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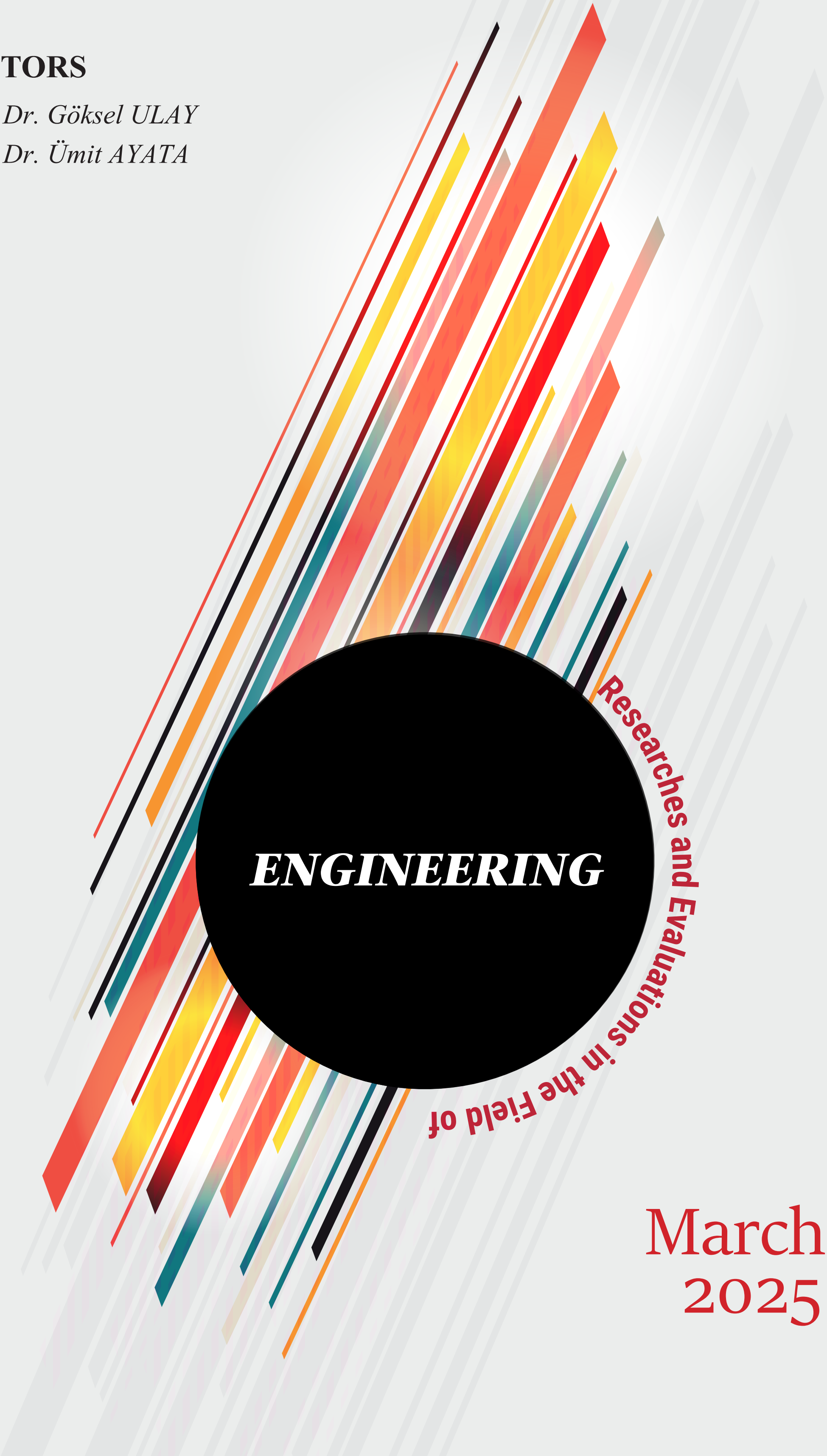

Researches and Evaluations in the Field of
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CHAPTER 1

EFFECTS OF BRICK AND FOUNDRY WASTES ON CEMENT MORTAR

Nazım Çağatay DEMİRAL[1]

Aylin ÖZODABAŞI[2]

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[1] Bilecik Seyh Edebali University Faculty of Engineering Civil Engineering Department. cagatay.demiral@bilecik.edu.tr ORCID No: 0000-0001-5927-7299.

[2] Bilecik Seyh Edebali University Faculty of Engineering Civil Engineering aylin.ozodabas@bilecik.edu.tr ORCID No: 0000-0002-6011-980X.

1. INTRODUCTION

Recycling is a key component of waste management and addresses one of the most important environmental issues facing modern societies. The rapid growth of population and industrial activities worldwide has led to the depletion of natural resources and the accumulation of waste. Since most waste contains chemicals and materials that are harmful to the environment, it disrupts the ecosystem balance and poses a threat to human health. Therefore, effective waste management and recycling are crucial to ensuring a sustainable future. In recent years, efforts to develop sustainable construction materials have intensified and the use of recycled materials in the construction sector has become increasingly important.

Ensuring environmental and economic sustainability necessitates exploring new and innovative solutions to reduce natural resource consumption and improve waste management in the construction sector. In this context, the use of recycled materials in cement-based construction products offers an environmentally friendly approach.

During urban transformation projects in our country, waste generated from demolished buildings holds significant importance in terms of its environmental impact and potential for reuse. These wastes typically consist of concrete, brick, ceramics, wood, iron-steel, plastic, glass, and gypsum. If not managed properly, these wastes can cause environmental pollution, energy waste, and storage problems. However, when well-planned, urban transformation projects offer opportunities for both sustainability and economic value creation.

Aggregate, which constitutes approximately 60-75% of the volume in concrete, is a crucial component. Aggregates are categorized based on particle size as fine (sand, crushed sand, etc.) and coarse (gravel, crushed stone, etc.). The economic significance of the construction sector, along with its substantial role in natural resource consumption and waste generation, amplifies its environmental impact. In this regard, the use of recycled aggregates obtained from construction and demolition waste as a substitute for traditional aggregates contributes to environmental sustainability in two ways: reducing natural resource consumption and minimizing land requirements for waste disposal. This situation has led to an increase in research analyzing the feasibility of recycled aggregates, particularly in terms of economic and environmental sustainability (de Andrade Salgado and de Andrade Silva, 2022).

Many researchers have extensively investigated the potential use of brick waste, which is abundant in demolition and construction sites, as an alternative to aggregates. Dependence on natural resources for concrete production could harm the environment (Raini et al., 2020). Therefore, recycling brick waste in concrete not only mitigates the waste problem but also reduces the need for raw materials, providing an eco-friendly alternative. Brick production does not require the use of chemicals, making it a safe and stable material widely utilized in the construction industry. In recent years, research has been conducted on using brick waste as coarse and fine aggregates or as a cement substitute in concrete. The partial replacement of cement with brick dust has the potential to enhance the strength of concrete. However, using brick waste as an aggregate may slightly decrease the mechanical properties of concrete; nonetheless, an optimal amount has been determined to produce concrete that meets the required standards (Wong et al., 2018).

Currently, in addition to construction waste, various recycled materials are being evaluated as alternative components for concrete mixtures. One such material is waste foundry sand, a byproduct from the ferrous and non-ferrous metal casting industries that can replace fine aggregates. Foundry sand is reused multiple times in molding and casting processes but is eventually discarded when it can no longer be used (Bhardwaj and Kumar, 2017). The Turkish foundry sector ranks as the fourth-largest producer in Europe after Germany, Italy, and France, with 80% of its production used in industries such as automotive, home appliances, defense, and construction. Despite the challenges of this 5000-year-old craft, it remains a critical sector that significantly contributes to employment and the economy (Çevik et al., 2017). The increasing amounts of industrial by-products and waste materials have made solid waste management a major environmental concern. Limited landfill space and rising costs make recycling an attractive alternative to disposal. The use of waste foundry sand in concrete and cement-based materials offers both economic benefits and solutions to disposal challenges (Siddique and Noumowe, 2008).

The aim of this study is to investigate the usability of recycled brick aggregate, brick dust, and foundry dust as materials in cement-based mortar production. The study will evaluate the effects of recycled materials on mortar properties by conducting mechanical and physical tests such as flexural strength, compressive strength, porosity, and water absorption on prepared mortar samples. This research aims to develop sustainable construction material that is both economically and environmentally beneficial. At the end of the study, the data obtained from the tests will be analyzed to determine whether the mortars produced with recycled materials meet the required performance criteria.

2. EXPERIMENTAL STUDY: MATERIALS AND METHODS

In this study, the aim was to produce mortar using recycled aggregate and natural river sand (NRS), with brick dust and foundry dust as cement replacements.

2.1. Mortar Mix

In the relevant study, the concrete mixture was prepared using recycled aggregate (RA), natural river sand, cement, brick dust, waste foundry dust, and water. Additionally, a superplasticizer was used when needed.

A total of 10 mixture series were prepared. In these series, brick dust (TT) and foundry dust (DT) were used as cement replacements at 10%, 20%, and 30% by weight. Additionally, combinations of TT and DT were added in equal proportions of 5%, 10%, and 15% to reach the total replacement amount. Furthermore, in the series where only TT was used, RA and river sand were incorporated in equal volumes.

2.2. Material Properties

In the study, Çimsa Cem II 42.5R cement, which complies with the TS-EN 197-1 (2012) standard, was used. Natural river sand with a maximum grain size of 4 mm was used as sand. Sieve analysis of the sand used was carried out according to TS EN 933-1 (2012) standard. Gradation curve is given in Figure 1. Recycled aggregate was obtained from clay bricks brought from construction waste sites. To be used in the study, blend bricks were first broken with a hammer, brought to crushing size in a crusher and then crushed with a jaw crusher. All of the crushed brick aggregates were passed through a 4 mm sieve. Subsequently, the brick aggregates were sieved through a 4 mm sieve and subjected to a sieve analysis in accordance with the TS EN 933-1 (2012) standard. Following this, the brick aggregates were placed in an oven for 24 hours, after which the process was repeated, resulting in the attainment of the appropriate granulometry (Figure 2). To obtain brick dust, the brick aggregate passing through a 0.025 mm sieve was ground in a ball mill for 2 hours. The ground brick dust was used in the study after being sieved through a 0.09 mm sieve. Foundry dust and chemical analysis results were obtained from Istikamet Dokum company. The chemical composition results of the foundry dust are given in Table 1 below. Tap water was used in the mixture.

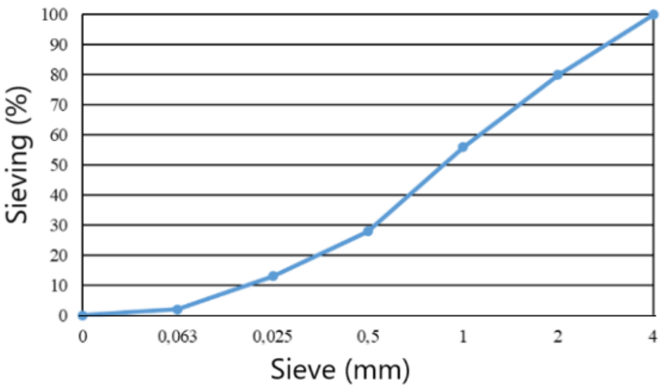
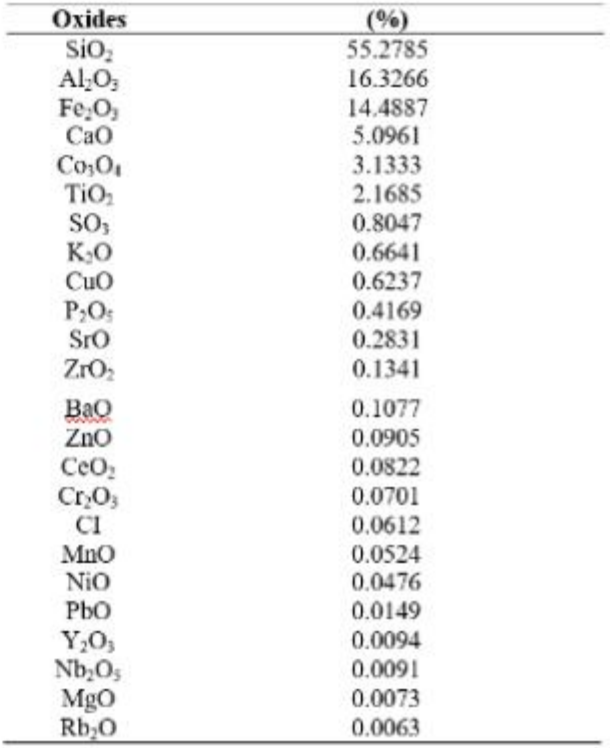


Figure 1. Gradation curve of the sand used

Figure 2. Preparation of brick aggregates according to appropriate granulometry

Table 1. Chemical components of foundry dust



Oxides	(%)
SiO_2	55.2785
Al_2O_3	16.3266
Fe_2O_3	14.4887
CaO	5.0961
Co_3O_4	3.1333
TiO_2	2.1685
SO_3	0.8047
K_2O	0.6641
CuO	0.6237
P_2O_5	0.4169
SrO	0.2831
ZrO_2	0.1341
BaO	0.1077
ZnO	0.0905
CeO_2	0.0822
Cr_2O_3	0.0701
Cl	0.0612
MnO	0.0524
NiO	0.0476
PbO	0.0149
Y_2O_3	0.0094
Nb_2O_5	0.0091
MgO	0.0073
Rb_2O	0.0063

2.3. Mixing Ratios

Cement mortar samples were prepared according to the method specified in TS EN 196-1 (2016). Natural river sand and recycled aggregate were used in the mixture used differently. In addition, foundry dust and brick dust were substituted for cement at certain rates. 7 and 28-day flexural and compressive strengths were performed on samples with different mixing ratios. A total of 60 mortar samples were produced, including six samples at 10%, 20% and 30% for foundry and brick dust, six samples at 5%, 10% and 15% for mixtures where foundry dust and brick dust were used together, and six control samples. A 5 L capacity power mixer was used to prepare 10 mixture series and the samples obtained are given in Figure 3.

The mixing ratios used in the preparation of the samples are as in Table 1. In addition, the mixing flow chart of the samples is given in Figure 4.

