Mühendislik Bilimleri ve Tasarım Dergisi
10(4), 1495 – 1508, 2022
e-ISSN: 1308-6693

Journal of Engineering Sciences and Design
DOI: 10.21923/jesd.875102

Derleme Makalesi Review Article

A LITERATURE REVIEW ABOUT EFFECTS of PHASE CHANGING MATERIALS on COMPRESSIVE STRENGTH and THERMAL CONDUCTIVITY of BUILDING COMPONENTS

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Keywords
Phase Change Material, Compression Strength, Thermal Conductivity, Encapsulation Size, Cement-Based Material.

Abstract
One of the important areas of Phase Changing Materials (PCM) is to increase the heat retention capacity of building components. Researches are carried out on the heat retention capacities of PCMs to store energy in building components and to ensure building temperature control. The use of PCM in building components has become an important tool for energy saving, since ensuring building temperature control in summer and winter conditions is a situation that requires continuity. This feature provided to the building component provides an improvement in the energy identity of the building. In general researches, the use of macro, micro encapsulated PCM decreases the heat conduction coefficient as it increases the heat retention capacity of the building components, but effects compressive strength positive or negative. However, when the capsule size used in micro capsule applications is reduced to 7 microns and below, it is seen that the strength increases, while the thermal conductivity coefficient continues to decrease. When the PCM capsule particle sizes used in the building components are reduced, it provides an improvement in the granulometry of the component, so a positive effect on strength is seen in the building components. As a result of this research, differences in compressive strength were observed depending on the macro, micro and nano dimensions and mixing ratios of the pcm addition. However, due to the continuous increase in the PCM ratio of the building component, the heat holding capacity of the building component increases and its thermal conductivity decreases.

FAZ DEĞİŞTİREN MALZEMELERİN YAPI ELEMANLARININ BASINÇ DAYANIMI VE TERMAL İLETKENLİĞE OLAN ETKİLERİ HAKKINDA LİTERATÜR ARAŞTIRMASI

Anahtar Kelimeler
Faz Değişim Malzemesi, Basınç Dayanımı, Termal İletkenlik, Kapsülleme Boyutu, Çimento Esaslı Malzeme.

Öz
Faz Değiştiren Malzemelerin (FDM) önemli alanlarından biri, bina bileşenlerinin ısı tutma kapasitesini artırmaktır. Bina bileşenlerinde enerji depolamak ve bina sıcaklık kontrolünü sağlamak için FDM'lerin ısı tutma kapasiteleri üzerinde araştırmalar yapılmaktadır. Yaz ve kış koşullarında bina sıcaklık kontrolünün sağlanması süreklilik gerektiren bir durum olduğundan, bina bileşenlerinde FDM'nin kullanılması enerji tasarrufu için önemli bir araç haline gelmiştir. Bina bileşenine sağlanan bu özellik, binanın enerji kimliğinde bir iyileşme sağlar. Genel araştırmalarda makro ve mikro kapsüllenmiş FDM kullanımı, bina bileşenlerinin ısı tutma kapasitesini artırdığı için ısı iletim katsayısını düşürür, ancak basınç dayanımını pozitif veya negatif etkiler. Ancak mikro kapsül uygulamalarında kullanılan kapsül boyutu 7 mikron ve altına düştüğünde mukavemetin arttığı, ısıl iletkenlik katsayısının düşmeye devam ettiği görülmektedir. Yapı bileşenlerinde kullanılan PCM kapsül partikül boyutları küçültüldüğünde, bileşenin granülometrisinde bir gelişme sağlar, böylece yapı bileşenlerinde mukavemet üzerinde olumlu bir etki görülür. Bu araştırma sonucunda, FDM ilavesinin makro, mikro ve nano boyutlarına ve karışım oranlarına bağlı olarak basınç dayanımında farklılıklar gözlenmiştir. Bununla birlikte, bina bileşeninin FDM oranındaki

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sürekli artış nedeniyle, bina bileşeninin ısı tutma kapasitesi artar ve ısıl iletkenliği azalır.

Alıntı / Cite

Çelik A.İ., Kayabaşı R., Şener, A., (2022). A Literature Review About Effects of Phase Changing Materials on Uniaxial Compressive Strength and Thermal Conductivity Coefficient of Building Components, Journal of Engineering Sciences and Design, 10(4), 1495-1508.

Yazar Kimliği / Author ID (ORCID Number)	Makale Süreci / Article Process	
A. İ. Çelik, 0000-0001-7233-7647	**Başvuru Tarihi/ Submission Date**	05.02.2021
R. Kayabaşı, 0000-0001-6195-7445	**Revizyon Tarihi / Revision Date**	05.02.2022
A. Şener, 0000-0001-7562-7631	**Kabul Tarihi / Accepted Date**	11.02.2022
	Yayım Tarihi / Published Date	30.12.2022

1. Introduction

Buildings and structures are indispensable for living and working life, engineering structures developed by human beings. In ancient times, what was expected of buildings was to meet only basic needs. Today, more features are expected from buildings. Thus, buildings turn into modern structures. Modern engineering structures must have a safe, high-strength, energy-efficient and environmentally friendly structure. The need for heating in the winter months and the need for cooling in the summer are the basic needs for providing comfort conditions in buildings. For these reasons, the use of energy in buildings and the energy identity of the building gain importance. To challenge environmental problems such as carbon dioxide emission and global warming, possible improvements should be made in buildings and energy use should be reduced. While making improvements regarding energy saving in reinforced concrete structures, strength properties should also be preserved or increased. The thermal energy storage capacity of composite materials using FDM increases. The material, which increased heat holding capacity can be used for heating, cooling, heat control and energy storage (Mert et al., 2019).

Insulation and Phase Change Materials (PCM) applied to building components reduce energy use in the building. The savings to be made in heating applications using fossil origin fuels will directly contribute to the economy as well as contribute to the reduction of environmental pollution. As a result of the decrease in energy use, carbon dioxide emissions will decrease and global warming due to greenhouse gases will decrease. Topics such as adding PCM using new methods suitable for the building component, determining the ideal mixing ratio, determining the ideal encapsulation dimensions in the building component and the ideal capsule size are considered as subjects worth researching. In this context, if 1% improvement is achieved in the building component in addition to the existing situation, the energy requirement in the buildings will decrease significantly.

