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HIGH THERMAL CONDUCTIVITY CONCRETE FOR ENERGY PILES

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Abstract.

Research is increasingly focusing on thermal properties of concrete with the aim of reducing the heat exchange between buildings and environment. On the other hand, concretes with high thermal conductivity could have interesting applications in the field of thermo-active ground structures as Geothermal Energy Piles (GEPs). This kind of foundations represent an environmentally friendly technology that allows exploiting the heat of the shallow earth surface to supply renewable energy for the air conditioning of buildings. GEPs are needed for structural and geotechnical reasons and allow recovering the installation costs connected to vertical boreholes. Concrete drilled or driven piles are equipped with a Primary Circuit (PC) of high-density polyethylene plastic pipes attached to the reinforcement cages. Thermal energy is extracted from or injected into the ground thought a carrier fluid that flows into the pipes of the PC. To improve the heat exchange between the pile and soil the thermal properties of the concrete should be considered as design parameters. Concrete thermal conductivity, contrary to what happens for the buildings, should be increased to optimise the thermal performance of the GEPs. Different solutions that modify the mix design of concrete are proposed to the aim of increasing the thermal performance of GEPs.

Keywords: Energy piles, high conductivity concrete, sustainability.

1. Introduction

Energy demand increasing is linked to the rapid economic development that is taking place worldwide.

However, the energy requirement cannot continue to be satisfied using fossil energy sources which are responsible for climate changes and environmental pollution [1]. The use of renewable energy source is promoted by European Parliament directive 2010/31/UE on energy performances of buildings [2].

Geothermal energy is one out of the possible and most easily available renewable energy sources. In fact, below the ground surface, at depths greater than 10 m b.g.l, temperature of ground is nearly constant throughout the year. Using this relatively constant temperature, the air conditioning of buildings, both in the heating phase and in the cooling phase, it is more efficient than other heating or cooling systems [3]. In the early 80's geothermal energy was initially extracted, in some parts of central Europe like Austria and Switzerland, from deep foundation elements like piles. In this technology, differently from conventional ground heat exchangers made by one or more U-shaped plastic absorber pile inserted in aăborehole, GEPs use thermal conductivity and thermal storage capacity of concrete because high-density polyethylene plastic pipes are installed directly in piles structures before concrete casting. Thermal energy is extracted from or injected into the ground via a heat carrier fluid that flows into the pipes of the PC [4]. Since GEPs combine both the structural and the energetic functions in a single solution, they are known to be cost effective [5].

In GEP's technology, concrete can play a very important role. Usually, the intrinsic characteristics of this material, in relation to its traditional applications for super-structures, do not allow to have high performances from the energetic point of view because its relatively high thermal conductivity is the main cause of heat dispersion inside the buildings.

For geothermal applications, concrete can gain a redemption opportunity. Its high thermal conductivity can be further increased, increasing at the same time the efficiency of the geothermal plant and without dramatic increases of the stress level within the structural sections of the piles. On this last aspect of course, a generalisation is not opportune and any case should be carefully designed and checked.

In this paper, the role of concrete in GEPs technology is analysed. The target is to analyse the effects of thermal conductivity increasing of concrete on energy and mechanical performances of GEPs. After an introduction about thermal properties of concrete and a review of literature about ways to enhance its ther-

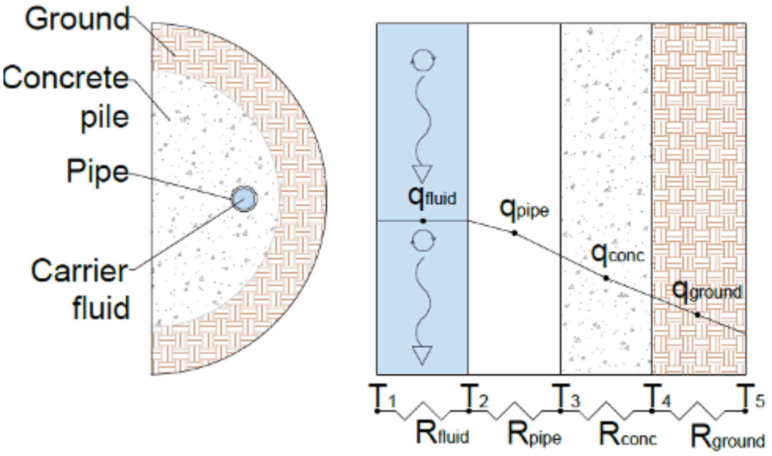

Figure 1. Description of mechanism of heat transfer from primary circuit of energy pile to ground.

mal conductivity, the evaluation of stresses in a GEPs structural was carried out through a Finite Element (FE) code software.

