Controlled low-strength materials for pavement foundations in road tunnels: feasibility study and recommendations

CONTROLLED LOW-STRENGTH MATERIALS FOR PAVEMENT FOUNDATIONS IN ROAD TUNNELS: FEASIBILITY STUDY AND RECOMMENDATIONS

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Abstract

This paper presents the results obtained during a laboratory and field investigation which focused on the assessment of the feasibility of using controlled low strength materials (CLSMs) in pavement foundations of road tunnels. The CLSM considered in the study, which contained a significant amount of recycled asphalt pavement (RAP), was designed by optimizing its flowability and by considering its sensitivity to changes in cement dosage. For comparative purposes, a standard low-strength Portland cement concrete mixture was also included in the investigation. Both mixtures were produced in a Portland cement concrete batching plant and were thereafter subjected to laboratory tests for the evaluation of flowability, consistency, compressive strength, California Bearing Ratio (CBR) and resilient modulus. Furthermore, full-scale slabs constructed with the two mixtures were subjected to plate loading tests and to the transit of a fully-loaded heavy vehicle. Obtained results indicated that both mixtures are suitable for the formation of pavement foundations since they exhibit a short-term mechanical behavior which is comparable to that of standard granular sub-base materials. However, the CLSM proved to be superior in terms of its improved flowability, easier long-term excavatability, lower production cost and enhanced sustainability. Finally, recommendations for future applications of cement-bound materials in pavement foundations were provided in the form of preliminary performance-based acceptance criteria.

Keywords: controlled low strength material (CLSM), pavement foundation, recycled asphalt pavement (RAP)

Abbreviations

CLSM: Controlled Low-Strength Material

RAP: Recycled Asphalt Pavement

CBR: California Bearing Ratio

1. INTRODUCTION

In the construction of pavements in road tunnels one of the most critical issues to be addressed is the selection and design of an appropriate foundation layer which supports the upper courses and may also act as a filling material in contact with the rock base or concrete lining. Materials which are considered suitable candidates to provide these functions include selected soils, unbound granular mixtures and cement-bound composites. A typical cross section of pavement in tunnel is shown in Fig. 1.

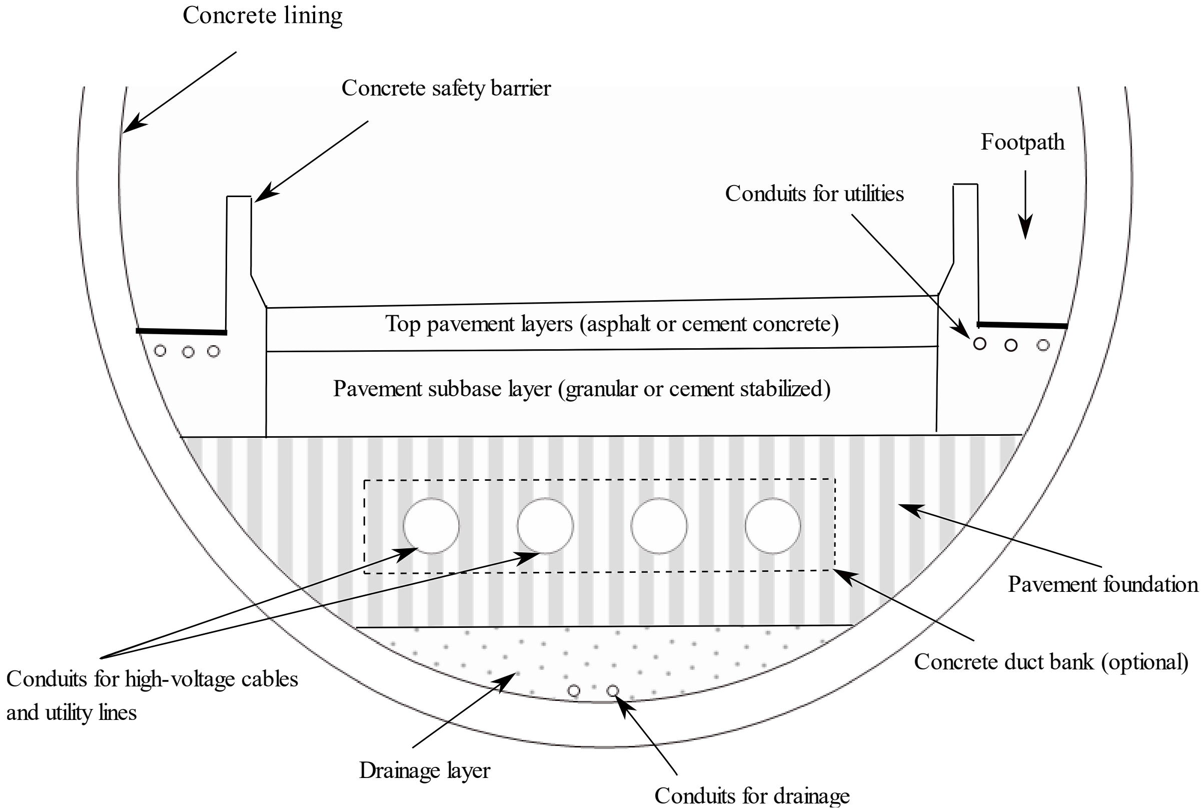

Fig. 1 Typical cross section of pavement in road tunnel

It should be emphasized that the composition of pavement foundations in tunnels may have a relevant impact on the quality of construction operations, on the service life of the infrastructure, and on maintenance activities which may be necessary in the course of time.

With respect to construction operations, one of the key factors which need to be considered in the selection of the foundation material is its compaction behavior [1]. This is especially true in those cases in which road tunnels house important utility lines (e.g. high-voltage transmission cables and optical fiber networks) that are buried below the top pavement layers in sets of conduits which sometimes may be encased in Portland cement concrete duct banks (see Fig. 1). When placing the foundation material, care should be taken in reaching the required target density and in filling all voids and cavities which are created by the complex arrangement of embedded pipes. However, when applying compacting efforts by means of rollers, such an operation may be of limited efficiency and may also pose the threat of damaging the conduits and the utilities themselves. Furthermore, the use of rollers in tunnels may significantly impact the economics and logistics of construction works. Thus, the use of self-levelling self-compacting mixtures which can be simply pumped up to the desired thickness may be extremely attractive.