PCM is generally applied on the surfaces of the buildings with various methods for temperature control purposes. In addition to heat savings in modern buildings, the importance of high-strength materials is increasing day by day. For this reason, the issue of strength should also be considered in studies on heat saving. In this study, a literature review has been made on the effect of PCM addition on compressive and flexural strength and heat transfer in cement-based materials. As a result of this research, differences in compressive strength were observed flexural on the macro, micro and nano dimensions and mixing ratios of the PCM addition.

2. Theoretical Framework

Importance of energy and energy resources is increasing in the world. In Turkey, according to the distribution of energy consumption data in 2017, the highest energy consumption in the residential and services sector with 24.8%, were occurred in the industrial sector with 24.4% as shown in Figure 1. Saving energy is seen as a necessity from the production stage to the consumption stage due to the continuation of Turkey's dependence on foreign energy consumption. Although it changes over the years, the energy consumption in houses in our country is in the range of (24-30)% (Anon n.d.). In addition to the importance of owning energy resources, the rapid increase in energy demand reveals the importance of efficient use of energy. In the world, a significant amount of energy is consumed in heating and cooling in buildings. Therefore, solutions for energy saving of buildings attract a lot of attention (Oktay, Yumrutaş, and Argunhan 2020). Researches are carried out to reduce the heat conduction coefficient of building components or to reduce energy use by increasing their heat retention capacity. Some of these studies aimed to use the building component in building heat control by adding PCM to the building components. Providing building heat control with PCM inside the building component will reduce the heating and cooling load.

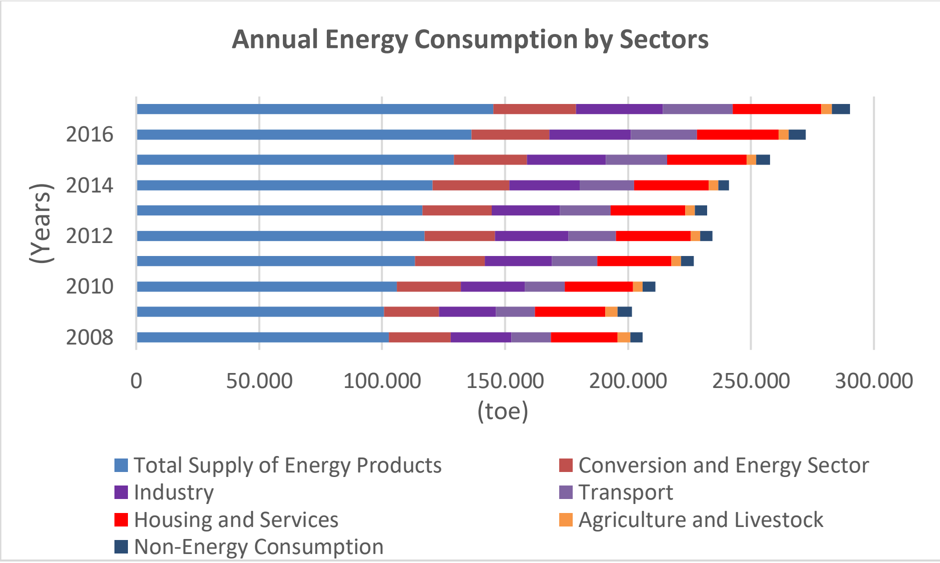

Figure 1: The Distribution Turkey's total energy consumption in 2017 (Anon n.d.)

More than one third of the global energy consumption in the world is used to provide thermal comfort conditions in buildings. Using PCM together with insulation material on the floor and ceiling reduces the heat load of the volumes. This means to spend less energy to provide thermal comfort conditions. While the annual energy use decreases, energy efficiency increases (Haydaraslan, Çuhadaroğlu, and Yaşar 2020).

2.1. Phase Changing Material and Energy-Saving

Energy saving is important in buildings as well as in materials applied for energy saving (Korkut and Torun 2017). PCM is used to store thermal energy in building heat control, heating and cooling applications (Kayabaşı and Kaya 2020). With the use of PCM, the building element gains the latent heat retention capability of the used PCM, as well as its own heat retention capability. PCM solid-liquid, liquid-gas and solid-solid (crystallization heat) are substances that take or give off heat from the control volume during phase change. It releases the latent heat it receives during phase change back to the control volume as the temperature decreases. The use of PCM with high heat holding capacity increases the heat retention potential in the system. During the daytime heating of the building, the PCM changes phase and turns into a liquid form and prevents further heating of the building by absorbing the heat of the building. At night, as the surrounding temperature decreases, it prevents the building from cooling by giving heat to the building, depending on its heat holding capacity.

While using PCMs in construction applications, disadvantageous situations may arise in building components. In case of leakage in the encapsulated PCMs, odor, chemical reaction or corrosion conditions may occur. This situation decreases the strength of the iron and shortens the life of the concrete. Depending on the chemical structure of PCMs, corrosion of steel reinforcement in concrete can accelerate. The strength reduction in the structural element due to the corroded structural element will reduce the strength of the building (Fernández et al. 2015; Ouglova, Berthaud, and Foct 2006).

If PCMs are integrated into building structure components, the heat storage capability of buildings increases. In addition, it prevents overheating even when the outdoor temperature and solar radiation are high. When the building starts to heat up, the heating slows down with the PCM, which has the heat holding capacity in the building component. Thus, the degree of comfort in the building can be passively improved (Bai et al. 2020). In an experimental study, in a commercial office without an active cooling system, microcapsule PCM was added to the plaster to reduce the temperature on the wall surface, thus increasing the thermal comfort of the office. By using microcapsule PCM, the comfort temperature of office was maintained for 6 hours more than the reference material (Schossig, Henning, and Gschwander 2005).

The PCM to be used in the building component should not decrease the strength of the material to which it is added. In structural elements, where the strength is insignificant, there is no suffer in terms of safety if the strength is within the allowed limits. Therefore, the appropriate PCM can be selected according to the properties of the building component. PCMs are as chemical classified under three main headings as organic, inorganic and eutectics is presented in Figure 2. Organic compounds refer to Paraffin and non-paraffin PCM. Inorganic PCMs are divided into salt hydrates and metallics.