2. Heat transfer in geothermal concrete energy piles

Heat transfer mechanism from the primary circuit of GEPs to soil (and vice versa) during heating or cooling of built structures is a complex mechanism that involves all the underground components of geothermal system (GEPs).

Primary Circuit consists of heat exchanging HDPE loops incorporated within piles foundation, heat exchangers fluid that flows inside pipes loops and concrete of the pile. Between the fluid circulating into the pipes inside the pile and the surrounding soil there is a thermal gradient due to differences of temperature and thermal properties of the fluid and the soil [6]. Heat transfer in a concrete energy pile occurs by heat convection between carrier fluid and wall of pipes and heat conduction between pipes' wall and concrete of pile and between concrete and soil [7]. Usually, for heat transfer in GEPs convection and radiation mechanisms are negligible [8].

According to Loveridge et al. [9] the larger dimensions of the diameter of the GEPs compared to traditional geothermal wells ensure that it cannot be considered a thermal steady state. In fact, since the concrete around the pipes can take several days to reach the steady state, the difference in the average temperature between the heat exchanger fluid and the average soil temperature on the edge of the exchanger cannot be considered constant. For this reason, thermal resistance of concrete could become a fundamental parameter to improve thermal performances of GEPs.

The heat transfer between the primary circuit fluid and the soil is given as [6]:

$$Q = \frac{T_1 - T_5}{R_{Tot}} \tag{1}$$

Where T_1 and T_5 are fluid and soil temperatures, respectively, and R_{Tot} is the total thermal resistance transfer, given as:

$$R_{Tot} = R_{fluid} + R_{pipe} + R_{concrete} + R_{ground} \tag{2}$$

The resistance of the following fluid is given as:

$$R_{fluid} = \frac{1}{2n\pi r_i h} \tag{3}$$

Where r_i is the internal pipe radius, n is the number of pipes, and h is the convective heat transfer coefficient. The pipe thermal resistance is given as:

$$R_{pipe} = \frac{\ln (r_0/r_i)}{2n\pi k_p} \tag{4}$$

Where r_0 is the pipe outer radius and k_p is the thermal conductivity of the pipe material.

Regarding thermal resistance of the concrete annular section, its steady state value could be calculated with the equation of the thermal resistance of a cylinder, but an assumption must be made for the effective inner radius of that cylinder r_{eff}.

The concrete thermal resistance using the equivalent diameter approach is given as:

$$R_{concrete} = \frac{\ln (r_b/r_{eff})}{2\pi k_c} \tag{5}$$

where r_b is pile radius, k_c is concrete thermal conductivity, and r_{eff} is the effective radius

$$r_{eff} = r_0\sqrt{n} \tag{6}$$

The equivalent cylinder approach does not consider actual positioning of pipes. The mechanism is explained in Figure 1.

