Production and characterization of concrete paving blocks containing ferronickel slag as a substitute for aggregates

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Abstract

The present work aims to investigate the potential valorization of ferronickel slag (FNS) as a substitute for aggregates in the production of H-shaped concrete paving blocks (CPB). FNS is a byproduct of the pyrometallurgical treatment of laterites for the recovery of Ni as ferronickel; its size distribution ranges within the specified limits for use as aggregates replacement, as shown by granulometric tests. Three compositions were prepared: a reference, containing only ordinary raw materials (CPB_{Ref}) and two others containing 10 wt% (CPB_{10}) and 20 wt% (CPB_{20}) aggregates replacement by FNS. Approximately 1000 blocks were produced in pilot scale for each composition. All mixtures were tested after 28 days of curing, in accordance with European Standard BS EN 1338 to determine water absorption, abrasion resistance, compressive and tensile/splitting strength. Spectral reflectance was measured on a UV-Visible-NIR spectrophotometer between 250 and 2500 nm, while thermal conductivity was determined by using a thermal conductivity analyzer. CPB morphological characteristics and microstructure were examined by scanning electron microscopy. Although it was found that limestone (LS) aggregates replacement by FNS relatively impaired the quality of the resulting CPB to a certain extent, the paving blocks using 10wt% FNS met the minimum requirements specified by BS EN 1338 standard.

Keywords: Concrete Paving Blocks, Ferronickel Slag; Physical & Mechanical Properties;

1. Introduction

The idea of using paving blocks dates back to 4000 BC in Assyria, where flagstones were being used to pave village streets. Although the road construction using brick was common in ancient times, it was the Romans who used tightly-fitted stone paving units on a compacted aggregate base. Concrete paving blocks continued this tradition and were first developed in Netherlands as an alternative for the paver clay bricks in the late of 40', which had become unavailable, as they were mainly used to the post-war rebuilding constructions. After the war, the roads of Rotterdam were almost entirely constructed from concrete block paving **[1,2].**

The concrete paving system could offer the advantages of the high-strength concrete, high abrasion and skid resistance, high resistance to freeze-thaw cycles and no damage in concentrated point loads. Its resistance to most chemicals, such as petroleum or soap products or detergents, it made it suitable for a range of applications, from ultra-heavy duty areas, such as industrial units, to lightly trafficked residential areas and hard landscaping projects **[3]**. Furthermore they presented low maintenance cost, ease of placement and removal, re-usage of original blocks and immediate usage after installation or repair **[4]**. Today, concrete blocks pavements have gained a rapid popularity in many countries as an alternative to concrete or asphalt pavements, and they covers an increasingly wide range of applications, essentially in municipal public areas (pedestrian walkways, sidewalks, service stations, intersections, bus lanes, port zones, parks, automobile or airport parking etc) and because of their variety in forms, colors and textures, provide an answer to concerns in urban design. The concrete block pavement (CBP) is now a standard surface in Europe, where over 100,000,000 m^2 are placed annually **[1,3]**.

CBP is formed from individual solid blocks that fit closely next to one another to form a pavement surface. The blocks are usually industrial products of pre-fabricated unarmed concrete, having various dimensions and special morphology. The raw materials required for their manufacture are Portland cement and different types of aggregates. A typical CBP is placed on a thin bed of sand overlaying a sub base with a variety of shapes and patterns, whereas during placement the joint spaces between blocks are filled with sand having suitable grading.

Due to the regulations, policies and environmental sustainability, byproducts or wastes utilization has been encouraged throughout the world, not only due to the need for resources conservation, but, regarding industrial wastes, minimization of soil/water contamination and disposal cost as well. Therefore, alternative ways for waste exploitation have been proposed in many sectors of building materials. As CBP have become an attractive engineering and economical alternative to both flexible and rigid pavements, various industrial wastes, such as metallurgical slags, fly ashes, glass, sludges and others, have been tested as a partial replacement of the aggregate or/and cement content.

Studies have focused on the properties of concrete paving blocks prepared with recycled concrete aggregates, commonly found in the construction and demolition waste, examining several properties such as, density, compressive strength, tensile splitting strength, water absorption value, abrasion resistance and skid resistance. Generally, it has been proved that it is feasible to allow high levels of recycled concrete aggregates and that is at least of equal durability as concrete manufactured with original aggregates **[5-7]**.