Phase Changing Material	Organic Compounds	Paraffins
		Non-Paraffin
	Inorganic Compounds	Salt Hydrates
		Metalics
	Eutectics	Organic - Organic
		Organic - Inorganic
		Inorganic - Inorganic

Figure 2: General classification of PCM

2.2. Energy Consumption in Buildings

Heat loss can be reduced by improving the physical structure of the building in order to save energy in residences. Improvements in the physical structure can be achieved by improving the strength of the building, applying insulation and physical improvement to be made on the windows (Güğül and Aydınalp Köksal 2018). With this situation, the energy requirement in buildings increases as the needs of human beings increase. While some of the energy need in buildings is required for the use of electrical machines, some is required for heating and cooling. It is important to use efficient electrical machines for energy saving, as well as to reduce the need for heating and cooling. With the determination of the comfort temperature according to the intended use of the buildings, the need for heating or cooling arises. In order to keep buildings in comfort conditions, heat loss and gain must be kept under control. In order to realize this situation, besides insulation applications, building heat control applications are performed. PCMs applied in concrete should be evaluated within this scope.

In 2018 25.7% of natural gas consumption in Turkey was consumed in the housing is seen Figure 3. 23.45% of the final energy consumption by 2018 in Turkey was consumed in housing again. Nowadays, 35% of the final energy consumption is spent for the heating and cooling of buildings. It is predicted that by 2050 there will be four times higher final use of renewable energy than today. 40% of the power generated from renewable energy sources will be spent in industry as electrical energy, and 44% in buildings for heating and other direct use. Efforts to reduce energy consumption, which is another branch of the studies to produce energy from environmentally friendly and renewable sources, have gained importance in recent years. In this context, more than 40% of energy consumption is spent for the heating or cooling of buildings. An improvement of 2% has a very important place in ensuring the building temperature control.

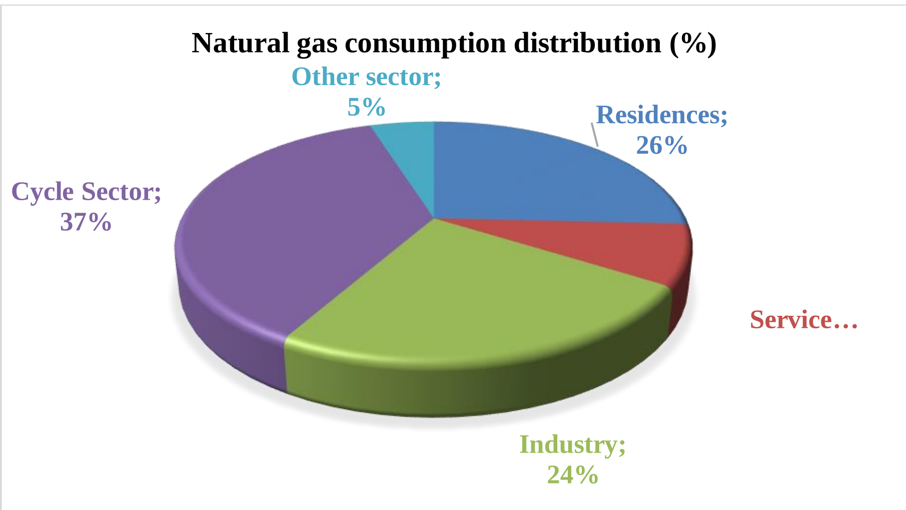

Figure 3. The distribution of natural gas consumption of Turkey for 2018 (Anon n.d.)

From 2010 to 2050, the number of households will have continued to increase rapidly. Per capita usage area in households is gradually increase as shown in Figure 4. Therefore, per capita heating and cooling costs in residences will increase rapidly. In addition, population growth will allow this situation to increase further. This situation will cause an increase in carbon emissions and an increase in global warming (Ürge-vorsatz et al. 2015).

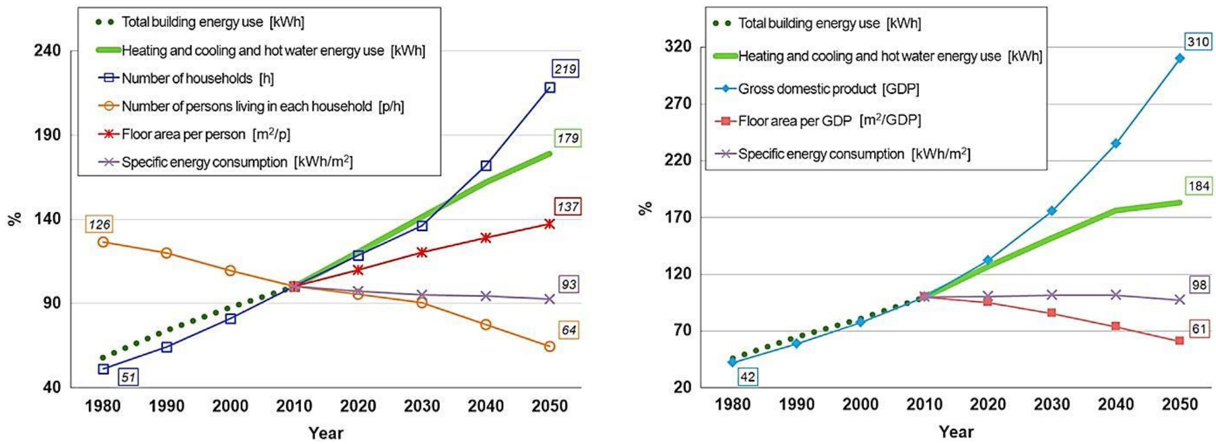

Figure 4. Trends in the different drivers of energy consumption in residential (left) and commercial (right) buildings (Ürge-vorsatz et al. 2015)

When the heat retention capability is gained to the building elements with the addition of PCM or other methods in buildings,

- Decrease in heating and cooling costs,
- Decrease in the use of high-power devices as the peaks for heating and cooling are minimized,
- Decrease in carbon emissions,
- Decrease in the rate of imported energy and decrease in energy deficit due to this situation,
- Regulation of heat distribution inside the building,
- Increasing indoor comfort,
- Important gains such as the increase in the real estate value of the building are achieved.