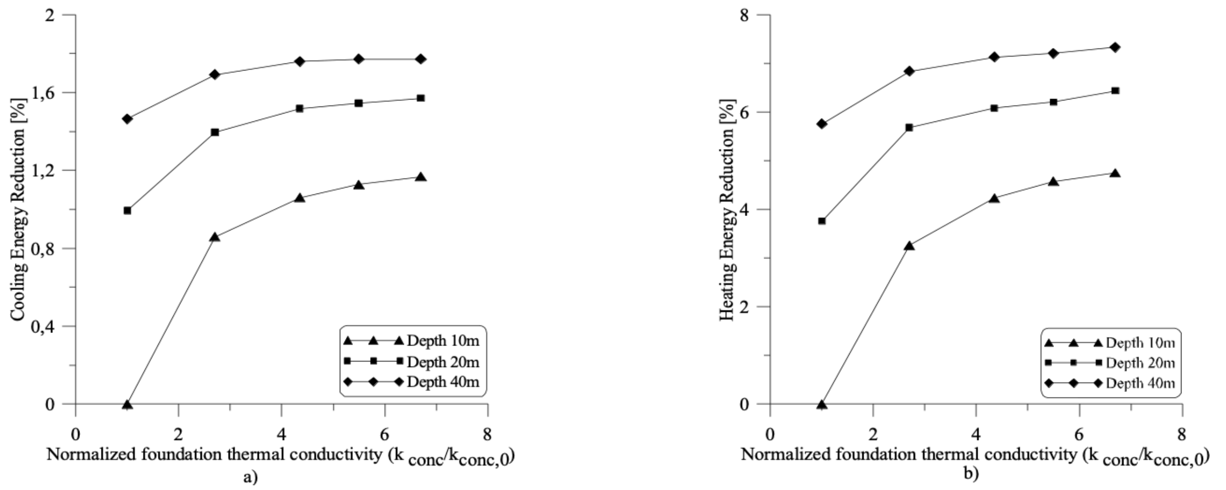

Figure 2. Cooling (a) and heating (b) energy usage of a building in Chicago compared to different concrete thermal conductivities (image reprinted from [6] and [10]).

3. Heat transfer enhancement: thermal conductivity of concrete

Equation 2 and the followings show that thermal conductivity k and/or convective heat transfer coefficient h increasing correspond to thermal resistance decreasing.

In this way, the heat transfer between the primary circuit fluid and the soil will increase.

According to Kwang et al. [10], increasing foundation thermal conductivity reduces the heating and cooling energy demands of a building (Figure 2). Therefore, to increase heat exchange between energy piles and soil, designers could work on thermal properties of thermal fluid, thermal properties of pipes, by optimizing pile dimensions and geometrical arrangement of pipes or by improving thermal properties of concrete modifying its mix design. This study focused on this later aspect.

Conduction is the most important mechanism of heat transfer for concrete. Thermal and mechanical properties of concrete are influenced by its porosity [11]. According to Asadi et al. [12], moisture, the specimen's condition and aggregate volume fraction appeared to be the main factors influencing the thermal conductivity of concrete. However, the most effective factors on the thermal conductivity are the water/cement ratio and type of admixture. The analysis of the variables that influence thermal conductivity, although in many studies is aimed at its reduction, is oriented towards a useful definition of a relationship between the density of concrete and its conductivity. Anyway, because the target is the realization of GEPs, any modification of mix design should not alter piles' resistance.

This kind of foundations in comparison to the ordinary piles are subjected to additional loading induced by thermal variations. Additional strains and stresses induced by the thermo mechanical coupled loadings occur. From this point of view the improvement of both thermal and mechanical properties could be an interesting point. This aim could be achieved developing mix designs which can boost compactness and density at the same time.

According to Kim [13] thermal conductivities of concrete mixtures were revealed independent of curing age. In relation to the components of the mixture and the relationships between them, Kim et al. (2003) show interesting results. First, the larger the amount of coarse aggregate in a concrete mix the higher the thermal conductivity of the mixture because of the well-known higher thermal conductivity value of aggregate than other constituents of the concrete mix. Furthermore, the nature of the aggregate also appears to have an influence on conductivity [14]. The siliceous aggregate, compared to the carbonate one, having a more regular molecular structure (crystallinity), has greater thermal conductivity. Even with an increase in the fine aggregate, an increase in thermal conductivity is obtained [13].

Low values of w/c ratio lead to higher conductivity of the concrete mix. In fact, the thermal conductivity of the cement is higher than that of the water and above all the water is responsible for the formation of the voids that are created after its natural evaporation. So, a lower w/c ratio corresponds to a lower porosity of the concrete. Thermal conductivity decreases linearly with temperature but this dependence is spread over large temperature ranges. As a matter of fact, in the temperature range in which the GEPs work the dependence of the conductivity from the temperature it is nearly negligible.

Finally, thermal conductivity increases when voids of concrete are filled with water instead than air. Zhang et al. [15] shows that under saturated conditions thermal conductivity increases by at least 50%. Other studies [16–19] provide reports to parameterize the increases in the k value as a function of the humidity and of the weight of the concrete both due to the absorption of water. Therefore, pile foundations made by concrete directly cast in place in soils below the groundwater table can boast greater performance as geothermal heat exchanger. Starting from these assumptions, it is possible to identify some precautions that mix design should have to optimize both the structural and the energy performance. The compactness to be maximized is certainly the right solution, which can be obviously obtained following different procedures.

High strength and significant compactness also make the cement matrix physically impenetrable to the aggressions of the environment, the microporosity being reduced too. Both are a guarantee of durability, a fundamental aspect of the performance for any concrete structural object and this is especially true for a foundation pile and even more for an energy foundation pile.

