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Research Article

The Effect of Expanded Glass and Expanded Clay Aggregate Additives on Water Vapor Diffusion Based on Wet Cup Method in Cementitious Lightweight Mortars for Sustainable Buildings

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ABSTRACT

Water vapor permeability is the ability of a material to allow vapor (such as water vapor or any gas) to pass through it. Water vapor permeability also indicates the breathability of the material. Water vapor permeability in building materials is an important factor that ensures that moisture formed in the interior of a building section can pass to the outside and that no damage occurs inside due to moisture. Water vapor permeability in cement-based building materials varies as a function of the structural properties of the material, and depends on porosity, aggregate characteristics, density and thermal effects, especially in the matrix structure. It is known that lightweight mortar combinations obtained by using porous aggregates are more prone to water vapor transmission. However, the extent to which the type and general form of the aggregate used in mortar mix designs affect this property requires a detailed examination. In this context, a series of cement-based composite mortar designs were created with samples of expanded glass and expanded clay aggregates with two different characteristic properties and in addition to physical and mechanical analyses, water vapor permeability properties were also comparatively investigated with respect to the control mortar sample. In the mixture designs, 32% of total aggregates were used as expanded glass-expanded clay lightweight aggregates. According to the study results, mixtures with expanded glass aggregates exhibited higher water vapor permeability properties than the test samples with expanded clay aggregates. Water vapor diffusion resistance coefficient values varied between 7.68 and 8.85 for the test samples with lightweight aggregates.

1. Introduction

Water and moisture problems are among the most important problems affecting the structure and human health. Water and moisture, which enter the structure in various ways, cause various problems in the structural elements and the interior environment. If both moisture and heat effects are seen in a structure, the building material is affected more and wears and deteriorates more quickly. Therefore, the concepts of moisture and heat cannot be examined separately. If cold air (which may be completely saturated with moisture) is heated, the amount of moisture in it decreases; thus, a drying process begins in the structure. If hot air cools, the danger of condensation water formation arises and if the freezing point of the air is exceeded, the situation can reach even more serious dimensions [1, 2].

Humidity is usually present in the air as water vapor. Evaporation from occupants and equipment can increase the humidity of the air inside a building. This water vapor turns into a liquid or condenses when the air it is in is completely saturated with all the vapor it can carry and reaches the dew point. Warm air has a higher dew point and a higher capacity to hold water vapor than cold air [1-3].

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Water vapor is formed after the vapor pressure decreases, and its direction can be in the opposite direction of the heat flow in extreme cases. Water vapor in the air is the main source of events that damage structural elements such as condensation, sweating and humidification. "Condensation", one of these concepts, is the condensation of some of the water vapor in the material and turning into water during diffusion due to different vapor pressures. In a structural element, a flow occurs between two environments with different vapor pressures, from the one with higher vapor pressure to the one with lower vapor pressure. The passage of vapor flow through the structures of materials due to this vapor pressure difference is called "diffusion" [2-5]. Sweating, on the other hand, is when there is a high difference between the temperature of the environment in an environment and the surface temperature of the surrounding structural element or material, some of the water vapor in the environment condenses near the surface of this structural element or material and turns into water. It is seen as water droplets on the surface. This event is called "sweating" [3, 4].

Water vapor, partial vapor pressure, which changes with temperature and relative humidity, encounters a resistance while moving from high to low. A 1 m² surface of building materials resists vapor diffusion depending on its thickness. The ratio of this resistance to the vapor diffusion resistance of the air is called the vapor diffusion resistance coefficient and is usually symbolized by "μ" [1-7]. The water vapor diffusion resistance factor characterizes how much the resistance of the material is compared to a stationary air layer of the same thickness and temperature under the same external environmental conditions. In other words, water vapor diffusion resistance expresses the amount of water vapor passing through a unit area in a unit time under certain temperature, humidity and thickness conditions of a material and indicates how many times more resistance any material shows compared to air. Water vapor permeability in new generation composite mortars can be defined in two different ways as "estimated value method" and "test method". In the estimated value method, the μ values stipulated in the TS EN 1745 standard are defined as an interval value for the unit volume mass value. This range value change is predicted as μ = 5- 20 for 250-1500 kg/m^3 and μ = 15 - 35 for 1600-2000 kg/m^3 [8].

The test method is, on the other hand, a method in which the water vapor permeability values of composite mortars are directly determined experimentally. This method is a definition based on experimental principles and the water vapor permeability of composite mortars can be determined according to the measurement and calculation methodology stipulated in the TS EN ISO 12572 standard [9]. Narloch et al. [10] conducted a research study aimed at determining the effect of cement addition on the water vapor resistance factor of stabilized compressed soil with a similar method. Soudani [11] examined the water vapor resistance factors of different building materials such as concrete, lime silica brick, solid brick, gypsum board, cellular concrete and lime plaster according to the dry cup and wet cup methods and analyzed the differences between two different measurement methods.

Pokorny et al. [12] designed a new generation of lightweight concretes containing waste aggregate as a suitable material for the repair of damp damaged walls. They measured the basic structural properties, mechanical resistance, water and water vapor transport properties of these concrete samples after 28 days of water curing and compared them with reference concrete values. They reported that the m values of the lightweight aggregate concrete samples were in the range of 14-99 according to the wet cup method depending on the density values. They also determined that the water vapor permeability values varied between 1.93-13.01 x10^{-12} (kg/m.s.Pa) [12]. Hall et al. [13] reviewed Water vapor permeability data on brick, stone, plaster and cement-based materials. They concluded that evidence indicates that the water vapor resistance factor decreases with increasing volume-fraction porosity, consistent with a simple porosity–tortuosity relationship. The data further demonstrate that the resistance factor declines as the mean relative humidity across the test specimen increases, with wet-cup measurements consistently yielding lower values

than those obtained using the dry-cup method for the same material.

Thermal conductivity, which expresses the ability of a material to conduct heat, is another important physical property that significantly influences building energy performance and indoor comfort. It depends on factors such as material density, porosity, and moisture content. In porous construction materials, higher moisture content generally increases thermal conductivity because water has a higher thermal conductivity than air. Therefore, water vapor permeability plays an indirect but important role in thermal conductivity behavior: materials with low vapor permeability are more prone to moisture accumulation, which can lead to increased thermal conductivity over time and reduced thermal insulation performance [14, 15].