2.3 Application Methods of PCM on Building Components

Within the scope of the research, the effect of the use of PCM in building components on the strength of the building component and the effect on the thermal conductivity of the building component was investigated by literature review. In the studies carried out, the effects of PCMs added to the building component on the strength and thermal conductivity value of the building component have been investigated.

While determining the methods to be used to add PCMs to concrete, prevention of leaks after phase change should be among the priority issues. Although there are many methods in the studies performed, these methods are classified in two main categories is presented in Figure 5. These methods are direct and indirect addition method (Berardi and Gallardo 2019). Direct use is prepared by mixing PCM into the mortar prepared for the building. In this case, since there is no obstacle between the concrete mix and PCM, it is in direct contact. PCM can change the properties of concrete in case of leakage. PCM applications made by immersion in concrete can also be evaluated within this scope. In encapsulated applications, the connection between concrete and PCM is interrupted and the interaction stops. For this reason, new researches continue by encapsulating PCMs and using them in building elements (Soares et al. 2013).

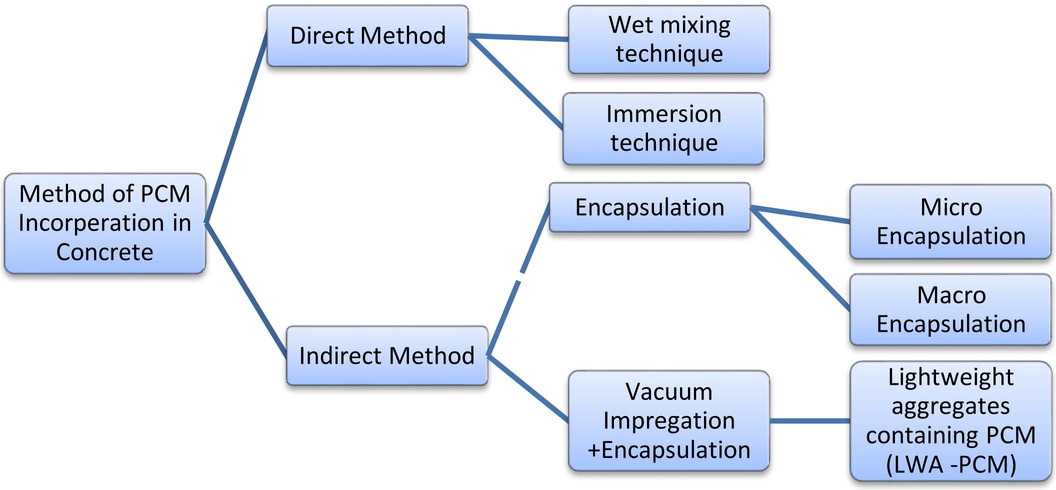

Figure 5. Application of PCM incorporation in concrete (Soares et al. 2013).

In the most of studies conducted in recent years, it is seen that indirect methods, that is, more encapsulation method, are used to include PCM in concrete. The method of adding liquid PCM while mixing wet concrete is called the direct addition method (Navarro, Gracia, Niall, et al. 2016). Although it is easy to apply the method of mixing PCM directly, it can cause leakage in the concrete and degrade the properties of the concrete due to no any barrier between liquid and concrete. In order to reduce the disadvantages in the direct addition method, applications are also made by dipping solid concrete directly into the PCM (Navarro, Gracia, Colclough, et al. 2016).

3. Literature Review

3.1 The Effect of PCM on Compressive Strength

Detailed research is needed on the structure, production technology and use of PCM microcapsules with in reinforced concrete structures. In modern buildings, strengthening is an important issue as well as heat saving. Therefore, it is important to accurately estimate the effect of PCM addition on the compressive strength of cement based reinforced concrete structures (Drissi et al. 2019). More studies are needed to determine performance and long-term durability aspects. In a recent study, it was possible to predict the compressive strength of cementitious composites integrated with PCM through machine learning. In the estimation made, it was found that the compressive strength decreases in concretes with PCM additives, in accordance with the literature. However, in the light of basic materials science, it has been emphasized that more extensive experimental studies and larger data sets are needed to address the chemical and also physical properties of PCM microcapsules with a better perspective (Marani and Nehdi 2020).

Mechanical properties of concrete containing 10% and 20% PCM by volume, according to the results obtained from the studies conducted by Fernandes et al, it has been observed that the inclusion of PCMs in concrete leads to a decrease in the compressive strength of concrete (Fernandes et al. 2014). However, it has been found that using silica ash as the binder alongside ordinary Portland cement improves the compressive strength of concrete mixes. Similarly, Ma and Bai, Ling et al., Cui et al. and Norvell et al. stated that when 30% PCM by volume is added to concrete, it results in a reduction in compressive strength of about 30%(Cui et al. 2015; Ling and Poon 2013; Ma and Bai 2018; Norvell, Sailor, and Dusicka 2013). However, it has been noted that the presence of coarse aggregate in concrete compared to the fine aggregate mortar mix supports the resulting compressive strength (Adesina et al. 2020).

In this study, a comparison has been made in Table 1 to compare the effects of PCMs on concrete strength. According to the results obtained from the literature, it has been observed that the compressive strength of concrete specimens generally decreases with PCM. However, it was observed that the strength increased, contrary to the general literature. Researchers attribute this to the replacement of fine particles in the aggregate with PCMs and the composite coating used in PCM microcapsules (Aguayo et al. 2016). In addition, Adesine (2019) stated that using PCM instead of fine aggregate together with coarse aggregate has a positive effect on strength (Adesina 2019). Based on this, it appears that there is a need for more detailed experimental studies on the use of composites as PCM encapsulation material and the use of PCM instead of fine aggregate.