In the literature, several authors [20–24] have carried out LCC and LCA evaluations of geothermal pump systems, equipped with energy piles also. They have also compared them with more conventional heating and cooling systems. These studies have shown a reduction of environmental impact of GHPs than conventional plants. In economic terms, according to Morrone et al, the NPV (Net Present Value) varies from about €12.000 to about €33.000 while the payback period varies from 4 to 11 years for GEPs installations depending on the climate zone considered in Italy [24].

However, other considerations and insights on LCC and LCA deserve a separate study.

4. GUIDELINES FOR A MIX DESIGN WITH HIGH THERMAL CONDUCTIVITY FOR PILES

In new concrete mixes, fillers are increasingly used with the main function of enhancing the workability in the wet state. It is known, however, that the performance changes are mainly characterized by an increase in the resistance, since the presence of the filler reduces the microporosity due to acompactness increasing.

Calcareous filler, with its physical action, only increases the compactness, while the pozzolanic filler, with its chemical action, also improves the resistance, involving lime in the formation of a second family of hydrate compounds [25]. Kim [13] and Demirboğa [26] test the effects of some pozzolanic fillers in partial replacement of cement and detect reductions in thermal conductivity. In fact, compared to the large and fine aggregate, the main function of the filler is that of a micrometric aggregate that can reduce microporosity. Therefore, inserted in the mix design as a new component, it can only increase the compactness at the micrometric scale and, consequently, increase density and mechanical resistance. This creates the conditions for greater thermal conductivity. Another correction of the mixture is the use of the new superplasticizing additives, also called water reducers, which allow to keep with the same degree of workability a low value of the w/c ratio. This suggestion among many of the guidelines on mix composition is the most important because thermal conductivity is inversely proportional to the w/c ratio. As a result, the viscosity is reduced without causing the segregation of the concrete. In addition, with their deflocculating action, they limit the formation of clots of the cement granules, which would form when dispersed in the water. Fillers and superplasticizers are two additional components that enter the new self-compacting concretes, in response to construction site management needs. With rather low w/c ratios and the consequence of reducing microporosity, Self-Compacting Concrete (SCC) [25] achieves high resistance values.

A "technology in technology" of SCC concrete is that of Continuous Flight Auger (CFA) piles. It is a technique to install replacement piles combining and axial thrust and an action of a torque on a continuous flight auger inserted in soil. The SCC could be pumped to the down hollow stem of the auger thanks to the exceptional workability characteristics. While SCC is pumped, without rotation the auger is pulled out. In this way, temporary supported are not necessary. Once the concrete has been cast in place pre-assembled reinforcement cage, is easily inserted into wet concrete. In the case of GEPs also geothermal pipes are fixed on the pre-assembled reinforcement cage. It could be added that the SCC casting performed from bottom allows the mixture to incorporate less air and therefore to reduce even more the microporosity. The possibility of execution in soils of any nature, even in the presence of groundwater, widens the application horizon, combining greater conductivity and mechanical resistance with easy execution on site, without cost increases [25, 27]. Asadi [12] relates the thermal conductivity of SCC concrete with the increase in temperature, highlighting intervals with increases and decreases starting from the room temperature value and reports the results of some studies done by Khaliq and Kodur [28] suggesting the following relationship between thermal conductivity and temperature for a range of temperature of concrete between 20°C and 400 °C (Equation 7).

$$k = 3.12 - 0.0045T \tag{7}$$

As can be seen from Equation 7, the increase in conductivity is inversely proportional to the temperature of concrete. Considering that the range of temperatures at which the GEPs work is very close to the lower limit of the range proposed by the authors, it follows that the conductivity values of the concrete remain quite high.

The use of steel fibers seems another interesting guideline, considering that the thermal conductivity of steel is approximately 50 times greater than that of concrete and that the density of steel is approximately 3ătimes that of concrete. Adeyanju and Manoha [29] show that the Fiber Reinforced Concrete (FRC) with steel fibers reaches high levels of thermal conductivity, of about 2,0-2,5 W/m°C compared to 1,01,3ăW/m°C of a concrete without fibers, with increases well above 100%. This increase is also accompanied by a higher density, once again signing a direct proportionality of the conductivity with both compactness and density. Nagy, Nehme and Szagri [30], comparing various investigations on FRCs with steel fibers, they find out values of thermal conductivity ranging from 2,0 to W/m°C 3,2 W/m°C.

