ISSN 1330-3651 (Print), ISSN 1848-6339 (Online)
https://doi.org/10.17559/TV-20240110001258
Subject Review

Fly Ash in Clay Composites for Enhanced EM Shielding and Improved Physical and Mechanical Properties-Literature Review

Ivan VRDOLJAK*, Ivana MILIČEVIĆ, Damir VAREVAC, Stanko ČOLAK

Abstract: An overview of the research on using clay with fly ash addition for enhanced electromagnetic (EM) properties in the frequency range up to 10 GHz with application in civil engineering materials was studied. In recent years, due to the development of technology, the use of devices that emit electromagnetic radiation, such as cell phone networks (3G, 4G, 5G), microwave ovens, global positional systems (GPS), radars, etc. has increased. Consequently, there is a growing concern about the harmful effects of EM radiation on human health. Fly ash has proven to have the potential for shielding against electromagnetic radiation in cementitious materials. This paper investigates the potential of fly ash in clay bricks to increase resistance to the penetration of electromagnetic waves, as well as the impact on its physical and mechanical properties.

Keywords: clay, compressive strength, electromagnetic shielding, fly ash

1 INTRODUCTION

In recent years, due to the rapid development of technology, human exposure to electromagnetic radiation has increased [1]. This is the reason why researchers have begun to address the issue of the harmful effects on public health [2-6]. The harmful effects of long-term exposure to electromagnetic radiation on human health are still questioned. Several studies have reported potential carcinogenicity [3, 5], whereas others have found no evidence of the harmfulness of electromagnetic radiation [2, 6]. As the harmfulness of exposure to electromagnetic radiation has not yet been fully clarified and defined, the International Commission on Non-Ionizing Radiation Protection has issued recommendations for electromagnetic radiation reference levels, which have become the basis for drafting national regulations in many countries [7]. Some countries in their regulations define a special control of electromagnetic radiation to areas housing vulnerable groups, such as schools, maternity hospitals, kindergartens, nursing homes etc., where the radiation must be at a very limited level. To meet prescribed conditions and also to reduce human exposure to potentially harmful electromagnetic radiation, an effort has been made to find different ways to reduce exposure. One of the ways to improve electromagnetic shielding is by coating [8, 9] or using composite materials with the ability of high protection against electromagnetic radiation. Composite materials used in protection against electromagnetic radiation can be used in both load-bearing and non-load-bearing materials. Non-load-bearing materials intended for protection against electromagnetic radiation are mostly fabrics or some other type of lining [10-13], whereas for load-bearing elements, cement-based materials are the most often investigated [14-17]. Fly ash has been proven to have the potential to shield against electromagnetic radiation in cementitious materials [14, 18, 19]. This literature review shows the extent of research on the application of these materials in fired clay bricks. In this review article, the mechanical properties and shielding effectiveness of clay with fly ash addition are analyzed.

2 BASIC PRINCIPLES OF ELECTROMAGNETIC SHIELDING

The purpose of electromagnetic shielding is to prevent the penetration of electromagnetic radiation through a shield or barrier. This process can sometimes be demanding because the reduction of electromagnetic field levels depends mostly on the source characteristics, shield topology, and materials. In electromagnetics, the shielding effectiveness (*SE*) is a concise parameter that is generally used to quantify the shield performance [20]. The total *SE* consists of the sum of 3 different mechanisms of shielding: protection through reflection (SE_R), protection through absorption (SE_A), and protection through multiple reflections (SE_M). When an electromagnetic wave comes to the surface of the shielding material, it splits into two waves. One wave reflects from the surface and returns to the environment, while other waves penetrate throughout the material where they start to absorb (Fig. 1). Upon absorption, heat is generated due to the conversion of electromagnetic energy to thermal energy. The amount of EM radiation absorption is highly dependent on the material thickness. When the penetrated wave comes to the other surface of the shielding material, it again splits into two different waves, one being a transmitted wave and the other being reflected. These repeatable reflections are called multiple reflections. Multiple reflections have the smallest impact on EM radiation shielding. Reflectivity can sometimes be undesirable from a safety perspective for people and the environment. After contact with the surface of the medium, a reflection of the incident wave occurs because of a significant difference in the impedance between the protection material and the incident wave [18]. Losses due to reflection, absorption, and multiple reflections can be expressed as follows:

$$SE_R = 106 + 10\log\left(\frac{\sigma_r}{f\,\mu_r}\right) \tag{1}$$

$$SE_A = 20\log\left(e^{-\frac{t}{\delta}}\right) \tag{2}$$

$$SE_M = 20\log\left(1 - e^{-\frac{2t}{\delta}}\right) \quad (3)$$

where:
δ - skin depth ($\sqrt{1/\pi\mu\sigma f}$),
σ - electrical conductivity / S/m,
f – frequency,
t - barrier thickness.

When the absorption exceeds 10 dB, the loss due to multiple reflections can be neglected [21]. From the equations above. It is clear that the shielding efficiency of a clay-based material is highly related to the composite's electric conductivity and electromagnetic properties [22]. This is the reason why a material's high conductivity is generally considered to be one of the most important factors for successful EM radiation shielding. Shielding through reflection is controlled by permeability and conductivity, whereas shielding through absorption is controlled by thickness, permeability, and conductivity [23]. The magnetic characteristics of materials contribute to their absorption owing to the interaction between magnetic fields and magnetic dipoles in materials [24]. High-specific surface materials increase the volume of parts that interact with radiation, a phenomenon known as the skin effect. Using small grain fillers also increased the specific surface area of the material, enhancing the EM shielding. This is why nanosized materials are mostly used as admixtures for effective EM shielding [25-27]. There are several methods for determining the shielding parameters, such as open-field, shielded box, transmission line, and shielded room methods [28]. Fly ash has been proven to have EM shielding potential when used in concrete as an admixture [29]. Fly ash as an admixture can slightly increase the conductivity of materials because of the hematite present in fly ash (up to 10%), which consequently increases the protection against EM radiation [30]. The greatest advantage of fly ash is its low cost. Features that determine how a material reacts to electric and magnetic fields are the electromagnetic properties of materials. Some important electromagnetic properties that ensure effective electromagnetic protection include:
- dielectric permittivity
- magnetic permeability
- tangent loss
- electrical conductivity