The service life of pavements in tunnels is affected not only by the volume and intensity of loading, but also by the particular temperature regime which occurs throughout the year. As proven by direct measurements, in comparison to the case of open roadways, temperatures tend to be significantly higher and are characterized by a lower daily and seasonal variability in tunnels [2], thus leading to lower stiffness values of the upper pavement layers whenever they are composed of asphalt concrete (see Fig. 1). Such an occurrence may be partially compensated by building stiff pavement foundations which contribute to the limitation of pavement deflections under loading and consequently to the enhancement of pavement life.

Another aspect which needs to be considered when analyzing the functions of pavement foundations in tunnels is their thermal conductivity, which affects the ampacity of buried high-voltage lines [3, 4]. Ampacity is defined as the maximum current-carrying capacity of a line which is a function of the maximum temperature which can be reached by the cables. In practical terms, the foundation material should have a sufficiently high thermal conductivity in order to efficiently dissipate the heat generated by the current, thereby guaranteeing the long-term integrity of the line.

Maintenance activities may be necessary in the course of time whenever malfunctioning of the underground utilities occur or when these need to be upgraded. Thus, it is essential for the pavement foundation to be easily excavatable, thus allowing the conduits to be accessed with the use of limited demolition efforts which should not jeopardize their integrity [5]. After completion of maintenance, repair of the foundation should take place by following procedures which are similar to those of initial construction in which compaction issues once again need to be taken into account.

Based on the discussion provided above, it can be concluded that an ideal foundation material for pavements in tunnels should possess several key properties which include self-compaction during construction, sufficient stiffness throughout the pavement service life, high thermal conductivity and stability, and adequate excavatability. However, none of the conventional materials which are employed in typical tunnel construction operations exhibit properties which match the set of listed engineering requirements. Selected soils and granular mixtures, although easily excavatable, require a thorough compaction after laying and are limited in stiffnesses. Furthermore, they usually have a low thermal conductivity and may undergo undesired dry-out phenomena which further reduce such a property. Standard cement-bound materials (e.g. cement-stabilized mixtures and Portland cement concrete) present advantages in terms of their stiffness and with respect to their thermal properties, which are positively affected by the presence of Portland cement. However, they still require external compaction and may be difficult to remove from the cross section especially in the very long term.

According to the Authors' opinion, materials which can provide an ideal balance of the engineering properties outlined above are those which belong to the category of controlled low strength materials (CLSMs) [5, 6]. Despite their desirable characteristics, illustrated in detail in the following, these mixtures have never been employed for the formation of pavement foundations in tunnels.

CLSMs, which contain hydraulic binder, mineral aggregates and water, are self-compacting cementitious materials characterized by low binder content and high porosity [6]. They are typically employed for backfilling walls and trenches, for utility bedding, as subbases in bridge approaches, and for void filling applications in sewers, tunnel shafts, basements and other underground structures [5]. Their relatively low strength, which can be tailored by adjusting composition, makes them ideal materials for applications in which it is anticipated that there may be the need of future excavations to be carried out in order to access buried utilities without damaging them [7-9].

In addition to their standard components, in some cases CLSMs may also include appropriate additives, which contribute to the optimization of flowability, and recycled materials, which reduce production costs and global environmental impact. Klaz and Klover [10] reported on the improvement of mechanical properties of CLSMs which can be achieved by employing asphalt dust, coal fly ash, coal bottom ash and quarry waste. Raghavendra and Udayashankar [11] investigated on the effects caused by recovered gypsum powder and fly ash, developing a corresponding mix design procedure which yielded acceptable CLSM formulations. Puppala et al. [12] showed that satisfactory flowability and density can be attained with CLSMs containing clayey soil, while Naganathan et al. [13] observed that the use of quarry dust may have a stabilizing effect on this type of mixtures. Other Authors found that for some specific waste materials, critical issues may need to be considered. When evaluating the incorporation of high volumes of paper sludge, Wu et al. [14] recorded detrimental effects related to its high water absorption, while fluidity concerns were highlighted by Wang and Chen [15] when employing steel slag fillers. Finally, Etxeberria et al. [16] were critical in the analysis of CLSMs containing fine aggregates coming from construction and demolition waste, due to the fact that significant adjustments in formulation were needed in order to guarantee adequate flowability and compressive strength.

RAP is the main waste material which is produced as a result of maintenance and rehabilitation activities carried out on distressed road pavements. It is constituted by mineral aggregates covered by thin, aged bitumen films and it is typically employed in substitution of part of the virgin aggregates in the production of cold and hot bituminous mixtures [17-24]. According to available statistics, approximately 50 million and 69 million tons of RAP material are stockpiled every year in Europe and in the U.S., respectively [25]. However, the current use of RAP in pavement recycling operations does not absorb these large quantities and as a consequence alternative recycling options need to be devised.

Published work on the design and characterization of CLSMs does not document any experience on the use of RAP. This is probably due to the fact that RAP typically contains, in addition to fine aggregates, coarse fractions which are seldom required to supplement virgin aggregates in these mixes. Nevertheless, in recent years some work has been done on Portland cement concrete and cement-stabilized mixtures as part of the general desire of identifying innovative, low-cost and sustainable materials. Huang et al. [26] observed that use of RAP can lead to a reduction of concrete compressive and tensile strength but may also enhance toughness characteristics. This was also reported by Abdel-Mohti et al. [27], who suggested that strength reduction may be mitigated by adding fibres during concrete production. The feasibility of including RAP in cement-stabilized mixtures was demonstrated by Taha et al. [28], who showed that in such cases cement and water content need to be conveniently adjusted and that the use of increasing quantities of RAP may indeed yield a reduction of compressive strength. On the other hand, Puppala et. al [29], while focusing on resilient modulus testing, found that mixtures containing RAP show a good potential for use as sub-base materials.

This paper presents the results of an experimental investigation which was carried out in order to assess the feasibility of using CLSMs in pavement foundations of road tunnels. In particular, a CLSM containing a significant portion of RAP (indicated as CLSM-R) was at first designed in the laboratory and thereafter produced in a cement concrete batching plant. For comparative purposes, a classical low-strength Portland cement concrete containing exclusively virgin aggregates (indicated as SC-V) was also considered in the investigation. Such a comparison was deemed useful in order to highlight some of the peculiar advantages which derive from the use of CLSMs in road tunnel pavement foundations. Both plant-produced mixtures were subjected to laboratory tests and were used for the construction of full-scale slabs which simulated operations which take place in road tunnels while forming the pavement foundation. As indicated below, the structural behavior of the slabs was also evaluated.

