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RESEARCH ARTICLE

AN ANALYSIS ON THE USE OF MODIFIED EXPANDED PERLITE AND PUMICE IN INORGANIC BONDED FIBROUS COMPOSITE BOARDS

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Abstract

It is often stated that there is an energy efficiency difference between optimum energy use and actual energy use in the world. In the construction industry, various building materials are produced and used to optimize energy efficiency in buildings. Among these building materials, inorganic bonded fibrous composite boards, whose energy efficiency criteria have begun to be improved, are widely used both in Türkiye and in the world. This article presents an experimental analysis of the utilization of modified expanded perlite and pumice as key constituents in the development of inorganic bonded fibrous composite boards. The study investigates the influence of these modified porous materials on the physical, mechanical, and thermal properties of the composite boards. For this purpose; composite mortars were produced using micronized quartz sand, a hybrid fiber consisting of cellulose and glass fiber, modified expanded perlite (MEP) with stearic acid (1, 2, 3, 4, 5, 6, 7, 8, 9 wt.%) and modified pumice (MPU) with stearic acid (1, 2, 3, 4, 5, 6, 7, 8, 9 wt.%). In order to make a comparison, a control mortar that did not contain modified expanded perlite and modified pumice was produced. Through a series of experiments, it is concluded that the density values of all other mixture designs with MEP and MPU aggregate additives under equivalent conditions are lower than the control sample. The water absorption values of the samples always remained below the control sample, and with the increase in the MPU ratio and decrease in the MEP ratio, the water absorption values of the samples also decreased. The average modulus of rupture (MOR) value of control sample in the analysis made after 14 days of curing under ambient conditions is 3.73 MPa. The highest MOR value of the test samples is 3.51 MPa, which is the mixture using the highest MPU. The thermal conductivity value of the control mixture is 0.352 W/mK. The thermal conductivity value of test mixtures with MEP and MPU aggregates varies between 0.175 W/mK and 0.287 W/mK.

Keywords

Coating for water resistance,
Cemented composite board,
Modulus of rupture,
Thermal properties,
Energy saving

Time Scale of Article

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1. INTRODUCTION

One of the most basic human needs is the need for shelter. Over time, human beings have begun to attach more importance to the security, durability, convenience, aesthetics and comfort of the structure. Additionally, the construction of buildings with sustainable materials that are easy to install and apply has increasingly gained importance. This has rapidly led humanity to research, development activities and applications of innovative and sustainable material production. Building designers and building users insist on developing healthy living and working environments to achieve a high degree of efficiency for the protection, health, and comfort of the residents and to satisfy sustainable development

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commitments [1]. While the increasing growth in the construction sector and the need to benefit from innovative technology in the construction sector continues, it is of vital importance to deteriorate the ecological balance due to the use of natural resources and energy consumption. In the construction industry, creative methods are needed in the selection of building materials to ensure the best use of available resources in building material production. In particular, 40% of the energy and 25% of the water consumed worldwide are spent in building construction or use [2, 3, 4, 5]. As the building system and culture change, the materials used in the building and the production styles also differ and develop to adapt to this change [6]. The construction of different building systems, within the context of processes and social/cultural structures in different physical environments, is shaped by cultural differences in human enculturation, through socialization, and intergenerational sharing of culturally worked content [7–10]. One of the most effective materials of this process has been the use of cement-bonded fiber reinforced boards products in building sections. These plate products are not only a facade cladding material, thanks to their flexible structure that can be used in all kinds of structures, but also have features that can be easily adapted to different project applications [11, 12, 13]. In addition, cement-bonded fiber reinforced boards, which can be used in different climatic conditions and change the appearance of buildings due to the material components used in their production, take their place among the environmentally and human-friendly materials [14, 15].

These boards contain one or more types of organic or inorganic fibers as reinforcing elements and cement as the binding element [16, 17]. However, different minerals, commonly containing quartz or similar high amounts of silica, can be used as other elements forming the structure as the main and/or filling material. Depending on the intended use of the boards, various additives can be added to the formulation to improve properties such as heat insulation, electrical resistance and fire resistance. The production of cement-bonded fiber reinforced sheets can be carried out by two different methods: air curing or autoclaving [17, 18, 19]. Regardless of the fiber used or the production method, all products within the scope of fiber reinforced cement board are evaluated within the scope of Standard EN 12467 [20]. These sheet products, according to their technical specifications, can be used for exterior and interior wall coverings of all kinds of prefabricated or reinforced concrete buildings, sandwich panel-shaped partition walls and separators, all kinds of ceiling and mezzanine floor chassis coverings, under-roof coverings, all kinds of prefabricated buildings and steel construction [21, 22, 23]. It can be used in the application of building elements.

Cement-bound fiber reinforced sheets can be produced in different density values ranging from 1200 to 1600 kg/m^3, depending on the place and purpose of use [23, 24]. It is known that the increase in density value and the type and amount of fiber reinforcement it contains have positive effects on the development of the mechanical strength of the plate. However, as a result of the rapid development of global and climate changes observed today, ensuring thermal comfort in building sections and the use of more energy efficient building material components gain special importance [25-27].

The development of energy efficiency in building sections in buildings directly depends on the components that make up the building section to be made of materials that provide high resistance to heat transfer. The use of plate products with low thermal conductivity and high thermal insulation performance in building sections is on the agenda as a new research topic. In order to achieve this, the use of aggregate derivatives with low density, high porosity, natural origin, and long-lasting durability [28-32] in plate production is an issue that needs to be investigated in detail. For this purpose, the use of expanded perlite and natural pumice rock of volcanic origin as fine-grained aggregate components in the production of cement-bonded fiber reinforced sheets [33-39] can be seen as an approach that can shed light on this issue. When the literature is examined, it can be observed that the studies in which expanded perlite or pumice aggregate used in the production of cement-based lightweight boards are directly added to the mixture after sizing are very limited. Also, these types of aggregates are quite porous and have a high water absorption capacity. It has been observed that there are not enough studies on the effect of using these types of aggregates in cementitious lightweight boards on the board products after coating. In an ongoing experimental research study, detailed technical analyzes are carried out on the use of coated expanded perlite and coated pumice aggregate components in the production of cement-bonded fiber reinforced boards and their effects on the physical, mechanical and thermal properties of the board, and the findings obtained are discussed comparatively in this article.

2. MATERIALS AND METHODS

2.1. Materials

2.1.1. Cement

CEM I 42.5R ordinary Portland cement (OPC), which is similar to ASTM Type I cement, was used in the mix design of ten different Inorganic Bonded Fiber Composite Board (IBFCB) samples. The specific gravity of cement is 3.15. In the entire study, OPC was used as the main inorganic binder material. Chemical composition of the cement is given in Table 1.

2.1.2. Micronized quartz sand

In the preparation of IBFCB test samples, classified micronized quartz sand (MQS) with a maximum size of 250 microns, obtained from market conditions, was used as the main aggregate material. The average bulk density of ground quartz sand is 1500±180 kg/m^3. Chemical composition of the micronized quartz sand is given in Table 1.

