Numerical and Experimental Analysis of the Raise-Temperature Effect of Quicklime in Cold Recycled Mixtures

Numerical and experimental analysis of the effect on mixture's temperature made by the adoption of quicklime as active filler in Cold Recycled Mixtures.

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Abstract. This study focuses on the development of a thermodynamic model to estimate the increment of temperature due to the adoption of quicklime as active filler in a Cold Recycled Mixture (CRM) and its evolution with time. CRM are commonly used mixtures for the rehabilitation of distressed flexible pavement sections and are recognized in pavement engineering for their sustainability, both from environmental and economic perspective. Those mixtures are prepared at low temperatures since there is no need to heat up the aggregates before the mixing process and they are primarily composed of Reclaimed Asphalt Pavement (RAP). One of the main limitations of Cold Recycling technologies is the need of having a sufficiently high environmental temperature to permit the merging of the components (in particular the dispersion of the bitumen) and the production of the mixture. For this reason, the construction time window for the application of those technologies is usually limited to the warm season, especially in colder regions. The introduction of quicklime as active filler in the mixture could help extending the construction season for Cold Recycling operations due to the heat produced by the lime hydration reaction. The model developed in this study allows to describe the temperature increase and evolution during the preparation of the mixture and the transportation to the site. In addition, the research can help identifying the most suitable application rate of quicklime in the mixture to reach the desired temperatures.

Keywords: Cold Recycled Mixtures; Cold Recycling Technologies; Quicklime; Reclaimed Asphalt Pavement; Thermodynamic model.

1. Background

Where an existing pavement is recycled, old seals or asphalt surfacing is usually mixed with the underlying layer and treated to form a new base or subbase layer. This new layer may be composed of the milled old pavement, treated with either bitumen emulsion or foamed bitumen, and an active filler, such as cement or hydrated lime. Active fillers help increasing the retained strength when immersed in water, serve as dispersion catalysts with foamed bitumen to promote its dispersion in the mixture, give better control over the breaking phase when used with bitumen emulsion, and also help having better control over the moisture content in case of exposure to rainfalls.

A Cold Recycled Mixture (CRM) can be quite customized to deal with specific operational issues, such as available time for reopening the rehabilitated pavement section to traffic, quality of the Reclaimed Asphalt Pavement (RAP) material used for mixture preparation and/or weather conditions on the construction site. This last issue is very important, since strict recommendations about the preparation of cold recycled layers (Stroup-Gardiner, 2011) must be respected: there are lower limits for air (~5-10° C) and for pavement temperature (~10-15° C), which strong influence the cost-effectiveness of the pavement rehabilitation solution.

On a previous study Gouveia et al. (2020) pointed out that the use of quicklime as an active filler for CRM, can be very convenient to deal with environmental limitations on the construction of CRM layers: lime hydration reaction can heat the mix to bring it to a proper mixing and compaction temperature, with minor to no impact on the desired mechanical characteristics.

Thus, the present study aims to present a thermodynamic model able to predict the temperature increment and its evolution with time as a function of the amount of added quicklime on the in-plant CRM mix design. The model may help constructors to decide, based on the ambient temperature at the construction site and distances between mixing plant and compaction site, the amount of quicklime necessary to bring the mixture to an adequate working temperature.

2. Quicklime and Hydrated Lime

Quicklime is a chemical compound, which consists mainly of calcium oxide (CaO), with magnesium oxide (MgO) as a secondary constituent. It is produced by the thermal decomposition of limestone, inside specific kilns at temperatures around 1100°C, in a process known as calcination. Limestone is a mineral mainly constituted of calcium carbonate, and their deposits occurs naturally and are distributed widely throughout the world (Oates, 2010). The use of quicklime and hydrated lime as an important construction matter dates to 1000 B.C. and it is an important ingredient in several industries to the present-day, such as water treatment, agriculture, construction, mortars, food processing and chemical industries (Leontakianakos et al., 2015). The U.S. Geological Survey (2019) estimated the global production of lime products to be over 420.000 ton in 2018.

Quicklime releases an important amount of heat energy when react with water, producing its hydrated form, $Ca(OH)_2$, commonly called hydrated or slaked lime, as presented in Eq. (1). The ratio of calcium hydroxide to calcium oxide is 1.32, based on the molecular weights, meaning that each kilogram of CaO, should be mixed with 320g of water, to produce 1.32 Kg of $Ca(OH)_2$ (Oates, 2010). So, each unit of $Ca(OH)_2$ must be prepared a minimum of 24% of its weight of water.

$$CaO + H_2O \leftrightarrow Ca(OH)_2 + 1135\ kJ/kg_{CaO} \tag{1}$$

The industry of infrastructure already adopts hydrated lime, as active filler in cold recycling mixtures. Instead of directly using the hydrated lime as active filler in the present work there are investigated the potentialities provided by realising the lime hydration reaction in the cold mixture. Some direct gains would include drying over wet RAP and/or virgin aggregates, heating the mixture due to the exothermic reaction increasing its workability and bitumen dispersion in cold weather workdays, reduction of production and transportation costs.