In the knowledge of the Authors, there are no prior studies in which laboratory tests and field trials were performed on CLSM mixtures for pavement foundations in tunnels. Hence, the performed investigation considered both the tests which are recommended in international guidelines available for CLSMs [5, 6] and typical tests that are used for conventional unbound foundation materials [30]. Tests which belong to the first group focus on characteristics of the CLSMs in the fresh and hardened state, thereby measuring flowability, compressive strength and California Bearing Ratio (CBR). Additional tests, usually employed for the assessment of the bearing capacity characteristics of pavement sub-bases and subgrades, were those which measure resilient modulus in the laboratory by means of a triaxial equipment and deformation modulus in the field by means of the classical plate loading procedure. Finally, since pavement foundations are usually subjected to construction traffic within a short period after laying, such a situation was simulated during the investigation by subjecting the constructed slabs to the passage of heavy vehicles.

Although the thermal properties of pavement foundation materials are of interest for practical applications in the presence of buried high-voltage cables, in the investigation described in this paper no specific tests were carried out. However, reference was made to the results obtained by the Authors on similar materials [4].

All tests included in the testing program have a clear performance-related value. Thus, it was envisioned that obtained results would be meaningful within the feasibility study and could provide the bases for the definition of preliminary performance-based acceptance criteria to be used for the selection of cement-bound pavement foundation mixtures in road tunnels.

recommendations for future applications of cement-bound materials in pavement foundations were provided in the form of performance-based acceptance criteria.

2. MATERIALS AND METHODS

2.1 Characterization of mixture components

Components to be included in the two cementitious mixtures considered in the investigation (SC-V and CLSM-R) were provided by a specialized Contractor that is active in the field of road and tunnel construction and that operates a Portland cement concrete batching plant.

Aggregates were sampled from the stockpiles available in the production plant and were preliminarily characterized by evaluating their particle size distribution and specific gravity (SG). They included a coarser fraction (indicated as 8-18 mm gravel) and two finer fractions (designated as 0-8 mm and 0-3 mm sand). Finally, RAP to be incorporated in the CLSM mixture was also retrieved from plant stockpiles and was denominated 0-16 mm RAP. All RAP particles retained on the 16 mm sieve were discarded in order to limit maximum aggregate size.

Additional component materials which were employed for the production of the mixtures included Portland cement, water and, in the case of CLSM-R, a suitable air-entraining additive. Cement was of class CEM II/A-L R42.5 as per EN 197-1 [31]. Potable water exempt from impurities was used for mixing operations. The employed additive was a commercially available product which is recommended for the preparation of flowable mixtures (MAPEPLAST LA).

Results obtained in the preliminary characterization of aggregates and RAP are displayed in Fig. 2 and in Table 1.

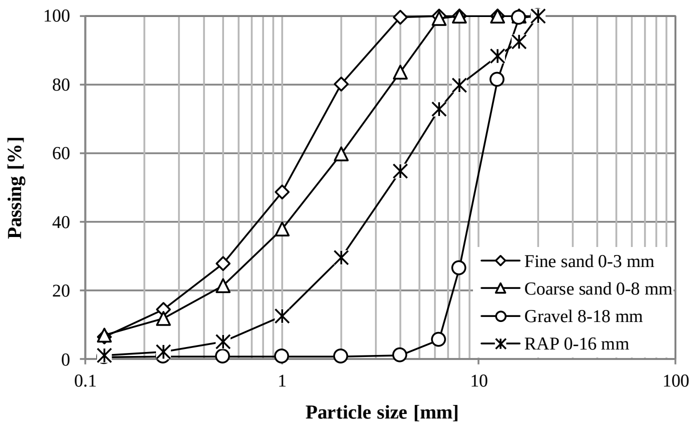

Fig. 2 Particle size distribution of employed aggregates and RAP

Table 1. Specific gravity of employed aggregates, RAP and cement

	SG
0-3 mm fine sand	2.680
0-8 mm coarse sand	2.745
8-18 mm gravel	2.771
0-16 mm RAP	2.502
Portland cement	3.150

2.2 Definition of mixture recipes

Production recipes of the two cementitious mixtures were defined by identifying the best combination of aggregates which matched the reference continuous size distribution corresponding to the following equation, also known as Fuller's law [32]:

$$\%P = \left(\frac{d}{D_{max}}\right)^{0.5} \cdot 100 \quad (1)$$

where %P (in percent) is the percent passing the generic sieve with aperture equal to d (in mm), d is the generic sieve aperture (in mm), D_{max} is the sieve aperture which corresponds to 100% passing (equal to 18 mm for mixture SC-V and to 16 mm for mixture CLSM-R).

Calculation of the percentage of each aggregate (and/or RAP) fraction was based on the combination of the individual particle size distributions shown in Fig. 1. For both mixtures, cement dosage was fixed at 200 kg/m^3. This was considered adequate given that in the design of pavement foundations in tunnels the major emphasis is placed on the achievement of adequate bearing capacity rather than on the development of high strength. In the process of recipe optimization, the effect of Portland cement on the total size distribution was not considered.

Mixture recipes and total particle size distribution curves are shown in Table 2 and Fig. 3, respectively. It can be observed that in the case of mixture CLSM-R, the finer 0-3 mm sand was not used since it was necessary to limit the number of employed fractions in the prospect of actual plant production, where only three feeding lines were available. It is also worth noting that introduction of RAP in the aggregate skeleton of the CLSM mixture allowed its percentage to be as high as 27%, which replaced the non-employed fine sand and part of the coarser 8-18 mm fraction.

Table 2. Composition of the aggregate skeleton of the design mixtures

	SC-V	CLSM-R
0-3 mm sand	17%	-
0-8 mm sand	48%	49%
8-18 mm gravel	35%	24%
0-16 mm RAP	-	27%

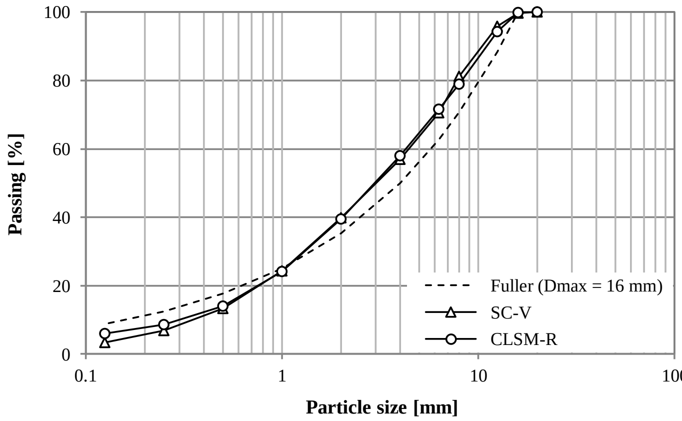

Fig. 3 Particle size distribution of the design mixtures

For the SC-V mixture, determination of water content and of the consequent water-to-cement ratio (w/c) was based on the definition of a target air void content of the mixture in its loose state (set equal to 15%), to be achieved in order to ensure adequate workability. Thus, calculation of corresponding water content was based on the volumetric balance of employed components taking into account their specific gravities (Table 1). As a result of this evaluation, the target w/c value was found to be equal to 0.8.