Figure 3. Mixer used in the mixture and samples placed in the molds

Table 1. Mixture amounts of materials used in the experimental study

Samples	Cement (g)	Water (g)	W/ C (%)	TT(g)	DT (g)	River sand (g)	RA (g)
KN	450	270	0.6	-	-	675	441
TT10	405	270	0.6	45	-	675	441
TT20	360	270	0.6	90	-	675	441
TT30	315	270	0.6	135	-	675	441
DT10	405	270	0.6	-	45	1350	-
DT20	360	270	0.6	-	90	1350	-
DT30	315	270	0.6	-	135	1350	-
TT-DT5	405	270	0.6	22.5	22.5	1350	-
TT-DT10	360	270	0.6	45	45	1350	-
TT-DT15	315	270	0.6	67.5	67.5	1350	-

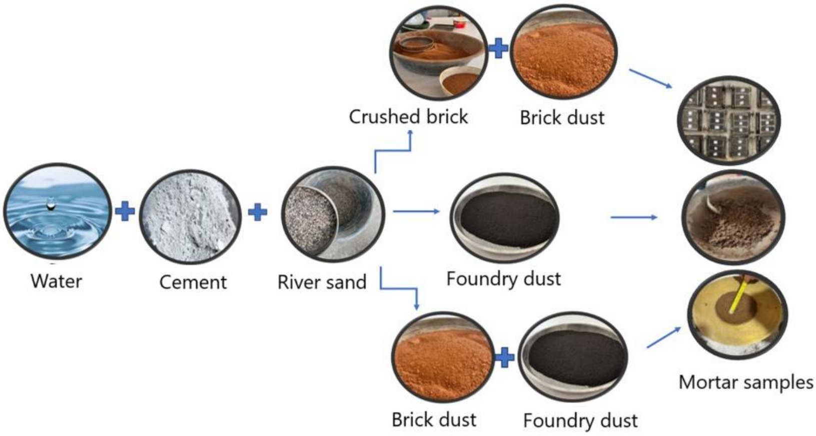


Figure 4. Flow chart of the experiments

3. Method

All mixtures were thoroughly compacted in two stages and placed in sample molds of 40×40×160 mm dimensions and their surfaces were smoothed. The poured and prepared samples were left to stand for one day in accordance with the TS-EN 196-1 (2016) standard to be used in the experiments, then removed from the mold and subjected to water curing (Figure 5).

Figure 5. Samples kept in the curing pool

3.1. Flow Table Test

Before being placed in the mold, the mixtures were subjected to the spreading table test in accordance with the TS EN 1015-3 (2000) standard. Before starting the test, the samples were again thoroughly tamped in three stages and filled into the container. The test was completed with a total of 15 drops, with one blow per second for the sample whose upper surface was flattened in the container. After this process, the spreading value on the table was recorded for both directions (Figure 6).

Figure 6. Flow table test

3.2. Water Absorption-Porosity Determination

Water absorption and porosity values of the samples were determined according to TS EN 772-4 (2000) standard. In the water absorption and porosity test, a total of 30 samples were produced, three from each series. The samples were removed from the water after a 28-day cure at (20 ± 5) °C. Then, they were kept in water with the help of an Archimedes balance and the wet weight (Ws) was found in a saturated state. Then, the surface was dried with a cloth and weighed. The weight found was the saturated weight (Wd). After these processes, the samples were dried in an oven at 105 °C for 24 hours and weighed. The weighed weight was the dry weight (Wk). The weights were taken as the average of the three samples.

Water Absorption (% by weight): $\frac{W_d - W_k}{W_k} \times 100$

Porosity (% by weight): $\frac{W_d - W_k}{W_d - Ws} \times 100$

3.3. Determination of Compressive and Flexural Strength

Compressive and flexural strength tests (Figure 7) were carried out in accordance with TS EN 196-1 (2016) standards.

Figure 7. Flexural strength test

4. DISCUSSION

4.1. Flow Table Test

The flow table test results are presented in Figure 8. According to the test results, the spread values in the KN, TT10, TT20, and TT30 series remained relatively constant at around 10 cm. The use of brick aggregate in these series limited the workability of the mixture. Since brick aggregate has a higher water absorption capacity, it reduced the fluidity of the mixture. In the DT series, this value increased. Notably, the spread values in the TT-DT series were higher, ranging from 14.2 to 17.0 cm, indicating an improvement in the workability of the samples in this series.

A study in the literature observed that when the waste foundry sand replacement ratio exceeded 20%, both workability and compressive strength decreased (García et al., 2024). Another study reported that as the proportion of brick aggregate increased, the fluidity of the mortar decreased (Bektas et al., 2009).

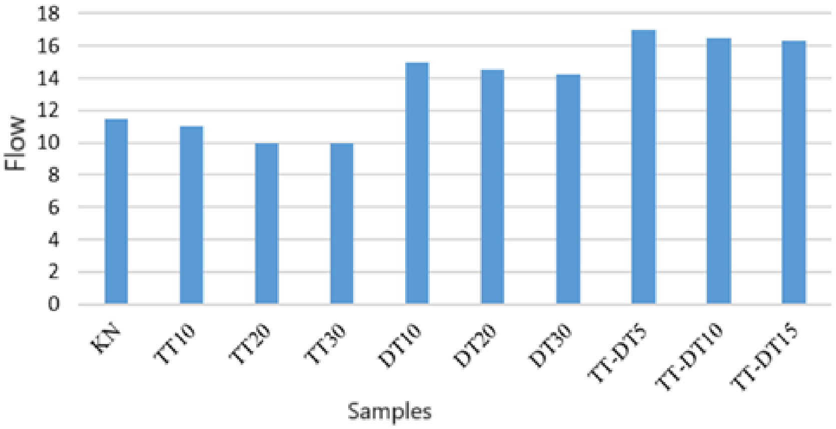


Figure 8. Flow table test results

4.2. Water Absorption and Porosity Test Results

When Figures 9 and 10 are examined, it is observed that the water absorption and porosity values in all series where TT was used alone or in combination with DT were lower compared to KN. This can be attributed to the filler effect of DT, which reduces the water absorption and porosity of the samples. Additionally, as the replacement ratio of TT and DT increased, a decreasing trend in water absorption and porosity values was observed. However, when the TT30 and DT30 ratios were reached, an increase in these values was noted. In the series where TT and DT were used together, porosity and water absorption values showed an increasing trend. A similar study in the literature (Aydın et al., 2021). investigated the use of recycled aggregate and found that an increase in RA content led to higher water absorption rates.

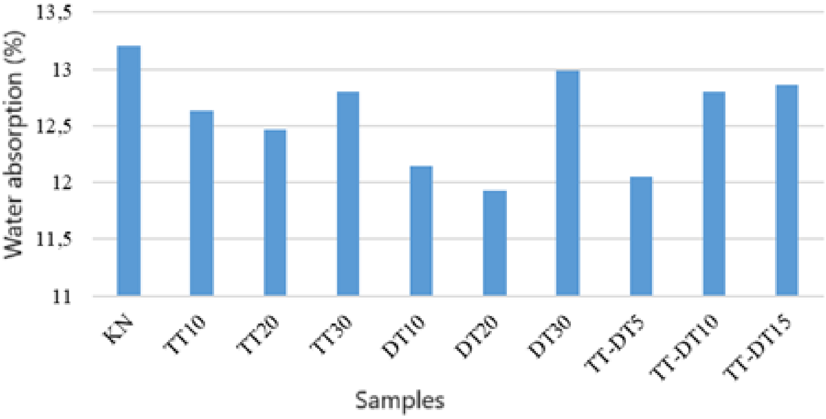


Figure 9. Water absorption test results

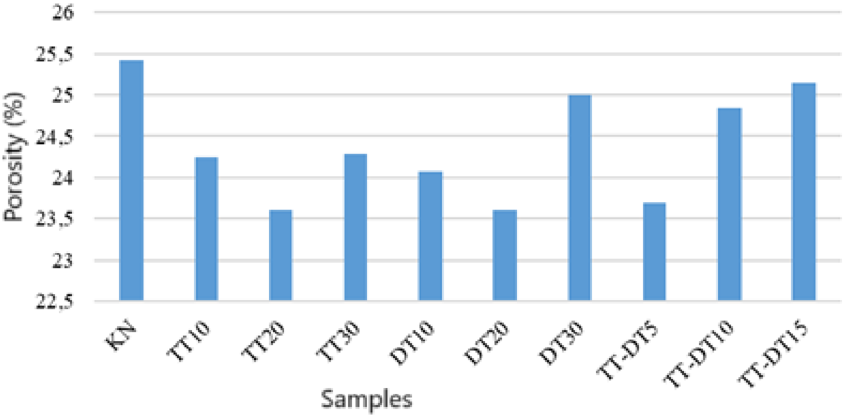


Figure 10. Porosity test results

4.3. Flexural Strength Results

When Figure 11 is examined, the highest flexural strength was obtained from the TT10 (5.7 MPa) series according to the 7-day test results, and the same was obtained from the TT20 (7.73 MPa) series according to the 28-day test results. It can be said that the highest contribution to the flexural strength in the short curing period was made by the TT addition and recycled aggregate. At the end of the 28-day curing period, it was determined that TT10 was the only series that had a higher strength than the flexural strength of KN. As the DT substitution increased, a decrease was observed in the 7-day flexural strengths. According to the 28-day flexural strength results, it was observed that the flexural values increased in all series. At the end of the 28-day curing period, it was observed that the flexural strengths decreased up to 30% substitution rate in all series produced with single combinations of TT and DT. In the dual combinations of TT and DT, it was observed that the flexural strength increased at a 10% substitution rate. In one example in the literature, flexural results have shown that 15% of the cement can be replaced with waste brick dust when recycled aggregate is not used. However, when both waste materials are used together, the maximum recommended waste brick dust ratio is 5% to avoid loss of properties of the final material (Letelier et al., 2018).

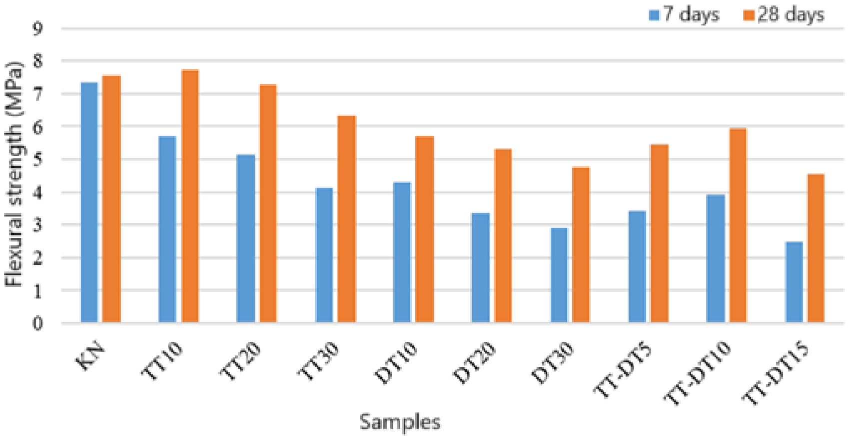


Figure 11. Flexural strength test results

4.4. Compressive Strength Results

When Figure 12 is examined, it is seen that the highest 7-day compressive strength values are obtained from the TT10 series. Similarly, the highest 28-day compressive strength was also recorded in the TT10 series. In the specimens replaced with TT, the TT10 specimen with 10% brick dust replacement showed approximately 8.1% lower compressive strength than KN at 7 days and 7.64% lower at 28 days. The TT20 specimen, with 20% brick dust replacement, exhibited lower compressive strength than KN at both 7 and 28 days. Similarly, the TT30 specimen, with 30% brick dust replacement, showed 25.92% lower strength than KN at 7 days and 20.23% lower at 28 days. For the specimens replaced with DT, the DT10 specimen, with 10% foundry dust replacement, exhibited approximately 35% lower compressive strength than KN at 7 days and 36.5% lower at 28 days. The DT20 specimen, with 20% foundry dust replacement, also showed lower strength than KN at both curing ages. Similarly, the DT30 specimen, with 30% foundry dust replacement, had 61% lower compressive strength than

KN at 7 days and 54% lower at 28 days. The TT-DT5 specimen, which contained 5% brick dust and 5% foundry dust, showed 41.5% lower compressive strength than KN at 7 days and 42.7% lower at 28 days. The TT-DT10 series exhibited 50.7% and 45.1% lower strength than KN at 7 and 28 days, respectively. Lastly, the TT-DT15 specimen, with 15% brick dust and 15% foundry dust replacement, showed 60.9% lower compressive strength at 7 days and 52.2% lower at 28 days compared to KN.

Results from an example in the literature showed that replacing 15% of cement with waste brick dust and 30% of aggregates with recycled materials did not cause a significant loss in the strength of the final material compared to the control concrete (Letelier et al., 2018). Another study found that when the replacement rate of waste foundry sand exceeded 20%, workability and compressive strength decreased (García et al., 2024). In conclusion, the use of brick and foundry dust in certain proportions as cement replacement can increase the compressive strength of concrete, but these proportions should be carefully optimized. An increase in the replacement rate can cause a significant decrease in strength, so appropriate usage rates should be determined and mix designs should be made considering the chemical and physical properties of the replacement materials.

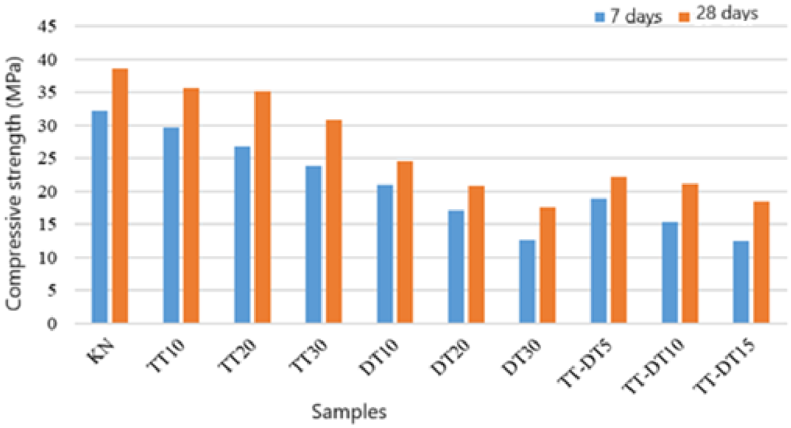


Figure 12. Compressive strength test results

CONCLUSION

• According to the test results, it is seen that the spreading values in the KN, TT10, TT20 and TT30 series remain constant at around 10 cm. The use of brick aggregate in these series limited the spreading ability of the mixture. Since the brick aggregate has a higher water absorption capacity, it reduced the fluidity of the mixture. This value increased in the DT series. It is seen that the spreading values are higher especially in the TT-DT series. This situation indicates that the spreading ability of the samples in the TT-DT series increased.

- In all series where TT was used alone or with DT, the water absorption and porosity values were lower than the control sample (KN). Water absorption and porosity values were lower in the TT20 and DT20 series but increased in the TT30 and DT30 series. It was observed that both binders (TT and DT) were applicable up to 20%, but the values increased when used at 30%.
- According to the compressive strength test results on the 7th and 28th days, the sample produced with brick powder, brick aggregate and cement was the sample with the highest strength. The compressive strength of the TT10 sample was found to be 35.68 MPa at the end of the 28th day. It was observed that the strength decreased as the DT ratio increased in the DT series. It was observed that the strength decreased as the ratio increased in the TT and DT dual combinations.
- The obtained flexural strength results reveal that the samples showed a significant increase in strength during both the 7-day and 28-day curing periods. From the graph, it is seen that the 28-day strength values in all samples are higher than the 7-day values. In particular, the TT10 sample reached the highest flexural strength as a result of 28 days of curing. While the TT-DT15 sample exhibited a low performance in the 7-day strength value, it significantly increased its strength at the end of 28 days.
- As the ratio of DT and TT substitutions increases, a decrease in the mechanical properties of the concrete is generally observed. However, DT and TT used in certain proportions can improve the performance of concrete. These proportions should be determined carefully and the chemical and physical properties of the substitute materials should be taken into account in the mix design.

