Journal of Futuristic Sciences and Applications
Vol. 3(2), Jul-Dec 2020, pp. 1-13
doi: 10.51976/jfsa.322001
www.gla.ac.in/journals/jfsa

Analysis of the Effects of Phase Changing Material on Concrete Pavement

Rashmi Sharma and Vipul Dev Avasthi***

ABSTRACT

In order to provide the public with better services, there is an increasing demand for efficient transportation. Concrete pavements are used more commonly in highway building today. Concrete pavement is more efficient because of its increased strength, dependability, and endurance; however, temperature stresses have a big impact on concrete pavements. This study investigates the potential use of phase-changing material (PCM) to reduce temperature stresses in concrete pavements. to compare the temperature differences between various PCM replacement amounts in concrete mixes and compressive strength A heat simulator indoors with temperature sensors was used to measure the temperature difference between concrete formulations. The difference in temperatures is one of the primary reasons that concrete pavement curls. The results imply that lowering thermal stresses in concrete pavement by increasing PCM content.

Keywords: *PCM; Temperature Stresses; Durability; Smart Material.*

1.0 Introduction

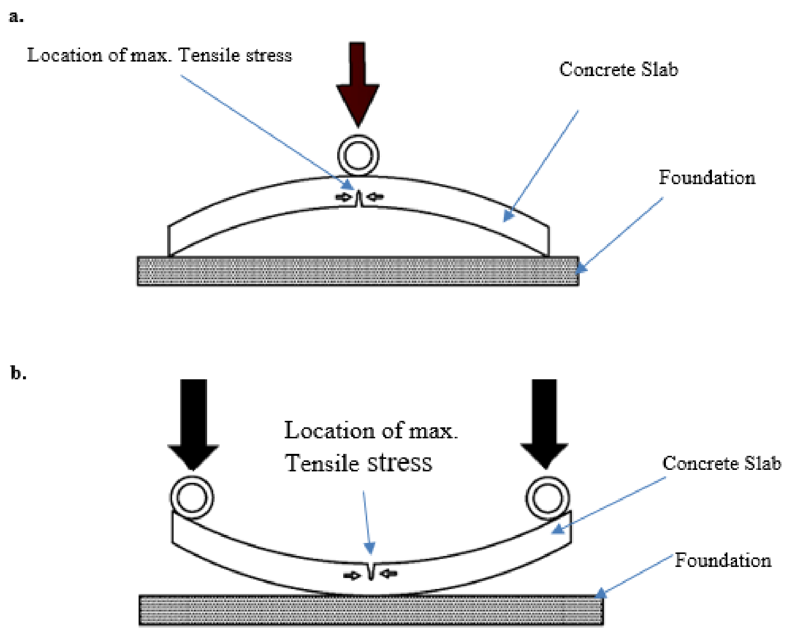
Concrete pavements are constructed for roadways to support heavy vehicle loads. Environmental loads, such as temperature and moisture gradients, as well as frequent driving loads, cause stresses in concrete pavements [1,2]. The combined effects of heavy loading and temperature changes increase the strain capacity of pavement. The primary causes of a first breakdown in concrete pavement are temperature fluctuations and pavement depth [3]. Shear stress and dynamic stability are two other factors that are impacted by temperature rise. Due to the fact that the top surface of the concrete is hotter than the bottom surface, the edges of a concrete slab migrate downward in proportion to the slab's centre during the day and upward at night [4]. This downward and upward curling of the slabs causes the biggest tensile strains to arise at the bottom and top of the slab. Only their own weight and the layer underneath them, which causes internal tensions, prevent concrete pavements from deforming [5]. As seen in Fig. 1, when combined with moving vehicle loads, concrete pavement is less able to endure these tensile stresses that lead to crack formation. The cyclic loads that develop as a result of temperature variation reduce the pavement's durability and useful life [6]. When a concrete pavement is subjected to temperature strains, failure occurs. During the day and at night, top-down cracking and bottom-up cracking, respectively, are the two terms used to describe these stresses. Temperature stresses must be considered carefully while building concrete pavements. According to Bradbury's equation [7], the maximum temperature difference and a significant slab depth factor are taken into account when evaluating temperature stresses.

**Corresponding author; Assistant Professor, Department of Computer Science, Ajay Kumar Garg Engineering College, Ghaziabad, Uttar Pradesh, India (E-mail: rashminonumanu@gmail.com)*
***General Manager, Shri Yamuna Infrastate Pvt Ltd. (E-mail: vipuldev0007@gmail.com)*

Doi: 10.51976/jfsa.322001

The term "temperature differential" refers to the variance in temperature between the top and bottom of a concrete slab. A bigger temperature difference leads to high-temperature stresses. In order to reduce curling, the maximum temperature differential must be decreased. Concrete’s temperature differential can be lowered by employing materials that change the concrete’s temperature gradient. Concrete’s thermal behaviour may be enhanced by materials that change their phase. Phase change materials (PCMs) transition from a liquid to a solid at a particular temperature and vice versa by releasing and absorbing energy in the form of latent heat. The small temperature range that can be selected to fit the operating temperatures for every specific technical application is where this energy release and absorption phenomenon takes place. Numerous studies have demonstrated that the use of PCM enhances the thermal behaviour of concrete [8]; this PCM property can also be exploited to reduce temperature stresses in concrete pavement. When constructing a structure, PCM concrete is primarily used to reduce energy consumption, thermal discomfort, and freeze-thaw failure in pavement [9]. There are numerous PCMs available for industrial use with a variety of phase transition temperatures [10]. PCM with a certain phasing temperature and latent heat can be put in concrete to maintain the research area’s required temperature conditions. The temperature gradient of the concrete pavement is lowered as PCM melts because latent heat is dissipated. By reducing thermal stress, concrete pavement’s lifespan and maintenance costs can be extended. PCMs can be added to concrete in two main categories: I inorganic PCMs and (ii) organic PCMs (paraffin and non-paraffins) (salt hydrates). However, because most inorganic PCMs have the ability to sub-cool and experience large volume variations, the use of organic PCMs in conjunction with concrete has increased [11]. Concrete can be directly or indirectly amended with PCM. The simplest and most practical approach to incorporate PCM into concrete, whether it is in a dry, solid, or liquid, wet state, is by this type of mixing. Encapsulating (macro or micro) and impregnation are more time- and resource-consuming methods of embedding PCM into concrete.