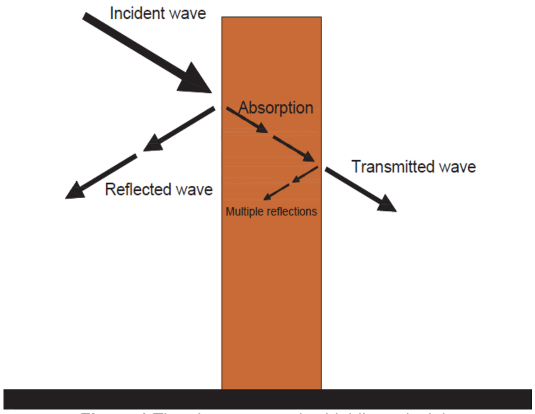

Figure 1 The electromagnetic shielding principle

The dielectric permittivity evaluates how well a material can store electrical energy in an electrical field. This property indicates the extent to which the material is polarized under an electric field. The larger the dielectric constant, the material better stores electrical energy. Magnetic permeability indicates how easily magnetic fields travel through substances. Materials with high permeability allow magnetic fields to pass through easily. The loss tangent is the amount of energy a substance loses when subjected to an electric field. If the loss tangent is high, more heat energy is lost during this process. Electrical conductivity is a widely used term that reflects how well materials transmit electricity. High conductivity enables the current to flow easily through the medium, thus improving the electromagnetic protection ability. The geometric-structural properties of a material refer to the physical properties and shape of the material that influence its behavior in the presence of electromagnetic radiation. The most important geometrical structural properties are:
- material thickness;
- porosity;
- density;
- specific material surface area.

In general, thicker materials provide better electromagnetic shielding. The thicker the material, the more efficiently it absorbs and reflects the electromagnetic waves. However, EM protection can be compromised in materials that are excessively porous. Therefore, material density is crucial for EM protection. Thus, denser materials are expected to contain more atoms per unit volume, leading to an increase in the absorption and reflection probabilities of electromagnetic waves. The specific surface area determines the extent to which a material point can "fight" electromagnetic radiation. Materials with a large specific surface area can absorb electromagnetic waves very well, precisely because a larger surface area enables stronger interaction with radiation.

3 FLY ASH

Incineration is an effective way to dispose of solid waste. This waste disposal method significantly reduces waste volume but results in two byproducts: bottom ash and ash collected from gases (fly ash). Fly ash is more harmful to the environment than lower ash. It contains heavy metals and is characterized as a toxic waste. Due to the increasing population over time [31], the problem of waste disposal has become critical. One way to partially reduce fly ash accumulation is to incorporate it into building materials [31-33]. The use of fly ash in clay materials is negligible compared to that in cementitious materials. The reason for this is that the addition of fly ash to concrete also improves other mechanical properties due to the pozzolanic activity associated with the high concentration of SiO_2 and Al_2O_3 [34]. A study by Yao et al. [35] investigated how fly ash can be reused and in what quantity. The authors report that the use of fly ash in bricks and ceramic materials in Europe is only 0.26 %, while for India and China much higher percentages are reported (6.86 % and 26.0 %). Fly ash was introduced as an admixture to some building materials in the 1940s [36, 37]. European standard EN 197-1:2011 divides fly ash, based on its chemical composition, into two types: siliceous and calcareous. The mass fraction of reactive calcium oxide (CaO) in silicon fly ash must be less than 10,0%. Additionally, the free calcium oxide content must not exceed 1.0% by weight. The mass fraction of free calcium oxide between 1.0% and 2.5% is still acceptable if the volume stability determined according to the European standard EN 196-3 is met. Reactive silicon dioxide must not exceed 25% by weight. Calcium fly ash is a fine powder that also has pozzolanic and/or hydraulic properties. It consists of reactive calcium oxide (CaO), reactive silicon dioxide (SiO_2), aluminum oxide (Al_2O_3), iron oxide (Fe_2O_3), and other compounds. The mass fraction of the reactive calcium oxide (CaO) must not be less than 10.0%. Calcium fly ash containing by weight 10% and 15.0% reactive calcium oxide (CaO) must not contain less than 25.0% silicon dioxide (SiO_2). According to the American standard ASTM C618-19, fly ash is divided into two classes, class F and class C. Class F fly ash is produced by burning younger lignite or sub-bituminous coal. It contains more than 20% CaO, and alkali and sulfate (SO_4) contents are generally lower, whereas class C fly ash is typically produced by burning older and harder anthracite and bituminous coal and contains less than 10% CaO. Fly ash particles usually vary between 0.5 μm and 150 μm, and sizes up to 50 μm are the most common [38]. According to Dondi et al. [38], to obtain better results, it is recommended that approximately equal grain sizes of fly ash and clay be used because larger differences in grain size could result in reduced homogeneity. Most studies have used equal particle sizes, except in the study by Leiva et al. [39], in which the mean grain size of fly ash was noticeably smaller than the mean clay grain size (20 μm compared to 86 μm). The authors also point out that the difference in grain size resulted in reduced homogeneity.

