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Impact of Phase Change Concrete on Thermal and Mechanical Performance: A review

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***Abstract*— Energy consumption in building is the key issue that needs to be addressed nowadays. Concrete is good recipient of thermal energy but it does not emit energy when surrounding temperature is low. The integration of Phase Change Materials (PCM) is having high attention as this material can adjust temperature of the surrounding ac-cording to its usage. By adding PCM one can successfully change thermal behavior of structure in positive way but at the same time maintaining concrete structural performance is the important task. There are various types and methods of usage of PCM in concrete but being outsider material its effect when added to concrete can help in improvement of concrete performance. This paper describes fundamentals of PCM, its types, specifications and integration methods for successful application in concrete and mortar. Furthermore, this paper compiles and summarize findings of different studies examining impact of addition of PCM on both thermal and mechanical properties of concrete.**

***Index Terms*— Phase Change Concrete, Encapsulation, Sustainability, Thermal Performance, Compressive Strength.**

I. INTRODUCTION

Usage of energy to complete electrical requirement is dependent on its time demand factor. It may vary according to its usage in industrial, domestic and commercial sector and according to time at being it is used. This variation is significant where hot and cold climatic condition is available. Concrete, mostly used material overall the world for rapid and durable construction purpose. The presence of concrete though solves durability and stability conditions of structure, still creating environment in need of low electricity usage is a still big task for the world. The Mechanical properties of concrete are the first concern while designing any concrete structure for its lifelong stability. This concern of compressive and flexural strength is the key issue to all the designers when any new type of concrete such as Phase Change Concrete with additional outsider material is used. Phase Change Material (PCM) which is also known as Thermal Storage Material (TSM) is the new concept which help in storing and releasing energy at specific enthalpy. PCM in wallboards, plasters and wall covering material is also implemented in concrete in late 1980 [1], [2]. Any material which can be called as Phase Change Material must be able to change its physical or chemical or both transformation either by absorption of heat or releasing heat [3]. In any building the most important elements that can store and release such type of energy are walls, ceilings and floors [3]. PCM in general can store 5-14 times more energy than other storage material like water, rocks, masonry, moreover they can absorb and release same energy at constant temperature which makes them suitable as latent heat storage material [2].

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The principle of working PCM for storing and releasing heat energy depends on outside temperature and endothermic process energy [4]. Rise in temperature will result in breakage of chemical bond in PCM which will allow it to absorb energy when material changes its stage from solid to liquid [4]. In case of cooling effect or decrease in temperature, the same chemical bond of PCM will be regenerated and heat will be released with change of state from liquid to solid. This whole process of changing temperature and state of PCM is also called as phase transition. Hence, use of PCM in building construction or adding it in concrete and mortar combination is helpful in preventing energy requirement of building.

II. Types of PCM's

Phase change materials are available in different forms for different energy storage requirements. There are several usages of PCM for various applications but there is not single PCM which can be viable option for all requirements of building [5]. There are mainly three different types of PCM's that are used shown in Figure 1 a) Organic b) Inorganic c) Eutectic and d) Polymers. Use of any type of PCM is dependent on several factors that affect strength, phase conditions, availability and cost of PCM [6],[5]. The specifications which any suitable PCM must possess is discussed in section 3.0.

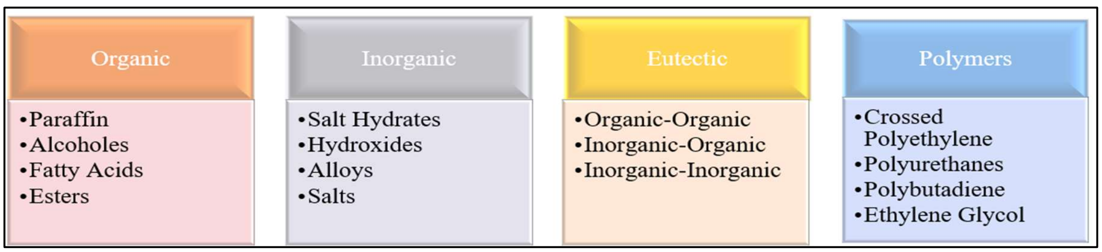


Figure 1. Types of Phase Change Materials (PCM)[5],[7],[8]

