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Comparison of low cost shielding-absorbing cement paste building materials in X-band frequency range using a variety of wastes

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Abstract

General concern for potential health effects of 24 h electromagnetic fields (EMF) exposure has increased over the last few years. This has led to the necessity of developing low cost electromagnetic interference (EMI) shielding and especially absorbing building materials. In the present study, the utilization of metallurgical slags and scrap tire wastes in cement paste for this purpose was investigated. Chemical and mineralogical analyses were performed to characterize all materials examined in this work. The results showed that cement paste specimens prepared by the addition of slags exhibited better shielding efficiency than similar ones based on tires waste, while absorption performance was increased and reached 80–85% for one admixture containing each waste respectively, all tested in the same X-band frequency range (8–12 GHz). Finally, the technological and environmental requirements for these cement based building materials were also established.

Keywords: B. Composites; C. Electrical properties; C. Magnetic properties; D. Traditional ceramics

1. Introduction

In 1839 Charles Goodyear discovered that natural rubber could be joined with sulphur (using ZnO as catalyst) to prevent chains from sliding. This process was called vulcanization and led the way in manufacturing tires. In Greece, more than 58,500 tons of worn mobile tires are generated annually, and this figure is expected to increase in the coming years along with an expected increase in traffic. Unfortunately, a large part of these tires often gets illegally discarded at dumpsites and since tires are not biodegradable, they will remain in dumpsites with very little degradation over time, presenting a continuing environmental hazard. Moreover in Greece, several laws and directives have been recently issued, concerning the means and terms for the alternative management of worn tires from automobiles all in compliance with the equivalent European Directives, which forbid the deposition of worn tires in landfills by mid-2006. Furthermore, according to these laws and directives, land filling of whole worn tires is forbidden (even for small particles of tires). Finally due to the severity of the environmental hazards that occurred, a legislated system was established in Greece since 2002, which deals with tire management and whose target is the application of the laws issued [1,2].

During the last decades, the steelmaking industries in EU countries have been transformed, as electric arc furnaces have largely replaced blast furnaces and LD (Linz–Donawitz) converters, leading to the appearance of new by-products: electric arc furnace (EAF) oxidizing slag or black slag and land furnace (LF) slag. Electric arc furnaces currently account for more than 40% of global steel production. In the interests of sustainable development, efforts must be made to reuse this product in various ways so as to contribute to a recycling-oriented society and to avoid excessive amounts being dumped in the environment [3].

Studies on addition of EAF as aggregates and LFS as binder on high strength and high performance concrete mixtures have been conducted with very satisfactory results concerning physical and mechanical characteristics of the mixtures produced [4].

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In Greece, there are five steel plants which are spread in North, Central and South Greece [5]. Only in the year 2009 these plants were estimated that had produced over 300.000 tones of electric arc and land furnace slags in general [6].

On the other hand, the strength of electromagnetic fields (EMF) to which humans are exposed has been increasing gradually with the growth of electric power generation and transmission, the development of new telecommunication systems, and advances in medical and industrial applications. Given the rapidly expanded use of such technology, any potential health impacts need to be properly assessed, ideally prior to widespread human exposure. Moreover, there is a general public concern about potential health effects of daily exposure, especially for sensitive groups in human population such as children or adults due to their occupational exposure to EMF. Unfortunately, this technological development and its applications usually outpace epidemiological and biological research and the development of proper health risk assessments and consequent standards [7]. Furthermore, at frequencies from 1 to 10 GHz, with wavelengths equal to or longer than the human body, much of the energy is absorbed below the superficial dermis. In this range, the threshold temperature for cellular injury (about 42 °C) is below the threshold for pain (about 45 °C). Hence, cutaneous perception of RF energy may not be a reliable response, which protects against potentially harmful levels of RF radiation at the lower microwave frequencies [8].

Consequently, considering the increasing severity of electromagnetic environment pollution, the study on building materials that can prevent electromagnetic interference (EMI) has caused great attention. Numerous studies have been carried out over the recent years into the development of cement based electromagnetic shielding and absorbing materials containing wastes in general as an admixture, nevertheless few studies have been reported regarding low cost cement based electromagnetic absorbing materials containing tires and slag wastes measured in open air [9].

Finally, the objective of this study was (i) to investigate the use of rubber tire wastes and metallurgical slag wastes from Greek steelmaking and automobile tire industries into plain cement paste as an admixture without any other cost procedures and reagents, in order to develop shielding and especially absorbing materials in X-band frequency range (8–12 GHz), characterized via both waveguide and free space measurements (ii) to maintain, as much as possible, the technological characteristics of this cement paste as a common building material and (iii) to examine if this cement paste is environmentally accepted.

2. Materials and methods

2.1. Sample preparation

For the investigation of the mineralogical characteristics of metallurgical slags and tire rubber wastes, two average samples were taken from two Greek plants, respectively [6,10]. The rubber tire samples were generated from the mechanical shredding of rubber waste and dried in a box dryer at 40 °C peak temperature while EAF and LF slag samples were mixed and homogenized in a cone mixture and dried in a box dryer at 105 °C peak temperature, respectively. Finally, both the automobile tire waste and metallurgical slag samples were kept in plastic bags in order to be used for the preparation of the cement paste building materials.

Table 1
Chemical composition of European tire.

Composition	Percentage (%)
Styrene–butadiene rubber (SBR)	60–65
Carbon black	29–31
Zinc oxide (ZnO)	1.9–3.3
Sulphur	1.1–2.1
Extender oil	2

2.2. Background data for scrap tire composition

Scrap tires waste is consisted of various components. A typical composition of a North American and European tire is presented in Table 1 while a typical elemental analysis of scrap tires is presented in Table 2, respectively [11]. Regarding rubber, Passenger tires tend to contain more synthetic rubber than natural rubber; truck tires consist of more natural rubber; and off-the-road (OTR) tires, including heavy mining tires as well as agricultural and industrial tires, have nearly no synthetic rubber.