In the case of mixture CLSM-R, a different approach was adopted for the definition of the target w/c value. In such a context it was observed that as a result of the wide variability of possible components of CLSMs, in literature there is no consensus on the procedure which should be adopted for mix design purposes [7, 33]. Thus, since the most distinctive feature of CLSMs is to achieve a high degree of fluidity, target w/c was derived from the results of flow consistency tests (as per ASTM D6103 [34], see section 2.4) carried out on several trial mixtures prepared with variable w/c values. For each w/c value, determination of the exact quantities of water to be added to the other components was based on the hypothesis of target zero void content.

Finally, as a supplement to the tests carried out on the CLSMs with variable w/c and constant cement dosage (equal to 200 kg/m^3), further tests were performed on batches of additional mixtures containing different quantities of cement (dosages equal to 250, 150 and 100 kg/m^3). This was deemed necessary in order to check the physical coherency of obtained results and to have information on the potential sensitivity of CLSM fluidity to variations in its composition.

In order to ensure an adequate flowability and to guarantee the formation of homogeneous mixtures, exempt from bleeding and segregation, an air-entraining agent was used in all considered CLSM mixtures, with its dosage set equal to 0.5 kg/m^3 as suggested by the manufacturer.

2.3 Production of mixtures and construction of slabs

Cementitious mixtures of the two types considered in the investigation were produced both in the laboratory and in the concrete batching plant. For laboratory production, which was limited to CLSMs, small batches were prepared by hand-mixing and subsequently used for flow consistency tests. In the case of plant production, mixtures were employed for the construction of slabs (3.0 × 3.0 m plan dimension, 0.6 m thickness) which were cast in timber formwork. Mixtures were transferred from the plant to a transit mixer and thereafter pumped into the formwork. In order to ease compaction, the SC-V mixture was subjected to the action of needle vibrators, whereas the CLSM-R mixture was allowed to freely self-compact under its own weight. During the construction of the slabs, samples of the placed mixtures were taken for the evaluation of relevant properties, both in the fresh and hardened state, by means of the procedures illustrated in section 2.4.

2.4 Assessment of mixture properties

CLSMs prepared in the laboratory and sampled at the production plant were subjected to flow consistency tests as per ASTM D6103 [34]. These tests consist in evaluating the spread diameter (D_s) of fresh CLSM samples which expand under their own weight after being released from standard cylinders (75 mm in diameter and 150 mm in height) in which they are previously poured. Additional visual observations are made on test specimens after spreading in order to record the possible occurrence of bleeding and segregation phenomena. It should be considered that for trench filing operations CLSMs are typically required to exhibit a D_s value ranging from 170 to 250 mm [6].

As a supplement to flow consistency tests, plant-produced mixtures in their fresh state were subjected to Abrams cone slump tests as per EN 12350-2 [35]. These tests, typically used for Portland cement concrete mixtures, yield information on mixture consistency, which is expressed in terms of the so-called slump value. Such a parameter is measured by recording the reduction in height of a specimen which is released from a truncated cone.

Additional information on the fresh properties of the plant-produced mixtures was derived from tests carried out for the determination of air content as per ASTM C231 (pressure method) [36]. This test entails the application of a known air pressure to a sample contained in a sealed chamber until equilibrium conditions are reached. Air content is then estimated based on the use of a calibrated pressure gauge.

Properties of the mixtures in their hardened state were assessed by means of compressive strength, California Bearing Ratio (CBR) and resilient modulus laboratory tests. Additional tests were carried out on the constructed slabs by performing static plate loading tests and by observing the effects caused by the transit of a fully-loaded heavy vehicle.

Compressive strength (R_c) was measured on cubical specimens casted in disposable polystyrene moulds with sides equal to 150 mm. Tests were performed as per EN 12390-3 after 1, 3, 7 and 28 days of curing in controlled temperature and humidity conditions [37]. Average results obtained for the two mixtures at each curing time were considered in the analysis. It was envisioned that for the purpose of foundation construction, short-term strength would be required to be above a minimum admissible limit in order to allow construction equipment to travel on the newly-laid material without causing excessive damage. However, an upper limitation to long-term strength was also considered necessary since for such applications it is essential to guarantee that maintenance works can be carried out on buried utilities with the possibility of easily excavating the filling. In this respect, the limiting compressive strength value (of cylindrical specimens, at 28 days of curing) which is referred to for CLSMs employed in trenches is equal to 8.3 MPa [6].

CBR tests are typically employed for the characterization of subgrade soils. Nevertheless, they were included in the investigation since it was considered that in the short term both considered materials may have a behavior similar to compacted soil. Tests were performed on specimens obtained by filling standard metallic moulds (152.4 mm in diameter, 177.8 mm in height) with fresh material, and by applying no compaction action. Specimens were then cured for 1 and 3 days in controlled temperature and humidity conditions and thereafter subjected to testing as per EN 13286-47 [38]. Slight deviations from the standard were introduced in the protocol, with no application of surface surcharge during piston penetration and no preliminary soaking.

Resilient modulus tests as per AASHTO T 307 [39] are required for the characterization of subgrade soils and sub-base granular materials in the context of pavement design [40]. However, in the specific case of the cementitious mixtures considered in the investigation, it was assumed that resilient modulus testing could also be relevant for the assessment of their short- and long-term bearing capacity.

Tests were performed by making use of a triaxial cell in which several stress histories can be imposed to a slender cylindrical specimen (100 mm in diameter, 200 mm in height) by controlling both confining pressure and deviatoric stress. The resultant response of the material is assessed by referring to the so-called resilient modulus (Mr) which is defined according to the following equation:

$$M_r = \frac{\sigma_d}{\varepsilon_r} \qquad (2)$$

where M_r is the resilient modulus, σ_d is the repeated deviatoric stress applied along the vertical direction and ε_r is the corresponding recoverable portion of vertical axial strain.

Test specimens were prepared by employing plastic cylinders in which the mixtures were poured and thereafter allowed to settle with the application of no compacting action. Specimens were then cured for 1 and 3 days in controlled temperature and humidity conditions. After completion of the prescribed curing period, specimens were subjected to testing by following the protocol suggested in AASHTO T 307 for sub-base materials, which when compared to the procedure recommended for subgrade soils entails the application of higher confining and deviatoric stresses.