Tuğla and Örgel [16] investigated the thermal properties of autoclaved aerated concrete (AAC) wall sections constructed with distinct mortars. They concluded that the thermal properties of walls made from different mortars, as well as the thermal variations within the walls caused by these mortars, could be identified using experimental data. However, it was found that theoretical data alone were inadequate for capturing these thermal differences.

Although these studies provide valuable data, there is still limited research focusing on the combined effects of expanded aggregate based materials and novel composite mortar formulations on water vapor permeability. Most existing studies evaluate either traditional building materials or lightweight concretes separately, without integrating expanded aggregates with performance-based permeability analysis.

The main objective of the present study is to investigate the water vapor permeability and vapor diffusion resistance of newly designed composite mortars incorporating expanded glass and expanded clay aggregate, using the standardized wet cup test method. The study aims to provide both practical design recommendations for sustainable building materials and reliable permeability data for future reference in the literature.

2. Materials and Methods

2.1.Materials used in test samples

In the preparation of cement-based expanded aggregate added lightweight mortar (CBEALM) test samples, CEM I 42.5 R type cement with an average specific gravity value of 3.0 g/cm³ was used as the main binding material. Quartz sand classified as 0-1 mm in size was used as the main aggregate material in the control mortar design, obtained from market conditions. The bulk density value of quartz sand was measured as 1430 ± 65 kg/m^3.

Using slaked lime in the production of cement-lime mortars has an effect that increases the adhesion of the mortar to the surface where it is applied and the bonding quality. In addition, it helps to minimize water penetration into the mortar and supports the development of moisture control in the application section. In this context, in the preparation of CBEALMtest samples, construction lime with an average bulk density of 600 kg/m^3 in powder form in CL-80-S norm was used by obtaining it from market conditions. The CaO+MgO composition of powdered lime is minimum 80% and the free water amount is maximum 2%. The CO_2 content is maximum 7% and the SO_3 content is maximum 2%. It is also considered that the lime hardens in the matrix structure as a result of the reaction with carbon dioxide in the air during the setting process of CBEALM test samples and provides added value to the general strength and durability value of the mortar.

Cellulose fibers are a type of additive that is preferably used due to their effect on the development of water vapor permeability properties of cement-based mortars with porous matrix structure [17]. In the preparation of CBEALM test samples, in order to prevent shrinkage of the mortar, minimize the risk of crack formation and at the same time increase workability, an environmentally friendly cellulose fiber obtained from 100% natural, renewable raw materials with an average length of 200 μm and an average fiber diameter of 20 μm compatible with cement binders was used by obtaining it from market conditions. The cellulose content of the fiber material used is

approximately 99.5% and the pH value (in 10% suspension) is between 5-7.5. The bulk density is between 120 - 160 kg/m^3.

In the preparation of CBEALM test samples, in order to provide the development of the strength value of the mortar and increase the adhesion value, a powder polymer based on vinyl acetate-Veova-acrylate and polyvinyl alcohol preservative compatible with cement binders at low film formation temperature was used as a polymer additive in all mixtures by obtaining from market conditions. The bulk density of the polymer additive is in the range of 450 - 600 kg/m^3 and the solid content is 98%-100%. The ash content is 10%-14% and it is in the form of white powder. It is generally used in Water insulation mortars, Joint fillers, Thermal insulation mortars, Polystyrene and Stone wool panel adhesive mortars, Ceramic, Granite adhesives, Repair mortars and gypsum based products.

Within the scope of the study, expanded lightweight aggregates of 2 different origins were used as additives in order to examine the performance changes in the design of CBEALMtest samples. These are: Expanded glass aggregate and expanded clay aggregate. As expanded glass aggregate, 2 different lightweight aggregates classified as 0-1 mm in equivalent sizes were used by obtaining from market conditions. The expanded glass aggregates provided were coded as EG-A and EG-B within the scope of the study. In the size distribution of both classified expanded glass aggregate samples, it was determined as 3.1% by weight for EG-A and 3.4% by weight for EG-B in the size range of 0-0.063 mm; 7.9% by weight for EG-A and 8.4% by weight for EG-B in the size range of 0.063 mm-0.125 mm; and 23.2% by weight for EG-A and 23.5% by weight for EG-B in the size range of 0.125 mm-0.500 mm. The remaining amounts were determined to be in the range of 0.500 mm-1 mm.
Since these weight percentage values are convergent, EG-A and EG-B aggregates were accepted to be in equivalent size ranges. EG-A aggregate is an ecological product produced by sintering recycled glass in a rotary kiln at temperatures between 750°C and 900°C (Figure 1). EG-A aggregate is a porous raw material that is non-toxic and free from hazardous substances, resistant to light and pressure, has a bulk density of <200 kg/m^3 and crushing resistance, is resistant to acids, alkalis and organic solvents and has dimensional stability up to 750°C. EG-B aggregate is an ecological product produced by sintering recycled glass in a rotary kiln at a temperature of 850°C to 950°C, similar to EG-A aggregate (Figure 2). EG-B aggregate is also a porous raw material that is non-toxic and free from hazardous substances, resistant to light and pressure, has a bulk density of <300 kg/m^3 and is resistant to crushing, has a sintered shell on the aggregate surface, is resistant to acids, alkalis and organic solvents and has dimensional stability up to 700°C.

Figure 1. General view of EG-A aggregate

Figure 2. General view of EG-B aggregate

Clays, clayey schists and shales that have a rapid sintering process and undergo a certain volume increase between 1100-1300ºC are generally called expanding clays. Today, they constitute an important raw material type in lightweight mortar production where high strength is desired. As expanded clay aggregate, 2 different lightweight aggregates classified as 0-1 mm in equivalent sizes were used by obtaining them from market conditions. The expanded clay aggregates provided were coded as EC-A and EC-B within the scope of the study. In the size distribution of both classified expanded clay aggregate samples, it was determined as 4.2% by weight for EC-A and 4.3% by weight for EG-B in the size range of 0-0.063 mm, 10.4% by weight for EC-A and 10.8% by weight for EC-B in the size range of 0.063 mm-0.125 mm and 25.1% by weight for EC-A and 25.4% by weight for EC-B

in the size range of 0.125 mm-0.500 mm. The remaining amounts were determined to be in the range of 0.500 mm-1 mm. Since these weight percentage values are convergent, EC-A and EC-B aggregates were accepted to be in equivalent size ranges. EC-A aggregate is a material produced by expanding special quality clays at 1150˚C.