Figure 1: (a) Day Time Condition of Bottom-Up Cracking (b) Night Time Condition of Top-Down Cracking. (Made using AutoCAD)



2.0 Research Methodology

2.1 Materials used

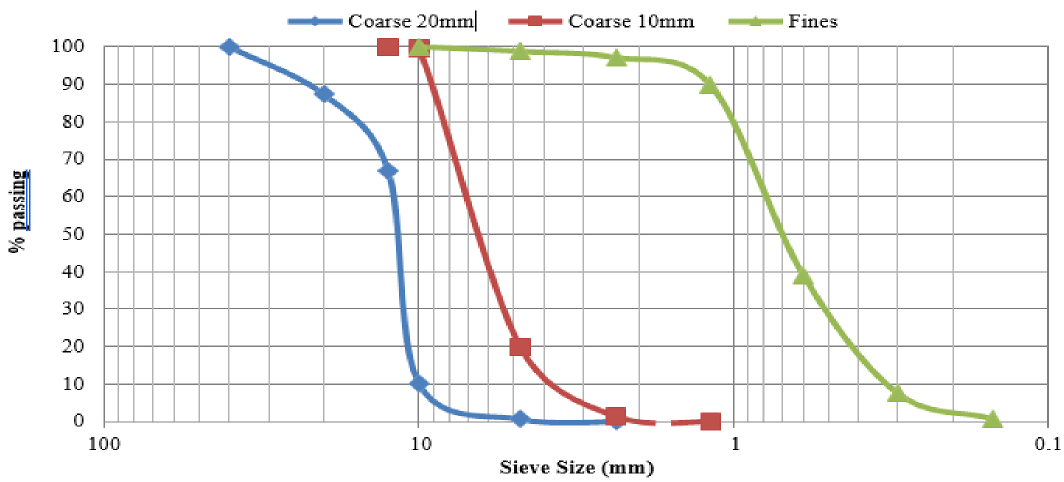
A phase-changing substance made of organic paraffin and crushed natural stone with nominal diameters of 20 mm and 10 mm were used as binders together with regular portland cement (43 grade). Sand from the Banas River with a maximum grain size of 4.75 was used as fine aggregate. The sieve size analysis of the coarse aggregates of Zone-II (size 20 mm & 10 mm) and fine aggregates of Zone-II shown in Fig. 2 was confirmed by IS: 383-1970 [12]. The physical parameters of cement, fine aggregate, and coarse aggregate are listed in Table 1.

Table 1: Physical Properties of Raw Material

Property	Cement	Fine Aggregate	Coarse Aggregate (10 mm)	Coarse Aggregate (20 mm)
Consistency (%)	27	–	–	–
Initial Setting Time (minute)	110	–	–	–
Final Setting Time (minute)	241	–	–	–
Specific Gravity	3.15	2.62	2.70	2.70
Water Absorption (%)	–	1	0.4	0.41
Fineness Modulus	–	2.67	5.79	7.02
Compressive Strength (MPa) 7 days	34.7	–	–	–
28 days	44.9	–	–	–

This paper examines the thermal and strength properties of concrete at various substitution levels using an organic-based PCM. The bulk PCM used in the project lacked encapsulation. Phase-changing substance was a patented, commercially successful product, thus the manufacturer hasn't provided information on its chemical composition. Images of the phase-changing material in its solid-state and liquid-state states are shown in Figs. 3(a) and (b), respectively. At a temperature of 51 C, this PCM starts to melt, and at 48 C, it starts to freeze. In order to phase transition from 48 C to 51 C using saturated paraffin and organic compounds, PCM was predominantly used. The main objective of this PCM is to maintain pavement surface temperatures in Rajasthan at or above 50 C during the summer. The technical information on the PCM that the supplier provided is listed in Table 2.

Figure 2: Sieve Size of the Aggregate



Journal of Futuristic Sciences and Applications, Volume 3, Issue 2, Jul-Dec 2020
Doi: 10.51976/jfsa.322001

Figure 3: (a) Liquid-State PCM and (b) Dry-State PCM

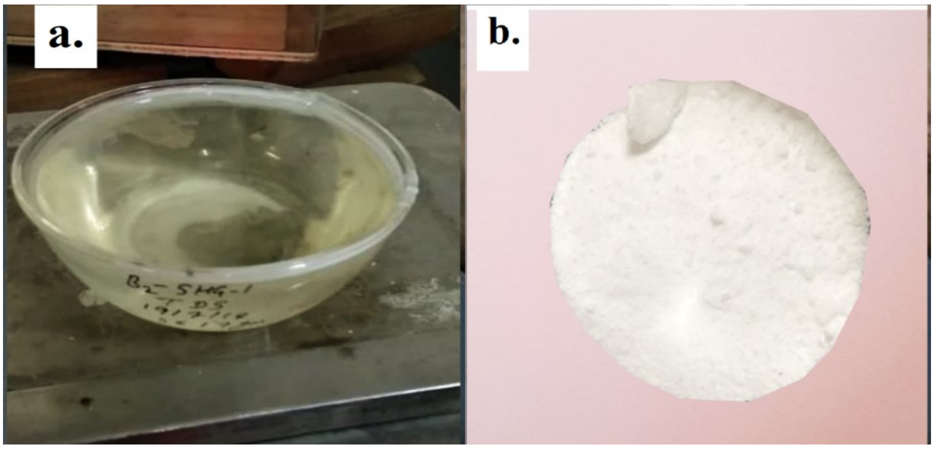


Table 2: Technical Specification of PCM

Property	Value
Melting Temp (°C)	51
Freezing Temp (°C)	48
Latent Heat (kJ/kg)	172
Liquid Density (kg/m^3)	875
Solid Density (kg/m^3)	960
Liquid Specific Heat (kJ/kg K)	2.35
Solid Specific Heat (kJ/kg K)	2.02