According to Oates (2010), the reactivity of quicklime can be defined as the rate at which it reacts with water. Complete hydration can take place in a matter of a few minutes or continue over a period of months, and some conditions that influence the rate of reactivity of quicklime are the content of MgO, presence of impurities, porosity, grain size, temperature of hydration water, and mechanical agitation (Leontakianakos et al., 2015).

3. *Thermodynamic model*

The physical problem is represented by the heat conduction inside a block composed of CRM. Quicklime and water are introduced in the CRM to use the heat released by the calcium oxide hydration reaction to increase the temperature of the material to a value that allows adequate workability and compactability on the site while preparing the new pavement layer. The amount of water and quicklime is relatively low when compared to the RAP in the CRM, which composes roughly the 97% of the total mixture weight. Therefore, the quicklime and water combination does not significantly modify the thermal properties of the whole mass of materials. For this reason, the hydration reaction and the related heat releasing can be modelled simply considering a heat source inside the domain composed by only RAP. Under these assumptions the energy balance equation inside the studied domain can be expressed in the form:

$$k\nabla^2 T + q_g(t) = \rho c_p \frac{\partial T}{\partial t} \tag{2}$$

where k, ρ and c_p are the RAP thermal conductivity, density, and specific heat, respectively. In this expression, since the heat released by the hydration reaction of quicklime is supposed to vary with time, the volumetric heat generation q_g in the domain is considered time dependent.

Two different kind of boundary conditions applied on the outer surface of the recycled RAP block were considered:

$$k\frac{\partial T}{\partial n} = T_s \tag{3a}$$

$$k\frac{\partial T}{\partial n} = \frac{(T_{env} - T)}{R_{env}} \tag{3b}$$

Eq. (3a) represents a Dirichelet boundary condition where T_s is the imposed temperature at the external surfaces of the recycled asphalt block and it useful to model the thermal contact between the block and the container. Eq. (3b) instead represents a Robin boundary condition which simulate the heat exchange between the free surface of the block and the surrounding environment; T_{env} is the environmental temperature and R_{env} is the overall heat-transfer resistance between the RAP block and the surrounding environment.

4. Verification of the heat released by the reaction

As first step it was verified that the heat released by the hydrating reaction of calcium oxide is completely transferred to the RAP domain thus resulting in an increase of the RAP temperature. The heat quantity generated by the stoichiometric calcium oxide reaction could be reduced and not completely traduced in RAP domain temperature increasing due to not perfect mixing of the materials that could create:

1) zones where the quicklime has not enough water to complete the reaction;

2) zones where the quicklime quantity is lower than the stoichiometric value.

To verify the previous hypotheses, a set of preliminary tests was performed: a 30 cm internal diameter cylindrical tank was partially filled with an about 10 cm thick layer of RAP, as shown in figure 1. Then a 3% in weight of quicklime was added with the stoichiometric quantity of water for the hydration process and the whole mixture was stirred for approximately 60 seconds. The temperature was monitored with multiple T-type thermocouples placed inside the material.

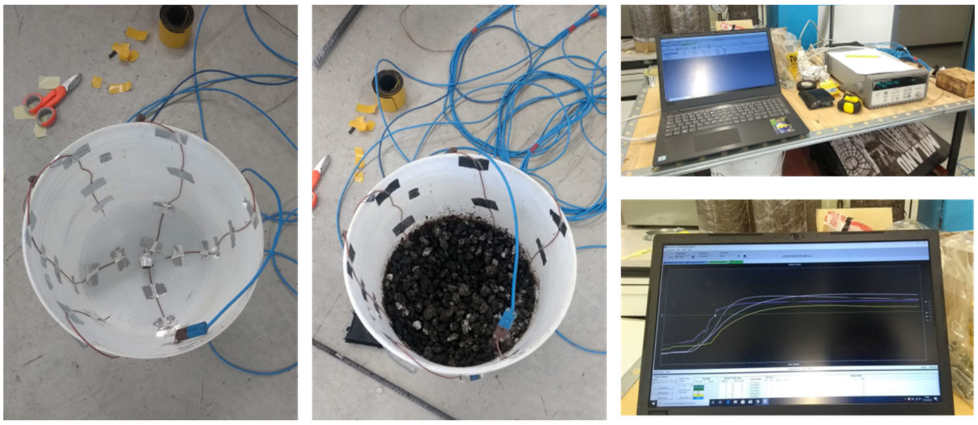

Figure 1: Preliminary Tests

To verify how much of the heat expected by the stoichiometric reaction is effectively provided to the RAP and how much is not released due to the two previously listed adverse conditions, it was adopted an inverse problem approach.

