Performance Evaluation of Innovative and Sustainable Pavement Solutions for Road Tunnels

PERFORMANCE EVALUATION OF INNOVATIVE AND SUSTAINABLE PAVEMENT SOLUTIONS FOR ROAD TUNNELS

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Abstract This paper summarizes the studies which were carried out to support pavement design and construction operations in a major motorway tunnel. Candidate pavement cross sections subjected to analysis included a subgrade and foundation layer constituted by self-compacting cement-bound granular mixtures. The potential use of standard cement-stabilized foundations was also considered. The self-compacting mixtures were designed to incorporate significant amounts of recycled materials including Reclaimed Asphalt Pavement and mineral sludge retrieved from aggregate washing operations. Expected performance of the innovative pavement solutions and of a reference standard cross section were assessed by means of a mechanistic-empirical approach which in most part relied on the outcomes of laboratory and field tests. In particular, a full-scale test section was constructed with the use of self-compacting mixtures in the subgrade and foundation, overlaid by two asphalt layers. The subsequent investigation included Falling Weight Deflectometer measurements and laboratory tests carried out for the assessment of volumetric and mechanical properties of laid mixtures. Obtained results led to the identification of an optimal pavement cross section and highlighted the potential performance achieved by the proposed innovative solutions. The additional advantages related to the greater efficiency of construction operations in tunnels and to the lower consumption of virgin aggregates were also discussed.

Keywords: self-compacting cement-bound mixtures; recycling; road tunnels; mechanistic-empirical pavement design

1. Introduction

Selection of a pavement solution for road tunnels depends upon several factors ranging from estimated traffic, safety, cost, availability of materials, presence of buried utility lines, logistics of construction operations, and expertise of involved contractors. Various pavement types can be selected, including flexible, rigid and semi-rigid, but designers may also need to deviate from standard solutions, identifying innovative materials and technologies which are compatible with site-specific requirements.

Pavements in road tunnels are subjected to a temperature regime which is different from that of open roadways. In particular, temperatures tend to be significantly higher and characterized by a lower daily and seasonal variability, thus leading to lower stiffness values of the bitumen-bound upper layers. Hence, in order to reduce deflections and strains under loading, pavements of the semi-rigid type can be selected, in which asphalt concrete layers are placed over a relatively stiff cement-stabilized foundation (Solanki and Zamam, 2017). Semi-rigid pavements constitute a significant portion of the European road network (Ferne, 2006) and have proven to exhibit satisfactory performance in service (Merril et al., 2006). Furthermore, they may easily incorporate waste materials in the foundation and may lead to a reduction of bitumen consumption as a result of the use of thinner asphalt layers (Zheng, 2012).

In the specific case of a newly constructed major motorway tunnel (13 km in length), a standard semi-rigid pavement cross section was chosen in the preliminary design phase, which focused on its load bearing capacity. However, the Authors of this paper were involved in its optimization which was deemed necessary in order to fulfill several additional needs. These were related to the potential constraints encountered in the compaction of subgrade and foundation materials, to the presence of underground utilities, including a high-voltage transmission line, and to the desire of reducing the consumption of virgin aggregates. Consequently, innovative pavement cross sections were identified, in which the use of self-levelling and self-compacting cement-bound mixtures was considered for the formation of the subgrade and foundation. These mixtures were designed in order to incorporate significant amounts of recycled materials such as Reclaimed Asphalt Pavement (RAP) and mineral sludge retrieved from aggregate washing operations. Laboratory and field studies included the assessment of flow, mechanical and thermal properties. Results obtained during these investigations are fully described elsewhere (Riviera, 2018; Choorackal et al., 2019a-2019b).

This paper summarizes the studies which were carried out as part of pavement optimization. Expected performance of the innovative solutions and of a reference standard cross section were assessed by means of a mechanistic-empirical approach in which predicted traffic and environmental conditions were taken into account. Mechanical properties of materials were mainly derived from the outcomes of field investigations carried out on a full-scale test section and of laboratory tests performed on materials sampled on site.

2. Pavement cross sections

The standard semi-rigid pavement cross section considered in the preliminary design phase (indicated as "CS") included a compacted soil subgrade, a cement-stabilized foundation (thickness 20 cm) and three layers of dense-graded asphalt concrete (total thickness 19 cm).