Prior to testing, the slabs constructed on site were allowed to cure for 1 day. In order to ensure an adequate development of hydration processes, during this short period of curing the surface of the slabs was kept wet and large ventilated heaters were continuously operated in order to guarantee a stable air temperature of approximately 15 °C.

After 24 hours of curing in the conditions described above, static plate loading tests were carried out on the slabs as per the Italian standard CNR 146 [41], with the consequent determination of the so-called deformation modulus (M_d), defined by the following equation:

$$M_d = \frac{\Delta p}{\Delta s} D \qquad (3)$$

where Δp is the increase in pressure (in MPa), Δs is the corresponding vertical displacement of the plate employed for load application (in mm), and D is the plate diameter (in mm).

As prescribed by the standard in the case of subbase courses, tests were carried out with pressure increments of 0.1 MPa up to a maximum pressure of 0.35 MPa. Deformation moduli were thereafter calculated by referring to the pressure increment applied between 0.15 and 0.25 MPa.

Specification for roadworks usually indicate minimum M_d values recommended for acceptance purposes of the order of 100 MPa for granular sub-bases and of 50 MPa for subgrades [30]. However, no previously validated requirements are available for cementitious mixtures used for filling purposes in tunnels.

Following plate loading tests, slabs were subjected to the slow passing of a fully-loaded 40 tons truck, the loading being applied by means of a front single axle with single wheels and a rear tandem axle with dual wheels. Tire inflation pressure was fixed at 0.55 MPa. The surface of the two slabs was thereafter visually inspected to assess possible displacements, distortions and/or cracks. Although such a test is empirical in nature, it was considered necessary in order to have full proof of the possibility of having a fast progression of construction operations in tunnels, with the consequent transit of hauling trucks and construction equipment on the newly-laid filling.

3. RESULTS AND DISCUSSION

3. 1 Design of the CLSM mixture

Results of the tests and analyses carried out for the definition of the optimal CLSM-R mixture and for the assessment of its sensitivity to composition changes are given in Table 3 and Fig. 4, respectively. In all cases, measurement of spread diameter D_s was supplemented by recording the occurrence of any bleeding and segregation phenomena.

Table 3. Results of flow consistency tests carried out on trial CLSM mixtures (200 kg/m^3 cement dosage).

w/c	D_s (mm)	Bleeding	Segregation
1.9	228	Y	Y
1.7	205	Y	N
1.5	198	N	N
1.3	184	N	N
1.1	167	N	N

Y: yes, phenomenon observed

N: no, phenomenon absent

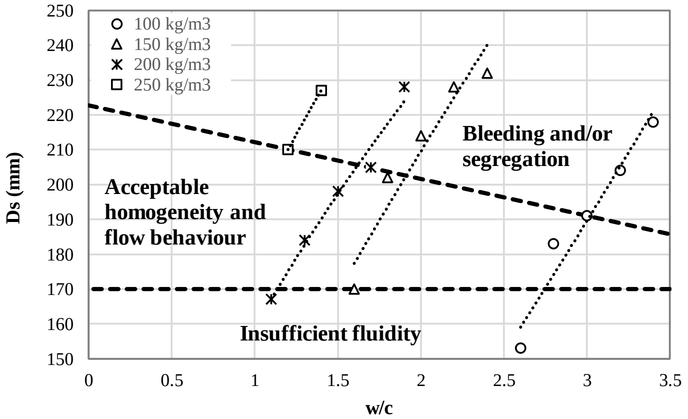

Fig. 4 Results of flow consistency tests carried out on trial CLSM mixtures (variable cement dosage)

Experimental results show that for all CLSM mixtures considered in the sensitivity study, as expected, flowability tended to increase with the increase of w/c values. However, bleeding and/or segregation phenomena occurred above certain limiting w/c values which were found to decrease with the increase of cement dosage. The same type of dependency upon cement dosage was observed in the case of limiting w/c values associated to the minimum spread considered acceptable for CLSMs (equal to 170 mm, as mentioned in section 2.4).

These outcomes can be explained by considering that in their fresh state CLSMs exhibit a behavior which is closely controlled by the quantity and consistency of the cement-water paste. This is a concept which is usually referred to in the design of self-compacting concrete [42, 43]. While paste consistency is a direct function of w/c, paste quantity can be assessed by referring to the ratio between its volume (V_p) and the volume of the granular fraction constituted by virgin aggregates and RAP (V_g). Values of V_p/V_g, calculated from the composition of the CLSMs and specific gravities of their components, are listed in Table 4 for both fluidity and homogeneity limiting conditions. It can thus be observed that there is a clear V_p/V_g range that ensures both mixture properties. When the quantity of paste is too low (i.e. with a V_p/V_g value lower than 0.38-0.44), the CLSM particles are not lubricated enough to flow under their own weight. However, as the quantity exceeds a certain threshold (i.e. when V_p/V_g is higher than 0.50-0.64), individual mixture particles are too far apart, and phase separation can consequently occur in the form of bleeding and/or segregation. These phenomena lead to the identification of w/c ranges associated to satisfactory CLSM properties which are clearly dependent upon cement dosage. In particular, it can be observed that the use of higher cement dosages leads to the need of employing dryer pastes, which however are associated to a greater width of the acceptable w/c range.

Table 4. Composition and volumetrics of the CLSM mixtures associated to limiting conditions in terms of fluidity and homogeneity.

Cement dosage (kg/m^3)	Fluidity		Homogeneity		Width of w/c range
	Min(w/c)	Min(V_p/V_g)	Max(w/c)	Max(V_p/V_g)	
100	2.75	0.44	3.02	0.50	0.27
150	1.51	0.38	1.91	0.50	0.40
200	1.14	0.41	1.62	0.64	0.48
250	n.a.	n.a.	1.20	0.61	n.a

Based on the discussion provided above, in the case of the CLSM prepared with target cement dosage (equal to 200 kg/m^3), the w/c value to be adopted for field trials and further experimental analyses (see sections 3.2-3.4) was set equal to 1.3. Such a value is located close to the center of the allowable range represented in Fig. 3, and should therefore guarantee mixture homogeneity even when taking into account possible variations in composition which may occur during plant production. Moreover, it falls within the typical range of w/c values reported in literature for CLSMs [16, 44].

3.2 Tests on fresh mixtures sampled during field production

During the plant production of the two mixtures, samples in the fresh state were subjected to testing for the assessment of fluidity (expressed in terms of spread diameter D_s, from flow consistency tests), consistency (expressed in terms of slump value, derived from Abrams cone tests) and air content (measured by means of a porosimeter, pressure method). Obtained results are given in Table 5.