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CHAPTER 2

INNOVATIVE MATERIALS IN THE AEROSPACE AND DEFENCE INDUSTRY: COMPOSITES AND FUNCTIONAL COATINGS

Fatma İrem ŞAHİN[1]

Yiğitalp OKUMUŞ[2]

Nil ACARALI[3]

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1 Yildiz Technical University, Department of Chemical Engineering, 34220, Esenler-Istanbul, Türkiye., 0000-0001-7670-8871

2 Functional Coatings and Transparencies Technology Center, Turkish Aerospace, 06980 Ankara, Türkiye., 0000-0002-9370-524X

3 Prof. Dr., Yildiz Technical University, Department of Chemical Engineering, 34220, Esenler-Istanbul, Türkiye, nbaran@yildiz.edu.tr ORCID: 0000-0003-4618-1540

1. INTRODUCTION

Carbon-reinforced polymer matrix composites are highly valued in defence technologies due to their superior physical properties, exceptional mechanical and thermal stability, and environmentally sustainable composition. Due to their cost-effectiveness, ease of fabrication, and versatility in design and processing, these composites hold significant potential for advancing defence technology, particularly in applications such as chemical sensors, radar technologies, and nanocomposites. Advanced defence technologies require not only efficiency and security but also superior mechanical and physical properties, environmental sustainability, and cost-effectiveness. One of the primary challenges in material development is the production of lightweight composites with reduced mass. Since lightweight components could be made without sacrificing durability, lightweight materials have become extremely important in defence applications. The defence industry is continuously researching the use of lightweight materials, including fiber, metal matrix, polymer, and ceramic matrix composites. Lightweight materials could prove to be the material of the future because of their capacity to make defence equipment more resilient to high temperatures, deterioration, and negative environmental effects Furthermore, these materials are at the top of the list of cutting-edge engineering materials that might be applied in any industry that uses technology or engineering. Many researchers were interested in composites and nanocomposites because of their many benefits, which include low cost and simple production, as well as high specific strength, hardness, and fatigue resistance [1, 2]. Since lightweight components could be manufactured without sacrificing durability, they have become extremely important in defence applications. The defence industry is actively researching the use of lightweight materials, including metal, polymer, and ceramic matrix composites to enhance equipment performance. These materials hold promise for the future, as they can improve defence equipment's resistance to high temperatures, degradation and harsh environmental conditions [3]. The application of composite materials in the defence industry is exemplified by body and tank coatings. Compared to conventional materials, composites offer several special qualities, such as low weight, high specific stiffness and strength, resistance to corrosion, visual appeal, and ease of manufacture. Advanced composites including aramid and carbon fiber reinforced composites, and nanocomposites offer a competitive edge in material selection for defence technology applications, particularly when exceptional structural integrity is required. The successful performance of materials and products in service depends on the evaluation and characterization of composite materials [4].

Advanced materials with corrosion resistance and heat barrier systems are required by the aerospace and defence industries. Properties such as heat conductivity of nanomaterials have been researched to evaluate the thermal barrier effect, corrosion potential, and associated corrosion rates to better understand the corrosion prevention behaviour, friction coefficient, and wear rates of coating materials. These coatings have considered the development of self-healing, camouflage, and cyber-protective materials for the military and defence industries [5]. The substantial rise in the use of composite materials based on thermoplastic and thermoset matrices is anticipated to result in high mechanical strength, low weight, high impact resistance and high durability, adequate fatigue performance, multifunctionality, and straightforward design and manufacturing processes [6, 7]. Along with mechanical, flame, and thermal stability, the aviation sector has also shown a great deal of interest in stealth technologies, radiation protection, and lightning strike resistance. As a result, the space capability of polymer/carbon nanocomposites has been investigated. The basic properties and stealth properties of nanocomposites are discussed in terms of lightning strike prevention, electromagnetic wave protection properties in aviation and space engineering. The inclusion of nanofillers in the production of aviation materials has provided better dispersion and percolation network formation and increased the electrical conductivity of composites. Issues such as electron transport are an important feature in increasing the resistance of aviation structures to lightning and incident radiation [8].

To produce nanocomposites, a range of organic polymers or organometallic compounds could be utilized with inorganic nanoclusters, clays, or semiconductors. Using nanocomposites is an effective way for developing multifunctional materials with significant improvements in electrical, physical, and chemical properties. The most common nanofiller types are metal oxides, graphene and other 2D materials, carbon nanotubes, and nano clays. Superior electrical conductivity, thermal conductivity, environmental stability, and exceptional mechanical properties are at the forefront of enhancing and expanding existing energy applications, as well as opening the door for the next generation of smart materials [9-11].

2. COMPOSITES

Composites are the physical combination of two different materials to provide superiority over the particular use case. This composition contains two or more components. It usually has better qualities than its components alone and consist of a combination of a base material called the matrix and the reinforcing materials found in this matrix. The newly formed composite material will have better properties than its components if it has a suitable design [12-14]. The combination of these materials occurs at the physical and macroscopic level. Thus, it allows the components to maintain their chemical and natural properties. It has the advantage of having high strength despite their low density. These materials usually have anisotropic properties, and many interfaces occur between the phases in the material. Those consisting of reinforcement and matrix have not lost their physical, chemical, and mechanical properties as in metal alloys. The continuous phase is the matrix and the discontinuous or fiber phases are in the phase as a separate part. The components were insoluble in each other, but in some metallic systems there might be some dissolution and interface reaction that affects their properties [13-15]. The classification according to the type of reinforcement was shown in Figure 1 [15].

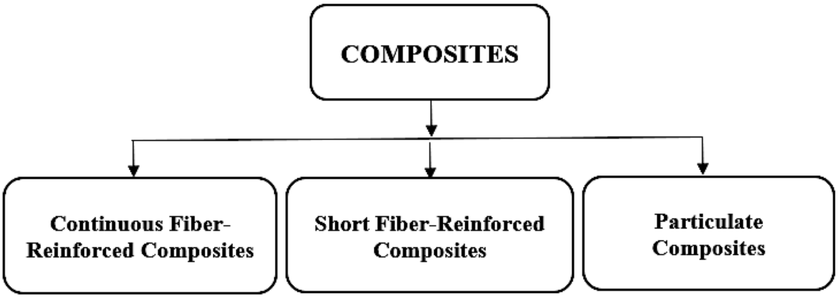


Figure 1. *Classification according to reinforcement materials [15]*

Matrices generally serve as load transfer elements between fibers, while reinforcing elements are load-carrying elements. Composite materials are generally preferred in areas such as the aviation industry due to their low specific gravity [16]. The matrix also contributes to overall mechanical performance, and the use of fibers alone is usually limited. Maintaining the fibers together, shielding them from harm during transit, and dispersing the strain on them are all tasks performed by the matrix. The matrix profoundly impacts the composite's mechanical characteristics, even though its mechanical qualities are often inferior to those of the fiber. Compressive strength, interlaminar shear strength, fatigue strength, transverse modulus and strength, shear modulus and strength, and coefficient of thermal expansion are some of these characteristics [17]. Matrices are generally classified as shown in Figure 1. The classification according to matrix type was shown in Figure 2 [17].

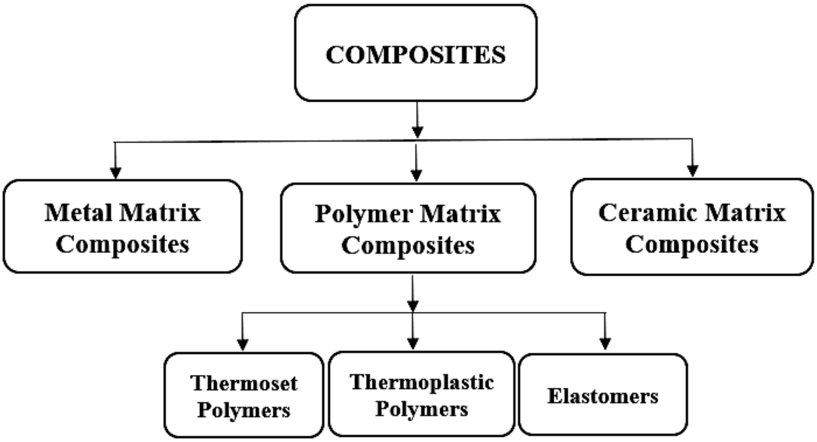


Figure 2. *Classification according to matrix type [17]*

Layered structures were obtained by stacking layers of different materials. These layers consisted of metals, polymers, and ceramics arranged one after the other. Multi-layered structures could be produced without the need for complex processes [18]. It was possible to improve the properties of metals with low corrosion resistance by coating them with resistant metals or plastic materials. Combining single layers with different fibers could improve load-carrying properties. These principles could be applied, for example, in the formation of layered structures used in tank production. In the types formed by the addition of particles, the dispersed phase consists of fine particles. Many of these consist of oxide particles such as aluminum oxide and non-oxide particles such as silicon carbide, boron, or titanium carbide. These are lower cost than fibers and help increase the elasticity and durability of the structural part. Preference with metal and polymer types causes increased durability and decreased toughness [18, 19].

For instance, carbon fibers have a substantially higher tensile strength than bulk graphite. The creation of fiber composites was sped up by the discovery of this fiber characteristic. Currently, they are utilized in a diverse array of applications, spanning from rocket engines to energy-efficient household appliances. Fibers may be discontinuous or derived from cutting lengthy fibers, or they could be continuous, extending continuously within the structure [20, 21]. Different types of fibers were shown in Figure 3 [22].

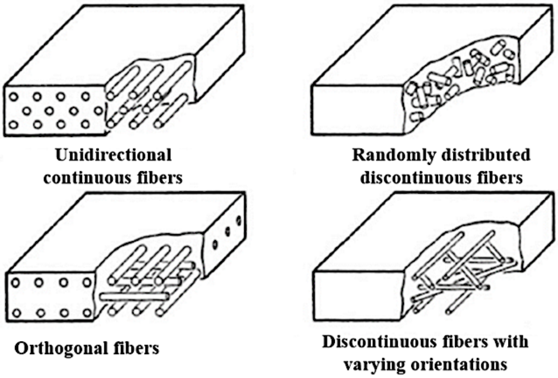


Figure 3. *Different types of fibers [22]*

The cross-section of the fibers could be circular or, less commonly, rectangular, hexagonal, or polygonal. Although these sections have some superior features, circular is superior in terms of cost and ease of use. The use of discontinuous fibers produced more useful results, even if continuous fibers exhibit superior orientation [22]. The matrix has a network structure with different geometric shapes. To produce these materials in an optimum way, insoluble and chemically non-reactive substances should be preferred [23, 24].

Synthetic materials called thermoset polymers undergo a chemical transformation during the process and form a three-dimensional structure. These heated and formed molecules could not be processed and shaped again. Thermoset composites could be recycled by mechanical, thermal and chemical processes. These polymers generally have superior properties than thermoplastics in terms of strength and temperature resistance [25].

Thermoset polymers are rigid structures where molecules are linked by cross-links, forming a three-dimensional structure. The polymerization reaction, also known as the curing, occurs through cross-linking initiated by heat, light or chemical agents, resulting in the hardening of thermosetting polymers. Thermoset polymers cannot be remelted upon heating after curing, rendering them non-recyclable through melting process. Thermoplastics have many advantages such as recyclability, meltability, thermoformability, strong resistance to chemicals and elements, and excellent electrical insulation. The disadvantages are that they cannot withstand heat like thermosets; instead, they flow and dissolve, their raw materials are more expensive, and there are not many thermoplastics in liquid form [26].

Elastomers are similarly made of long chain molecules that are cross-linked. These are polymers that could withstand very low pressures and still undergo significant deformation. There were two types of rubber to work with; natural rubber, which is rubber derived from certain biological plants, and synthetic polymers, thermoset and thermoplastic polymers, were used and produced by similar polymerization processes. As elastomers became increasingly crosslinked, they became stiffer and had a more linear elastic modulus. Corrugated fibers were used to reinforce the elastomers. This resulted in soft composites that had high strength due to the reinforcing fiber, but maintained the flexibility of the matrix elastomer, and allowed for great elongation until the fiber flattened. These composites could be used to produce biomedical devices for uses that included skin-like properties or soft tissue, including synthetic tendons. Elastomers could be made durable by using helically wound fibers, knitted textiles, or corrugated planar fibers to make composites. Compression molding could be used to reinforce knitted fabrics used in elastomeric matrix materials to create planar soft composites [27-29].

Nanocomposite structures consist of the first phase crystalline matrix. The other phase is the nanometer-sized particles distributed in the phase as additives used to improve the strength, electrical and mechanical properties. The presence of fibers and particles in these structures generally provides the matrix to reach a more durable structure. In fact, when these additives are distributed in the matrix, the applied loads are transferred to the particles in an orderly manner. By distributing the additive particles in the matrix, the durability, hardness and porosity qualities change, and the growth of the crack formed could be delayed or prevented. In addition, the interaction between the matrix and the additives and on the surface is relatively more successful in these structures [30].

The ratio of surface area to volume was high in nano powders. High surface areas are effective in giving these properties to the composite. as well as a higher sintering capacity. Additionally, there is a financial disadvantage when costly chemicals are used in manufacture [31-33].

Polymer-based nanocomposites have received the most interest among nanocomposites. The distinct mechanical, chemical, and physical characteristics of polymer nanocomposites enable their broad application. Reinforcing polymers using a variety of additives is a frequent practice. Small additions of nanoparticles to the polymer result in a notable improvement in tensile strength, yield strength, and elastic modulus [34, 35]. Illustration of surface coatings in different sizes was given in Figure 4 [35].

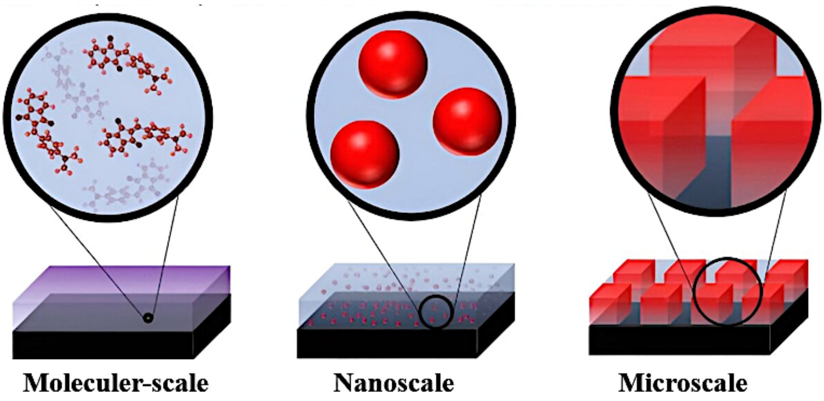


Figure 4. *Illustration of surface coatings in different sizes [35]*

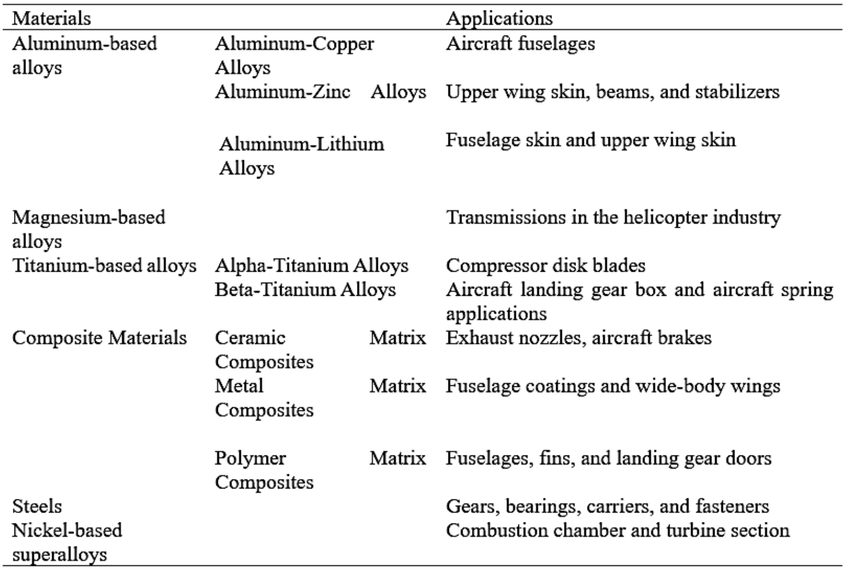
Fracture toughness could be increased by adding the necessary particles and fibers. In the case of these reinforcements in nano sizes, the highest fracture toughness was reached [36]. Metal-based nanocomposites are low-weight and have been widely preferred in automobiles and aviation due to reasons such as high hardness and durability. Transforming composites into nanocomposites increased durability and eliminated the limitations mentioned above. Metal-based nanocomposites were primarily produced by powder metallurgy techniques. The various uses of these nanocomposites have drawn attention, particularly those based on magnesium, which have grown considerably in popularity recently because of their low density, high strength, and good thermal resistance [37].

