Performance requirements, challenges and existing solutions of PCM in massive concrete for temperature control

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Abstract. The development of new solutions and techniques targeted towards better control of the temperature rise in massive concrete at early ages aiming at the reduction of thermal cracking risk, is of paramount importance, namely in respect to durability. To mitigate this issue, one of the most researched solutions that has attracted most interest is the incorporation of Phase Change Materials (PCMs) into massive concrete. PCMs have the capacity to store and release energy in the form of heat within a specific temperature range. The application of PCM in massive concrete, with a melting temperature point/range in between the casting temperature of concrete and the expectable peak temperature (had PCM not been added in the mixture), has the potential to reduce the internal temperature rise, and associated temperature gradients. Therefore, the internal thermal stresses are reduced, and consequently the inherent thermal cracking risk. This paper carries out a critical review on requirements and challenges of different applications of PCMs into massive concrete structures.

Keywords: Phase change materials (PCMs), massive concrete, heat of hydration, cracking

1 Introduction

According to ACI 116R [1], massive concrete is defined as "*any volume of concrete with dimensions large enough to require that measures be taken to cope with generation of heat from hydration of the cement and attendant volume change, to minimize cracking*". In concrete structures such as dams, a very high/huge quantity of hydration heat is generated in the concrete curing process, inherently to the large volumes of concrete involved. Existing data shows that that massive volumes of concrete are very susceptible/vulnerable to early age cracking during the construction period, therefore there is the need for attention towards the issue of temperature control [2]. This subject has been attracting the attention of both researchers and practitioners for several years. The 1988 report of International Commission on Large Dams (ICOLD) [3] for dam work status displayed that the vast majority of concrete dams which have been built in the world, may suffer temperature cracking phenomena. Indeed, 30 out of the 243 dams mentioned in the report, have suffered thermal cracking. According to Ke *et al.* [4], concrete thermal cracking can greatly reduce the durability and even the safety of the structure. Therefore, active measures need to be taken to reduce thermal cracking risks. Amongst such measures, temperature control techniques are frequently the chosen strategy, as they mitigate the cause of thermal cracking at its origin [5].

Traditionally, temperature control has been addressed through several strategies, such as: (i) reducing the heat generation potential of the concrete mixture by combining cement with supplementary cementitious materials, and therefore reducing cement content [6]; (ii) use of low heat of hydration cement (cements with decreased amount of Portland clinker e.g. CEM II / CEM V) while, bearing in mind, that the development of the mechanical properties of such concrete is slower in compare with Portland cement CEM I [7]; (iii) lowering initial temperature of concrete upon placement by using cooler aggregates/water, using ice chips in the mixture, or even liquid nitrogen for cooling [8]; (iv) using active cooling measures for concrete after placement through embedded cooling pipes [9]; (v) construction management (phasing), including scheduling of construction stages and procedures to achieve lower temperatures [10]. Another possibility for the mitigation of thermal cracks in hardening concrete has been proposed in recent years, by incorporating phase change materials (PCMs), which are able to store latent heat, as additives in concrete [11]. The principle of operation of PCMs in the scope of massive concrete can be explained through the following example in the context of the construction of a structure. In a recently cast concrete element, when the increasing core temperature of massive concrete (heat released due to cement hydration heat) reaches the melting point of the embedded PCM, it induces the corresponding phase change and inherent heat absorption/storage (endothermic process), thus reducing the internal temperature rise of concrete, as compared to the on expectable if PCM had not been embedded. As temperature rises are smaller, so are temperature gradients (both temporal and spatial), therefore the thermal cracking risk is comparatively reduced. The aim of this paper is to focus on the overall following fundamental questions: (1) what are the methods and typical quantity of incorporation of PCM (in weight or volume) in massive concrete?; (2) what is the typical global energy that the PCMs in massive concrete are being able to store?. Giving some insight on the above mentioned questions, may pave the ground for the feasibility of future conduction of experimental and numerical studies based on the lessons learnt from the review on past literature.

2 Phase change materials in massive concrete application

2.1 Classification of PCMs

The most typical classification of PCMs are organic, inorganic and eutectic [12]. Table 1 presents a list of the advantages and disadvantages of the three types of PCMs.

Table 1. Classification, advantages and drawbacks of PCMs [adapted from12].