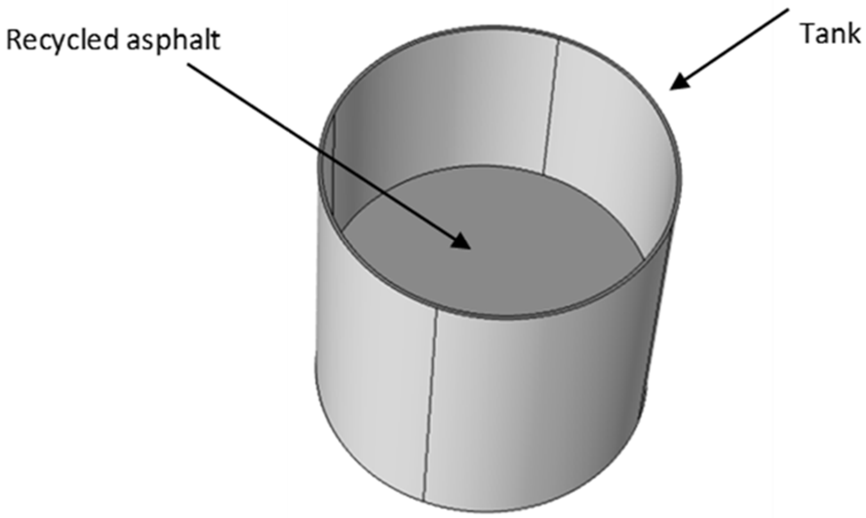

Figure 2: Sketch of the numerical model

Eqs (2,3) represent the direct formulation of the problem under study that is concerned with the determination of the temperature distribution in the RAP domain when the heat released by the calcium oxide reaction is known. The last term is expressed as q_g in Eq. (2) and it varies with time. In the inverse formulation, q_g is instead regarded as being unknown, whereas the temperatures in the RAP domain are measured.

To solve the direct problem a 3-D numerical finite element model of the whole test body (tank and volume of material) was implemented within the Comsol Multiphysics® environment (see Figure 2). The temperature distribution can be easily computed numerically, by imposing a trivial q_g distribution. In the inverse formulation, this computed temperature distribution is forced to match the experimental temperature by tuning the heat generated by the calcium oxide reaction q_g. The matching of the two temperature distributions (the computed and the experimentally acquired) could be easily performed under a least square approach (Beck et al. 2016).

Naming Y (Y_i = measured temperature at time i, i = 1,. . ., n) the temperature data experimentally measured and T the corresponding simulated temperature obtained from the solution of the numerical problem by imposing a function of heat releasing q_g, the estimation problem is solved by minimizing the following function:

$$S = \sum_{i=1}^{n} (Y_i - T_i)^2 \tag{4}$$

Another important information that can be obtained by following this approach it is the time evolution of the heat released by the hydrating reaction. This information can be useful to predict CRM temperature evolution during production and transportation to the construction site. Knowing the heat realising time and its progression can permit to choose the proper mixing time and the insulation of the mixing set up to avoid heat losses to the ambient in the period during which the heat released by the hydration reaction is more significant. Additional information could be given also about the conservation process that follows the mixing operations.

Following the inverse approach, the function of heat releasing is modified until reaching the values that allows to minimize the target function *S*: the obtained distribution represents the best approximation of the real value that characterize the studied sample.

In this paper, the minimization of *S* was performed by the Nelder-Mead algorithm (Nelder et al. 1965) that is a well-known algorithm for multidimensional unconstrained optimization.

Figure a shows the estimated function of heat releasing and **Figure** b reports the comparison between the experimentally measured temperatures and the restored temperature distribution, during time *t*, obtained by solving the direct problem adopting the q_g function shown in Figure 3a.

a) b)