Table 5. Properties of the plant-produced mixtures in the fresh state

	D_s (mm)	Slump (cm)	Air content (%)
SC-V	-	9	11
CLSM-R	195	23	12

Experimental results listed in Table 5 show that as a result of its low w/c value, standard concrete mixture SC-V exhibited poor fluidity characteristics. In fact, when subjected to the flow consistency test, it exhibited a negligible settlement under its own weight, and measurement of spread diameter was consequently impossible. Such an outcome was coherent with the very low slump value (equal to 9 cm), which as per EN 12350-2 classifies the mixture as belonging to the S2 consistency category (which corresponds to mixtures that are not self-compacting and are not suitable for pumping). It is interesting to note that measured air content of the mixture (equal to 11%) was close to the design value (equal to 15%, see section 2.2). However, residual porosity did not have any beneficial effects on the actual flow behavior of the mixture, which proved to be unsatisfactory.

Results obtained on mixture CLSM-R were coherent with those recorded in the design phase (see section 3.1). Spread diameter measured on site (equal to 195 mm) was only 6% higher than the one observed in the laboratory (equal to 184 mm), presumably as a result of small variations in composition and of the better homogeneity which was achieved by means of full-scale batch mixing. Such a result was consistent with the slump value derived from Abrams cone tests (equal to 23 cm), which classified the mixture in the S5 consistency category, corresponding to mixtures which are recommended for self-levelling applications that do not require any compaction. Finally, it should be noted that although the mixture was proportioned according to a zero-void volumetric balance, the employed air-entraining agent was effective in generating a non-negligible residual porosity, with a corresponding air content equal to 12%. It can be postulated that the presence of distributed small-size air bubbles, combined with the relatively high w/c value (and with the corresponding adequate value of V_p/V_g, see Table 4), was at the origin of the satisfactory flow and self-compacting behavior recorded for the produced mixture.

3.3 Tests on hardened mixtures sampled during field production

Mixtures sampled during plant production were employed for the preparation of several types of specimens which were subjected to laboratory tests for the assessment of mechanical properties in the hardened state. As mentioned in section 2.4, measured characteristics, which were evaluated at different curing times, included compressive strength, CBR and resilient modulus. Obtained results are displayed in Tables 6 and 7 and in Fig. 4-6.

Table 6. Compressive strength and CBR of plant-produced mixtures

	Compressive strength (MPa)				CBR (%)	
	1 day curing	3 days curing	7 days curing	28 days curing	1 day curing	3 days curing
SC-V	2.5	3.9	5.2	7.9	58.7	260.1
CLSM-R	1.1	2.8	3.6	5.3	15.0	87.4

As shown in Table 6, standard mixture SC-V exhibited a higher compressive strength than mixture CLSM-R as a result of its significantly lower w/c value (0.8 instead of 1.3). This was recorded from the very beginning of the curing process (after 24 hours), and observed up to the point at which it is generally assumed that mixtures reach stable strength conditions (at 28 days). Based on the available experimental results, it cannot be established whether or not this is the case of the considered mixtures. However, available data do indicate that strength increase occurred with a rate that for mixture SC-V was definitely higher than that of mixture CLSM-R (0.13 MPa/day instead of 0.08 MPa/day, calculated from strength values recorded at 7 and 28 days of curing). Such an outcome seems to suggest that mixture SC-V could have further developed its strength at very long curing times, whereas CLSM-R may have been very close to its stable conditions. Thus, excavatability of the former mixture in the very long term could be jeopardized. On the contrary, mixture CLSM-R seemed to be acceptable from such a viewpoint, and in fact the strength value recorded after 28 days of curing (equal to 5.3 MPa) was lower than the threshold value typically referred to for this type of material [6].

Results obtained from CBR tests (Table 6) confirm the superior strength and faster strength development of mixture SC-V with respect to mixture CLSM-R, and once again this can be explained by referring to the difference between their w/c values. Such an interpretation is consistent with the mechanics of the CBR testing procedure, in which penetration of the loading piston into the test specimen occurs by deforming and possibly fracturing the cement paste and the fine aggregate fraction with which it is intimately mixed. Furthermore, relative displacements may occur at the interfacial transition zone, and it may be postulated that such a phenomenon may be more significant in the presence of RAP as a result of the existence of thin bitumen films covering its aggregates.

It should be emphasized that CBR testing is typically employed for the characterization of subgrade soils. Thus, although its inclusion in the investigation was justified by the expectation of obtaining a soil-type response under loading in the early stages of curing (i.e. during construction), results obtained on cement-bound mixtures should be analyzed with due care. In particular, they cannot be simply compared to specification requirements set for sub-base materials and subgrade soils [30], given that they refer to materials of a different type and are typically obtained from tests carried out by following a protocol which differs from the one adopted in this investigation (see section 2.4).

All the results obtained from resilient modulus tests performed on the two mixtures after 1 and 3 days of curing are presented in Fig. 4, where they are plotted as a function of the first stress invariant (θ) which provides an overall quantification of the global level of stress. Experimental data are compared to the typical variation range indicated by Huang for standard granular sub-bases [45]. It can be observed that both mixtures exhibited a stress-stiffening behavior (i.e. resilient modulus tended to increase for increasing values of θ) and that measured values were contained within the abovementioned variation range. Furthermore, while the two mixtures showed a comparable stiffness after 1 day of curing, mixture SC-V developed a higher stiffness than mixture CLSM-R after 3 days of curing as a result of the lower w/c value adopted in its formulation. On the contrary, the stiffness gain achieved by mixture CLSM-R when passing from 1 to 3 days of curing was quite limited. These observations are consistent with those made when analyzing the results of compressive strength and CBR tests (Table 6).

