Review Paper

Fire resistance of composite made with waste cardboard, gypsum, pumice, perlite, vermiculite and zeolite

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Abstract

In this study, the fire resistance of composites made by waste cardboard, gypsum, pumice, perlite, vermiculite and zeolite is investigated. The bulk density, water absorption rate, thermal conductivity and ultrasound transmission velocities of the samples were determined. The results showed that these composites had very low thermal conductivity and ultrasound transmission velocity. Furthermore, the longest burning time was obtained from triple mixtures. On the other hand, the shortest burning time happened to be for dual mixtures, particularly those with gypsum and perlite. Finally, it was concluded that composites obtained by dual, triple mixtures of waste cardboard, gypsum, pumice, perlite, vermiculite and zeolite provided enough resistance to fire and retarded burning.

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Graphic abstract

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1 Introduction

Fire is the most important development that has reached from the ancient times of humanity until present time. For 4000 years, humans have shaped fire mines and as long as they could keep fire under control, they benefitted from its presence. Great fires took place in the past when fire could not be controlled and citywide devastations occurred. More important than the monetary and materialistic losses caused by fires are their disruptive effects on the human, animal and plant lives and the environmental balance in the geographic area where they occur.

As a result of the faster vibration of atoms during fires materials expand due to the increase between the atoms to change. Thus, fire causes materials their forms such as melting or softening. The heat energy that will arise with increasing temperature during the fire will change the internal structure of the material whether crystalline like in metals and stones or plastic like in zeolite or amorphous like in concrete and ceramic. As a result internal stresses, cracks form, and some kind of dissolution takes place depending on the temperature reached by fire. Fire is a natural disaster that takes place as the combustion reaction during the merger of materials with oxygen and heat at the same time. It is a chemical event, which enhances the heat energy more and more.

Fires are defined in the following classes: Class A Fires—they are solid matter fires. Removing the flammable substances and cooling extinguishes them. Class B Fires—flammable liquids fall into this class. They are quenched by cooling and choking. Class C Fires—they are caused by the combustion of various flammable gases such as liquefied petroleum gas, air gas and hydrogen. Class D fires—they are caused by the combustion of flammable light metals and alloys. Dry chemical powders are used to extinguish them. When a material begins to burn, temperature rises and if the stuff is burnable itself, its combustion temperature being exceeded the fire is enhanced.

There are extremely negative effects of fires on living organisms and environmental balance, in addition to material damage in the geographical area where the fire occurs. One of the basic requirements of humans is safety against fire. Fire is one of the most important events that threats human life and safety. For example, the US, Canada and England are the top three countries using the most energy per capita in the world and, according to statistics, they have higher annual loss of life due to fires than all other countries. Thus, as long as technology advances and developments occur in industrial area, more and more fire events are going to occur. Therefore, both national and international fire safety measures must continually be revised and improved. More fire-resistant material production is one of the most important measures. Besides the material of the load-bearing members, the fire performance of the materials of other components must also be considered [1].

Number of studies concerning the improvement of the fire-resistances of building materials have increased in recent years. Using lightweight materials such as slag, perlite, and pumice instead of quarts and sandstone will improve the fire-resistance property of structures [2]. The burning speed of the outer walls in buildings with length and width open to streets must be 1 h and that in buildings with no face open to streets must be at least 2 h. In order to ensure these periods, the thicknesses should be determined sufficiently according to the demanded combustion time between the structural members and various refractory filling materials should be used. For example, for a temperature of 800 °C with 1-h duration, diatomite of 5.3 cm thickness, vermiculite of 3.8 cm thickness or furnace stone of 4.3 cm thickness are sufficient. For a temperature of 1000 °C with 4 h duration perlite of 12.5 cm thickness, diatomite of 12 cm, vermiculite of 8 cm, pumice of 9.2 cm or stone, glass wool slab are sufficient [3–5].

2 Materials and method

2.1 Materials

2.1.1 Waste cardboard

The main raw material in this study is wood. Wood is derived from coniferous or sandarac trees. An important raw material of paper is waste cardboard. Any kind of disposable paper and cardboard is called waste paper. Consumption of paper and cardboard is increased due to rapid population growth, development of comfortable living conditions, urbanization, improving education quality of community and underdeveloped packaging industry [6, 7].

2.1.2 Gypsum

In the present work, powder form of gypsum is used.

