Mix design and mechanical characterization of self-compacting cement-bound mixtures for paving applications

Mix design and mechanical characterization of self-compacting cement-bound mixtures for paving applications / Choorackal, Eldho; Riviera, Pier Paolo; Santagata, Ezio. - In: CONSTRUCTION AND BUILDING MATERIALS. - ISSN 0950-0618. - ELETTRONICO. - 229:(2019), pp. 1-11. [10.1016/j.conbuildmat.2019.116894]

Publisher:
Elsevier Ltd

Published
DOI:10.1016/j.conbuildmat.2019.116894

MIX DESIGN AND MECHANICAL CHARACTERIZATION OF SELF-COMPACTING CEMENT-BOUND MIXTURES FOR PAVING APPLICATIONS

Eldho Chooracka, Pier Paolo Riviera, Ezio Santagata*

Department of Environment, Land and Infrastructure Engineering
Politecnico di Torino, Corso Duca degli Abruzzi, 24, 10129 Torino, Italy

(*) corresponding author: ezio.santagata@polito.it
phone: +390110905633; Fax: +390110905614

Abstract

This paper presents the results of an experimental investigation which focused on self-compacting cement-bound mixtures to be employed for paving applications, especially for pavement foundations in road tunnels. Recipes of the investigated mixtures, which contain reclaimed asphalt pavement material and mineral sludge, were defined by optimizing the packing of the aggregate skeleton and by checking the flowability characteristics of cement pastes and composite mixtures. Long-term stiffness and strength properties were evaluated by means of triaxial and quick shear tests. Based on the obtained results and on their interpretation, a mix design procedure was proposed. General conclusions were drawn with respect to the behaviour of self-compacting cement-bound mixtures and to the possible developments of future research.

Keywords: cement-bound mixtures; mix design; flowability; resilient modulus; quick shear strength

1. INTRODUCTION

Use of cement-bound or cement-stabilized mixtures in pavement construction is quite common due to the remarkable contribution they can provide to the enhancement of bearing capacity [1-4]. Past studies have widely discussed their mix design and performance-related characterization, and as a consequence they are included as standard materials in technical specifications and design manuals [5-7].

In the specific case of road tunnels, the use of cement-bound mixtures can be of interest not only for the formation of the sub-base, but also for the construction of the so-called foundation, which is comprised between the base of the tunnel and the pavement [8-9]. In particular, it may be especially attractive to make use of self-compacting cement-bound mixtures (hereafter indicated as SC-CBMs) which can be quickly laid on site with no need of compaction even in the presence of a congested network of buried utilities [10]. Such mixtures are required to possess a limited strength, which corresponds to an acceptable excavatability, since they should allow easy access to buried conduits in case of maintenance. Furthermore, when designed with the supplementary objective of guaranteeing a low thermal resistivity, they can aid the dissipation of heat produced by high-voltage cables which are embedded in the pavement foundation [10-12].

Based on the discussion provided above, it is apparent that SC-CBMs are quite similar to Controlled Low Strength Materials (CLSMs), which are usually employed for trench filling operations [13]. However, they are different in terms of their composition, which entails the presence of coarser aggregates, and of their expected functions in service, which include bearing capacity.

Typical components of SC-CBMs are fine and coarse aggregates, Portland cement, water, and various admixtures. However, their composition can be much more complex since they may also include a wide range of industrial by-products and recycled materials to reduce costs and increase sustainability of construction operations. As in the case of CLSMs, cement kiln dust, fly ash and slag can be used as partial replacements of cement, while virgin aggregates can be substituted by construction and demolition wastes, recycled concrete aggregates, scrap tyre particles and reclaimed asphalt pavement (RAP) [14-20].

Whatever the available set of component materials, SC-CBMs should be designed based upon their performance requirements. However, no mix design method is currently recognized as a standard.

As illustrated in this paper, the Authors worked on the development of a mix design procedure for SC-CBMs in which optimal mixture composition is identified as a function of engineering requirements which are expressed in terms of flowability, stiffness and strength. These properties are dependent upon several factors, among which the most relevant are cement content, water content and particle size distribution. A further tailoring of the characteristics of SC-CBMs can be obtained by making use of the various admixtures and by adjusting their dosage.

The proposed method combines elements which were drawn from other studies carried out on CLSMs and on Self-Compacting Concrete (SCC), which share with SC-CBMs common flowability characteristics. SCC design methods are well-defined, whereas CLSMs are mostly designed by means of empirical approaches [21].

A key role in the definition of the optimal mixture recipe was given to aggregate packing, which in the mix design of SCC is addressed by referring to target distributions containing relevant portions of filler [22-24]. Such a feature was also considered in the investigations carried out on CLSMs by Pajudas et al. [25], who based the choice of optimum proportions of constituents on wet packing tests carried out on a large number of trial mixtures.

With respect to the assessment of mechanical properties, the main references were taken from research work carried out on CLSMs, which possess low strength characteristics that are similar to those of SC-CBMs. In particular, it was observed that Janardhanam et al. [26] proposed a mix design method which takes into account workability, setting time, mechanical properties and durability, while Bhat and Lovell [27] suggested a procedure which included the evaluation of unconfined compressive strength. Consideration was also given to the studies carried out by Bouzalakos et al. [28], which employed response surface methods to highlight the sensitivity of mixture behaviour to variations of the different components. Finally, relevant information was drawn from the work of Alizadeh [29] which led to the definition of a mix design procedure that requires the combined adjustment of various ratios defining the composition of CLSMs.

Development of the proposed mix design method was based on a laboratory experimental investigation carried out by considering a given set of component materials. These included virgin aggregates and two granular components of recycled origin. Given that flowability is a prerequisite of SC-CBMs, use was also made of a superplasticizing additive. Experimental results highlighted the effects of several composition parameters on the flowability and mechanical properties of the considered SC-CBMs. As a result, the mix design procedure was rationalized and presented in a form which may be of practical use to designers.

2. MATERIALS AND METHODS

Aggregate fractions employed for the mix design of SC-CBMs were crushed silica coarse sand (0-6 mm) and medium-fine gravel (8-16 mm). In addition, for the formation of the aggregate skeleton, two further granular materials were considered: RAP coming from aged and distressed pavement, and mineral sludge obtained from the washing of crushed natural aggregates. It was envisioned that by including these recycled materials in the SC-CBMs, they would lead to the design of mixtures with reduced production costs and enhanced sustainability characteristics [30-34].

RAP, which was provided by a local contractor, derived from the milling of dense-graded asphalt wearing courses, but its exact age was unknown. Since SC-CBMs have to satisfy the previously mentioned long-term excavatability requirements, the potential strength reduction due to the presence of RAP in these mixtures was considered as a positive factor. Similar advantages were attributed to the use of mineral sludge, which does not lead to any pozzolanic reactions in the presence of water. Furthermore, the fineness of the mineral sludge was regarded as essential in order to improve the flowability and stability of the SC-CBMs.

The virgin and recycled granular materials indicated above were preliminarily oven-dried until reaching constant weight either at 105°C (as in the case of the aggregate fractions and of the mineral sludge) or at 60°C (in the case of the RAP). A lower drying temperature, which entailed longer conditioning times, was selected for the RAP in order to prevent the softening of residual bitumen to take place.

All the dried components were then subjected to sieve analyses for the determination of particle size distribution as per EN 933-1 [35] and to pycnometer tests for the determination of specific gravity as per EN 1097-6 [36]. RAP samples were also subjected to the determination of bitumen content as per EN 12697-39 [37], which entails the evaluation of the mass loss caused by a high-temperature treatment (at 540°C).

Cement pastes and trial SC-CBMs were prepared in the laboratory by employing a standard Portland cement and a commercially available superplasticizer. According to the information provided by suppliers, cement was of the CEM I R42.5 type (EN 197-1) [38], with a specific gravity of 3.150, while the superplasticizer (Advaflow 455, Grace Products) was a liquid polycarboxylate product with a specific gravity of 1.060. Whenever used, the superplasticizer was employed with the dosage suggested by the supplier, equal to 0.5% by weight of cement.

Cement pastes and SC-CBMs were prepared by making use of a mechanical mixer in batches of 200 g and 2000 g, respectively. The superplasticizer was added in the required quantity by preliminarily mixing it with the water to be employed in each batch.

Immediately after mixing, both the cement pastes and the trial SC-CBMs were subjected to flowability tests. In the case of SC-CBMs these tests were carried out by following the procedure indicated in ASTM D6103 [39], while for the cement pastes the procedure, although similar to the standardized one, was much simpler.