2.3. Analytical methods

Mineralogical analyses of the EAF–LF slag samples, plain cement paste and tire waste average sample (Fig. 1a–d) were performed, respectively, by using randomly oriented samples, on a Philips PW 1820/00 diffractometer, equipped with a PW1710/00 controller. CuKα radiation and a Ni-filter were used. The samples were scanned over an interval of 3–63° 2θ at a scanning speed of 1.2°/min. Chemical composition of the cement paste (Table 3), the EAFS and LFS samples separately and 3 mixtures containing 25–75 (mix 1), 50–50 (mix 2) and 75–25 (mix 3) wt.% of EAFS and LFS (Table 4) were determined, respectively, by using a Perkin Elmer AAnalyst 800 atomic absorption spectrophotometer, either with flame or graphite furnace Furthermore, partical size analysis of mixed slags and tire waste samples were determined, respectively, by using an Endecott's octagon digital vibrating shaker and various testing sieves with different mesh (Table 5).

Table 2
Elemental analysis of scrap tire.

Carbon	Hydrogen	Oxygen	Nitrogen	Sulphur	Ash
85.16	7.27	0.54	0.38	2.30	4.36

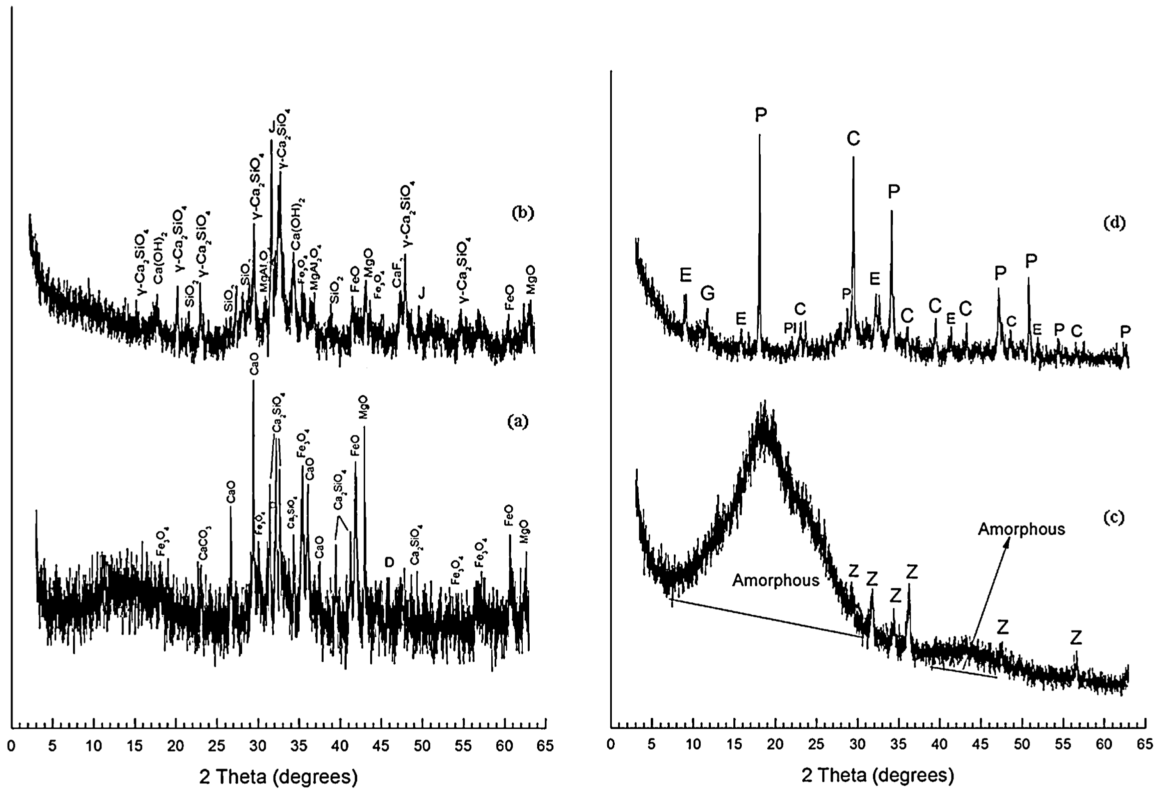

Fig. 1. (a–d) X-ray diffractogramm of: EAF slag dust samples (a). Main phases identified: FeO, Fe_3O_4, Ca_2SiO_4, D and CaO. LF slag dust samples (b). Main phases identified: J: Jasmundite, γ-Ca_2SiO_4, $Ca(OH)_2$, FeO, $MgAl_2O_4$ and Fe_3O_4. Tire waste average sample (c). Main phases identified: Z: ZnO. Plain cement paste (d). Main phases identified: E: ettringite, P: portlandite, C: calcite, Pl: palgioclase, G: gypsum.

Table 3
Chemical composition of cement paste.

Chemical composition (wt.%)							
Fe_2O_3	CaO	Al_2O_3	SiO_2	Na_2O	K_2O	MgO	LOI[a]
3.64	61.45	3.65	22.48	0.49	0.35	2.58	5.36

[a] Loss on ignition.

Table 4
Chemical composition of EAF, LF and mixed slag samples.