Fig. 1 Materials used

Table 1 Physical properties of materials used

Materials	Specific gravity (g/cm^3)	Blaine (cm^2/g)	Sieve analysis (%)	
			Residue on 90 µm	Residue on 200 µm
Gypsum	2.24	2300	0.06	0.4
Pumice	1.870	2500	0.05	0.6
Perlite	0.678	2400	0.06	0.5
Vermiculite	0.455	2600	0.03	0.7
Zeolite	2.183	2600	0.05	0.3

2.1.3 Pumice

Pumice is a volcanic rock formed as a result of volcanic events. It is cavernously, lightweight, glassy and durable against physical and chemical effects. It involves a high rate of isolated small pores, contains 50% moisture water, gets rather hard when it turns into powder form has adequate compressive strength and heat and sound insulation properties. Pumice can be in the form of an acidic or basic compound [8]. The basic pumice used in the present work is obtained from Osmaniye region. Turkey has extensive deposits of pumice. The vast majority of pumice reserves are in East and Central Anatolia regions, especially in the cities of Bitlis, Van, Kayseri, Nevsehir and Agri. Besides these reserves, there are also some reserves in the Aegean and Mediterranean regions [9, 10].

2.1.4 Perlite

Perlite is a construction material, which has an important function, especially in building sector. It involves about 74% SiO and 15% Al_2O_3 [9]. It is a substance of volcanic character. The most important feature of perlite is that

Table 2 Chemical and physical properties of materials used

Materials	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Crystal water	FeO
Gypsum	–	–	–	–	–	42.8	19.4	–
Pumice	43.60	14.80	12.60	9.80	8.90	–	–	–
Perlite	67.12	11.81	3.73	1.23	0.16	–	–	–
Vermiculite	44.34	12.43	13.56	–	12.15	–	–	2.34
Zeolite	67.15	11.81	1.49	2.18	1.15	–	–	–

Table 3 Mix proportions (g)

Samples	Cardboard	Gypsum	Pumice	Perlite	Vermiculite	Zeolite	Water
CG10	200	20	–	–	–	–	25
CG20	200	40	–	–	–	–	25
CG30	200	60	–	–	–	–	25
CPU10	200	–	20	–	–	–	25
CPU20	200	–	40	–	–	–	25
CPU30	200	–	60	–	–	–	25
MPE10	200	–	–	20	–	–	25
CPE20	200	–	–	40	–	–	25
CPE30	200	–	–	60	–	–	25
CV10	200	–	–	–	20	–	25
CV20	200	–	–	–	40	–	25
CV30	200		–	–	60	–	25
CZ10	200	–	–	–	–	20	25
CZ20	200		–	–	–	40	25
CZ30	200	–	–	–	–	60	25
CG10Z10	200	10	–	–	–	10	25
CG20Z20	200	20	–	–	–	20	25
CPU10V10	200	–	10	–	10	–	25
CPU20V20	200	–	20	–	20	–	25
CPE10V10	200	–	–	10	10	–	25
CPE20V20	200	–	–	20	20	–	25

it is very light in weight. Perlite is 50% lighter in weight compared to its alternative substances and mixtures, as a building material. Perlite used in this work was obtained from Nigde in the size of cement.

2.1.5 Vermiculite

Vermiculite is a mineral derived from volcanic magma. Processing at high temperatures it expands, its bulk density decreases noticeably and its permeability increases. It is a clay mineral compound of formed by natural wear of mica. Vermiculite used in this work was obtained from Sivas Yıldızeli.

2.1.6 Zeolite

Zeolites are formed as a result of several reactions of some minerals containing alumina and silica. Zeolites are micro-pore crystalline solids containing aluminum, silica and oxygen in their lattice structures and cations and water in their pores. Atoms of silica and aluminum are connected to each other in tetrahedral form, thanks to the common oxygen atom. Zeolite of cement size used in this study was obtained from Manisa Gördes. Zeolites are aluminum silicates of alkaline and earth alkaline elements having a crystalline structure. The images of materials used in present study is given in Fig. 1. The physical properties of the materials used in this research are given in Table 1 and their chemical contents in Table 2.