As indicated in ASTM D6103 [39], the standardized procedure involves the filling with fresh cementitious mixture of an open-ended cylinder (of 75 mm diameter and 150 mm height, with a corresponding maximum theoretical volume of 662.7 cm^3) resting on a horizontal, smooth and non-absorbent surface. The cylinder is then quickly lifted, allowing the mixture to spread under the effect of its own weight. Following such an operation, the so-called spread diameter (D_s, expressed in mm) is measured as the average of two readings taken along perpendicular directions. Furthermore, the mixture is visually inspected in order to detect the signs of any undesired phenomenon such as segregation or bleeding.

When considering CLSMs employed for trench filling applications, it is usually required that D_s is comprised between 170 mm and 250 mm in order to ensure a high flowability and simultaneously guarantee the absence of any bleeding or segregation phenomena [13]. In the case of the SC-CBMs, which contain coarse aggregates which are larger than those typically employed in CLSMs, greater values of D_s are expected. Thus, a target range of 200-350 mm was considered more appropriate. Visual verification of a satisfactory mixture stability (i.e. absence of bleeding or segregation) was retained as a fundamental phase of testing. Values of D_s greater than 350 mm did not seem compatible with mixture stability which needs to be absolutely avoided in order not to jeopardize the long-term behaviour of the mixtures in service.

For the analysis of the flow characteristics of cement pastes, a smaller cylinder was employed, with a volume of 283.7 cm^3. Such a size was found to be adequate with respect to the volume of the batches which could be prepared in a representative manner and compatible with the observed spreads. Rather than measuring D_s values, flowability tests carried out on the pastes only entailed the visual assessment of the uniformity of flow and of the possible occurrence of clear phase separation phenomena. Although such a test is merely qualitative, it was found to be useful in order to discriminate between the flow properties of the various cement pastes.

In order to assess the mechanical properties of SC-CBMs in the hardened state, for each trial mixture four specimens were cast in cylindrical moulds (diameter 100 mm, height 200 mm) with no application of any vibration and levelling actions. Specimens were then demoulded after 24 hours and sealed in plastic bags in order to ensure an optimal curing process. Such a process was carried out by storing the specimens at room temperature for 28 days, when it was considered that fully cured conditions were reached.

Hardened SC-CBM specimens were subjected to testing in accordance to AASHTO T 307-99 [40] (sub-base protocol) for the determination of the resilient modulus (M_r). Such a parameter is usually adopted for the description of the stress-strain response of soils and granular materials under traffic loading conditions [41-43] but has also been employed to assess the mechanical behaviour of cement-stabilized and cold-recycled bituminous mixtures [44-46]. Tests are carried out by making use of a triaxial apparatus which allows the simultaneous control of confining pressure (σ_3), which is kept constant, and of deviatoric stress applied in the vertical direction (σ_d), which varies in time by following a haversine-shaped function. Corresponding strains (ε_1), of reversible and permanent nature (ε_{1r} and ε_{1p}, respectively), are measured in the vertical direction.

According the reference standard, a single specimen is subjected to 15 loading sequences composed of 100 cycles with various combinations of σ_3 and σ_d which are comprised in the 0.0207-0.1379 MPa and 0.0186-0.2482 MPa, respectively. These stress components lead to values of the bulk stress, given by the sum of the three principal stresses applied to the test specimen, comprised between 0.08 MPa and 0.66 MPa, thereby allowing experimenters to capture the non-linear response of the considered materials. According to its definition, for each considered stress condition, resilient modulus is calculated by means of the following expression:

$$M_r = \frac{\sigma_d}{\varepsilon_{1r,max}} \tag{1}$$

where $\varepsilon_{1r,max}$ is the maximum value of the recoverable portion of vertical axial strain recorded in the 100 loading cycles associated to the applied deviatoric stress σ_d.

In absolute terms, no threshold values can be fixed for the definition of M_r acceptance requirements in the case of SC-CBMs. This is due to the fact that for each specific application the minimum long-term bearing capacity is inherently dependent upon pavement cross section, expected loading conditions and target design life [8]. Nevertheless, it may be considered that technical specifications frequently refer to a minimum modulus assumed in pavement design calculations which for roads of primary importance is of the order of 100-120 MPa [7, 47-49]. In the case of road tunnels, where it may be convenient to reduce the thickness of the upper bound layers as a results of high service temperatures, such a limit may be increased on a project-specific base [8].

After being tested for the evaluation of resilient modulus, and by making use of the same triaxial equipment, SC-CBM specimens were subjected to the so-called quick shear tests [40]. As per the corresponding standard, applied axial load was progressively increased by imposing a vertical strain rate of 1 %/min, which approximately corresponds to a displacement rate of 2 mm/min. Although the reference standard requires the application of a confining pressure for subgrade soils and granular subgrades (equal to 27.6 kPa and 34.5 kPa, respectively), in the case of the SC-CBMs tests were carried out by applying vertical loads only. Thus, the adopted procedure is similar to the one described in ASTM D1633 [50] for the determination of compressive strength of soil-cement, which requires a slightly lower displacement rate (equal to 1.3 mm/min).

In quick shear tests, values of applied load are recorded by a load cell and can be converted into normal vertical stresses (σ_1), while average axial strains induced in the specimens (ε_1) can be calculated from imposed vertical displacements. As a result, stress-strain curves can be obtained, and the values corresponding the peak load may be indicated as quick shear strength (σ_{qss}) and strain at failure (ε_f).

When considering the failure properties of SC-CBMs, excavatability requirements need to be taken into account. In such a context, upper limits have been defined for CLSMs by referring to a maximum compressive strength determined on cylindrical specimens equal to 2.1 MPa [51-52]. Such a limit was maintained when analysing the results of tests carried out with the quick shear protocol in the absence of confining pressure.

Table 1 provides a synthesis of the experimental tests carried out on the various materials. Listed codes correspond to the section numbers in which obtained results are presented and discussed.

Table 1 Synthesis of experimental tests

Materials	Sieve analyses	Specific gravity tests	Flowability tests	Resilient modulus tests	Quick shear tests
Granular components	3.1	3.1	-	-	-
Cement pastes	-	-	3.2	-	-
SC-CBMs	-	-	3.4	3.5	3.5

3. RESULTS AND DISCUSSION

3.1 Characterization of granular components

Results obtained from particle size distribution analyses and specific gravity (SG) tests are provided in Fig. 1 and Table 2, respectively.

It was observed that silica sand and RAP were characterized by continuous size distributions which seemed suitable to form most part of the composite skeleton of the SC-CBMs, whereas the available gravel was almost single-sized, and therefore fit for use in order to provide bulk effects to the mixtures. In the case of the mineral sludge, it was recorded that it possessed a very high content of filler, of the order of 60%. Such a characteristic made it a very good candidate to ensure an adequate filling of the voids structure of SC-CBMs and to guarantee a proper flowability of their cementitious paste.

With respect to SG values, very similar values were recorded for the aggregates and sludge (of similar lithological origin), whereas the RAP fraction presented a significantly lower value due to the presence of oxidized bitumen.

Finally, it should be mentioned that ignition tests carried out for the determination of binder content of the RAP fraction yielded an average value (from two replicates) of 4.60% with respect to the total mass of aggregates.

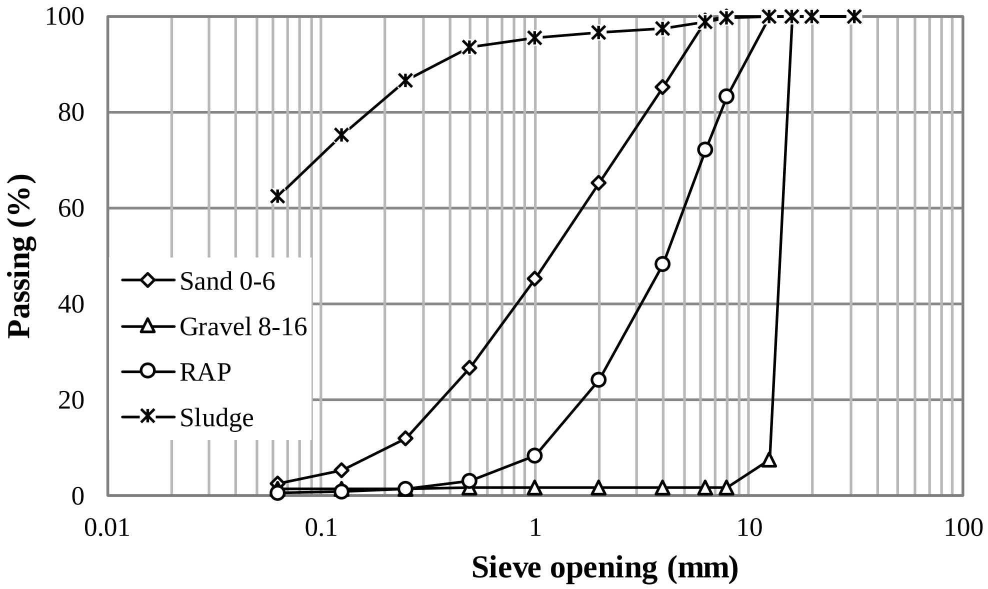

Fig. 1. Particle size distribution of aggregates, RAP and mineral sludge

Table 2. Specific gravity of aggregates, RAP and mineral sludge

Fraction	SG
Sand 0-6	2.745
Gravel 8-16	2.733
RAP	2.527
Sludge	2.785

3.2 Flowability of cement paste

Cement paste in SC-CBMs not only controls the time-dependent development of stiffness and strength, but also has a direct effect on their flowability characteristics in the fresh state. Thus, identification of the optimal composition of cement paste was carried out by means of the simple flowability tests described in section 2.

