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Evaluation of the use of microwave energy on green floor/wall tile drying process

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ABSTRACT

Drying green ceramic tiles is necessary before the decoration and sintering processes and constitutes an important input in terms of energy consumption in the production step. Nowadays, natural gas-fueled vertical dryers are used to dry green ceramic tiles. However, alternative energy-efficient and environmentally friendly technologies are being investigated and used in many drying applications, such as microwave energy. In this study, the effects of magnetron power and drying rate on moisture, surface temperature, and dried bending strength of green ceramic tiles were experimentally examined. First, floor and wall tiles with a wet-based moisture content of 6% were shaped with an industrial hydraulic press with the specific pressures of 320 kg/cm^2 and 300 kg/cm^2 at the sizes of 33 × 33 cm and 25 × 40 cm, respectively. The shaped green floor and wall tiles were dried separately with a horizontal pilot-based microwave dryer at 20, 35, and 50 kW magnetron powers and 0.5, 1.0, 1.5, and 2.0 m/min belt speeds, and then the changes in moisture, surface temperature, and bending strength values were measured. The minimum and maximum 51 °C/143 °C and 50 °C/138 °C surface temperature values were obtained for the floor and wall tiles, respectively, after the microwave drying. The moisture values changed in direct proportion to the magnetron power and inversely to the belt speed. The moisture values were reduced from 6% to a minimum of 0.1% under the conditions of 35, 50 kW of magnetron powers with 0.5 m/min of belt speed for floor tile and 50 kW of magnetron power with 0.5 m/min of belt speed for wall tile. In addition, the corner moisture values of microwave-dried tiles were lower than those in the center on the surface. The bending strength increased as the belt speed and magnetron power decreased within the working conditions. The maximum bending strength values for the floor and wall tiles were obtained as 29.2 kg/cm^2 and 31.2 kg/cm^2 at 20 kW magnetron power and 0.5 m/min belt speed, respectively. Of 52.4% and 42.6% energy savings in economic terms, 1000% and 837.5% increase in drying capacity, and 50.0% and 42.1% of environmental gain were calculated for the drying of floor and wall tiles with microwave energy compared to the natural gas, respectively. This study indicates that microwave energy can be used as a more energy efficient and capacity booster environmentally friendly process than natural gas-fueled vertical dryers in green ceramic drying.

Units: m/min: meter per minute, speed; kg/cm^2: kilogram-force per square centimeter, force μm: micrometer, length; mm: millimeter, length; cm: centimeter, length; m: meter, length; kW: kilowatt, power; MHz: megahertz, frequency; GHz: gigahertz, frequency; g: gram, weight; kg: kilogram, weight; Sm^3: standard cubic meter, volume; m^2: square meter, area; kWh: kilowatt-hour, energy

Abbreviations: FT: floor tile; WT: wall tile; SiO_2: silicon dioxide; Na_2O: sodium oxide; K_2O: potassium oxide; LOI: loss on ignition; CaO: calcium oxide; Al_2O_3: aluminum oxide; TiO_2: titanium dioxide; Fe_2O_3: ferric oxide; MgO: magnesium oxide; d_{50}: average particle size; ISO: international organization for standardization; CO_2: carbon dioxide; H_2O: water; MW: microwave drying of wall tile; NW: natural gas drying of wall tile; MF: microwave drying of floor tile; NF: natural gas drying of floor tile

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Microwave energy; ceramics; green floor and wall tiles; rapid drying

1. Introduction

Drying or dehydration is the process of removing vaporizable substances, such as water from solid materials in which heat and mass transfer occur together. However, the main objective of the drying process is to remove moisture from the product, and the removal can be done by various methods such as convective, radiative, dielectric, or freeze-drying, etc.[1] The products to be dried show different properties due to their structure. Therefore, it is not possible to dry every product with the same method in an

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efficient way[2,3]. A product can be separated from moisture with less energy by different mechanical methods, such as filtering, pressing, centrifugation, settling, and sieving[4,5]. If the product to be dried is not suitable for such methods, drying by evaporation is usually achieved by applying heat transfer to the product with gas flow. Alternative techniques can also be used as heat sources[6].

In the conventional drying method, heat is gradually transferred from the surface of the dried material to the inner parts due to the temperature difference between the hot surface of the product and the cooler inner part during the drying process. Thus, first the surface and then the inner side of the product dry, and the hard layer formed due to shrinkage on the outer surface prevents the transfer of heat to the inside[7]. In the microwave drying method, selective heating is performed by directly targeting the water molecules in the material unlike traditional drying methods, thus electromagnetic field affects the material as a whole[8]. As a result, the moisture transfer is realized from inside to outside due to the vapor pressure difference by heating in very short periods. Thus, the heat transfer problem that occurs in conventional drying methods is eliminated by microwave drying[9]. Although the use of microwave drying alone has many advantages, it also brings disadvantages. These can be listed as high initial investment costs, deformation and physical damage possibility on the product, the necessity of taking high safety precautions, and the difficulty of ensuring homogeneous microwave distribution in the drying environment[10,11]. Microwave refers to radio waves with a wavelength of 1 mm to 1 m and a frequency between 300 MHz and 300 GHz[12]. Microwave emerged in the late 1800s and was initially used only in telecommunications[13]. Later, its use for heating purposes was also discovered (1945) and developed over time under the name "microwave oven" and today it has become a food heater found in almost every home. Microwave drying is becoming popular in industrial and commercial applications because this technique has several advantages such as shorter processing times, volumetric distribution of energy throughout a product, high-energy efficiency, and improvement in product quality[14]. With the appropriate surface area, microwave intensity, and processing time, the desired moisture content can be achieved with a very low amount of energy[15].

A microwave oven is mainly formed by three main sections. First, the magnetron, where the microwaves are generated from electrical energy; second, the waveguide, where the generated microwaves are transmitted to the product to be affected; and last, the cavity inside the oven, also called the applicator[16]. The magnetron used as the energy source in a microwave oven is an oscillator tube consisting of a perforated cylindrical anode and an electron-emitting cathode in the center. A low direct current at high voltage fed to the anode converts electrical energy into microwave energy. Electromagnetic waves are transmitted to the applicator *via* waveguides or transmission lines, such as coaxial cables[17]. In microwave applications, waveguides with lower losses at high frequencies are preferred. Microwave ovens are divided into continuous and discontinuous according to the operating continuity. Due to the negative effects of free microwaves on the environment on living health, devices operating with closed systems are used in all kinds of microwave devices[18]. The power applied in the microwave, initial humidity, and product shape are variables that affect the efficiency. While microwave heating is generally known for household uses, its use in various applications, such as drying of rubber, composites, food, and ceramic materials is rapidly increasing[19].