The general appearance of EC-A and EC-B aggregate samples is given in Figure 3 and Figure 4. EC-A aggregate is a porous raw material with a bulk density of 485±40 kg/m^3, a water absorption rate of 11% and dimensional stability up to 825°C. Its aggregate strength is high and it has a form that can be used as lightweight aggregate in semi-load-bearing lightweight concrete productions. It has a distinct and hard sinter shell layer on the outer shell of the aggregate during the sintering process. On the other hand, EC-B aggregate is also a porous raw material with a bulk density of 565±50 kg/m^3, a water absorption rate of 13% and dimensional stability up to 840°C. Its aggregate strength is relatively higher than EC-A aggregate and it has a form that can be used as lightweight aggregate in semi-load-bearing lightweight concrete productions. It has a hard sinter shell layer of >15 µm on the outer shell of the aggregate during the sintering process.

Figure 3. General view of EC-A aggregate

Figure 4. General view of EC-B aggregate

Pure water, devoid of minerals, obtained by distilling normal tap water using boiling and cooling methods, was used as mixed water.

2.2. CBEALM mixture design and preparation of test samples

In order to analyze the effect of the amount of expanded glass and clay aggregate usage in cement-based mortar samples on the physical, mechanical and water vapor diffusion properties of the mortar, a control mortar design was first made that did not contain any expanded glass and/or clay aggregate additives in the mix design and was coded as CNT within the scope of the study. In this mix design, 32% cement, 3.8% slaked powdered lime, 62.85% quartz sand, 1.5% cellulose fiber and 1.2% powdered polymer additive were used by weight. In all prepared mixes within the scope of the study, the amounts of cement, powdered lime, cellulose fiber and powdered polymer additives were kept constant.

However, in order to examine the technical properties of the mortar, expanded glass and clay aggregate types were used in mix designs as replacements with quartz sand by weight. In all mortar designs with expanded aggregate additives, the replacement ratio with quartz sand was constant and was 32%. In all mix designs, the Aggregate/Cement ratio was kept constant and A/C=1. The amount of mixing water in determining the consistency of the mixtures was designed to have a spreading value of 155 mm for all mixtures, and the water/cement ratios were determined according to this spreading value. The materials used in the mixtures and their usage amounts are given in Table 1.

In the preparation of the mixtures, cement, quartz sand, powdered lime, cellulose fiber and polymer additives were weighed and blended in dry powder form and mixed with a low-speed mixer for an average of 3 minutes to ensure homogeneous powder mixtures. In mixtures containing expanded glass or clay aggregate, the amount of lightweight aggregate in the design was first weighed and the surface was moistened in a separate container, and then blended with other materials.

Afterwards, mixing water was added to the mixture at the determined fixed water/cement ratio and the mixing process was continued for 3 minutes until a homogeneous mixture was obtained.

Table 1. Mixture components of CBEALMtest samples (by weight)

Mixture	Cement (kg/m^3)	EG-A (kg/m^3)	EG-B (kg/m^3)	EC-A (kg/m^3)	EC-B (kg/m^3)	Slaked Lime (kg/m^3)	Quartz Sand (kg/m^3)	Cellulose Fiber (kg/m^3)	Polymer (kg/m^3)	W/C
CNT	414.0	-	-	-	-	49.2	813.2	1.94	15.53	1.34
EGA	128.7	128.7	-	-	-	15.3	124.0	0.60	4.83	1.16
EGB	139.9	-	139.9	-	-	16.6	134.9	0.66	5.25	1.09
ECA	156.6	-	-	156.6	-	18.6	151.0	0.73	5.87	1.25
ECB	172.6	-	-	-	172.6	20.5	166.4	0.81	6.47	1.13

The fresh mortar obtained was rested for approximately 5 minutes and mixed again for an additional 30 seconds, and then the wet mortar was made ready for molding the test samples and also for wet mortar measurements. The spreading values of the CBEALM samples belonging to each wet mortar design were first tested using the spreading table method in order to control the consistency evaluations. Then, all wet CBEALM samples were cast into steel cube molds with dimensions of 50 × 50 × 50 mm^3 and steel ring molds prepared in circular form. 15 cube-sized samples and 5 circular-formed ring-shaped samples were produced from each mixture design.

After casting, each of the samples was kept in the laboratory for 24 hours before removal from the mold, and the 1-day unit volume mass values of the test samples removed from the molds were measured and recorded. All samples removed from the mold were subjected to natural curing in an environment of 23±2°C until the test day. After 28 days, the samples whose curing was completed for the tests were first dried in a ventilated oven, the unit volume mass values were measured and recorded, and mass water absorption, apparent porosity and compressive strength analyses were performed on the cube test samples of each test sample under atmospheric conditions. Water absorption and apparent porosity values of the test specimens were determined according to the ASTM C20 Standard Test Methods for Measurements of Apparent Porosity and Water Absorption of Refractory Bricks and Shapes Fired with Boiling Water.

The test specimens were dried in a ventilated oven at 104–110°C to a constant weight of 0.1 g, and their dry weight (D) was determined. Then, all test specimens were boiled in water for 2 hours in a closed container. During the boiling process, the specimens were completely immersed in water and were not allowed to contact the bottom of the container. After the boiling period, the specimens were cooled to room temperature while completely covered with water and allowed to remain in the water for at least 12 hours after boiling before weighing the specimens. The weight (S) of each test specimen after boiling and while suspended in water was determined in grams, rounded to the nearest 0.1 g. After determining the suspension weight in this manner, each sample was lightly moistened to remove all water droplets from its surface, dried with a smooth cotton cloth, and weighed in air to determine the saturated weight value (W) in grams, rounding to the nearest 0.1 g. The apparent porosity and water absorption values of each test sample were calculated according to the calculation methodology prescribed in this standard.