Chemical composition (wt.%)											
	FeO	MnO	Cr_2O_3	CaO	Al_2O_3	SiO_2	Na_2O	K_2O	P_2O_5	MgO	LOI[a]
EAF slag											
Sample 1	40.85	5.03	0.81	21.66	8.13	12.30	0.12	0.03	0.11	3.95	7.01
Sample 2	40.32	6.18	0.94	21.35	7.56	11.42	0.19	0.08	0.15	4.05	7.76
LF slag											
Sample 1	15.45	1.36	0.19	47.90	4.46	15.03	0.18	0.12	0.05	7.96	7.3
Sample 2	16.96	1.62	0.21	45.87	3.72	15.92	0.21	0.18	0.06	8.02	7.23
Mix 1 (EAF–LF)											
25–75	21.77	2.25	0.34	41.83	5.31	14.17	0.16	0.10	0.06	6.87	7.14
Mix 2 (EAF–LF)											
50–50	28.97	3.16	0.49	34.38	6.22	13.51	0.15	0.07	0.08	5.89	7.07
Mix 3 (EAF–LF)											
75–25	35.06	4.08	0.65	27.98	7.15	12.87	0.13	0.05	0.09	4.91	7.02

[a] Loss on ignition.

Table 5
Partical size analyses of mixed slag and tire waste samples.

Partical size (mm)	Scrap tire sample 1	Scrap tire sample 2	Mix 1 (EAF–LF) 25–75	Mix 2 (EAF–LF) 50–50	Mix 3 (EAF–LF) 75–25
>2.0	0.64	0.48	3.51	3.64	2.85
2.0–1.4	2.79	2.11	5.73	5.42	6.71
1.4–1.0	5.07	6.46	8.86	9.79	9.22
1.0–0.5	40.43	41.21	15.79	17.36	15.37
0.5–0.25	25.88	23.79	35.27	38.75	34.19
0.25–0.1	22.37	22.82	27.42	21.73	28.75
<0.1	2.82	3.13	3.42	3.31	2.91

2.4. Cement paste specimens preparation

The cement used was ordinary Portland cement (Type I) from TITAN SA. The water–cement ratio was kept constant at 0.35. No aggregate was used in any form, whether fine or coarse. The scrap tire waste samples were < 1000 μm in size in order to avoid as much as possible decrement in mechanical properties and workability of the cement paste specimens, although according to the literature this was inevitable [12–15].

Therefore, cement paste specimens were prepared (water/cement ratio = 0.36) with the addition of 2.5 and 5% by mass of scrap tire waste. On the other hand, according to literature, slags in general and especially LFS can develop certain cementitious hydraulic properties and must be recycled in construction and civil engineering applications [16–18].

Since the objective of this study was to develop low cost shielding and especially absorbing materials in X-band frequency range and to maintain mechanical and technological properties rather than increase them, a small addition of 5% by mass of the prementioned mixes (mix 1, 2 and 3 – Table 4) was chosen for each cement paste specimen respectively with a water/cement ratio = 0.36. A rotary mixer with a flat beater was used for mixing. Cement, water, tire waste and mixed slag samples were mixed for 3 min. After pouring into oiled molds (30 × 30 × 5 cm for shielding efficiency measurements and 2.5 × 2.5 × 10 cm and 2.5 × 2.5 × 2.5 cm for mechanical properties respectively), an external electrical vibrator was used to facilitate compaction and decrease the number of air bubbles. Finally, for shielding efficiency and absorption measurements, mechanical characteristics such as compressive and flexural strength, and scanning electron microscopy (by using a Scanning Electron Microscope JEOL JSM-840 connected to an X-ray Energy Dispersion Spectrometer-EDS LINK-AN 10000) the specimens were cured for 28 days at 20 ± 2 °C and 100% relative humidity.

2.5. Electrical and magnetic properties measurements of cement paste samples in X-band frequency range

Measurements of electrical and magnetic properties have been performed by measuring reflection and transmission properties of the cement paste building materials with the aid of a Hewlett-Packard HP-8720 (50 MHz–20 GHz) network analyzer (Fig. 2a). Each cement paste sample was placed in a small WR90 waveguide part of length equal to 3.75 mm and a cross-section of 22.86 × 10.16 mm. Using TRM calibration, the *S*-parameters (reflection and transmission coefficients) of the samples have been measured (both amplitude and phase). Finally, the analytical expressions relating the *S*-parameter matrix to the unknown material properties [19] have been inverted to provide estimates of the complex relative dielectric permittivity and magnetic permeability and also the electric and magnetic loss tangents.

2.6. Shielding efficiency, absorption and reflection measurements of small cement paste walls in X-band frequency range

For a better approximation of real conditions (e.g. constructions – houses near radio and television transmitters) a second free-space measurement approach was chosen. From the measurement of *S*-parameters, shielding efficiency and absorption–reflection coefficients of the cement paste small walls (30 × 30 × 3) were calculated. The 6 small dimensioned cement paste walls were clamped on a home-made sample holder (brass) and were placed at a distance of 10 cm from the edge of the radiating antenna and equally 10 cm from the edge of the receiving antenna to approximately ensure free space conditions. The sample position is at the maximum of the beam where the field can be considered planar and the incidence normal (Fig. 2b). Using the HP-8720 (50 MHz–20 GHz) network analyzer, the *S*-parameters, S_{11} and S_{21}, were measured. Power reflection coefficient, R, and transmission coefficient, T, are given as $R = |S_{11}|^2$ and $T = |S_{21}|^2$. The power absorption coefficient, A, can be obtained from the simple relation $A + R + T = 1$. The EMI shielding efficiency, SE, is defined as the ratio of the power of the incident wave P_I to that of the transmitted wave P_T [20].

$$\mathrm{SE} = 10 \log\left(\frac{P_I}{P_T}\right) (\mathrm{dB}) \quad (1)$$

From the above equation, it is evident that the shielding effectiveness of a cement based material correlates closely to the electric conductivity and the electromagnetic parameters of the composite. In contrast to a polymer matrix, which is electrically insulating, the cement matrix is slightly conductive and its shielding effectiveness is closely pertinent to its conductivity.