Tavares and Franco examined the use of electroplating waste (blasting dust and electroplating sludge) for the production of concrete paving blocks, testing the mechanical and micro-structural properties, after curing at 7, 14, 28, 60 or 90 days **[8]**. According to the results, the blocks produced with 5wt%, 10wt% and 15wt% blasting dust and those with 5wt% electroplating sludge presented compression resistance values above the limit established by Brazilian standards (35.43MPa). Gencel et al determined the feasibility of using waste marble as a substituted for aggregates in fabrication of concrete paving blocks and the effects on physical and mechanical properties of the produced **[9]**. Although the compressive strengths decreased with increasing marble content in the concrete, the blocks presented satisfactory strength values after 28 days, whereas the presence of marble aggregates caused a very small decrease of splitting tensile strength. Uygunoglu et al studied the influence of fly ash content and the replacement of crushed sand stone aggregate with concrete wastes and marble wastes in pre-fabricated concrete interlocking blocks [10]. According to the results, the replacement of crushed sand stone with concrete waste and marble waste resulted in lower physical and mechanical properties. Wattanasiriwech et al investigated the use of waste mud from ceramic tile production in paving blocks [11]. The effects of water and cement content, immersion in water, as well as compaction pressure on compressive strength were determined and the values were compared with the corresponding standards. Shinzato and Hypolito examined the potential use of the black dross washed residue in the production of concrete blocks [12]. The blocks were tested according to the Brazilian standard and they passed dimension, humidity and absorption tests but not compressive strength tests. In a recent study, the viability of using sewage sludge ash as a raw material in the concrete blocks production was analyzed [13]. It was proved that the addition of SSA in concrete used for manufacturing blocks cured for 28 d provided densities and resistances similar to the control sample (without SSA) and significantly reduces the water absorption.

In the present study FNS was used as a substitute for LS aggregates in the production of H-shaped concrete paving blocks. FNS is a byproduct obtained from smelting of laterite ore in an electric arc furnace at a high temperature with the presence of a reducing agent, for the production of ferronickel alloy [14,15]. The FNS from the electro-reduction furnace is produced at a rate of approximately 2000 kt/y and for every tone of FeNi alloy the amount of FNS produced is estimated at 4 tones [14,16]. Currently, FNS is granulated through sudden cooling in sea water, leading to an amorphous material, which, due to its properties it has been classified as non-hazardous waste, according to the European Catalogue for Hazardous Wastes [17]. Today a small part of the produced FNS is used as a sand-blasting material, as a raw material in cement clinker production or as an inert additive in high strength concrete [18]. However, the largest amount of the produced slag is temporary disposed in areas closed to the metallurgical plant and for that reason alternative ways for its exploitation are introduced in order to reduce or eliminate cost of disposal and avoid potential soil and water contamination. In a recent work, the properties and hydration of ferronickel slag blended cements containing 5, 10, 15, and 20 wt% cement replacement were examined; all cement mixtures satisfied the requirements for strength class 42.5 as per EN 197-1. In addition, the leachability behavior of the produced blended cements was determined by the Toxicity Characteristic Leaching Procedure (TCLP) test and the tank diffusion test for monolithic samples (NEN 7375). In all cases the concentrations of leached heavy metals were found to be substantially below the regulatory thresholds **[19]**.

Three different batches of CPB were prepared in a pilot scale; one with ordinary raw materials and two others with 10wt% and 20wt% aggregates replacement by FNS. For each composition approximately 1000 blocks were produced according to the wet process. All mixtures were tested after 28 days of curing for water absorption, abrasion resistance, compressive and tensile/splitting strength, spectral reflectance and thermal conductivity, while their morphological characteristics and microstructure were examined by scanning electron microscopy.

2. Experimental

2.1 Materials

The cement used in all mixtures was a CEM I 52.5 Ordinary Portland Cement (OPC), produced by Heracles General Cement Company of Greece. FNS, supplied from LARCO smelting plant located at Larymna, was used as a substitute for natural aggregates in the production of H-shaped concrete paving blocks (CPB). The original natural aggregates used were crushed limestone (LS) in size of -4mm. The particle size distribution of both crushed LS and FNS aggregates was determined by sieve analysis and is presented in Figure 1.