Classification	Advantages	Disadvantages
Organic PCMs	• Available in a large melting temperature range (from 12ºC to +135ºC) • High latent heat capacity (between 80kJ/kg to 260kJ/kg) • No supercooling • Chemically stable • Recyclable • Good compatibility with host materials • Relatively cheap • No corrosive to metal	• Low thermal conductivity (around 0.2W/m K) • Relatively large volume change (e.g. 10% in paraffin PCMs) • Flammability
Inorganic PCMs	• High latent heat capacity • High thermal conductivity (around 0.5W/m K) • Low volume change • Low cost	• Corrosive to metal
Eutectics	• Sharp melting temperature • Properties can be tailored to match specific requirements • High volumetric thermal storage	• Limited data on thermo-physical properties for many combinations • High cost

2.2 Strategies for incorporation of PCMs into massive concrete

In principle, it would be desirable to add PCMs into massive concrete for effective temperature control, without impairing any other performance requirement. The typical incorporation methods that have been used are direct incorporation, impregnation of lightweight aggregates, and encapsulation (micro and macro) [13]. For the purpose of clarity, different incorporation methods of PCM are illustrated schematically in fig. 1. From temperature control point of view in the concrete, use of PCM impregnated LWAs can provide better distribution of PCM in the concrete and therefore, PCM can homogenously transfer the heat through the matrix when compared with embedded pipes. Microencapsulation or macro encapsulation are techniques in which PCMs are enclosed in a micro/macro capsule, which can be incorporated into the concrete in different manners [14]. A key drawback of this form of capsuled PCM is the cost of production associated to the encapsulation process [15].

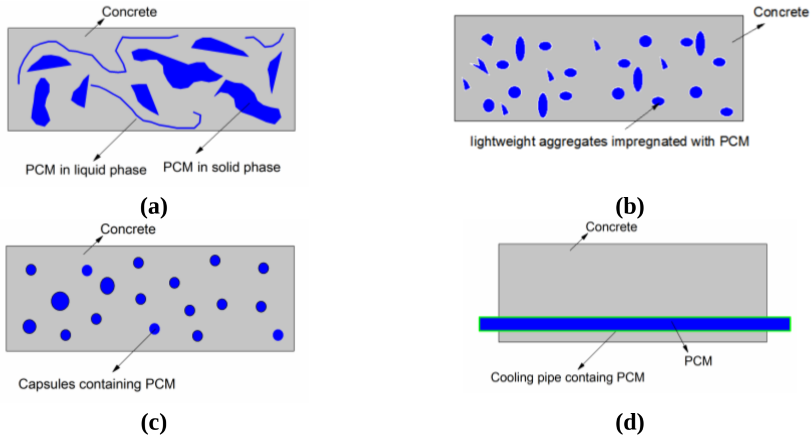
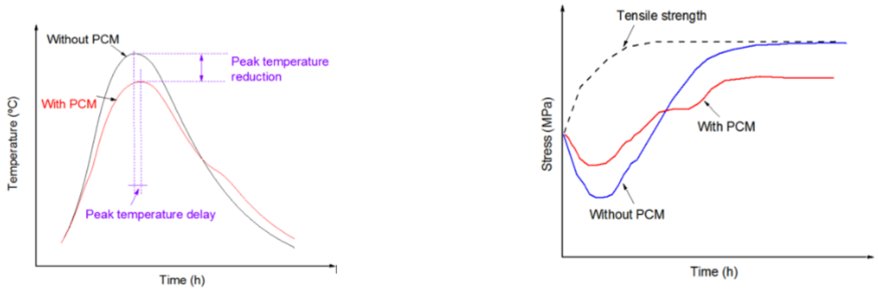


Fig. 1. Schematic illustration of four methods to incorporate PCM into massive concrete: (a) direct incorporation of PCM; (b) impregnating PCM into light weight aggregates; (c) encapsulation (micro or macro) containing PCM; and (d) Cooling pipe with PCM.