Tests were performed on water-cement pastes prepared with and without superplasticizer. Obtained results indicated that for w/c values increasing up to 0.60, regardless of the presence of the superplasticizer, the pastes did not reach sufficiently fluid conditions in order to evenly spread under their own weight. Satisfactory flow was observed when starting to consider w/c values equal to or higher than 0.70. Thus, as explained in detail in section 3.4, such a threshold value was employed as a reference for the preparation of SC-CBMs which were subjected to flowability tests carried out in accordance to ASTM D6103 [39].

3.3 Identification of target particle size distribution

The optimal combination of the available granular materials composing the aggregate skeleton of the SC-CBMs was identified by considering their combined particle size distribution and by minimizing its deviations from a reference curve. Such a curve, which is also known as the “modified Andersen and Andreasen curve”, was proposed by Funk and Dinger [53] for the design of SCCs and is given by the following expression:

$$P(D) = 100 \cdot \frac{({D_{max}}^{q} - D^{q})}{({D_{max}}^{q} - {D_{min}}^{q})} \tag{2}$$

where D is the diameter of aggregate particles (in mm), P(D) (expressed in %) is the cumulative percentage passing the sieve with opening equal to D, D_{max} is the maximum diameter of aggregate particles in the mixture (in mm, fixed at 16 for all mixtures and corresponding to a P(D) equal to 100%), D_{min} is the minimum diameter of aggregate particles in the mixture (in mm, assumed to be equal to 5 µm for all mixtures), q is the so-called distribution modulus.

The distribution modulus q defines the balance of coarse and fine aggregates within the lithic skeleton. As reported in literature [22], smaller values of q are required in order to increase the volume of fines, thus obtaining a more suitable packing of the aggregate structures. The values of q can vary between 0 and 1 depending upon workability requirements, even though for highly flowable mixes values lower than 0.23 are usually adopted [54].

It should be underlined that in the definition of the particle size distribution of the SC-CBMs, the effects associated to the presence of the cement particles was not considered. This approximation is reasonable since the cement dosage adopted in SC-CBMs is generally comprised between 30 kg/cm^3 and 100 kg/cm^3. As indicated in section 3.4, cement dosage of the SC-CBMs prepared during the investigation was fixed at 60 kg/m^3.

Results obtained by optimizing the composition of the aggregate skeleton of the SC-CBMs are given in Table 3. These are listed as a function of the distribution modulus, for which three different values were considered (equal to 0.21, 0.23 and 0.25), centred on the previously mentioned reference value of 0.23. Corresponding particle size distributions are displayed in Fig. 2.

Table 3. Composition of the aggregate skeleton of selected SC-CBMs

Fraction	Percentage by weight (%)		
	q = 0.21	q = 0.23	q = 0.25
Sand 0-6	34	33	33
Gravel 8-16	10	11	11
RAP	28	30	32
Sludge	28	26	24

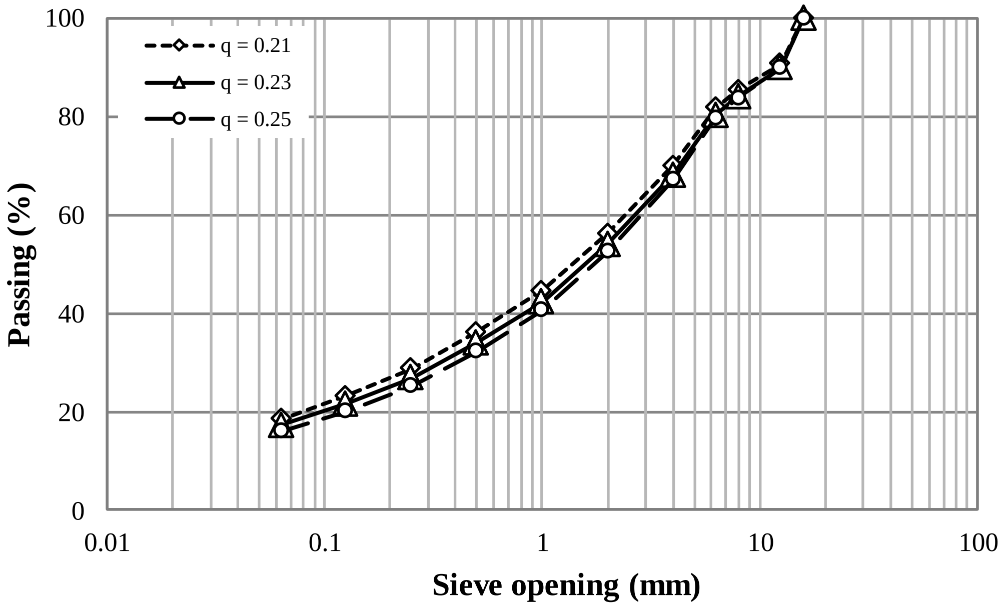

Fig. 2. Particle size distribution of the aggregate skeleton of SC-CBMs

3.4 Flowability of SC-CBMs

Composition of the SC-CBMs subjected to flowability tests as per ASTM D6103 [39] contained optimized aggregate skeletons identified as indicated in section 3.3 and a reference Portland cement dosage of 60 kg/m^3. With respect to cement paste, results obtained from flowability tests carried out as described in section 3.2 indicated that a minimum w/c equal to 0.70 was necessary in order to achieve satisfactory flowability characteristics. However, in SC-CBMs, which are characterized by a significant quantity of particles passing the 0.075 mm sieve, rather than referring to w/c, it was considered more appropriate to base the definition of paste composition on an alternative and more meaningful parameter, the so-called water-to-powder ratio (w/p) [55]. In this case, “powder” is the term which is used to collectively indicate Portland cement and the filler fraction, which for the considered SC-CBMs mainly derives from the contribution of mineral sludge. As a result of this rationale, when defining the composition of trial SC-CBMs, it was postulated that the previously identified w/c threshold (equal to 0.70) could be employed to estimate the corresponding value of w/p. For such a purpose, the different specific gravity of Portland cement and powder (equal to 3.150 and 2.785, respectively, see Table 2) were taken into account by converting the w/c value into a ratio by volume and by thereafter translating it into a w/p ratio by weight. This simple calculation led to a reference value of w/p equal to 0.80, to be employed for the definition of the composition of SC-CBMs. Nevertheless, it was considered essential to directly evaluate the flowability of SC-CBMs as a function of the variations of this parameter. Since in the tests carried out on cement pastes the benefits of using the superplasticizer were appreciated in terms of stability and uniformity, all SC-CBMs subjected to testing were prepared by employing such an additive with its standard recommended dosage (equal to 0.5% by weight of cement).

In order to capture the effects of variations of both q (which dictates the quantity of cementitious paste in the mixture) and w/p (which controls the consistency of the mixture in the fresh state), five different mixtures were prepared. Three were characterized by a constant w/p value, equal to 0.80, and a variable q, equal to 0.21, 0.23 and 0.25 (previously identified as discussed in section 3.3). The other two possessed a constant q value, equal to 0.25, and a variable w/p, equal to 0.75 and 0.70. In the rest of the paper the various mixtures are associated to a code which combines q and w/p values (e.g. “0.21-0.80”).

Results obtained in this second stage of flowability tests carried out on the SC-CBMs are shown in Table 4, while images of the specimens after spreading are provided in Fig. 3.