Microwaves can be reflected, absorbed, or transmitted depending on the type of material[20]. Permittivity refers to the electrical charge capacity of a material in a given volume and can be expressed as a dielectric constant. The permittivity of the raw materials is affected by morphological, mineralogical, chemical composition, and crystal formation[21,22]. Ceramic tile bodies are mainly composed of clay minerals, quartz, alkali feldspars, and carbonate minerals such as calcite and dolomite. Quartz, calcite, and feldspar are not microwave-receptive and cannot be heated easily, however, iron-bearing sulfide minerals can be heated well due to their dielectric properties[23,24]. Clay minerals and quartz with similar properties can be used in common in ceramic tile bodies, the distinctive raw materials are the use of feldspar in floor tiles and carbonated raw materials, such as calcite and dolomite in wall tile bodies. The dielectric permittivity of albite is slightly higher than calcite mineral and cannot show different characteristics in microwave drying. However, gangue minerals such as anatase, magnetite, hematite, etc., will be determinant materials in the microwave drying of ceramic tile bodies[25,26]. The processing conditions also influence the permittivity of ceramic powders[27].

The ceramic body is primarily formed by grinding raw materials taken from nature in mills in a wet medium. The ground ceramic slip is then sent to spray dryers to obtain formable granules with a moisture content of 5–6%. After the humidified granules are shaped by stamping, green tile is obtained and

dried in natural gas-powered vertical dryers using traditional methods[28]. Green ceramic tile refers to the raw tile after the 5–6% humidified granules are shaped in a hydraulic press. Afterwards, decoration processes are applied and the dried tile is sintered in kilns. The drying of clay, brick, and 3D vitrified ceramics by microwave and convective methods have an important impact on product quality and energy consumption. These methods can be used combined or separately in a continuous or intermittent flow. Intermittent use of microwave and convective methods in combination for drying clay and bricks with high moisture content is suggested in terms of product quality[29]. On the other hand, microwave drying is much more efficient than conventional tunnel airflow drying with regard to drying speed and energy consumption in clay roof tile. However, heterogeneous distribution in moisture content and surface temperature can create a problem with the material properties[30]. In the ceramic process, the moisture of the green tile must be properly evaporated and removed before the sintering step to gain a qualified final product. If the drying process is too fast, cracking and deformation may occur after glazing and firing[31]. Microwave drying accelerates the process by drying the product directly rather than heating the medium compared to convective drying. Homogeneous and fast drying can be achieved even in thick-layered products with proper magnetron design and arrangement. The process can be carried out quickly, thus reducing stockpiling and gaining in terms of capacity with automation systems. In addition, an environmentally friendly production is realized since energy consumption is ensured[32].

In this study, it was aimed to show the suitability of a continuous microwave conveyor belt on the pilot-based green ceramic floor and wall tile drying process. In this regard, the effects of microwave power and drying rate on the material moisture, surface temperature, and dried bending strength were studied experimentally. Lastly, the capacity, energy consumption, and CO_2 emissions originating from direct fueling were calculated and compared with traditional natural gas-fueled vertical dryers in the manner of technical, productivity, and environmental concepts.

2. Materials and methods

2.1. Materials

In this study, floor tiles with a residue of 4% for +45 µm sieve aperture and wall tiles with a residue of 2% for +63 µm sieve aperture were used after particle size reduction in aqueous media with discontinuous ball mills. The recipe raw material ratios and mineralogical compositions used in the studies are presented in Table 1.

The sintered floor tile body composition is formed by mullite crystal and glass phases having low water adsorption[33,34]. While the formation of the mullite crystal is primarily provided by clay minerals as an aluminum source, the glass phase is mainly provided by quartz minerals as the main element and feldspar minerals as melters in the composition[35]. As seen in Table 1, the floor tile body mainly consisted of illite, montmorillonite, and kaolinite as clay minerals, and contained a small amount of palygorskite. Albite and sanidine were analyzed as feldspathic minerals and quartz and cristobalite were seen as SiO_2 sources. Jarosite mineral was seen as an impurity. Wall tile has high water adsorption characteristics (10–20%) with a porous structure and contains anorthite, diopsite, gehlenite, quartz, and glass phases[36]. The porosity is provided by calcite and magnesite having carbonate in their composition[37,38]. The clay minerals supply dried strength before sintering and support crystal phase formation. The mineral composition of wall tile body raw materials is also given in Table 1.

The chemical compositions of floor and wall tile bodies were determined using PANALYTICAL Brand AXIOS MAX model X-Ray Spectrophotometer (XRF) device (Table 2). There were many differences between floor and wall tile body compositions. The SiO_2 content was high in floor tile composition, which was an indicator of quartz mineral compared to the wall tile. Besides, the alkaline contents, such as Na_2O and K_2O, which were used to reduce the melting temperature of the glass phase, were also high in floor tile body compositions. The LOI and CaO values were more in quantity in the wall tile body due to the calcite content, which was used to form porosity after sintering. The Al_2O_3 contents mainly originated from clay minerals.

The ceramic slips obtained after particle size reduction in aqueous media were then dried to 6% humidity in a spray dryer to obtain floor and wall tile granules, separately. The results for the particle size distributions for the floor and wall tile granules are given in Figure 1.

Approximate, d_{50} values for floor and wall tile ceramic granules were found to be 0.39 and 0.33 mm, respectively. In conclusion, the particle size distributions of the sample indicated that the FT sample had a bigger size compared to the WT granule.

Table 1. Mineralogical analysis of raw materials and ceramic recipes.