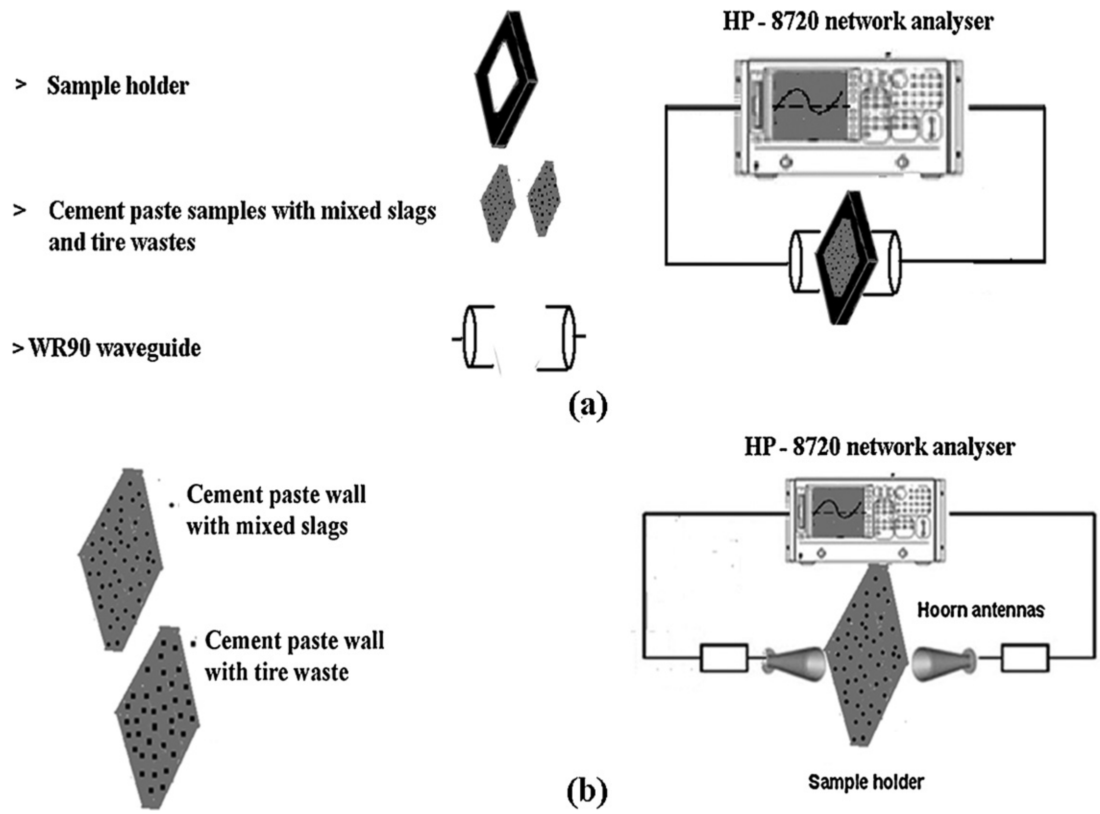

Fig. 2. (a and b) Schematic presentation of electric and magnetic properties of cement paste samples with mixed slags and wastes and SE, absorption and reflection measurements of cement paste walls all in 8–12 GHz frequency range.

2.7. Leaching test

Leaching tests on EAF and LF slags, scrap tires, and cement paste specimens with 5 wt.% addition of the above wastes were performed according to EN 12457 [21].

3. Results and discussion

3.1. Electrical and magnetic properties measurements of cement paste samples in X-band frequency range

In general the accuracy of electric and magnetic properties measurements in materials originated form wastes, is limited due to impurity, large partical size distribution and inhomogeneity of the wastes. This was particularly the case for measurements of low values of imaginary parts of complex electric and magnetic properties and the associated loss tangents. However, there was a strong indication for an electric conductivity in all samples and also, in most cases, a slight but noticeable magnetic conductivity, appropriate enough for making these cement paste materials suitable for EMI shielding applications (in X-band frequency range). Specifically, as presented in Fig. 3(a–c) and Table 6, the average electric loss tangent ($\tan \delta_e$) for cemtire 2.5 wt.% was 0.020 while for cemslags 5 wt.% mix 2 it reached a value of 0.081. Materials with such high electric loss tangent can be a perfect candidate as electromagnetic absorbing materials. Furthermore, the average magnetic loss tangent for cemtire 2.5 wt.% was 0.027 while for cemslags 5 wt.% mix 3 it reached a value of as high as 0.067, indicating possible additional electromagnetic reduction by means of magnetic losses. In particular, the increase in magnetic loss tangent $\tan \delta_m$ can be attributed mainly to the higher percentage of magnetite containing in mix 3 (Fig. 3a and b, and Table 4) Finally, in the case of cemslags 5 wt.% mix 3 and cemtire 5 wt.% electric and magnetic loss tangents were comparable, indicating a possibility of better shielding and absorption performance for these materials in X-band frequency range.

3.2. Shielding efficiency, absorption and reflection measurements of small cement paste walls

3.2.1. Shielding efficiency

The variation in EMI shielding of 6 cement paste walls with different wt.% in addition of wastes in general (slags–scrap tires), in the X-band frequency range was measured and the respective results are shown in Fig. 4. Higher values of shielding effectiveness in decibels are associated with lower amounts of electromagnetic energy passing through the sample, i.e. 10 dB means that 10% of the incident power passes the sample, while 20 dB indicates a percentage of only 1%. The measured values of shielding effectiveness can be considered the combined result of electromagnetic reflection from the material's surface and absorption of the EM energy within the sample, via the additional mechanism of multiple internal reflections [22].

