REUSE OF RECYCLED ASPHALT PAVEMENT AND MINERAL SLUDGES IN FLUIDIZED THERMAL BACKFILLS

Eldho Choorackal*, Pier Paolo Riviera, Davide Dalmazzo, Ezio Santagata, Lorena Zichella, Paola Marini
Department of Environment, Land and Infrastructure Engineering
Politecnico di Torino, Corso Duca degli Abruzzi, 24, 10129 Torino, Italy

(*) corresponding author: eldho.choorackal@polito.it; phone: +390110905624; Fax: +390110905614

The main purpose of the study described in the paper was to explore the possible use of recycled materials, such as Reclaimed Asphalt Pavement (RAP) and mineral sludge, in self-levelling and self-compacting Fluidized Thermal Backfills (FTBs). The assessment was performed by considering FTB mixtures containing different percentages of RAP and mineral sludges of three different types. Tests carried out in the laboratory focused on flowability, thermal conductivity and thermal stability. It was observed that all prepared FTBs exhibited satisfactory flow properties, with the occurrence of bleeding and segregation phenomena only when employing certain sludges in combination with excessive water content. Thermal conductivity of the FTBs was also found to be satisfactory and was observed to be significantly affected by cement content, RAP dosage, water-to-powder ratio and sludge type. Finally, thermal stability of the mixtures was checked in order to understand their behaviour in critical exposure conditions.

Keywords: Reclaimed Asphalt Pavement, mineral sludge, Fluidized Thermal Backfill, flowability, thermal conductivity

1. INTRODUCTION

The construction of new tunnels and road networks is often combined with the placement of utility lines such as high-voltage transmission cables which in most cases are buried underground to ensure safe and reliable power transfer. Their current carrying capacity depends on several factors, among which temperature of the conductor plays a crucial role. Hence, heat dissipation capacity of the material surrounding cables should be ensured by employing the so-called thermal backfills [1-4]. If needed, these can be designed as Fluidized Thermal Backfills (FTBs), which are self-levelling and self-compacting flowable mixes constituted by a proper combination of hydraulic binder, aggregates, fly ash and water [5-7]. Their formulation can be adjusted to include several recycled components which contribute to the reduction of costs and environmental impact associated to construction operations [4, 5, 8].

FTBs are significantly different from conventional backfill materials like soils [9-11] due to their pumpability, improved thermal conductivity and remarkable thermal stability. The latter aspect is of special relevance since it refers to the capability of the material to guarantee constant thermal properties despite drying phenomena which may occur in proximity of the cables as a result of their high in-service temperature [5, 10]. Although mechanical properties of FTBs may vary significantly depending upon project-specific configurations and needs, their stiffness and strength need to be sufficient for the protection of buried cables from the effects of traffic loads. However, limitations to the maximum strength achieved in long-term conditions are frequently introduced as additional design requirements in order to facilitate the removal of such materials in the case of post-construction maintenance operations. As a consequence, FTBs with such characteristics belong to the wider category of Controlled Low Strength Materials (CLSMs) which are employed in several civil engineering applications [12].

In the experimental investigation described in this paper the Authors focused on the design and performance assessment of FTBs containing significant quantities of recycled materials. In particular, FTBs were prepared by employing Reclaimed Asphalt Pavement (RAP) derived from milling operations carried out on damaged road pavements and mineral sludges produced by the crushing of mineral aggregates and by the cutting of natural stones. Consistently with the intended end-use of considered FTBs, relevant properties which were measured in the laboratory included flowability, thermal conductivity and thermal stability.

2 MATERIALS AND METHODS

2.1 FTB components

Aggregates used for the formation of the lithic skeleton of FTBs were obtained from a road construction contractor and were preliminarily characterized by evaluating their particle size distribution and specific gravity (SG) as per corresponding EN standards [13-14]. Employed aggregate fractions included a coarse gravel (indicated as 8-18 mm), coarse sand (designated as 0-8 mm) and RAP (preliminarily treated to reduce its maximum particle size to 12.5 mm). Use of RAP was considered to be compatible with the low strength requirements of the FTBs, while it was assumed that its effects on fluidity and thermal properties could be directly assessed during design.