3 PCM for temperature control of massive concrete

Massive concrete has high cracking probability due to the temperature differences between exterior surface and the core of the concrete structure by heat of hydration after pouring and casting of a large amount of concrete. Core temperature of the fresh concrete increases due to the chemical reactions during hydration of cement [16]. The development of tensile strain rises due to the temperate differentials within a concrete section, exceeding the actual tensile strain capacity of the concrete this could cause early age cracking. Therefore, temperature control is essential in attaining the structural integrity, serviceability and durability of massive concrete structures, as to avoid the inherent damage. As mentioned above, one of the possibilities to reduce thermal cracking in hardening concrete through temperature control involves the use of PCMs embedded into concrete. The principle of operation of incorporated PCM for control of temperature in mass concrete is schematically illustrated in fig. 2.

As can be seen, when the temperature increases, the PCM absorbs heat by melting. Thus, the peak temperature of the concrete is attenuated/decreased and the delay of maximum temperature is notorious (fig. 2a). This has implications on the stress development of the concrete. First when the temperature increases results in occurrence of compressive stresses. The magnitude of these stresses decreased with the incorporation of the PCM (fig. 2b). Several research works have been carried out on methods of incorporating PCM into massive concrete structures at both laboratory scale and real scale levels. All previous research work reports that refer to different forms of incorporating PCM into concrete identify distinct procedures of incorporation [17-20]: (i) replacement with sand; (ii) replacement/addition ratio of the amount of cement; (iii) addition of a % of the total weight of concrete; and (iv) addition of total volume of concrete; (v) impregnation of PCM into lightweight aggregates (then coated or without coating) used in concrete. Different quantities of PCM into the concrete have been attempted in the literature as: 0.78kg/m^3 [21], 23.3-113.7kg/m^3 [18], 40kg/m^3[20], 50-120kg/m^3[22], 150kg/m^3[19] and 180kg/m^3 [23].



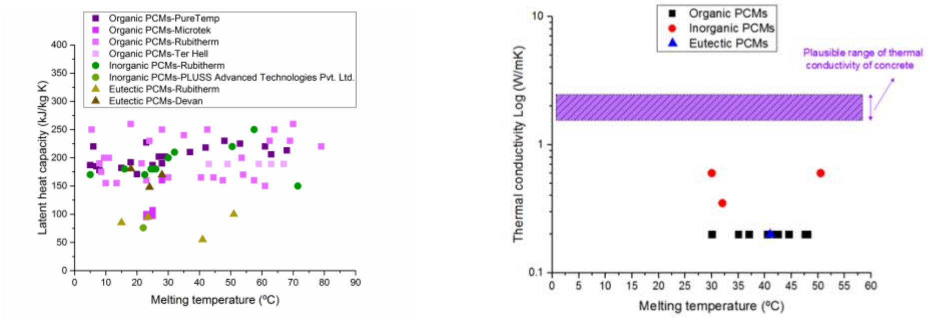
(a) **(b)**

Fig. 2. Function of PCM in concrete: (a) on the temperature variation; and (b) on the stress performance.

When designing a massive concrete structural component, this action requires the control of the heat of hydration, therefore it is important to know the performance requirements for heat storage of PCM's in massive concrete, in a quantitative manner. Hence, is necessary to frame the typical energy involved on behalf of the cement present in a given concrete mixture. Cement content (here understood as the weight of cement per unit volume of concrete, and expressed in kg/m^3) has a large influence on the strength of concrete and the amount of heat generated in the concrete. The average hydration heat of normal cements is about 292 kJ/kg, whereas for low heat cements, the average hydration heat is of 205 kJ/kg [24]. Therefore, one criteria for the selection of the PCM should be based on the amount of hydration of the cement used in the proposed concrete as to be able to successfully mitigate thermal stress in massive concrete components.

4 PCM use for massive concrete

A large number of PCMs are known to melt with a latent heat capacity in any required range compatible with the main purpose of temperature control of massive concrete applications (e.g. a range between 30ºC and 50ºC that is likely attained in most concrete massive structures). However, for their incorporation as latent heat storage materials they should exhibit desirable thermodynamic, kinetic and chemical properties. Furthermore, economic considerations and availability in the markets has to be taken in to account. It is important to show relationships between properties of PCMs in order to provide insights for the designers and engineers when PCM is worthy for application in massive concrete structures. Fig. 3a shows, the relationship between melting temperatures and the latent heat capacity of different types of commercially available pristine PCM solutions (as announced by manufacturers) which will allow to understand better different options in the range of interest. Organic PCMs have relatively higher latent heat capacity when compared with inorganic and eutectic PCMs.