The innovative pavement solutions included self-levelling and self-compacting cement-bound mixtures (SCMs) for the formation of both the subgrade and foundation (cross section "GG") or of the subgrade only (cross section "CG"). In the latter case, it was hypothesized that the foundation would be constructed with the same type of standard cement-stabilized mixture (CBM) considered as part of cross section CS. For both pavements, as in the case of cross section CS, the foundation thickness was maintained equal to 20 cm and total thickness of the asphalt layers was fixed at 19 cm since such a value was considered adequate for the prevention of reflective cracking (Austroads, 2017). It was hypothesized that the 19 cm would be constituted by 10 cm base course, 5 cm binder course and 4 cm wearing course.

For all pavement solutions the total thickness of subgrade considered in calculations was equal to 1 m. Such a value results from the geometry of the tunnel invert, which is filled in its lower portion by lean Portland cement concrete that acts as a rigid base. It should be mentioned that after completion of preliminary design, the tunnel administration accepted to allow the installation of a high-voltage transmission line within the pavement subgrade. The corresponding design led to the identification of an appropriate layout of conduits and cables to be buried at a depth below the subgrade surface equal to approximately 80 cm.

3. Performance evaluation of pavement solutions

Performance evaluation of the considered pavement cross sections was carried out by means of a mechanistic-empirical approach which required the prediction of traffic volumes, environmental conditions and mechanical properties of materials.

The motorway tunnel for which the study was carried out is a new infrastructure, recently excavated in parallel to an existing tunnel, open to traffic since 1980. Thus, data available for the existing tunnel were employed for the identification of traffic and temperature conditions relevant for the design of the new pavement (see sections 3.1 and 3.2). Mechanical properties of materials constituting the various pavement layers were derived from field and laboratory tests, from available literature, and from technical specifications (see section 3.3). Transfer functions employed for the calculation of design lives, briefly discussed in section 3.4, were those provided by the SAPEM, South African Pavement Design Manual (SANRA, 2014).

3.1. Design traffic

A synthesis of the two-way traffic data collected for the existing tunnel for a period of five years is shown in Table 1, in which the number of passes are given for light (motorcycles, cars and vans) and heavy vehicles (buses, trucks and trailers). The percentage of heavy vehicles, of the order of 40%, was approximately constant in time. It was observed that annual traffic growth values were quite variable, ranging between 0.1% and 7.0%. Thus, the average value, equal to 3.0% was assumed for traffic predictions.

Table 1 Traffic data collected for the existing tunnel

Year	2014	2015	2016	2017	2018
Light vehicles	998,342	1,115,511	1,129,051	1,100,382	1,099,845
Heavy vehicles	701,728	703,653	736,248	766,561	813,233
Total	1,700,070	1,819,164	1,865,299	1,866,943	1,913,078

In subsequent calculations, light vehicles were neglected, whereas the heavy vehicles were converted into 80 kN equivalent single axle loadings (ESALs) by taking into account the vehicle sub-categories and relative percentages recorded at the tunnel entrance for toll collection. Individual truck factors were derived from the axle loads indicated in the Italian pavement catalogue (CNR, 1995) and by referring to the equivalent axle load factors (EALFs) reported in the 1993 AASHTO Guide for a Structural Number (SN) equal to 5 and a final Present Serviceability Index (PSI) equal to 3.0. The average truck factor obtained by means of such an approach was found to be equal to 2.0. A lane factor equal to 0.8 was assumed for design purposes.

Monthly traffic distribution was also made available by the tunnel administration and it was found that no significant changes occurred in the considered years (with the only exception of the year 2015, which was treated as an outlier). These data were later used in damage calculations for the considered pavement cross sections (see section 3.5).

It was planned that pavement construction would occur in two stages. In particular, it was envisioned that after laying of the binder course, the tunnel would be accessed for 2 years exclusively for the instalment of all accessory utilities, including ventilation, lighting and safety systems. The pavement would then be completed with the laying of the 4 cm wearing course. Construction traffic anticipated in the 2 years of finishing operations was estimated based on the planned daily activities and was found to correspond to 7,508 passes of three- and four-axle trucks on each lane. For the considered vehicles the average truck factor was equal to 2.14.

Upon request of the tunnel administration, pavement design life, inclusive of the 2 years of tunnel completion, was set equal to 20 years. Based on the data and assumptions illustrated above, corresponding total design traffic expressed in ESALs was found to be equal to 16.2 million.