3.1 Density

European standard EN 771-1: 2011 divides bricks into high- and low-density bricks. Low-density bricks have a maximum density of 1.0 g/cm^3, whereas bricks with densities greater than 1.0 g/cm^3 are considered high-density bricks. Tab. 1 lists the densities of the clay bricks with the addition of fly ash in the analyzed studies, where none of the analyzed brick samples were low-density bricks. From the available results, it is noticeable that the density of the composite bricks varied with the addition of fly ash. In all the studies (Tab. 1), except for Lin et al. [40], the addition of fly ash to clay samples fired at lower temperatures (< 900 °C) resulted in a decrease in density compared with the reference sample. For example, in a study by Abbas et al. [41], firing the samples at 800 °C with the addition of 25% fly ash resulted in a density decrease to 1.20 g/cm^3, whereas the reference sample had a density of 1.35 g/cm^3. This decrease in density is logical because fly ash has a lower specific density than clay [39]. The differences in the results in some cases can be explained by the higher temperatures during the firing of the samples (Leiva et al. [39], Lin et al. [40], and Sultana et al. [42]. Due to an increase in fly ash content, the density increases. Such an increase did not occur in all studies. Lingling et al. [43], Türkel and Aksin [45], and Quesada et al. [44] reported no increase in density despite high firing temperatures. Leiva et al. [39] in their study explained the increase in density at higher temperatures due to the addition of fly ash, assuming that at higher temperatures, in addition to clay vitrification (creation of glass structure), vitrification of fly ash also begins to occur, resulting in denser and more compact material. No explanation has been found in the available literature as to why in some studies there was no density increase due to the addition of fly ash when samples were exposed at higher temperatures. One of the assumptions is that due to the different chemical compositions of fly ash, vitrification of fly ash does not occur simultaneously but potentially occurs at even higher temperatures. It should also be noted that in all the studies, due to the increase in firing temperature with the same amount of fly ash, the density of the samples increased. Leiva et al. [39] cited several reasons for this increase: a higher degree of brick sintering (a process in which fine-grained materials melt into solid material at high temperatures, Fig. 2), higher vitrification rates, and the formation of a viscous amorphous phase.

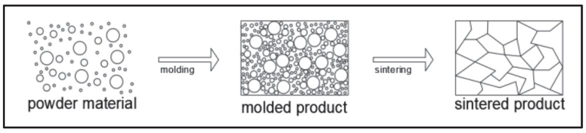

Figure 2 Mass compaction (sintering) [45]

Table 1 The density of composite clay bricks with different proportions of fly ash

Study	FA addition / %	Firing temperature / °C	Density / g/cm^3
Leiva et al. [39]	0 - 80	800	1.70 - 1.52
		900	1.72 - 1.68
		1000	1.78 - 2.10
Lin [40]	0 - 40	800	1.68 - 1.78
		900	1.80 - 1.84
		1000	1.86 - 1.94
Sultana et al. [42]	0 - 15	1050	1.70 - 1.74
Lingling et al. [43]	50 - 80	1000	1.61 - 1.35
		1050	1.72 - 1.43
Türkel and Aksin[46]	0 - 30	1000	1.65 - 1.25
Quesada et al. [44]	0 - 50	1000	1.84 - 1.79
Abbas et al. [41]	0 - 25	800	1.35 - 1.20
Queralt et al. [47]	40	900	2.0
		1000	2.30
		1100	2.40
Pereira et al. [48]	15	1050	1.34
		1075	1.37
	20	1050	1.28
		1075	1.29
Kayali[49]	100	1000	1.45
Singh et al. [59]	10 - 50	-	1.73 - 1.54

3.2 Compressive Strength

The change in compressive strength due to the addition of fly ash depends on several factors: firing temperature, type of fly ash, type of clay, etc. The compressive strength of a composite clay is closely related to its porosity and density. By analyzing Tab. 1 and Tab. 2, where the properties of density and compressive strength due to the addition of fly ash are analyzed, it can be concluded that as the density of the sample increases, so does its compressive strength. When the addition of fly ash to the clay decreases its density, it also results in a decrease in compressive strength. Similar to density, in some studies, at higher firing temperatures, an increase in compressive strength was observed as the fly ash percentage. In a study by Leiva et al. [39], the authors concluded that the increased compressive strength of samples fired at higher temperatures was due to a greater degree of sintering than that of samples fired at lower temperatures. Vitrification also significantly affects the development of compressive strength. Karaman et al. [50] analyzed the compressive strength variation of clay bricks exposed to various firing temperatures. As expected, the compressive strength increased with an increase in firing temperature. At lower temperatures, the increase in compressive strength was relatively low. Above 950 °C, a significantly higher increase occurs than at lower temperatures. For example, at temperatures of 725 °C, 750 °C, and 775 °C, the compressive strengths were 10.01 MPa, 10.30 MPa and 10.69 MPa, respectively, while at temperatures of 925 °C, 950 °C and 975 °C were 17.06 MPa, 20.01 MPa and 25.99 MPa. The authors attribute this increase to vitrification [50]. However, as with the above-mentioned density, in some studies [43, 44, 46], despite high firing temperatures, there was no increase in compressive strength. No explanations related to this phenomenon were found in the available literature. Standard EN 771-2: 2011 specifies a minimum brick strength of 5 MPa. An analysis of Tab. 2 shows that all the observed samples met the minimum compressive strength except for those reported by Leiva et al. [39] and Pawar and Gerud [51]. In a study by Leiva et al. [39], samples that did not meet the minimum compressive strength had an extremely high percentage of fly ash (80%) and the firing temperature was relatively low (800 °C), whereas in the Pawar and Gerud[51] study, bricks were used with initially low strength. The reference sample has a compressive strength of 4.35 MPa. The influence of fly ash particle size on compressive strength was investigated by Lingling et al. [43]. For the mixture of fly ash and clay at a ratio of 60:40, a compressive strength of 39.6 MPa was reported, while for the same ratio but using crushed fly ash, a compressive strength of 85.9 MPa was reported, more than double. For fly ash to clay ratios of 80:20, a smaller increment was reported, but an increase in compressive strength due to the crushing of fly ash particles was still observed. From the above research, it can be concluded that the process of sintering and vitrification is an important factor in developing the compressive strength of bricks. Increasing the firing temperature results in an increase in compressive strength, which can be attributed to a higher sintering degree, i.e., a higher degree of melting of small particles into a solid material. This phenomenon was observed in all the research results, where the compressive strength increased as the firing temperature increased for the same amount of fly ash. In certain studies, at higher firing temperatures, the compressive strength was increased by the addition of fly ash. From the above research, it can be assumed that the increase in compressive strength resulting from the addition of fly ash is due to a higher degree of vitrification of the fly ash. Due to the different chemical compositions of fly ash, vitrification does not always occur at the same temperatures, i.e. it occurs somewhere at higher or lower temperatures. In this way, it could be explained why in some studies, this increase did not occur, and in others, it has already occurred at 800 °C [52].