Recipe	Raw material	By weight (%)	Qualitative raw material XRD analysis
Floor Tile (FT)	Kaolin A	32.0	Quartz, sanidine, albite, kaolinite, cristobalite, jarosite
	Kaolin B	17.5	Quartz, kaolinite, illite
	Kaolin C	7.5	Quartz, sanidine, albite, kaolinite, cristobalite
	Kaolin D	10.0	Quartz, sanidine, palygorskite, illite
	FT Fired Waste	6.0	Mullite, cristobalite, albite, quartz, glass phase
	Clay	27.0	Quartz, kaolinite, illite, montmorillonite
Wall Tile (WT)	Limestone	11.4	Calcite, quartz
	Kaolin E	1.9	Quartz, kaolinite, alunite, rutile
	Kaolin F	15.3	Quartz, sanidine, kaolinite, trydimite, illite
	Kaolin D	4.8	Quartz, sanidine, palygorskite, illite
	Kaolin B	14.2	Quartz, kaolinite, illite
	Kaolin G	3.8	Kaolinite, quartz, halloysite
	WT Fired Waste	7.6	Quartz, anorthite, diopsite, gehlenite, mullite
	Clay	41.0	Quartz, kaolinite, illite, montmorillonite

Table 2. Chemical compositions of floor and wall tile body.

Composition		LOI (%)	SiO_2 (%)	Al_2O_3 (%)	TiO_2 (%)	Fe_2O_3 (%)	CaO (%)	MgO (%)	Na_2O (%)	K_2O
Floor tile	(%)	3.7	68.6	17.3	0.7	2.0	0.8	0.4	2.0	4.5
Wall tile		9.7	59.2	17.6	0.7	1.6	7.6	0.7	0.7	2.2

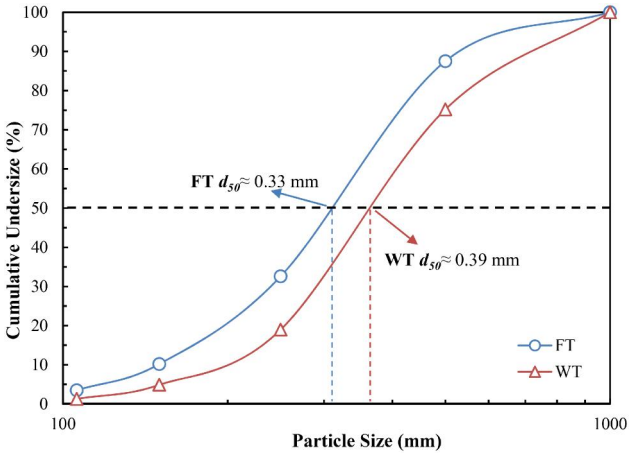


Figure 1. Particle size distributions of floor and wall tile granules.

2.2. Methods

Floor tile granules were stamped and shaped in 33 × 33 cm size at 320 kg/cm^2 specific pressure and wall tile granules were shaped in 25 × 40 cm size at 300 kg/cm^2 specific pressure in industrial-scale hydraulic press to obtain green tiles. The thickness of green tiles was measured in the range of 8.2–8.4 mm using calipers. The microwave drying experiments were carried out with green tiles prepared under these conditions.

The microwave drying experiments were realized with a pilot-scale microwave dryer of the Megatron Company, İzmir/Türkiye. The green tiles were fed manually into a closed pilot-based microwave dryer with a belt width of 60 cm and a total length of 15 m (each 1.5 m of oven inlet and outlet + 12 m of drying zone). In the microwave dryer, there were 5 magnetrons on the top of the microwave chamber with 2.4 m intervals, the power of which could be controlled by an inverter. In the experiments, the effects of magnetron power and conveyor belt speed on surface temperature, moisture value, and dried bending strength were investigated. The schematic representation of the pilot-based microwave dryer and side view dimensions is shown in Figure 2.

The atmospheric air, which had 20 °C of temperature and 65% humidity, was used in the experiments. The air was blown at 650 L/min and drawn out of the microwave chamber at 1000 L/min of flow rate by the ventilation system. The temperatures of the tile surfaces' were measured at four different corners and centers with a Trotec brand BP21 model laser thermometer and averaged. After microwave drying, the samples were taken from four corners and the center of the tiles in 5 × 5 cm pieces, then crushed in a mortar and reduced to −500 µm particle size. After the homogenization process by cone and quartering method, moisture measurements were carried out with 8 g samples. Radwag brand MAC 50/NH model analyzer was used for the moisture determination. In moisture determination, the initial weight of the sample was recorded, and then the sample was dried with a halogen radiator while an integrated balance continuously recorded the sample weight. The total weight loss was interpreted as moisture content. The samples from four corners (1, 2, 3, 4) and center (C) were also analyzed to see the moisture difference on the tile surface, separately. The moisture values were measured for each piece and average moisture was calculated accordingly. In each experiment, the dried sample was taken once 10 times after the first feed realized to make temperature and moisture

measurements and repeated five times continuously. Additionally, a three-experiment repetition was made to avoid measurement uncertainties. The illustration of tiles arrangement in the microwave chamber, microwave-dried sampling, moisture, and temperature measurement are shown as a flow chart in Figure 3.

Sigma Aldrich brand gas oil with CAS number: 8008-20-6 was applied to the tile surfaces with a sponge to see the presence of microcracks that could not be seen visually after the microwave drying process (Figure 4).

The bending strength values of the microwave-dried tiles were carried out using Equation (1) according to the method given in the ISO 10545-4 standard[39]. GABRIELLI Brand S.R.L CR5 Model strength device was used for bending strength measurements.

$$C_r = \frac{3}{2} \; x \; \frac{G \; x \; M}{L \; x \; d^{\,2}} \tag{1}$$

where C_r is the bending strength (kg/cm^2), G is the fracture load (kg), M is the distance between supports (cm), L is the breaking length (cm), and d is the thickness of the tile (cm).