III. Specifications of Suitable PCM's

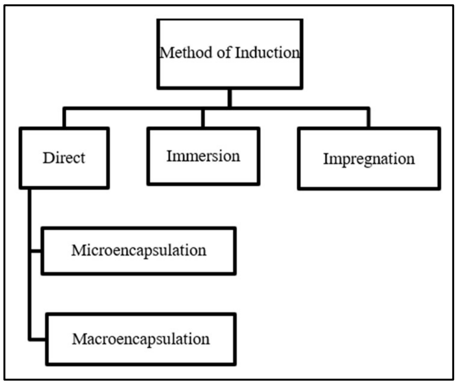
- Phase Transition: PCM's must be able to convert its temperature to human comfort conditions which ranges from 17-23°C and latent heat storage capacity as 130-200 kJ/kg [3].
- Phase Conditions: Phase Condition is the process in which PCM changes its stage according to available temperature. This condition must be temperature dependent reversible [3]. It should possess suitable melting temperature along with high cycling stability with small change in volume [4],[5],[9].
- Density: PCM should be dense having low void ratio so that it should be bulky to store more heat energy. The phase change cycle must attain repetitive cycle throughout its lifespan [3],[9].
- Thermal Conductivity: The thermal conductivity of PCM should be such that it should be able to phase both high and low temperature according to exposed temperature conditions [7,8,9].
- Stability: It should be corrosion free, inflammable, and should not decomposed when mixed with cement or any other binding material which is to be used as structural constituent material [4],[5],[9].
- Availability: Not all PCM's are cost effective, but it is expected that PCM's should be cost effective and should easily available in local market for easy procurement [3],[4].

IV. Application Method of PCM in Concrete

PCM being extra material which is not core part of concrete must be critically added in concrete to retain its effectiveness so that ultimate properties of concrete shall not be adversely affected. The factors that are affecting usage of PCM in concrete are concrete pore structure, viscosity and duration of immersion [10]. The size and structure of pores and voids present in concrete structure will affect the flow and storage of PCM [10]. More the porous form of aggregates presents in concrete more will be capacity of PCM to get absorbed in concrete in mixing process because of more space available in concrete structure [10]. Figure 2 shows typical methods of incorporation of PCM which are widely adopted [11]. These methods as title suggest are named as per their process of addition of PCM in desired mixture.

A. Direct Method

This is the most commonly method used while addition of PCM in concrete. due to change in physical and chemical composition of concrete and phase change material, before addition of PCM in concrete it must be carefully protected in stable shell or capsule form which is called as encapsulation. To prevent breakage and leakage of PCM into concrete, shell of PCM capsule is kept indestructible and sustainable [11]. Coating material should be such as, it should be able to stand as non-reactive to PCM as well as material outside it, i.e concrete or mortar [13]. There are two methods of encapsulation; a) Microencapsulation b) Macro-encapsulation. The major difference between both of these method lies in process by which PCM is stored and mixed subsequently [12],[14]. Microencapsulation is like little container which stores PCM and is done by covering core material coated with thin film made up of polymeric material of thickness micrometer to millimeter, hence called as microencapsulation [14],[15]. It can handle phase change material having melting temperature between -10°C to 80°C having advantage over other methods [14],[15]. Figure 3 shows carious physical and chemical methods that can be adopted while encapsuling phase change material.



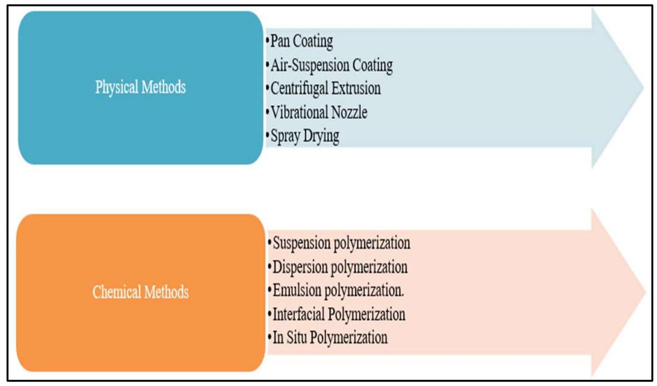


Figure 2. Methods of PCM induction

Figure 3. Methods of Microencapsulation based on application of polymeric material [15],[16]