Chemical analyses carried out with X-ray Fluorescence (Spectro–Xepos) and Atomic Absorption Spectrophotometry (Perkin Elmer 4100) are shown in Table 1, along with physical characteristics. The mineralogical phases of FNS, LS and CEM I52.5 used in this study were determined by XRD analysis, using a Bruker D8-Focus diffractometer with nickel-filtered CuKa radiation (λ=1.5406 Å), at 40 kV and 40 mA. FNS morphology and microstructure was examined by Scanning Electron Microscopy (SEM) with a Jeol 6380LV.

2.2 Mixtures & Making Process

The mixing ratios are presented in Table 2. Two different syntheses were prepared, replacing the natural LS aggregates by 10wt% and 20wt% with FNS. A reference mixture was also synthesized for reasons of comparison. The cement and water proportions in the mixtures were kept constant, in order to determine the effect of LS replacement by FNS, whereas in all cases of superplasticizer was added during mixing in a proportion of 1 kg/m^3.

Preliminary experiments in laboratory scale were carried out, by initially mixing LS and FNS aggregates with cement in a 5 L mixer. After of 2 min of homogenization, the water together with the superplasticizer was poured into concrete mixer for another 3 min. The fresh mixes were fed into the steel moulds and cured for 28 days. Trials were also performed in a pilot scale with a paving block making machine, producing approximately 1000 blocks for each synthesis (Figure 2). Initially, LS, FNS and cement were mixed in a pan mixer, and then water together with superplasticizer were added to the raw meal and mixed again until the desired moisture content was obtained. The mix was transported to the machine hopper via a bucket conveyor system. The concrete mix was discharged into steel moulds with internal dimensions of 200 mm length, 100 mm width and 60 mm depth. All concrete paving blocks were prepared using pressure and vibration until complete compaction was obtained. After 24 h the blocks were declamped and conditioned for 28 days at 25±1 ^{o}C and 65±5% relative humidity

2.3 CPB Characterization

After 28 days of curing, the paving block samples were tested for compressive strength according to the ASTM C936, using a 3000KN servo controlled compression test unit, keeping the rate of loading constant at 13.5 KN/sec [20]. The compression load was applied to the nominal area of paving blocks (200mm×100 mm).

The splitting tensile strength was determined according to BS EN 1338, by applying the load over the longest side of the paving block samples [21]. The block specimen was located and packed in the split tensile frame using two steel packing plates on the top and bottom faces in contact with the platens of the loading machine. The compression rate was low and fixed at 0.5 mm/min, until the point of failure.

Abrasion resistance was also determined in compliance with BS EN 1338, using a Technotest GT0112 abrasion test apparatus with a steel disc of 200 mm in diameter and rotating speed of 75rpm. During test procedure, corundum (Al_2O_3) powder, which was used as abrasive dust, was flowed between the disc and the block specimen from the powder box, while a constant pressure of 142.5 N was applied to the specimen during the disc rotation. The resistance to abrasion was determined by measuring the length of the footprint on the block sample due to wear.

Water absorption was determined on the produced paving blocks, after 28 days of curing, by the weight measurements of saturated specimens in water according to BS EN 1338. After the immersion of the samples for 3 days in water at 20±1 ^{o}C, they were taken out, allowed to drain on a metal wire mesh and weighted immediately. After obtaining the saturated weight content, they were placed into an oven at 105 °C and dried to a constant mass. The water absorption was expressed as a ratio of the mass of the absorbed water of the soaked block to the dried mass of the same block.

A UV–vis–NIR spectrometer (Jasco V-670) with a 150 mm integrating sphere was used for the determination of the produced blocks spectral reflectance. More specifically, the instrument measures the reflected part of radiation produced by two automatically selected lamps in the range from 300 nm to 2500 nm, which includes more than 99% of solar radiation at the earth surface. The absolute reflectance was integrated and weighed to the Global Horizontal spectral irradiance in order to calculate the total solar reflectance (TSR), as well as the reflectance in the UV, Visible and NIR range. The thermal conductivity of the produced blocks was evaluated using a C-Therm TCI^{TM}

thermal conductivity analyzer. Tests were performed at room temperature on sample with 25 mm diameter. Finally, morphological analysis and observation of hydration products, after 28 days of curing, were performed with SEM at 20kV using a Jeol 6380-LV equipped with an Oxford INCA Energy Dispersive Spectrometer (EDS).