Composite materials are engineered by combining reinforcements with matrix materials to achieve specific mechanical and physical properties. It is possible to tailor composite structures to meet desired performance criteria by adjusting the type, orientation and volume fraction of reinforcements. Hybrid nano composite laminates were formed by Kumar et al. (2021) employing reinforcement materials such glass fiber, kenaf, and banana fiber together with varying weight percentages of graphene and epoxy resin as nano-additives. The results demonstrated that the mechanical characteristics of hybrid nano composites and the performance of kenaf were improved by combining graphene with resin [38]. Materials used in the aerospace field and their applications were listed in Table 1 [39].

In their 2023 review, Zhang et al. analysed and summarized the research status of organic aviation coatings, with classification and development, effecting factors and mechanisms, experimental techniques and methods for evaluating service life. They concluded that future research should focus on advancing nano modification technologies to enhance organic anticorrosive aviation coatings [40].

Epoxy resin is a material defined by its strength, durability, and thermal properties and has been frequently preferred as paints and coatings in the aerospace, construction, and automotive industries. However, thermoset polymer resins were generally known to be brittle and have low fracture toughness. Baghdadi et al. (2020) focused on the reinforcement of an epoxy resin system with zinc oxide nanoparticles in its pure form and a further modified form. Tensile testing showed that the use of pure zinc oxide increased the strength of the composite, while the fracture toughness of the resin increased when reinforced with triethoxysilane-functionalized zinc oxide [41].

Table 1. *Materials Used in Aviation and Their Applications [39]*



Materials		Applications
Aluminum-based alloys	Aluminum-Copper Alloys	Aircraft fuselages
	Aluminum-Zinc Alloys	Upper wing skin, beams, and stabilizers
	Aluminum-Lithium Alloys	Fuselage skin and upper wing skin
Magnesium-based alloys		Transmissions in the helicopter industry
Titanium-based alloys	Alpha-Titanium Alloys	Compressor disk blades
	Beta-Titanium Alloys	Aircraft landing gear box and aircraft spring applications
Composite Materials	Ceramic Matrix Composites	Exhaust nozzles, aircraft brakes
	Metal Matrix Composites	Fuselage coatings and wide-body wings
	Polymer Matrix Composites	Fuselages, fins, and landing gear doors
Steels		Gears, bearings, carriers, and fasteners
Nickel-based superalloys		Combustion chamber and turbine section

3. FUNCTIONAL COATINGS

Functional coatings are specialized surface treatments designed to impart specific properties beyond standard protection and decoration. The functional coatings extend the applications of materials and enhance their properties by modifying surface characteristics or introducing new functions. Coatings that are easy to clean, self-cleaning, antimicrobial, stain-resistant, and resistant to heat, scratches, and abrasions are examples of functional coatings [42].

In general, functional coatings are expected to be durable, easy to apply, cheap and environmentally friendly (Figure 5). The most effective method for providing these properties is nano coatings. Functional nano coatings could be applied to all types of surfaces such as glass, metal, ceramic, concrete, paper, textile and plastic after the chemical formulations that will provide the desired properties are created. The development of surface coating technology provides benefits in aviation, wind turbines and telecommunication antennas. Coating experiments have concentrated on making it easier to remove ice from the surface and lessening the ice bonding force on the surface. To remove the ice form from the surface, low shear stress is required. When developing corrosion-preventive or self-cleaning coatings, the same reasoning is applied. For this reason, the aim is to provide hydrophobic or hydrophilic properties to the surface when preparing most of the functional coatings [43].

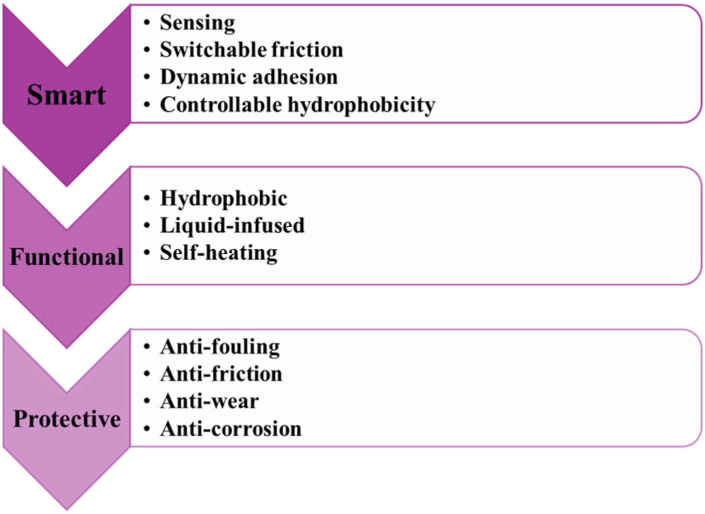


Figure 5. *Smart, functional and protective characteristic of coatings [43]*

Due to their potential for use in better engineered materials, functional coating technology research has attracted more attention recently. The traditional method entails applying a coating to a surface to offer aesthetic qualities or environmental protection. The growing need for multipurpose, engineered materials has recently accelerated the creation of novel, intelligent, and high-performing coatings for a range of application areas. To provide specific capabilities like durability in harsh environmental conditions, chemical, thermal and mechanical stability and mechanical stability, customized surface morphology, or environmental sustainability, these materials must be designed for use in various industrial contexts or targeted applications [44, 45]. Purposes of using functional coatings in various sectors was given in Figure 6 [45].

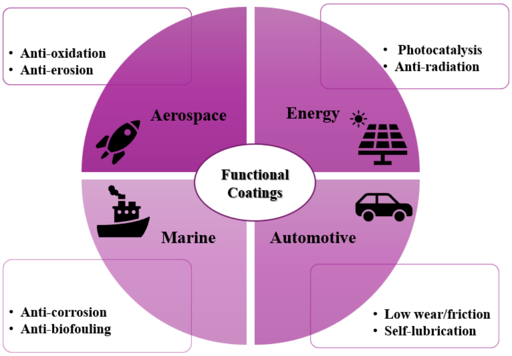


Figure 6. *Purposes of using functional coatings in various sectors [45]*

4. RECENT STUDIES

Researchers Cai et al. (2023) investigated producing an aqueous coating based on epoxy that would be more resistant to corrosion. More crystallization water was present in zinc phosphate particles having a multi-interface structure, which favoured growth along the crystallographic plane. For corrosion resistance and the connection with the resin. By decreasing the pores, the addition of zinc phosphate particles having a two-dimensional, multi-interface structure assisted in flattening the aqueous epoxy resin covering [46].

High-performance epoxy has found wide use in aviation industry. Although it has superior performance, it may compromise fracture toughness due to its bond structure. Studies have been conducted on different nanomaterials such as carbon nanosheets, graphene and inorganic nanomaterials for the development of these composites. Graphene is one of the most widely used two-dimensional nano-reinforcers. After the discovery of graphene, the attention of the research community was drawn to other 2-dimensional nanomaterials with a thickness of a few atoms. Therefore, in addition to graphene, inorganic nanosheets such as hexagonal boron nitride was also investigated. Nevertheless, these nanomaterials' inherent health risks, lack of standardization, and dispersion problems have kept them from becoming commercially available. Although graphene was discovered more than ten years ago, there are still worries about the environmental and health risks related to the production of aerospace composites and the scale-up of nanostructures from lab to industry [47].

Taşyürek et al. (2021) investigated the effect of incorporating boron carbide particles into epoxy on wear. To produce test samples, B4C was homogeneously distributed into the epoxy resin. The tribological characteristics of the pure resin and the reinforced samples were contrasted. The boron carbide ratio was shown to be the primary variable influencing the tribological characteristics. By incorporating boron carbide particles into the resin, wear resistance was enhanced. It was known that when the correct size and additives are applied, a ceramic particle that is frequently used in the industry to increase resin's durability to wear, could additionally improve the wear resistance of pure epoxy [48].

Compounds such as aluminum trihydroxide, zinc borate and melamine could be used as flame retardants to inhibit combustion and make it thermally stable. These materials that had no adverse effects on the environment and human health. Riyazuddin et al. (2020) conducted LOI tests to evaluate the flame properties of the composites. As a result, the TGA results of the system showed thermal stability up to 600°C [49].

Yuan et al. (2023) attempted to assess the active corrosion inhibition and passive barrier properties of Zn-doped polydopamine boron nitride nano pigments in silicon epoxy coatings. After that, it was examined how well nanoparticles inhibited corrosion in the liquid phase. Additionally, composite coatings were prepared using the generated nano pigments. Investigations were conducted into the passive barrier qualities of all coatings as well as the corrosion inhibition capabilities of nano additives in coatings. Electrochemical investigation revealed the presence of zinc oxide, boron nitride, and nano additives, which could suppress corrosion [50].

To enhance the coatings' heat transfer and corrosion resistance, Chen et al. (2021) utilized graphene oxide, polyvinyl butyral and resin coatings with varying graphene concentrations. The graphene oxide composite coating was demonstrated to have the highest corrosion protection effectiveness. It was more effective in preventing corrosion than a pure epoxy coating. The coating's ability to withstand corrosion was largely dependent on how evenly graphene and graphene oxide were distributed [51].

Özcan et al. (2019) added different proportions of silica particles and graphene nanoplatelets to the coating matrix separately and together. It was discovered that silica and graphene substances dispersed in composites improve their mechanical properties. In the study, the properties of epoxy coatings were addressed in many aspects with thermal, physical and mechanical analyses in a multidimensional manner. The findings demonstrated that after the addition of particles to the matrix, when compared to pure resin, the coatings› versatility and impact resistance improved. The interaction between the organic and inorganic networks led to a modest increase in thermal stability, but overall, the thermal characteristics remained relatively same. The findings demonstrated that, in situations where interaction with the polymer matrix on the surface is established, adding nanoparticles to epoxy resins is a successful method of enhancing the qualities of resin coatings. While coatings supplemented with silica and hybrid particles were more beneficial in terms of hardness and scratch resistance, graphene nanolayer-reinforced coatings were shown to improve elasticity [52].

Zinc nanoparticles were included into epoxy resin by Apşak et al. (2021). The study's analyses were mostly conducted on samples that had been cured for a day at room temperature. The findings demonstrated that the mechanical characteristics of the epoxy matrix improved with the inclusion of zinc particles. Both post-cured and untreated nanocomposites showed an improvement in tensile strength. Through immersion testing, the coatings' ability to withstand corrosion was examined. These findings showed that the epoxy composite with 1% zinc particles offered the highest surface protection for the steel [53].

Shariff et al. (2023) concentrated on developing and analysis of a novel epoxy-based hybrid composite that combines additives, glass sheets, aluminum, boron nitride particles, and powdered leaf to enhance mechanical properties. The goal of this hybrid structure was to form a superior material with increased mechanical strength by combining the unique strengths of the particle reinforcements. These reinforcements were chosen because of the special qualities of leaf powder, including its high strength-to-weight ratio of alumina, boron nitride, exceptional mechanical qualities of glass sheets, and biodegradability and environmental friendliness. It was decided to use experimental techniques to optimize each additive's weight ratio. The results demonstrated that the mechanical properties of these hybrid materials were significantly improved by their incorporation. It displayed improved flexural and tensile strength because of the additives' reinforcing behaviours [54].

5. CONCLUSION

Composite materials have been utilized extensively in defence technologies because of their outstanding qualities, which include resistance to environmental effects, high strength, light weight, and thermal resistance. The use of carbon matrix and reinforced composites in the defence sector presents many benefits, particularly regarding mechanical and thermal stability. Equipment durability is increased, and overall weight is decreased by using lightweight materials, which also saves fuel and improves operational efficiency. Within this review's scope, the function of composite materials in the defence industry was thoroughly investigated, and the benefits of composites were highlighted. Despite the difficulties in the production process and high costs of thermoset matrix composites, it was determined that they have great potential due to the mechanical durability, thermal stability and corrosion resistance they provide. Nanocomposites are increasingly used in the defence industry with their properties such as electrical conductivity, thermal conductivity, mechanical strength and environmental stability. Hybrid nanocomposites supported by nanofillers such as carbon nanotubes, graphene, nano clays and metal oxides are of great importance in aviation and space applications, especially in terms of resistance to lightning strikes, radiation protection and mechanical durability. In addition, these materials could be specially designed for defence technologies with their corrosion resistance, friction properties and flame-retardant structures. As a result, innovative materials such as carbon-based composites, nanocomposites and epoxy-based hybrid composites have significant potential for industries such as defence, aviation and space. In the future, the production of more durable, lightweight, environmentally friendly and high-performance composite materials will be possible by developing and optimizing these materials.