Table 1. Comparison of compressive strength in concrete with PCM additives

Reference	Sample No	PCM type (mg)	PCM ratio by mass (%)	Phase changing temperature (°C)	Compressive Strength (MPa)
(Norvell et al. 2013)	**Control 0%**	**-**	**0**	**0**	**-**
	10% Series A	3	0,375	19	-
	20% Series A	3	0,75	19	-
	30% Series A	3	1,125	19	-
	40% Series A	3	1,5	19	-
	50% Series A	3	1,875	19	-
	10% Series B	3	0,1	19	-
	20% Series B	3	0,2	19	-
	30% Series B	3	0,3	19	-
	40% Series B	3	0,4	19	-
	50% Series B	3	0,5	19	-
	10% Series C	3	0,275	19	-
	20% Series C	3	0,55	19	-
	30% Series C	3	0,825	19	-
	40% Series C	3	1,1	19	-
	50% Series C	3	1,375	19	-
(Aguayo et al. 2016)	OPC	0	-	-	45
	PCM-5%	6	5	-	38
	PCM-10%	12	10	-	34
	PCM-15%	19	15	-	30
	PCM-20%	26	20	-	28
	OPC	0	-	-	44
	PCM-5%	6	5	-	54
	PCM-10%	12	10	-	55
	PCM-15%	19	15	-	60
	PCM-20%	26	20		45
(Cellat et al. 2017)	RE	-	-	31,3	54,16
	FA	5	2%	30,8	38,95
	mPCM	5	10%	30,5	33,8
(Beyhan et al. 2017)	PCM	-		24,1	-
	MPCM-1	-	61,9	21,53	-
	MPCM-2	-	65,5	19,98	-
(Jiang et al. 2008)	Paraffin	-	25,1	35,6	-
(Sarı, Alkan, and Karaipekli 2010)	n-heptadecane	-	38	18,4	-
(Shan et al. 2009)	n-octadecane	-	70	30	-
(Ma et al. 2014)	Butyl stearate-paraffin mixture	-	63,7	30,1	-
(Chen et al. 2013)	Stearic acid	-	90,6	53,5	-
(Cao, Tang, and Fang 2014)	Paraffin	-	87,1	58,6	-
(Konuklu, Unal, and Paksoy 2014)	Caprylic acid	-	59,3	17,12	-
(He, Wang, and Wu 2014)	n-octadecane	-	41,8	27,96	-
(Sarı, Alkan, and Altıntaş 2014)	Myristic acid	-	48,7	47,5	-
(He, Wang, and Wu 2015)	n-nonadecane	-	41,1	25,8	-
(Lecompte et al. 2015)	M1	-	0	28	20
	M2	-	12,2	28	13,3
	C1	-	0	28	52,1
	C2	-	9,8	28	9,8
	m ref	-	0	28	60,5
	m3	-	14,4	28	16,3
	m4	-	10,1	28	22,9
	m5	-	6,3	28	30
	c ref	-	0	28	54
	c3	-	11,9	28	8,3
	c4	-	5,5	28	20,8
	c5	-	3,5	28	30,5
(Cellat et al. 2015)	Reference	-	-	-	45,2
	Capric acid (CA)	-	0,01-0,02	32	39,81
	Lauric acid (LA)	-	0,01-0,02	42	34,13
	Myristic acid (MA)	-	0,01-0,02	49	37,5
	Palmitic acid (PA)	-	0,01-0,02	61	33,87
	Reference	-	-	-	54,16
	Capric acid (CA)	-	0,01-0,02	32	47,12
	Lauric acid (LA)	-	0,01-0,02	42	38,95
	Myristic acid (MA)	-	0,01-0,02	49	43,38
	Palmitic acid (PA)	-	0,01-0,02	61	37,72
(Figueiredo et al. 2016)	PCM-I	-	0,4	26	15,5
	PCM-II	-	0,4	26	18,33
	BR-I	-	0,4	26	57,77
	BR-II	-	0,4	26	49,73
	PCM-I- Temp	-	0,4	26	17
	BR-I- Temp	-	0,4	26	54
(Hunger et al. 2009)	Reference	-	0	41	74,05
	PCM%1	-	24,96	39,8	52,19

	PCM%3	-	76,6	39,4	34,96
	PCM%5	-	124,3	37,6	21,36
(Zhang et al. 2013)	Reference	-	-	-	23,7
	PCM_05	-	-	26,84	16,1
	PCM_12	-	-	25,38	13,9
	PCM_17	-	-	26,37	12,1
	PCM_25	-	-	25,79	10,5
(Xu and Li 2013)	NC	-	-	-	50
	TESC-10	-	-	41,11	36,6
	TESC-15	-	-	41,11	36,5
	TESC-20	-	-	41,11	28,4
	TESC-30	-	-	41,11	26
(Dakhli, Chaffar, and Lafhaj 2019)	Control 0%	-	0	-	Pure cement
	PCM 10%	-	10	31,4	0,6 x pure cement
	PCM 20%	-	20	31,4	0,6 x pure cement
	PCM 30%	-	30	31,4	0,5 x pure cement
(Eddhahak-Ouni et al. 2014)	Control 0%	-	0	-	25
	PCM 1%	-	1	23-26	21
	PCM 3%	-	3	23-26	19
	PCM 5%	-	5	23-26	17

Concrete strength and reliability in PCM mixed concrete is an issue that needs to be examined in detail. Because any change in the composition of the concrete mix can affect the strength and density of the final product (Paksoy et al. 2017). The addition of PCM in both direct and microencapsulated forms reduce the compressive strength of concrete. In one study, the reference sample and the eutectic-like fatty acid mixture (FA) were compared with the sample. In comparison, it was observed that a significant decrease in concrete compressive strength results was observed with the addition of PCM, and the reduction was calculated as 38% in the 28-day compressive strength tests. This is a result of aggregates being replaced with PCM. According to the results, it has been observed that the compressive strength for a concrete in C50 class has dropped to C37 concrete class as a result of PCM mixture. Although this result is seen as a disadvantage, it has been stated that it is a highly suitable concrete for structures that are not very risky (Cellat et al. 2017).

Standard phase-change materials in polymer capsules are considered to be micro-encapsulated phase-change materials (ME-PCMs) between 1 and 300 μm in size. Particle size of portland cement in solid concrete is between 1 μm and 50 μm, while the diameter of fine aggregate can be approximately 150 μm and more (Norvell et al. 2013). When the cement reacts with water, it binds the aggregate particles together and the strength of the concrete increases thanks to these particles. Particularly, particles smaller than 125 μm other than cement, thanks to the packing density they create, reduce the pores in the cement and its homogeneity increases. This causes positive effects on strength. In other words, fine particles in concrete create a strong bond between cement and coarse aggregates and affect strength (Aguayo et al. 2016). In Figure 6 some references result and maximum strength values are comparison.