Finally, the pilot-based microwave belt dryer used in the experiments and industrial natural gas-fueled vertical dryer parameters were compared in terms of energy and capacity. In the vertical dryer experiments, 33×33 cm raw floor tiles in 3×3 rows and 40×25 cm raw wall tiles in 5×2 rows were placed in the drying chamber. The floor and wall tiles were dried at 150 and 160 °C in the 1st zone, 120 and 150 °C in the 2nd zone, 93 and 110 °C in the stabilization zone for a total of 90 and 75 min, respectively. 1 row of dried tiles was taken at 15 min intervals for a total of 5 times. The dried tiles were sampled and

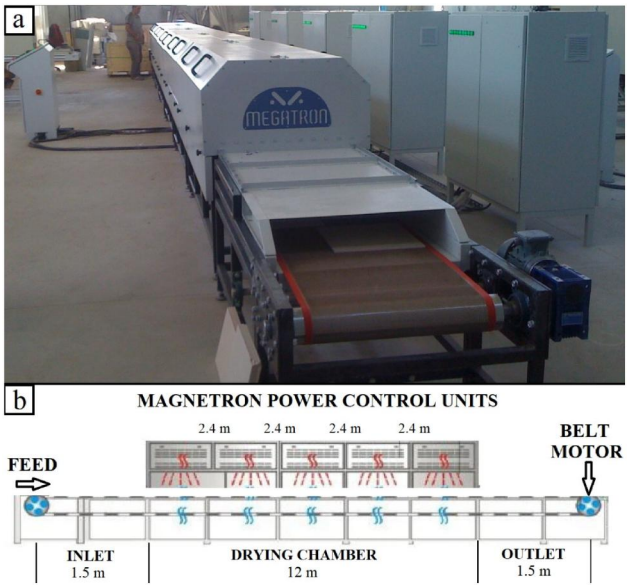


Figure 2. (a) Pilot-based microwave dryer used for experiments; (b) Schematic representation of experimental setup.



Figure 4. Microcrack detection with kerosene.

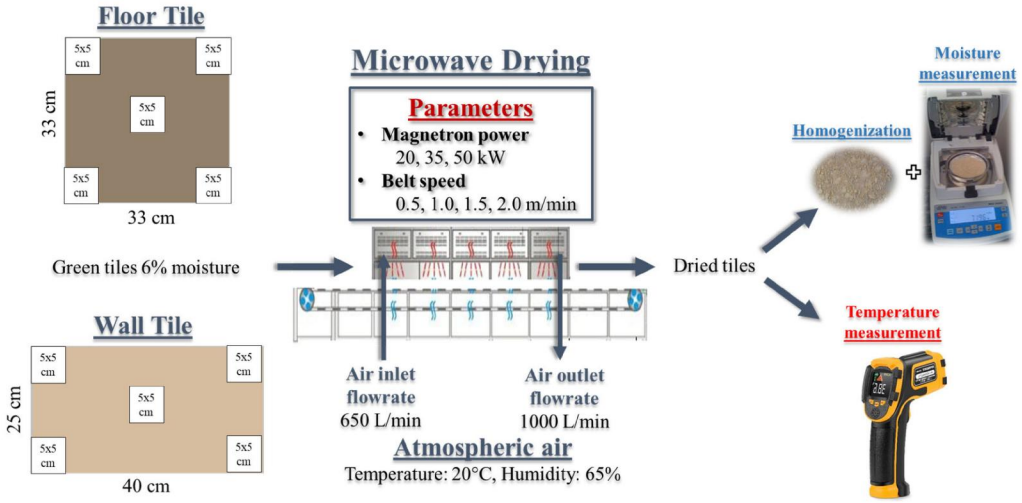


Figure 3. The basic flow chart of the study.

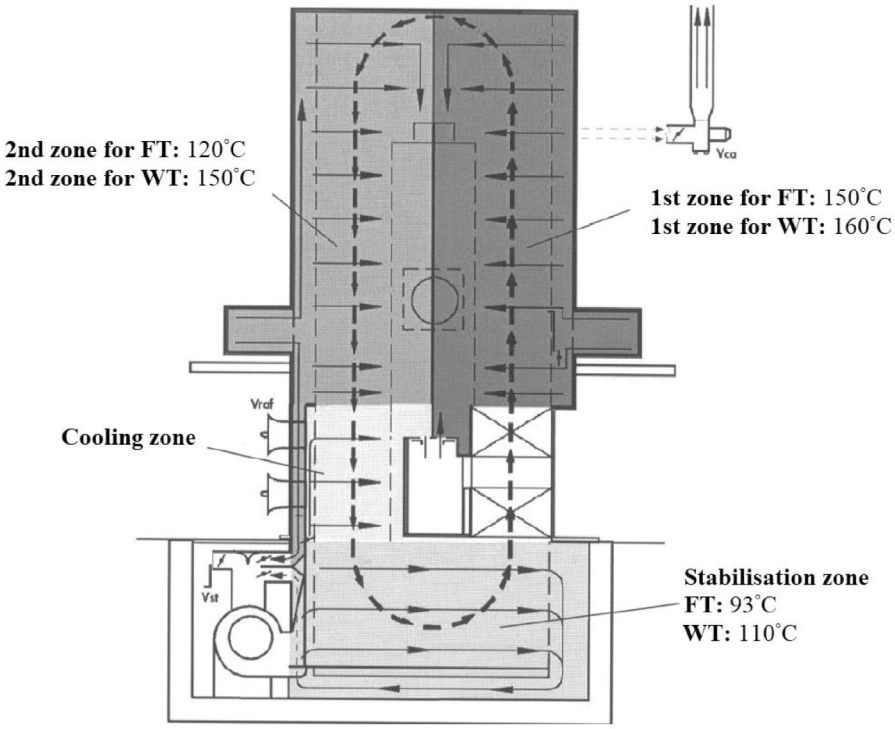


Figure 5. The sectional temperatures of industrial vertical dryer [41].

moisture measurements were performed as shown in Figure 3. Horizontal belt microwave drying energy and capacity calculations were made in m^2 and kWh considering belt speed and magnetron power. The energy consumption of the vertical dryer was calculated by converting the number of tiles fed in one cycle into m^2 depending on the drying duration. 1 Sm^3 natural gas: 10.55 kWh equivalent was used for comparison for natural gas-fueled vertical dryer and microwave dryer energy conversion and, 1 kWh electricity: 0.39 kg CO_2 emission equivalent was taken into account by considering the conversion coefficients taken from the US Environmental Protection Agency[40]. The schematic representation and sectional temperatures of the industrial vertical dryer are shown in Figure 5.

3. Results and discussion

The effects of belt speed (0.5, 1, 1.5, and 2 m/min) and magnetron power (20, 35, and 50 kW) on the surface temperature, moisture, and flexural strength of green 33 × 33 cm sized floor tile and 25 × 40 cm sized wall tile were investigated using a microwave dryer within the scope of the experimental studies. The microwave exposition duration for floor and wall tiles was calculated as 9.9, 19.8, 29.7, 39.6 m^2/h and 7.5, 15, 22.5, and 30 m^2/h according to 0.5, 1, 1.5, and 2 m/min of belt speeds, respectively.