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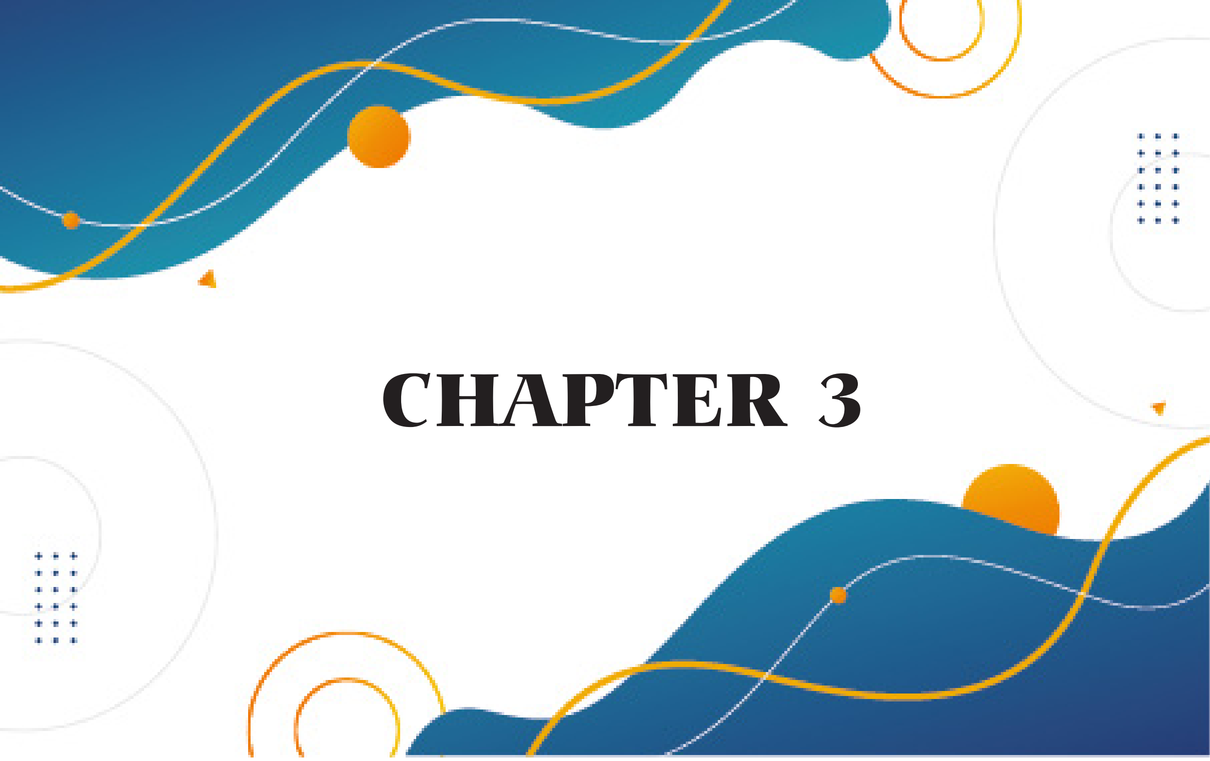

CHAPTER 3

APPLICATIONS OF PHASE CHANGE MATERIALS IN LIGHT OF CURRENT RESEARCH

Perihan ÇULUN[1]

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[1] Bingöl University, Faculty of Engineering and Architecture, Mechanical Engineering Department, Bingöl, Türkiye

Perihan ÇULUN ORCID No: 0000-0002-1797-9695

*Corresponding author: pculun@bingol.edu.tr

1. Introduction

One of the recent current researches on its use and development has been phase change materials. PCMs provide good heat absorption by absorbing heat in suitable environments, and they have the ability to release high amounts of heat in their bodies in suitable environments and conditions. PCMs absorb heat when they are in a higher temperature environment and when there is sufficient heat, they pass from the solid phase to the liquid phase, when the temperature is lower, they lose (radiate) heat and when sufficient heat transfer is provided, they pass from the liquid to the solid state. Therefore, if the PCM is in solid form and the environment it is used in is above the melting point of the material, the material will absorb heat or be charged, and in the opposite case, that is, if the material is in liquid form and the temperature of the environment it is in is below the solidification point, it will solidify by emitting heat, i.e. it will be discharged. PCMs, which are available as organic, inorganic or eutectic, have different areas of use according to the latent heat amounts they have and melting/freezing temperatures. Among these, inorganic materials seem to be more advantageous due to their cheaper and easier supply. However, other PCMs also find various applications.

The main area of current use of PCMs is energy efficiency. As it is known, the limited availability of energy resources or the low efficiency of an infinite energy source such as the sun make it essential to use existing energy resources efficiently and effectively. In this respect, the basis of academic studies in the field of energy from past to present has been either to develop renewable energy sources or to use existing energy more efficiently. PCMs have also taken their place among academic studies on the efficient use of energy due to the significant energy savings they provide in their places of use. These materials are currently used in a wide range of industrial applications such as energy efficiency of buildings, storage of thermal energy[1-3], food and beverage sector, cooling [4, 5], air conditioning systems[6], health and medicine, pharmaceutical sector and heat storage[7], and automobile air conditioners. In addition, it is possible to see their application areas in the development of new building materials, textiles and many other places [8-10].

Under suitable conditions, PCMs can absorb significant amounts of heat (liquefaction or charging of PCM) or release it (solidification or discharge of PCM) and therefore, it is possible to discover wider application areas than the current application areas. Using the energy of hot exhaust gases in different places by absorbing them[11], using them to prevent engine fuel temperature from falling below a certain value, offering them as a usable option for increasing engine efficiency or reducing emissions in LPG vehicles [12] show the interesting application areas of PCMs. It is clear that the application areas of PCMs will not be limited to these as research progresses sufficiently. Expanding the current areas of use of PCM materials, discovering new areas of use, and further developing these materials in accordance with their intended use will only be possible with the increase in the studies to be carried out in this field. Despite the disadvantage of the low heat transfer coefficient of the relevant materials, it is shown that this situation is no longer a problem with the development of the materials with the help of various nano additives[13]. Again, the difficulty of supplying the relevant materials, their high costs, etc. Although disadvantages such as these will limit their areas of use in the near future, the areas of use of related materials will expand in the long term with their development. In order to popularize PCM materials and ensure their sustainability, studies are ongoing to improve and develop their disadvantageous features as well as their various areas of use.

In order to contribute to the areas of use of PCMs, the areas of use of phase change materials were examined in this study within the scope of national and international literature studies. Current application areas were discussed in detail, and general evaluations were made by emphasizing possible future areas of use. The relevant study will constitute an important resource for applications and literature research in the field of PCMs.

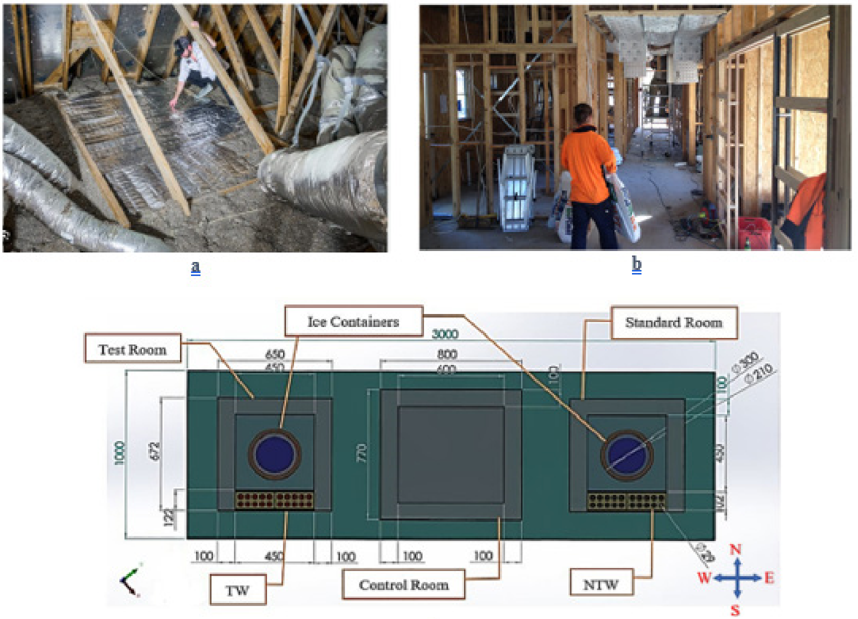
2. APPLICATION AREAS OF PCMs

PCM materials are generally used in buildings, food and beverage sector, health and medicine sector, pharmaceutical sector, industrial applications where efficiency and heat recovery are studied, automobile air conditioners[14], passive cooling processes of photovoltaic panels (PV) [15], cooling of electronic devices[16], food sector, cooling of food[17], pharmacy and medicine applications. Although the general usage areas of PCMs are like this, the details of these usage areas are presented under separate headings. It is clear that with the widespread use of these materials and their increasing recognition, wider application areas will emerge. In fact, the cooling, heating or heat storage process to be carried out with PCM material is a passive process that does not require additional energy. This means that the relevant process is as cheap as the initial cost of the PCM material. PCMs are especially used in heat storage and various heat transfer applications. They store or release thermal energy when passing from the solid phase to the liquid phase or vice versa from the liquid to the solid phase within their melting/freezing temperature ranges. The general application areas of PCMs, which have quite wide application areas, are discussed under basic headings below.

3. USE OF PCM'S AS INSULATION MATERIAL AND HEAT STORAGE

Although the low heat transfer coefficients of these materials are disadvantageous in most PCM applications requiring high heat transfer coefficients [18, 19], this feature is suitable for insulation applications. In fact, low heat transfer coefficients are sought in insulation applications. PCM materials provide significant energy savings in energy storage systems (TES) in homes and buildings, up to 20%, thanks to their wide heat storage properties [20]. PCM materials used in building components can return the energy they store during the day to the environment when the weather is cold at night or can cool the environment during the day by storing the cold effect during the night. Thus, PCM material components absorb and store solar energy and unwanted ambient energy in the summer, and release it to the environment when it is cool at night, ensuring that the environment is warmer. Thus, the air conditioning/heating usage needs that perform this job are either reduced or can be reduced to zero, or the heating need can be reduced even more in winter. This significantly reduces the energy spent for heating and air conditioning operations. PCMs used in buildings can be used on walls, roofs, bricks or interior spaces to provide thermal balance and reduce energy consumption (Figure 1).

In new insulation applications, various applications of PCM materials such as roof insulation are encountered (Figure 1a and b). Research is being conducted on the use of PCM capsules in brick cavities[21, 22] and concrete applications[23, 24]. It is known that as a result of these applications, an average of 5°C temperature decrease is provided in the comfort zone or the temperature fluctuations in the environment are significantly reduced to 1-2°C[1, 21]. In the study where PCM was used on the roof for the purpose of creating less heat load in the summer, it was thought that the temperature fluctuations in the room were reduced and this would have a significant effect on reducing the air conditioning cost[1, 21].



a

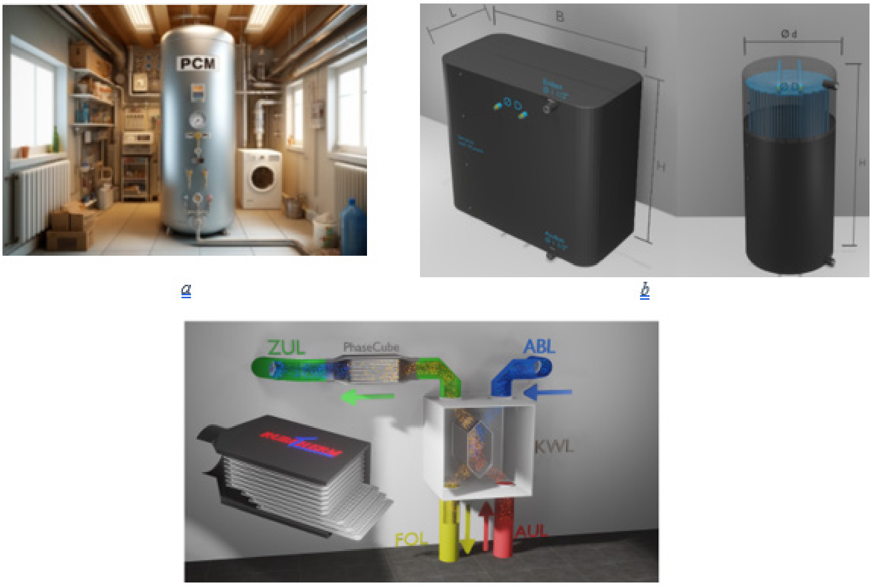
b

c

Figure 1. a and b) Use of PCM for insulation purposes in roof[1] and other building components, c) Brickwork containing PCM material capsule[2]

With appropriate PCM material applications in buildings, it is also possible to reduce building energy consumption and therefore CO_2 emissions[25]. Indeed, reduced energy use actually reduces the release of CO_2 and similar harmful gases into nature as a natural result of less fossil fuel consumption. Although there are many sample studies on the use of PCM materials in building components for insulation and heat storage purposes, they are insufficient in terms of determining the appropriate amount of use of PCM materials and their melting/solidification temperatures. Important studies are also needed on the thickness of the PCM materials used, in what volumes, for how long, and how much heat they absorb[26].

It is known that inorganic materials are mostly used as PCM materials in the construction sector. PhaseTubes developed for this purpose are mostly used in water-based systems in structures and phase change tubes containing more than one phase change module have been developed in order to maintain the hot or cold water for a long time (Figure 2a and b). These cubes are produced in different sizes and temperatures in order to bring the temperature of the air or water to the desired range (Figure 2.c). This application has been used in solar energy-supported air heating systems[27] and various heat storage systems [28]. PCMs used for heat storage are either filled into specially developed tanks or containers or PCM capsules prepared in different sizes can be used[29].



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b

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Figure 2. Example application areas of PCMs, a) PhaseCube, b)PhaseTube, c) PhaseDrum (Retrieved from https://www.rubitherm.eu/en/*)*

4. PCM applIcatIons In the MEDICAL, FOOD AND PHARMACY SECTORS

The wide range of heat absorption properties of PCM materials are of great importance in the food and beverage sector in terms of preserving the desired temperature of the food to be transported. Thanks to insulated transport boxes supported by PCM material, it is possible for food products to preserve their thermal energy during transport without using any other energy. In order to prevent food or food products from spoiling due to heating during long-distance transport, PCMs with low melting points such as RT2HC are preferred. Despite the widespread use of PCMs for cold storage of food, the use of PCMs for the purpose of preserving the temperature of hot foods is not common. However, the use of PCM materials with high melting points can provide significant energy savings by ensuring that hot foods maintain their temperature for a long time and preventing these foods from being reheated repeatedly. For example, PCM materials with high melting points such as RT70HC, RT80HC can be used in places such as restaurants or delivery units to maintain the temperature of hot foods until they reach the final point for customer satisfaction. In food distribution venues such as restaurants or cafeterias where meals need to be heated frequently, the use of appropriate PCM can prevent additional energy requirements to keep meals hot for longer periods.