Table 4 Unit weight and water absorption values

Samples	Unit weight (g/cm^3)	Water absorption (%)
CG10	1.48	78
CG20	1.51	71
CG30	1.65	68
CPU10	1.69	81
CPU20	2.15	76
CPU30	2.24	63
CPE10	1.62	73
CPE20	1.68	69
CPE30	1.77	61
CV10	1.79	74
CV20	1.35	45
CV30	1.56	44
CZ10	2.49	42
CZ20	2.88	47
CZ30	3.57	55
CG10S10	1.51	51
CG20Z20	1.88	45
CPU10V10	2.02	56
CPU20V20	1.25	41
CPE10V10	1.44	36
CPE20V20	1.64	30
CPU5PE5V5	1.35	26
CPU10PE10V10	1.42	22
CPU5PE5Z5	1.39	25
CPU10PE10Z10	1.45	21
CPU5PE5V5Z5	1.25	18
CPU7.5PE7.5V7.5Z7.5	1.35	15

2.2 Method

2.2.1 The preparation of mixtures

The contents of composite mixtures are given in Table 3. The coding used is as follows: waste cardboard (C), gypsum (G), pumice (PU), expanded perlite (PE), vermiculite (V) and zeolite (Z). At first, waste cardboard sheets were kept in water for 24 h to provide their softening. Samples having dimensions 16 × 16 × 4 cm were prepared according to the rates given in Table 3. Mixtures were made in a mixer and they were compressed by 10 bar.

2.2.2 Specific bulk density and water absorption rate

Specific bulk densities of produced samples were made according to TS EN 2823 and their water absorption rates according to 67-03, ASTMC.

2.2.3 Ultrasound transmission velocities and thermal conductivity coefficients

The ultrasonic wave velocity was determined by measuring the time needed for the sound waves, created by an ultrasonic test device, to be transmitted from one face of the sample to the other. Obtain the relation of the calculated ultrasonic wave velocity, compressive strength of the material and other properties can approximately [10]. Wave velocity is calculated using the following formula:

$$V = (S/t) \cdot 10^6$$

where V = wave velocity (km/h), S = surface area of the material used (cm^2) and t = the distance between the surfaces. Mutual smooth surfaces of the samples used in this test and the two caps of the pundit device were greased. The two caps were fixed on the surfaces of the sample and then readings were made from the pundit device [10]. The smallest of these readings was taken for each sample and the ultrasound velocity was determined with the formula above.

2.2.4 Determination of fire resistance

The determination of the fire resistance of the produced material was made at different temperatures in the muffle furnace according to ASTM-E 60-50 [11].

2.2.4.1 Cautery in muffle furnace After curing, the samples were exposed to 75, 100, 125 and 150 °C for 10 min. Weight changes of the samples were determined at high temperatures.

Table 5 The ultrasound transmission velocities and thermal conductivity coefficients

Samples	Ultrasound transmission velocities (km/sn)	Thermal conductivity coefficients (w/mK)
CG10	0.39	0.1061
CG20	0.31	0.1023
CG30	0.25	0.1002
CPU10	0.64	0.0194
CPU20	0.61	0.0135
CPU30	0.59	0.0985
CPE10	0.65	0.0199
CPE20	0.62	0.0145
CPE30	0.68	0.0933
CV10	0.68	0.0205
CV20	0.66	0.0195
CV30	0.63	0.0167
CZ10	0.69	0.0096
CZ20	0.76	0.0078
CZ30	0.73	0.0045
CG10S10	0.78	0.0673
CG20Z20	0.75	0.0071
CPU10V10	0.72	0.0068
CPU20V20	0.75	0.0065
CPE10V10	0.71	0.0055
CPE20V20	0.78	0.0051
CPU5PE5V5	0.79	0.0064
CPU10PE10V10	0.83	0.0068
CPU5PE5Z5	0.86	0.0071
CPU10PE10Z10	0.97	0.0058
CPU5PE5V5Z5	1.05	0.0051
CPU7PE7V7Z7	1.14	0.0044

2.2.4.2 Fire resistance according to ASTM E 160-50 The combustion experiments were carried out according to ASTM E 60-50. Before cautery, samples were kept in the air conditioning room where the temperature was 27 ± 2 °C and relative humidity was 30 ± 5% until they reached 7% moisture. 24 samples were burned being put in the form of a square prism in 12 layers. Gas pressure was kept at 0.5 kg/cm^2 constant value during the operation.

3 Test results and discussion

3.1 Unit weight and water absorption rates

Unit weights and water absorption rates of samples are given in Table 4. As unit weights of insulating materials produced by pumice, perlite, vermiculite and zeolite get lower their water absorption rates get higher. Especially unit weights of the composites produced as triple and quadruple mixtures were found to be larger than dual mixtures. With an increase in the additive ratio, composites produced with pumice, perlite, vermiculite and zeolite as triple and quadruple mixtures got higher bulk density values, whereas, lower water absorption rates.