The thermal conductivity properties of circular test samples were determined using a Quick Thermal Conductivity tester, which consists of a single heating wire and a thermocouple equipped with a box-type probe (sensor). The device operates in the measurement range of 0.023-12 ± 5% "W/mK" using the hot wire system. Before all experiments, the device was calibrated, and measurements were taken automatically for 60 seconds on each sample surface. Test measurements were carried out at an ambient temperature of 20°C-25°C with a tolerance of ±5°C. After each test sample measurement, the heated wire was placed on a cooling plate to reach the reference value for the next measurement.

Water vapor permeability analyses were also conducted using these circular test samples, prepared according to the principles stipulated in the TS EN ISO 12572 standard. Mortar consistencies of CBEALM mixtures prepared in

fresh wet form and representative images of circular test samples are given in Figure 5.

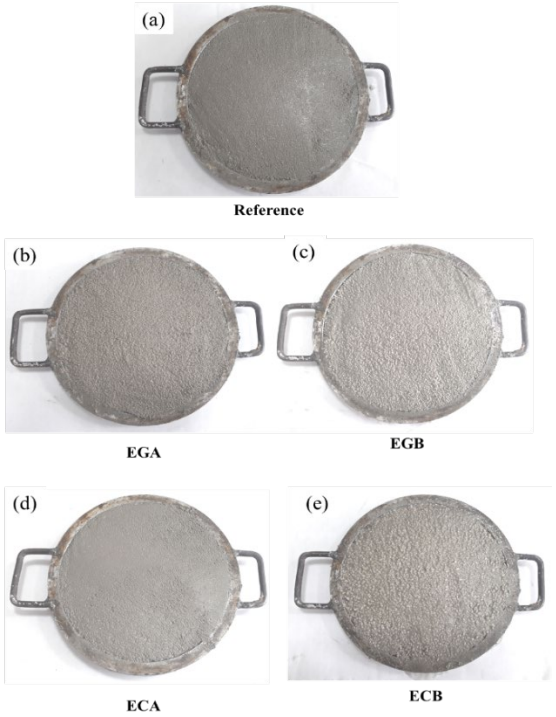

Figure 5. General views of CBEALM test samples

2.3.Determination of water vapor diffusion resistance coefficient of CBEALM samples

Water vapor diffusion resistance coefficient of cement-bound composite mortar products can be performed on samples taken from the hardened mortar form or on mortar samples poured into specially prepared test molds. Circular or square section composite mortar plate samples can be prepared for water vapor diffusion resistance coefficient analysis [9]. Symbolic test sample views are given in Figure 6. In this study, 150 mm diameter and 30 mm thick circular section mortar samples were prepared and used for the water vapor permeability analysis of CBEALMmixtures.

The TS EN ISO 12572 standard [9] was used as the primary standard in this study because it encompasses a test method based on container tests for determining water vapor transmission through building products and the water vapor permeability of building materials under isothermal conditions. It also allows measurements to be made using test sets for different test conditions.

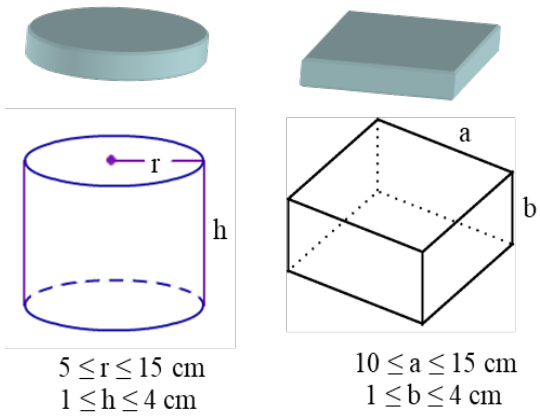

Figure 6. Symbolic test sample views for water vapor permeability analysis

Therefore, all tests, measurements, and calculations were performed according to the principles set forth in this standard. 3 samples of the same mixture were prepared for the test and these samples were dried in an oven environment until they reached constant weight. After the oven, they were stored in a desiccator without taking in moisture until they were placed in the test setup. In order to ensure that the moisture and vapor transfer in the high humidity environment of the test samples was represented, the wet cup "Wet Cup" method stipulated in TS EN ISO 12572 standard was applied. In this method, 94% concentration Potassium Nitrate (KNO_3) solution was prepared and placed in the test container.

This chemical solution tends to form vapor rapidly due to its characteristic and is based on the principle that the vapor formed in the test container passes from the body of the test sample to the external environment [9]. In other words, in the wet cup method, the vapor flow direction is the formation of a current from the solution compartment in the test container environment to the external surface. This phenomenon and a prepared test container are symbolically shown in Figure 7. As a result of such a vapor flow, the unit weight of the test sample will tend to decrease continuously over time in the measurement system. The initial unit weight of the test sample decreases over time according to the vapor permeability characteristic.

In vapor permeability tests performed using potassium nitrate (KNO_3) solution, more effective measurement results can be obtained, especially in composite mortar structures where porous materials are predominantly used, due to

the density of the vapor medium formed during the test process.

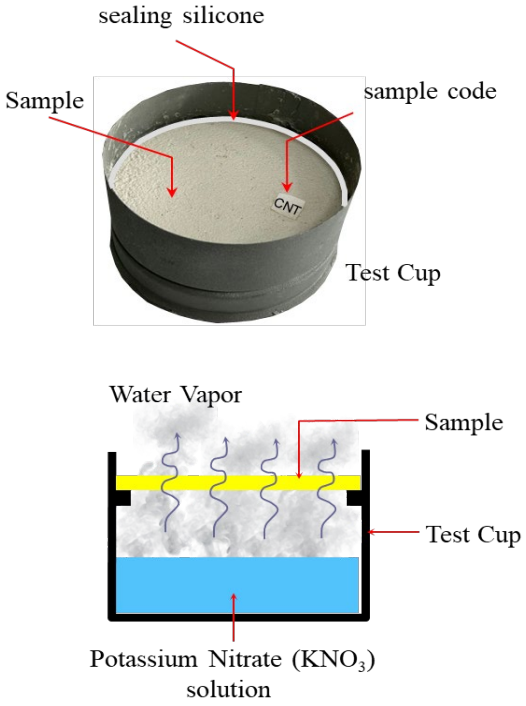

Figure 7. General principle of the wet cup method and symbolic representation of a test cup

Before starting the test and measurement systematic, the measurement time interval was defined in the test process. A period was calculated according to Equation 1 to determine the test measurement accuracy and measurement interval. This calculated period was then used as a time interval for reading values in all test measurements to be made. Periodically, measurement results were recorded according to this period [9].

$$t_1 = \frac{200 \times mp \times \mu \times d}{\delta_a \times \Delta P_v \times A \times X} \quad (1)$$

Where;

t_1 : Applicable test measurement range, s,
mp : Acceptable repeatable error, kg,
μ : Estimated water vapor diffusion resistance coefficient,
d : Sample thickness, m,
δ_a : Water vapor permeability of air, kg/m.s.Pa
ΔP_v : Water vapor pressure difference between environments, Pa,
A : Sample surface area, m^2,
X : Desired measurement accuracy, %.