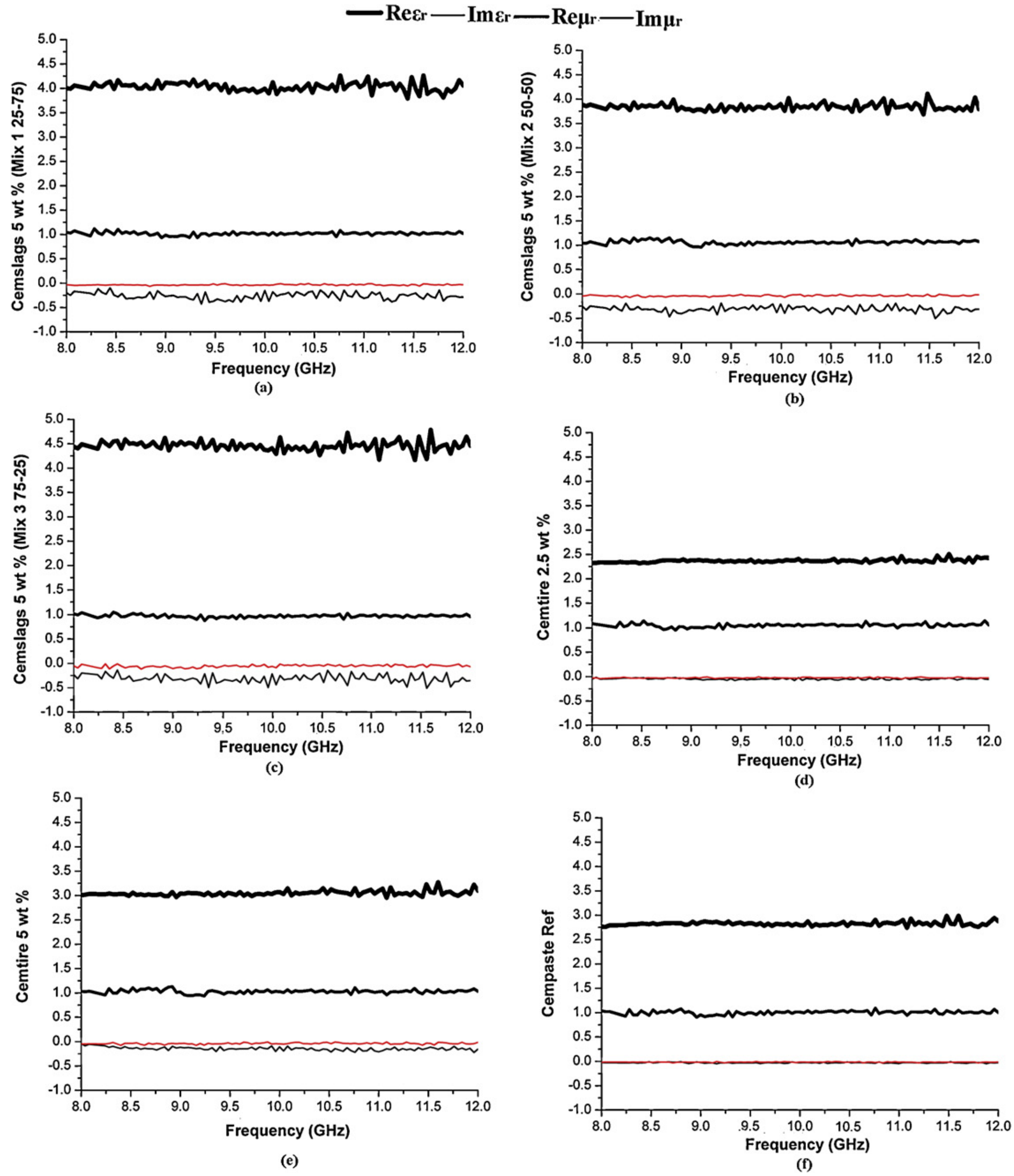

Fig. 3. (a–f) Electric and magnetic properties measurements at 8–12 GHz frequency range of cement paste samples containing mixed slags and tire wastes respectively.

It is evident from Fig. 4a that SE was increased with the increment of addition in scrap tire waste. In this case, shielding efficiency can be attributed mainly to the existence of carbon black (Table 1). Average SE for cement paste walls (5 cm thick) was 19 dB for 2.5 wt.% in addition of scrap tire waste, while a 23 dB average SE was reached for the small cement paste walls containing 5 wt.% in addition of scrap tire waste, respectively. Furthermore, a cement paste wall without any addition was also measured in order to determine the SE that was attributed to cement paste. In this case average SE reached 11 dB which is attributed mainly to the existence of Fe_2O_3 (Table 3), some remaining humidity to the thickness of the specimen (5 cm) and finally to the conductivity of the cement matrix (slightly conductive) while it is known that SE is closely pertinent to its conductivity.

Regarding average SE for the specimens containing metallurgical slags, a value of as high as 30 dB for 5 wt.% in addition of mix 1 was achieved, while for mixes 2 and 3, even higher values of 34 and 39 dB average SE were achieved, respectively. In both 3 prementioned cases, SE was attributed to the existence of FeO and Fe_3O_4 in both EAF and LF slags (Table 4 and Fig. 1). Although metal powder has a disadvantage in contrast to metal fibers of high density, which results in lower shielding effectiveness with a small introduction and both an increase of density and a decrease of mechanical strength of the composite material, the present study has focused in the production of low cost cement based EMI shielding materials; therefore other additional procedures regarding the waste admixtures (beside partical size separation) were not considered.

Table 6
Average values of electric, magnetic properties and loss tangents at 8–12 GHz frequency range of cement paste samples containing a variety of wastes.