Studies documented in literature clearly indicate that in order for FTBs to exhibit a fluid behavior and achieve a dense state after setting, it is necessary to include in their formulation a relevant amount of fines. In such a context, possible use of three recycled mineral sludges of different types and origin was considered in the study. One sludge, referred to as “aggregate sludge” (AS), was retrieved from the crushing and washing operations of the abovementioned natural aggregates (coarse gravel and coarse sand). The others were obtained as by-products of the cutting and polishing of granite stones in two different plants: depending upon the respective cutting process, they were indicated as “sawmilling sludge - diamond disc” (SS-D) and “sawmilling sludge - framewire saw” (SS-F).

At the moment of sampling all sludges were characterized by a very high water content (of the order of 20-30%), but during the preparation of FTBs they were used in their oven-dried state. Preliminary characterization of the sludges was carried out by means of the same procedures employed for aggregate fractions (determination of particle size distribution and specific gravity). Furthermore, since it was expected that sludges would be contaminated due to the wear and tear of crushing, cutting and sieving tools, chemical analyses were performed by means of an ICP (inductively coupled plasma) mass analyzer in order to determine their heavy metals content.

Further component materials employed in the FTBs included cement, belonging to class CEM II/A-L R42.5 as per EN standard [15], potable water, totally exempt from impurities, and a commercially available polycarboxylate-based superplasticizer used to improve fluidity.

Results obtained in the preliminary characterization of component materials are synthesized in Fig. 1 and Table 1, while Table 2 lists the data obtained from chemical analyses performed on the mineral sludges.

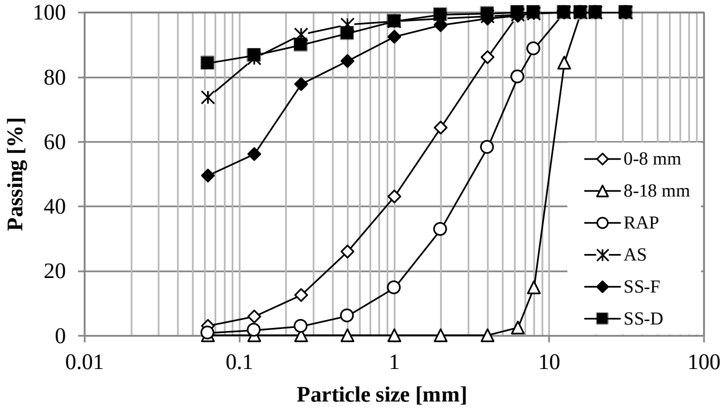

Fig. 1 Particle size distribution of employed aggregates, RAP and mineral sludges

Table 1 Specific gravity of employed components

Fractions	SG (g/cm^3)
0-8 mm	2.745
8-18 mm	2.733
RAP	2.527
AS	2.785
SS-F	2.954
SS-D	2.666
Portland cement	3.150

Table 2 Heavy metals content of mineral sludges

Sludge	**Co [mg/kg]**	**Ni [mg/kg]**	**Cu [mg/kg]**	**Fe [%]**	**Cr [mg/kg]**	**Zn [mg/kg]**	**Pb [mg/kg]**	**W [mg/kg]**
AS	23.9	88.7	43.1	27.2	143.9	89.7	19.8	39.8
SS-D	20.2	0.4	<0.1	4.1	3.0	17.5	28.9	5.6
SS-F	21.3	69.5	96.7	29.9	88.0	85.3	17.5	21.9

With respect to the results of sieve analyses, it was found that the RAP material is characterized by a continuous particle size distribution which makes it a good candidate for inclusion in FTBs. Significant differences were recorded when comparing the three sludges. In particular, while sludges AS and SS-D were almost entirely passing the 0.25 mm sieve, sludge SS-F proved to be definitely coarser.

As expected, it was observed that the specific gravity of AS sludge was close to those recorded for the aggregate fractions from which it was derived, while RAP exhibited a relatively low SG value due to the presence of aged bitumen films covering individual particles. Finally, SG values measured on the SS-F and SS-D sludges confirmed their different origin in terms of cutting operations and mineralogical composition.

Differences in the composition and origin of sludges were also reflected by the results of chemical analyses. However, in all cases the concentration of heavy metals was found to be lower than the legal limits defined by Italian legislation for use in industrial and commercial applications [16]. In such a context it should be emphasized that when including the considered sludges in FTBs, a reduction of their free leaching potential is expected due to the immobilizing effect induced on heavy metals by cement stabilization [17, 18]. Nevertheless, in future developments of their research work the Authors will address such an issue by means of direct measurements.