Depending on this measurement interval time value, the prepared test samples were placed in the test environment setup according to the conditions stipulated in the standard, the weight change of each sample per unit time was measured and recorded, and the mass change depending on time was analyzed graphically [9] (Figure 8).

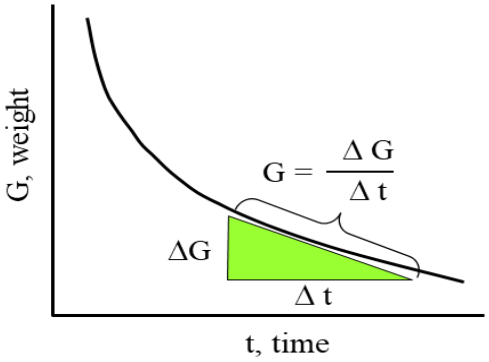

Figure 8. Analysis of weight change over time

With the findings obtained in this graphical analysis, the water vapor flow rate of the test sample was defined by determining the average slope value of the curve drawn as a linear function (ΔG/Δt), and the water vapor flow of the test sample was calculated with Equation 2 [9];

$$G = \frac{\Delta G}{\Delta t} \quad (2)$$

Where;

G : Water vapor flow, kg/s,
ΔG : Weight difference at steady state, kg,
Δt : Time difference at steady state, s,

Depending on the water vapor flow value and the sample surface area where the water vapor transmission of the test sample occurs, the "water vapor flow density" was calculated according to Equation 3 [9]:

$$g = \frac{G}{A} \quad (3)$$

Where;

g : Water vapor flow density, $kg/m^2.s$,
G : Water vapor flow, kg/s,
A : Sample surface area, m^2.

The water vapor permeability value of the test sample was calculated according to Equation 4 [9]:

$$W = \frac{G}{A \times \Delta P_v} \quad (4)$$

Where;

W : Water vapor permeability, kg/(m^2.s.Pa),
ΔP_v : Water vapor pressure difference between environments, Pa.

The water vapor permeability of the test sample was calculated according to Equation 5 [9].

$$\delta = W \times d \quad (5)$$

Where;

δ : Sample water vapor permeability, kg/m.s.Pa,
W : Water vapor permeability, kg/m^2.s.Pa,
d : Sample thickness, m.

According to all these calculations and evaluations made respectively, the water vapor diffusion resistance coefficient "μ" of the test sample was calculated according to Equation 6 [9].

$$\mu = \frac{\delta_a}{\delta} \quad (6)$$

Where;

μ : Sample water vapor diffusion resistance coefficient,
δ_a : Air water vapor permeability, kg/m.s.Pa,
δ : Sample water vapor permeability, kg/m.s.Pa.

3. Results and Discussion

Some technical findings obtained from the composite mortar samples designed based on cement within the scope of the study are given in Table 2.

Table 2. Some technical findings of cement based designed composite mortar samples

Mix	Fresh Mortar Density (kg/m^3)	Hardened Mortar Density (g/m^3)	Consistency (mm)	Compressive Strength (28 days) (N/mm^2)	Apparent Porosity (%)	Water Absorption by Mass at Atmospheric Environment (%)	Thermal Conductivity (W/mK)	Thermal Resistance (mK/W)
CNT	2082	1559	155	3,91	8,2	13,60	0,937	1,07
EGA	631	488	155	1,33	23,3	8,14	0,134	7,49
EGB	674	527	155	1,67	21,4	7,67	0,150	6,67
ECA	777	590	155	1,88	26,4	9,21	0,200	5,00
ECB	826	639	155	1,97	23,7	8,37	0,201	4,97

3.1.Unit volume mass analysis

The unit volume mass value of the CNT coded control mortar sample after 28 days of setting was determined as 1559 kg/m^3 on average. The unit volume mass value of the mortar samples belonging to all mixture designs with expanded aggregate additives is lower than the control sample value, and the unit volume mass values of the mortar samples with expanded aggregate additives are given in Figure 9. The unit volume mass values of the expanded glass aggregate mortar samples with EGA and EGB codes are 488 and 527 kg/m^3 on average, respectively. According to the unit volume mass value of the expanded aggregate-free reference mortar samples prepared in the study, density decreases of 69% and 66% were obtained, respectively, and it has a lighter material structure compared to the control sample. The low unit density value of the expanded glass aggregate used in the mixture design also reduced the density of the mortar in which this material was used as an additive, making it lighter. The lightening of the mortar material due to porosity can be evaluated as a parameter that will provide significant advantages, especially in terms of water vapor permeability performance.
In this study, similarly, the unit volume mass values of the expanded clay aggregate mortar

samples with ECA and ECB codes are 590 and 639 kg/m^3 on average, respectively. These density values also provided a 62% and 59% lightening, respectively, compared to the density value of the reference mortar samples. Again, these density values can be considered to represent more effective values in terms of water vapor permeability performance from a technical perspective. Pokorny and his friends [12] in their study defined the density limit for lightweight concrete as 1800 kg/m^3 and emphasized that the water vapor diffusion resistance value of concrete and mortar mixtures with densities lower than this limit value changes. They stated that as the concrete density becomes lighter, the water vapor diffusion resistance value also decreases, thus improving water vapor permeability. For example, they reported the average concrete density as μ=14 for 800 kg/m^3, μ =21 for 1200 kg/m^3, μ =30 for 1400 kg/m^3, and μ =57 for 1700 kg/m^3.