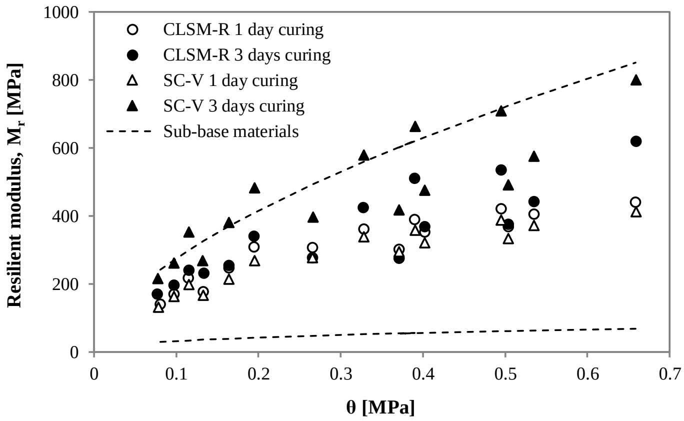

Fig. 5 Results of resilient modulus tests carried out on the plant-produced mixtures

In order to more thoroughly analyze the results provided in Fig. 5 and to discuss the non-linearity of the resilient response of the considered mixtures, experimental data were fitted to the following model proposed by Puppala et al. [29]:

$$M_r = k_1 \cdot p_a \cdot \left(\frac{\sigma_3}{p_a}\right)^{k_2} \cdot \left(\frac{\sigma_d}{p_a}\right)^{k_3} \quad (4)$$

where p_a is atmospheric pressure (in MPa), σ_3 is confining stress (in MPa), σ_d is deviatoric stress (in MPa), k_1, k_2 and k_3 are material-dependent constants.

Results obtained from model fitting are shown in Fig. 6, while the corresponding values of the material-dependent constants and associated coefficients of determination (R^2) are listed in Table 7. It can be noticed that the employed model proved to be perfectly suitable for the representation of experimental data, with an overall excellent match between measured and calculated resilient modulus values. The dependency upon confining stress, indicated by the value of constant k_2, was found to be similar for the two mixtures in the very short term (i.e. after 1 day of curing), when their behavior was found to be close to that of unbound granular materials. In such conditions the mixtures also exhibited a similar dependency upon deviatoric stress, as proven by the small difference between the respective k_3 values, and an almost equivalent lower limiting value of the resilient modulus (k_1). As a consequence of the 3 days curing and of the associated development of a stiffer binding cementitious matrix, both mixtures changed their type of response under loading, showing an almost negligible dependency upon confining stress as proven by the very low k_2 values. As in the case of 1 day of curing, the mixtures also exhibited a similar dependency upon deviatoric stress (i.e. similar k_3 values), with a difference in the stiffness at 3 day curing mainly deriving from the significant difference between the respective k_1 values (equal to 5067.1 MPa and 3795.9 MPa for mixtures SC-V and CLSM-R, respectively).

Fig. 7, in which the measured resilient modulus values are directly plotted as a function of deviatoric stress regardless of applied confining stress, supports the discussion provided above on the type of non-linear response of the considered mixtures. It can be observed that resilient modulus clearly increased with deviatoric stress, although in the very short term (i.e. after 1 day of curing) it reached an upper limiting value equal to approximately 400 MPa for stresses of the order of 0.125 MPa.

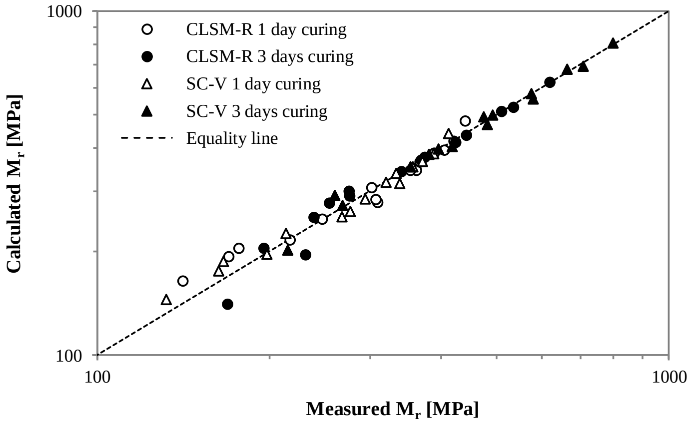

Fig. 6 Comparison between measured and calculated resilient modulus of plant-produced mixtures

Table 7. Model parameters of resilient modulus response of the plant-produced mixtures

	1 day curing				3 days curing			
	k_1	k_2	k_3	R^2	k_1	k_2	k_3	R^2
SC-V	3203.5	0.2102	0.2712	0.9784	5067.1	0.0475	0.4901	0.9885
CLSM-R	3466.6	0.1929	0.2821	0.9633	3795.9	0.0708	0.5126	0.9657

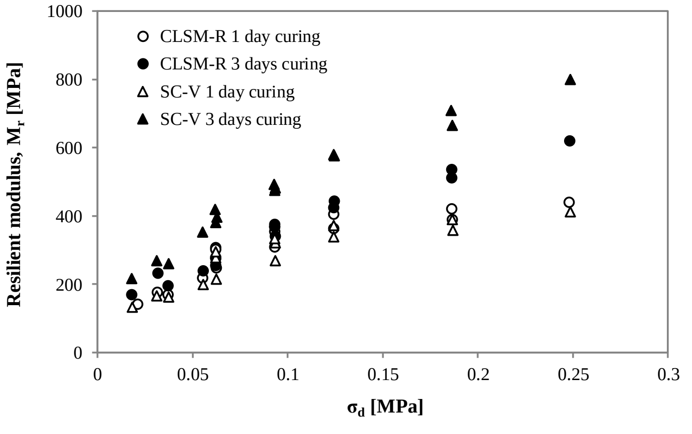

Fig. 7 Influence of deviatoric stress on resilient modulus of plant-produced mixtures

3.4 Tests on field-constructed slabs

Slabs constructed in the premises of the concrete batching plant were subjected to testing for the assessment of the achieved level of bearing capacity after 24 hours of curing. As mentioned in section 2.4, the evaluation included determination of the deformation modulus (M_d) followed by the actual loading of a 40 tons truck.

Results obtained from plate loading tests showed that both mixtures reached a satisfactory bearing capacity, with M_d values equal to 103.4 MPa and 300 MPa for the SC-V and CLSM-R mixture, respectively. Both values are greater than the typical acceptance limit considered for standard pavement foundations, generally set equal to 100 MPa [30].

Although in the laboratory investigation the CLSM-R mixture after 1 day of curing exhibited lower values of compressive strength, CBR and resilient modulus than the SC-V mixture, in the field it exhibited a greater bearing capacity. Such an outcome is believed to be the result of the enhanced flowability of the CLSM-R mixture which was designed (see section 3.1) as a self-compacting composite (with an acceptable spread diameter and slump characteristics which are associated to the S5 consistency category). On the contrary, the SC-V mixture was observed to be of the S2 consistency category and it is possible that the simple use of vibrating needles may have been of limited efficiency, with the consequent non-uniform settlement of the mixture in the formwork.

The difference in bearing capacity of the two slabs was not reflected by significant differences in their response under the loading action of the 40 tons truck. In fact, in both cases only minor deformations were observed on their surface and no visible cracks were developed.