B. Immersion Method

This method is adopted successfully by [10] in 1992 (Figure 4). The method involves dipping of concrete products which are porous in nature in PCM based liquid which will absorb PCM in it [10],[11]. The effectiveness of PCM absorption in concrete is dependent of temperature, absorption capacity of concrete and type of PCM being used [11], hence it takes several hours to complete the process. This method is mostly adopted in case of use of porous lightweight aggregate for concrete preparation is demanded [10],[16] as these aggregates can absorb more quantity of PCM within it. Immersion method is quite similar to impregnation method, but major factors that one need to consider while opting for this method is type of PCM and temperature of PCM while immersing as it directly affects effectiveness of absorbing capacity of concrete that is going to immerse [17]. Reference [10] concluded that autoclaved concrete blocks are more suitable for this technique as they possess high porosity and absorption capacity.

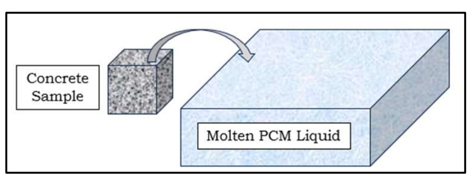


Figure 4. Graphical representation of Immersion Method

In case of immersion method possibility of leakage of PCM is more as concrete is dense and hence it may not be able to absorb PCM in suitable quantity [10]. [18] indicates that this method is costlier than direct method.

C. Impregnation Method

Direct mixing of PCM into concrete may adversely affect core properties of concrete including workability and strength. Therefore, the utmost need of another method of induction of PCM was necessary. Impregnation method is used mostly in case of lightweight aggregate (LWA) so that PCM can be properly filled in porous part of LWA. Direct impregnation method involves drying of aggregate at specific temperature which will remove any moisture present in it [17]. The dried aggregates are then soaked in PCM for desired percentage of PCM soaking values. In vacuum impregnation method, first air is removed from porous part of aggregate using air vacuum pump and then PCM is embedded in it. This allows this method for superior absorption capacity of

LWA [14]. But due to time consuming and complexity in nature, this method is mostly avoided as it may not be beneficial financially [14]. Lauryl alcohol in the form of organic PCM when impregnated in concrete made up using fly ash and granulated blast furnace slag replaced with cement shows chances of getting minimum strength requirement when restricted for maximum 5% dosage by weight of cement [18]. The application methods of addition of PCM in concrete is most important factor as it directly affects strength and thermal properties of concrete. Hence careful consideration must be taken into account before adopting method of induction. This will ultimately help in getting desire phase change cycle and hence optimum phase change temperature conditions.

V. Thermal Performance of PCM based Concrete- an Investigation

In past it is observed that concrete wall of thickness 16 cm with PCM in it possess more latent heat storage capacity than concrete wall having thickness 50 cm [13]. Certain experiments also help to find average volume of latent heat storage that can be obtained by addition of PCM in concrete, this volume as good as 4 times greater than elements that do not have PCM in it [13]. As shown in figure 5, five various samples are prepared by replacing PEG impregnated PCM aggregates with porous aggregates at 25% interval upto 100% [19]. To investigate effect of PCM on concrete, thermal conductivity is analyzed for two different temperatures 25 °C and 50 °C [19]. From figure 5 it is conclusive that thermal conductivity of PCM aggregate concrete increases with increase in solid state with highest thermal conductivity at 0.841 W/m°C [19]. At the same time, in liquid phase thermal conductivity of conventional concrete is 0.647 W/m°C which is higher than sample at 25 °C. This further justify effect of phase change condition and energy storage principle of PCM [19]. As PCM has phase changing ability and hence it is not regular liquid, with the rise in temperature thermal conductivity is decreasing due to phase transition of PCM, shown in figure 5. RADCOOL is numerical simulation method based on finite difference method which is used to analyze latent heat storage of wallboard [20]. Reference [20] measured performance of conventional wallboard and PCM treated wallboard having different percentage of PCM used in wallboard.