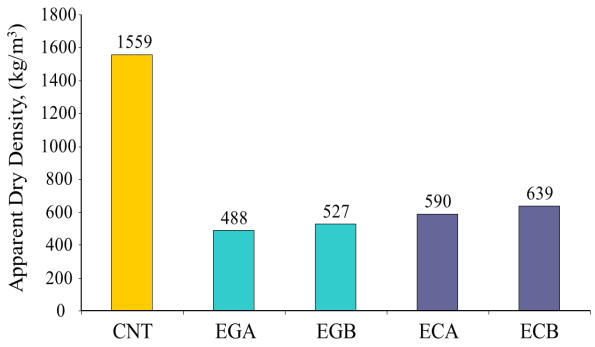

Figure 9. Unit volume mass values of mortar samples

3.2.Compressive strength analysis

The compressive strength of the CNT coded control mortar sample after 28 days of setting was determined as 3.91 N/mm^2 on average. The compressive strength value of the mortar samples belonging to all mixture designs with expanded aggregate additives is lower than the value of the control sample, and the compressive strength values of the mortar samples with expanded aggregate additives are given in Figure 10.

As seen when Figure 10 is examined, the compressive strength values of the expanded glass aggregate mortar samples coded EGA and EGB are 1.33 and 1.67 N/mm^2 on average, respectively. Compared to the compressive strength value of the reference mortar samples prepared in the study without expanded aggregate, 66% and 57% strength decreases were obtained, respectively.

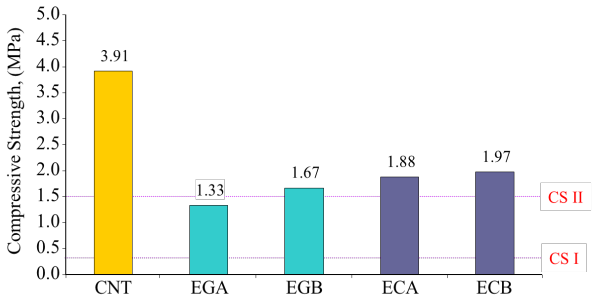

Figure 10. Compressive strength values of mortar samples

The reason for this decrease in the compressive strength value of the mortar is the porous structure of the expanded glass aggregate used as a replacement with quartz sand in the mixture design, the low aggregate density and also the brittle characteristic structure of the aggregate in the glassy phase after the expansion process were evaluated as the main factors. In addition, the compressive strength values of the expanded clay aggregate samples coded ECA and ECB are 1.88 and 1.97 N/mm^2 on average, respectively. According to the compressive strength value of the reference mortar samples, strength decreases of 52% and 50%, respectively, were obtained in these samples as in the glass aggregate samples.

However, when considered in terms of the magnitude of the compressive strength values, the strength values of the expanded clay aggregate mortar samples were obtained greater than the values of the expanded glass aggregate samples. When examined within the limits predicted for 28-day compressive strength values of cement-based composite mortars within the scope of TS EN 998-1 standard [18]; the control mortar is included in class CS III according to this standard (3.91 N/mm^2 ≥ 3.5 N/mm^2 _CS III class). Mortar samples with EGA code are included in class CS I according to this standard (1.33 N/mm^2 ≥ 0.4 N/mm^2 _CS I class). However, mortar samples with codes EGB, ECA and ECB are included in CS II class according to this standard (≥ 1.5 N/mm^2 _CS II class). In this context, although a decrease in the strength of mortar samples with expanded glass and clay aggregates was obtained, it is understood that they have technically applicable design values

since they meet the 28-day compressive strength limits of the TS EN 998-1 standard [18].

3.3.Water vapor permeability analysis

Water vapor diffusion resistance is evaluated as a measure of how resistant materials are to the passage of water vapor. A low water vapor diffusion resistance means that the material prevents the movement of water vapor better. In contrast, a high water vapor diffusion resistance makes it more difficult for water vapor to pass through the material. Water vapor moves from a high partial vapor pressure to a low one, depending on the temperature and relative humidity of the environment where the material is used. It also encounters resistance during this process. Each material resists vapor diffusion depending on its thickness. If water vapor passes completely through the material, it is expressed as μ=1 [19]. If it does not pass through the material, it is expressed with numbers much larger than 1. The larger this value, the more vapor impermeable the material is.

Materials with μ=10,000–100,000 are generally called "vapor barriers". It is important to consider this value when selecting insulation materials [19]. Narlock et al. [10] reported a water vapor resistance factor of 16.6 for unstabilized compacted soil composed of different soil mixtures. With the addition of 9% cement, water vapor resistance factors ranging from 27.9 to 31.8 were obtained, depending on the soil particle size. They reported a nearly linear relationship between the cement addition and the water vapor resistance factor. Pokorný and colleagues [12] determined that water vapor permeability properties measured on concrete with different silica sand and lightweight aggregate ratios, obtained for both dry and wet cup configurations, were in the range of 14-57. They reported that partial or complete replacement of natural aggregate with artificial lightweight aggregate resulted in a gradual increase in both water vapor permeability and water vapor diffusion coefficient, and a decrease in the water vapor resistance factor [12].

A closer look at the data obtained in this study clearly reveals the differences between the dry and wet cup methods [12]: With a 25% by weight replacement of natural aggregate with artificial lightweight aggregate, the vapor diffusion resistance was reported to be 66 according to the dry cup method and 57 according to the wet cup method. Similarly, with a 75% by weight replacement of natural aggregate with artificial lightweight aggregate, the vapor diffusion resistance was reported to be 24 according to the dry cup method and 21 according to the wet cup method. In test samples using fully artificial lightweight aggregate, the vapor diffusion resistance was 16 according to the dry cup method, while the vapor diffusion resistance was 14 according to the wet cup method.

This study shows that the wet cup method provides higher vapor diffusion resistance values [12]. The post-setting water vapor resistance factor of the CNT coded control mortar sample was determined as 17.20. However, the post-setting water vapor resistance factor values of the mixture designs prepared with quartz sand and expanded aggregate added with 32% replacement by weight in the mixture combinations differ considerably from the control sample value. The water vapor resistance factor values of all mortar combinations prepared within the scope of the study are given as average values in Figure 11.

While the water vapor resistance factor of the expanded glass aggregate mortar samples with EGA code was determined as 8.20 on average, the water vapor resistance factor of the expanded glass aggregate mortar samples with EGB code was determined as 8.85 on average. These values show that the expanded glass aggregate addition to the composite mortar composition provided 52.3% and 48.5% higher water vapor permeability compared to the control sample, respectively, in terms of the characteristics of the aggregate.