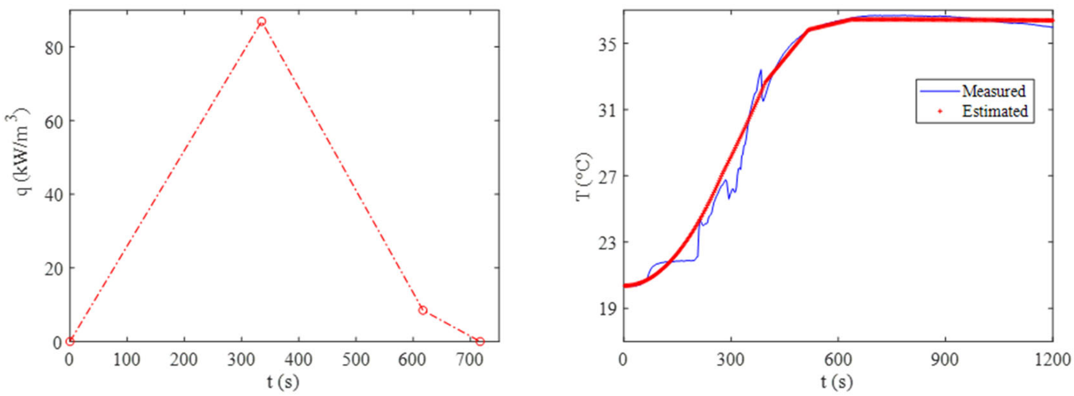

Figure 3: Function of heat releasing (a) and comparison between estimated and measured temperature distribution(b)

It is possible to see from Figure 3b that the reconstruction of temperature is satisfactory and by integrating the area subtended by the curve reported in Figure 3a, the value of the heat released during the reaction can be found, and it corresponds to that reported in Eq. (1) with an uncertainty of less than 15%.

It confirms that the reaction is completed and therefore in the following the two adverse conditions listed before were considered to produce negligible effects.

5. *Studied Scenarios*

Two hypotheticals scenarios were used to simulate the influence of the quicklime hydration reaction on a real scale in-plant mix, with the production of 20 tons of mix (average capacity of one truck), every 6 minutes.

The first scenario refers to the case of environment temperature equal to 5° C, and required compaction (i.e., hypothetically after 1 hour) temperature of 15° C. The model is meant to identify the optimal application quantity of quicklime that allows to increase the temperature sufficiently to have, considering its decrease during one hour of permanence inside the truck, the final temperature equal to 15° C for laying and compacting the new pavement layer. This analysis allows estimating if this is a possible solution for a real scale scenario when dealing with low air temperatures while performing recycling operation.

The second scenario refers to an analogue recycling operation, but with environment temperature at 35° C, and with a 3.8% addition of CaO by weight of dry RAP (i.e., a final hydrated lime content of 5%). The model should try to answer the maximum increase of temperature during mixing phase, and its decrease during one hour of permanence inside the truck. This second analysis was carried out for a completely different reason from the previous one: to understand the maximum temperature that can be reached while having high initial environment temperature and high quicklime application rate. This was done to understand if the temperature reached in such a scenario could be high enough to start mobilizing some of the bitumen in the RAP composing CRM.

~~6. Materials and Methods~~ Model validation

To experimentally validate the proposed numerical model by an example case, it was considered an emulsion-stabilized cold mix with lime with a neutral pH experimental emulsion, with 60% of residual bitumen, following the procedures from Asphalt Academy (2009). The residual bitumen is a neat 50/70 penetration grade, introduced in the mixture in a 2% content by weight of total dry materials for all the mixtures that will be presented. The RAP used in the designed mix has a 4.3% average amount of aged bitumen and comes from uncovered stockpiles from milling works on local roads in Italy. The quicklime used on the project is classified EN459-1 as CL90-Q, size gradation 0-90μm, which describes a highly pure (CaO + MgO content > 90%; MgO content < 5%) and fine powder quicklime. To avoid modifications in the mixture's aggregates size distribution, the total content of filler was kept constant in all the mixtures, at 5% of total dry mass, making a reduction of the mineral filler when the content of active filler was increased. The investigated CRMs were made with 1, 2, 3, 4 and 5% of final hydrated lime, hence, the amount of added quicklime was, respectively, 0.76, 1.52, 2.28, 3.04, and 3.8%, and the amount of reaction water, added beyond the Optimum Fluid Content (OFC), were respectively 0.24, 0.48, 0.72, 0.96, and 1.20%. The final emulsion-based CRM design is detailed on .

The testing batches were prepared in the laboratory using Wirtgen's WLM 30 mixer. All dry aggregates (RAP, mineral filler, and quicklime) were placed in the mixing chamber and pre-mixed for 30 seconds. Then, the required amount of water was added, and mixed for another 30 seconds. Finally, required amount of bitumen emulsion was added, and the material was mixed for another 60 seconds. After mixing, the material was placed into a container, ready to be subjected to the temperature measurements. The mixing equipment is illustrated on **Errore. L'origine riferimento non è stata trovata.**.