3.2. Design temperatures

Available data consisted in hourly air temperatures recorded for one year along the existing tunnel in 4 fixed stations. As expected, lower values were reached near the tunnel entrance. Thus, as part of a conservative approach, average values derived only from the 3 stations closer to the tunnel center were considered in subsequent analyses. Hourly data were converted into average daily and monthly temperatures. As a result, four different periods characterized by a similar average monthly temperature were identified and were then associated to average air temperature values ($T_{air,p}$).
In order to calculate pavement design temperatures, the presence of the buried high-voltage line was considered. Thus, its operating temperature was calculated by taking into account the requirements fixed by line designers and by making use of the model proposed by Neher and McGrath (1957). In each of the abovementioned periods, air temperature was considered representative of far field conditions, while the resistivity of the materials surrounding the cables and conduits varied from one cross section to the other. In the case of cross section CS, calculations were carried out by considering the presence of a lean concrete duct-bank and of a soil backfill, with thermal resistivity values equal to 1.368 K·m/W and 1.2 K·m/W, respectively. For the GG and CG pavements, no duct-bank was planned to be constructed, so modelling was based on a single resistivity value, equal to 0.860 K·m/W, representative of the SCM intended for use for the formation of the subgrade. Thermal resistivity values indicated above for lean concrete and for the SCM were measured by the Authors by means of the thermal needle probe technique indicated by ASTM D 5334-14 (Chooracka1 et al., 2019a). In the case of the backfill soil, the considered value was retrieved from literature.
In order to derive pavement temperature profiles, surface temperature was considered equal to air temperature, whereas at 120 cm below the surface, temperature was assumed to be equal to the average of the temperatures reached inside the conduits of the 4 cables constituting the high-voltage line. Temperature gradients within the pavement layers and subgrade were assumed to be inversely proportional to the corresponding thermal resistivity values. Representative pavement design temperatures ($T_{pav,p}$) were thereafter calculated for each period at a depth from the surface equal to one-third of the total thickness of the asphalt layers.
Results obtained by means of the modelling approach synthesized above are provided in Table 2.

Table 2 Air and pavement design temperatures

Period	Months	$T_{air,p}$ (°C)	$T_{pav,p}$ (°C)			
			Final phase of construction	Service life		
			CS-GG-CG	CS	GG	CG
1	January-March	20.8	20.8	22.7	22.2	22.2
2	April-May	24.6	24.6	26.3	25.9	25.9
3	June-November	28.4	28.4	30.0	29.6	29.5
4	December	20.8	20.8	22.7	22.2	22.2

3.3. Mechanical properties of materials

Assessment of the mechanical properties of materials constituting the various pavement layers was carried out by focusing on elastic moduli. Values of Poisson's ratio were derived from relevant literature.

A full-scale pavement section was constructed by replicating cross section GG with a reduced asphalt thickness of 15 cm (10 cm binder course, 5 cm wearing course). The test section had a length of 14 m and width of 4 m. The SCM subgrade and foundation had a thickness of 100 cm and 20 cm, respectively. Both asphalt mixtures, which were intended for use in the final construction of the pavement in the tunnel, contained polymeric additives for the improvement of rutting and fatigue resistance.

Following previous investigations, the SCMs were designed to achieve a satisfactory flowability, while guaranteeing adequate short-term and long-term mechanical properties. In particular, a 170-300 mm acceptance range was fixed for spread diameter (ASTM D 6103) and threshold values were identified for compressive strength (EN 12390-3), which was required to be greater than 0.5 MPa at 3 days of curing and less than 2.0 MPa at 28 days of curing.

The SCMs employed in the test section and proposed for use in the tunnel contained 20% gravel, 36% fine sand, 20% RAP and 24% aggregate sludge (percentages by weight). Cement content was set equal to 100 kg/m^3 and 60 kg/m^3 in the subgrade and foundation, respectively. Water content was that corresponding to a water-to-powder ratio equal to 0.8 ("powder" being the sum of cement and aggregate sludge).

During the construction of the test section, samples of the two SCMs were taken for the immediate assessment of spread diameter which in both cases was found to be of the order of 250 mm. Specimens were also prepared for the laboratory evaluation of compressive strength. Corresponding results obtained after 3 and 28 days of curing, respectively equal to 0.84 MPa and 1.67 MPa for the mixture with 100 kg/m^3 cement dosage and to 0.50 MPa and 0.9 MPa for the mixture with 60 kg/m^3 cement dosage, satisfied the previously mentioned acceptance requirements.