2.1.3. Mixed fiber

In the preparation of IBFCB test specimens, a mixture of fiber materials of two different origins was used as fiber reinforcement in order to provide reinforcement elements in the matrix structure. These fiber materials are cellulose and glass fiber. The cellulose material in the mixture was first subjected to an opening process and fibrillized, and was transformed into pulp with water in the thinnest fibrous form possible. However, other fiber additive material was used as textile type glass fiber obtained in different sizes by physical recycling of uncontaminated fabric waste/residues generated in the production of wind turbine blades. The nominal length of the glass fiber material is 6 mm on average. Specific gravity weight of glass fiber is 2.58 g/cm^3, fiber diameters are 13-15 (±15%) microns, tensile strength is >3200 MPa, Elasticity Modulus is ≥70 GPa, moisture content is <0.15%, yarn ratio is <0%, 20 and application temperature is between -60°C and 650°C. In order to prepare the test samples, a mixed fiber additive (FIB) consisting of 40% cellulose fiber by weight and 60% textile type glass fiber material by weight was prepared and used in the production of all test samples.

2.1.4. Modified expanded perlite

In the preparation of IBFCB test samples, in order to reduce the unit volume weight of the mortar and create a lighter mortar design, 0-1 mm expanded perlite, obtained from market conditions, was first coated with the help of heat treatment using 3% stearic acid under laboratory conditions. With this process, expanded perlite aggregates are given a water-impermeable feature. However, it was also observed that after the coating process, the grain strength of the perlite aggregate increased, and it became more resistant to crumbling. Throughout the study, the lightweight aggregate obtained as a result of this process was named as modified expanded perlite (MEP) material. The average bulk density of MEP material after the coating process was 145 kg/m^3 and it is off-white in color. Chemical composition of the modified expanded perlite is given in Table 1.

2.1.5. Modified pumice

In order to reduce the unit volume weight of the mortar and create a more porous matrix structure in the preparation of IBFCB test samples, 750 µm size classified pumice aggregate was obtained from the Nevşehir region in Turkey under market conditions. As with the MEP material, pumice aggregates were also coated with the help of heat treatment using 4% stearic acid under laboratory conditions. With this process, fine-grained pumice aggregates are given a water-impermeable feature. Throughout the study, the pumice obtained as a result of this process was used as lightweight aggregate, modified pumice (MPU) material. The bulk density of the MPU material after the coating process is 640 kg/m^3 on average and it is light grayish in color. Chemical composition of the modified pumice is given in Table 1.

General view of all ingredients of IBFCBs are shown in Figure 1. Sieve analysis of MQS, MPE and MPU are represented in Figure 2.

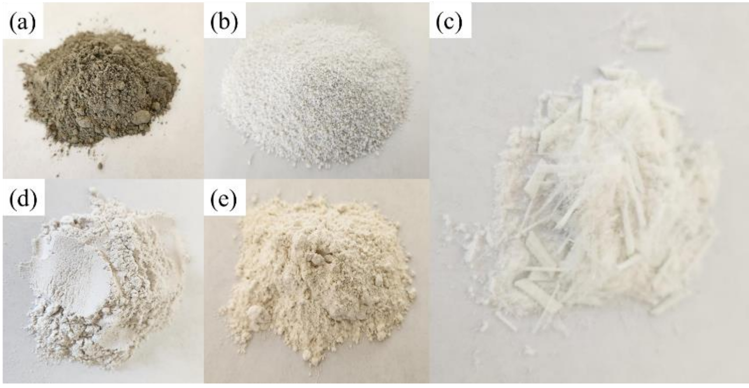

Figure 1. (a) OPC; (b) MEP; (c) FIB; (d) MPU; (e) MQS

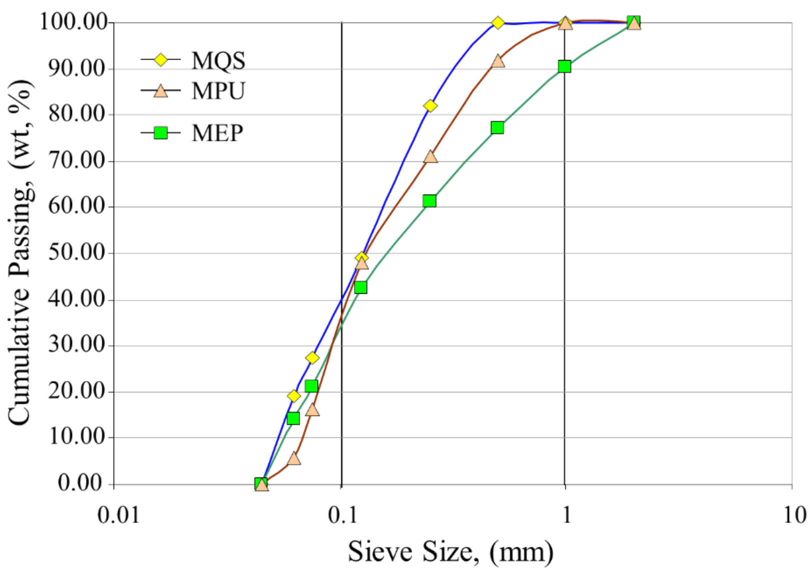

Figure 2. Sieve analysis of MQS, MEP and MPU

Table 1. Proportions of trial mixtures (% by weight)

Chemical composition (%)	Cement	MQS	MEP	MPU
SiO_2	19.22	98.32	72.20	74.10
Al_2O_3	4.84	0.33	11.40	13.45
Fe_2O_3	3.69	0.24	0.53	1.40
MgO	0.91	0.01	0.33	0.35
CaO	64.72	0.02	0.63	1.17
Na_2O	0.45	0.47	3.30	3.70
K_2O	0.67	0.20	4.20	4.10
SO_3	2.48	-	1.87	-
LOI (%)	3.01	0.40	0.56	1.34

2.2. Methods

2.1.1. IBFCB production

In this experimental study, nine different proportions of composite mortar mixtures were designed to investigate the extent to which modified expanded perlite and pumice aggregates affect the technical properties of inorganic bonded fiber composite boards (IBFCB). In order to represent board samples in these mixture designs, test samples were prepared with flat surface features with an average thickness of 12 mm and a nominal surface area of 250x250 mm^2. The components and usage rates of the board mortar designs applied within the scope of the study are given in Table 2. Test samples were prepared by applying the principles stipulated in the TS EN 12467 standard [20]. All test samples were considered for the category of boards designed to be used in places (indoors) that may be exposed to heat and moisture, but not frost.