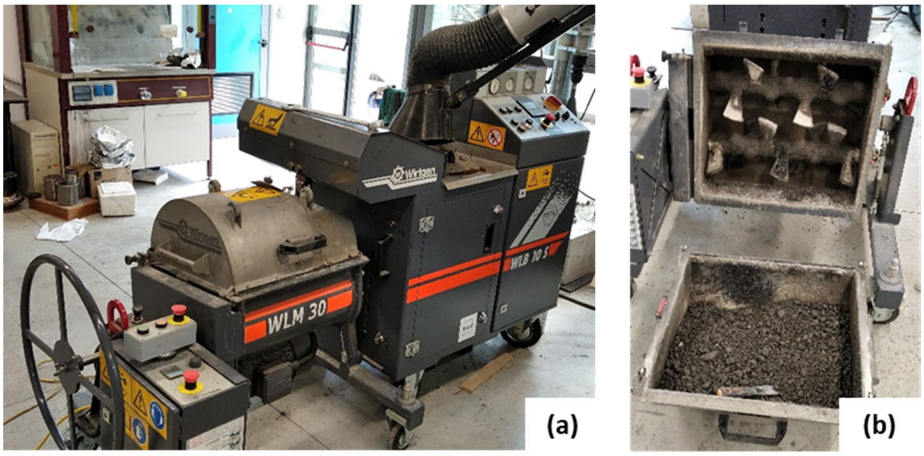

Figure 4: Specimens preparation using Wirtgen's WLM 30 mixer

For the temperature measurements, batches of 24kg of emulsion-based CRM were prepared exactly as reported above, one batch for each one of the 5 different contents of quicklime. After mixing, the material was dumped into a container, and five T-type thermocouples were immersed at different points inside the mixture. Each thermocouple realized one temperature measurement every 3 seconds, for a total of 15 minutes. Thus, it was possible to determine the maximal temperature reached, and its evolution to the top and decrease. It is important to underline one point: all the mixture preparation procedure was made with the same equipment for preparation of the specimens of CRM.

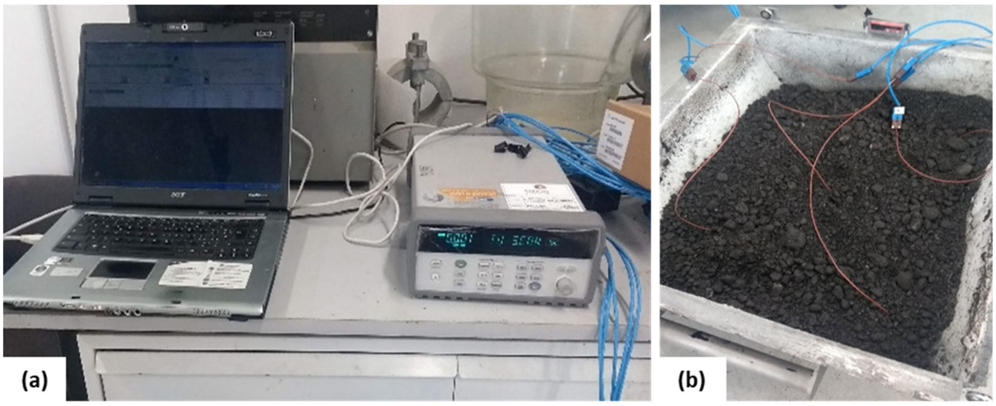

Figure 5: Temperature measurements on emulsion-based CRMs

In order to validate the proposed procedure, the experimental average temperature measured by the 5 thermocouples was compared to the average domain temperature obtained with the numerical model for all the 5 cases. In figure 6 there are reported two representative images of the temperature comparison for the cases of 2.28% and 3.8% of quicklime.

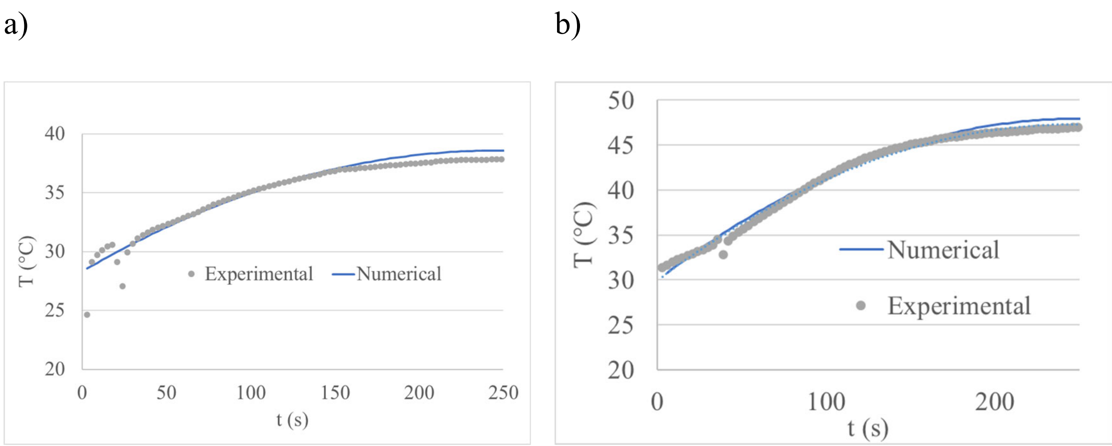

Figure 6: Comparison between measured and simulated temperatures for the case of 2.28% (a) and 3.8% (b) of quicklime

It is possible to notice that the correspondence between the two temperature distributions is satisfying thus demonstrating the goodness of the adopted model.