On the other hand, in the case of composites with gypsum, as the additive ratio increased both the bulk density value and the water absorption rate increased. This situation can be explained by the structure of gypsum. The lower water absorption rates in the composites produced as triple and quadruple mixtures are due to the filler effect of those minerals in the composite. Thus, due to the decrease in the void ratio water absorption rate decreases.

3.2 Ultrasound transmission velocities and thermal conductivity coefficients

Ultrasound transmission velocities and thermal conductivity coefficients are given in Table 5. According to both the Turkish and the international standards, for a material to be defined as an insulation material, its thermal conductivity coefficient must be smaller than 0.1 W/mK. When Table 5 is examined, it can be seen that all samples other than CG10, CG20 and CG30 are acceptable as insulation materials. This can be explained by the many connected and unconnected voids in their microstructure.

The reason for this is the cellular structure of perlite and pumice that absorbs the sound waves as they travel through the material. Another point, which should be mentioned, is that the thermal conductivity coefficients and ultrasonic sound permeability values of the triple and quadruple mixtures of pumice, perlite, vermiculite and zeolite were lower than the dual ones.

3.3 Determination of fire resistance

3.3.1 Cautery in muffle furnace

Mass losses of samples were found after heat treatment at 75, 100, 125 and 150 °C for 10 min according to their weights. Dual mixture results are given in Fig. 2 and the triple and quadruple mixture results in Fig. 3. For composites produced as dual mixtures, the effect of burning according to their mass losses, as furnace temperature increases mass loss increases, also. In all samples, mass losses decrease as additive ratio increases. Generally, mass losses of samples with gypsum at all temperatures were found higher than the others. The lowest mass losses were obtained for samples with pumice. Mass losses increase as furnace temperature increases for composites produced as triple and quadruple mixtures. For all samples, mass loss decreases as additive ratio increases. Generally, for triple mixtures, mass losses obtained at all temperatures were found higher than others were. On the other hand, for quadruple mixtures mass losses were lower. Mass losses of the triple and quadruple mixtures at 75, 100, 125 and 150 °C temperatures were, respectively, 12, 15, 22 and 25% lower than the dual ones. This can be explained as tighter construction having higher resistance to fire.

3.3.2 Fire resistance according to ASTM E 160-50

Duration of complete burning for the composite samples with two minerals are given in Fig. 4 and those for the samples with triple and quadruple minerals are given in Fig. 5. The limit put on the heat transfer behavior is important so that the ignitions of both the surface exposed to flames and the materials in the vicinity of it are hindered. Out of the composites with dual minerals fire resistance of 20% zeolite added sample has the longest complete burning duration. In this group, the sample that burns completely earliest is the 10% gypsum added one, CG10. From the others the sample that has the highest resistance to burning is the one with 20% pumice, 20% perlite and 20% zeolite. The complete