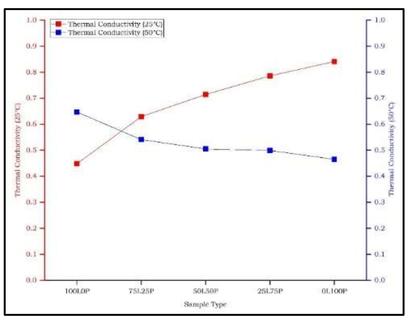


Figure 5. Thermal Conductivity of Concrete for Solid-Liquid phase [19]

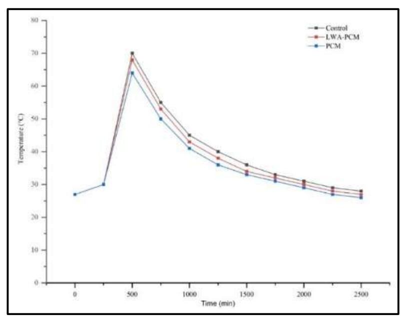


Figure 6. Semi-adiabatic Temperature Curves of various mixes[23]

The finite difference approximation technique [21] used to simulate performance of real-life small room model of size 1.25m x 1.80m x 1.70m shows that stable and comfortable room temperature can be maintained when PCM is used in walls and roofs conforming to both analytical and numerical results. To evaluate effect of incorporation of PCM into cubicles, three different cubicles having thickness 0.12m are prepared and tested for temperature effect with the help of sensors placed at middle of the cubicle room at height 1.2m and heat flux sensor installed inside south wall panel at height 2.0m [22]. The size of all three cubicles was same, 2m x 2m x 2m having door on north wall and window of size 1.7m x 0.6m at both east and west wall and window of size 0.75m x 0.4m on south wall [22]. The experiment is carried out in Puigverd of Lleida (Spain) for duration 23rd March to 01st April 2005 shows that decrease in temperature of south wall of cubicle having PCM as compared to non-PCM south wall [22]. Figure 5 shows that thermal performance of three different types of mortar is analyzed by [23] to study effect of addition of PCM in it. Figure 6 indicates that both LWA/PCM and PCM mortar samples shows relatively lower peak temperature and faster colling rate than control sample. Control sample which is conventional mortar have tendency to release higher amount of heat whereas addition of PCM and LWA in it helps in reduction of heat energy [23]. Experimental work done by [24] on several cubicles constructed with conventional bricks and alveolar bricks were tested for energy accumulation and related energy saving. From figure 7, we can conclude that least energy consumption is done by mostly by Alveolar and SP25+Alveolar bricks for all the durations. The energy consumption of conventional bricks i.e reference sample accounts for twice than these two [24].

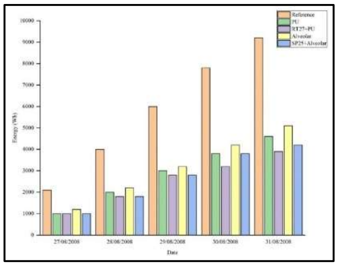


Figure 7. Energy Accumulation Consumption at Set point 24°C [24]

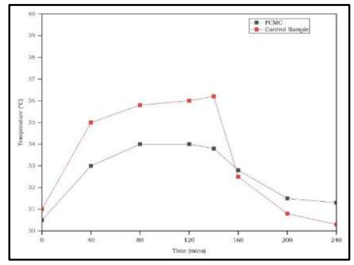


Figure 8. Thermal Performance of lightweight concrete having PCMC and Control Sample [27]