3. Results and discussion

3.1. Raw materials

The ferronickel high rate cooled slag appeared black-grey and glassy. As mentioned above, the material is produced by cooling under a sea water shower, resulting in a size fraction of -5mm. Its particle size distribution is presented in Figure 1. 90 wt% of it exhibits a grain size smaller than 2 mm, whereas the 50 wt% was below 0.9 mm. It can also be observed that the distribution of the as received FNS particles closely resembled the corresponding of the crushed LS aggregate, which presented a size fraction of -4mm, with the 50 wt% of it being below 1.5mm.

Chemical analyses along with physical characteristics are given in Table 1. In case of FNS, iron and silicon were the main constituents and accounted for 81 wt% of the slag mass. Other constituents such as Al_2O_3, CaO, MgO were found in lower quantities. The cement used in all mixtures was an ordinary Portland cement of CEM I52.5 class, whose physical and mechanical properties are presented in Table 3. The crushed limestone used as reference aggregates presented 1.10 wt% water absorption and a specific gravity of 2.70 g/cm^3.

In all cases superplasticizer was used in a proportion of 1kg/m^3 in order to minimize the w/c ratio, reduce the water absorption and increase the concrete blocks strengths. It was a commercially available blend of polycarboxylic polymer, which meets the requirements for superplasticizer according to EN 934-2 **[22]**. Its density was 1.08 kg/L with a pH of 4.3 and zero chloride content. The extra fluidity gained by the use of superplasticizer also reduces the effort required to remove the blocks from the mould.

X-ray diffraction pattern of FNS (Figure 3) reveals its amorphous nature, as reflected by the presence of a diffuse wide band from the glassy phase, located approximately at 2-theta 30^o and is extended in the range of 20-40°. The spinel phase [$(Fe^{2+},Mg)(Fe^{3+},Al,Cr)_2O_4$] was the only crystalline mineralogical phase that was detected in the slag. The above observations were also confirmed by SEM analysis (Figure 4). The glass phase appears colourless and is chemically heterogeneous, as it is formed mostly by silicon, iron, aluminium and magnesium. Within the isotropic glass, complex spinel phases [$(Fe^{2+},Mg)(Fe^{3+},Al,Cr)_2O_4$] are the most abundant and some magnesium silicate crystalline phases are less common. Spinels appeared most frequently as cubic to octahedral euhedral crystals. Although the coarse alloy has been recovered, the ferronickel slag still contains small amounts of metallic particles with various complicated forms (drop-like, vermicular and oval). EDS analysis of metallic parts revealed the presence mainly of Fe and Ni with smaller amount of Cr.

3.2. Concrete Paving Blocks Characterization

Three different syntheses were prepared: a reference, containing only ordinary raw materials and two others containing 10 wt% and 20 wt% FNS (Table 2). The cement and water proportions in the mixes were kept constant in order to determine the effect of natural LS substitution by FNS.

3.2.1 Compressive Strength

The results of the compressive strength test, after 28 days of curing, together with density values of the produced blocks are presented in Table 4. According to the results, the density of the blocks increases with the increase of FNS content in the mixture, a fact that was expected because FNS presented a higher particle density compared to that of natural LS aggregates. After 28 days of hydration, the compressive strength of the reference block is approximately 15% lower (53.9 MPa) than that of the CPB_{10} mixture (62.5 MPa). The addition of FNS and the LS replacement acted beneficial in the mechanical properties of the final product, a fact that was attributed to the pozzolanic nature of the slag. As it was noticed above, slags with high amorphous silicon oxide content can be used as substituted for clinker, in the cement production, acting as a pozzolanic material and presenting influence in enhancing mechanical properties and durability, especially on the later ages of hydration [23,24]. Regarding FNS pozzolanic activity, the percentage of reactive silica has been determined at 40.71 wt%, whereas its pozzolanicity was determined at 5.9 MPa (mortars of slag with $Ca(OH)_2$ and standard sand) [25]. Although FNS was initially used in the mixture as an aggregate substitute, it seems to participate to the cement hydration as pozzolanic binder (mainly the finer fractions), thus improving the hydraulic behavior of the final blocks. The above observation was also confirmed by SEM analysis. As a result, while the strength development of reference blocks depends mainly on pure cement hydration rate, in blocks with 10 wt% FNS a cement-slag system is developed, which depends not only on the cement hydration, but on the latent hydraulic reactions of slag as well. On the contrary, in case of 20 wt% substitution (41.4 MPa) a decrease of 30% was observed, a fact that was mainly attributed to lower intrinsic strength of the FNS aggregates, which changed the strength and the fracture properties of blocks. The compressive strength of the concrete blocks is controlled by the strength of the cement, by the aggregates used and by the interfacial strength at the matrix-aggregate. Although the increase of the FNS addition by 20 wt% was also resulted in a strong matrix-aggregate interface, due to the slag pozzolanic nature, the lack of the higher strength LS aggregates led to the reduction of the compressive strength.