Table 2 Compressive strength of composite clay bricks with different proportions of fly ash

Study	FA addition / %	Firing temperature / °C	Compressive strength / MPa
Leiva et al. [39]	0 - 80	800	9.0 - 1.0
		900	13.0 - 7.0
		1000	14.0 - 46.0
Lin [40]	0 - 40	800	10.0 - 23.0
		900	22.0 - 31.0
		1000	62.0 - 63.0
Lingling et al. [43]	50 - 80	1000	50.0 - 14.7
		1050	98.5 - 25.4
Türkel and Aksin[46]	0 - 30	1000	35.9 - 7.0
Quesada et al. [44]	0 - 50	1000	60.0 - 29.0
Abbas et al. [41]	0 - 25	800	23.0 - 7.0
Kayali[49]	100	1000	43.0
Pawar, Garud. [51]	5 - 50	1000	4.4 - 0.8
Kumar et al. [53]	100	-	12.59

3.3. Flexural Strength

As expected, the flexural strength was less well investigated in relation to the compressive strength. Three studies have investigated this property: Abbas et al. [42], Türkel and Aksin [46], and Kayali [49]. In these studies, variations in compressive strength and density coincided with variations in flexural strength. Abbas et al. [41] reported an approximately linear decrease in the flexural strength due to the addition of fly ash at a firing temperature of 800 °C. Compared with the reference sample having a flexural strength of 6.1 MPa, the addition of fly ash of 5%, 15%, 25% reduced the flexural strength to 5.8 MPa, 4.2 MPa and 3.0 MPa, respectively. The addition of 25% fly ash by weight of clay reduced the flexural strength by approximately 50%. The constant drop by the addition of fly ash was attributed to the low firing temperature (800 °C). Türkel and Aksin [46], who added fly ash to clay in amounts up to 30%, also reported a constant decrease in the flexural strength. The authors used a firing temperature higher than that used by Abbas et al. [41] (800 °C) which was 1000 °C. The bending strength of the control sample without fly ash was 4.4 MPa, and with the addition of fly ash in the amounts of 10%, 20%, and 30%, it was reduced to 1.83 MPa, 1.12 MPa and 0.4 MPa, respectively. The Kayali study [49] compared bricks made of 100% fly ash with standard clay bricks. The results showed a three times higher bending strength of bricks made of 100% fly ash compared to ordinary clay bricks. The fly ash brick had a bending strength of 10.3 MPa, while the clay brick had a bending strength of 3.6 MPa.

3.4. Water Absorption

Water absorption is closely related to the strength and density of the material. The decrease in water absorption was due to the increase in material density while reducing the number of pores in the material. The sintering process significantly contributes to the reduction of pores. During sintering, the crystalline phase melts and flows by which internal pores are filled due to surface tension forces [39]. Fig. 3 shows the grain growth during the sintering process [45]. Sintering usually occurs at high temperatures from 430 °C to 850 °C [54]. Lin et al. [40] reported that water absorption was 20.0% in samples without fly ash added and fired at 800 °C. When the temperature was increased to 900 °C, the water absorption was 19.0%. As shown in Tab. 3, it can be observed that at lower firing temperatures and due to an increase in fly ash content, water absorption increases. In Abbas et al. study [41], the increase in water absorption is attributed to the high fly ash absorption ability. When samples were exposed to 800 °C, Leiva et al. [39] reported that in samples without fly ash, the absorption was 10.50%, whereas with the addition of fly ash of 80%, the absorption increased to 18.40%. However, firing at high temperatures melts silicate materials, causing a certain degree of vitrification in the samples and, together with the sintering process, reducing their porosity. Leiva et al. [39] reported that adding fly ash at higher temperatures (1000 °C) reduced water absorption. The absorption of the control sample was 8.80%, and after adding fly ash, the absorption continued to decrease. By adding 80.0% fly ash relative to the clay mass, the absorption was 6.0%. Several analyzed studies did not show a decrease in absorption at higher temperatures [43, 46]. No explanation for this behavior of the material was found in the available literature. The assumption is that the different behaviors and vitrification temperatures at which the drop in absorption occurs are hidden by the different chemical composition of the fly ash. To fully clarify this phenomenon, more detailed research is required.