Cement paste samples	Electric properties		Magnetic properties		Loss tangents	
	$Re\{\varepsilon_r\}$	$Im\{\varepsilon_r\}$	$Re\{\mu_r\}$	$Im\{\mu_r\}$	$\tan\delta_e$	$\tan\delta_m$
Cemslags 5 wt.% (mix 1, 25–75)	4.040	−0.268	1.016	−0.038	0.066	0.037
Cemslags 5 wt.% (mix 2, 50–50)	3.843	−0.313	1.057	−0.043	0.081	0.040
Cemslags 5 wt.% (mix 3, 75–25)	4.461	−0.313	0.972	−0.065	0.070	0.067
Cemtire 2.5 wt.%	2.363	−0.047	1.047	−0.029	0.020	0.027
Cemtire 5 wt.%	3.042	−0.147	1.028	−0.044	0.048	0.043
Cempaste ref.	2.824	−0.029	1.001	−0.018	0.010	0.018

Finally, it is noted that in all cases percolation threshold was not reached. Percolation threshold refers to the volume fraction above which the admixture units touch to form a continuous conduction path [23].

3.2.2. Absorption measurements

Electromagnetic absorption in materials (in this case cement matrix components) can be attributed to either electric or magnetic loss [24–26]. As was presented in Fig. 4c, absorption

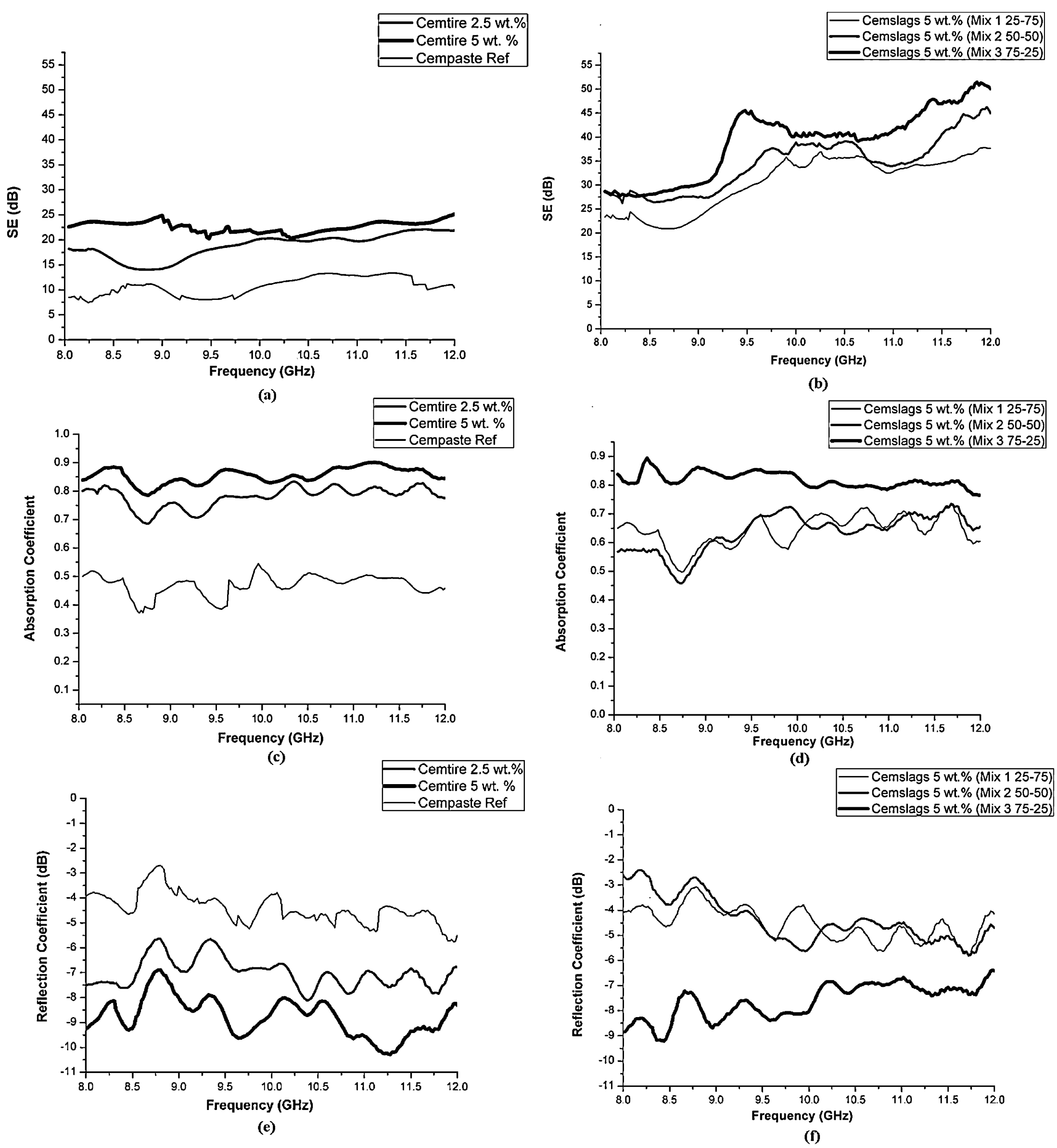

Fig. 4. (a–f) SE, variation of absorption and reflection coefficient of small cement paste walls containing mixed slags and tire wastes respectively at 8–12 GHz frequency range.