(a) **(b)**

Fig. 3. (a) Latent heat capacity versus melting temperature for different types of studied PCMs; (b) Thermal conductivity values (solid phase) versus melting temperatures for different types of studied PCMs [25-30].

To evaluate and rank different PCMs can be very complicated as there are a number of factors that can be accounted for. Indeed, PCMs with melting peak temperatures in the range of 30ºC - 50ºC is of main interest. Figure 3b plotted the relationships between the logarithmic thermal conductivity (W/m K) and the melting temperatures (ºC) for different PCMs. Thermal conductivity of the concrete is normally in the range of 1.7 W/m K to 2.53 W/m K according to ACI standard [31], therefore, in the case of using PCM, since all the considered PCMs have lower values of thermal conductivity (below the value of concrete), can affect the thermal conductivity of the final product and cause effects on temperature development.
The latent heat capacity, melting temperature and thermal conductivity of the studied PCMs are shown in Table 2. Commercial organic PCM number 7, from RUBITHERM manufacturer (it will be referred to as “Manufacturer A”) with melting temperature of 42.5ºC, latent heat capacity of 250 J/g, thermal conductivity of 0.2 W/m K has the highest enthalpy value among others, which, indicate higher capacity potential for absorption of heat (due to the cement hydration in concrete).

Table 2. Latent heat capacity and thermal conductivity scores of the considered PCMs.

No.	Type	Melting temperature (ºC)	Latent heat capacity (J/g)	Thermal conductivity (W/m K)	References
1	Organic	37	210	0.2	[25]
2	Organic	42	218	0.2	[25]
3	Organic	48	230	0.2	[25]
4	Organic	30	165	0.2	[27]
5	Organic	35	240	0.2	[27]

6	Organic	40.5	165	0.2	[27]
7	Organic	42.5	250	0.2	[27]
8	Organic	44.5	165	0.2	[27]
9	Organic	47.5	160	0.2	[27]
10	Organic	43	189	-	[28]
11	Organic	49	189	-	[28]
12	Inorganic	30	200	0.6	[27]
13	Inorganic	32	210	0.35	[27]
14	Inorganic	50	220	0.6	[27]
15	Eutectic	41	55	0.2	[30]

-such values were not available.

For the purpose of comparison, fig. 4 shows the logarithmic average cost values (€/kg) versus melting temperature (ºC) for the different types of PCMs. The market price of the PCMs was given by the producers based on direct quotations sourced from the suppliers from November 2018 to December 2018 for 100kg of pristine PCM. Both types of organic and inorganic PCMs from "Manufacturer A" have the same price range (8 €/kg and 10 €/kg). However, the price of a commercially available organic microencapsulated PCM is roughly 10 times more expensive than the pristine PCM. This is due to the microencapsulation technique and many functionally additives for improving of their effectiveness.

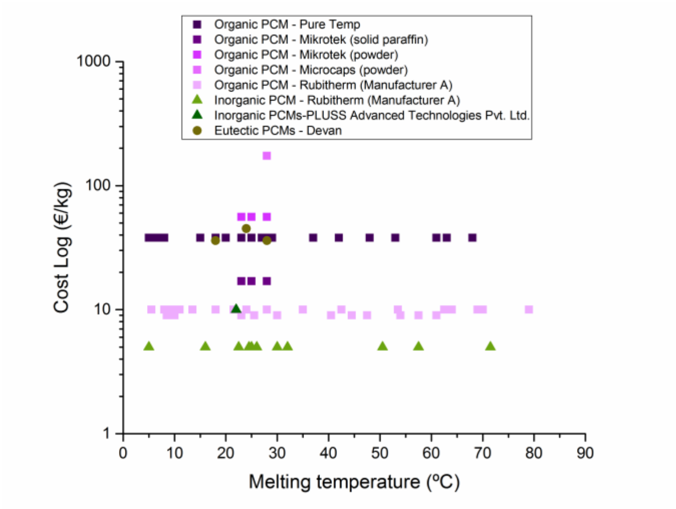


Fig. 4. Cost values versus melting temperatures for different types of PCMs [25-30].