Table 3 Water absorption of composite clay bricks with different amounts of fly ash additive

Study	FA addition / %	Firing temperature / °C	Water absorption / %
Leiva et al. [39]	0 - 80	800	10.50 - 1840
		900	10.00 - 16.90
		1000	8.80 - 6.00
Lin [40]	0 - 40	800	20.0 - 17.0
		900	19.0 - 18.0
		1000	14.0 - 16.5
Sultana et al. [42]	0 - 15	1050	7.60 - 10.28
Türkel and Aksin[46]	0 - 30	1000	21.0 - 38.0
Abbas et al. [41]	0 - 25	800	11.0 - 24.0
Queralt et al. [47]	40	900	9.0
		1000	3.20
		1100	1.50
Pereira et al. [48]	15	1050	32.1
		1075	29.8
	20	1050	37.1
		1075	35.6
Kayali[49]	100	1000	10
Pawar and Garud. [51]	5 - 50	1000	21.67 - 26.51
Kumar and Hooda [53]	100	1000	9.77

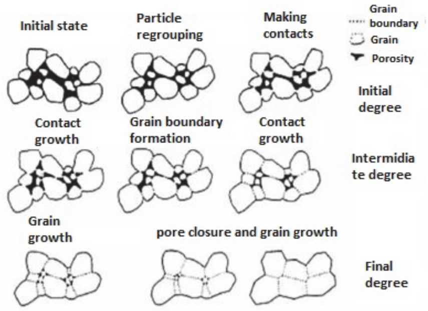

Figure 3 Grain growth during sintering process [45]

3.5. Mass Loss

Fly ash and clay lose part of their mass as a result of firing at high temperatures. There are several reasons: during firing process, at 100 °C, water evaporates from brick, organic matter of plant origin burns at temperatures of 200 °C [54], loss of CO_2 from carbonates occurs at temperatures up to 500 °C [55], and combustion of all carbons except graphite occurs up to 900°C. Tab. 4 shows the weight loss during firing. From the table, it can be inferred that clay loses more mass than fly ash. These results are expected because clay contains a higher amount of organic matter. In addition, fly ash samples were previously exposed to high temperatures, and reheating did not lead to mass changes.

Table 4 Mass loss

Study	Clay / %	Fly ash / %
Lin [40]	6.80	0.03
Lingling et al. [43]	5.66	2.82
Türkel and Aksin [46]	7.84	0.91
Quesada et al. [44]	12.51	4.74
Queralt et al. [47]	N.D.*	2.70

*N.D. - not determined

3.6 Electromagnetic Radiation Protection

Protection against EM radiation using bricks with fly ash addition is a poorly researched area. A review of the available literature did not reveal any work dealing with shielding against EM radiation of bricks with the addition of fly ash at lower frequencies (up to 10 GHz). Most studies that have dealt with the application of fly ash in building materials have investigated their ability to protect at very high frequencies of about $1,5^{20}$ Hz (Concrete [56, 57], Brick [58, 59], Glass [60, 61]). Shielding against EM radiation of fly ash bricks ([58, 59]) at high frequencies proved to be very effective when a proportion of fly ash up to 50% by weight of clay was used. Both studies concluded that successful shielding against gamma radiation can be achieved using this type of composite brick. These results cannot be extrapolated to lower frequencies, which are the focus of this review.

4 CONCLUSION

This review paper presents an overview of the research of properties of clay composite bricks with fly ash addition for potential EM shielding. A review of the available research can lead to the following conclusions:

- Adding a certain proportion of fly ash to brick at higher firing temperatures can result in increased brick strength and reduced water absorption due to the sintering process and vitrification. The maximum increase in compressive strength reported was 30 MPa (80% of fly ash, 1000 °C firing temperature). However, it should be noted that in some studies, this increase did not occur. The maximum decrease in compressive strength reported was 73,1 MPa (80% of fly ash, 1050 °C firing temperature [43]). As no research has explained why fly ash addition sometimes resulted in strength increase and sometimes in decrease, a more detailed investigation of this phenomenon should be conducted. One of the assumptions is that fly ashes chemical composition is critical to the behavior of clay composites. All authors who investigated the influence of fly ash on flexural strength reported a constant drop;

- The thorough investigation conducted during this literature review identified a notable deficiency in current research: no studies have investigated the EM shielding capabilities of fly ash-enhanced clay bricks at non-ionizing radiation frequencies. The current literature primarily examines the consequences of ionizing radiation. This gap that has been identified suggests a potential area for future research, indicating the possibility for creative studies to investigate and create new uses of fly ash in clay composites. The absence of studies in this specific field serves as a strong foundation for additional research, which has the potential to greatly improve the comprehension and application of these materials for enhanced electromagnetic shielding, as well as improve their physical and mechanical characteristics.

Acknowledgment

This work has been supported by Operational Program Competitiveness and Cohesion 2014 - 2020., Investing in science and innovation KK.01.1.1.04: "Development and application of advanced building materials for the construction of healthy buildings: protection against non-ionizing radiation" ref. no. KK.01.1.1.04.0105.

5 REFERENCES

[1] Cerezci, O., Kanberoglu, B., & Yener, S. C. (2015). Analysis on trending electromagneti c exposure levels at homes and proximity next to base stations along three years in a city. *Journal of Environmental Engineering and Landscape Management, 23*(1), 71-81. https://doi.org/10.3846/16486897.2014.959523

[2] Zamanian, A. & Hardiman, C. (2005). Electromagnetic Radiation and Human Health: A Review of Sources and Effects. *High Frequency Electronics*.