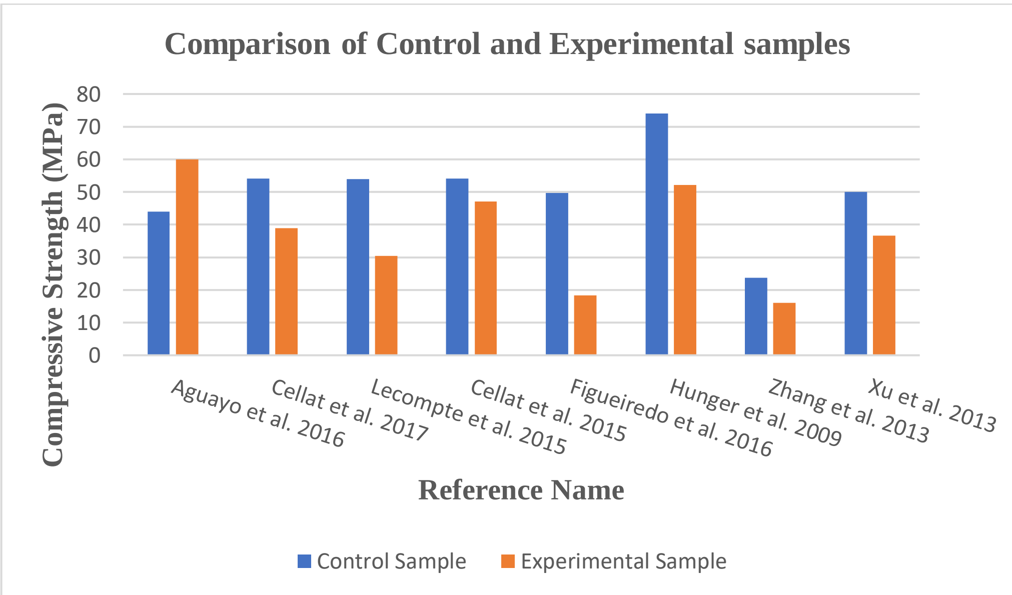

Figure 6. Comparison of the Control Sample and Experimental the Sample by the Maximum Compressive Strength

Moosberg et al. Observed that the strength of the homogeneous concrete formed by the quartz sand particles they added to concrete in varying sizes increased. In addition, they found that adding coarse aggregate or cement instead of fillers tended to reduce strength. In fact, they found that filling materials with particle sizes of 4 µm and 2.2 µm were more effective than average cement particles (Moosberg-Bustnes 2004). In a like study, Çelik and Marar (1996) by replacing the crusher powder with a particle size of 75 µm with 10% fine aggregate, as a result of the study, it was found that the strength of concrete subjected to compression and bending tests increased (Çelik and Marar 1996). Norvell et al. (2019), by adding ME-PCM proportional to the dry materials added to the concrete, group A work, group B work with ME-PCM instead of cement, and group C studies by adding ME-PCM instead of sand, they compared their results with the strengths of the control sample. In the samples, it has been determined that the volume of the voids between the sand particles allows to fully spread, and this has a positive effect on the strength in proportion to the expectations. It may be because of the incomplete cementation of the spaces between the particles, ie. more cementation. The fact that the strength values of all samples are outside the standard error range of the control samples suggests that the effect of integrating ME-PCM into the samples is important.

Cellat et al. (2015) conducted 7-day and 28-day tests by adding bio-based fatty acids to improve concrete heat retention capacity. Compressive strength data for 7 and 28 days for concrete with and without PCM, a systematic decrease in strength properties with increasing PCM content was observed. In addition, for concretes containing 1% and 2% PCM, the total compressive strength varied between 33.87 and 39.81 MPa and 37.72 and 47.20 MPa for 7 and 28 days of concrete, respectively (Cellat et al. 2015).

Density loss in concrete with the addition of PCM was found to be 10.5% on average in the study conducted by Figueiredo et al. (2016) (Figueiredo et al. 2016). With the PCM included, the concrete compressive strength loss was approximately 68%. The effect of the joining method of PCM and the addition of water to the mixing process led to a lower loss of compressive strength in concrete samples with the addition of PCM. Final strength of concrete with PCM was increased by approximately 8% (Hunger et al. 2009). As a new mix design is implemented in concrete, higher strength is expected compared to the standard composition with equal cement content. Therefore, a modification of the Féret equation was applied to obtain an indication for possible compressive strength at 28 days. This modification includes the contribution of other cement-based materials and is expressed by the formula below (Hu C, Saucier F, Lanctôt MC 1999).

$$f_c = (K_g R_c)/((1 + 3.1\frac{W+A}{C(1+K1+K2)+BFS}) \quad (1)$$

Here, Aggregate coefficient of 5.4 for crushed aggregate and 4.8 for round aggregate with standard value is accepted, W total effective water content, Rc standard cement strength, C cement weight and A volume of fluid air (in kg/m3), BFS, K1, K2 pozzolanic and potential shows hydraulic effects.

A significant difference was noted between the compressive strength tendencies of PCM-M and PCM-E containing mortars are shown in Figure 7. The compressive strengths of PCM-M (a) and PCM-E (b) are shown. Standard deviation in compressive strength is between 2 and 5 MPa in the first days. It is between 4 and 10 MPa in the 28-day sample. (C) The standard deviation of the flexural strengths at 28 days in the PCM volume fraction is less than 0.8 MPa. It can be said that the decrease in strength is due to the addition of a material with low mechanical resistance or the interaction of PCM with cement as a result of rupture of capsules. According to the control sample, PCM-M has been found to reduce the compressive strength at all mixing ratios (Figure 7-a). However, in PCM-E, it is observed that the compressive strength increases in all mixing ratios compared to the control sample and it is seen from the graph that the optimum mixture ratio for this PCM type is 10% (Figure 7-b). It is observed that the higher the ratio of PCM-M in the mixture, the lower the flexural strength compared to the control sample. In PCM-E, it is observed that the flexural strength increases up to 10% mixing ratio, and after this value it is observed that the flexural strength decreases (Aguayo et al. 2016).