The thermal conductivity of PCM based concrete analyzed using host disk TPS 2500S instrument showed that it is constant even when PCM percentage is increased [25]. This concludes that heat storage capacity of concrete is increased with the addition of PCM in it [25]. To find out thermal performance of geopolymer mortar performance with PCM in it, [26] had created three cubicles of size 12” x 12” x 12” with 2” slab on it with temperature sensor installed in air at distance of 1 foot from cubicle to measure and compare temperature within cube and outside ambient temperature for the period of 24 hours. Results obtained from sensors shows that at peak temperature hour, temperature of bottom surface of slab having PCM 10% and 20% shows lower temperature as 3.3°C and 6.2°C respectively [26]. Compared to standard cubes, cubes having 10% and 20% PCM in it have 4.4°C and 5.5°C lower temperature in peak hours [26]. Hence this will summaries that geopolymer mortar with PCM will help to reduce energy consumption in building as it will reduces temperature of surrounding [26]. Paraffin recycled concrete composite is used as fine aggregate for the constitution of lightweight concrete [27]. The thermal performance of prepared sample when compared to control mix shows temperature variation as shown in figure 7 due to presence of PCM [27]. As shown in figure 8, the maximum temperature achieved is 36 °C and 34.1 °C for control sample and PCM based sample, respectively. This temperature difference of 1.9 °C is observed mainly due to process of heat exchange between outdoor environment and PCM and subsequent heat transfer [27]. LWA when used as PCM carrier prevents leakage of PCM into concrete as amount of PCM absorption is equal to porous capacity of LWA which further helps in stopping its interference towards hydration reaction [28]. Thermal conductivity of both mortar and concrete with Micronal based microencapsulated PCM mixed during wet process is found out using C-therm and needle-based method [29]. As thermal conductivity of sand used in mixing process is higher than that of PCM, reduction of thermal conductivity is observed which also accounts for increase in heat capacity as percentage of PCM in concrete and mortar is increased [29]. The thermal performance of LWA-PCM combination is studied by [30] by observing condition of temperature variation of room made up with concrete panel and also at the inner and outer surface of concrete panel. Table I shows that temperatures observed at various positions of different mixes prepared by [30]. This indicates that PCM-LWA is capable of decreasing indoor temperature which is measure at center.

TABLE I. TEMPERATURE OBSERVED AT VARIOUS LOCATION FOR VARIOUS CONCRETE COMBINATIONS

Concrete Samples	Center	Outside	Inside
Control Sample	38.3 °C	49.7 °C	46.0 °C
25PCM-LWA	36.8 °C	44.7 °C	42.9 °C
50PCM-LWA	36.2 °C	43.6 °C	40.9 °C

Table II shows change in temperature (ΔT) of concrete panel for various combinations observed at various locations by [31] to study effect of PCM on thermal storage capacity as well as compressive strength of concrete.

TABLE II. CHANGE IN TEMPERATURE (ΔT) FOR VARIOUS COMBINATIONS [31]

Panel Type	Change in temperature (ΔT) at various depth locations		
	50 mm	100 mm	150 mm
Control	25 °C	23 °C	21 °C
Control+GGBS	23 °C	21 °C	19 °C
ME PCM	19 °C	17 °C	15 °C
ME PCM+GGBS	22 °C	18 °C	16 °C
LWA-PCM	18 °C	16 °C	14 °C
LWA-PCM+GGBS	19 °C	18 °C	16 °C

It is observed that concrete panel with microencapsulated PCM and GGBS shows lowest temperature at 150 mm location as compared to other two locations. Therefore, thermal storage of both types of panels increases with increase in depth irrespective of PCM combinations used, which indicates that presence of PCM certainly helps in achieving temperature conditions. LWA-PCM+GGBS sample shows greater thermal storage because of presence of more specific heat storage capacity in sample due to addition of GGBS in it [31]. In case of building thermal conductivity is directly connected to average annual energy consumption. Figure 9 shows thermal conductivity of paraffin PCM based foamed concrete block using expanded graphite developed by [32]. Thermal conductivity of pure foamed concrete block is 0.55 W/mK whereas in case of paraffin based foamed concrete block thermal conductivity is gradually increasing with the increase in percentage of mass fraction of PCM. This phenomenon occurs because both paraffin PCM and foamed based concrete made up using expanded graphite has excellent thermal conductivity [32].