[3] Hardell, L. & Sage, C. (2008). Biological effects from electromagnetic field exposure and public exposure standards. *Biomedicine and Pharmacotherapy, 62*(2), 104-109. https://doi.org/10.1016/j.biopha.2007.12.004

[4] Lin, J. C. (2016). Human exposure to RF, microwave, and millimeter-wave electromagnetic radiation [Health Effects]. *IEEE Microwave Magazine, 17*(6), 32-36. https://doi.org/10.1109/MMM.2016.2538540

[5] Baan, R., Grosse, Y., Lauby-Secretan, B., El Ghissassi, F., Bouvard, V., Benbrahim-Tallaa, L., Guha, N., Islami, F., Galichet, L., & Straig, K. (2011). Carcinogenicity of radiofrequency electromagnetic fields. *The Lancet Oncology, 12*(7), 624-626. https://doi.org/10.1016/s1470-2045(11)70147-4

[6] Haarala, C., Bergman, M., Laine, M., Revonsuo, A., Koivisto, M., & Hämäläinen, H. (2005). Electromagnetic field emitted by 902 MHz mobile phones shows no effects on children's cognitive function. *Bioelectromagnetics, 26*(7), 144-150. https://doi.org/10.1002/bem.20142

[7] Vecchia, P. (2007). Exposure of humans to electromagnetic fields. Standards and regulations. *Annali Dell'Istituto Superiore Di Sanita, 43*(3), 260-267.

[8] Park, J., Hu, X., Torfeh, M., Okoroanyanwu, U., Arbabi, A., & Watkins, J. J. (2020). Exceptional electromagnetic shielding efficiency of silver coated carbon fiber fabrics: Via a roll-to-roll spray coating process. *Journal of Materials Chemistry C, 8*(32), 11070-11078. https://doi.org/10.1039/d0tc02048F

[9] Radivojevic, V. M., Rupcic, S., Milicevic, I., & Otkovic, I. I. (2020). Electromagnetic wave attenuation by plane concrete in the frequency range of 4G and 5G systems. *Proceedings of 2020 International Conference on Smart Systems and Technologies, SST 2020*, 31-38. https://doi.org/10.1109/SST49455.2020.9264076

[10] Roh, J. S., Chi, Y. S., Kang, T. J., & Nam, S. W. (2008). Electromagnetic Shielding Effectiveness of Multifunctional Metal Composite Fabrics. *Textile Research Journal, 78*(9), 825-835. https://doi.org/10.1177/0040517507089748

[11] Wang, Y., Wang, W., Ding, X., & Yu, D. (2020). Multilayer-structured Ni-Co-Fe-P/polyaniline/polyimide composite fabric for robust electromagnetic shielding with low reflection characteristic. *Chemical Engineering Journal, 380*, 122553. https://doi.org/10.1016/j.cej.2019.122553

[12] Gao, J., Luo, J., Wang, L., Huang, X., Wang, H., Song, X., Hu, M:, Tang, L.-C., & Xue, H. (2019). Flexible, superhydrophobic and highly conductive composite based on non-woven polypropylene fabric for electromagnetic interference shielding. *Chemical Engineering Journal, 364*, 493-502. https://doi.org/10.1016/j.cej.2019.01.190

[13] Lu, L., Xing, D., Teh, K. S., Liu, H., Xie, Y., Liu, X., & Tang, Y. (2017). Structural effects in a composite nonwoven fabric on EMI shielding. *Materials and Design, 120*, 354-362. https://doi.org/10.1016/j.matdes.2017.02.025

[14] Cao, J. & Chung, D. D. L. (2004). Use of fly ash as an admixture for electromagnetic interference shielding. *Cement and Concrete Research, 34*(10), 1889-1892. https://doi.org/10.1016/j.cemconres.2004.02.003

[15] Micheli, D., Pastore, R., Vricella, A., Morles, R. B., Marchetti, M., Delfini, A., Moglie, F., & Mariani Primiani, V. (2014). Electromagnetic characterization and shielding effectiveness of concrete composite reinforced with carbon nanotubes in the mobile phones frequency band. *Materials Science and Engineering B: Solid-State Materials for Advanced Technology, 188*, 119-129. https://doi.org/10.1016/j.mseb.2014.07.001

[16] Zhang, Y., Wang, X. H. & Luo, J. H. (2014). Research on absorbing property of cement-based material blending with nano-TiO2 and steel fibers. *Advanced Materials Research, 853*, 207-211. https://doi.org/10.4028/www.scientific.net/AMR.853.207

[17] Li, X., Kang, Q., & Zhou, C. (2003). Research on absorbing properties of the concrete shielding material at 3mm wave bands. *Proceedings - Asia-Pacific Conference on Environmental Electromagnetics, CEEM 2003*, 536-540. https://doi.org/10.1109/CEEM.2003.238407

[18] Wanasinghe, D., Aslani, F., & Ma, G. (2020). Effect of water to cement ratio, fly ash, and slag on the electromagnetic shielding effectiveness of mortar. *Construction and Building Materials, 256*, 119409. https://doi.org/10.1016/j.conbuildmat.2020.119409

[19] Lingvay, I., Velciu, G., Lingvay, D., Bors, A. M., & Moanta, A. (2019). Increasing shielding capabilities of cement mortars by fly ash addition. *Revista de Chimie, 70*(8), 2742-2746. https://doi.org/10.37358/rc.19.8.7419

[20] Montgomery, D. C. & Runger, G. C. (2008). Applied statistics and probability for engineers.

[21] Joshi, A. & Datar, S. (2015). Carbon nanostructure composite for electromagnetic interference shielding. *Pramana - Journal of Physics, 84*(6), 1099-1116. https://doi.org/10.1007/s12043-015-1005-9

[22] Guan, H., Liu, S., Duan, Y., & Cheng, J. (2006). Cement based electromagnetic shielding and absorbing building materials. *Cement and Concrete Composites, 28*(5), 468-474. https://doi.org/10.1016/j.cemconcomp.2005.12.004

[23] Fenical, G. (2010). The Basic Principles of Shielding What is EMI ?