Table 2. Proportions of trial mixtures (% by weight)

Mixture	OPC	MQS	FIB	MEP	MPU	w/c
CS0	30	64	6	0	0	1.00
CS1	30	55	6	9	0	1.17
CS2	30	55	6	8	1	1.17
CS3	30	55	6	7	2	1.17
CS4	30	55	6	6	3	1.17
CS5	30	55	6	5	4	1.17
CS6	30	55	6	4	5	1.17
CS7	30	55	6	3	6	1.17
CS8	30	55	6	2	7	1.17
CS9	30	55	6	1	8	1.17
CS10	30	55	6	0	9	1.17

Samples coded as CS0 are samples prepared without the use of modified expanded perlite (MEP) and modified pumice aggregate (MPU), and were evaluated as control and comparison mixture designs throughout the study. In all mixture designs, a constant ratio of 30% cement by weight as the main binder material and 6% mixed fiber (FIB) was used. In the other 9 designs (CS1-CS10), MPE and MPU were used in varying amounts, totaling 9% by weight. In the CS1 series, only 9% MEP by weight was used as the modified aggregate component, and this weight ratio was used substituting from the MQS value. Similarly, in the CS10 series, only 9% MPU by weight was used as the modified aggregate component, and this weight ratio was used substituting from the MQS value. In the change from the CS2 series to the CS9 series, the mixture designs were arranged by increasing the MPU ratio, with a 1%

increase in each series. It is aimed to examine the effects of the use of MEP and MPU in these designs on the technical properties of the prepared board test samples. In the design of the CS0 control mixture, the w/c ratio was applied as 1.0, and since porous aggregate was used in the CS1 – CS10 designs, the w/c ratio was used as 1.17 in all series. The consistency (flow value) of the control mixture was balanced as 155 mm on average. The other mixtures in the study were also brought to the consistency value of the control mixture, which could be close to 155 mm ± 2 mm. In the preparation of these samples, prepared wet mortar samples were poured into a mold made of stainless steel with a square surface area, and they were placed evenly by the vibration method. All samples were kept under laboratory conditions for 7 to 14 days as stipulated in the TS EN 12467 standard. 10 test samples for each mixture design were prepared. 5 of these samples were used to determine mechanical properties, and the other samples were used to determine physical and thermal properties. General views of IBFCB test samples after mixing are given symbolically in Figure 3.

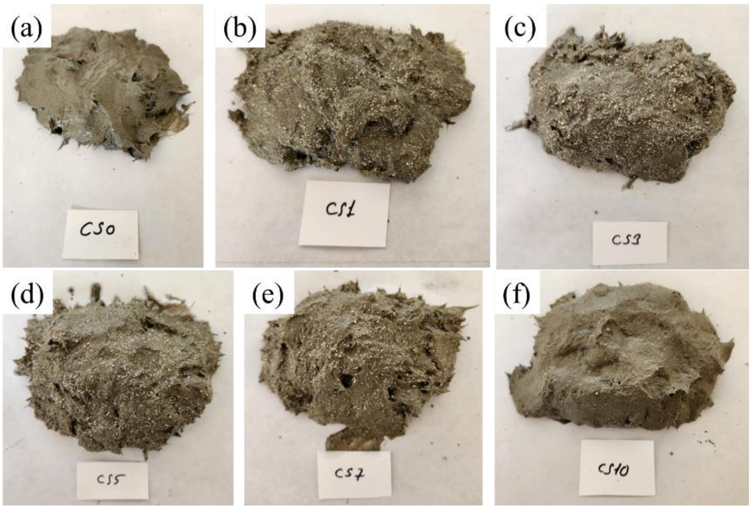

Figure 3. Post-mix symbolic overviews of IBFCB test samples (a) CS0, (b) CS1, (c) CS3, (d) CS5, (e) CS7, (f) CS10

2.2.2. Physical and mechanical tests

As physical properties of IBFCB test samples, apparent unit volume mass values and water absorption values by mass under normal environmental conditions were analyzed according to Article 7.3.1 of the TS EN 12467 standard [20]. In the application of apparent unit volume mass tests, samples to be subjected to mechanical testing were used. After drying for 24 hours in an air circulation oven at 100-105oC, the determined weight was recorded as the mass of the sample. Based on the volume calculated using the external dimensions of the sample, the ratio value of the sample weight to the sample volume was evaluated as unit volume mass. This value expresses the average unit volume mass of the material, including voids (Equation 1).

$$\rho = \frac{m}{V} \tag{1}$$

where, ρ is apparent unit volume mass, (g/cm^3), m is dry mass of the test sample (g), and V is volume of the test sample (cm^3). After the measurements, all values were converted to kg/m^3 and recorded.

To analyze the water absorption value by mass of IBFCB test samples under normal environmental conditions, 3 samples from each mixture were taken and dried in an air circulating oven at 100 – 105 °C for 24 hours and then the unit weight was recorded. Then, the test samples were placed by immersion in a water bath where the temperature was maintained at 20±2 °C, they were taken out of the water bath every 12 hours and their weights were measured, and the process of keeping them in the water bath continued until the weight of the sample reached a constant weight. Water saturated unit weights of the samples that reached constant weight were recorded and water absorption values were determined using the equation given in equation 2.

$$w = \frac{(m_1 - m_0)}{m_0} \times 100 \tag{2}$$

where, w is water absorption value by mass under normal environmental conditions (%), m0 is dry mass of the test sample before the test (g) and m1 is saturated dry mass of the test sample after the water bath (g).

Mechanical evaluation of IBFCB test samples was analyzed on 5 samples of each mixture design as the modulus of rupture value (MOR) at the smallest bending under ambient conditions. In these analyses, samples kept for 14 days in laboratory conditions were tested, taking into account the board conditions stipulated in the TS EN 12467 standard [20], which are designed to be used in places (indoors) that may be exposed to heat and humidity, but will not be exposed to the effect of frost. For the purpose of the modulus of rupture analysis in bending, a bending test machine with a 3-point loading mechanism, which can load at a constant speed while applying the load, and whose accuracy error and repeatability error are ≤3%, was used (Figure 4). The clearance between supports was used as 200 mm as the loading condition of the test samples, and the condition "The ratio between the span between the supports / the nominal thickness of the sample should be 15 or greater" stipulated in the TS EN 12467 standard was met in all tests.

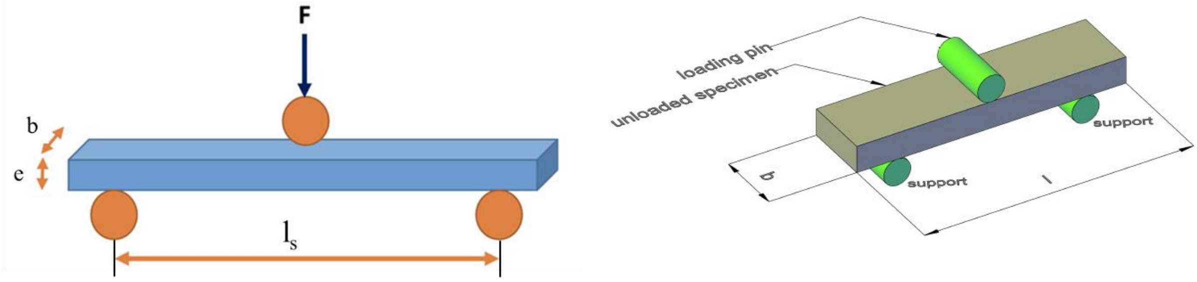

Figure 4. Symbolic general principle of flexural testing machine and testing application.

