and porous asphalt concrete, and cement concrete, the results of which were equal to 47.3°C, 39.8°C, and 38.1°C, respectively[27]. Liuproposed a novel permeable pavement called evaporation-enhancing permeable pavement. Their results showed that the proposed pavement is cooler than a conventional permeable pavement by as much as 9.4°C[28].

Methodology

The design of a multi-layered system, i.e. a pavement which aims at assessing geometry and the composition of each mixture[29].

There are many factors to be taken into consideration such as volume (e.g., AV[30]), mechanics (e.g., fatigue, plastic deformation, thermal cracking), resistance (e.g., Marshall stability[31]), workability-related properties (e.g., bitumen viscosity), and (for the friction course) surface properties (e.g., friction, surface texture, acoustic absorption, drainability).

A synergetic and concurrent design is needed[32], e.g.:

1) designing the friction course in order to comply with the CPX requirement (fig. 1);
2) predicting the corresponding consequences in terms of L_{den}[33];
3) predicting the consequences, if any, in terms of the remaining surface-related properties (e.g., drainability, friction, and texture);
4) predicting the consequences in terms of mechanistic properties (fig. 1);
5) deriving the life expectancy for each layer of the pavement system;

25. Stempihar *et alii* 2012.
26. Mohajerani, Bakaric, Jeffrey-Bailey 2017.
27. Ibrahim *et alii* 2018.
28. Liu, Li, Peng 2018.
29. Platì 2015; Praticò, Briante, Licitra 2019.
30. Praticò, Moro, Ammendola 2009.
31. Praticò, Moro, Ammendola 2010.
32. Garbarino *et alii* 2016.
33. European Parliament, Council Of The European Union 2002.

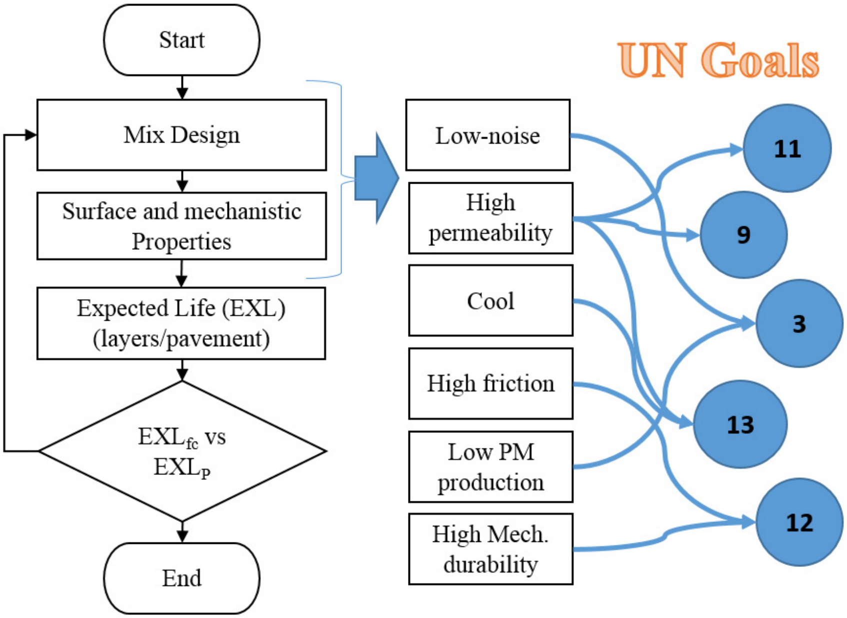

Figure 1. Methodology (Author’s own compilation).

6) deriving the life expectancy of the pavement (without the friction course);

7) comparing the life expectancy of friction course and pavement;

8) going back to the design of layers (and, particularly, friction course) in order to have the highest life expectancy of the pavement, the highest life expectancy of the friction course, being the first n times the second one.

Conclusions

This paper aims at providing a methodology to set up innovative technologies for more sustainable transportation infrastructures.

A comparative table to show how these solutions can satisfy the 2030 agenda has been proposed. Finally, a methodology, which takes into account the main parameters associated with road pavement design, has been presented.

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