Fig. 5 illustrates logarithmic cost (€/kg) versus latent heat capacity (kJ/kg) of the studied PCMs. It can be stated that, lower cost with higher latent heat capacity can be considered as a favourable PCM choice. For example, PCMs from "Manufacturer A" both organic and inorganic solutions clearly show the lowest cost and highest latent heat capacities, when compared with other types of the PCMs. It is interesting to note that, the cost of the PCM does not normally vary with melting temperatures of the PCM when ordered from the same producer. In fact, the quantity of the ordered PCM is also a very important factor to take into account as it may change the price of PCMs as well as shipping costs and packaging costs. It is also important to mention that, in the cases of some companies there is a minimum batch quantity for ordering PCMs.

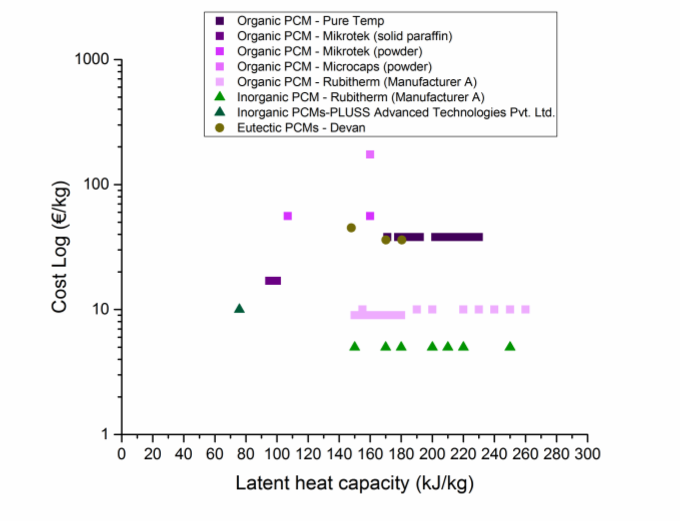


Fig. 5. Log cost values versus latent heat capacity for different types of PCMs [25-30].

Regarding the application of the PCM into the massive concrete, it is interesting to give an example of one cubic meter of ordinary ready-mix concrete in Portugal costs about 50 euros. Let's consider an example of one cubic meter of the concrete and the possibility of incorporation 90 kg of PCM per cubic metre of concrete would be required [32]. This amount of PCM will be able to reduce the peak temperature rise of the concrete around 10 ºC [32]. With a cost of 10 Euro/kg, it will cost in total 900 euros (concrete only would represent 6% of the total cost of 1m3), which is of course, not reasonable from a practical point of view at today's prices. Foreseeing that PCMs in other industrial fields becomes more generalized (e.g. in thermal comfort of buildings), the scale effect in production can make drop the price that can make the use of PCM more competitive for applications of temperature control of massive concrete structures during early ages.

5 Concluding remarks and outlook

Generally, when designing a latent heat capacity system based on PCMs, the following processes that need to be considered are: (i) Choice of the PCM type for the operational temperature range (depending on the ambient temperature) and identification of a suitable PCM with high latent heat capacity for the heat exchange with the concrete matrix; (ii) Best possible cost-effectiveness of the PCM chosen; and (iii) Definition of the adequate method for the PCMs incorporation.

A simple ranking method based on the phase change enthalpy was considered to identify the optimal solution among the studied PCM regarding thermal performance of PCM. It was concluded that the inorganic PCM from with melting temperature of

42.5ºC with latent heat capacity of 250J/g and thermal conductivity of 0.2 W/m K was the best ranked PCM from the group under study.

Selected incorporation strategy of PCM into the concrete should be considered as a way of raising the latent heat capacity of the concrete, thereby reducing the temperature evolution generated from cement hydration within concrete structure in early ages. Direct incorporation technique of PCMs in massive concrete structures, reveals to be the most practical and easy way of PCM incorporation, retaining all the traditional processes of mixing and casting of the concrete industry (i.e. lowest impact on people and processes).

As a final note, even though, PCMs that are available on the market, they are still costly, technology is likely to bring down the prices, specifically for higher capacity of latent heat solutions or for better performance requirements. Another crucial issue is the strategy of incorporating PCM into the concrete, that should besides being cost efficient, have the ability to induce temperature control in mass concrete in an evenly manner with good PCM dispersion. Future research works on concrete containing PCMs are still needed, in respect to many features, such as the methods of preparation, clear mitigation of the strength reduction, as well as durability issues. The production of concrete incorporating PCM should be driven by sustainable, eco-efficient and cost-benefit advantages.

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