2.2. Mix proportioning

Concrete pavement must have a minimum 28-day compressive strength of 40 MPa, in accordance with IRC 58:2015 [13]. When performing trial mixing for M40 grade concrete, IS 10262:2009 requirements are followed [14]. The coarse aggregates of size 20 mm and 10 mm were blended in equal amounts to obtain the requisite grading. The ratios of water to cement, fine aggregate, and coarse aggregate must be 0.4, 1: 1.77, and 2.98, respectively, in order to achieve the target strength of 48 MPa at a standard deviation of 5.0. Super-plasticizer (Master Glenium SKY) was admixed into the concrete mixture to suit the project's requirements. PCM is directly included into concrete at varied substitution levels in both the solid and liquid stages to measure compressive strength. PCM is substituted at levels ranging from 2 to 12 percent of the cement volume, with additions happening every 2 percent. The ratios of all the components for various PCM mixes were displayed in Table 3.

Table 3: Proportioning of Materials to Prepare Concrete in Kg/m3

PCM Mix (%)	Cement	Water	Fine Aggregate	Coarse Aggregate	Admixture	PCM
0	399	160	708	1191	2.79	0
2	399	160	708	1191	2.79	2.44
4	399	160	708	1191	2.79	4.88
6	399	160	708	1191	2.79	7.32
8	399	160	708	1191	2.79	9.75
10	399	160	708	1191	2.79	12.19
12	399	160	708	1191	2.79	14.63

The solid and liquid PCM components were manually mixed to create the concrete mix. Fig. 4 shows the heating of liquid-state PCM to a constant temperature of 50 C following direct mixing with other components. The dry elements were then combined with solid-state PCM.

Figure 4: Mixing of PCM in Liquid State

2.3 Workability test

Slump test is analysed using IS 7320:1974 [15]. Slump assesses how much concrete may sink without support and serves as a gauge for how easily new concrete can be worked. A cone has a top diameter of 100 mm, a bottom diameter of 200 mm, and a height of 300 mm, respectively. In this study's concrete, a superplasticizer based on poly-carboxylic ether (PCE) was used to achieve the requisite workability.

2.4. Compressive strength test

Compressive strength is an important mechanical criterion to assess before pouring concrete, according to IS 516:1959 [16]. A typical specimen of 150 x 150 x 150 mm was cast to evaluate compressive strength. The average strength of three samples with different levels of PCM substitution is calculated after 28 days of curing. If the PCM is altering the samples' strength in a solid or liquid phase, it can be determined from the concrete's strength after 28 days.

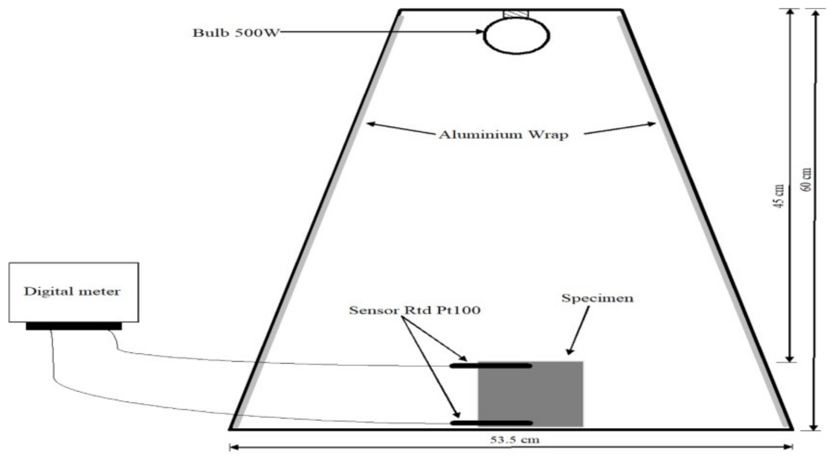
2.5. Temperature variation test

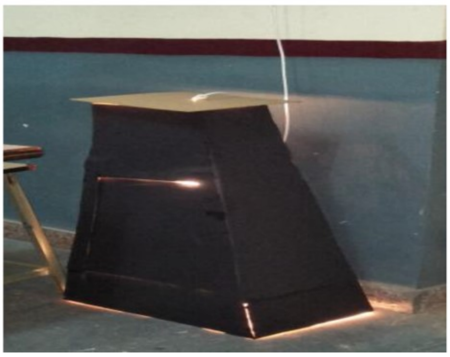
The temperature change in concrete is calculated using the indoor heat simulation setup. The schematic diagram and constructed image of the indoor heat simulation setup are shown in Fig. 5(a) and (b), respectively.

The height and area of an indoor heat simulation are determined using the solar radiation reflection index of the light that the earth's surface receives. India obtains 4–7 kWh of solar energy per square metre every day [17]. It was believed that Rajasthan may receive solar radiation of 7 kWh per square metre per day during the summer (as it is a desert state of India). About 50% of the radiation emitted by the upper atmosphere is determined to be infrared [18]. Therefore, it was believed that 50% of all radiations that reached the planet's surface were infrared radiations.