2.2 FTB mixtures

Composition of FTB mixtures prepared in the laboratory was defined by considering, for each type of sludge, variable cement content (equal to 60, 80 and 100 kg/m^3), RAP content (equal to 0, 15, 20 and 30%), and water-to-powder ratio (W/P, equal to 0.70, 0.75 and 0.80). The term powder is herein used to collectively indicate cement and sludge, which jointly contribute to paste fluidity and void filling.

The full-factorial testing matrix was reduced to a more manageable test plan in which the effects of each variable could still be highlighted. This is shown in Table 3, which lists the composition of all prepared FTBs. For each fixed combination of cement content, RAP content and W/P, dosages of the other components (aggregate fractions and sludge) were derived by minimizing deviations from a reference particle size distribution considered acceptable for flowable mixtures [19]. To avoid biasing effects stemming from the combined use of components with different specific gravities, size distributions were expressed in volumetric terms.

FTB mixtures were prepared by making use of a laboratory mortar mixer and by adopting a protocol which consisted of preliminary mixing of dried aggregates and cement, followed by addition of premixed solutions of water and superplasticizer additive, and completed by continuous mixing until achievement of a homogenous composite.

Table 3 Composition of FTB mixtures

FTB mixtures	**RAP [%]**	**Cement [kg/m^3]**	**W/P [-]**	**Sludge [%]**	**0-8 mm [%]**	**8-18 mm [%]**
AS-RAP20-C60-0.8	20	60	0.8	24	39	17
AS-RAP20-C80-0.8	20	80	0.8	24	39	17
AS-RAP20-C100-0.8	20	100	0.8	24	39	17
AS-RAP0-C100-0.8	0	100	0.8	21	57	22
AS-RAP15-C100-0.8	15	100	0.8	23	44	18
AS-RAP30-C100-0.8	30	100	0.8	25	31	14
AS-RAP20-C100-0.75	20	100	0.75	24	39	17
AS-RAP20-C100-0.7	20	100	0.7	24	39	17
SS-D-RAP20-C100-0.7	20	100	0.7	23	40	17
SS-D-RAP20-C100-0.8	20	100	0.8	23	40	17
SS-F-RAP20-C100-0.7	20	100	0.7	32	30	18
SS-F-RAP20-C100-0.8	20	100	0.8	32	30	18

Flowability of the investigated mixtures was evaluated by making use of the flow consistency test described in ASTM D 6103 [20]. As prescribed by the standard protocol, an open-ended cylinder of 75 mm diameter and 150 mm height is filled with FTB which is thereafter allowed to spread over a non-absorbent flat surface by lifting the cylinder. The spread diameter (D_s) is then measured and the test sample is visually observed to identify any segregation or bleeding phenomena. It is reported that a flow spread of 170-250 mm can be considered adequate for trench filling applications [12].

Thermal conductivity properties of FTBs were measured as per ASTM D 5334 [21] by employing a thermal needle probe (KD2 Pro Thermal Properties Analyzer of Decagon Devices Inc.) which has been extensively used by different researchers for the evaluation of thermal conductivity of soils and cement composites [6, 22-25]. In the present study, thermal conductivity tests were performed on cylindrical specimens 100 mm in diameter and 200 mm in height which were cured at room temperature. Three holes were drilled on the top surface of each specimen before hardening in order to allow the later introduction of the needle probe (100 mm long and 2.4 mm in diameter). To avoid any misreading in measurements, a sufficient free clearance was kept between adjacent holes and between the holes and the lateral specimen surface.

The needle probe acts both as a transient line heating source and as a temperature sensor. Temperature measurements are recorded, at the same intervals, after heating the needle for a fixed duration and during cooling. Thermal conductivity is consequently assessed according to the following equation:

$$k = \frac{q}{4\pi a}$$

where k represents the thermal conductivity (expressed in W/mK), q the heating power of the needle and a indicates the slope of the straight line which models temperature as a function of the logarithm of time.

Tests were carried out at different curing times (7, 14 and 28 days). Furthermore, after 28 days of curing, specimens were oven-dried at 60 °C for 48 hours in order to obtain further thermal conductivity measurements which are believed to be representative of low-moisture conditions which may occur during the service life of FTBs. Such measurement conditions are referred to as “lab-dried”.

3. RESULTS AND DISCUSSION

Experimental results obtained during the investigation are synthesized in Table 4. Spread diameter (D_s) was derived from measurements performed along two orthogonal directions after specimen spreading. Thermal conductivity (k) was calculated as the average of the readings obtained from the three measurements performed on each specimen.