After the drying process of the shaped tiles, the surface temperature is important depending on the decoration type, application conditions, belt conveyor length, and ambient conditions in ceramic tile production. Figure 6 shows the surface temperature measurements after the microwave drying at 20, 35, and 50 kW of magnetron powers and at 0.5, 1.0, 1.5, and 2.0 m/min of belt speeds, separately.

As the belt speed increased from 0.5 m/min to 2 m/min, the surface temperatures of the microwave-dried floor tiles decreased from 90 ± 1.7 °C to 51 ± 0.7 °C, from 128 ± 2.5 °C to 57 ± 0.8 °C and from 143 ± 3.1 °C to 74 ± 1.1 °C; the surface temperatures of the microwave-dried wall tiles decreased from 90 ± 1.6 °C to 50 ± 0.7 °C, from 110 ± 2.1 °C to 55 ± 0.8 °C, and from 138 ± 3.0 °C to 71 ± 1.0 °C for magnetron powers of 20, 35 and 50 kW, respectively (Figure 6).

In ceramic tile production, a maximum value of 0.3% is targeted for the moisture content of dried tile on an industrial view due to the sufficient bending strength requirement for decoration processes and cracking probability with sudden moisture output in the sintering step. Today, the drying process is carried out with natural gas-powered vertical dryers operating at a maximum ambient temperature of 200 °C[42]. In this part of the study, the microwave drying was

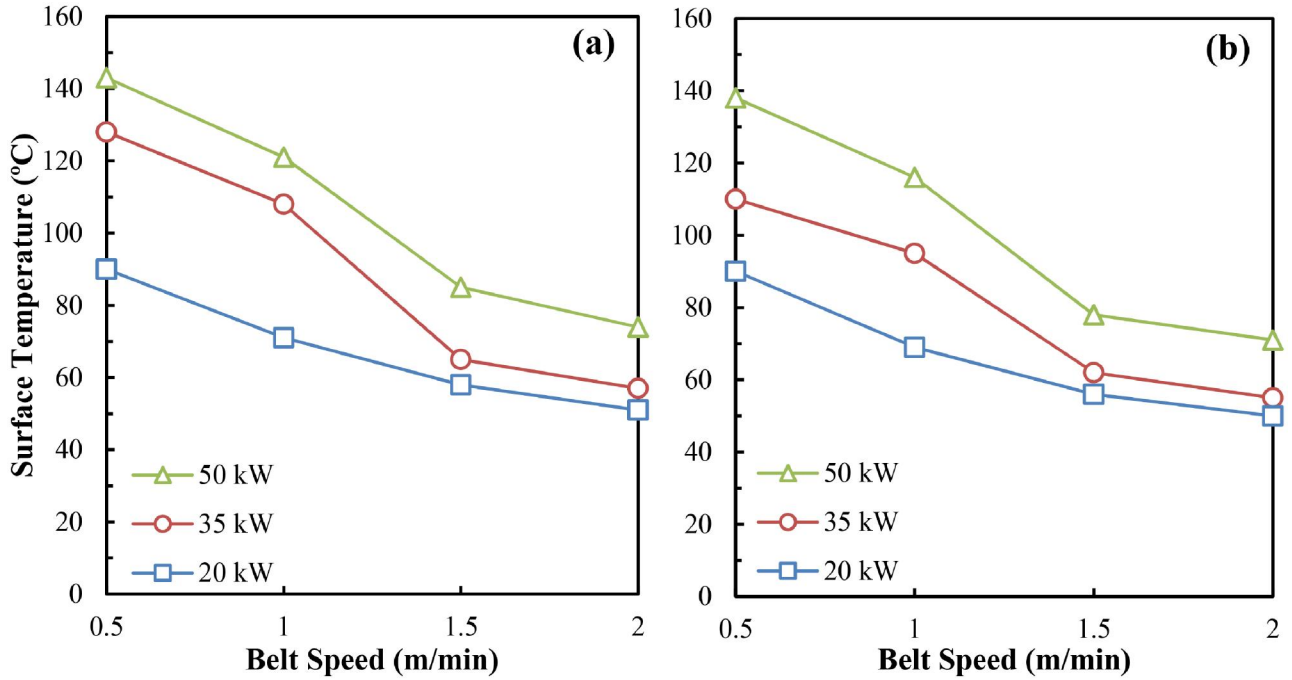


Figure 6. Surface temperatures of microwave-dried (a) floor tile and (b) wall tile at different magnetron powers according to belt speed.