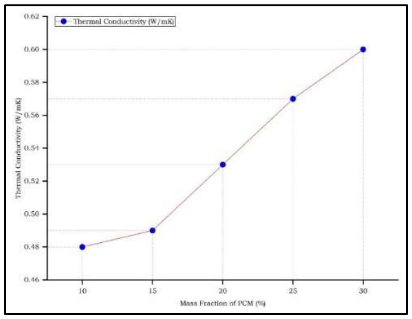


Figure 9. Thermal Conductivity vs. Mass of PCM Fraction [32]

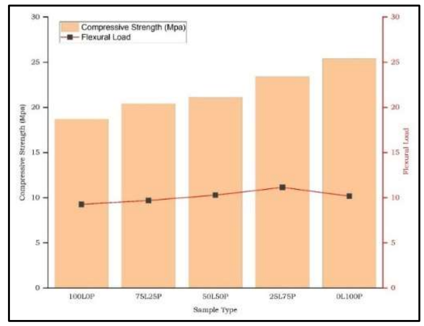


Figure 10. Compressive Strength and Flexural Load of Impregnated PCM Samples [19]

VI. MECHANICAL PERFORMANCE OF PCM BASED CONCRETE- AN INVESTIGATION

The results of study of compressive strength along with flexural load capacity by [19] are indicated in figure 10 As we can see, with the increase in replacement of PEG impregnated PCM aggregate with conventional porous aggregates, the compressive strength is increased and 25.42 MPa is achieved at 100% replacement [19]. In case of flexural load capacity, it is increasing upto replacement value 75% and then slightly decreasing [19]. This decline in flexural load capacity as shown in figure 10 is due to lower capacity of PCM coating material under flexural stress developed around it [19]. 1% 3% and 5% Micronal DS 5001 X PCM of total volume of concrete is used to prepare cylindrical and prismatic mound samples [25]. These sample when tested for compressive strength showed that presence of PCM weakens maximum 32% less compressive strength of concrete due to late heat of hydration in concrete in presence of PCM [25].

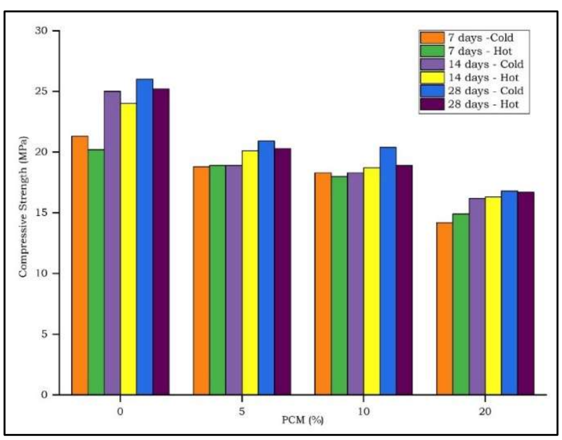


Figure 11. Compressive Strength of PCM incorporated hot and cold geopolymer mortar [26]

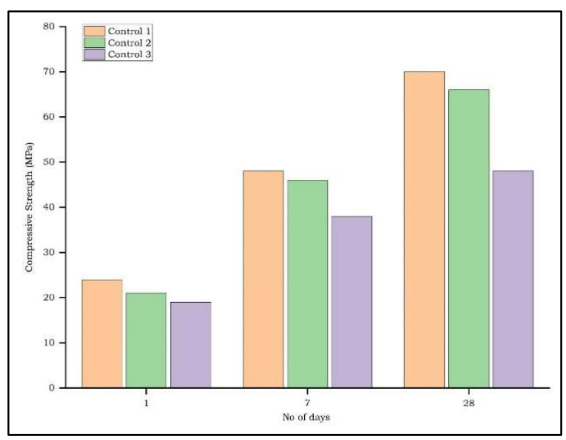


Figure 12. Compressive Strength of Control Mixtures [33]