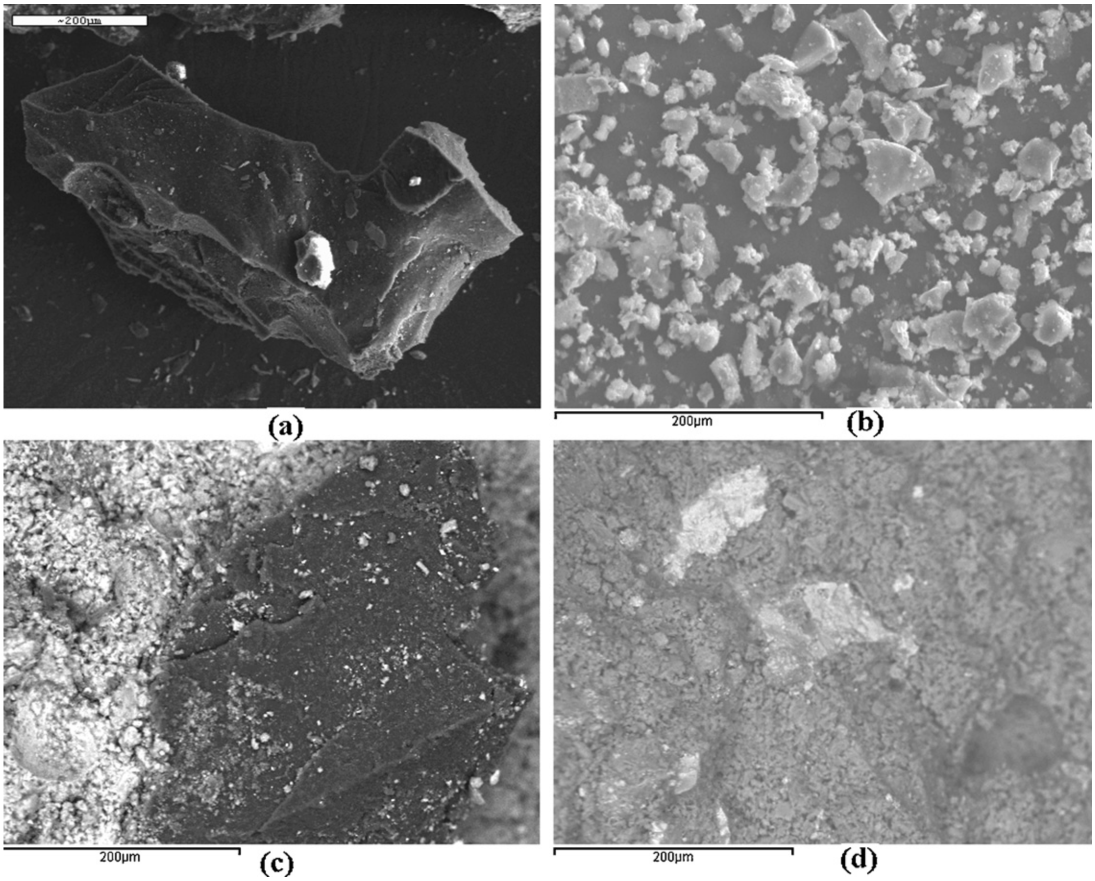

Fig. 5. (a–d) Scanning electron images (backscattered) of tire wastes and mixed slags particles and areas of cement paste samples containing tires wastes and mixed slags respectively.

coefficient was increased with the addition of scrap tire waste from 50% to 85% (average electromagnetic absorption) regarding electromagnetic radiation reduction. Increase in absorption coefficient was attributed to carbon black contained in scrap tire waste, having a high electric loss tangent (tan δ_e) and the electromagnetic energy is mainly attenuated via resistive losses. An additional important figure that is related to the absorption and shielding effectiveness is the skin depth

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}} \quad (2)$$

in m, where f is frequency (Hz), μ the magnetic permeability (H/m) and σ the electrical conductivity of the material (Ω^{-1} m^{-1}). The skin depth is the distance within the conductor, where the electromagnetic fields has values $1/e$ related to their values at the surface. Smaller skin depths are associated with better shielding capacity. Furthermore, regarding specimens containing metallurgical slags (Fig. 4d) the increase in absorption coefficient (from 60% to 82%) was attributed to the kind of the mixture of the cement paste. As it was also presented, mix 3 (Fig. 1 and Table 4) contained a greater percentage of magnetite. Magnetite is highly ferrimagnetic and presents 90–92 Am^2/kg saturation magnetization at room-temperature [27,28]. Magnetite has higher magnetic loss tangent and absorbs electromagnetic energy by mechanisms such as hysteresis loss and magnetic domain resonance. Finally, although a difference in absorption efficiency between mix 1 and 2 was expected, this was not the case. This was attributed mainly to thickness of the specimens (5 cm), in combination with the total amount in FeO where in cases of mixture 1 and 2 percolation threshold was not reached.

3.2.3. Reflection measurements

The variation of reflection coefficient of the cement pastes containing scrap tire waste at X-band frequencies were given in Fig. 5e. Reflection coefficient is slightly increased with the addition of scrap tire waste, although the general trend remained the same. Furthermore, it is evident that reflection in cement paste specimens containing scrap tire waste was frequency independent. Reflection reduction remained almost constant from 8 to 12 GHz range (X-band). On the contrary, for cement specimens containing metallurgical slags as admixtures, a frequency dependency regarding shielding efficiency due to reflection took place. Reflection, except for mix 3 was increased from 8 to 12 GHz range (X-band). This was attributed to the metallic nature of the slags which effected reflection, although electromagnetic reduction due to absorption did also occur. Furthermore, it was evident from Fig. 5f that reflection for mixture 3 was slightly decreased. In mix 3, basic mechanisms for shielding efficiency was absorption (an as

Table 7
Mechanical properties of cement paste specimens containing a variety of wastes.