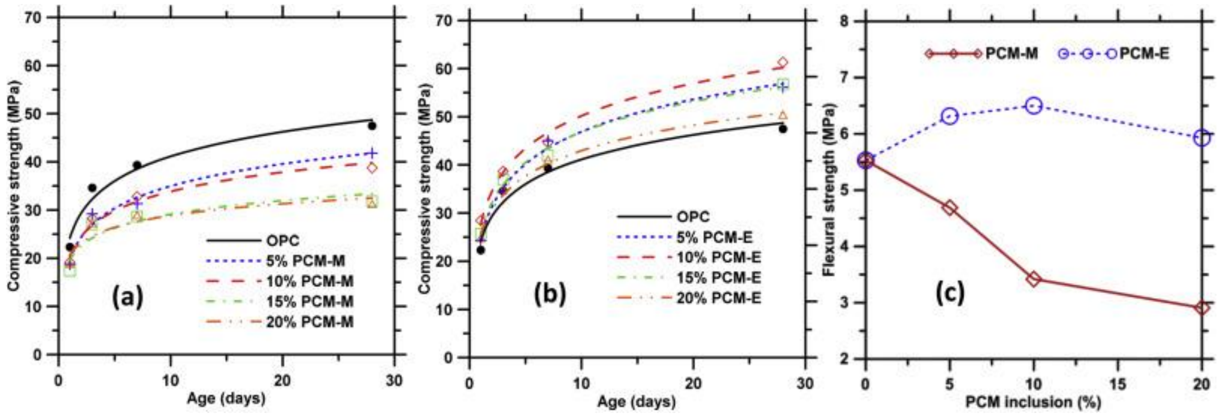

Figure 7. The effect of pcm ratio and pcm type on the compressive strength of concrete (Aguayo et al. 2016)

In the study conducted by Fu et al., 3 different nano PCM types were added to cement based materials and 7-day and 28-day compressive strength was measured. Accordingly, it is seen that the optimum pcm ratio in the mixture is between 0.1% and 2% at the point where the compressive strengths are the highest compared to the control sample according to the added PCM type (Fu et al. 2020).

3.2. The Effect of PCM on Thermal Conductivity

Due to the high heat retention capability of PCMs, it is possible to use them in heat storage systems and temperature control. The use of PCM in the building element increases the heat holding capacity of the building element. Control volumes surrounded by structural elements with increased heat retention capability are less affected by the changing ambient temperature due to climatic conditions. The fact that the building is less affected by the changes in ambient temperature allows the temperature control of the control volumes to be achieved by consuming less energy.

In a study by Hunger et al. (2009), 100 × 100mm × 50mm samples were prepared to determine the effect of PCM ratio in concrete on thermal conductivity value and 1% PCM, 3% PCM and 5% PCM were added in proportion to the weight of the concrete. By measuring three mixes and a reference, it was observed that PCM particles decrease the thermal conductivity of concrete (Hunger et al. 2009). Berardi and Gallardo conducted an experimental study to reduce the thermal conductivity of the building in their study. They made experiments to determine the effect of PCM on building thermal conductivity. As a result, they saw that thermal conductivity of the concrete decreased when microencapsulated paraffin (according to the mass of the concrete) was added at 1%, 3% and 5% as shown in Figure 8 (Berardi and Gallardo 2019).

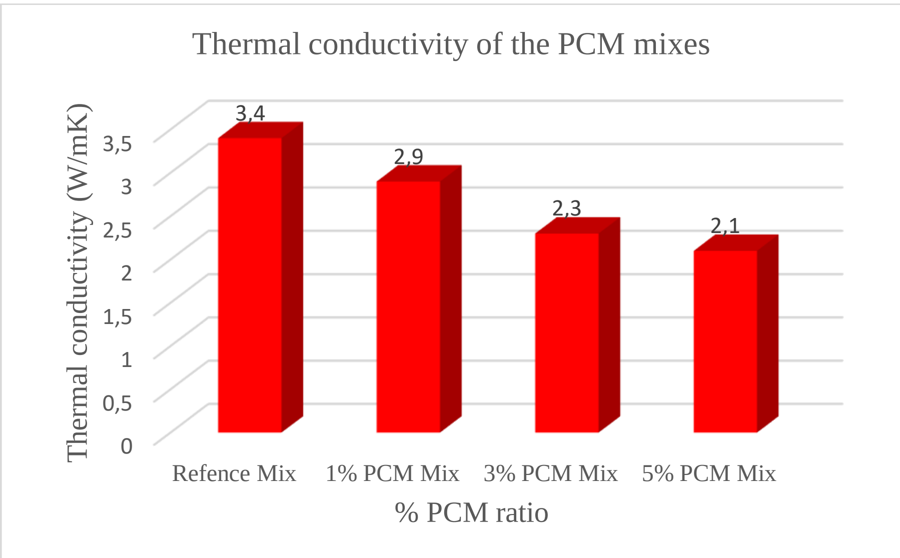

Figure 8. Thermal conductivity of the PCM mixes (Hunger et al. 2009).

The phase change temperature, heat holding capacity and other properties of the PCM type to be preferred while providing building heat control will affect the heat retention capability to be provided to the building. Decreasing the heat transfer coefficient of the building element (wall, floor, ceiling, roof) reduces the total heating and cooling load of the building. Decrease of thermal conductivity results in concrete by means of different encapsulated is presented in Figure 9.