In the analysis of the modulus of rupture at the smallest bending, the test specimens were placed so that their lower faces rested on the supports, and a load was applied to the specimen with the loading rod placed in the center. A load is applied to the sample at a rate that will cause fracture within a period of 10 seconds to 30 seconds. In the experiment, care was taken to keep the deflection increase rate constant. The flexural modulus of rupture MOR was calculated in megapascal (MPa) unit, using the breaking load determined by the experiment in each direction, with the help of the equation given below (equation 3).

$$MOR = \frac{3 \times F \times l_s}{2 \times b \times e^2} \tag{3}$$

where *F* is breaking load (N), *ls* is clearance between the vertical axes of the support (mm), *b* is width of the test sample (mm) and *e* is thickness (mm). The flexural modulus of rupture of the test samples was determined as the arithmetic average of five values (two values in each direction) and was examined based on the limits of the smallest MOR values under ambient conditions specified in Article 5.4.3 (Table 6) of the TS EN 12467 standard [20].

2.2.3. Thermal properties tests of IBFCBs

In order to determine the thermal properties of the samples, the thermal conductivity values and specific heat values of the test samples of each mixture were analyzed using experimental methods. For thermal conductivity value analysis, 3 rectangular samples of each mixture design with a nominal size of

200x400x12 mm^3, flat on both sides, were prepared by casting and left to cure for 14 days under ambient conditions. After the curing process, the samples were dried for 24 hours in an air circulating oven at 100 – 105 ^{o}C and then tested in (W/mK) unit using a laboratory scale hot box device. This laboratory-scale hot box device is a steady-state measurement device via conduction [40]. However, in specific heat value measurements, 3 cube samples of 50x50x50 mm^3 nominal size were prepared and used in a separate steel mold. In order to determine the specific heat value (J/kgK) of IBFCB samples, a calorimeter device with technical features defined in the literature and relevant empirical approaches were used [40, 41].

Using these two thermal properties and the determined physical properties of the test samples, the thermal diffusion value and heat storage amount analyzes of each mixture design were defined using the calculation algorithm. The thermal diffusion of the mixture designs was determined with the approach given in Equation 4 [40, 41].

$$\alpha = \frac{\lambda}{\rho \times C_p} \tag{4}$$

where; α is thermal diffusivity (m^2/s), λ is thermal conductivity (W/mK), ρ is dry unit weight (kg/m^3) and C_p is specific heat (J/kgK).

The amount of heat stored depends on the specific heat of the medium, the temperature change, and the amount of storage material and it is expressed by Eq. 5 [40, 42].

$$\Delta Q = m \times \int_{T_i}^{T_f} C_p(T).\, dT \tag{5}$$

Where, ΔQ is the heat stored (J), m is the mass of specimen (kg), C_p is specific heat (J/kgK), dT is temperature difference.

3. RESULTS AND DISCUSSION

3.1. Physical and Mechanical Tests

The physical and mechanical properties of *IBFCB* specimens produced in this study are given in Table 3. Exact values are shared as separate tables, and the experimental results are given and discussed graphically along with regression analyses one by one.

Table 3. Physical and mechanical properties of IBFCB specimens.

Mixture	MEP	MPU	Dry Unit Weight (kg/m^3)	Water Absorption (by mass, %)	Modulus of rupture at smallest bending at 14 days, MOR (N/mm^2)
CS0	0	0	1326	40.7	3.73
CS1	9	0	875	39.1	2.22
CS2	8	1	892	36.4	2.33
CS3	7	2	925	33.8	2.55
CS4	6	3	979	32.5	2.60
CS5	5	4	1000	31.2	2.76
CS6	4	5	1041	30.3	2.83
CS7	3	6	1070	29.7	2.92
CS8	2	7	1125	28.4	3.07
CS9	1	8	1186	27.4	3.44
CS10	0	9	1240	27.0	3. 51

The average density value of the CS0 control sample after 14 days of curing under ambient conditions is 1326 kg/m^3. This value is almost equivalent to the density values of cement-based fiber reinforced plate products used in the construction industry under current market conditions [23, 24].

It is seen that the density values of all other mixture designs with MEP and MPU aggregate additives under equivalent conditions are lower than the control sample, in other words, they show a lighter plate feature. The lowest density value was obtained in the CS1 mixture with 9% MEP additive by weight, and it is 34% lighter than the control sample. As the MEP contribution rate decreases and the MPU contribution rate increases in mixture designs, the density values of the samples increase in an approach that can be considered linear (Figure 5). The average apparent density value of the CS10 mixture with the highest MPU aggregate additive usage is 1240 kg/m^3, which is 6.5% lighter than the control sample. As can be seen here, the use of MEP in mixture designs has played a more active role than MPU in terms of reducing the apparent density. In reducing the building dead load caused by the use of plate in buildings, the use of MEP and/or MPU aggregate in the board mortar is important, provided that other technical features of the board products are taken into account.

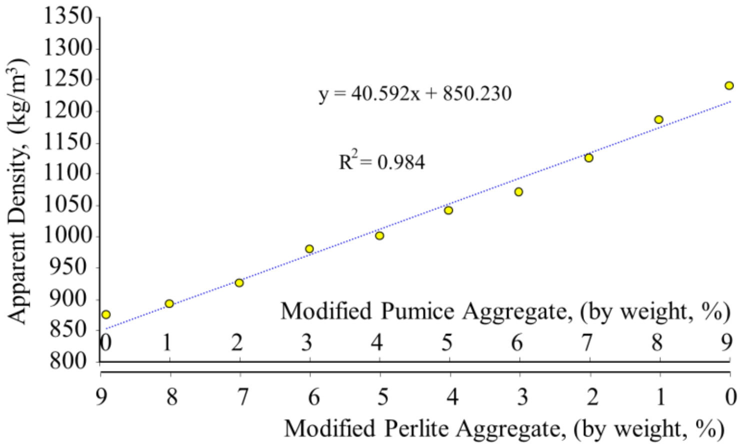

Figure 5. Apparent density change depending on MEP and MPU usage rate of test samples.

The water absorption capacity of inorganic bonded fibrous composite mortars is also considered as a parameter showing the water retention ability. It is inevitable for fibrous composite plates, which have high water absorbency values, to exhibit dimensional mobility in terms of the ratio of absorbed and retained water. Dimensional mobility is not technically desirable, regardless of the orientation of the board. However, it does not seem possible to achieve zero-scale dimensional mobility. For this reason, the minimum acceptable dimensional mobility value should be determined in terms of the usage areas of the boards [43]. Important factors that increase water absorption in composite boards include the structural forms of the aggregate components that make up the board matrix and the water absorption capacities of the fibers that make up the matrix reinforcement. Cellulose fiber additives are generally known as water-retaining components, while glass fiber additives have much lower water retention capabilities due to their structural form [12, 16, 21, 23]. However, the fact that the board mortar matrix contains components with a porous structure and high water retention capacity increases the water absorption ability of the board product and increases the risk of dimensional mobility. In practical applications, it is seen that alternative methods can be used to reduce water absorption ability in board production. For example, adding water-repellent agents of different origins and different proportions to the mixture designs or coating the board product surface with a water-repellent solution. Although these and similar applications provide positive results, it can be seen that they cannot exhibit sustainable material matrix structures due to the risk of losing their water repellency properties over time. In industrial uses, reducing the apparent density value of the board product and minimizing its water absorption ability can be seen as an important technical development. In this context, it is thought that the use of expanded perlite and natural pumice aggregates as modified additives in the board mortar after coating their surfaces with water-repellent material and providing them with a water-impermeable feature can be successful in this regard. In the experimental study carried out to gain experience with this technical feature development, this interaction was clearly seen in the test samples obtained by adding MEP and MPU aggregate to the mixture in different proportions (Figure 6).