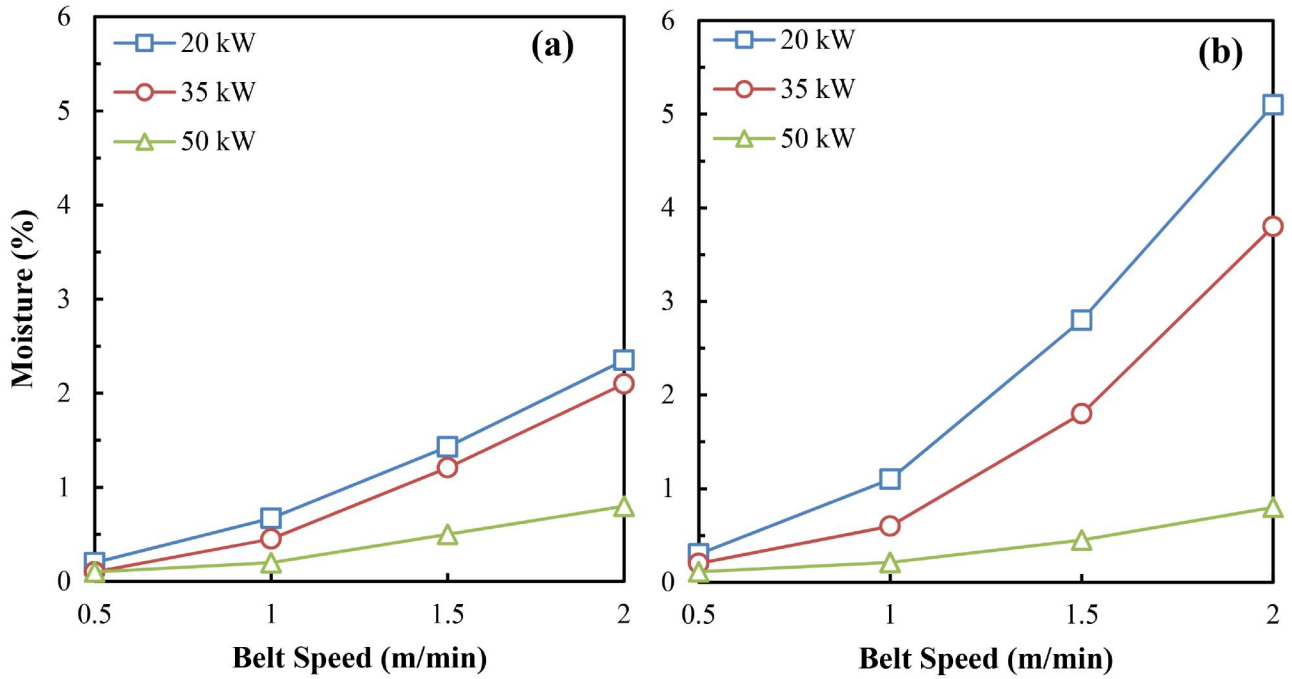


Figure 7. Moisture values of microwave-dried (a) floor tile and (b) wall tile at different magnetron powers according to belt speed.

experienced at 20, 35, and 50 kW of magnetron powers and 0.5, 1.0, 1.5, and 2.0 m/min of belt speed conditions, and the average moisture values of microwave-dried tiles are given in Figure 7.

The moisture values decreased from 2.4 ± 0.16% to 0.2 ± 0.05%, from 2.1 ± 0.13% to 0.1 ± 0.06%, and from 0.8 ± 0.09% to 0.1 ± 0.05% for floor tiles; from 5.1 ± 0.30% to 0.3 ± 0.07%, from 3.8 ± 0.24% to 0.2 ± 0.08%, and from 0.8 ± 0.11% to 0.1 ± 0.04% for wall tiles as the belt speed reduced from 2 m/min to 0.5 m/min at magnetron power values of 20, 35, and 50 kW, respectively (Figure 7). Minerals in nature behave differently in the presence of microwave energy due to different polarization abilities and dielectric

properties depending on the mineralogical properties and elemental content[42]. In Figure 7, it was seen that the moisture values of the green floor tile decrease faster with different magnetron power and band speeds compared to the wall tile. When analyzed structurally, the main difference between the ceramic bodies was the calcite content in the wall tile and alkaline minerals, such as albite and sanidine in the floor tile composition. There is no significant difference in dielectric constants between these minerals[43]. On the other hand, iron oxides generally have higher dielectric constants than hydroxides and silicates. Therefore, as the iron content in the ore or rock increases, the material is more affected by microwave energy, and the heating effect increases[44–46]. The fact that the faster moisture decrement in the floor tile compared to the wall tile with microwave energy was related to the excess iron content in the structure (Table 2).

In order to understand the moisture distribution on the surface, samples were taken separately from four corners and the center of the tiles after microwave drying at different belt conveyor speeds and magnetron powers, and then the moisture measurements were performed (Figure 8).

Corners have lower moisture contents than centers for both floor and wall tiles after microwave drying at all magnetron powers and belt speeds (Figure 8). As the maximum and minimum differences were considered, it was seen that the average moisture value of the samples taken from the corners at 0.5 m/min belt speed and 50 kW magnetron power for the floor tile was 0.1 ± 0.05%, while the moisture of the center was 0.2 ± 0.03% with a minimum difference of 0.1%, the maximum difference (0.7%) was analyzed at 2.0 m/min belt speed and 20 kW magnetron power with the average corner moisture value of 2.1 ± 0.10% and the center moisture value of 2.8 ± 0.16%. For the wall tile, the difference between the moisture values of the samples taken from the corner and center was determined to be 0.1% in the drying experiments performed at 0.5 m/min belt speed and all magnetron powers, while the maximum difference (0.9%) was reached at 2.0 m/min belt speed and 20 kW magnetron power with the average corner moisture of 4.7 ± 0.25% and the center moisture of 5.6 ± 0.33%. Figure 8 clearly shows that as the microwave power increases, the difference between the two moisture levels also increases.

In order for ceramic tiles to come out of the decoration and sintering processes in good quality, the bending strength after drying must be at the appropriate level in terms of working criteria. This strength is primarily related to the clay content and type of composition, but drying parameters also affect the dried bending strength[47]. The effects of magnetron power and belt speed on the flexural strength of microwave-dried tiles are given in Figure 9.

As the belt speed increased from 0.5 m/min to 2 m/min, the flexural strengths decreased from