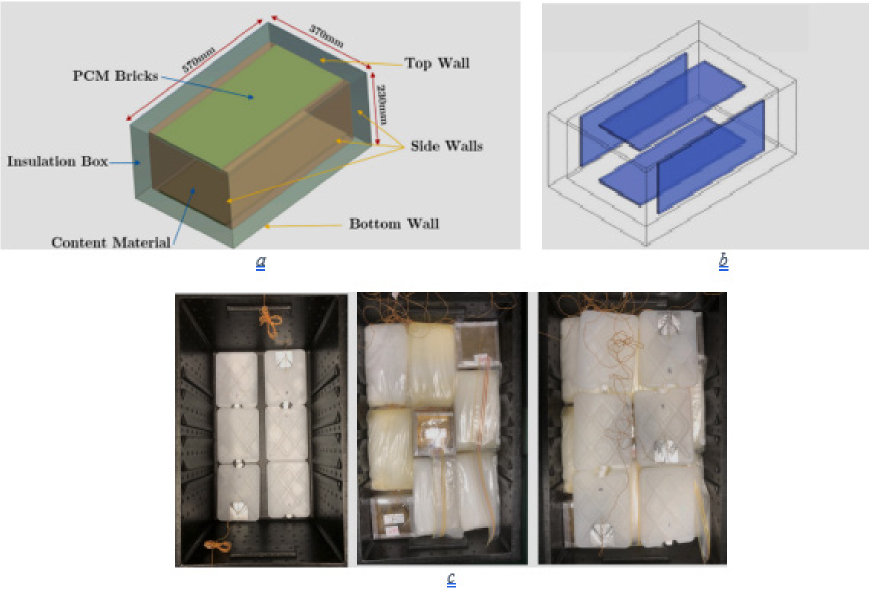
In PCM applications, heat and cold storage will be 100% recyclable for thousands of cycles and will be as cheap as the first cost. Research is ongoing to develop storage boxes used in this area[4]. PCMs can also be used temporarily to extend the life of food products that are about to spoil or instead of spoiled cold storage. In the medical, pharmaceutical and food sectors, materials such as RT5, RT5HC are used in Macroencapsulation-Thermal Packages of different sizes containing PCM material in different weights, and it is possible to transport drugs from one place to another by absorbing an average of 180-250kJ/kg of energy between +2 and +8°C (Figure 3). It is known that the use of RT5HC is of great importance especially in pharmaceutical logistics.

a

b

Figure 3. a) Macroencapsulation - Thermal Packages containing PCM material, b) PCM macroencapsulation: filled polymer bags

Research is ongoing on cold chain distribution applications that will constitute important uses of PCM encapsulations in the food and pharmaceutical sectors[5]. In cold chain applications, high threshold times and high latent heat properties are extremely important. In this respect, experimental and numerical analyses of the threshold times and latent heat performances of different PCM materials with different melting temperatures are of great importance in studies. Every study to be conducted in this field will help to spread the use of these materials in food, medical and pharmaceutical applications (Figure 4).



a

b

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Figure 4. Example optimization study of cold chain distribution applications of PCM encapsulated packages[5]

5. USE OF PCMs IN COOLING

Phase change materials are finding interesting areas of use day by day. They can be used almost everywhere where temperature and heat control is required. PCMs are used in vapor compression cooling systems, cooling of electrical and electronic devices to prevent vaccine heating problems, and cooling of food and medicine. It is known that 40% of the energy consumed is used in buildings, and a significant portion of this is consumed for ambient comfort and air conditioning cooling, etc.[30]. Vapor compression cooling systems increase electricity consumption by 15% during the busy hours of the day. On the other hand, the energy consumed for air conditioning systems increases by 50% in hot summer seasons[31]. PCM materials can be used to reduce the energy consumed in the air conditioning and cooling field, which covers a significant portion of this consumed energy.

5.1. PCM applications in vapor compression refrigeration systems

PCMs are being investigated for the purpose of increasing efficiency in areas such as heat pumps and ventilation systems based on vapor compression cooling systems[32]. It is possible to reduce energy consumption values by using PCM for cold energy charging, discharge, overcooling, etc. at various points in vapor compression cooling systems[33]. In another similar air conditioning study, water was used as PCM material for pre-cooling in order to increase the condenser capacity in a vapor compression cooling system. Before entering the condenser, the refrigerant passed through a tank containing 300L water at 25°C, namely the PCM tank, and released some of its heat. After this pre-cooling, it was sent to the condenser. At the end of one day, COP increased from 2.17 to 2.33, resulting in a 7% increase and a 10.3% decrease in compressor energy consumption[33]. Research studies in this area are limited and more studies are needed. In particular, we have very few national studies in this area.

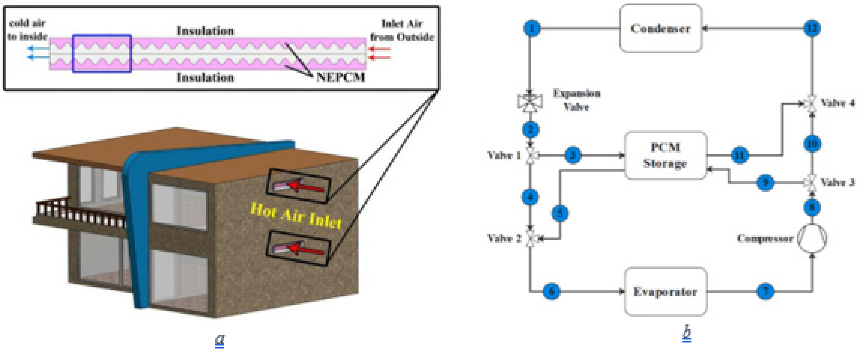


Figure 5. Application of PCM in a) Air-conditioning[34], b)Vapor compression cooling systems[31]

5.2. PCM applications in cooling of electrical and electronic devices

The use of PCMs in thermal management systems of power cells is becoming increasingly widespread. Using the phase change latent heat of PCMs to control the temperature of the cell can effectively reduce the temperature rise of the cell under high-speed operating conditions and improve the temperature uniformity[35]. In this respect, PCMs have the potential to solve many temperature-related problems in all vehicle systems or to reduce energy consumption[36]. Overheating of electronic batteries, devices, etc. results in both a decrease in the efficiency of the cells and a shortened lifespan[37, 38]. In order to prevent both a decrease in efficiency and a longer lifespan of the cells, it is important to cool the devices in question. There are air-based, liquid-based, thermoelectric-based, PCM and heat pipe-based cooling methods proposed in the past[39]. Air and liquid-based systems are active cooling systems that dissipate the heat from the cell with the flow of the refrigerant. Thermoelectric, PCM and heat pipe-based cooling methods are passive. Since the continuous flow of air or water fluid is provided by a fan or pump, there is significant energy consumption. The most popular among passive cooling methods is the PCM-based cooling method. Because with the selection and use of the appropriate PCM material, the material absorbs the heat of the device during the operating process, and when the device is inactive, it solidifies again by releasing the heat in its structure to the environment, and in this way, it provides cooling without requiring any additional energy in a cycle.

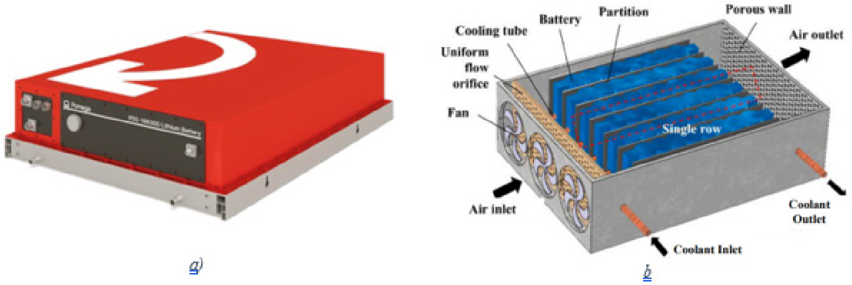


Figure 6. active cooling of battary, a) Liquid cooled high voltage Lithium-ion battery (taken from: https://tr.pomega.com/tr/urunlera), b)Air cooled battary[39]

Recently, traditional internal combustion engine vehicles have been replaced by electric vehicles. One of the important problems encountered in electric vehicles is the cooling of the electric battery system. Literature studies indicate that one of the alternative cooling process candidates for batteries will be PCM materials[35]. Currently, battery cooling methods are basically done with cooling blocks in two different ways, liquid cooling or hybrid cooling. Cooling, known as hybrid cooling, is formed by using PCM and liquid cooling, or thermoelectric cooling and liquid cooling methods together. The applicability of passive cooling applications with PCM material alone will be determined as a result of long-term research[39].

6. PCM APPLICATIONS IN SOLAR SYSTEMS

When PCMs are used for heat storage in solar energy systems, the stored energy can be used even when there is no sunlight. The use of PCM in solar energy systems is basically in two ways: in photovoltaic panels and in collectors. In photovoltaic panels, it is used as a cooling system that protects the panel from overheating and increases the panel's electrical efficiency. In collectors, it stores the excess energy when there is a lot of solar energy during the day as latent energy and allows this energy to be used at night. Thus, it is possible to provide hot water through collectors at night or when there is no sunlight.

In photovoltaic panels, panel surface temperatures that increase up to 80-100°C in the summer months significantly reduce panel electrical efficiency and shorten the effective life of the panel. As seen from Figure 7 panel surface temperatures can be reduced with two different methods, namely active and passive cooling[40]. Although some efficiency increases are achieved by reducing temperatures with active cooling systems, the fact that active systems use pumps or fans negatively affects the final efficiency of the entire system. In this respect, scientific research on passive cooling of panels with PCM continues [41]. The main difficulty encountered in heating and cooling applications with PCM is the selection of materials with the appropriate melting point and latent heat amount for the process to be used. For example, in the cooling process of PV panels, it is useful to know the surface temperatures of the panels seasonally and regionally in order to select the appropriate PCM material[40].

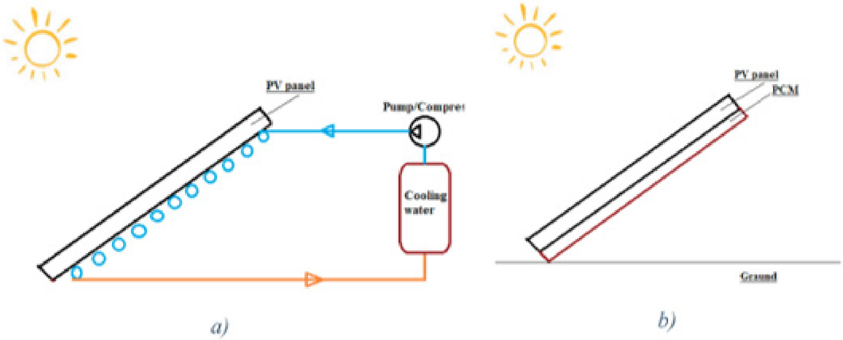
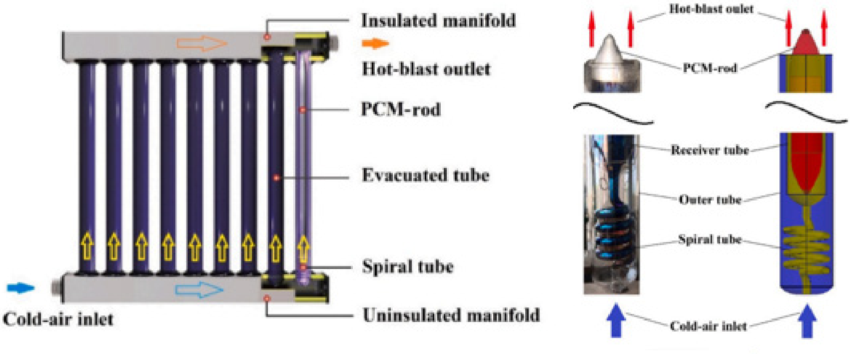


Figure 7. a) PV active cooling method, b) PV passive cooling method[4]

There are also various applications of PCM materials in solar collectors and PV/T systems to benefit from solar energy with higher efficiency and to ensure that hot water remains hot for longer periods of time[42, 43]. Thanks to the ability of PCM materials to store and release energy for a long time, a high rate of increase in thermal efficiency is achieved especially in PV/T applications[44]. The use of PCM in solar collectors can be in various ways such as heat storage tank (PCM tank), direct placement of PCM on the collector or air vacuum tube collector[45]. In vacuum tube collectors, PCM rod can be used to prevent excessive heat resulting from solar radiation from bursting the vacuum tube and to increase collector efficiency (Figure).



a b

Figure 8. Use of PCM in air solar collectors[45]

In order to overcome the disadvantage of low heat transfer coefficient in PCM materials, it is possible to increase the heat transfer coefficient of the system by using metal fin reinforcements or metal oxide mixtures of these materials in applications where these materials are used. It is also known that electrical and thermal efficiency increases are obtained in PV and PV/T panels as a result of improving the heat transfer coefficients of new generation nanofluid PCMs [46, 47].

7. PCM APPLICATIONS IN THERMAL SYSTEMS

PCMs can be used to balance ambient temperatures in transportation vehicles, increase fuel efficiency and in various industrial thermal managements. The energy of hot exhaust gases, which is one of the types of waste heat energy, can be absorbed by PCM and used in different places. For example, it is possible to transfer the waste exhaust energy of the cold vehicle environment to the vehicle environment with the help of PCMs in winter[10]. In fact, PCM usage is being investigated in thermal comfort of vehicles[[48]]. PCMs can be used to increase engine efficiency or reduce emissions in LPG vehicles by using them to prevent the engine fuel temperature from falling below a certain value. In the sample study conducted for this purpose, it was mentioned that the cold start problem can be solved, fuel economy can be provided and emission values can be reduced thanks to the heat storage LPG regulator using salt hydrate as PCM[11]. Other application examples of PCMs in vehicles are the cooling of electronic batteries in vehicles[49], energy saving in cold storage, in cold chain transportation vehicles and coolin or heating of air conditioning systems of vehicles[50].

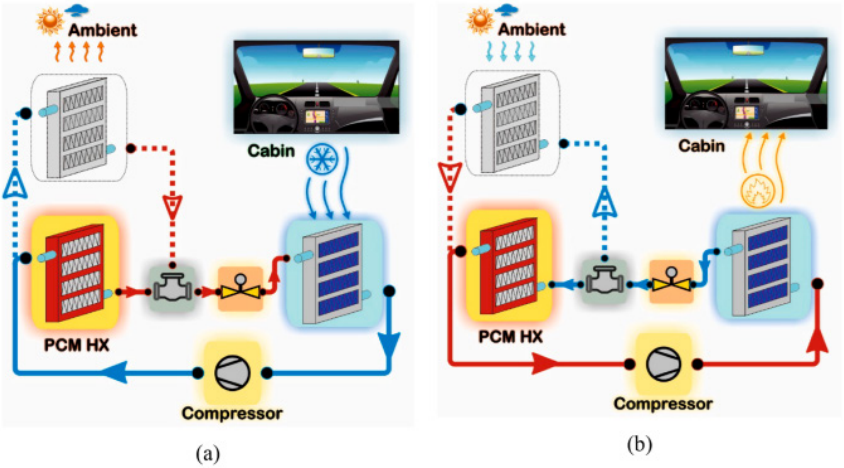


Figure 9. Air-conditioning system of vehicles with PCM [50]

8. PCM APPLICATIONS IN TEXTILE INDUSTRY

The textile industry should aim to protect people from environmental risks in the products they produce, to provide thermal comfort, and to produce flexible clothing that will provide ease of movement. For example, it is an important necessity to protect people exposed to harsh environmental conditions in regions where it is extremely hot in the summer and extremely cold in the winter from these adverse climate conditions, to reduce dangers such as fire extinguishing, exposure to chemicals, etc., and to produce appropriate textile products to protect employee health and safety. In this respect, it is essential that the textile products produced also use developing technology. In this sense, studies on developed smart textiles that provide protective and effective responses to dangerous signals in the environment such as intense heat, extreme cold, magnetic, radiation, electricity, chemicals continue. With the use of developing new technologies in the clothing sector, the production of passive and active smart products has begun. In products called passive smart, such as traditional thick or thin dresses developed in accordance with summer and winter climate conditions, protection is provided independently of the environmental effect. On the other hand, an example of active smart clothing is the phase change of PCM according to the changing environmental temperature, where PCM materials are used [51]. PCMs can provide body comfort by melting and solidifying according to the effects of extreme heat and cold, warming the body and providing a cooling sensation[52]. PCMs, which are integrated into clothing developed especially for use in cold climate conditions, can protect the body against the effects of cold external air for a certain period of time[53].