Cement paste samples	Compressive strength (MPa)	% Change	Flexural strength (MPa)	% Change
Cemslags 5 wt.% (mix 1, 25–75)	60.62	5	10.7	3.9
Cemslags 5 wt.% (mix 2, 50–50)	58.24	1	10.3	–
Cemslags 5 wt.% (mix 3, 75–25)	55.10	−1	9.88	−4.1
Cemtire 2.5 wt.%	46.20	−19.9	8.9	−13.6
Cemtire 5 wt.%	40.84	−29.18	8.34	−19.02
Cempaste ref.	57.67	–	10.3	–

high as 82% absorption coefficient) due to the higher percentage of magnetite for all 3 mixtures. Therefore, a small decrease in reflection measurements was expected.

3.3. Mechanical characteristics (flexural and compressive strength) and SEM study

3.3.1. Compressive and flexural strength

Flexural and compressive strengths had been examined according to specifications (EN196-1). For flexural strength, prismatic specimens of 2.5 × 2.5 × 10 cm and for compressive strength cubic ones of 2.5 × 2.5 × 2.5 cm had been prepared. Finally, tests were conducted after 28 days according to specifications (Table 7).

According to results, addition of slag provided mixtures with quite satisfactory results. Mechanical strengths were almost familiar to the ones with no slag for mixtures with slag mix 2, while the third one showed worse performance than the conventional one.

For scrap tire waste, mechanical strength was reduced in general, while the increment of addition in scrap tire waste led to higher losses in mechanical properties respectively. These losses limited the amount of tire rubber that had been used at percentage up to 5%. However, strength's reduction for that percentage was very high. Moreover, reduction in compressive strength was bigger than the one in flexural, which can be attributed to the nature of rubber.

As far as mixtures with addition of slag were concerned, results indicated a slight increase in strength, however, for mix 3 a decrease on strength had been observed. This reduction was not as high as in mixtures containing tire rubber. This difference was attributed mainly to the different nature of the two kinds of wastes, since tire rubber particles considered to be soft ones, while slag's were not due to their metallic nature.

3.3.2. SEM study

SEM study was performed by using a Scanning Electron Microscope (JEOL JSM-840) connected to an X-ray Energy Dispersion Spectrometer-EDS (LINK-AN 10000).

Tire rubber particles had irregular shape while their surface was smooth while slag's particles were quite circular sharp and not too smooth in surface. Furthermore, cement paste, slag and tire particles found to uniform a quite satisfactory structure, while bonding between them was adequate enough for using these materials in building applications.

3.4. Leaching test

The disposal of EAF and LF slag to the environment presents serious problems due to the extremely high leachability mainly because of Pb presence. The results of leaching experiments (Table 8) indicate that hazardous elements (Pb) in EAF and especially in LF can be stabilized completely within a cement paste based material, being strong enough to be used in building construction. The concentrations of heavymetals (Pb) in the leachates of cement paste specimens were found to be extremely low. Furthermore, regarding scrap tire waste serious problems presented due to Fe and Zn presence. In this case also the leachates of cement paste specimens were stabilized completely within the cement based materials and showed element's concentrations below specifications' limits.

Table 8
Leaching tests results of slags, scrap tire wastes and cement paste specimens.

Element	Quantity leached of slugs (mg/kg)			Quantity leached of cement paste specimens (mg/kg)			Accepted limit (mg/kg)	Measured limit (mg/kg)
	EAF	LF	Tire	EAF	LF	Tire		
As	ND	ND	0.108	ND	0.107	ND	2	0.05
Pb	0.435	16.667	ND	ND	0.093	ND	10	0.05
Mn	0.5	ND	ND	ND	ND	ND	–	0.2
Cu	ND	ND	30.5	ND	ND	5.271	50	0.5
Cd	ND	ND	0.552	ND	ND	ND	1	0.03
Ni	ND	ND	1.911	ND	ND	0.491	10	0.06
Cr	0.545	0.07	2.184	0.103	0.128	1.962	10	0.06
Fe	ND	ND	877.2	1.591	ND	45.215	–	0.5
Zn	0.292	0.833	772.7	0.241	0.241	39,832	50	0.1

4. Conclusions

The study showed that metallurgical slags (EAF and LF slags) and scrap tire wastes can be utilized as admixtures in the production of low cost shielding-absorbing cement paste building materials. Measurements of electric and magnetic properties for cement paste samples, containing metallurgical slags and scrap tire wastes, suggest the potential use of these materials for EMI shielding applications, as it has been confirmed by open air measurements in larger scale cement paste samples.

In particular, a small plain cement paste wall presented an average SE up to 10 dB (cempaste Ref), while a cement paste wall of the same dimensions that was prepared by adding 2.5–5 wt.% scrap tire waste, presented an average SE up to 23 dB (cemtire 5 wt.%). Moreover, a cement paste wall containing the same amount of metallurgical slags presented an average SE up to 39 dB (cemslags 5 wt.% mix 3 75–25) in the X-band frequency range. For electromagnetic absorption, a similar trend was observed. Absorption coefficient was increased and reached 80–85% for one admixture containing each waste respectively, with only a small reduction in the stability of absorbing electromagnetic radiation performance. Reflection measurements were shown to be almost independent from the increment of addition in both slags and scrap tire wastes, especially for admixtures with the best absorption performance phenomenon (cemtire 5 wt.%–cemslags 5 wt.% mix 3 75–25), that confirms the role of cement paste building materials containing metallurgical slags and scrap tire wastes as absorbing building materials. Furthermore, the prepared cement paste specimens containing metallurgical slags presented mechanical characteristics familiar to conventional ones, with no by-products, although in some cases (cemslags 5 wt.% mix 1 25–75), a small increment did also occur. On the contrary, addition of scrap tire waste led to mixtures with decreased mechanical characteristics due to the nature of scrap tire rubber. This is why addition of such waste (scrap tire rubber in the form of powder) in cement based products was limited to low percentages, up to 5 wt.%. Finally, a leaching test was performed, showed stabilization of all studied toxic elements within the cement paste structure in cement pastes containing slags and scrap tire wastes, respectively.

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