Table 4. Results of flowability tests carried out on SC-CBMs

Mixture	D_s (mm)
0.21-0.80	300
0.23-0.80	320
0.25-0.80	350
0.25-0.75	260
0.25-0.70	150

q = 0.21
w/p = 0.80

q = 0.23
w/p = 0.80

q = 0.25
w/p = 0.80

q = 0.25
w/p = 0.75

q = 0.25
w/p = 0.70

Fig. 3. SC-CBM specimens subjected to flowability tests

When considering the results obtained on the first three SC-CBMs listed in Table 4, it was observed that for a given value of w/p (equal to 0.80), the progressive increase of q, which corresponds to a reduction of the content of fines, led to an enhancement of flowability, with increasingly high values of D_s. However, visual observations made on the SC-CBM samples indicated that such a change in behaviour in terms of flowability was coupled with a slight reduction of homogeneity displayed after spreading (see Fig. 3). These outcomes are due to the fact that when the consistency of the paste remains constant (i.e. with a constant w/p), as its volume is reduced (i.e. with an increasing q), its overall lubricating effect within the bulk structure of the mixture tends to decrease. For the explored range of q values, variations of D_s were quite limited, all the measured values being contained within the previously defined target range of acceptance (200-350 mm, see section 2). Physical expectations suggest that the reduction in D_s associated with the decrease in q could be compensated by an increase of w/p, which would reduce paste consistency. However, trials carried out in the laboratory indicated that such modifications could not to be operated since the corresponding SC-CBMs showed clear signs of bleeding and segregation.

When focusing on the last three mixtures listed in Table 4, experimental results indicated that by keeping the q value constant (equal to 0.25) and by reducing w/p, a significant reduction of flowability was obtained. These results are in line with those discussed above, since they can be explained by referring to the progressive increase of paste consistency (i.e. reduction of w/p) associated to the presence of smaller quantities of free water in the given volume of powder paste (i.e. with a constant q), which leads to a reduction of lubricating effects. Obtained results showed that the SC-CBMs were extremely sensitive to variations of w/p, D_s being reduced to 260 mm in the case of w/p equal to 0.75, and to 150 mm for the mixture with w/p equal to 0.70. The first mixture met the D_s requirements, while the second one was not acceptable from such a viewpoint. It can be postulated that adjustments to the flow behaviour of these last two mixtures could be obtained either by increasing w/p (and therefore going back to the formulation of the third mixture listed in Table 4) or by increasing the content of fines by means of an adequate reduction of q (e.g. by assuming values of the order of 0.21-0.23).

3.5 Assessment of mechanical properties

Results of triaxial tests carried out on the SC-CBMs after 28 days of curing are shown in Fig. 4, where the logarithm of resilient modulus, expressed in MPa, is plotted as a function of the logarithm of bulk stress (θ), also expressed in MPa. Minimum and maximum M_r values recorded for each mixture are given in Table 5.

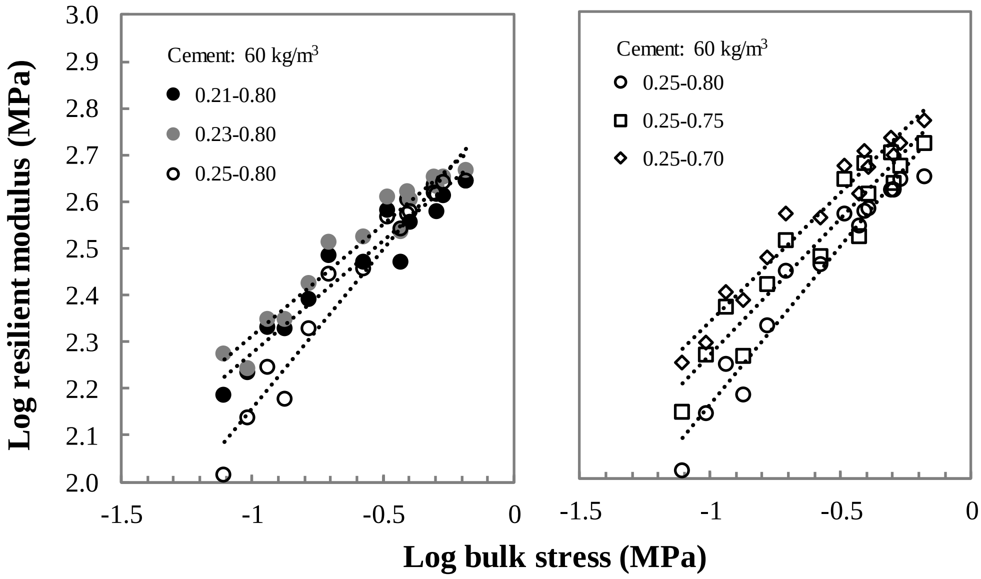

Fig. 4. Resilient modulus experimental data and typical range for granular sub-base materials

Table 5. Resilient modulus ranges of the SC-CBMs

Mixture	$M_{r,min}$ (MPa)	$M_{r,max}$ (MPa)
0.21-0.80	153	441
0.23-0.80	175	467
0.25-0.80	104	443
0.25-0.75	139	524
0.25-0.70	177	584

Recorded resilient modulus ranges synthesized in Table 5 are in line with those reported for high-quality sub-base granular materials and stiff subgrade soils [56-60]. However, as mentioned in section 2, they cannot be compared to any fixed acceptance threshold since the structural suitability of SC-CBMs should be established on a project-specific basis [8].

It was found that the effects caused by variations of q for a constant value of w/p (equal to 0.80) were non-negligible. Such an outcome highlights the fact that the resilient response under loading of the SC-CBMs with a composition of the aggregate skeleton defined as indicated in section 3.3 is not only related to their bulk structure and to the stiffness of cementitious paste, but is also dependent upon the content of fines and on the corresponding volume of cementitious paste. It was observed that the highest stiffness values were obtained for an intermediate value of q (equal to 0.23), thus indicating that the filling effect provided by the fines and by the associated paste can lead, beyond a certain limit, to a reduction of the packing of the coarser aggregate particles.

Significant variations of the resilient modulus were recorded when reducing the w/p ratio as the value of q (equal to 0.25) was kept constant. Quite intuitively, this is due to the fact that as the volume of water decreases, during the hardening process the microstructure of the SC-CBM, as that of any other cementitious component, is characterized by decreasing porosity [61]. Such an evolution is beneficial in terms of stiffness since micropores, as a function of their size, distribution and total volume, can act as points of weakness under the application of external loads.

Results displayed in Fig. 4 indicate that all considered SC-CBMs displayed a non-linear stress-hardening behavior, with M_r values which significantly increased as a function of θ. Such a behavior is consistent with other findings documented in literature on similar cement-stabilized materials and on granular sub-bases [62-64]. It is interesting to observe that the stress-sensitivity of the mixtures was affected by the aggregate packing and content of fines as indicated by the recorded variations of the slope of interpolation lines as a function of q. The influence on stress-hardening of variations of paste stiffness was less evident, with similar slopes of the interpolation lines recorded for all mixtures regardless of their w/p value.

For a more detailed assessment of the stress sensitivity of the SC-CBMs, experimental data were modelled by means of the three-parameter function proposed by Puppala for the evaluation of lime-treated soils and cement-stabilized pavement base layers [65-66]. This function is provided in the following:

$$M_r = k_1 \cdot p_a \cdot \left(\frac{\sigma_3}{p_a}\right)^{k_2} \cdot \left(\frac{\sigma_d}{p_a}\right)^{k_3} \tag{3}$$

where p_a is the reference atmospheric pressure (equal to 0.10133 MPa) and k_1, k_2 and k_3 are non-dimensional material-dependent constants.

The results of regression analyses carried out by referring to Equation (3) are shown in Table 6, which contains the calculated values of the fitting constants and coefficients of correlation between measured and modelled data (R^2).

Table 6. Results of resilient modulus modelling

Mixture	k_1	k_2	k_3	R^2
0.21-0.80	3535.1	0.19	0.27	0.971
0.23-0.80	3903.8	0.25	0.20	0.954
0.25-0.80	3633.6	0.38	0.21	0.949
0.25-0.75	3940.7	0.29	0.24	0.953
0.25-0.70	4521.5	0.26	0.26	0.979

Values of parameter k_1, which can be considered as an indicator of the overall magnitude of the resilient modulus, showed non-negligible changes as a result of variations of the q parameter (while keeping w/p constant at 0.80) and of the w/p ratio (for q equal to 0.25). Such an outcome was already discussed when considering the M_r ranges given in Table 5 and can be explained by referring to the same physical phenomena mentioned in such a context.

Although the overall stress dependency of the SC-CBMs was qualitatively assessed by referring to the slope of interpolations lines provided in Fig. 4, more interesting observations could be made when analysing the individual effects of confining pressure and deviatoric stress.