Similarly, the water vapor resistance factor of the expanded clay aggregate mortar samples with ECA code was determined as 7.68 on average, while the water vapor resistance factor of the expanded clay aggregate mortar samples with ECB code was determined as 7.96 on average. These values show that the expanded clay aggregate addition provided 55.3% and 53.7% higher water vapor permeability to the composite

mortar composition compared to the control sample, respectively. It was observed that expanded clay aggregates exhibited a more effective performance in terms of water vapor permeability compared to the use of expanded glass aggregate.

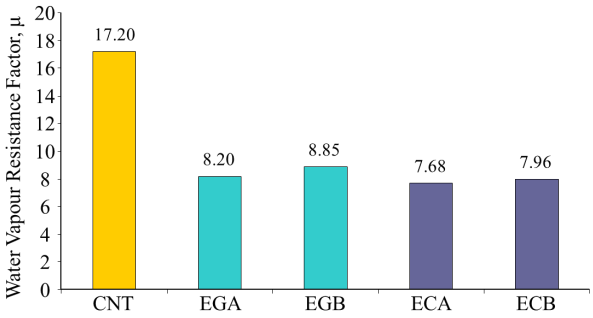

Figure 11. Average water vapor resistance factor values of mortar samples

It was observed in the examination findings that the compressive strength values and also the thermal resistance values of the mortar samples after 28 days of curing affected the structural properties of the mortar as well as the change in the water vapor resistance factor. In this context, the increase in the compressive strength of the composite mortar also affects the increase in the water vapor resistance factor (Figure 12). The decrease in the porosity rate in the matrix structure due to the increase in the compressive strength of the mortar weakens the development of water vapor diffusion. This causes an increase in water vapor resistance. The fact that the mortars with expanded glass and/or clay aggregate additives have lower compressive strength compared to the control mortar showed the development of vapor permeability properties.

The graphical relationship between the thermal resistance values of the control mortar, expanded glass and expanded clay aggregate added mortar samples after 28 days of curing and the water vapor resistance factor is given in Figure 13. Compared to the thermal resistance value of the control mortar, the thermal resistance of the expanded glass aggregate added mortars increased by approximately 6.5 times, while their water vapor diffusion resistance decreased by an average of 2 times.

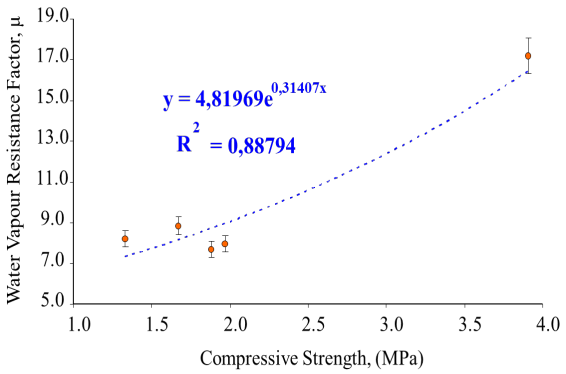

Figure 12. Compressive strength of mortar samples - water vapor resistance factor relationship.

On the other hand, the thermal resistance of the expanded clay aggregate added mortars increased by approximately 4.7 times, while their water vapor diffusion resistance decreased by an average of 2.2 times. It is seen that as the structural form of the composite mortar gains thermal resistance, its water vapor diffusion property improves. In other words, as the structural form of the composite mortar gains a heat insulating property, its water vapor diffusion resistance value decreases. This represents a higher comfort property for an insulating material.

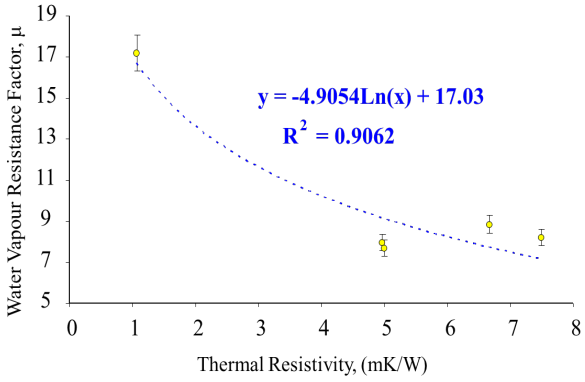

Figure 13. Thermal resistance of mortar samples - water vapor resistance factor relationship

Water vapor permeability (δp) is evaluated as a measure of the behavior of a material in moisture transmission, in other words, the amount of water vapor passing through a unit surface of the material in unit time when there is a difference in unit vapor pressure for a sample with unit thickness. The δp value of the control mortar sample coded CNT after setting was determined as $1.13x10^{-11}$ (kg/m.s.Pa). The post-setting δp values of the expanded aggregate added mixture designs prepared with 32% replacement by

weight with quartz sand in the mixture combinations have higher vapor permeability than the control sample. While the δp value of the expanded glass aggregate mortar samples coded EGA is 2.377x10^{-11} (kg/m.s.Pa), the δp value of the expanded glass aggregate mortar samples coded EGB is 2.191x10^{-11} (kg/m.s.Pa). The expanded glass aggregate additive increased the water vapor permeability of the mortar by 110% and 94%. Similarly, the δp value of the ECA coded expanded glass aggregate mortar samples was 2.526x10^{-11} (kg/m.s.Pa), while the δp value of the ECB coded expanded glass aggregate mortar samples was 2.436x10^{-11} (kg/m.s.Pa). The expanded clay aggregate additive also increased the water vapor permeability of the mortar by 124% and 116%. These increase rates obtained for each expanded aggregate type were determined to be an important factor due to the apparent porosity value of the composite mortar matrix structure depending on the structural form of the aggregate (Figure 14).