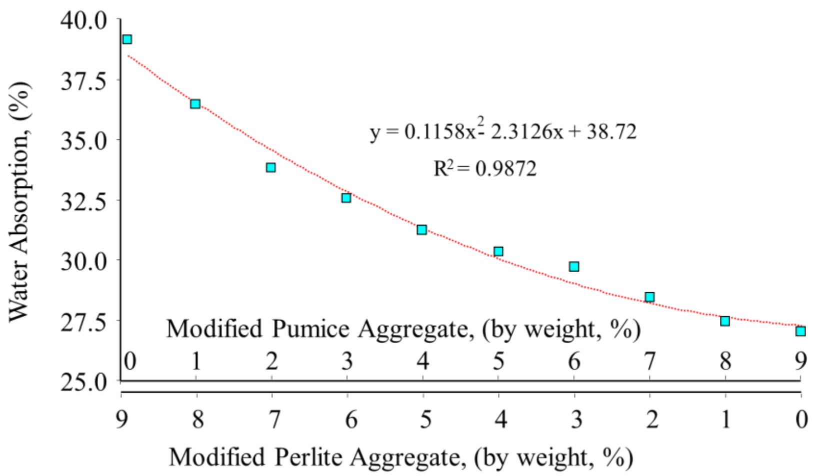

Figure 6. Water absorption change depending on MEP and MPU usage rate of test samples.

In the water absorption rate determination of the CS0 control sample after 14 days of curing under ambient conditions, an average water absorption value of 40.7% by weight was determined. This value not only shows that the matrix structure of the board sample absorbs water on a significant scale, but also represents a potential to exhibit dimensional stability. However, the highest water absorption rate of the CS10 mixture with MPU aggregate additive was obtained as 27% on average. This value is the mixture design with the lowest water absorption value within the scope of the study, and it has approximately 34% lower water absorption ability than the control mixture. This naturally means that this mixture will have a lower risk of dimensional stability. However, it is seen that as the MPU ratio decreases and the MEP ratio increases in mixture designs, the water absorption rate values increase. The average water absorption rate of the CS1 mixture with the highest MEP aggregate additive was 39.1%. This value has approximately 4% lower water absorption ability than the control mixture. These interactions can be examined as the effectiveness of the water absorption rate in the board matrices in the mixture designs (Figure 7). However, it is clearly seen that the water absorption rates of all test samples with MEP and MPU additives are lower than the control mixture. The change in the effectiveness of the water absorption rate in the test samples can also be described as a preliminary criterion of a development that may be positively reflected in the dimensional stability of the board products produced in these design components. Akyuncu and Sanliturk [44] also stated that coating of lightweight aggregates decreased the water absorption values of final products when compared with the one produced with uncoated lightweight aggregates.

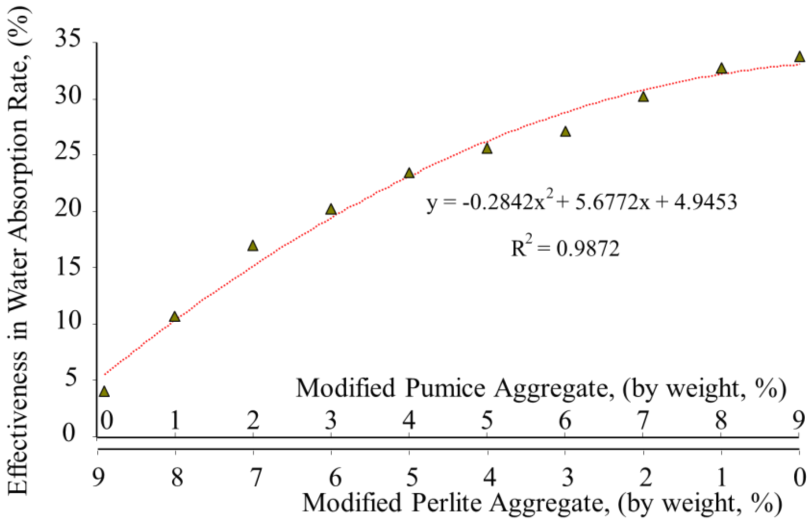

Figure 7. Efficiency analysis on water absorption rate in test samples.

Another important feature of cement and fiber reinforced composite board samples is the lowest modulus of rupture value. This value is also generally known as the MOR value. For building materials to be used as board products, TS EN 12467 standard Article 5.4.3 (Table 6) limits the lowest modulus of rupture values for test samples in wet conditions and ambient conditions. The lowest MOR values under ambient conditions are predicted to vary between 4 MPa and 22 MPa, according to 5 different classes specified in the standard. However, in the test findings, it has been accepted as a rule that the modulus of rupture at the smallest bending in the weakest direction of the test sample should not be smaller than 70% of these defined limit values. Considered in this context, for the suitability of the mixture design for Class 1 at these limit value changes, the smallest MOR value must be greater than 4 MPa × 70% = 2.8 MPa. When examined in this context, the average MOR value of CS0 control sample in the analysis made after 14 days of curing under ambient conditions is 3.73 MPa. This value appears to provide the limit value prescribed by the standard. The average MOR value of CS10 mixture, on the other hand, with the highest MPU aggregate additive usage is 3.51 MPa. This value is 5.9% lower than the control sample and provides the smallest limit value prescribed by the standard. It has been observed that in mixture designs, as the MPU ratio decreases and the MEP ratio increases, MOR values decrease with an exponential function trend (Figure 8). Therefore, the lowest MOR value was obtained in CS1 mixture and was 2.22 MPa. This value largely does not meet the prescribed limit of the standard. When the changes in all mixture designs were examined, it was observed that CS1 – CS4 mixtures did not similarly meet the predicted limit. In this context, when the MEP and MPU contribution ratio was examined in terms of the mechanical strength of the boards, it was determined that the MEP ratio should be <5% and the MPU ratio should be >4% by weight.