Doi: 10.51976/jfsa.322001

Figure 5: Indoor Heat Simulation Setup (a) Schematic (b) Image





The result was that each square metre of the earth's surface received 3.5 kWh of infrared radiation daily. The radiation production per square metre per hour at this location, assuming the sun is present for 12 hours each day, was 291.67 Wh, or 0.02916 Wh per square centimetre each hour. Most bulbs only convert 10% of the input power into visible spectrum; the remaining 90% of the power is lost as heat energy [19]. The main method through which energy is lost from a bulb is by infrared radiation. It was believed that infrared radiations were responsible for 80% of the input energy that was lost from the bulb. As a result, the 500W bulb used 400 Wh of energy in an hour. The setup box therefore required 13714 cm2 of area. A 2.0 safety factor was assumed in this location. This meant that the setup box needed 6857 cm2 of area. The slope height angle was 39.4 degrees with respect to the vertical. It was believed that all of the rays left the truncated cone at a 39.4 degree angle to the vertical. It took a height of 43.41 cm from the top of the truncated cone to produce a scatter light projection that covered an area of 6857 cm2. The specimen was therefore kept at a height of 45 cm. During the summer, the effects of the sun are often felt from 10 am to 4 pm, or six hours, and are at their peak between 12 pm and 2 pm, or two hours. A top-mounted 500W light was utilised to simulate the effect of the sun during the full test, which was scheduled to take place between 12 and 2 o'clock. This was like compressing the 6-hour intensity of the sun into a 2-hour span. The lesser alternative, 2286 cm2, was chosen because doing so would have required either a threefold increase in power or a threefold reduction in area. A hardboard measuring 53.5 cm by 45.0 cm was chosen in order to maximise reflection, and the interior surface was lined with an aluminium wrap, leaving an affective dimension of 53 cm by 44.5 cm (2358.0 cm2). Readings from the temperature sensor probe (RTD Pt100), which is accurate to 0.1 C, were taken on the top and bottom of the concrete specimens as the temperature around it was increased inside the heat simulation system. The sensors were implanted at the top and bottom of the specimen using drilling, and the exposed outside section was then sealed off. According to data from India's Metrological Department, the highest air temperature in the state of Rajasthan has varied between 45 and 47 C over the past ten years. The pavement's surface temperature is typically 10 to 15 degrees Celsius higher than the surrounding air temperature, depending on a variety of environmental parameters, such as moisture content, wind speed, and other factors. Since a specimen inside the setup had to attain a top surface temperature of close to 60 C for this study, continuous monitoring was done up until that point. Because the indoor heat simulation setup raises the top surface temperature of a concrete specimen to 62 C in 60 min, the temperature of each specimen was monitored for an hour at intervals of five min.

3.0 Result Discussion

3.1 Slump test

To determine how the PCM addition impacts how workable fresh concrete is, slump values are examined. The substitution of PCM in the concrete mix gradually increases workability in both ways of mixing. The slump value for the control mix is 98 mm. The slump values of dry PCM mix concrete are lower than those of liquid PCM mix concrete, as shown in Fig. 6. PCM particle size affects how easily fresh concrete can be worked [20]. The flat surface and lack of water adhesion of the material may be the cause of the better workability of mixes containing PCM.

Figure 6: Slump Values Concrete at Various Substitution of PCM

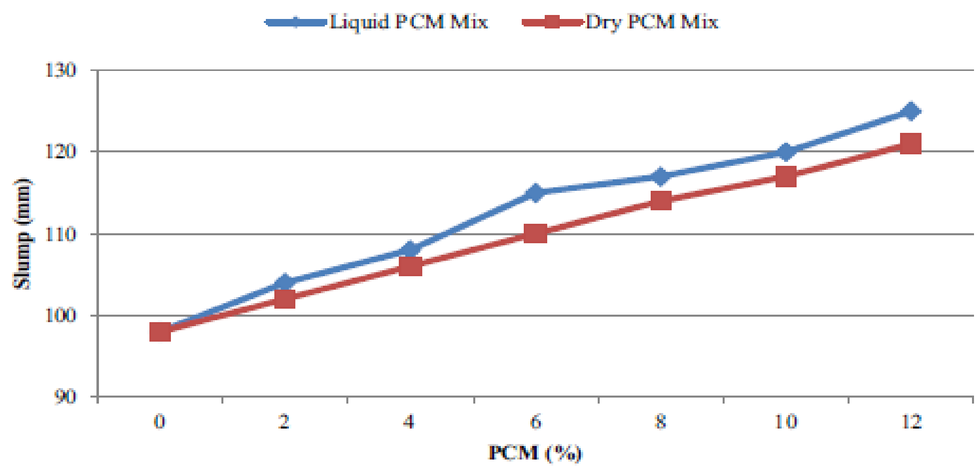


Fig. 6. Slump values concrete at various substitution of PCM.