As the content of fines decreased (i.e. as the value of q increased), k_2 and k_3 tended to increase and decrease, respectively, thereby showing an increased dependency upon confining pressure coupled with a reduced dependency upon deviatoric stress. These trends are consistent with the change in structure of the SC-CBMs, which with the increase of q progressively tend towards coarser aggregate skeletons that reflects into a greater display of volumetric effects and a lower occurrence of shear strains. In the case of the first mixture listed in Table 6, k_2 was smaller than k_3, while the opposite was observed for the following two coarser mixtures, with k_2 greater than k_3. Observed trends are similar to those which have been reported for other types of materials subjected to resilient modulus testing [60].

As the value of w/p decreased with a constant q value, k_2 and k_3 tended to decrease and increase, respectively, displaying variations which were opposite to those discussed above. The decrease of volumetric effects can be explained by referring to the enhancement of the stiffness of the powder paste, while the increasing occurrence of shear effects can be related to the gradual embrittlement of the cementitious powder paste. The first two SC-CBMs considered in the analysis of the effects of w/p variations exhibited k_2 values greater than k_3 values, while the two parameters were equal in the case of the third mixture.

The reliability of the model employed for data fitting is proven by the high values of the coefficient of correlation which are given in Table 6. The overall reliability of the model can also be appreciated by considering the plot provided in Fig. 5, where M_r values calculated by means of Equation (3) ($M_{r,calc}$) are displayed as a function of measured values ($M_{r,meas}$). For the entire set of data, the total coefficient of correlation was equal to 0.961.

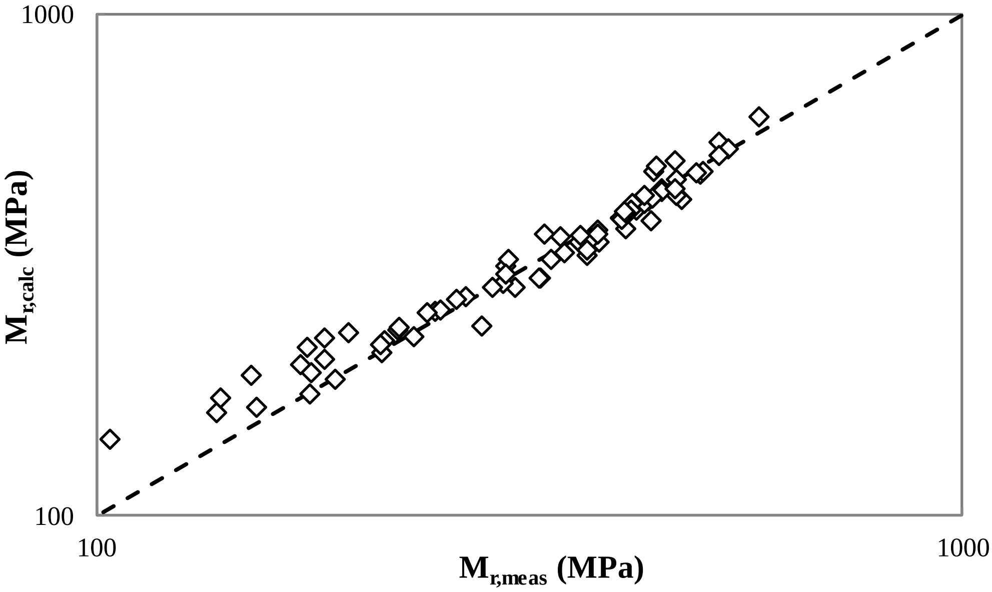

Fig. 5. Reliability of resilient modulus modelling

As mentioned in section 2, after triaxial testing the SC-CBMs were subjected to failure tests carried out in accordance to the quick shear protocol [39]. Experimental results are synthesized in Table 7, which lists the values of quick shear strength (σ_{qss}) and strain at failure (ε_f), calculated from the experimental data recorded for each set of 4 tested specimens. Stress-strain curves exhibited by the SC-CBMs during testing are shown in Fig. 6.

Table 7. Stress and strain at failure of SC-CBMs subjected to quick shear tests

Mixture	σ_{qss} (MPa)	ε_f (%)
0.21-0.80	0.404	0.603
0.23-0.80	0.416	0.459
0.25-0.80	0.405	1.038
0.25-0.75	0.449	0.662
0.25-0.70	0.609	1.123

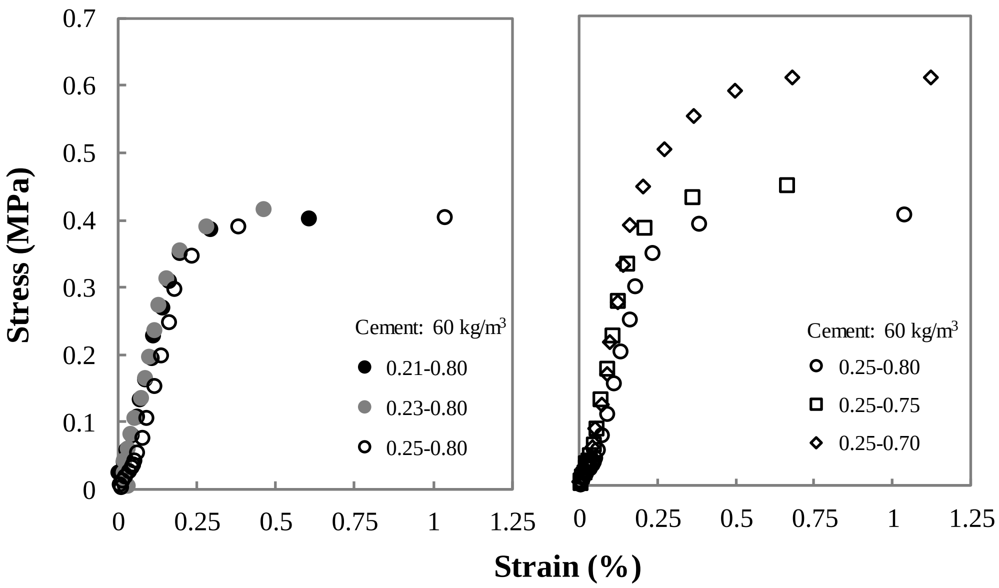

Fig. 6. Stress-strain curves obtained from quick shear tests

Experimental results given in Table 7 and in Fig. 6 indicate that with the progressive increase of q, the SC-CBMs did not exhibit any relevant changes in strength, with σ_{qss} values very close to each other. On the contrary, recorded values of ε_f varied significantly, with the lowest value associated to the stiffer mixture (see Table 6) characterized by a q value equal to 0.23. These results are consistent with the composition of the SC-CBMs and with the discussion of resilient modulus test results provided previously. As expected, strength seems to be controlled by the w/p ratio (which did not change for the first three mixtures listed in Table 7), while ductility at failure is influenced by the variable packing of the aggregate skeleton and by the variable content of fines.

When considering the results obtained on the last three mixtures, characterized by a progressive decrease of w/p, σ_{qss} was found to increase as a result of the gradual reduction of micropores in the cement paste that can trigger microcracking phenomena under loading. However, ε_f did not display a clear trend, and as a consequence it was not possible to confirm that the degree of brittleness of the SC-CBMs is mainly controlled by q (which did not change for these mixtures).

As mentioned in section 2, for the purpose of acceptance of the SC-CBMs, reference can be made to the maximum allowable limit defined for excavatable CLSMs, equal to 2.1 MPa [51-52]. Thus, the results given in Table 6 indicate that from the viewpoint of exacavatability all the considered SC-CBMs can be considered fit for purpose.

4. PROPOSED MIX DESIGN PROCEDURE

Based on the results presented in section 3, a mix design procedure for SC-CBMs can be proposed. Such a procedure is presented in the flowchart of Fig. 7, in which the component blocks are grouped into a sequence of 6 conceptual stages. Four of them (numbered from 2 to 5) include activities which are analogous to those which were carried out in the described experimental investigation. The scheme also displays a preliminary stage of preparation (stage 1) and a final stage of mixture selection (stage 6) which completes the decision process. Employed shapes have the usual meaning that is assigned to flowchart blocks in the representation of algorithms (ovals for beginning and ending conditions, rectangles for straightforward processes, diamond for questions which employ two possible outcomes).

In order to provide a tool readily available for use in most practical applications, the procedure illustrated in Fig. 7 has been limited in width, with the objective of reaching the final design SC-CBM with minimum efforts. Nevertheless, it can be expanded in order to allow designers to have a more thorough understanding of the effects of all the variables considered in the formulation of SC-CBMs on a wider set of performance-related properties.