Falling Weight Deflectometer (FWD) tests were performed over the finished pavement surface at three different loading levels (47, 63 and 83 kN). At the time of testing, a temperature of 16°C was recorded at mid-depth in the asphalt layers. Back-calculation was carried out with an iterative procedure by employing the BISAR software (Shell, 1998) and by hypothesizing full slip between the bottom asphalt course and the extremely smooth underlying foundation. Computed elastic modulus values were equal to 3,500 MPa, 350 MPa and 1,000 MPa for the asphalt layers, foundation and subgrade, respectively. For the subgrade soil and for the CBM foundation included in cross section CS, values of 200 MPa and 800 MPa, respectively, were assumed consistently with preliminary design hypotheses.

In the case of the asphalt layers, cores were taken in order to assess their volumetric characteristics. Unfortunately, due to the physical constraints imposed by the test section, which was quite narrow and with a working surface located 1 m above the ground, achieved compaction level was lower than expected. In particular, measured air void content, equal to 9.7%, was definitely higher than the target value of 7.0%, compatible with mix design studies and technical specifications.

For the purpose of pavement evaluation, the elastic modulus of the asphalt layers was adjusted for temperature (WSDOT, 2005). Moreover, it was assumed that during construction operations in the tunnel, target void content would be reached. Thus, the modulus was adjusted further by making use of the same functional dependency proposed by Bonnaure et al. (1977) for stiffness values measured in the bending mode. Results obtained by means of the procedure outlined above are given in Table 3, where they are presented for each temperature period, pavement cross section and phase.

Table 3 Elastic modulus of asphalt layers

Period	Months	Elastic modulus (MPa)			
		Final phase of construction	Service life		
		CS-GG-CG	CS	GG	CG
1	January-March	3,185	2,742	2,845	2,855
2	April-May	2,334	2,007	2,083	2,090
3	June-November	1,660	1,428	1,481	1,486
4	December	3,185	2,742	2,845	2,855

3.4. Transfer functions

Transfer functions used for performance evaluation were drawn from the SAPEM (SANRA, 2014). Minor adjustments were needed in order to take into account the specific properties of the employed materials.

In the case of the asphalt layers, analyses focused exclusively on fatigue cracking, the transfer function of which depends upon elastic modulus and thickness. However, an additional shift factor of 1.10 was introduced in calculations in order to account for the performance-related benefits deriving from the use of polymeric additives.

Performance of the CBM and SCM foundation layers was analyzed in two phases. In phase 1, the layers were assumed to be intact and were consequently modelled in terms of their fatigue resistance under bending. The corresponding transfer functions were selected by fitting the considered materials into the categories indicated by the SAPEM (C3 for the CBM, C4 for the SCM). In phase 2, reached as a result of cracking, they were considered as unbound granular materials with a reduced modulus (of classes EG4 and EG5, respectively, for the CBM and for the SCM). In such a state, their performance was assessed in terms of their resistance to shear failure.

For all pavement cross sections, the same transfer function was employed for the performance assessment of the subgrade. In particular, a reliability of 95% was selected, which corresponds to a terminal rut depth of 10 mm.

Design calculations were performed by combining the results obtained in the various temperature periods and by introducing the concept of cumulated damage. The response under loading of the pavement cross sections in each period was assessed by means of the BISAR software by assuming full adhesion between the layers and by considering a standard dual-wheel single axle with a contact pressure of 577.4 kPa.

3.5. *Design life*

The design life of each pavement solution, expressed in terms of allowable ESALs and corresponding years of traffic, was computed as the sum of three terms associated to the final stage of construction and to the previously mentioned phases 1 and 2. Obtained results are synthesized in Table 4. In all cases final conditions were reached as a result of fatigue cracking in the asphalt layers, thus indicating that their performance potential was fully exploited. Furthermore, accumulation of permanent deformation in the subgrade was not of concern for any of the considered solutions.