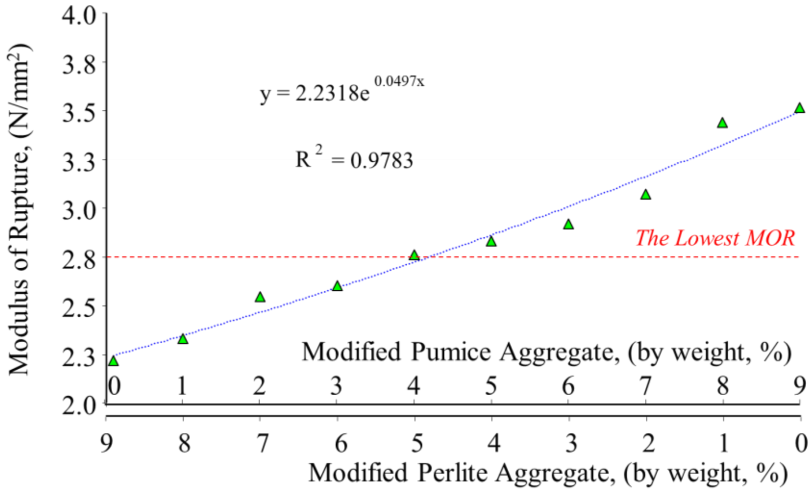

Figure 8. Relation between MEP & MPU ratios in IBFCB mixtures and MOR of IBFCBs

Another situation observed within the scope of the study is that as the apparent density of the test samples decreases, the MOR values also decrease. It is thought that the factor here is that the porosity phenomenon in the matrix structure of the test sample tends to increase in the context of decreasing density and a structural form that is weaker against bending is formed (Figure 9). In order to achieve the lowest MOR value stipulated in the standard, it is seen that the apparent density value of the board must be >1000 kg/m^3 in designs with MEP and MPU additives.

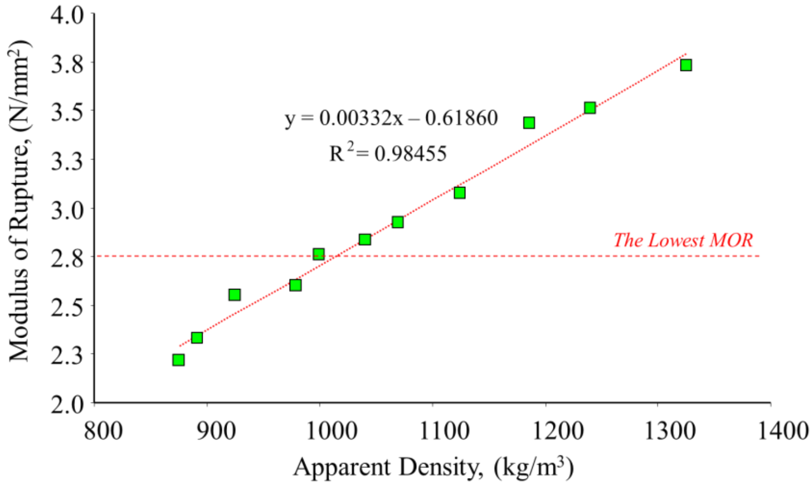

Figure 9. Relation between apparent density and MOR in IBFCB mixtures.

3.2. Thermal Properties Tests of IBFCBs

Thermal properties of all test samples are given in Table 4. The thermal conductivity value of the CS0 control mixture is 0.352 W/mK. The thermal conductivity value of IBFCB mixtures with MEP and MPU aggregates varies between 0.175 W/mK and 0.287 W/mK. The main factor in this change is the MEP and MPU ratios used in the mixture design, and as the MEP ratio increases, the thermal conductivity value decreases. Generally, thermal conductivity in cement-based materials is associated with the porosity and density of the material [45-47]. However, when the optimum mixture design is taken into consideration to ensure the lowest MOR value stipulated in the TS EN 12467 standard and mentioned above, it becomes clear that the variation range in the thermal conductivity values of the test samples is

0.201 W/mK to 0.287 W/mK. The thermal conductivity change of the test samples depending on the MEP and MPU usage rate in mixture designs is given in Figure 10.

Table 4. Thermal properties of tested specimens

Mixture	MEP	MPU	Thermal Conductivity (W/mK)	Cp (J/kgK)	Thermal Diffusivity x10^{-6} (m^2/s)	Heat Stored* ΔQ (calories)
CS0	0	0	0.352	785	0.338	2486
CS1	9	0	0.175	944	0.212	1973
CS2	8	1	0.182	938	0.218	1998
CS3	7	2	0.189	922	0.221	2037
CS4	6	3	0.198	891	0.227	2083
CS5	5	4	0.201	872	0.230	2083
CS6	4	5	0.223	857	0.250	2131
CS7	3	6	0.223	846	0.246	2162
CS8	2	7	0.245	833	0.261	2238
CS9	1	8	0.268	812	0.278	2300
CS10	0	9	0.287	805	0.288	2384

*Heat Stored, ΔQ is related to for 10 mm thickness and 1 m^2 surface application area for a 1°C temperature increase in the surface of board layer.

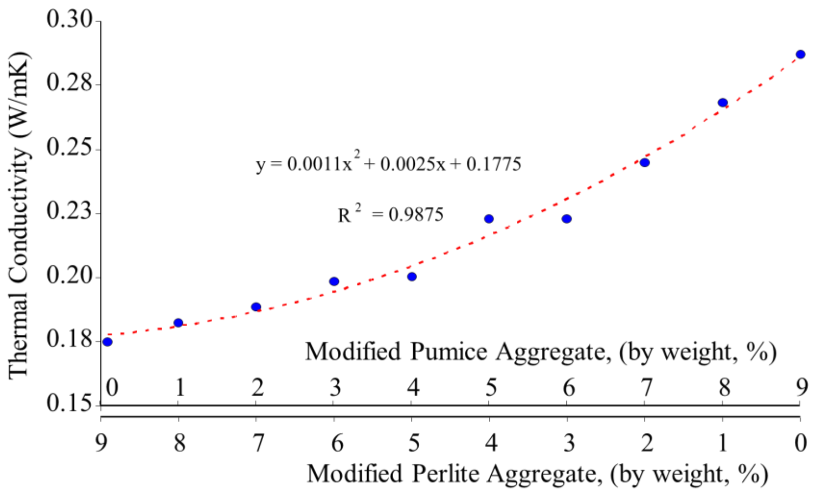

Figure 10. Relation between MEP & MPU ratios in IBFCB mixtures and thermal conductivity of IBFCBs

As can be seen when Figure 10 is examined, as the MEP ratio increases in mixture designs, the matrix structure becomes more insulating, and as the MPU ratio increases, the matrix structure becomes more conductive. In order for board products to contribute to insulation in buildings, it is generally desired that their thermal conductivity values are low. In this context, the necessity of carefully optimizing MEP and MPU usage rates, as far as technical values allow, comes to the fore. Considering only the thermal conductivity value of the test samples, in the most optimum mixture design (CS5), a maximum of 43% insulation could be achieved compared to the control sample.