4. PERFORMANCE-BASED ACCEPTANCE CRITERIA

Based on the experimental results and observations illustrated in the previous section, recommendations for future applications of cement-bound materials in road tunnel pavement foundations can be made in the form of performance-based acceptance criteria. It should be emphasized that such criteria derive from an investigation which included a wide array of relevant tests which however were performed only on two different mixtures. Thus, they need to be considered as preliminary and will necessarily undergo future validation.

With respect to flowability and consistency, acceptance thresholds may be defined as a function of the expected complexity of the arrangement of conduits buried in the foundation. In the absence of buried utilities or for those cases which are characterized by wide clearances between ducts, the use of Portland cement concrete mixtures belonging to consistency category S2 [35] may be sufficient, with no specific requirement on the spread diameter measured as per ASTM D6103 [34]. In such case, the use of needle vibrators to ease compaction is mandatory. In the presence of multiple ducts with narrow clearances, it is recommended to assume a minimum required spread of 170 mm [6] and an S5 consistency category. These results can be achieved by employing a properly designed CLSM.

When focusing on the strength properties, care should be taken in checking that the value reached by compressive strength after 28 days of curing is lower than 8.3 MPa [6] in order to ensure an adequate excavatability regardless of the type of cement-bound mixture employed for the formation of the pavement foundation. With respect to the minimum required short-term strength, different accetance thresholds may be defined as a function of the anticipated structural needs of the foundation. However, based on the experimental work documented in this paper it can be observed that a satisfactory resistance to the loading of heavy vehicles, simulating the action of construction equipment, was achieved for mixtures which exhibited a compressive strength greater than 1 MPa after 1 day of curing. Thus, such a value can be considered as a tentative acceptance limit.

As discussed previously, carrying out the CBR test on cement-bound mixtures may be complicated and requires deviations from the standard procedure defined for unbound sub-base materials and subgrade soils. As a consequence, the use of such a test is not recommended for acceptance purposes until further studies will be performed and it is believed that strength assessment can be based exclusively on the evaluation of compressive strength.

Requirements on the bearing capacity of the pavement foundation may be defined as a function of the desired structural behavior of the entire pavement during its service life. In such a context, time-dependent and stress-dependent resilient modulus values need to be employed as input values to the multi-layer elastic calculations which are performed for the assessment of cumulative damage under traffic loading. Resilient modulus thresholds with a general validity cannot be defined; rather, they should be specified for each project by the pavement designer.

With respect to the deformation modulus coming from plate loading tests carried out in the short term (after 24 hours curing), for acceptance purposes it seems to be reasonable to refer to the same minimum value which is typically considered for standard pavement foundations, equal to 100 MPa [30]. In fact, as proven by the results collected in the investigation, by satisfying such a requirement, cement-bound foundation mixtures are not damaged by early construction traffic. Depending upon the specific needs of each project and of the assumptions made as part of pavement design, the minimum required deformation modulus can be increased in order to guarantee the construction of a foundation characterized by a stiffer response under loading.

Finally, thermal properties of pavement foundation materials should also be considered as part of their acceptance process in those cases in which buried underground utilities include high-voltage transmission lines. From previous work carried out by the Authors, it is recommended to refer to a minimum thermal conductivity value, measured as per ASTM D5334 [46], of 0.8 W/(m·K). However, acceptance of any mixture should also be supported by ampacity calculations which may be heavily dependent upon the actual arrangement of cables [47].

5. CONCLUSIONS

The feasibility study described in this paper leads to the general conclusion that a properly designed CLSM can be used for the formation of pavement foundations in tunnels. In fact, as indicated by the outcomes of laboratory and field tests, this type of mixture can exhibit both a high degree of flowability and mechanical properties which are satisfactory in the short and long term. The comparison with a reference low-strength Portland cement mixture, which was also found to be suitable for pavement foundations, also highlighted the fact that CLSMs may exhibit superior properties in terms of excavatability and homogeneity deriving from self-compacting properties. Finally, CLSMs can also be considered more attractive as a result of the proven possibility of easily including in their structure a relevant quantity of RAP, which reduces production costs and increases overall sustainability of construction operations.

It should be underlined that despite their desirable characteristics, CLSMs have never been employed for the formation of pavement foundations in tunnels. In order to contribute to the introduction of such mixtures in full-scale applications, based on the results obtained in the experimental study, performance-based acceptance criteria were proposed. It is envisioned that they may be adjusted in the future as more studies are carried out.

Although the feasibility study focused on the use of cement-bound mixtures in pavement foundations of road tunnels, it can be hypothesized that similar applications may be possible in open roadways. In particular, CLSMs may be of great interest as a result of their quick installation and of the absence of compaction operations. In such a context, the preliminary specifications provided in this paper may be used as a reference even for such applications.

Further research developments should focus on the fine-tuning of the formulation of CLSMs for pavement foundations by trying to increase the volume of employed recycled components. In particular, it is envisioned that significant benefits can be achieved by making use of granular waste materials which may be included in the very fine fraction of the CLSM aggregate skeleton in order to enhance mixture flowability and possibly allow a reduction of cement dosage. Further improvements in the design and performance of these mixtures may also be sought by employing appropriate superplasticizer and accelerating additives. Finally, a direct assessment of long-term behavior will be essential in order to guarantee, with a higher level of confidence, the achievement of pavement performance as hypothesized in design.

CONFLICT OF INTEREST

The Authors declare that they have no conflict of interest.

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Figure Legend

Fig. 1 Typical cross section of pavement in road tunnel

Fig. 2 Particle size distribution of employed aggregates and RAP

Fig. 3 Particle size distribution of the design mixtures

Fig. 4 Results of flow consistency tests carried out on trial CLSM mixtures (variable cement dosage)

Fig. 5 Results of resilient modulus tests carried out on the plant-produced mixtures

Fig. 6 Comparison between measured and calculated resilient modulus of plant-produced mixtures

Fig. 7 Influence of deviatoric stress on resilient modulus of plant-produced mixtures

Table Title

Table 1. Specific gravity of employed aggregates, RAP and cement

Table 2. Composition of the aggregate skeleton of the design mixtures

Table 3. Results of flow consistency tests carried out on trial CLSM mixtures (200 kg/m^3 cement dosage).

Table 4. Composition and volumetrics of the CLSM mixtures associated to limiting conditions in terms of fluidity and homogeneity.

Table 5. Properties of the plant-produced mixtures in the fresh state

Table 6. Compressive strength and CBR of plant-produced mixtures

Table 7. Model parameters of resilient modulus response of the plant-produced mixtures