Table 4 Design life of considered pavement solutions

	ESALs			Years		
	CS	GG	CG	CS	GG	CG
Construction + Phase 1	9.19E+06	9.83E+06	9.71E+06	13.3	14.0	13.8
Phase 2	7.25E+06	1.78E+06	1.42E+07	6.9	1.8	12.2
Total	1.64E+07	1.16E+07	2.39E+07	20.2	15.8	26.0

From the data listed in Table 4 it can be observed that the CG pavement cross section provided the highest design life, equal to 26 years, followed in ranking by solutions CS and GG. Both cross sections with a CBM foundation satisfied the requirement of 20 years design life. On the contrary, the cross section with the two-layer SCM supporting system was found to have a shorter design life, close to 16 years, which in any case corresponds to a remarkably high traffic (equal to 11.6 million ESALs).
It can be observed that the three solutions exhibited a similar design life associated to the sum of the construction completion phase and of the phase 1 pre-cracking stage. However, the highest number of allowable loadings were found in the case of cross section GG, followed in ranking by CG and CS. This is due to the fact that phase 1 transfer functions employed for calculations yield numbers of loadings to cracking of the cement-stabilized layers which depend not only upon load-induced tensile strains but also on the ductility of the mixtures (expressed in terms of the so-called strain-at-break). Thus, less stiff materials such as the SCMs (associated to category C4), may yield higher fatigue lives in comparison to stiffer materials such as the C3-type CBMs. Despite their similar early behavior, the three cross sections showed a totally different response in phase 2, the highest and lowest lives being associated to solutions CG and GG, respectively. As highlighted in Figure 1, this is essentially due to the fact that asphalt damage in both phases progressed with completely different rates, which were affected by the stiffness of both the foundation and the subgrade. Figure 1 also shows that a similar dependency upon stiffness support was exhibited by the cement-stabilized foundations in phase 2, the lowest damage rates being associated to the cross sections containing the stiffer SCM subgrade (GG and CG).

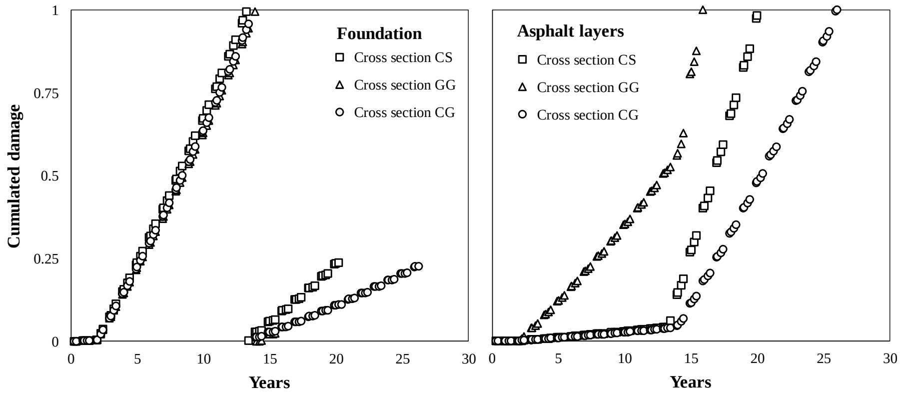

Fig. 1 Cumulated damage of considered pavement solutions

4. Conclusions

Based on the results obtained in the optimization activities illustrated in this paper, the Authors recommended the tunnel administration to adopt the innovative CG pavement cross section as the final construction solution. In fact, it was shown that such a choice leads to a non-negligible improvement of design life with respect to the CS cross section initially proposed in the preliminary design phase, thereby accommodating for unexpected variabilities occurring during construction and in service. Furthermore, it yields supplementary advantages which are related to the ease of construction (i.e. no need for subgrade compaction), to the better thermal conductivity (relevant due to the presence of a high-voltage buried line) and to the possibility of employing significant amounts of recycled materials. In such a context, it should be underlined that the laying of the SCM subgrade for a length of 1 km in the tunnel implies the use of 1,700 tons and 2,000 tons of RAP and aggregate sludge, respectively. This leads to a significant reduction of the consumption of virgin materials and of waste landfilling, thereby increasing the sustainability of construction operations.

The pavement cross section including two SCM layers (solution GG) proved to be inferior to other two solutions in terms of design life. Nevertheless, it should be considered for other future applications characterized by a design traffic corresponding to the calculated ESALs (equal to 11.6 million). Moreover, further improvements may be sought by employing high-performance asphalt mixtures which may allow designers to fully exploit the low damage rate exhibited by the SCM foundation. Finally, it should be emphasized that such a pavement solution may provide further advantages with respect to the use of recycled materials, with a further increase of the quantities of employed RAP and aggregate sludge of the order of 25%.

Although preliminary data suggest that the innovative CG and GG pavements are highly cost-effective, future investigations will include life-cycle cost analyses which will necessarily take into account environmental impacts.

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