4.1 Stage 1 – Preliminary data collection

The preliminary stage of design (stage 1) is dedicated to the retrieval of information relevant for the paving project and to the sourcing of materials for laboratory activities. Information which may be of interest for the purposes of mix design is related to pavement cross section, local constraints, available materials, expected design life, technical specifications, production costs, and estimated environmental impacts. However, other data not included in this list may be crucial for specific paving projects. From the list of available materials, the SC-CBM designer needs to select those which may be of interest for the production of the SC-CBM. Consequently, these have to be made available to the laboratory in order to carry out the subsequent stages of the mix design procedure.

4.2 Stage 2 – Characterization of component materials

The second stage of design is focused on the characterization of component materials. In such a context, it should be underlined that required tests are quite limited and in the case of granular components they are those which are carried out as part of routine quality control procedures (determination of particle size distribution and specific gravity). Furthermore, for Portland cement and superplasticizing additives, tests are not mandatory as they can be replaced by the assessment of data sheets provided by manufacturers. Although the investigation described in this paper considered a limited number of component materials, whenever possible and if justified by the extent and importance of the construction project, a wider the set of materials may include in this stage of design. This may allow the identification, in the following stages (3 and 4), of several alternative optimized cement pastes and aggregate skeletons, which may thereafter lead to significantly different SC-CBMs. As in the case of the performed investigation, it is recommended to include recycled materials in the evaluation in order to identify design mixtures the production of which can be attractive also in terms of enhanced sustainability and limited environmental impact.

4.3 Stage 3 – Identification of optimal cement paste

The third stage of design has the goal of identifying an optimal cement paste, the composition of which can then be converted into an optimal powder paste (which includes water, cement and filler). The underlying decision-making process is based on the outcomes of simple, quick and low-cost flowability tests which exclusively require visual observations. Results presented in section 3 indicate that although such an approach is empirical in nature, it leads to the identification of cementitious pastes which can perform properly, both in the fresh and hardened state, in the SC-CBMs in which they are included. As previously mentioned, for projects which deserve such an extension, analyses can be performed on several combinations of cementitious binders and additives. Although manufacturers usually suggest the recommended dosage of superplasticizer, it may also be of interest to explore the effects on flowability deriving from its variation. In the scheme of Fig. 7 the activities composing stage 3 are enclosed in dashed blocks since it is envisioned that when considering only one pair of cement and superplasticizer, the designer may decide to skip such stage of design, directly moving to stage 4. In such a case, values of investigated water-to-powder ratios may be assumed on the basis of previous experience or investigated during stage 4 by means of a trial-and-error approach.

4.4 Stage 4 – Optimization of aggregate skeleton

The fourth stage of design addresses the optimization of the aggregate skeleton of SC-CBMs. As illustrated in the paper, use can be made of the reference Andersen and Andreasen gradation curve, which leads to gradations in which the presence of a bulk structure and of a relevant quantity of fines is adequately balanced, thus ensuring adequate packing and flowability. The latter property can be measured with the standardized ASTM tests which are similar in simplicity, speed and cost to those which are carried out in stage 3 on cement pastes. It is required to perform such tests on trial SC-CBMs in which the water-to-powder ratio can be drawn from the previous stage of design, but such a parameter should also be conveniently varied in order to directly assess the effects of its variation. Target values of flowability have been proposed for the specific application which inspired the investigation, but these can be conveniently adjusted based on the requirements of specific projects. For direct application of the procedure in its basic form, designers are required to start with set values of cement dosage and distribution modulus and by terminating the stage when achieving the desired flowability characteristics with a single value of the water-to-powder ratio. However, for a more comprehensive design, several options can be kept open by choosing several alternative values of the distribution modulus and of the water-to-powder ratio.

4.5 Stage 5 – Mechanical characterization of SC-CBMs

The fifth stage of design deals with the mechanical characterization of the SC-CBMs which, as a result of the outcomes of the previous design stages, have been identified as suitable candidates for the considered application. Requirements which in this phase can be employed for the acceptance of the candidate mixtures are expressed in terms of minimum stiffness and maximum strength achieved in fully cured conditions. In the investigation described in section 3 these characteristics were assessed by referring to AASHTO standards, but they may also be evaluated by means of other test procedures. When the requirements are not met, the procedure entails a new iteration which starts with the assumption either of a new set of granular components or of a modified cement dosage. The initial value of distribution modulus may also be changed.

4.6 Stage 6 – Selection of design SC-CBM

The sixth and final stage of design is concentrated on the selection of the design SC-CBM. If more than one of the candidate mixtures satisfy the requirements, they need to be compared to one another. Factors which may be kept into account to identify the best mixture are expected performance, production costs and associated environmental impact. In such a context, knowledge of engineering details of the project in which the SC-CBM will be used are vital, and the involved analyses may require the application of specific models. Even in the case of a single candidate mixture successfully coming through the previous stages, it is recommended to carry out the abovementioned analyses in order to corroborate the outcome of the mix design procedure.

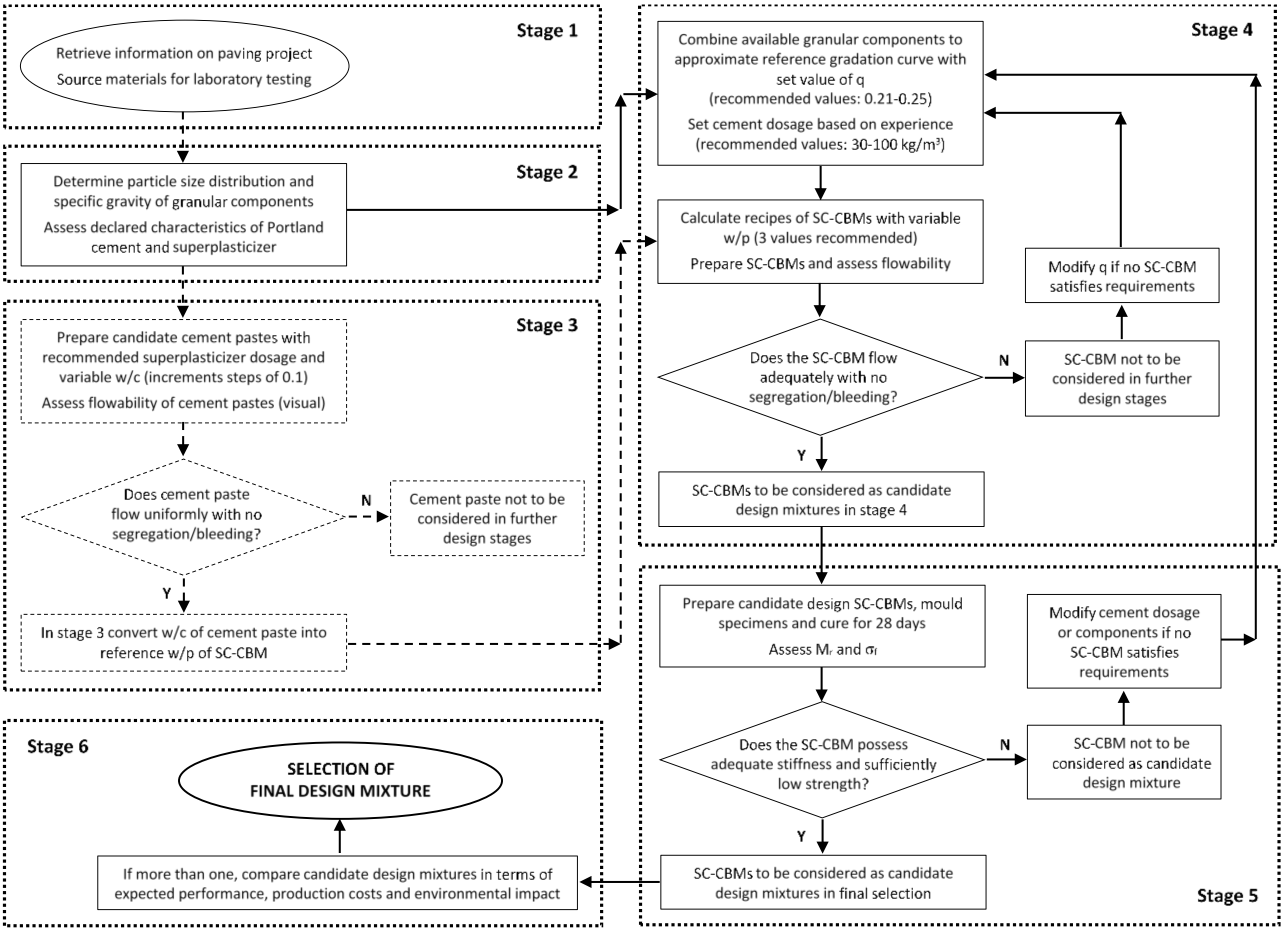

Fig. 7. Flow chart of the proposed mix design procedure

5. EXAMPLE APPLICATION OF THE MIX DESIGN PROCEDURE

As a proof of the feasibility of the proposed method, the experimental results presented in section 3 can be placed within its decision process for the identification of the design SC-CBM.