Another important parameter in examining the thermal comfort properties of building materials is the specific heat (Cp) value of the material. Depending on the matrix structure and components of a material, there may be a difference between the characteristic of the thermal conductivity value and the specific heat value. For example, while the thermal conductivity value of the material increases, the specific heat value may tend to decrease. Within the scope of this study, the specific heat value of the control sample coded CS0 was determined as 785 J/kgK. On the other hand, the highest specific heat value was determined in the CS1 sample and is Cp = 944 J/kgK. The Cp value of this sample with 9% MEP by weight is 20.3% higher than the control sample. However, the Cp value of the 9 wt% MPU added sample is 805 J/kgK, which is 2.5% higher than the control sample. As can be seen here, Cp values decrease as the MEP ratio decreases and the MPU ratio increases in the mixture design. However, the Cp values of all samples with MEP and MPU additives are higher than the control sample (Figure 11).

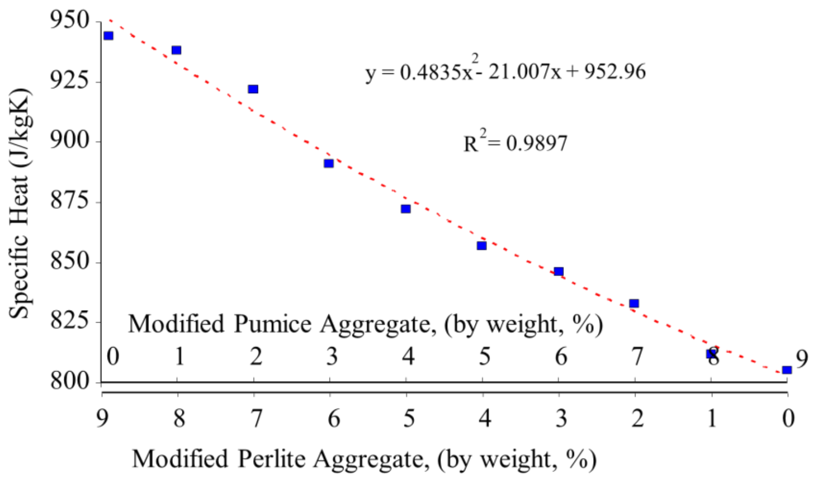

Figure 11. Relation between MEP & MPU ratios in IBFCB mixtures and Cp values of IBFCBs.

The effect of solar radiation and environmental temperature on the building constantly changes throughout the day. Regardless of their origin, all building materials have the ability to store heat, albeit with different characteristics. During the heating of the material, it stores heat, albeit in certain amounts. This phenomenon varies depending on the specific heat of a building component, its density, thickness and the temperature difference it is exposed to [25, 27, 46]. Improvement of thermal insulation performance in a building section can be achieved by keeping the heat storage ability of the components that make up this building section at as low values as possible. Considering cement-based fiber-reinforced composite boards as an important component of building sections, it is desirable to have high insulation values in terms of thermal comfort. It can be thought that the ability to achieve this is due to the low heat storage ability of the form that forms the matrix structures of the board products. Because it is important not to store the heat acting on the surface during use, but to reflect the heat back to the environment where it spreads. The storage of heat by changing the temperature of the substance is called "sensible heat storage", and the storage of heat by phase change is called "latent heat storage" [48-50]. The heat storage ability of many materials used as building materials in buildings is generally seen as "sensible heat storage". When examining the heat transfer in a building element located in a building section, the multiplication value of the density value of the building element to its specific heat value (ρ*Cp) is called "heat capacity of the material". The specific heat of the material "Cp" and the heat capacity "ρ*Cp" represent the ability of a material to store heat [46, 48-50].

According to the research findings, the sensible heat storage ability of the control sample coded CS0 was determined as 1.04 J/m^{3}K. On the other hand, the lowest sensible heat storage ability belongs to the square with code CS1 and the highest MEP usage rate, and its value is 0.83 J/m^{3}K. It represents approximately 20.2% less heat storage than the control sample. In the general evaluation of the sensible heat storage capabilities of the test samples, it is seen that as the MPU ratio increases in the mixture design, the heat storage ability increases, in other words, by absorbing the heat acting on the surface, the insulation value weakens. It was determined that the heat storage abilities of MEP and MPU added test samples varied between 0.83 J/m^{3}K - 1.00 J/m^{3}K depending on the increasing MPU ratio. It was observed that the heat storage abilities of all samples with MEP and MPU additives were lower than the control sample.

Another material property that is important in time-dependent heat transfer is "thermal diffusivity". Thermal diffusivity is a quantity that represents how quickly heat spreads on the surface and body of a material, and its unit is "m^2/sec". The thermal diffusivity values of all tested mixtures are given in Table 4. The thermal diffusivity value of the control sample is $0.338x10^{-6}$ m^2/s. The thermal diffusivity of MEP and MPU added test samples varies between 0.212 $x10^{-6}$ m^2/s - 0.288 $x10^{-6}$ m^2/s depending on the increasing MEP ratio in the mixture. Compared to the control mixture, the thermal diffusivity of all porous aggregate samples is lower than that of the control sample. In other words, if the control sample has a higher thermal diffusivity than other samples, it represents that the thermal diffusivity from the material to the indoor environment will be higher. The algorithmic analysis has shown that as the MEP ratio increases in the mixture design, the thermal diffusivity property decreases due to the decreasing density, and it represents that the heat is converted into heat energy in a large amount of material and is absorbed. However, the magnitude of the thermal diffusivity value can be considered as an indicator that the heat flow through the material is faster and its insulating properties are weakening. In this context, the change in thermal diffusivity of all test samples within the scope of the study compared to the control sample was examined as a "%" value in the context of the comparison criterion. Accordingly, as the MEP ratio in the mixture increases, the change in resistance of the matrix structure of the material to thermal diffusivity increases, whereas as the PMU ratio increases, the change in resistance to thermal diffusivity decreases. This change trend is given graphically in Figure 12.

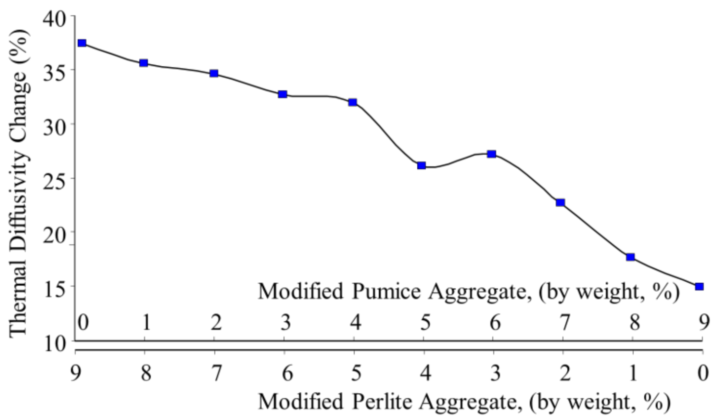

Figure 12. Relation between MEP & MPU ratios in IBFCB mixtures and thermal diffusivity changes of IBFCBs.

As Figure 12 is examined, the changes in thermal diffusivity of MEP and MPU added test samples vary between 15% and 37.4% compared to the control mixture. While the MEP usage rate transforms the matrix structure of the material into a more resistant form against thermal diffusivity, the increase in the MPU usage rate partially negatively affects this feature. However, considering that the board products that can be obtained at these mixed ratios must also meet the minimum MOR value stipulated in the standard, it is seen that a maximum gain of 32% can be achieved compared to the control sample in the optimum mixture design.