On the other hand, Khaliq, Kodur, experiment with composite details. These are fiber-reinforced SCCs with thermal conductivity values ranging from 3,0 W/m°C to 3,5 W/m°C.

Obviously, the size and quantity of the fibers also influence the formation of the voids. Indeed, Nagy, Nehme and Szagri [30] find out that by increasing the quantity of steel fibers the thermal conductivity starts to decrease. This phenomenon is due to the formation of voids for effect of the greater quantity of fibers.

Lie and Kodur [14] also report an interesting relationship between thermal conductivity and temperature in a concrete in which the effects of steel fibers and the nature of the aggregate are added. Equation 8 is related to siliceous aggregate for a range of concrete temperature between 0 °C and 200 °C, while Equation 9 is related to carbonates aggregate for a range of concrete temperature between 0 °C and 500 °C.

$$k = 3.22 - 0.007T \tag{8}$$

$$k = 2.00 - 0.001775T \tag{9}$$

The comparisons show the order of magnitude of the thermal conductivity k which, at temperatures close to those of the soil, presents high values when the compactness is high and there is the right amount of steel fibers. Furthermore, in all these mixtures with steel fiber reinforcement, characterized by high mechanical properties, the action of the fibers does not induce any improvement in compressive strength, but only in tensile one. Furthermore, metal fibers have little influence on the heat capacity at low temperatures [14] even for high quantities of fibers [30]. The integration with microcapsules in PCM is another possible guideline. Asadi [12] found that the thermal conductivity of cementitious materials with PCM is lower than conventional cementitious materials and several authors have parameterized this decreasing [31, 32]. The encapsulation system is crucial because the use of small quantities of microcapsules could reduce the microporosity. PCM microcapsules could increase thermal capacity without having too strong effects on the reduction of thermal conductivity, improving the storage capacity of the concrete dampening indirectly the already modest temperature fluctuations affecting the soil supporting the steady-state hypothesis.

As shown in the section there are a lot of potential paths to enhance the efficiency of concrete piles as heat exchangers optimizing the heat transmission mechanism.

5. Effect of concrete Thermal conductivityăon pile-soil thermo-mechanical interaction

Heat transfer enhancement in concrete improves the heat transfer process among the heat exchanger piles and the soil. Several studies report the beneficial effects in terms of energy performance of geothermal systems, but the conductivity improvement should be considered also in terms of load carrying capacity of the pile foundation that should however not be compromised [5]. If the heat transfer phenomena inside the pile are modified, additional investigations about pile-soil thermo-mechanical interaction are needed. Herein the effects of concrete thermal conductivity improvement on the short term thermo-mechanical behaviour of a single energy pile are briefly presented. Four different cases are compared. Case 0 where concrete thermal conductivity is assumed 2,4 W/mK, Case 1, Case 2 and Case 3 where thermal conductivity is assumed 2,88 W/mK, 3,6 W/mK and 4,8 W/mK respectively. A CFA pile of 13 m length with 0,60 m diameter, embedded in a multi-layered pyroclastic deposit with a socket in yellow tuff 3,00 m deep is modelled. The pile is the prototype used recently in the foundation project of a new trading centre in city of Napoli [33]. Transient fully coupled analyses are carried out with the FE software PLAXIS 2D. One day of heating, characterized by a maximum temperature variation of 13 °C, and one day of cooling, characterized by a maximum temperature variation of 17 °C, are simulated [34]. To reproduce realistic operational conditions, thermal loadings are combined to the live mechanical top load. The mechanical load, assumed as the 40% of the pile bearing capacity, is thus applied and kept constant during thermal loadings fluctuations. The effects of the thermal conductivity on pile-soil thermo mechanical interaction are analysed in terms of axial loading along the pile shaft. All the thermo-mechanical cases presented (Case 0, Case 1, Case 2 and Case 3) are compared to the purely mechanical case (Mechanical) where only the live mechanical top load, (i.e. 2400 kN), is applied to the pile. The axial load along pile shaft is reported during and at the end of the cooling phase (respectively labelled C for Cooling and EC for End Cooling) and during and at the end of the heating phase (H for Heating and EH for End of Heating) for each thermo-mechanical case (Figure 3). From Figure 3 it could be