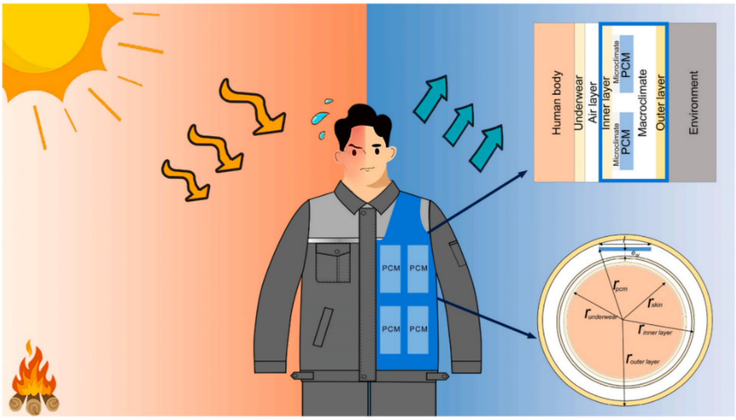


Figure 10. Wearing with PCM [54]

9. PCM APPLICATIONS IN THERMOELECTRIC MODULES

In applications where multiple thermoelectric modules are generally connected in series (TEG), the continuity of the heating on the hot side and the cooling on the cold side of these modules is directly related to the continuity of the electricity produced. In this respect, in these modules, this continuity is provided on both sides and the temperature difference between the hot and cold surfaces is actually tried to be kept constant. In this way, electricity production can continue without decreasing and continuously. There are various application studies for the cooling of TEGs or the continuity of heat on the hot side of PCM materials.

In the studies conducted by using PCM on the electrically heated source side of the TEG system, namely on the hot side of the TEG, it is aimed to provide continuity in the thermal source of the modules and to provide electricity production for a longer period of time. In an example study, it was aimed to prevent sudden interruption of the system's electricity production due to a short-term interruption in the hot source [55]. Indeed, with the advantage of storing heat for a long time and in large capacity, PCMs will act as a suspension when the hot source is disabled when used on the hot side of the TEGs and continuity of electricity production will be ensured. In fact, this is an extremely useful situation in terms of using the hot source on the heated side of the TEG modules with maximum efficiency rather than the cooling side. When we consider the hot exhaust gases of the vehicles, electricity production will also stop as soon as the hot exhaust is cut off after the vehicle stops in the TEG systems used here. However, if PCM with high latent energy is used on the side in contact with the hot source of the TEGs, then more electrical energy will be produced by using the thermal energy stored by the PCM after the vehicle stops[56]. If this generated electrical energy is transferred to the alternator, an average of 3% increase in fuel efficiency will be achieved and gas emissions will be reduced.

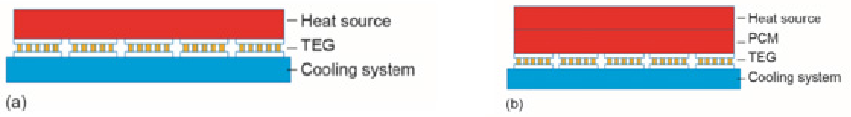


Figure 11. Using PCM on the hot side of TEG[47]

By combining PCMs with flexible thermoelectric materials, it is possible to produce thermal management and self-powered wearable technologies in harsh climate conditions such as winter and summer[47]. However, due to the difficulties in heat dissipation and electrical connection, there are currently very few studies in this area.

10. CONCLUSIONS AND RECOMMENDATIONS

PCM materials can be used in almost every place where heat management is needed thanks to their high latent heat properties and the availability of many different materials with different melting temperatures. In particular, inorganic PCM salts should be given priority in studies due to their natural availability, ease of supply and being cheaper than other PCMs. In addition to occupying a significant space in energy saving applications, PCMs will provide significant energy savings if they are used in a wider area since they are not harmful to humans and the environment. Today, PCMs are widely used in various heating, cooling areas, building energy saving, construction materials, hot and cold storage. Vapor compression cooling systems, heat exchangers, photovoltaic module cooling studies of PCM materials, cold storage studies in the medical, food and pharmaceutical sectors are also ongoing PCM topics. The use of these materials in cooling electronic devices, in the production of protective active smart products in textile products, and in increasing the efficiency of thermoelectric modules are also current applications. The biggest disadvantage of PCMs is that their heat conduction coefficients are low and especially organic PCMs are expensive and difficult to supply. Especially with the development of high heat conduction coefficient and cheap PCMs, the areas of use of these materials will increase.

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CHAPTER 4

PHASE CHANGE MATERIALS AND THEIR PROPERTIES WITHIN THE SCOPE OF CURRENT STUDIES

Perihan ÇULUN[1]

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[1] Bingöl University, Faculty of Engineering and Architecture, Mechanical Engineering Department, Bingöl, Türkiye

Perihan ÇULUN ORCID No: 0000-0002-1797-9695

*Corresponding author: pculun@bingol.edu.tr

1. INTRODUCTION

Phase change materials have been included in important academic research due to their high latent heat and their significant energy saving properties. Phase change materials (PCMs) not only provide good heat absorption by absorbing heat in suitable environments, but they also have the ability to release the high amount of heat they contain under appropriate conditions and environments. PCMs absorb heat when in a higher temperature environment and, if there is sufficient heat, transition from solid phase to liquid phase. In a lower temperature environment, they lose (release) heat and, when enough heat transfer occurs, transition from liquid to solid phase. Therefore, if the PCM is in a solid state and the environment in which it is used is above the material's melting point, the material will absorb heat. Conversely, if the material is in a liquid state and the ambient temperature is below the solidification point, it will release heat and solidify. PCM's, which are available in organic, inorganic, or eutectic forms, have different areas of application based on their latent heat capacities and melting/freezing temperatures. Although their main applications are heating, cooling, and energy savings, it is clear that these materials will find much broader applications in the future.

The main current usage area of PCMs is energy saving. As it is known, the limited energy resources or the low efficiency of the existing infinite energy source such as the sun make it essential to use the existing energy resources efficiently and effectively. In this respect, the basis of academic studies in the field of energy from the past to the present has been either to develop renewable energy sources or to use the existing energy more efficiently. This situation has enabled PCMs to take their place among academic studies in the field of energy saving. As a matter of fact, these materials are currently used in a wide range of areas such as energy efficiency of buildings[1, 2], food and beverage sector, cooling[3, 4], health and medicine field, pharmaceutical sector and industrial applications on heat storage[5], air conditioning systems[6]. In addition to the advantages of the relevant materials, disadvantages such as low heat transfer coefficient[7], difficulty in supplying the relevant materials, high costs, etc. limit their usage areas. In order to popularize and ensure sustainability of PCM materials, their disadvantageous properties need to be improved and developed.

In this study, which was prepared with the aim of contributing to the development of the properties or usage area of PCM materials and the reduction of their costs. PCMs material types and properties were introduced in detail, and the technologies in this field were mentioned, taking into account the current studies in which the materials were used. Ongoing studies on the development of PCM materials are commonly studies on the development of heat transfer coefficients and latent heats with the help of various additives, research on new additives that can be used as PCM materials, research on the application areas of the found materials, integration, etc. For this purpose, the development of various eutectic PCMs, nano-doped PCM (NPCM), polymer PCM, etc. materials is ongoing. In this study, with the aim of contributing to the field of PCM materials, issues such as the types of PCMs, their properties, the properties that need to be developed and development methods were discussed. In addition, the gaps in academic studies in the field of PCM and the importance of numerical studies to be carried out in this field were mentioned.

2. PHASE CHANGE MATERIALS

PCMs should generally have high thermal capacity, high latent heat, low cost, high conductivity coefficient and be able to change phase without decomposition for a long time to reduce additional energy requirements and provide energy savings. One of the general common features of PCM materials is that they all have high latent heat. The feature that provides the general usability of these materials in heating, cooling and heat storage areas is their high latent heat. The total latent heat amount (Q) released during the melting/freezing phase of PCM materials is found in the unit of joules by multiplying the mass (m) and specific latent heat (h) of the material as in Eq. 1. Thermal power () can be found in the unit of Watts by multiplying the mass flux () and the latent energy as in Eq. 2.

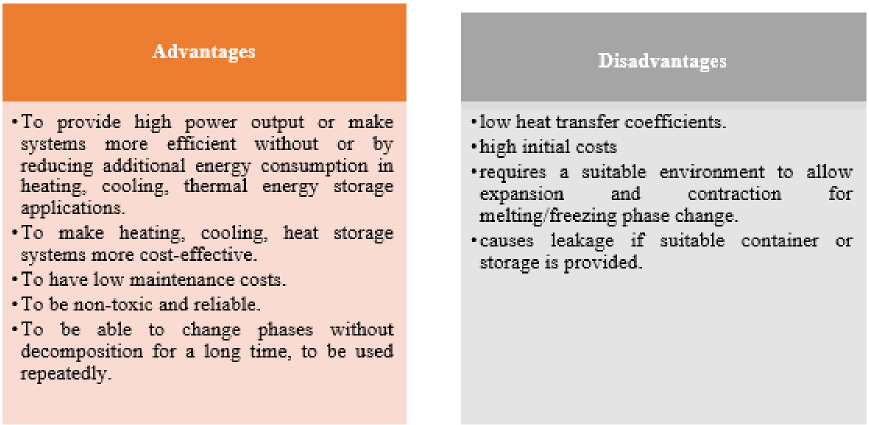
$$Q = m \times h \text{ (Joule)} \tag{1}$$

$$= (m \backslash T)\ x\ h = xh \quad \text{(W)} \tag{2}$$

When we look at the application areas of PCM materials, it is generally possible for these materials to undergo many phase changes without decomposition for a long time. This allows the relevant materials to be used repeatedly for the same purpose for a long time. Therefore, this situation prevents additional energy expenditures in the relevant area of use or provides energy savings. The fact that PCM materials are generally non-toxic and not harmful to health is another advantage that contributes to the expansion of their application areas (Table 1).

There are also some aspects to be considered and some disadvantages encountered in PCM materials (Table 1). PCMs are materials whose volumes decrease in the liquefaction phase and therefore increase during freezing. In this respect, an environment that can easily provide the shrinkage and expansion that will occur during phase changes with temperature changes, i.e., which will be flexible against shrinkage and expansion processes, should be provided. It can be said that the low thermal conductivity coefficient is again a common feature of all PCMs [8]. This feature limits the possible application areas of PCMs. In order to effectively benefit from the advantages of PCMs in wide application areas, academic studies such as the latent heats of these materials, melting/freezing temperatures, doping with cheaper materials or searching for new PCMs should be diversified.

Table 1. Advantage and disadvantages of PCMs



Advantages	Disadvantages
•To provide high power output or make systems more efficient without or by reducing additional energy consumption in heating, cooling, thermal energy storage applications. •To make heating, cooling, heat storage systems more cost-effective. •To have low maintenance costs. •To be non-toxic and reliable. •To be able to change phases without decomposition for a long time, to be used repeatedly.	•low heat transfer coefficients. •high initial costs •requires a suitable environment to allow expansion and contraction for melting/freezing phase change. •causes leakage if suitable container or storage is provided.

3.phase change materIals types

PCMs are found in different types such as organic, inorganic, hydrated salts, eutectic PCMs, composite PCMs, and are generally divided into three common classes as organic, inorganic and eutectic. Each type of PCM is different in terms of advantages, disadvantages and applications. While environmentally friendly and economical features are prominent in organics, inorganics stand out with their ability to withstand high temperatures and high heat conduction coefficients. Hydrated salts are widely used especially in the field of energy storage and temperature regulation. Due to the unique advantages and limitations of each material, where the material will be used depends on the requirements of the application. PCMs are generally available in powder form on the market. They can be purchased in the desired amount upon request, or they can be supplied as encapsulated in various sizes and quantities[9] (Figure 1). It is important for organic PCMs to be encapsulated to increase the heat transfer area and control volume change[10].

Figure 1. PCM forms available on the market, a) Powder form of PCMs, b) encapsulated PCMs (taken from https://www.rubitherm.eu/en/)

3.1.Organic Phase Change Materials

Organic PCMs are composed of carbon compounds and are generally divided into two groups as paraffins and non-paraffins [10]. Paraffins are also classified as alcohols and carboxylic acids. These materials generally have low melting temperatures, high energy storage capabilities, low costs, high thermal stability and are biodegradable, that is, they are environmentally friendly [8]. They have the ability to store high amounts of heat at approximately a constant temperature. Being chemically inert allows them to work in harmony with building materials[11]. Their volume changes during phase change are small. They have high latent heat capacities up to 120 - 210 kJ/kg, and their non-toxicity and reliability are also important features [10]. The slower heat transfer of organic PCMs during phase change is a result of their low heat conduction coefficients [8] [12].

Paraffins: Paraffins are the most common among organic PCMs. They have high heat storage capacity for low melting temperatures, generally 20-70°C. They are very stable and safe materials (Table 2 and Figure 1). It is understood that the heat transfer coefficients and specific heat values of these organic RT(Parafins) class, are low and almost the same and are 0.2W/mK, 2 kJ/kgK respectively[13-15].

Table 2. *Examples of Organic PCMs (Paraffins) [13, 16, 17]*

Commercial name	**RT21**	**RT27**	**RT31**	**RT35**	**RT44**	**RT55**
PCM category	Organic	Organic	Organic	Organic	Organic	Organic
Melting point	20–23	25–28	27–33	34–36	43–44	51–57
Latent heat (kJ/kg)	190	179	165	240	250	170
Density (kg/m3)	880 for solid and 770 for liquid					
Thermal conductivity (W/m-k)	0.2 for both phases					
Specific heat capacity (kJ/kg-k)	2.0 for both phases					
Corrosion to metallic container	No Chemical classification Paraffin wax					
Volume expansion	%14					

Alcohols: They are PCMs with low melting points. They have cooling systems and building applications.

Carboxylic Acids: Carboxylic acids also have high melting points and good energy storage properties. Their environmental friendliness, high energy storage capabilities and low cost are also important features. The disadvantages of carboxylic acids are their low thermal conductivity and high leakage risks during the melting phase due to their high viscosity. This requires the application or storage containers to be sturdy.

3.2. Inorganic phase change materials

Inorganic PCMs have higher heat transfer coefficients and higher melting temperatures than organics. Therefore, these materials offer energy storage at higher temperatures than organics. Their widespread presence in nature also ensures that their costs are low. However, inorganic PCMs have the danger or difficulty of overcooling, phase separation and corrosion. Inorganic PCMs consist of salts, salt hydrates, metals and alloys. Inorganic PCMs are preferred over organics because they can maintain their melting temperatures for a long time despite numerous melting and solidification cycles[18] and have a heat storage capacity twice as high per unit volume compared to organic materials[19]. They are the most preferred PCM material type because they are easily available and inexpensive.

3.2.1. Metals and alloys

Metals are also included in the inorganic PCM class. Metal PCMs are used in high-temperature industrial areas due to their ability to store heat energy at higher melting temperatures. They can generally have melting temperatures above 100°C [20]. They respond quickly to phase changes due to their higher thermal conductivity compared to organic PCMs. They are useful in systems requiring large amounts of energy due to their high latent heat. Their basic advantages are their resistance to long-term temperature changes, low risk of chemical degradation, long life and reliability. Inorganic metal PCMs consist of metal alloys and pure metals.