[24] Chung, D. D. L. (2020). Materials for electromagnetic interference shielding. *Materials Chemistry and Physics, 255*, 123587.

https://doi.org/10.1016/j.matchemphys.2020.123587
[25] Li, Z., Dong, S., Wang, X., Yu, X., & Han, B. (2020). Electromagnetic Wave-Absorbing Property and Mechanism of Cementitious Composites with Different Types of Nano Titanium Dioxide. *Journal of Materials in Civil Engineering, 32*(5), 04020073. https://doi.org/10.1061/(asce)mt.1943-5533.0003133
[26] Li, Z., Han, B., Yu, X., Dong, S., Zhang, L., Dong, X., & Jinping, O. (2017). Effect of nano-titanium dioxide on mechanical and electrical properties and microstructure of reactive powder concrete. *Materials Research Express, 4*(9), 095008. https://doi.org/10.1088/2053-1591/aa87db
[27] Sharif, M., Ping, C. S., & Leong, K. Y. (2017). Electromagnetic interference shielding performances of MWCNT in concrete composites. *Solid State Phenomena, 266*, 283-286. https://doi.org/10.4028/www.scientific.net/SSP.266.283
[28] Kondawar, S. B. & Modak, P. R. (2020). Theory of EMI shielding *Materials for Potential EMI Shielding Applications*, 9-25. https://doi.org/10.1016/b978-0-12-817590-3.00002-6
[29] Vrdoljak, I., Varevac, D., Miličević, I., & Čolak, S. (2022). Concrete-based composites with the potential for effective protection against electromagnetic radiation: A literature review. *Construction and Building Materials, 326*. https://doi.org/10.1016/j.conbuildmat.2022.126919
[30] Ozturk, M., Karaaslan, M., Akgol, O., & Sevim, U. K. (2020). Mechanical and electromagnetic performance of cement based composites containing different replacement levels of ground granulated blast furnace slag, fly ash, silica fume and rice husk ash. *Cement and Concrete Research, 136*, 106177. https://doi.org/10.1016/j.cemconres.2020.106177
[31] Ferreira, C., Ribeiro, A., & Ottosen, L. (2003). Possible applications for municipal solid waste fly ash. *Journal of Hazardous Materials, 96*, 201-216. https://doi.org/10.1016/S0304-3894(02)00201-7
[32] Barišić, I., Grubeša, I. N., Dokšanović, T., & Marković, B. (2019). Feasibility of agricultural biomass fly ash usage for soil stabilisation of road works. *Materials, 12*(9). https://doi.org/10.3390/ma12091375
[33] Ristić, N., Grdić, Z., & Topličić-Ćurčić, G. (2015). Hydro-Abrasive Resistance and Mechanical Properties of Concrete With Added Fly Ash. *Elektronički Časopis Građevinskog Fakulteta Osijek, 11*, 1-8. https://doi.org/10.13167/2015.11.1
[34] Siddique, R. (2002). Effect of fine aggregate replacement with Class F fly ash on the mechanical properties of concrete. *Cement and Concrete Research, 33*(4), 539-547. https://doi.org/10.1016/S0008-8846(02)01000-1
[35] Yao, Z. T., Ji, X. S., Sarker, P. K., Tang, J. H., Ge, L. Q., Xia, M. S., & Xi, Y. Q. (2015). A comprehensive review on the applications of coal fly ash. *Earth-Science Reviews, 141*, 105-121. https://doi.org/10.1016/j.earscirev.2014.11.016
[36] Kluge, R. W., Sparks, M. M.,, & Tuma, E. C. (1949). Lightweight Aggregate Concrete. *Journal Proceedings, 45*(5), 625-642. https://doi.org/10.14359/12175
[37] Davis, R. E., Carlson, R. W., Kelly, J. W., & Davis, H. E. (1937). Properties Of Cements And Concretes Containing Fly Ash. *Journal Proceedings, 33*(5), 577-612. https://doi.org/10.14359/8435
[38] Dondi, M., Marsigli, M., & Fabbri, B. (1997). Recycling of Industrial and urban wastes in brick production : A review. *Tile & Brick International, 13*(3), 218-225.
[39] Leiva, C., Arenas, C., Alonso-Fariñas, B., Vilches, L. F., Peceño, B., Rodriguez-Galán, M., & Baena, F. (2016). Characteristics of fired bricks with co-combustion fly ashes. *Journal of Building Engineering, 5*, 114-118. https://doi.org/10.1016/j.jobe.2015.12.001
[40] Lin, K. L. (2006). Feasibility study of using brick made from municipal solid waste incinerator fly ash slag. *Journal of Hazardous Materials, 137*(3), 1810-1816. https://doi.org/10.1016/j.jhazmat.2006.05.027
[41] Abbas, S., Saleem, M. A., Kazmi, S. M. S., & Munir, M. J. (2017). Production of sustainable clay bricks using waste fly ash: Mechanical and durability properties. *Journal of Building Engineering, 14*, 7-14. https://doi.org/10.1016/j.jobe.2017.09.008
[42] Sultana, M. S., Hossain, M. I., Rahman, M. A., & Khan, M. H. (2014). Influence of Rice Husk Ash and Fly Ash on Properties of Red Clay. *Journal of Scientific Research, 6*(3), 421-430. https://doi.org/10.3329/jsr.v6i3.15343
[43] Lingling, X., Wei, G., Tao, W., & Nanru, Y. (2005). Study on fired bricks with replacing clay by fly ash in high volume ratio. *Construction and Building Materials, 19*(3), 243-247. https://doi.org/10.1016/j.conbuildmat.2004.05.017
[44] Eliche-Quesada, D., Sandalio-Pérez, J. A., Martínez-Martínez, S., Pérez-Villarejo, L., & Sánchez-Soto, P. J. (2018). Investigation of use of coal fly ash in eco-friendly construction materials: fired clay bricks and silica-calcareous non fired bricks. *Ceramics International*, *44*(4), 4400-4412. https://doi.org/10.1016/j.ceramint.2017.12.039
[45] Marković, I. (2009). Utjecaj temperature sinteriranja na tvrdoću aluminij oksidne keramike. Zagreb.
[46] Türkel, S. & Aksin, E. (2012). A comparative study on the use of fly ash and phosphogypsum in the brick production. *Sadhana - Academy Proceedings in Engineering Sciences, 37*(5), 595-607. https://doi.org/10.1007/s12046-012-0099-8
[47] Queralt, I., Querol, X., López-Soler, A., & Plana, F. (1997). Use of coal fly ash for ceramics: A case study for a large Spanish power station. *Fuel, 76*(8), 787-791. https://doi.org/10.1016/s0016-2361(97)00024-0
[48] Fernández-Pereira, C., De La Casa, J. A., Gómez-Barea, A., Arroyo, F., Leiva, C., & Luna, Y. (2011). Application of biomass gasification fly ash for brick manufacturing. *Fuel, 90*(1), 220-232. https://doi.org/10.1016/j.fuel.2010.07.057
[49] Kayali, O. (2005). High Performance Bricks from Fly Ash. *World of Coal As*.
[50] Karaman, S., Gunal, H., & Ersahin, S. (2006). Assesment of clay bricks compressive strength using quantitative values of colour components. *Construction and Building Materials, 20*(5), 348-354. https://doi.org/10.1016/j.conbuildmat.2004.11.003
[51] Pawar, A. S. & Garud, D. B. (2014). Engineering Properties of Clay Bricks With Use of Fly Ash. *International Journal of Research in Engineering and Technology, 03*, 75-80. https://doi.org/10.15623/ijret.2014.0321016
[52] Lin, K. L. (2005). Effects of SiO2 and Al2O3 on the hydration characteristics of MSWI fly ash slag. *J. Ind. Eng. Chem*, 834-840.
[53] Kumar, R. & Hooda, N. (2014). An Experimental Study on Properties of Fly Ash Bricks, 56-67. https://doi.org/10.17758/uruae4.ae10181011
[54] Miletić, I. (2007). Struktura keramičkoga materijala. Sisak.
[55] Schulte, E. E. & Hopkins, B. G. (2015). Estimation of Soil Organic Matter by Weight Loss-On-Ignition, *49*(46), 21-31. https://doi.org/10.2136/sssaspecpub46.c3
[56] Akkurt, I. & Akyildirim, H. (2012). Radiation transmission of concrete including pumice for 662, 1173 and 1332 keV gamma rays. *Nuclear Engineering and Design, 252*, 163-166. https://doi.org/10.1016/j.nucengdes.2012.07.008
[57] Singh, K., Singh, S., Dhaliwal, A. S., & Singh, G. (2015). Gamma radiation shielding analysis of lead-flyash concretes. *Applied Radiation and Isotopes, 95*, 174-179. https://doi.org/10.1016/j.apradiso.2014.10.022
[58] Mann, H. S., Brar, G. S., Mann, K. S., & Mudahar, G. S. (2016). Experimental Investigation of Clay Fly Ash Bricks for Gamma-Ray Shielding. *Nuclear Engineering and Technology, 48*(5), 1230-1236. https://doi.org/10.1016/j.net.2016.04.001