The results of flowability tests carried out in stage 4 would limit the choice to the mixtures with a w/p value equal to 0.80, excluding the ones with w/p values equal to 0.75 and 0.70. Among these three mixtures, preference should be accorded to the two with a finer aggregate skeleton, associated to q values equal to 0.21 and 0.23, which appeared more homogeneous and exhibited D_S values not too close to the maximum allowable value (equal to 350 mm). This second aspect may be of practical interest since it is expected that in full scale production operations there may be physiological variations of composition which should be accounted.

The two mixtures shortlisted in stage 4 (0.21-0.80 and 0.23-0.80) exhibited mechanical properties, assessed in stage 5, that satisfied hypothesized acceptance requirements. Such an outcome would indicate that both can be considered as candidate design mixtures.

As part of stage 6, the two candidate mixtures seem to be practically equivalent in terms of their production costs and associated environmental impact as a result of their common percentage of recycled components, equal to 56% by weight of all granular components. However, when comparing them in terms of expected performance, a slight preference can be accorded to the mixture with q value equal to 0.21, as a result of its higher strain at failure since it may be less prone to cracking in service. Such a phenomenon may be detrimental because of its possible consequences in terms of initiation of reflective cracks which can propagate through the overlying pavement.

Based on the discussion provided above, as a result of the investigation described in section 3, and in the absence of any further details related to a specific paving project, the final design SC-CBM which may be selected for the formation of pavement foundations in road tunnels would be the one with w/p equal to 0.8 and q equal to 0.21.

6. CONCLUSIONS AND RECOMMENDATIONS

The investigation described in this paper provided a thorough insight into the most relevant engineering properties of self-compacting cement-bound mixtures (SC-CBMs) to be employed for the paving applications, especially for pavement foundations in road tunnels. It was shown that the composition of the SC-CBMs can be defined by optimizing the characteristics of the cementitious paste and of the aggregate skeleton. Key factors which should be considered in such a context are combined particle size distribution of granular components, content of fines and water-to-powder ratio. It was also postulated that the dosage and type of employed cement and superplasticizing additive may have a relevant role in controlling the main performance-related properties. These include flowability in the fresh state, and stiffness and strength in the hardened, fully cured state achieved in the long-term.

Based on the experimental results obtained in the entire investigation, a mix design procedure was proposed. One of its distinctive features is that it leads to the definition of the design composition of an SC-CBM with a limited number of experimental tests, thus minimizing required time and involved costs. It is also structured in such a way to be expanded to provide a more detailed analysis of materials and to be easily adapted to other applications by amending the set of considered properties and by conveniently adjusting target values. Feasibility of following the mix design procedure was demonstrated by referring to the obtained experimental results and by identifying the optimal SC-CBM formulation.

It is recommended that future studies related to the proposed mix design procedure of SC-CBMs should include a more thorough evaluation of the role played by superplasticizers, possibly by considering various alternative products. Moreover, efforts should be made in trying to base the comparative analysis of cement pastes on the measurement of rheological characteristics which may supplement the visual observations performed as per the current version of the design method.

Further improvements to the mix design method may be sought by including in the selection process the assessment of the short-term mechanical properties of SC-CBMs. Such an evaluation may be relevant from a practical point of view since it may be necessary to allow construction traffic to move on top of the pavement foundation in its early stages of curing, with the occurrence of no significant damage in the mixture. Thus, minimum acceptance limits for stiffness and strength may be introduced into to design procedure.

Finally, it is recommended that future studies should address the validation of the mix design procedure by using a wider set of materials and possibly by including other recycled components such as construction and demolition wastes and industrial by-products. In such a context, full scale validation activities as those already initiated by the Authors [67] will be essential in order to consolidate the method and promote its widespread application.

ACKNOWLEDGEMENTS

The financial and technical support of SITALFA S.p.A., ITINERA S.p.A. and SITAF S.p.A. are gratefully acknowledged.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

REFERENCES

[1] K.P. George, Characterization and structural design of cement-treated base, Transp. Res. Record 1288 (1990) 78-87.

[2] B. Ferne, Long-Life Pavements - a European study by ELLPAG, Int. J. Pavement Eng. 7(2) (2006) 91-100.

[3] D. Merrill, A. Van Dommelen, L. Gaspar, A review of practical experience throughout europe on deterioration in fully-flexible and semi-rigid long-life pavements, Int. J. Pavement Eng. 7(2) (2006) 101-109.

[4] P. Solanki, M. Zaman, Design of semi-rigid type of flexible pavements, Int. J. Pavement Res. Technol. 10 (2017) 99-111.

[5] M. Nunn, Development of a more versatile approach to flexible and flexible composite design, TRL Report 615, TRL Limited, Wokingham, U.K. (2004).

[6] J. Zheng, Design guide for semirigid pavements in China based on critical state of asphalt mixture, J. Mater. Civ. Eng. 25(7) (2012) 899-906.

[7] Austroads, Guide to pavement technology part 2: Pavement structural design, AGPT02-17, Austroads Ltd., Sydney, Australia. (2017).

[8] P.P. Riviera, E. Choorackal, E. Santagata, Performance evaluation of innovative and sustainable pavement solutions for road tunnels, in: 5th International symposium on asphalt pavements and environment (APE) (2019).

[9] P.P. Riviera, G. Bertagnoli, E. Choorackal, E. Santagata, Controlled Low-Strength Materials for pavement foundations in road tunnels: Feasibility study and recommendations, Mater. Struct. 52(4) (2019).

[10] E. Choorackal, P.P. Riviera, D. Dalmazzo, E. Santagata, L. Zichella, P. Marini, Performance-related characterization of fluidized thermal backfills containing recycled components, Waste Biomass Valorization (2019).

[11] K. Malmedal, C. Bates, D. Cain, The effect of underground cable diameter on soil drying, soil thermal resistivity and thermal stability. In: Proceedings of IEEE Green Technologies Conference (2016) 35–39.

[12] Y. Shen, H. Niu, Y. You, X. Zhuang, T. Xu, Promoting cable ampacity by filling low thermal resistivity medium in ducts, In: Proceedings of Asia-Pacific Power Energy Eng. Conf. APPEEC (2013) 13–16.

[13] American Concrete Institute (ACI), Controlled low-strength materials, ACI 229R-13, ACI Committee 229, Farmington Hills, MI (2013).

[14] M.A. Gabr, J.J. Bowders, Controlled low-strength material using fly ash and AMD sludge, J. Hazard. Mater. 76 (2000) 251–263.

[15] A. Katz, K. Klover, Utilization of industrial by-products for the production of controlled low strength materials (CLSM), Waste Manage. 24(5) (2004) 501-512.

[16] M. Lachemi, K.M.A. Hossain, M. Shehata, W. Thaha, Controlled low strength materials incorporating cement kiln dust from various sources, Cem. Concr. Compos. 30(5), (2008) 381-392.

[17] R. Siddique, Utilization of waste materials and by-products in producing controlled low-strength materials, Resour. Conserv. Recycl. 54 (2009) 1-8.

[18] M. Etxeberria, J. Ainchil, M.E. Pérez, A. González, Use of recycled fine aggregates for Control Low Strength Materials (CLSMs) production, Constr. Build. Mater. 44 (2013) 142-148.

[19] T. Raghavendra, B.C. Udayashankar, Flow and strength characteristics of CLSM using ground granulated blast furnace slag, J. Mater. Civ. Eng. 26(9) (2014).

[20] H. Wu, B. Huang, X. Shu, J. Yin, Utilization of solid wastes/byproducts from paper mills in Controlled Low Strength Material (CLSM), Constr. Build. Mater. 118 (2016) 155-163.

[21] K.J. Folliard, L. Du, D. Trejo, C. Halmen, S. Sabol, D. Leshchinsky, Development of a recommended practice for use of Controlled Low-Strength Material in highway construction, NCHRP Report 597 (2008).

[22] H.J.H. Brouwers, H.J. Radix, Self-compacting concrete: the role of the particle size distribution, In: Proceedings of the First International Symposium on Design, Performance and Use of Self-Consolidating Concrete SCC20058 (2005).

[23] G. Hüsken, H.J.H. Brouwers, A new mix design concept for earth-moist concrete: A theoretical and experimental study, Cem. Concr. Res. 38(10) (2008) 1246-1259.

[24] H.T. H.T., M. Müller, K. Siewert, H.-M. Ludwig, The mix design for self-compacting high performance concrete containing various mineral admixtures, Mater. Des. 72 (2015) 51-62.