Figure 11 shows that 4 different variations of PCM based geopolymer mortar with hot and cold conditions are prepared and tested for uniaxial compressive strength by [26]. The result clearly indicates that with the increase in percentage of PCM 28 days compressive strength is decreased by 22% in cold sample and 25% in hot sample [26]. This phenomenon occurred as PCM has smaller shear strength and stiffness than geopolymer mortar which when added lead to failure [26]. LWA and Rice Husk Ash (RHA) can absorb sufficient quantity of PCM out of which some proportion is released in cement paste while reaction [28]. But addition of PCM in LWA decreases compressive strength of sample within acceptable range which permits its usage wherever strength is not major issue [28]. [33] analyzed total 11 various samples which consist of three control samples; control 1 is standard mortar with no PCM in it, control 2 contains expanded clay aggregates soaked in water and control consist of pumice aggregates soaked in water. From the remaining 8 samples, 4 samples consist of expanded clay aggregates and 4 samples with pumice aggregates, both groups having PCM6, PT6, PEG600, PEG400 as phase change material in it. Figure 12 shows that reduction in compressive strength when expanded clay and pumice is used to prepare mortar without PCM in it. This is mainly because LWA is able to unable to carry higher compressive strength. Figure 13 and figure 14 indicates constant decrease in compressive strength of mixture than control mixture due replacement of normal sand with pumice and expanded clay aggregates [33]. As compared to control sample, control 3 sample which is made up of water-soaked pumice has consistent decrease in strength in all ages [33]. The particle distribution of pumice aggregate is constant which directly affects packing strength of mortar and hence compressive strength is reduced [33]. In drainage test it is observed that due to PCM coating to pumice and expanded clay aggregates most of the PCM is remains at outer surface of aggregates which obstruct cement hydration process [33].

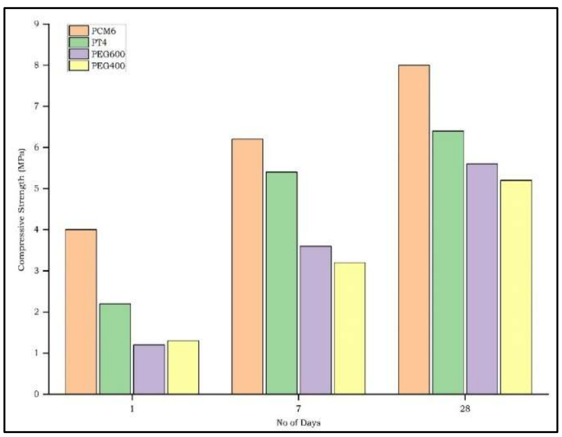


Figure 13. Compressive Strength of various PCM based mixtures having expanded clay aggregates

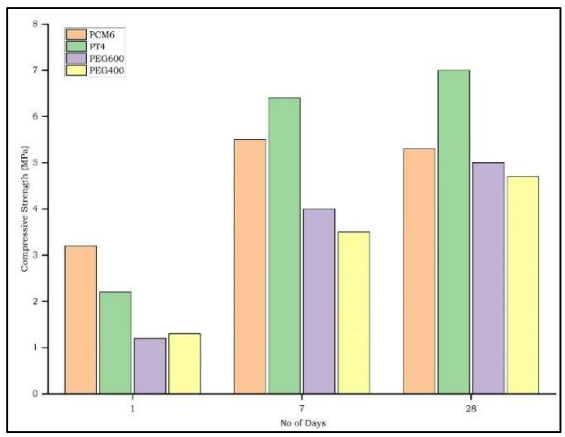


Figure 14. Compressive Strength of various PCM based mixtures having pumice aggregates [33]