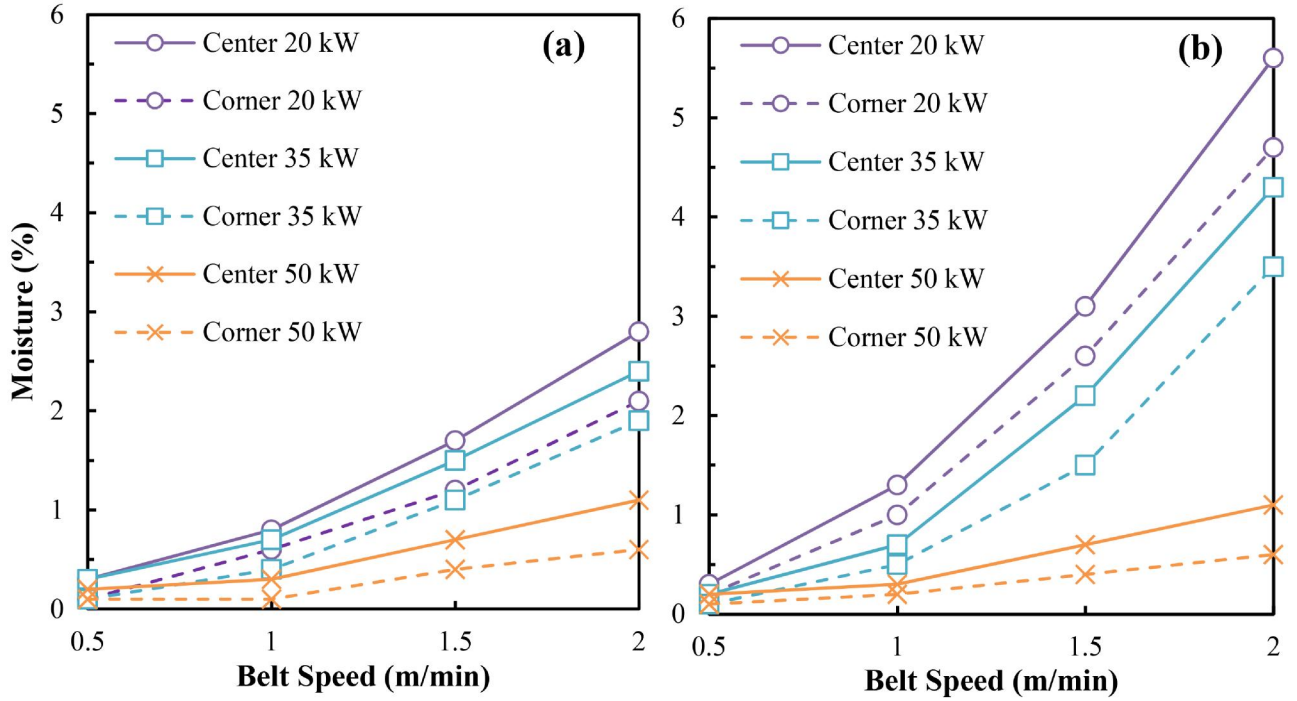


Figure 8. Corner and center moisture values of microwave-dried (a) floor tile and (b) wall tile at different magnetron powers according to belt speed.

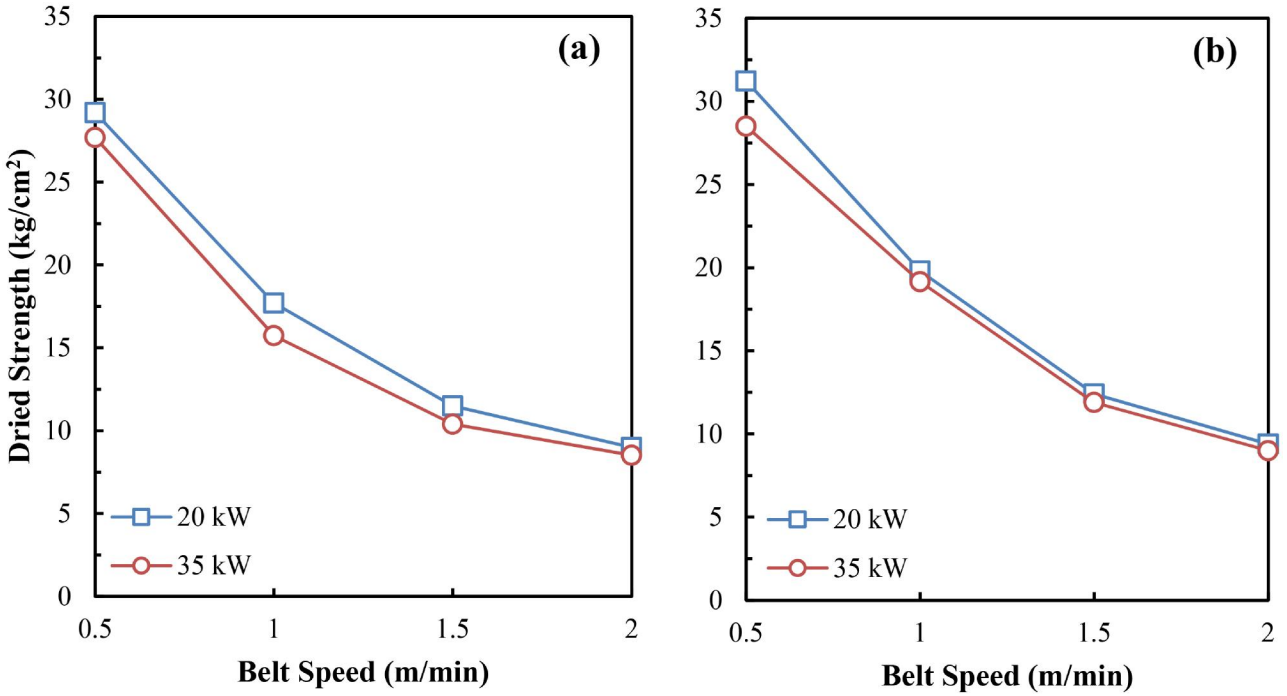


Figure 9. Breaking strengths of microwave-dried (a) floor tile and (b) wall tile at different magnetron powers according to belt speed.

29.2 ± 2.4 kg/cm^2 to 9.0 ± 1.4 kg/cm^2 and 27.7 ± 2.2 kg/cm^2 to 8.5 ± 1.2 kg/cm^2 for floor tiles; from 31.2 ± 2.7 kg/cm^2 to 9.4 ± 1.5 kg/cm^2 and from 28.5 ± 2.4 kg/cm^2 to 9.0 ± 1.5 kg/cm^2 for wall tiles, at 20 kW and 35 kW magnetron powers, respectively. One of the most important factors affecting the bending strength of green and dry ceramic tiles is the type/amount of clay in the body as well as the application parameters. Typically, the bending strength of green and dried tile increases with the clay content in the ceramic body[48]. The main reason for the high bending strength values for wall tile compared to the floor tile after microwave drying was explained by the high clay content (Table 1). The ability of clay minerals to absorb water into their structures allows them to obtain formable granules with a swelling character[49]. After the granules are shaped into green tiles, the physically bound water between the clay layers evaporates, and the distance between the layers decreases. Thus, the bending strength of the dried tile increases with the structure formed by clay minerals[50]. The moisture reduction by the removal of H_2O in the structures of especially 3-layered montmorillonite clay mineral and the decrease in the distance between the layers with the magnetron power increment resulted in a bending strength decrease in both microwave-dried floor and wall tiles (Figure 7).