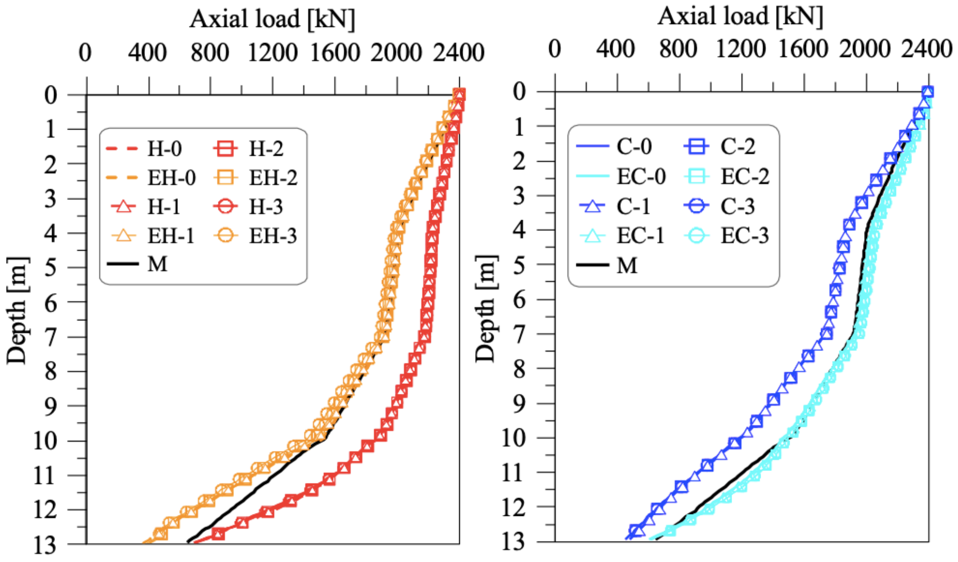

Figure 3. C Axial loads along the pile shaft for different thermal conductivity of concrete.

observed that an improvement of concrete thermal conductivity, for a daily thermal cycle, does not determine significant effect on the thermal axial loading both for cooling and heating modes. For Case 1 and Case 2 the maximum thermal axial load increasing during heating and decreasing during cooling are coincident and equal to 390 kN and 320 kN respectively. In Case 3 the maximum thermal axial load increasing during heating and decreasing during cooling are almost 380 kN and 330 kN respectively. In terms of axial load, increments of 20%,50% and 100% of the thermal conductivity of concrete determine comparable effects. Comparing Case 0 to Case 3, corresponding to minimum and maximum thermal conductivity respectively, a difference of almost 4% of the thermal axial load is observed. The enhance of concrete thermal conductivity, for a short time analysis, seems not to determine significant axial thermal load variations. For long term analyses should also be considered that an enhance of thermal conductivity could determine a beneficial effect in terms of temperature distribution on the cross section and therefore a more uniform axial stress distribution. As a matter of fact, normal stresses induced by mechanical and thermal loadings are not uniform in the cross section. The trend of the axial stress is characterised by sudden variations close to the primary circuit position. An improvement of thermal properties of concrete could mitigate this effect and could be beneficial even in terms of durability of concrete.

6. CONCLUSIONS

In this paper the thermal conductivity of concrete and the use of high conductivity concretes for special applications like GEPs was analysed.

After an introduction about thermal properties of concrete and a review of literature about ways to enhance its thermal conductivity, guidelines for a mix design with high thermal conductivity was laid out and simulations through FE analyses about the potential effects of the thermal improvement on mechanical behaviour were reported. The axial stress induced by live loadings combined to heating or cooling was evaluated for a potential Energy CFA pile characterised by different thermal conductivities.

For a concrete with high thermal conductivity low w/c ratio is necessary to reduce the voids inside the cement matrix. For this reason, the use of fillers, superplasticizers or both at the same time is desirable to achieve the goal. The addition of steel fibers within the mix design of concrete is another possible expedient. In addition to improving the mechanical capabilities of concrete, they also increase its thermal conductivity with negligible influence on thermal capacity at low temperatures. The effect of microcapsules with PCM should not affect conductivity very much but an increase in the thermal capacity is typically expected.

The simulations carried out with FE software for a prototype pile embedded in a layered soil profile similar to a real foundation project in the eastern area of the city of Napoli has shown that the change in the thermal properties of the concreted is not producing large effects on the structural performance. Computed axial compression loading changes for the thermal induced strains is in a range of ±15% compared to the axial loadings obtained by the head load corresponding to a typical live load according to Italian NTC 2018.

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