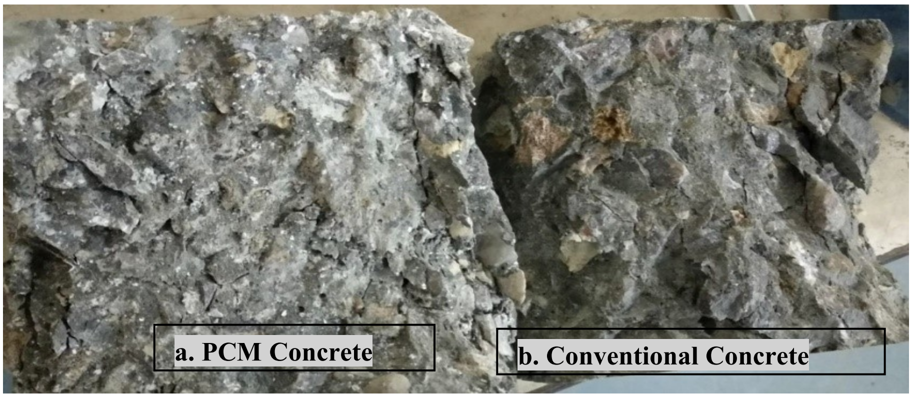
3.2 Compressive strength test

Compressive strength of concrete is measured in both the wet and dry states at varied PCM mixing substitution percentages. Compression strength decreases as PCM content in concrete rises, as shown in Fig. 7. The compressive strength of concrete decreases when PCM is added; this could be because, as was seen in other research [21,22], the PCM leads to the formation of air bubbles and holes in the concrete matrix. Strength has been decreased because PCM is less stiff and strong than other concrete materials [23]. The concrete matrix and PCM have a poor bond and little adhesion, which reduces strength [24]. Performance of PCM-concrete in a dry state is superior to that of PCM-

Doi: 10.51976/jfsa.322001

concrete in a liquid state. It is recommended to utilise dry PCM mixing because it yields better results. The failure surface of PCM mixed concrete was smoother than that of the conventional concrete in Fig. 8.

Figure 7: Failure Surface of PCM Concrete and Conventional Concrete.



The compressive strength of concrete pavement must not be less than 40 MPa after 28 days of curing, as per the criteria of IRC 58:2015 [12]. Compressive strength test results indicate that PCM can be substituted for liquid and dry state mixing at rates of 6 and 8 percent, respectively, in pavement concrete.

Figure 8: Compressive Strength of Concrete for Different PCM Mixes

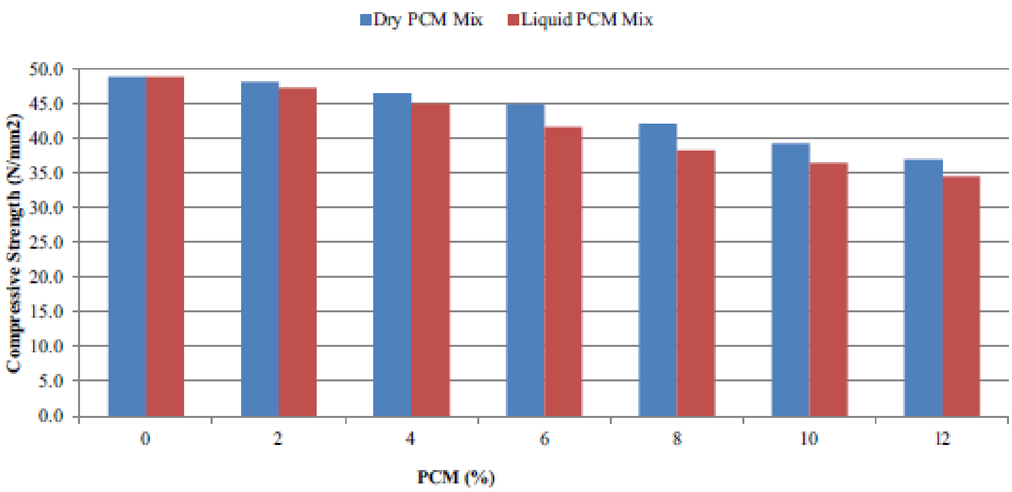


Fig. 7. Compressive Strength of concrete for different PCM Mixes.

3.3 Temperature variation

The methodology involved using an indoor heat simulation setup to gauge the temperature variation of a different concrete specimen. With maximum temperature differentials of 12.5 C, 13.1 C, 14.3 C, and 15.8 C for slab thicknesses of 15 cm, 20 cm, 25 cm, and 30 cm, respectively, according to IRC 58:2015, the state of Rajasthan is classified as being in Zone I [12]. The temperature variation at and below the concrete with different PCM content substitutions is shown in Figs. 9, 10, and 11.

Concrete that has been PCM changed displays less temperature change than unmodified concrete [9,25]. The temperature differential between the top and bottom of concrete pavement is shown in Fig. 12 to decrease as PCM concentration increases. The specimens with the 4 percent PCM mix, 6 percent PCM mix, and control mix had the largest temperature differences, which were 14.3, 10.9, and 17.3 degrees Celsius, respectively. The pavement's sensitivity to temperature is increased by the addition of PCM, which reduces curling strains.