Two different concrete panel, one having encapsulated paraffin PCM and other having vacuum impregnated brutyl stearate PCM based LWA are tested for compressive strength by [34] out of which nearly 50% of 50 MPa compressive strength is achieved by both the concrete panel. One of the main reasons behind lesser compressive strength is leakage of PCM on surface of concrete due to poor bond between cement paste and aggregate during hydration process [34]. To study effect of addition of microencapsulated PCM in concrete and its performance for samples with 75kg of PCM, 18 cubes of 150 x 150 x 150 mm, 12 cylinders of 150 mm diameter and 300 mm height and 12 beams of size 800 x 200 x 200 mm were prepared and tested [35]. The results indicate the loss of compressive strength when PCM is added is nearly 68% whereas in case of density is 10.5% in average [35]. When PCM sample is heated for 40 °C and then cooled for ambient temperature it is observed that temperature rise is slow than control sample [35]. Thereafter in cooling phase condition, temperature difference between control sample and PCM sample concrete accounts for 1 °C which is due to release of previously stored heat energy from heating phase in PCM concrete, and hence PCM concrete cools down slowly [35]. Concrete mixes prepared with PCM with 10%, 20% and 30% by volume concentration. To investigate its impact on compressive strength tests were conducted after 7 and 28 days for curing at both 23 °C and 40 °C [36]. Compressive strength analysis by [36] indicating reduction in compressive strength for both curing temperatures and for both age of day of curing with increase in PCM percentage in concrete [36]. As we can see there is increase in loss of compressive strength of concrete as PCM percentage is increased for all ages and for all curing temperature conditions. In comparison to all the cases, the compressive strength of concrete with no PCM in it of 28 days of ages with 40 °C curing condition have greatest compressive strength and concrete with 20% PCM with 7 days ages and 28 days ages with 40 °C have similar compressive strength which is least of the all [36]. This reduction and lower compressive strength of PCM based concrete makes it unsuitable for its use in structural element. A different approach was covered by [30] to study effect of LWA-PCM combination and its suitability against compressive and thermal state of concrete. it is found that compressive strength of PCM-LWA concrete at 28 and 56 days of curing ranges from 22.02 MPa to 42.88 MPa which is suitable for its use as structural elements, as per [30]. The compressive strength of LWA-PCM combination with 25% PCM replacement is found more than concrete with 25% LWA replacement for 28 days pf curing time [30]. In comparison to control sample having strength 20 MPa, concrete with only LWA replacement have shown lesser strength which is mainly due to its porousness nature [30]. Various concrete panels with ME-PCM and LWA-PCM tested for compressive strength of concrete by [31]. Results obtained indicates that addition of PCM in both the sample have decreased compressive strength drastically than control sample [31]. These findings of lesser compressive strength in presence of PCM was discussed by various researchers mentioned in this section earlier. One other notable factor is that there is comparatively lesser difference in compressive strength between ME-PCM sample and LWA-PCM sample, which simplifies that presence of LWA does not influence compressive strength of concrete. Two different types of PCMs are added in concrete by [37], one is Fatty Acid Eutectic PCM (FA) and other one is polystyrene shell microencapsulated PCM (mPCM) which are tested for 7 days and 28 days of curing time. The reduction in compressive strength is observed by [37] due to replacement done for aggregates by PCM. As per Turkish Standards class C30/37, the compressive strength achieved by both types of PCM samples, is still suitable for its use for earthquake design concrete [37]. These findings of [37],[38] are also verified with findings of [39], in which [39] found out that PCM decreases compressive strength of mortar and concrete even after 28 days of curing. According to [39] reduction in compressive strength is mainly due to poor bonding and leakage of PCM in cement paste while mixing which accounts for loss of desired strength which is also described by [34],[38].

VII. Conclusion

The purpose of this review study is to understand importance of PCM to address energy demand in building consumption sector. There are several types of PCM which can be used along with each own advantages and disadvantages, but one must careful in selection of PCM as it directly affects core physical, chemical and thermal properties of concrete. This paper also includes micro and macro encapsulation techniques highlighting importance of preventing leakage to ensure lifelong durability of concrete. the immersion and impregnation methods were also discussed specially for lightweight concrete along with its limitations. The evidence strongly indicates that PCMs have the potential to significantly enhance concrete's thermal performance. The reviewed studies demonstrate that incorporating PCMs improves thermal conductivity, stabilizes temperature fluctuations, and decreases overall energy usage in buildings. The study highlights potential use of PCM in concrete to enhance thermal performance. While some studies reports that use of PCM decreases compressive strength, others also suggest that careful selection and implantation of PCM in concrete may help in maintain desired strength parameters. This paper also points out importance of use of lightweight aggregate as promising position to mitigate negative impact of PCM on mechanical performance of concrete. By introducing PCM into concrete, it helps in improvement of internal temperature and thermal properties which allow to lower energy footprint of building, this study confirm this dialogue. Ultimately, this review study makes a valuable contribution to the field of sustainable construction materials, with a particular important role of PCM integration in enhancing the energy efficiency of buildings.

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