Table 4 Synthesis of experimental results

FTB mixtures	**D_s [mm]**	**k [W/mK]** **at 7 days**	**at 14 days**	**at 28 days**	**lab-dried**
AS-RAP20-C60-0.8	213	1.512	1.627	1.475	0.820
AS-RAP20-C80-0.8	225	1.661	1.662	1.697	1.022
AS-RAP20-C100-0.8	235	1.809	1.865	1.745	1.068
AS-RAP0-C100-0.8	204	1.670	1.549	1.386	0.863
AS-RAP15-C100-0.8	222	1.869	1.775	1.639	1.017
AS-RAP30-C100-0.8	-	-	-	-	-
AS-RAP20-C100-0.75	225	1.609	1.514	1.371	0.902
AS-RAP20-C100-0.7	210	1.632	1.635	1.333	0.864
SS-D-RAP20-C100-0.7	240	1.652	1.519	1.620	0.794
SS-D-RAP20-C100-0.8	-	-	-	-	-
SS-F-RAP20-C100-0.7	260	1.908	1.675	1.450	0.873
SS-F-RAP20-C100-0.8	-	-	-	-	-

As shown in Table 4, all the investigated FTBs exhibited flow spreads greater than 200 mm, thus satisfying the requirements suggested in ACI guidelines [12]. However, bleeding and segregation phenomena occurred in mixtures manufactured with SS-D and SS-F sludges when the W/P ratio reached a value of 0.8, thus preventing the measurement of flow spread. These effects, which probably derive from the specific water absorption properties of employed sludges, do not allow the use of the corresponding FTBs as trench filling materials since a non-homogeneous distribution of air voids and moisture can lead to unacceptable thermal properties. Mixes with 30% RAP also showed similar segregation and bleeding and therefore were not considered in subsequent thermal conductivity analyses.

With respect to thermal conductivity, results were analyzed to identify the effects of variations of curing time, cement content, RAP dosage, W/P ratio and sludge type. Furthermore, results obtained in lab-dried conditions were considered in order to have information on thermal stability.

Fig. 2 shows the results obtained on FTBs prepared with variable cement content and by employing the AS sludge with 20% RAP and W/P equal to 0.8. In agreement with other studies [26-29], it was observed that curing time has a negligible effect on thermal conductivity, probably as a result of the presence of a densely packed aggregate skeleton which results in a low void content. Furthermore, cement content has a significant influence on thermal conductivity, which increases by 20% (passing from 1.475 to 1.745 W/mK) when changing cement content from 60 to 100 kg/m^3. Such a variation is due to the thermal conductivity of the products formed during the hydration process of cement, which is higher than that of water (equal to 0.604 W/mK) and lower than that of dry cement powder (1.55 W/mK) [22]. Moreover, experimental outcomes can also be explained by considering the porosity reduction induced by making use of higher cement dosages [24-25].

Effects due to other composition variations are represented in Fig. 3, which refers to thermal conductivity measurements carried out on selected sets of FTBs after 28 days of curing. It can thus be noticed that all considered factors may have an impact on the thermal properties of FTBs.

In the case of RAP, observed variations may be attributed to the concurring change in dosage of the other components (such as sludge) and to the associated effect on particle size distribution, porosity and cement paste volume. A 22% difference was observed between the FTB with only virgin aggregates and the one containing 20% RAP (mixtures with 100 kg/m^3 cement, AS sludge and W/P equal to 0.8).