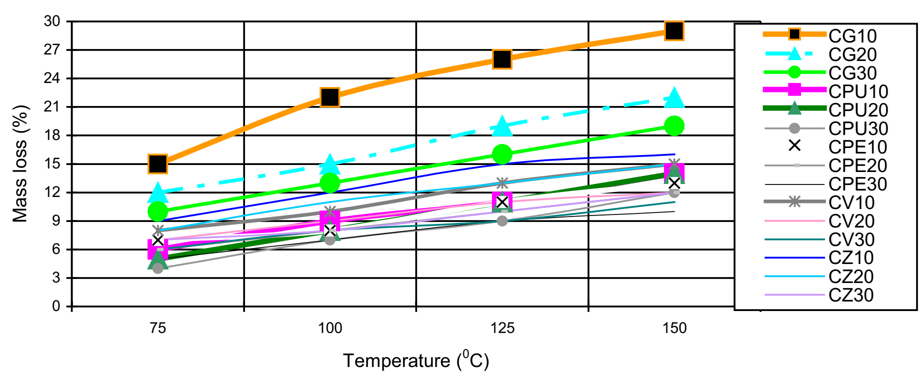

Fig. 2 Mass loss of the dual mixtures after the fire resistance test

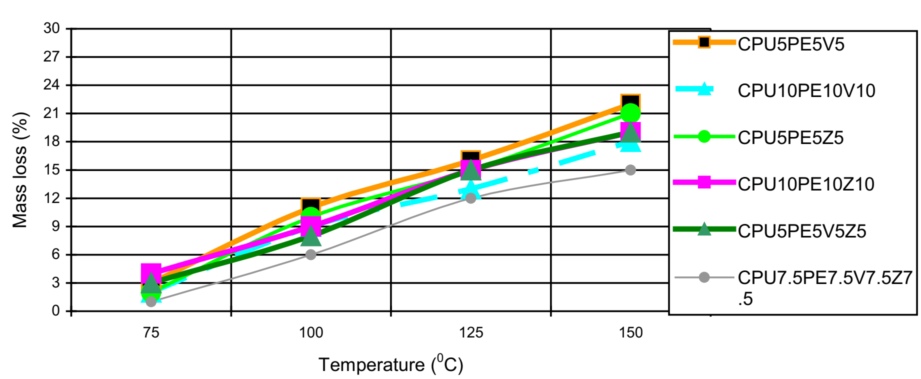

Fig. 3 Mass loss of the triple and quadruple mixtures after the fire resistance test

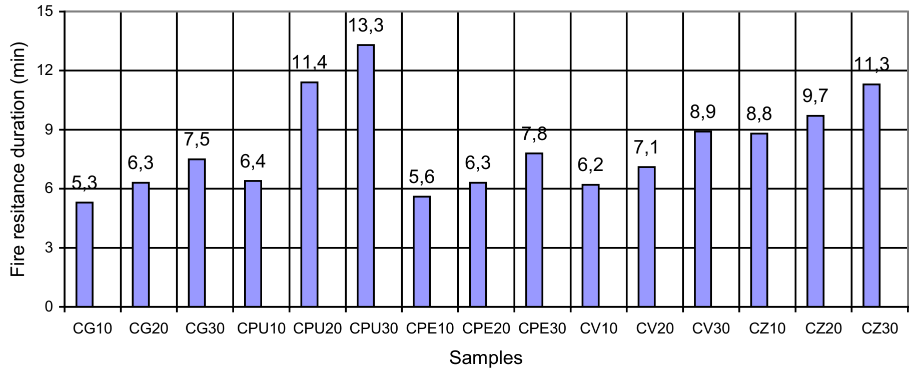

Fig. 4 Fire resistance test of dual mixtures with blowtorch

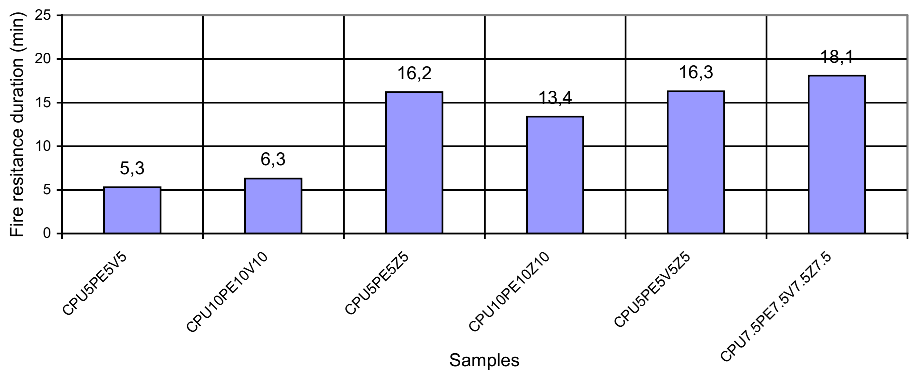

Fig. 5 Fire resistance test of triple and quadruple mixtures with blowtorch

burning duration for this sample was 15.7 min. However, this value for the sample with 10% pumice, 10% perlite and 10% vermiculite was 6.8 min. This result shows the fire resistance of zeolite.

4 Conclusions

Below this one results were obtained from this study.

1. Maximum weight loss occurred in gypsum added samples according to the burning test results. Composites produced as triple and quadruple mixtures of pumice, perlite, vermiculite and zeolite yielded the best results from the weight loss point of view.
2. Weight loss occurring in combustion and combustion temperature values were consistent with the standards and the results of other works in the literature.
3. Ultrasound transmission velocities and thermal conductivity coefficients of composites as dual mixtures of gypsum, pumice, perlite, vermiculite and zeolite were found to be lower.
4. Unit weights of the composites produced as triple and quadruple mixtures of gypsum, pumice, perlite, vermiculite and zeolite were higher but their water absorption rates were lower than the others.

In this work, a comparative investigation concerning the fire-resistance of composites involving various combinations of waste cardboard, gypsum, pumice, perlite, vermiculite and zeolite was carried out. The results found will be the stepping-stones for further studies on the subject. The subject is very important for the construction of schools, homes and industrial buildings, as well as, furnaces, bakeries and baths.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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