7. *Modelling of the scenarios*

1st scenario

Since it was verified that the heat released by the hydrating reaction of quicklime is almost completely transferred to the RAP material domain producing an increasing of its temperature, the heat generation through the hydration reaction of the quicklime was not modelled. It was considered the ideal case of complete hydration of the quicklime with all the heat released by the reaction converted in an increasing of the RAP temperature.

Under this assumption the quantity of quicklime that must be added to the RAP ($20 \cdot 10^3$ kg) to obtain the increase of temperature from 5°C (ambient temperature) to 15 °C (working temperature) is around 300kg (1.5% in weight). To consider the possible reductions in the heat provided to the RAP material due to the not perfect mixing process a correction factor of about 1.2 could be taken, making a virtual increasing of the amount of used quicklime. Moreover, if the title of quicklime is less than 100% the amount of it in the mix has to be increased accordingly with. Then it is necessary to understand if the transport to the working site inside a truck for 1 hour could cause an excessive reduction of temperature that compromise its direct usage on the site. To find out the temperature reduction, a 3D model of the material fitted in a truck with 3.5 (x) x 2 (y) x 1.4 (z) m of dimensions was realized (see Figure 7).

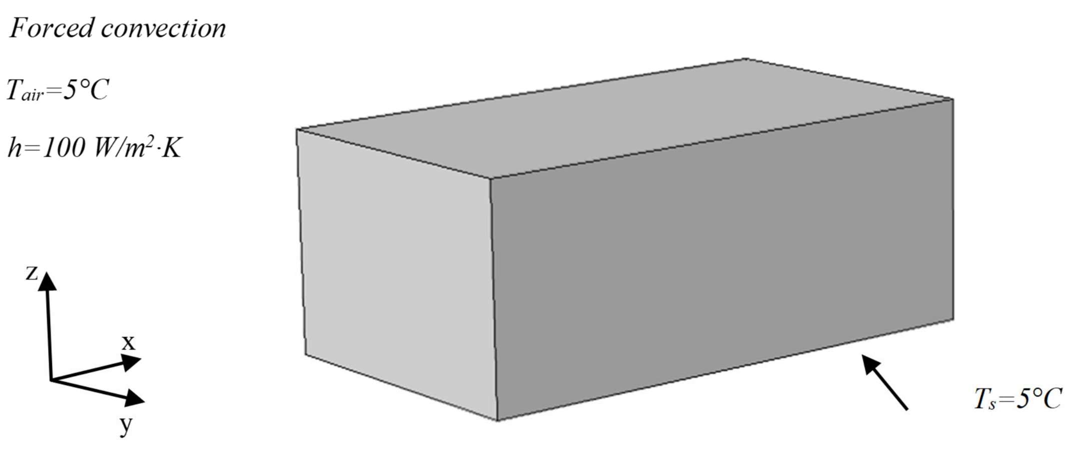

Figure 7: Sketch of the 3D numerical model and boundary conditions

The domain was a parallelepiped with the dimensions above mentioned and composed by RAP material (λ = 0.756 W/m·K, c_p =1674 J/kg·K, ρ = 2100 kg/m^3). The initial temperature was set to 15° C that is the temperature reached by the material thanks to heat released by the quicklime hydration reaction.

On the lower surface, the one that lays on the cargo bed, it was considered a conservative condition of imposed temperature T_s = 5° C that is the environment temperature. On the other 5 surfaces it was imposed a condition of forced convection (Eq. 3b): the overall heat-transfer resistance with the environment R_{env} was considered equal to 0.01 m^2·K/W, that represents a typical value of forced convection with air at high velocity (~ 100 km/h). Even this condition is quite conservative because it was considered the absence of the cargo covering that would significantly reduce the cooling effect caused by air.

2nd scenario

The domain is the same of the first scenario but in this case the starting temperature is 35° C which is also the environment temperature. It is added to the domain 5% by weight of dry materials of $CaOH_2$ (3,8% of CaO) . As in the first scenario the material after the quicklime hydration is transported with a truck to the construction site with an itinerary of 1 hour. On the lower surface it was considered a condition of imposed temperature T_s = 35° C that is the ambient temperature. On the other 5 surfaces it was imposed a condition of forced convection and the overall heat-transfer resistance with the environment R_{env} was considered equal to 0.01 m^2·K/W.