[59] Mann, K. S., Kaur, B., Sidhu, G. S., & Kumar, A. (2013). Investigations of some building materials for γ-rays shielding effectiveness. *Radiation Physics and Chemistry, 87*, 16-25. https://doi.org/10.1016/j.radphyschem.2013.02.012
[60] Tuscharoen, S., Kaewkhao, J., Limkitjaroenporn, P., Limsuwan, P., & Chewpraditkul, W. (2012). Improvement of BaO:B 2O 3:Fly ash glasses: Radiation shielding, physical and optical properties. *Annals of Nuclear Energy, 49*, 109-113. https://doi.org/10.1016/j.anucene.2012.05.017
[61] Kumar, A. (2017). Gamma ray shielding properties of PbO-Li2O-B2O3 glasses. *Radiation Physics and Chemistry, 136*, 50-53. https://doi.org/10.1016/j.radphyschem.2017.03.023

Contact information:

Ivan VRDOLJAK
(Corresponding author)
Faculty of Civil Engineering and Architecture,
Josip Juraj Strossmayer University of Osijek,
Vladimira Preloga 3, 31000 Osijek, Croatia
E-mail: ivrdoljak@gfos.hr

Ivana MILIČEVIĆ, Assosciate professor
Faculty of Civil Engineering and Architecture,
Josip Juraj Strossmayer University of Osijek,
Vladimira Preloga 3, 31000 Osijek, Croatia
E-mail: ivana.milicevic@gfos.hr

Damir VAREVAC, Full professor
Faculty of Civil Engineering and Architecture,
Josip Juraj Strossmayer University of Osijek,
Vladimira Preloga 3, 31000 Osijek, Croatia
E-mail: dvarevac@gfos.hr

Stanko ČOLAK
Faculty of Civil Engineering, Architecture and Geodesy,
University of Mostar, Faculty of Civil Engineering,
Matice hrvatske bb, 88000 Mostar, Bosnia and Herzegovina
E-mail: stanko.colak@gf.sum.ba