In addition, the moisture content of the tiles decreased with the belt speed decrement due to the sufficient time provided for drying, and as a result, the bending strength increased for both floor and wall tiles with microwave drying. The bending strength analysis could not be performed due to the crack formation in the tiles at 50 kW of magnetron power. In ceramic structures, illite/montmorillonite type clays take more water into their structures during aqueous preparation and the distance between the layers is widened compared to the two-layered clay minerals such as kaolinite and halloysite[51]. Therefore, illite/montmorillonite clay containing ceramic bodies leave the physical water in the structure during drying and the interlayer closes compared to the 2-layered clay mineral, so the crack formation may occur in the body also depending on the clay content[52]. Additionally, the quartz amount in the clay mineral has also opposite impact on the crack formation while drying[53]. On the other hand, if the drying happens too fast, the physically bound water may suddenly move away and cause cracks in the structure[54]. At 50 kW magnetron power, the cracks formed in the wall and floor tiles were realized as a result of the sudden removal of water in the structure. No crack existence was found on tile surfaces at 20 and 35 kW of magnetron powers with kerosene treatment.

Today, natural gas-fueled vertical dryers are used in the traditional green tile drying process. In this study, it was seen that the maximum moisture value of 0.3%, which was suitable for the working

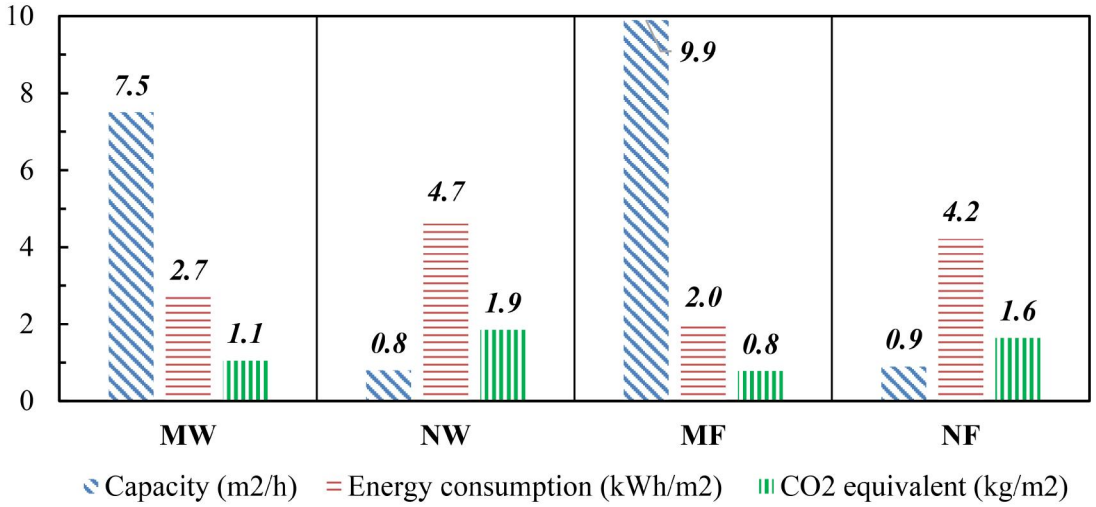


Figure 10. Microwave and natural gas drying comparison in terms of economy, capacity, and environment.

conditions of a natural gas industrial vertical dryer, could be technically achieved with a horizontal pilot-based microwave dryer. Figure 10 shows the energy consumption, capacity, and CO_2 emission comparison for drying green floor and wall tiles with an industrial-based natural gas-fueled vertical dryer and pilot-based horizontal microwave dryer.

33×33 cm sized green floor and 25×40 cm sized green wall tiles were dried with 0.9 m^2/min and 0.8 m^2/min capacity in industrial vertical dryer operating on natural gas and were dried with 9.9 m^2/min and 7.5 m^2/min capacity in pilot-based horizontal microwave dryer, respectively. In economic terms, 0.45 and 0.40 Sm^3 (1 Sm^3: 10.55 kWh) of natural gas were consumed with a vertical dryer, and 2.7 and 2.0 kWh of electricity were consumed with a microwave dryer to dry 1 m^2 of wall and floor tile, respectively. In other words, 3.1 and 2.1 kWh of electricity in microwave drying and 0.51 and 0.42 Sm^3 natural gas in the vertical dryer were needed to evaporate 1 kg of water from the wall and floor tiles, correspondingly. Thus, 132.5 and 96.4 kg of CO_2 were emitted with microwave, and 228.9 and 192.8 kg of CO_2 were emitted with natural gas to dry 1 m^3 of wall and floor tile, respectively. In natural gas vertical dryers, the environment is first heated and then the drying process takes place to the heat flow between the environment and the material to be dried. However, microwave energy directly targets the water molecules in the material and a selective drying process takes place. Since there is no energy and time spent to heat the environment as in the vertical dryer makes microwave drying energy and capacity efficient method[55].

4. Conclusions

In the pilot-based drying with a horizontal microwave dryer, surface temperatures of floor tiles were obtained as a minimum of 51 °C and a maximum of 143 °C under the conditions of 20 kW magnetron power with 2 m/min belt speed and 50 kW magnetron power with 0.5 m/min belt speed, respectively. The surface temperatures of wall tiles were obtained as a minimum of 50 °C and a maximum of 138 °C under the conditions of 20 kW magnetron power with 2 m/min belt speed and 50 kW magnetron power with 0.5 m/min belt speed, respectively. After the microwave drying, the maximum value of 0.3%, which is suitable moisture for dried tile in industrial ceramic production, could be reached at all magnetron powers and 0.5 m/min band speed for both floor and wall tile. In addition, the corner moisture values of the tiles were lower than the center moisture values for both floor and wall tiles, and this moisture difference increased with the magnetron power and belt speed increment. On the other hand, as the belt speed decreased the bending strength increased with microwave drying. At 50 kW magnetron power, bending strength measurement could not be performed due to the cracking problem. Higher dried strength values were obtained at 20 kW compared to 35 kW magnetron power. The maximum bending strength values of 29.2 kg/cm^2 for floor tile and 31.2 kg/cm^2 for wall tile were reached at 20 kW magnetron power with 0.5 m/min belt speed. An energy saving of 52.4% and 42.6%; and a capacity increase of 1000% and 837.5% were calculated by using a horizontal microwave dryer in the conditions of 20 kW magnetron power with 0.5 m/

min belt speed compared to the conventional natural gas-fueled vertical dryer in the raw floor and wall tile drying process, respectively. Finally, it was seen that microwave drying would emit 50.0% and 42.1% less CO_2 in floor and wall tile drying compared to natural gas drying in environmental terms.

Disclosure statement

The author declares no conflict of interest.

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