Figure 9: Temperature Variation at Top and Bottom of Control Mix Concrete

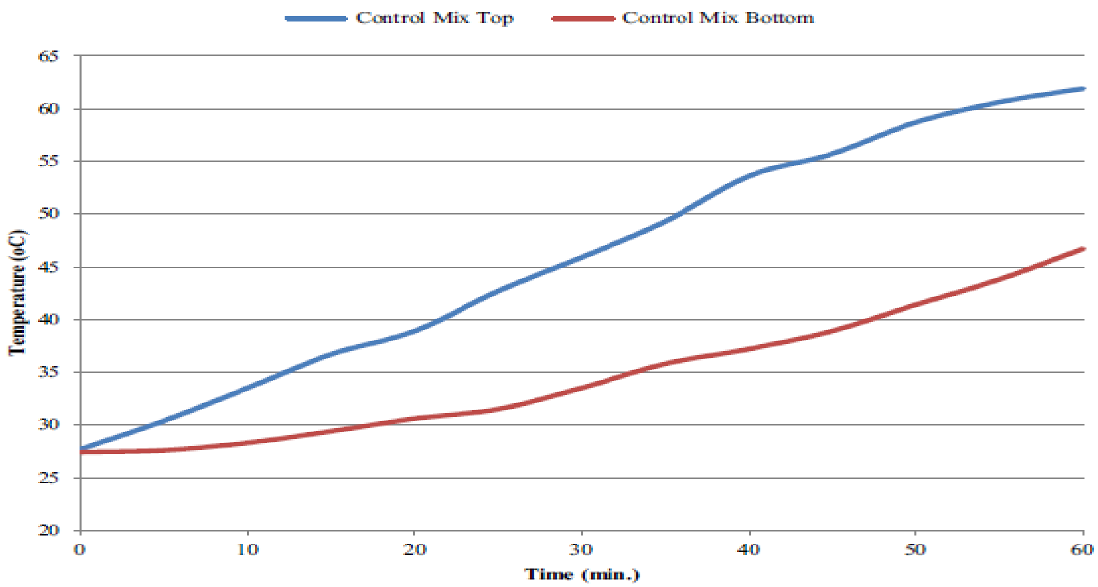


Fig. 9. Temperature variation at top and bottom of control mix concrete.

Figure 10: Temperature Variation at Top and Bottom of 4% PCM Concrete

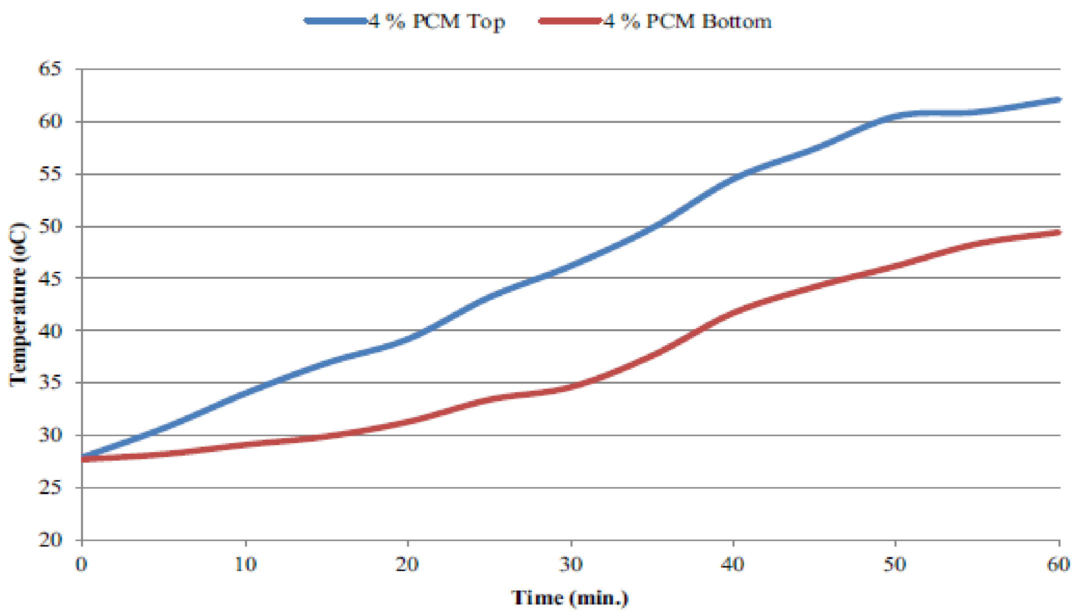


Fig. 10. Temperature variation at top and bottom of 4% PCM concrete.

Journal of Futuristic Sciences and Applications, Volume 3, Issue 2, Jul-Dec 2020
Doi: 10.51976/jfsa.322001

Figure 11: Temperature Variation at Top and Bottom of 6% PCM Concrete

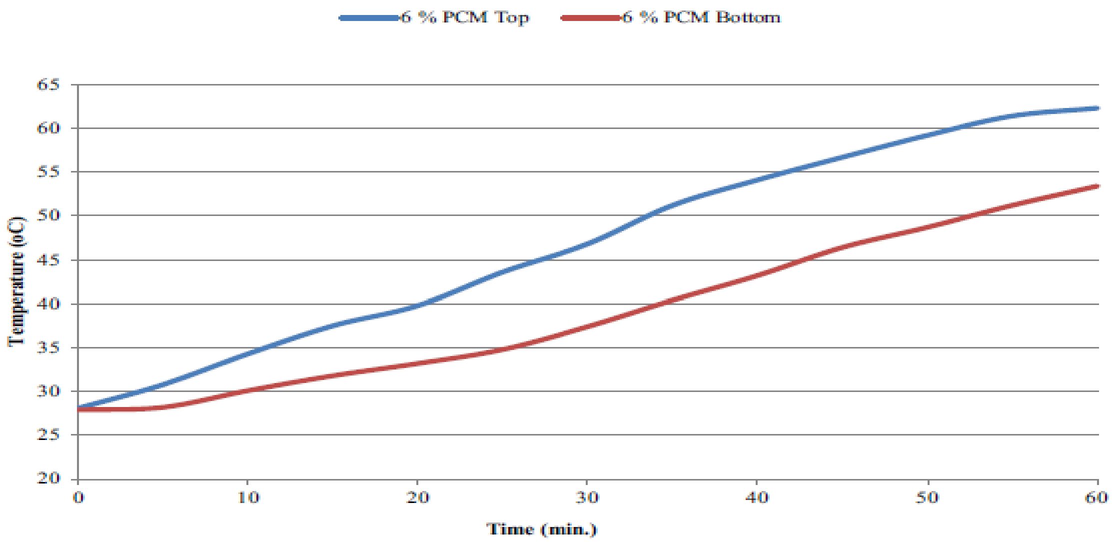


Fig. 11. Temperature variation at top and bottom of 6% PCM concrete.