8. Results and Discussions

1st scenario

In **Errore. L'origine riferimento non è stata trovata.** it is reported the temperature distribution on three different plans of the material parallelepiped after 1 hour of transport on the truck under the boundary conditions above described. During the transportation, the temperature of the external layers of the material decreases but only less than 10 cm of material are interested by this reduction.

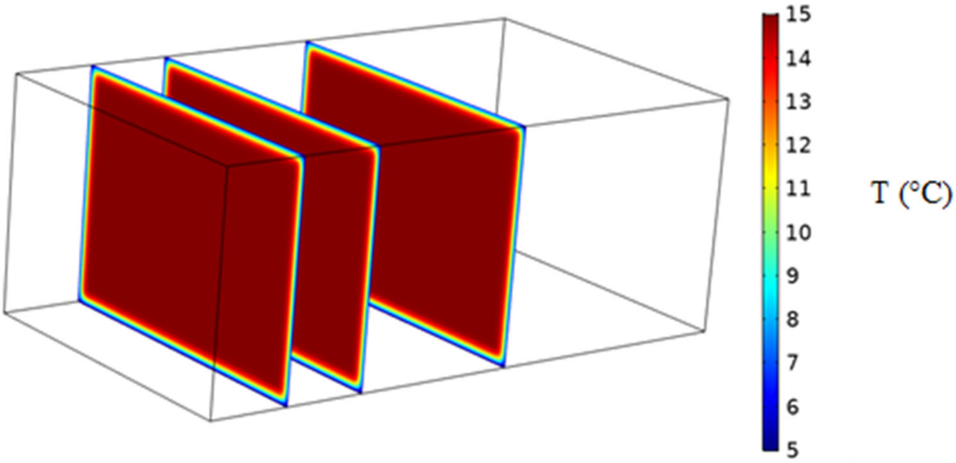

Figure 8: Temperature distribution on 3 different plans after 1 hour

The average temperature of the whole volume diminishes of about 0.7° C going from 15° C to 14.3° C. To better figure out the quantity of material involved in a significant temperature reduction, in **Errore. L'origine riferimento non è stata trovata.** there are reported the temperature distributions for the coordinates z = 0.7 m and x = 0.5 m and a particular of this distribution. It could be seen that only the first 9 cm are interested by a substantial decrease of temperature after 1 hour.

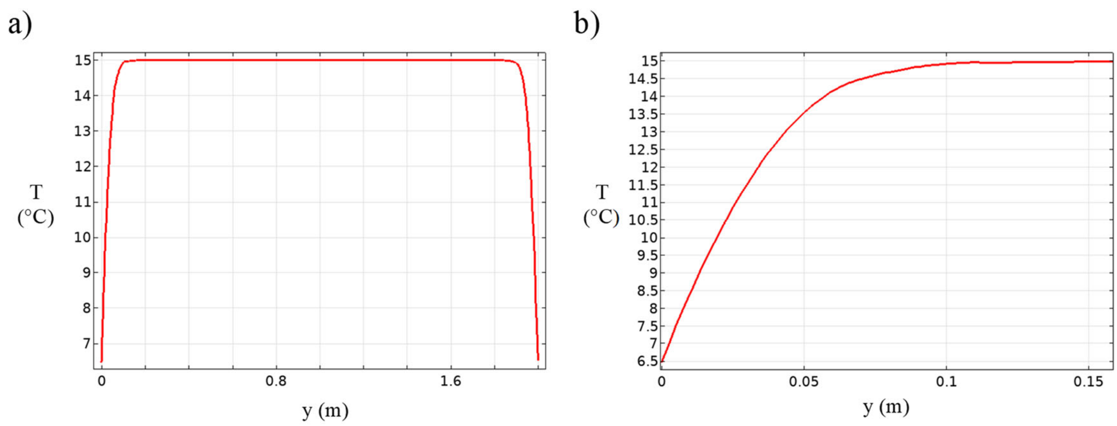

Figure 9: (a) temperature distribution for the coordinates z = 0.7 m and x = 0.5 m; (b) a particular of the distribution

The situation is the same in the perpendicular direction as it is shown in

where there is reported the temperature evolution of 3 different points, 1 cm, 5 cm, and 20 cm from the upper border, respectively.