Moreover, it can be concluded from Table 4 that the heat storage capacity of the test samples increased from 1973 calories to 2486 calories (see Figure 13). According to Figure 13, in MEP and MPU added mixtures, in the context of the decreasing thermal conductivity value depending on the MEP additive amount, a lower amount of heat is required to increase the temperature on the surface of the board mortar layer by 1˚C. This feature represents that the heat value of the board surface can be increased with lower thermal energy, thus creating a more ergonomic usage environment in terms of energy efficiency. In thermal comfort evaluations, the higher surface temperature of building material components in building sections means that the section will exhibit higher efficiency in terms of thermal insulation. In this context, faster and more economical heating comfort can be achieved in an indoor space with low thermal energy consumption. In order to achieve this rationally, it is desired that the building cross-section absorbs the heat emitted from a heat source indoors at a minimum level, has a low thermal diffusivity despite heat transfer through the cross-section, and has a feature that allows the surface temperature to rise with low calories. In this context, as the MPU ratio increased in the test samples prepared within the scope of the study, the heat storage capacity increased from 1973 calories to 2384 calories. The main factor contributing to this is the increase in the thermal conductivity value of the material matrix structure. However, the heat storage capacity value of all test samples with MEP and MPU additives was lower than the control sample value on a caloric basis. This shows the effect of MEP and MPU contribution on thermal performance.

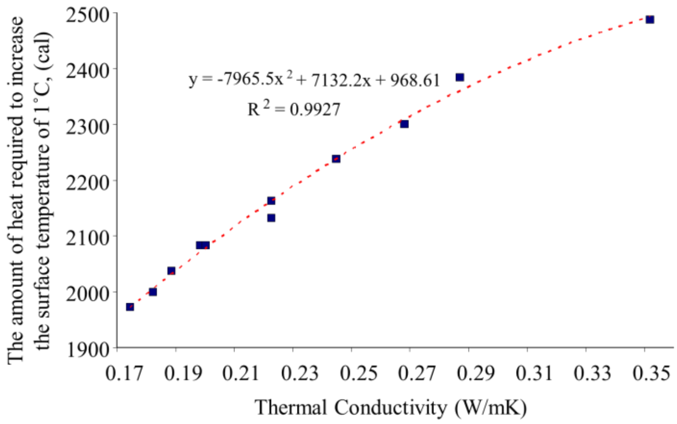

Figure 13. Relation between the amount of heat required to increase the surface temperature of 1˚C and thermal conductivity of IBFCBs.

Figure 14 shows the heat storage efficiency of IBFCBs according to thermal diffusivity values. This graphical analysis represents that higher thermal comfort can be achieved by storing less heat within the material due to the decreasing thermal diffusivity value. The improvement of the thermal insulation value in building sections depends on the low value of the heat acting on the material surface, through the diffusion of the heat passing through the material surface and the material section. Conditions where heat storage is minimized, and surface temperature rises with low energy are also important for this situation. In this experimental study, MEP additive having higher porosity creates an effect improving the thermal comfort efficiency. This efficiency reaches up to approximately 21% in samples containing 9% MEP by weight compared to the control mixture. However, the use of pumice aggregate as a component in the mixture, which having lower porosity rate than expanded perlite, has a reducing effect on this efficiency. It is seen that as the MPU ratio increases, this efficiency value decreases up to 4%. In other words, as the MPU ratio increases, the heat flow through the material becomes relatively higher and higher heat energy is needed to increase the material surface temperature.

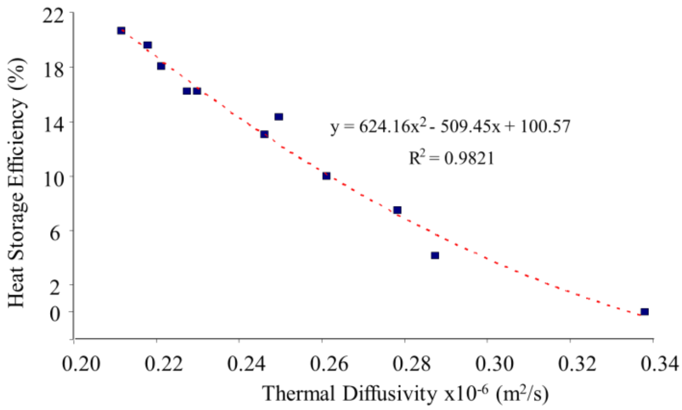

Figure 14. Relation between heat storage efficiency and thermal diffusivity of IBFCBs.

4. CONCLUSION

In this experimental research study, detailed technical analyzes were carried out on the use of modified expanded perlite and modified pumice aggregate components in the production of cement-bonded fiber reinforced boards and their effects on the physical, mechanical and thermal properties of the board, and the findings obtained are discussed comparatively. According to the test results;

1. The use of MEP and MPU was found to be a factor that lightens the plates compared to the control sample. The lowest density value was obtained in the CS1 mixture with 9% MEP by weight, and it is 34% lighter than the control sample.
2. It was observed that the water absorption values of the plate samples produced with aggregates coated to minimize water absorption properties decreased. When comparing CS0 and CS10 samples, a decrease of approximately 34% in water absorption was detected.
3. The average MOR value of CS0 sample is 3.73 MPa. The MOR value of CS10 mixture, with the highest MPU aggregate usage, is 3.51 MPa. This value is 5.9% lower than the control sample and provides the smallest limit value prescribed by the relevant standard.
4. The thermal conductivity value of the CS0 mixture is 0.352 W/mK. The thermal conductivity value of IBFCB mixtures with MEP and MPU varies between 0.175 W/mK and 0.287 W/mK. As the MEP ratio increases, the matrix structure becomes more insulating, and as the MPU ratio increases, the matrix structure becomes more conductive.
5. The specific heat value of the control sample was determined as 785 J/kgK. On the other hand, the highest specific heat value was determined in the CS1 sample and is Cp = 944 J/kgK.
6. The sensible heat storage ability of the control sample coded CS0 was determined as 1.04 J/m^{3}K. The lowest sensible heat storage ability belongs to the square with code CS1 and the highest MEP usage rate, and its value is 0.83 J/m^{3}K.
7. MEP addition having higher porosity creates an effect improving the thermal comfort efficiency. This efficiency reaches up to 21% in samples containing 9% MEP compared to control mixture.

The findings reveal significant improvements in providing valuable insights into the potential applications of these composite boards in thermal performance requirements. This research contributes to the ongoing efforts to develop sustainable and high-performance building materials with enhanced properties, offering potential solutions for environmentally conscious and resilient construction practices.

CONFLICT OF INTEREST

The authors stated that there are no conflicts of interest regarding the publication of this article.

CRediT AUTHOR STATEMENT

Lütfullah Gündüz: Writing-Original draft, Writing- Reviewing & Editing, Conceptualization, Methodology, Validation, Investigation, Resources. **Şevket Onur Kalkan:** Writing- Original draft preparation, Writing- Reviewing and Editing, Formal analysis, Visualization, Methodology.

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