Figure 12: Temperature Differential of Different Concrete Mixes

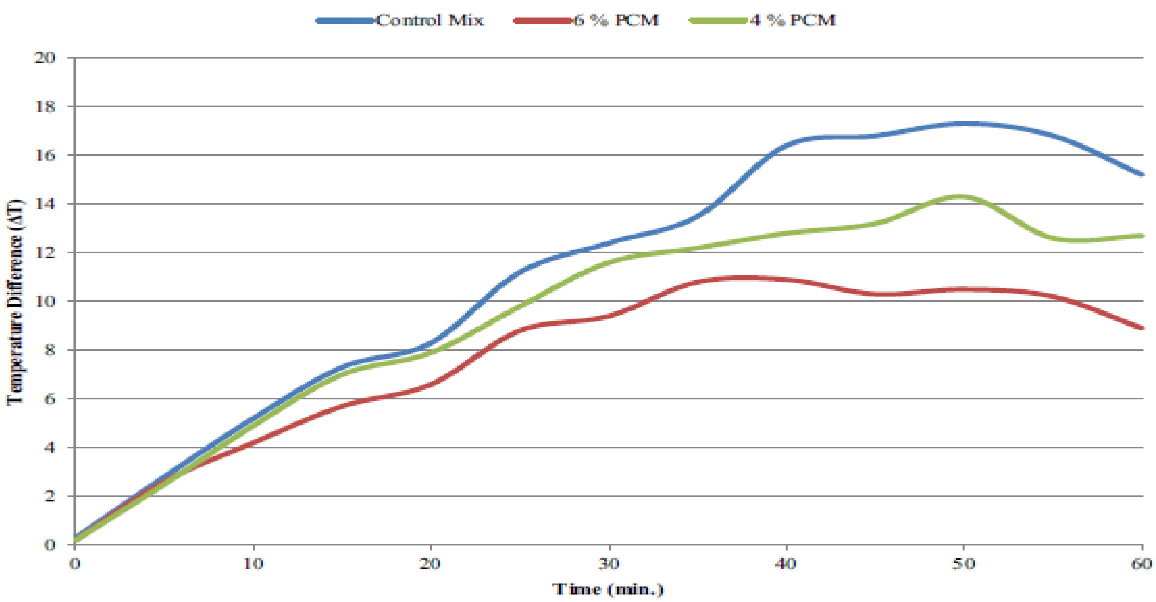


Fig. 12. Temperature differential of different concrete mixes.

4.0 Conclusion

In this study project, the results of compressive tests and indoor heat simulation tests on concrete mixtures with different PCM percentages were noted. Reviewing the results of compressive strength tests revealed that adding additional PCM to concrete (in both the dry and wet stages) results in a reduction in the material's compressive strength. It has been noted that liquid PCM-mixed concrete has a lower compressive strength than dry PCM-mixed concrete. It could be that the liquid PCM coating on the fine and coarse material hinders cement from effectively sticking to the combination. Microscopic examination can be used to look more closely at the air gaps that PCM's inclusion leaves behind and which result in a reduction in compressive strength. The necessary characteristic compressive strength for paving construction was achieved for liquid-state and dry-state mixing at replacement levels of PCM 6 and 8 percent, respectively. Because the dry PCM mix concrete has better compressive strength results, more study has been done on it. After looking at the test findings of the indoor heat simulation, temperature and temperature stresses were found. Based on these results, it was determined that the Conventional Concrete mix exhibits a maximum temperature differential of 17.3 C, which is more than the amount advised by IRC rules. The temperature difference for concrete containing 4 percent and 6 percent of PCM is 14.3 C and 10.9 C, respectively. With an increase in PCM content, it was observed that the temperature difference between the top and bottom of the concrete decreased. This may indicate a reduction in temperature stresses. Temperature and bending stress are reduced by 17 and 37%, respectively, as compared to control mix concrete for PCM content values of 4 and 6%.

References

[1] H.J. Oh, Y.K. Cho, S.M. Kim, Experimental evaluation of crack width movement of continuously reinforced concrete pavement under environmental load, Constr. Build. Mater. 137 (2017) 85–95, https://doi.org/10.1016/j.conbuildmat.2017.01.080.

[2] A. Bianchini, Evaluation of temperature-induced curling in concrete slabs using deflection difference analysis, J. Transp. Eng. 139 (2) (2013) 130–137, https://doi.org/10.1061/(ASCE)TE.1943-5436.0000490.

[3] S.M. Kim, J.H. Nam, Measurements and experimental analysis of temperature variations in Portland cement concrete pavement systems, Road Mater. Pavement Des. 11 (3) (2010) 745–771, https://doi.org/10.1080/14680629.2010.9690302.

[4] H.J. Oh, Y.K. Cho, Y. Seo, S.M. Kim, Experimental analysis of curling behavior of continuously reinforced concrete pavement, Constr. Build. Mater. 128 (2016) 57–66, https://doi.org/10.1016/j.conbuildmat.2016.10.079.

[5] M. Belshe, M.S. Mamlouk, K.E. Kaloush, M. Rodezno, Temperature gradient and curling stresses in concrete pavement with and without open-graded friction course, J. Transp. Eng. 137 (10) (2011) 723–729, https://doi.org/10.1061/(ASCE)TE.1943-5436.0000254.

[6] R. Combrinck, W.P. Boshoff, Tensile properties of plastic concrete and the influence of temperature and cyclic loading, Cem. Concr. Compos. 97 (2019) 300–311, https://doi.org/10.1016/j.cemconcomp.2019.01.002.

[7] R.Y. Liang, Y.Z. Niu, Temperature and curling stress in concrete pavements: analytical solutions, J. Transp. Eng. 124 (1) (1998) 91–100, https://doi.org/10.1061/(ASCE)0733-947X(1998)124:1(91).