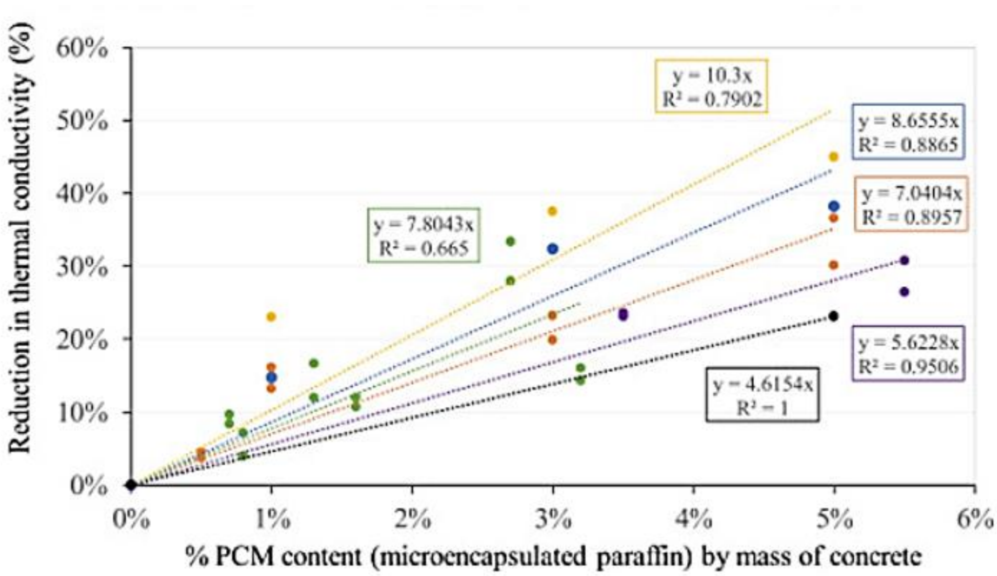

Figure 9. Decrease of thermal conductivity results in concrete by means of different encapsulated PCM (Berardi and Gallardo 2019).

The use of insulation material and the use of PCM in building elements provides benefits to the buildings in terms of energy saving. PCM used in buildings has the potential to reduce the heating and cooling load by up to 50%. In winter, the temperature of the wall using PCM is 5°C higher than the reference wall. This application provides energy savings of up to 13% per year(Paksoy et al. 2017). The energy savings achieved during the summer periods were different from those achieved during the winter periods. While the total energy saving that can be achieved in the building increases with insulation material, it increases 2.3 times when PCM or insulation material is applied. This situation provides about 66.2% benefit. For this reason, researchers recommend PCMs with high thermal conductivity (Drissi et al. 2019).

In the study of Dakhli et al., thermal conductivity measurement was performed to evaluate the effect of cement and PCM integration on thermal conductivity. For each PCM integration, the sample was tested 3 times and averaged. An average of 0.701 W/mK was found for 0% PCM integration. An average of 0.599 W/mK was found for 10% PCM integration. An average of 0.565 W/mK was found for 20% PCM integration. Finally, an average of 0.534 W/mK was found for 30% PCM. The thermal conductivity for pure cement is 0.7 W/mK. Thermal conductivity drops to 0.6W/mK for 10% PCM integration. Thermal conductivity continues to drop down to 0.56 W/mK for 20% PCM integration. Finally, the thermal conductivity for 30% PCM integration gives 0.53 W/mK. Thermal conductivity decreases when the addition of PCM to cement increases. This proves that the integration of PCM into cement can improve thermal insulation (Dakhli et al. 2019).

In a study, nanofibers containing FDM were produced by electro spinning system. The structure of nanofibers is fatty acid-based (Özmen and Alay, 2020) FDMs. Lauric acid (LA), capric acid (KA) and myristic acid (MA) were used in the study. The heat storage capacity was highest in nanofibers containing lauric acid. Ouni et al. added 0%, 1%, 3% and 5% PCM to Portland concrete cement in their study. The thermal conductivity decreased by about 0.02 W/mK with the addition of PCMs. In the study, it was observed that the PCM addition was relatively stable between 0% and 5%, and the thermal conductivity change was reduced with 10% and more additions.(Eddhahak-Ouni et al. 2014).

4.Conclusion

The materials used in the construction industry are constantly being developed and renewed. These considerations are the strength of the building component and the thermal resistance of the building component. In building components, thermal conductivity is as important as strength. For this reason, the developed material should both increase the strength and provide thermal resistance to the structure. Thus, the strength of the buildings will increase and the thermal comfort in the buildings will be provided by consuming less energy. In this study, the effect of macro, micro and nano-encapsulated PCMs on the compressive strength and thermal conductivity of cement-based materials was investigated by literature review. The following results were obtained from the literature review studies.

1- In Macro PCM addition, it is seen that the compressive strength decreases as the PCM mixture ratio increases. On the other hand, as the PCM mixture ratio increases in the macro PCM addition, the thermal conductivity of the structural element decreases.
2- It has been observed that micro sized PCMs have positive and negative effects on compressive strength. It has been determined that the PCM particle size is smaller in cases that have a positive effect on the compressive strength than the pcm in the negative conditions. Compared to the control sample, it was observed that the change in compressive strength ranged from -60% to + 50%. On the other hand, as the PCM mixture ratio increases in micro PCM addition, the thermal conductivity of the building element decreases.
3- According to Aguayo et al (2016), although higher compressive strength was obtained than the reference sample with the addition of Nano PCM in the range of +%18 and +%23, it was determined that the compressive strength decreased after 10% PCM mixture amount. On the other hand, as the mixture ratio of PCM increases in nano-PCM addition, the thermal conductivity of the building element decreases.
4- By developing composite encapsulation methods, the strength of concrete can be increased and PCM leaks are prevented throughout the life of the concrete. Preventing leaks that may occur in concrete over time will ensure the strength of concrete and steel reinforcement.
5- PCMs to be used in building components must be encapsulated in compliance with building components, with low volume changes and not causing leakage.
6- New production methods and application methods to building components should be developed in order for the materials to be used as PCM to be economical.
7- The priority in building components is the strength of the building component. For this reason, PCMs used for low heat conduction coefficient sought for energy saving should not reduce the strength of the building component.
8- Generally, PCM encapsulation applications are made in scientific laboratories. But this is not economical. For the widespread use of PCM in building elements, economical mass production encapsulation methods should be developed. Hence it will be increase PCM application in building elements.
9- PCMs with phase change temperature range suitable for the operating temperature range of building components in summer and winter conditions and with high heat retention capacity should be investigated.
10- For building heat control in summer and winter conditions, PCMs that reduce the heat load of the building and have high heat holding capacity should be investigated.

Conflict of interest

No conflict of interest has been declared by the authors.

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