3.2.2 Splitting Tensile Strength

According to the results of the splitting tensile test, presented in Table 5, it can be observed that after 28 days of curing, the values were decreased with the increment of FNS content. In case of using 10 wt% FNS a decrease of 7.28% in the splitting tensile strength was observed, whereas in case of CPB_{20} the corresponding value reached at 17%, as compared with the control sample. However, the drop in splitting tensile strength of CPB_{20} was relatively lower than the corresponding obtained from the compressive strength test, a fact that was attributed mainly to the bonding behavior of the slag on the concrete matrix. Contrary to the compressive strength, the cement matrix rather than aggregate quality is more important for the splitting tensile strength of paving blocks **[6,9]**. The replacement of the LS aggregates with the more reactive FNS, led to the improvement of the interfacial transition zone, as the amount of hydration products formed during the later hydration stages were increased due to the pozzolanic nature of the slag. In case of CPB_{10} the average value of the tests is 3.83 MPa at 28 days, a value that satisfies the strength (3.6 MPa) required by the standard BS EN 1338. For the paving blocks with 20 wt% LS substitution, the average splitting failure value is 3.46 MPa, a value that could be tolerated by the standard, which requires 3.6 MPa, as the values of each individual block is greater than 3.4 MPa.

3.2.3 Abrasion Resistance

The abrasion resistance is the ability of CPB to resist mechanical action (rubbing, scraping, sliding etc) that tends progressively to remove material from its surface. This allows the initial product to retain its integrity and hold its form. Abrasive wear is known to occur on the CPB surface, upon which abrasive forces are applied between the surfaces and moving objects. It is a very important property, related with the service life of the final product and it is mainly depended on the compressive strength and aggregate properties **[9]**. As a result, factors such as water to cement ratio or type of aggregates that affect the CPB strength, will also affect abrasion resistance. According to the results presented in Table 6 the addition of FNS led to a slightly decrease regarding the abrasive resistance. An average value of 7% reduction was obtained for the paving blocks with 20% LS aggregates replacement. This agrees with the fact that the ability of concrete to withstand abrasion improves with the increase in the concrete strength **[6]**. In all cases the results indicated that the produced syntheses satisfied the requirements (<23 mm) of the standard BS EN 1338 and they were ranked to the 3^{rd} class of the Grade H.

3.2.4 Water absorption

The weathering resistance of concrete paving blocks was determined by conducting the water absorption test. According to the results, after 28 days of curing, also presented in Table 9, the obtained values are similar in all cases. The water absorption is mainly related to the pore distribution inside the cement matrix, whereas the influence of aggregate is relatively small and do not contribute to the total blocks water absorption. Furthermore, it is significantly affected by the properties of cement used. Consequently, the hardened cement paste, whose nature and quantity is the same in all cases, has the greatest effect on the absorption of fully compacted concrete **[10]**. In case of CPB_{20} the relatively higher value should be attributed to the pozollanic nature of FNS. Its lower fraction, which is rich in amorphous silica, can react with the produced $Ca(OH)_2$ from the cement hydration and to form secondary CSH, the matrix of which is more porous and weaker at earlier ages. According to the water absorption value required by the BS EN 1338 standard (6 wt%), all mixtures are ranked to the 2^{nd} class of the Grade B.