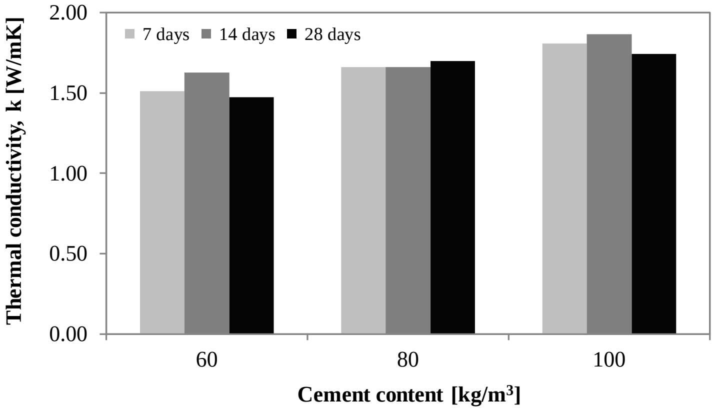

Fig. 2 Effect of cement content and curing time on thermal conductivity

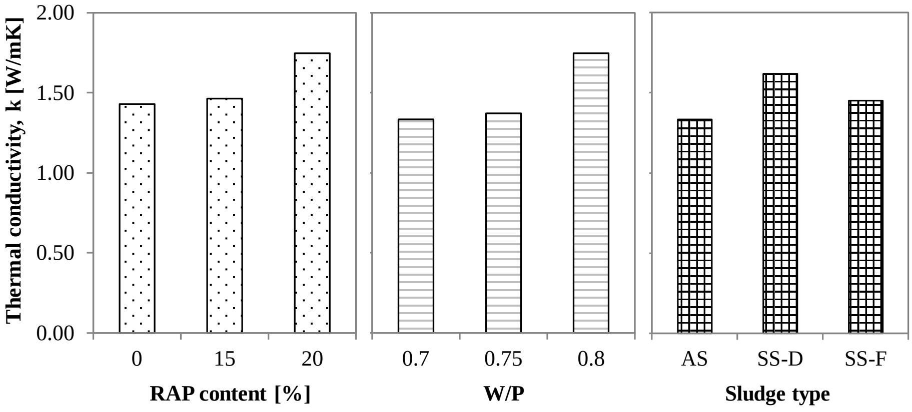

Fig. 3 Effects of composition variations on thermal conductivity

Recorded effects due to W/P variations were also non-negligible. In particular, thermal conductivity increased significantly (by approximately 30%) when W/P reached the highest value considered in the investigation (equal to 0.8, for mixtures prepared with 100 kg/m^3 cement, AS sludge and 20% RAP). Such an occurrence can be explained by considering that water has a higher conductivity than air, and that mixtures characterized by an excess moisture are prone to be highly conductive.

Finally, effects related to variations of sludge type were also apparent as a result of their variable mineralogical and chemical composition (already discussed in section 2.1). In particular, this is shown in Fig. 3 by considering mixtures prepared with 100 kg/m^3 cement, 20% RAP and W/P equal to 0.7.

As mentioned in section 1, thermal stability is an essential requirement of FTBs in the case of buried high-voltage cables which continuously transfer heat to the surrounding backfilling material, causing a progressive reduction of moisture. Thus, in the present study assessment of FTB thermal stability was carried out by comparing thermal conductivity measured in lab-dried conditions to that recorded after 28 days of curing.

In general terms it was observed that the very low moisture content reached in lab-dried conditions led to a significant reduction of thermal conductivity. However, values recorded in these limiting conditions were still compatible with typical design requirements, which indicate 0.8 W/mK as the recommended minimum limit. This is once again due to the dense packing of the aggregate skeleton comprised in the considered FTB mixtures and to the presence of a highly conductive hydrated cement paste.

Examples of the results obtained during the investigation are provided in Fig. 4, which refers to mixtures prepared with variable cement content and by employing the AS sludge with 20% RAP and W/P equal to 0.8. It can be observed that for these mixtures the thermal conductivity reduction was in all cases of the order of 40%.

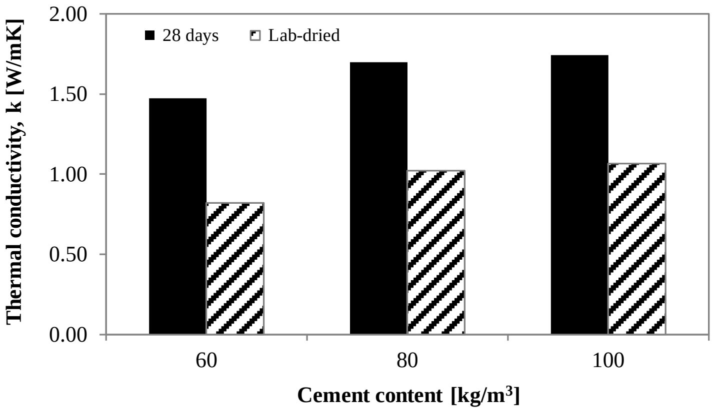

Fig. 4 Thermal stability of selected FTBs

4. CONCLUSIONS

Results of the experimental investigation described in this paper show that Fluidized Thermal Backfills (FTBs) containing significant quantities of recycled materials can be successfully designed by ensuring satisfactory flowability and thermal conductivity properties. Although the design exercise has been performed on a limited set of component materials and mixtures, the Authors believe that obtained results may be of value for other applications and that the observed effects of composition variables should be taken into account in the development of further studies. Additional investigations will also need to include specific measurements carried out for the assessment of the leaching potential of FTBs, which may be especially critical when considering the use of recycled components.

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