Pure metals such as Aluminum, Copper, Lithium are used as PCM materials[7, 21]. Aluminum, which has a melting temperature of 660°C, is generally used in high-temperature systems. Aluminum, which has a high latent heat storage capacity, also has a thermal conductivity. Copper, which has a melting temperature of 1085°C, is also known for its high thermal conductivity. Copper is used in high-temperature thermal energy storage and heat management systems[22]. Lithium is used in low-melting temperature applications such as 180°C. Lithium is preferred in applications where weight is important due to its low density, and in terms of using lighter materials. Metal PCMs experience performance loss when electronic devices overheat in high-temperature applications such as solar energy storage and industrial heating. They can be used in high-temperature industrial applications such as steel production, glass processing, and other processes requiring high temperatures. However, the low phase transformation efficiency and the high cost of some metal PCMs such as Copper limit their areas of use.

Sodium-Potassium Alloys (Na-K) have lower melting points than other metal PCMs with a melting point of 100-300°C. These alloys are used in high temperature applications with their high latent energy storage properties. Another example for metal PCMs is Bakelite. They are known for their use in high temperature industrial applications and their durability in corrosive environments.

3.2.2. Salt Hydrates

Salt hydrates bind water molecules in their crystal structures and can store high thermal energy during phase change. These salts can change phase by binding to water or releasing water with the change of temperature. Salt hydrates are used especially in energy storage as PCM materials, in applications such as temperature regulation and thermal insulation. The fact that these salts can store high amounts of energy during phase change, their melting temperatures are generally constant, their costs are low, they can be degraded in nature and they are environmentally friendly increases the demand for these materials as PCM materials. Salt hydrates, which are formed by combining salts such as sodium sulfate (Na_2SO_4) or calcium chloride ($CaCl_2$) with water, are used as PCM materials for heat storage and temperature control[23]. Salt hydrates release a certain number of water molecules bound to their structures during phase change or are re-incorporated into crystallization. Sodium Sulfate (Na2SO4), known as thenardite mineral, combines with water and forms sodium sulfate deca hydrate (Na2SO4·10H2O) white, crystalline structure. CaCl2 compound combines with 6 water molecules to form Calcium chloride Hexahydrate (CaCl2.6H2O) (Figure 2). There are various examples of Calcium Sulfate ($CaSO_4 \cdot 2H_2O$) combining with two water molecules, Sodium Sulfate ($Na_2SO_4 \cdot 10H_2O$) combining with ten water molecules, Magnesium Sulfate ($MgSO_4 \cdot 7H_2O$) combining with seven water molecules. Salt hydrates provide phase change in certain temperature ranges and are especially used in industrial applications. High energy storage capacity, constant melting temperature, salt solutions containing water are environmentally friendly features that come to the fore. Among inorganic PCMs, salt hydrates are seen to be preferred more in research due to their economic nature[23] or example, sodium acetate trihydrate salt is a phase-changing inorganic salt containing water molecules in its structure and is used in many areas such as medicine, textile, energy, etc. It is one of the important PCM materials with its 58 ° C melting point, 264 kJ/kg latent heat energy storage capacity and cheap and easy supply[24].

Figure 2. Salt hydrates a)Magnesium chloride hexahydrate ($MgCl_2$•$6H_2O$), b) Calcium chloride hexahydrate ($CaCl_2$•$6H_2O$)

There is a possibility of crystallization problems or chemical stability problems during the melting phase. Hydrated salts are used for energy storage in applications such as solar energy, heating/cooling systems in the medium temperature range. They can also be used to balance indoor temperature fluctuations and reduce energy consumption by absorbing heat in buildings. It is estimated that these materials will significantly reduce building energy consumption in smart building applications. Some hydrated salts can chemically deteriorate and their performance may decrease with long-term exposure to heat, but this is rare. They can be used for a long time by taking the necessary leakage precautions.

3.3. Eutectic phase change materials

Eutectic PCMs are formed by the combination of two or more organic and inorganic compounds[25]. In this way, the best properties of the materials with different properties that come together are revealed. For example, a mixture of Sodium Chloride (NaCl) and Potassium Chloride (KCl) forms a eutectic PCM. A mixture of NaCl and KCl in certain proportions forms a eutectic system that keeps the melting temperature constant at a value. The melting point of the mixture is below the melting point of each of the components and is fixed at a certain point depending on the component ratios[26]. In other words, a eutectic PCM melts or solidifies at a fixed and specific temperature. Ensuring melting and solidification at a specific temperature facilitates heat management. Phase changes are provided with high efficiency in these materials. Phase change processes occur quickly. In particular, constant melting temperature, high efficiency in energy storage, rapid phase changes as a result of fast heat transfer, low cost and environmental friendliness constitute the advantages of preferring these PCMs. Eutectic PCMs are used in high-efficiency thermal energy storage systems. They are used to provide temperature balancing in buildings, especially to store excess heat in summer and release heat in winter, and to increase thermal insulation and energy efficiency in buildings. They can also be used in cooling electronic devices. Electronic devices experience performance loss when overheated; such PCMs are used to keep the temperature of the device constant and prevent overheating[27]. In addition, eutectic PCMs are used to protect the cold chain, especially in food and drug transportation, preventing products from spoiling. The crystallization that occurs during phase change, the low thermal conductivity of some eutectic PCMs, and the risk of leakage during transportation and storage during phase change constitute the disadvantages of these materials.

3.4.Composites and Nano-Additive Phase Change Materials

In order to improve the properties of organic or inorganic PCMs, new generation composite PCMs or nano PCMs (NPCM) are produced by reinforcing them with nano materials. In this way, the thermal conductivity, energy storage and release rates of PCMs are increased, and their performance and stability are improved. In order to increase the thermal conductivity of PCMs, organic and inorganic PCMs are doped with graphite, carbon nanotubes (CNT) or metallic nano materials. Graphite-reinforced PCMs have the advantages of higher thermal conductivity and fast heat transfer properties at a melting point of 45°C -80°C. Composite PCMs, whose costs increase due to the added material, go through more complex production stages compared to pure organic or inorganic PCMs. Due to the higher production costs of composite or NPCMs and the ongoing research in this area, their commercial use is limited. The thermal conductivity of NPCM depends on the concentration of the added nano material, thermal conductivity, shape, size, aggregation tendency of nanoparticles, etc. it depends on the features[8].

Metallic nanomaterials used for the purpose of improving PCM properties are commonly Aluminum and Copper, which have high thermal conductivity and high heat storage properties. Therefore, NPCMs with higher heat transfer rate and heat storage capacity are produced with metallic nanomaterial additives. Salts are other additives widely used for phase change materials. The use of salts such as Sodium chloride (NaCl) and Calcium chloride ($CaCl_2$) in nanoscale, which have a wide melting temperature range, can accelerate the melting and freezing processes of the material. Nano polymer additives such as Polypropylene (PP) and Polyethylene (PE) are also used to increase the mechanical strength of PCMs with low melting points. Carbon nanotubes (CNT), graphene and nanostructured silica are other additives used for the purpose of improving the thermal conductivity and mechanical properties of PCMs. Although the material ratios used in nano PCMs vary according to experimental studies, nanometallic material ratios are generally between 1-5%, nano salt ratios are 5-15%, and nanopolymer and carbon nanotube ratios are generally between 2-10%.

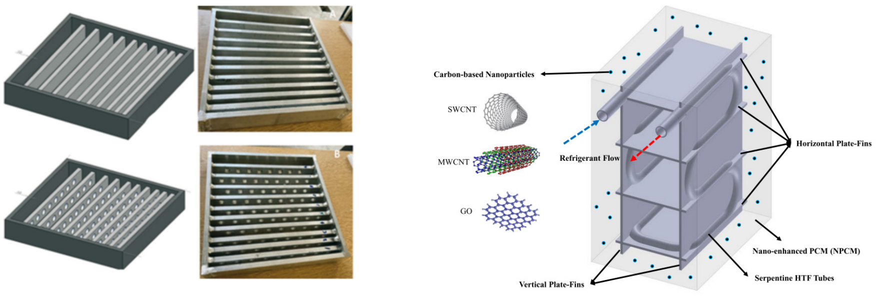
4. IMPROVEMENT OF THE PROPERTIES OF PCM MATERIALS

Studies on PCM materials are in the form of producing PCM materials that operate with high efficiency and stability in a wide temperature range, improving heat transfer coefficients, developing materials with high latent heat energy, producing cheaper materials, etc. Some PCM materials degrade over time due to repeated phase changes. Therefore, it is extremely important for the selected PCM materials to be sustainable for a long time without deterioration in order to have a longer life[28]. In addition, it is extremely important to prevent leaks during melting/freezing of PCM materials, to allow for shrinkage and expansion, and to reduce physical deterioration with phase change.

4.1. Evelopment of Heat Conduction Coefficients of PCM Materials

The biggest problem encountered in PCM material applications is the low thermal conduction coefficients of these materials. Academic research also points out that low heat conduction coefficients actually make PCM materials extremely suitable for use in the insulation sector[29]. However, they slow down heat transfer in applications where heat transfer and storage are important, apart from insulation. Especially the low heat conduction coefficients of organic PCMs and some eutectic PCMs make it difficult to use these materials in heat storage areas. In order to develop these materials in this field, the possibility of producing new generation PCM materials with higher heat conduction coefficients by combining them with various nano powders and graphite is being investigated[30]. It has been stated that Paraffin-PCM with a heat transfer coefficient that is 44 times higher can be obtained when foams such as copper and nickel are used as additives to paraffins, and up to 18 times higher with aluminum additive[31].

On the other hand, other methods investigated for these materials to better absorb or emit heat from the environment are appropriate fin applications and appropriate container applications in the environments where they are used. In this way, more interactive and more efficient results are obtained[32-34]. In order to improve the heat conduction of PCM materials, aluminum containers or fins are generally used because they are more economical, lighter and easier to supply[35]. In PCM material cooling where flat and perforated aluminum fins are used, a 7.43% power increase was achieved as a result of a temperature decrease of 8.32°C with flat fins and 8.55°C with perforated fins[36].



a

b

Figure 3 a) PCM containers with flat and shaped aluminum fins [36], b) Improvement of heat transfer coefficient with NPCM [6]

Other examples of studies where the heat conduction coefficients of PCM materials are improved are nanomaterial addition studies. Especially nanometals with high heat conduction coefficients provide faster heat transfer and higher capacity energy storage in materials. İf nanomaterials such as graphene oxide is used in appropriate amounts in paraffins, it is possible to significantly increase the heat conduction coefficient without changing the enthalpy of the PCM material[37, 38] Nanomaterial supported PCMs, polymer material supported polymeric materials, nanocomposite PCMs[39] are materials with improved heat conduction coefficients[6].

4.2. Melting/freezing characteristics and latent heats of PCM materials

Since the nanomaterials used are also effective on the melting and solidification stages of PCM materials, how these additions affect the melting and solidification stages is also important. In this respect, studies conducted in the relevant field are also of great importance [40, 41]. Another important issue in these materials is the development of latent heat rates. Studies are also being conducted on improving the latent heat of PCM materials [42]. Latent heat refers to the heat that the material absorbs and retains at constant temperature and pressure under melting or freezing conditions or the heat it emits. The heat absorption or emitting feature of a PCM is actually related to the amount of latent heat it has. Every pure material has a latent heat. For example, the latent heat of water melting/freezing is 80 cal/gr, and the latent heat of evaporation/condensation is 540 cal/gr. The latent heat generally used in PCM material applications is the latent heat of melting or freezing.

It is known that the prices and volumes of PCMs with high latent heat increase in proportion to their increasing latent heat. This volume change, which increases slightly when PCM materials solidify, can restrict the use of the relevant materials in some applications. These materials increase in volume just like the volume increase of water when it freezes at zero degrees and below. In this respect, the volume fraction that expands when the materials solidify, i.e. the container or tube etc. where the materials are used, should be well considered before completely filling the volumes. In fact, if the materials are filled and adjusted as solids in the storage containers, there will be no problem. The real problem may occur when the material is placed in the storage container as melted. Academic studies have shown that if molten PCM is to be placed in the container, a space of at least 15% of the container volume should be left. Indeed, in Table 1, the volume expansion for paraffins is 14%[43] and 12% for RT44HC, and in a similar application, 14% of the PCM container by volume was left empty[44].

An important problem encountered in applications where PCMs are used is that the fusion/solidification or melting times cannot be determined well in accordance with the requirements of the application. In fact, this requires the melting temperature of the selected material, the amount of latent heat and the amount of material to be well adjusted. In this respect, experimental studies conducted specifically for each material in the relevant field are extremely important.

5. NUMERICAL ANALYSIS OF PHASE CHANGE MATERIALS

Performing all the experimental analyses of new PCM properties obtained by combining PCM materials with nano powders or nano fluids would be both a significant waste of time and cost. In order to prevent this situation, numerical examination of these new generation material property analyses prevents both time and money waste. Therefore, one of the important contributions to the PCM field will undoubtedly be the examination of the property analyses and applications of new generation PCMs with CFD studies[45, 46]. Expansion of CFD studies in this field will enable the use of better materials in a shorter time and in wider areas[47]. Performing thermal energy storage, heat management and efficient energy use, performance and optimization analysis of PCM materials within the scope of numerical studies is important in terms of energy/time savings and faster results[48]. The efficiency of PCM energy storage and thermal systems can be improved with numerical modeling and simulations. PCM material analyses may include studies examining thermal, chemical and mechanical properties and evaluating their performance, determination of melting and freezing temperatures, calculation of heat storage capacities[49], thermal conductivity and heat distributions, mechanical stability life cycle, simulation of phase transitions[50].

The melting and freezing temperatures of PCMs, the energy storage/release process, are usually measured by the differential scanning calorimetry (DSC) technique. This process complicates the process in terms of being both costly and time-consuming. Performing this analysis using various numerical programs will provide significant progress in this area. Matlab, COMSOL Multiphysics, Ansys Fluent software can be used for temperature distribution and phase changes. The problem of low thermal conductivity of PCMs is tried to be solved by adding graphene, metal oxides or carbides to PCMs [51, 52]. The effect of these additives can be modeled with numerical analysis, since it takes a long time to examine experimentally or theoretically and is costly. Undoubtedly, it will be possible to obtain similar results faster and at lower costs with low error margins in numerical modeling. Durability tests for problems such as crystallization and chemical degradation in long-term use of PCMs can be supported by life cycle analysis (LCA) as well as laboratory conditions. Thermal management in buildings, balancing temperature fluctuations and reducing energy consumption can be created using modelling software such as structural design and energy flow management using EnergyPlus or TRNSYS programs[53].

6. CONCLUSIONS AND RECOMMENDATIONS

PCM materials find wide usage areas in energy sector due to their high latent heat. Although their initial cost is high, their reusability without decomposition and undergoing phase changes for a long time reduces their costs in the long term. Although low heat transfer coefficient makes these materials important for insulation sector, it is actually undesirable situation in the applications where heat transfer and storage are important. PCM properties are improved by using 1-5% nanometallic material, 5-15% nano salts and 2-10% nanopolymers and carbon nanotubes. It is especially important to investigate experimentally the long-term applications of these new NPCM and polymeric materials. It is necessary to determine the problems such as sedimentation encountered in nano-additive NPCMs or to clarify the long-term applicability of these materials. In applications such as storage containers where PCM and its derivatives are used, the expansion and contraction shares of the related materials of 15% on average should not be ignored. It has been understood that numerical studies in this field are insufficient and therefore it is extremely essential to increase numerical analyzes.

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