3.2.5 Solar Reflectance

The average solar reflectance, determined as the fraction of the incident solar energy reflected by the CPB surface, is presented in Figure 5. The corresponding values calculated by using the standard solar spectrum are given in Table 7. According to the results, the addition of FNS and the replacement of LS aggregates by 10 wt% led to a slight decrease of total reflectance of about 5.75%. However, a significant drop has been noticed in case of 20 wt% substitution, which reached at 28%. Regarding the visible reflectance (in the visual part of the solar spectrum – wavelengths: 400-700 nm) the extent of decrease is similar. The above reduction was mainly attributed to the darker shade of the slag used, but also to the consumption of $Ca(OH)_2$ produced, due to the pozzolanic reaction inside the concrete block matrix. Regarding the color of aggregates used it has been observed that lighter colored materials, such as limestone, generally present a higher solar reflectance (reflect heat from the sun). On the contrary, the darker materials, such as the black particles of ferronickel slag used, present a lower solar reflectance and as a result it is possible to absorb more heat from the sun. A further decrease in solar reflectance should be also attributed to the $Ca(OH)_2$ consumption, produced during cement hydration and it constitutes about 25% of the mass of a fully hydrated cement and it generally improves the total solar reflectance of the concrete block **[26]**. The addition of FNS led to the partial consumption of $Ca(OH)_2$, because of the pozzolanic reaction with amorphous silica contained in slag, especially at later stages of hydration, thus concerting the water-soluble calcium hydroxide to secondary CSH gel. However, in all cases the SRI is greater than 29, the minimum value that paving materials should present, according to the ASHRAE 189.1 Standard **[27]**.

3.2.5 Thermal Conductivity

According to the results also presented in Table 7 the thermal conductivity of the blocks is decreased with the increase of LS substitution by FNS. The thermal conductivity value of the reference block was determined at 1.22 W/mK. A replacement of 10wt% led to a reduction of 8%, whereas the corresponding value in case of 20 wt% addition reached at 29%. This reduction should be attributed to the nature of the aggregates used, as they can cause nearly twice a decrease in thermal conductivity of concrete, mainly due their degree of crystallization **[28]**. Aggregates with crystalline structure present higher heat conduction than the amorphous and vitreous ones. Because of the amorphous nature of the ferronickel slag, both syntheses presented better thermal insulation properties.

3.2.6 CPB Microstructure

Figures 6 and 7 show backscattered electron micrographs of CPB_{10} and CPB_{20} polished sections, after 28 days of hydration. It is possible to distinguish unreacted anhydrous cement grains with an external rim of inner calcium silicate hydrated products, outer CSH, which is the hydration product that fills the matrix, and slag particles surrounded by secondary CSH gel. The dark gray regions forming the matrix, in which the unreacted clinker phases were embedded, mainly consisted of hydration products. The CSH gel has formed a fibrous dense network structure. CSH near the cement grains is much denser and stronger, while the density of the CSH is more uniform. On the other hand, partially hydrated slag particles were detected, showing a microstructure with a dense rim of hydration products. The external surface of the slag glassy particles has been partially dissolved, due to the alkali environment of the concrete matrix and has further combined with $Ca(OH)_2$ to produce a secondary CSH gel rim around the particles (the smaller the particles, the greater the reaction). As a result, the volume of hydration products in the aggregate-paste interface zone has been increased, thus improving the cohesion between the cementitious matrix and FNS.

4. Conclusions

Ferronickel slag, a non hazardous glassy waste, consisting mainly of amorphous silicate matrix and spinel phases, was used as a substituted for limestone aggregates in the in the production of H-shaped concrete paving blocks. After 28 days of hydration, the compressive strength of the reference block was approximately 15% lower (53.9 MPa) than that of the CPB_{10} mixture (62.5 MPa). On the contrary, in case of 20 wt% substitution (41.4 MPa) a decrease of 30% was observed. Regarding splitting tensile strength, the addition of 10 wt% FNS led to a decrease of 7.28%, whereas the corresponding of the CPB_{20} reached at 17%. Furthermore, the use of FNS as a partial replacement of LS aggregates did not negatively affect the abrasion resistance (AR) and the water absorption (WA) of the produced blocks and all syntheses satisfied the requirements (AR<23 mm and WA<6 wt%) of the standard BS EN 1338. The solar reflectance of the paving blocks with 10wt% substitution was slightly decreased (5.75%), a fact that was attributed to the darker shade of the FNS, but also to the partial consumption of $Ca(OH)_2$ due to pozzolanic reaction. However, a significant drop has been noticed in case of 20 wt% substitution (28%). Finally, both syntheses with FNS addition presented better thermal insulation properties, mainly because of the amorphous nature of the slag. According to the results, the FNS combination with LS aggregates, presented a potential to be used in the production of concrete paving block, satisfying the requirements as per standard EN 1338.