Doi: 10.51976/jfsa.322001

[8] D.P. Bentz, R. Turpin, Potential applications of phase change materials in concrete technology, Cem. Concr. Compos. 29 (7) (2007) 527–532, https://doi.org/10.1016/j.cemconcomp.2007.04.007.

[9] S. Nayak, N.A. Krishnan, S. Das, Microstructure-guided numerical simulation to evaluate the influence of phase change materials (PCMs) on the freeze-thaw response of concrete pavements, Constr. Build. Mater. 201 (2019) 246–256, https://doi.org/10.1016/j.conbuildmat.2018.12.199.

[10] N.P. Sharifi, K.C. Mahboub, Application of a PCM-rich concrete overlay to control thermal induced curling stresses in concrete pavements, Constr. Build. Mater. 183 (2018) 502–512, https://doi.org/10.1016/j.conbuildmat.2018.06.179.

[11] U. Berardi, A.A. Gallardo, Properties of concretes enhanced with phase change materials for building applications, Energy Build. 199 (2019) 402–414, https://doi.org/10.1016/j.enbuild.2019.07.014.

[12] IS:383-1970, Indian Standard Specification for Coarse and Fine Aggregates from Natural Source for Concrete. New Delhi: Bureau of Indian Standards.

[13] IRC: 058-2002 & 2015, Guidelines for the Design of Plain Jointed Rigid Pavement for Highways, Indian Road Congress, New Delhi, India.

[14] IS:10262-2009, Guidelines for Concrete Mix Design, Bureau of Indian Standards, New Delhi, India.

[15] N. Sharma, P. Sharma, and S. kr Verma, "Influence of Diatomite on the properties of mortar and concrete: A Review," in *IOP Conference Series: Materials Science and Engineering*, 2021, vol. 1116, no. 1, p. 12174.

[16] IS:516-1959, Indian Standard Code of Practice-Methods of Test for Strength of Concrete, New Delhi: Bureau of Indian Standards.

[17] V.B. Gawande, A.S. Dhoble, D.B. Zodpe, S. Chamoli, Experimental and CFD based thermal performance prediction of solar air heater provided with right angle triangular rib as artificial roughness, J. Braz. Soc. Mech. Sci. Eng. 38 (2) (2016) 551–579, https://doi.org/10.1007/s40430-015-0391-8.

[18] ITACA. [Online]. http://www.itacanet.org/the-sun-as-a-source-of-energy/part-2-solar-energy-reaching-the-earths-surface/.

[19] L.I.N., Edeko, F.O., Itabor, N.A., Olatuji, J., Ogbomida, E.T., and Emeribe, C.N. Ezemonye, Energy efficient lighting: luminance assessments of CFLs and incandescent bulbs. J. Energy Technol. Policy 4(9) (2014) 40–44.

[20] S.K. Park, J.H.J. Kim, J.W. Nam, H.D. Phan, J.K. Kim, Development of anti-fungal mortar and concrete using Zeolite and Zeocarbon microcapsules, Cem. Concr. Compos. 31 (7) (2009) 447–453, https://doi.org/10.1016/j.cemconcomp.2009.04.012.

[21] A.M. Thiele, Z. Wei, G. Falzone, B.A. Young, N. Neithalath, G. Sant, L. Pilon, Figure of merit for the thermal performance of cementitious composites containing phase change materials, Cem. Concr. Compos. 65 (2016) 214–226, https://doi.org/10.1016/j.cemconcomp.2015.10.023.

[22] T. Lecompte, P. Le Bideau, P. Glouannec, D. Nortershauser, S. Le Masson, Mechanical and thermo-physical behaviour of concretes and mortars containing phase change material, Energy Build. 94 (2015) 52–60, https://doi.org/10.1016/j.enbuild.2015.02.044.

[23] P. Meshgin, Y. Xi, Effect of phase-change materials on properties of concrete, ACI Mater. J. 109 (1) (2012), https://doi.org/10.14359/51683572.

[24] A. Agrawal, N. Sharma, and P. Sharma, "Designing an economical slow sand filter for households to improve water quality parameters," *Materials Today: Proceedings*, vol. 43, no. xxxx, pp. 1582–1586, 2020, doi: 10.1016/j.matpr.2020.09.450.

[25] A. Arora, G. Sant, N. Neithalath, Numerical simulations to quantify the influence of phase change materials (PCMs) on the early-and later-age thermal response of concrete pavements, Cem. Concr. Compos. 81 (2017) 11–24, https://doi.org/10.1016/j.cemconcomp.2017.04.006.

[26] N. Sharma, P. Sharma, and A. K. Parashar, "Incorporation of Silica Fume and Waste Corn Cob Ash in Cement and Concrete for Sustainable Environment," Materials Today: Proceedings, Apr. 2022, doi: 10.1016/J.MATPR.2022.04.677.

[27] N. Sharma, P. Sharma, and A. K. Parashar, "Use of waste glass and demolished brick as coarse aggregate in production of sustainable concrete," Materials Today: Proceedings, May 2022, doi: 10.1016/J.MATPR.2022.04.602.

[28] Saxena, K. K., Srivastava, V., & Sharma, K. (2012). Calculation of Fundamental Mechanical Properties of Single Walled Carbon Nanotube Using Non-Local Elasticity. Advanced Materials Research, 383–390, 3840–3844. https://doi.org/10.4028/WWW.SCIENTIFIC.NET/AMR.383-390.3840

[29] Sharma, K., & Shukla, M. (2014). Molecular modeling of the mechanical behavior of carbon fiber-amine functionalized multiwall carbon nanotube/epoxy composites. New Carbon Materials, 29(2), 132–142. https://doi.org/10.1016/S1872-5805(14)60131-1