[25] P. Pujadas, A. Blanco, S. Cavalaro, A. Aguado, Performance-based procedure for the definition of controlled low-strength mixtures, J. Mater. Civ. Eng. 27(11) (2015).

[26] R. Janardhanam, F. Burns, R.D. Peindl, Mix design for flowable fly-ash backfill material, J. Mater. Civ. Eng. 4(3) (1992) 252-263.

[27] S. Bhat, C. Lovell, Design of flowable fill: waste foundry sand as a fine aggregate, Transp. Res. Record 1546 (1196) 70-78.

[28] S. Bouzalakos, A.W.L Dudeney, B.K.C. Chan, Formulating and optimising the compressive strength of controlled low-strength materials containing mine tailings by mixture design and response surface methods, Miner. Eng. 53 (2013) 48-56.

[29] V. Alizadeh, New approach for proportioning of controlled low strength materials, Constr. Build. Mater. 201 (2019) 871-878.

[30] Y. Huang, R. Bird, O. Heidrich, A review of the use of recycled solid waste inasphalt pavements, Resour. Conserv. Recycl. 52 (2007) 58–73.

[31] A.C. Carpenter, K.H. Gardner, J. Fopiano, C.H. Benson, T.B. Edil, Life cyclebased risk assessment of recycled materials in roadway construction, Waste Manage. 27 (2007) 1458–1464.

[32] C.T. Chiu, T.H. Hsu, W.F. Yang, Life cycle assessment on using recycledmaterials for rehabilitating asphalt pavements, Resour. Conserv. Recycl. 52 (2008) 545–556.

[33] A. Farina, M.C. Zanetti, E. Santagata, G.A. Blengini, Life cycle assessment applied to bituminous mixtures containing recycled materials: Crumb rubber and reclaimed asphalt pavement, Resour. Conserv. Recycl. 117 (2017) 204–212.

[34] E. Santagata, O. Baglieri, L. Tsantilis, G. Chiappinelli, P.P. Riviera, Re-use in asphalt pavements of fillers from natural stone sawmilling sludge, In: Proceedings of the AIIT International Congress on Transport Infrastructure and Systems TIS 2017 (2017) 371-378.

[35] EN 933-1, Tests for geometrical properties of aggregates - Part 1: Determination of particle size distribution - Sieving method. Brussels: European Standards (EN) CEN European Committee for Standardization.

[36] EN 1097-6, Tests for mechanical and physical properties of aggregates - Part 6: Determination of particle density and water absorption. Brussels: European Standards (EN) CEN European Committee for Standardization.

[37] EN 12697-39, Bituminous mixtures. Test methods for hot mix asphalt. Part 39: Binder content by ignition. Brussels: European Standards (EN) CEN European Committee for Standardization.

[38] EN 197-1, Cement - Part 1: Composition, specifications and conformity criteria for common cements. Brussels: European Standards (EN) CEN European Committee for Standardization.

[39] ASTM D6103/D6103M-17, Standard test method for flow consistency of controlled low strength material (CLSM), West Conshohocken, PA: ASTM International.

[40] AASHTO T 307-99, Standard method of test for determining the resilient modulus of soils and aggregate materials. Washington, DC: American Association of State and Highway Official.

[41] F. Lekarp, U. Isacsson, A. Dawson, State of the art. I: Resilient response of unbound aggregates, J. Transp. Eng. 126(1) (2000) 66-75.

[42] R. Pratibha, G.L. Sivakumar Babu, G. Madhavi Latha, Stress–strain response of unbound granular materials under static and cyclic loading, Indian Geotechnical Journal 45(4) (2015) 449-457.

[43] J-P. Bilodeau, C.O. Plamondon, G. Doré, Estimation of resilient modulus of unbound granular materials used as pavement base: combined effect of grain-size distribution and aggregate source frictional properties, Mater. Struct. 49(10) (2016) 4363–4373.

[44] E. Santagata, G. Chiappinelli, P.P. Riviera, O. Baglieri, Triaxial testing for the short term evaluation of cold-recycled bituminous mixtures, Road Mater Pavement 11(1) (2010) 123-147.

[45] R. Taha, A. Al-Harthy, K. Al-Shamsi, M. Al-Zubeidi, Cement stabilization of reclaimed asphalt pavement aggregate for road bases and subbases, J. Mater. Civ. Eng. 14 (2002) 239–245.

[46] S. Fatemi, R. Imaninasab, Performance evaluation of recycled asphalt mixtures by construction and demolition waste materials, Constr. Build. Mater. 120 (2016) 450-456.

[47] CIRS, Performance-related technical specifications for the construction and maintenance of road pavements. Interuniversity Road and Airport Research Center, Ancona, Italy (in Italian) (2001).

[48] ZTVE-StB., Additional technical contractual conditions and guidelines for earthwork in road construction and technical instructions for soil and rock in road construction, Research Society of Road and Traffic, Germany, (2004).

[49] AASHTO, "Mechanistic-empirical pavement design guide – A manual of practice." Washington, DC (2015).

[50] ASTM D1633-17, Standard Test Methods for Compressive Strength of Molded Soil-Cement Cylinders, West Conshohocken, PA: ASTM International.

[51] C.E. Pierce, H. Tripathi, T.W. Brown, Cement kiln dust in controlled low-strength materials, ACI Mater. J. 100(6) (2003) 455-462.

[52] D. Trejo, K.J. Folliard, L. Du, Sustainable development using controlled low-strength material, In: Proceedings of International Workshop on Sustainable Development and Concrete Technology (2004) 231-250.

[53] J.E. Funk, D.R. Dinger, Predictive process control of crowded particulate suspension applied to ceramic manufacturing, ISBN 978-0-7923-9409-9, Springer US (1994).

[54] V. Senthil Kumar, M. Santhanam, Particle packing theories and their application in concrete mixture proportioning, Indian Concrete Journal 77(9) (2003) 1324-1331.

[55] C. Shi, Z. Wu, K. Lv, L. Wu, A review on mixture design methods for self-compacting concrete, Constr. Build. Mater. 84 (2015), 387-398.

[56] A.R. Dawson, M.J. Mundy, M. Huhtala, European research into granular material for pavement bases and subbases, Transp. Res. Record 1721(1) (2000) 91-99.

[57] A. Nataatmadja, Y.L. Tan, Resilient response of recycled concrete road aggregates, J. Transp. Eng. 127(5) (2001) 450-453.

[58] P. Kumar, S. Chandra, R. Vishal, Comparative study of different subbase materials, J. Mater. Civ. Eng. 18(4) (2006) 576-580.

[59] L.N. Mohammad, A. Raghavandra, A., B. Huang, Laboratory performance evaluation of cement-stabilized soil base mixtures, Transp. Res. Record 1721(1) (2000) 19–28.

[60] A. Ardah, Q. Chen, M. Abu-Farsakh, Evaluating the performance of very weak subgrade soils treated/stabilized with cementitious materials for sustainable pavements. Transp. Geotech. 11 (2017), 107-119.

[61] P. Chindaprasirt, S. Hatanaka, T. Chareerat, N. Mishima, Y. Yuasa, Cement paste characteristics and porous concrete properties, Constr. Build. Mater. 108 22(5) (2008), 894-901.

[62] A. Mohammadinia, A. Arulrajah, J. Sanjayan, M.M. Disfani, M.W. Bo, S. Darmawan, Laboratory evaluation of the use of cement-treated construction and demolition materials in pavement base and subbase applications, J. Mater. Civ. Eng. 27(6) (2015).

[63] W. Fedrigo, W.P. Núñez, M.A. Castañeda López, T.R. Kleinert, J.A.P. Ceratti, A study on the resilient modulus of cement-treated mixtures of RAP and aggregates using indirect tensile, triaxial and flexural tests, Constr. Build. Mater. 171 (2018) 161-169.

[64] M. Bassani, P.P. Riviera, L. Tefa, Short-term and long-term effects of cement kiln dust stabilization of construction and demolition waste, J. Mater. Civ. Eng. 29(5) (2017).

[65] A.J. Puppala, L.N. Mohammad, A. Allen, Engineering behavior of lime-treated Louisiana subgrade soil, Transp. Res. Record 1546 (1996) 24-31.

[66] A.J. Puppala, L.R. Hoyos, A.K. Potturi, Resilient moduli response of moderately cement-treated reclaimed asphalt pavement aggregates, J. Mater. Civ. Eng. 23 (7) (2011) 990-998.

[67] E. Santagata, E. Chooracka l, P.P. Riviera, Self-compacting cement-bound pavement foundations for road tunnels: performance assessment in field trials, Submitted to the Int. J. Pavement Eng (2019).