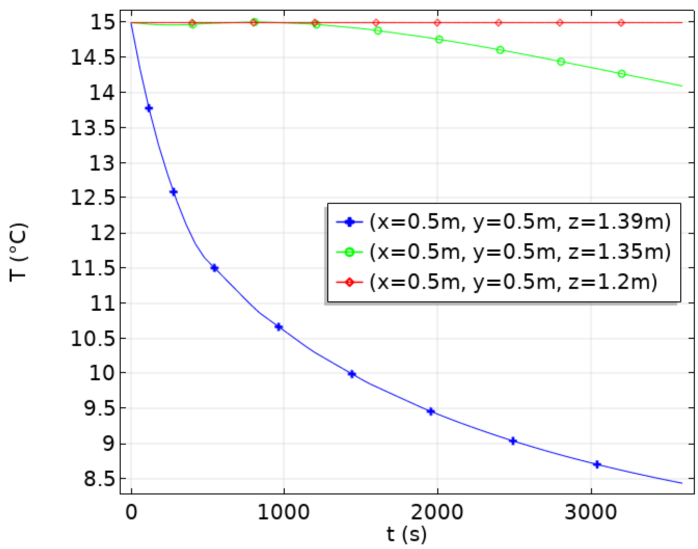

Figure 10: Temperature evolution in 3 different points, in the first simulation scenario

This fact means that the external 9 cm of material could be eliminated, and the remaining part could be used on the construction site. The portion of discarded material correspond to about 350 kg (1.75 % of the total amount). These results are very promising and furthermore, considering that the boundary conditions adopted are very cautious, the amount of discarded material would be probably substantially lower.

2nd scenario

In this scenario, thanks to the high environment temperature and the huge amount of quicklime, the temperature reached at the end of the mixing is 60.7° C. These data confirm, for the case under investigation, a reduction of the need of new bitumen in the mix design and consequently a reduction of the cost of the overall CRM.

Moreover, the average temperature of the whole volume decreases of about 2° C going from 60.7° C to 58° C at the end of 1 hour of transport in a truck under the boundary conditions above defined. In Figure 11 it is reported the temperature evolution of 3 different points, 1 cm, 5 cm, and 20 cm from one of the upper corners, respectively.

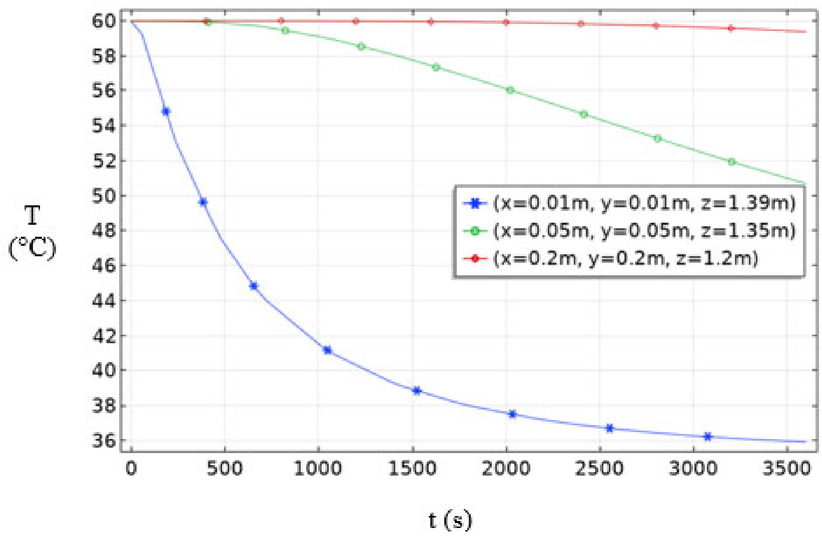

Figure 11: Temperature evolution in 3 different points, in the second simulation scenario

Also for this scenario, only the superficial layers (less than 10 cm) are interested by the temperature reduction and the portion of discarded material will therefore be limited.

9. Summary and Conclusions

The proposed study gives an insight on how to model CRM temperature increment and evolution with time when quicklime is introduced as active filler in the mix. Experimental studies were carried out in the laboratory using different quicklime application rates for the preparation of different CRM and monitoring the evolution of temperature with time using thermocouples. Subsequently, a thermodynamic model for the prediction of material temperature increment and evolution with time while it is placed in a truck for transportation to the site, was realized.

The main conclusions are listed below:

- The introduction of quicklime in a CRM can significantly impact the post-mixing temperature and the temperature increment can be maintained for a significant time after the preparation of the material.
- A model for the prediction of material temperature increment and evolution with time was developed.
- The thermodynamic model for CRM in the truck predicted that after the material temperature reaches 15° C after preparation in the plant, it can be transported for 1 hour while having an environment temperature at 5° C without a significant decrease in the overall material temperature. This proves the possibility of extending the construction season for Cold Recycling technologies simply utilizing quicklime as active filler in the mix and leverage the self-generated heat derived by the chemical reaction to warm up the material.
- The model also showed how with a starting temperature of 35° C, a final material temperature after mixing of over 60° C can be reached. This could potentially have an effect in terms of mobilization of the RAP bitumen in the mixture. This phenomena could reduce the need of new bitumen in the mix design and

consequently reduce the cost of the overall CRM but this is an effect that it’s strongly related to the RAP characteristics and that it needs to be further deeply analysed and studied in the future before drawing any conclusion.

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