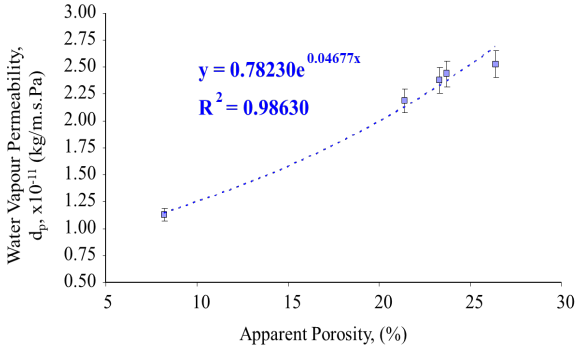

Figure 14. Apparent porosity - δp values relationship of mortar samples

As can be seen when Figure 14 is examined, as the apparent porosity of the matrix structure of the mortar increases, the water vapor permeability also increases. The main factors that are effective here are the presence of interconnected porous transitions between the pores of the aggregate and the presence of micro and/or semi pores in the matrix structure, which provide a higher possibility for the passage of this vapor. In the microscopic structural examinations, as the pore diameters increase or the presence of low-diameter pores in the matrix structure at a high rate, water vapor permeability becomes more possible. Another examination conducted on mortar samples was the determination of the water vapor diffusion flow density. This parameter indicates the amount of water vapor passing through the unit surface of the material in unit time and is generally expressed in the unit of (g/m^2.h). The greater the amount of water vapor transferred from the material body in unit time, the higher the diffusion property of those materials. It is important in determining the use of healthier products in terms of moisture control in material usage areas in the construction sector.

In this context, the post-setting water vapor diffusion flow density value of the control mortar sample coded CNT was determined as 1.93 g/m^{2}h. The post-setting water vapor diffusion flow density values of the mixture designs with expanded lightweight aggregate additives allowed higher amounts of water vapor transfer from the material compared to the control sample. The water vapor diffusion flow density values of the expanded glass aggregate mortar samples coded EGA and EGB are 3.90 and 3.62 g/m^{2}h, respectively. The expanded glass aggregate additive increased the water vapor diffusion flow density of the mortar by 102% and 88%. Similarly, the water vapor diffusion flow density values of the expanded glass aggregate mortar samples coded ECA and ECB are 4.13 and 3.99 g/m^{2}h, respectively. The expanded clay aggregate additive increased the water vapor diffusion flow density of the mortar by 114% and 107%. These increase rates obtained for each expanded aggregate type were analyzed by relating them to the water absorption values of the composite mortar by mass under atmospheric pressure after setting, depending on the structural form of the aggregate (Figure 15).

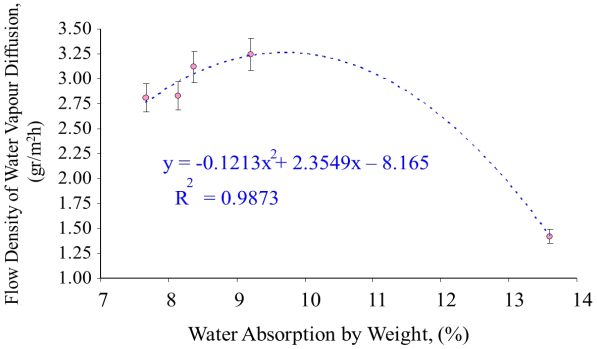

Figure 15. Water absorption - water vapor diffusion flow density relationship of mortar samples

When Figure 15 is examined, when the water absorption rate by mass increases up to 10.5%, the water vapor diffusion flow density of the mortar increases and it is seen that it exhibits a performance that allows more water vapor to pass through the body. However, it is seen that the performance of the material matrix in terms of water vapor diffusion flow density decreases when the water absorption rate by mass reaches a value greater than >10.5%. The finding obtained here is due to the fact that the water absorption values of expanded glass and expanded clay aggregate materials are very low under normal conditions.

A similar phenomenon may not be seen for materials of different origins that will be equivalent to the porosity and bulk density values represented by these aggregate types. The sinter shell formed during the expansion process in the outer shell parts of the expanded aggregates used within the scope of the study makes the aggregate surfaces resistant to water absorption and the water absorption rates are at low values. However, it was also seen that the resistance of these sinter shells against water absorption is not equivalent to water vapor diffusion. In other words, it was observed that the sinter crust formations on the aggregate surfaces were formed in a form that allowed vapor transmission.

4. Conclusion

This study investigated the effects of using expanded glass and expanded clay aggregates on the water vapor permeability of cement-based composite mortars. Findings obtained as a result of the study:

1. The use of lightweight aggregates significantly reduced the unit volume mass of cement-based mortars, resulting in lighter materials with improved thermal insulation properties.

2. Compressive strength decreased compared to the control mortar due to the porous nature, low density, and brittle characteristics of the lightweight aggregates. However, the 28-day compressive strength limits specified in the TS EN 998-1 standard [18] were met, confirming the suitability of the mortars for practical applications.

3. In terms of water vapor permeability, mortars containing expanded clay aggregates exhibited higher vapor permeability compared to those with expanded glass aggregates.

4. Water vapor diffusion resistance coefficient (μ) values ranged between 7.68 and 8.85 for mortars with lightweight aggregates, indicating an enhancement in the breathability of the material.

5. Thermal resistance increased approximately 6.5 times for mortars with expanded glass aggregates and 4.7 times for those with expanded clay aggregates compared to the control mortar, providing advantages in terms of energy efficiency.

6. The water vapor diffusion flow density of mortars with lightweight aggregates showed a significant increase compared to the control sample. Expanded clay aggregates facilitated vapor diffusion more effectively than expanded glass aggregates.
7. Increased porosity contributed to improved water vapor permeability. The interconnected pores between the aggregate and the matrix structure enhanced vapor transmission.

Future studies can investigate the long-term durability of these mortars under different environmental conditions to assess changes in vapor permeability and mechanical properties over time.

Article Information Form

Authors' Contribution

Conceptualization, L.G.; methodology, L.G.; validation, L.G. and Ş.O.K.; formal analysis, L.G. and Ş.O.K.; investigation, L.G. and Ş.O.K.; resources, L.G.; data curation, L.G. and Ş.O.K.; writing—original draft preparation, L.G. and Ş.O.K.; writing—review and editing, L.G. and Ş.O.K.; visualization, L.G. and Ş.O.K.; supervision, L.G.; All authors have read and agreed to the published version of the manuscript.

The Declaration of Conflict of Interest/ Common Interest

No conflict of interest or common interest has been declared by authors.

Artificial Intelligence Statement

No artificial intelligence tools were used while writing this article

Copyright Statement

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