5. **References**

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Table 1

Chemical analysis and physical characteristics of cement and slag used

Oxides	***Chemical Analysis (wt%)***		
	CEM I52.5	*FNS*	*LS*
SiO_2	21.25	41.18	0.09
Al_2O_3	3.77	5.98	0.54
Fe_2O_3	4.27	40.02	0.16
CaO	64.35	4.12	54.62
MgO	1.25	7.79	0.75
K_2O	0.44	0.37	0.02
Na_2O	0.12	0.09	0.01
SO_3	2.40	0.64	-
MnO	0.15	0.52	-
TiO_2	0.23	0.12	-
NiO	0.05	0.13	-
Cr_2O_3	0.13	2.75	-
free CaO	0.15	-	-
LOI	1.25	-3.44	43.56
Physical Characteristics			
Specific surface (cm^2/g)	3870	-	-
Specific gravity (g/cm^3)	3.14	3.18	2.61
Water Absorption (wt%)	-	0.32	1.10

Table 2

Mixtures Proportions

Code	*CEM I52.5 (kg/m^3)*	*w/c*	*LS (kg/m^3)*	*FNS (kg/m^3)*	*Superplasticizer (kg/m^3)*
CPB_{Ref}	175	0.45	1569	-	1.0
CPB_{10}	175	0.45	1412	157	1.0
CPB_{20}	175	0.45	1255	314	1.0

Table 3

Physical and mechanical properties of the cement used

	Water Demand (wt%)	*Setting Times (min)*		*Le Chatelier Expansion (mm)*	*Flow of Normal Mortar (%)*	*Compressive Strengths (MPa)*		
		Initial	*Final*			*2 days*	*7 days*	*28 days*
CEM I52.5	27.8	145	185	0.5	97.5	24.1	39.2	54.2

Table 4

Compressive Strengths of CPB different mixtures

Mixture	*Weight (kg)*	*Density (kg/m^3)*	*Rate (kN/s)*	*Load (kN)*	*Stress (MPa)*	*Compr. Strength (MPa)*
CPB_{Ref}	2.631	2192.5	13.5	1023	51.1	53.9
	2.627	2189.2	13.5	1072	53.6	
	2.715	2262.5	13.5	1138	56.9	
CPB_{10}	2.737	2280.8	13.5	1299	64.9	62.5
	2.566	2138.3	13.5	1203	60.3	
	2.680	2233.3	13.5	1244	62.2	
CPB_{20}	2.585	2154.2	13.5	787	39.4	41.4
	2.560	2133.3	13.5	736	36.8	
	2.698	2248.3	13.5	962	48.1	

Table 5

Splitting Tensile Strengths of CPB different mixtures

Mixture	*Load (N/mm)*	*Splitting Strength (MPa)*	*Average (MPa)*
CPB_{Ref}	459	4.1	4.13
	479	4.3	
	442	4.0	
CPB_{10}	460	4.2	3.83
	414	3.7	
	403	3.6	
CPB_{20}	394	3.6	3.53
	397	3.6	
	379	3.4	

Table 6

Abrasion Resistance and Water Absorption of CPB different mixtures

Mixture	*Abrasion Resistance (mm)*	*Water Absorption*	
		wt%	*Average*
CPB_{Ref}	21.0	4.9	5.3
		5.5	
		5.5	
CPB_{10}	21.5	5.7	5.6
		5.6	
		5.5	
CPB_{20}	22.5	5.8	5.7
		5.6	
		5.6	

Table 7

Results of solar reflectance and values

Code	*Reflectance (%)*				*Thermal Conductivity (W/mK)*
	Total 250-2500 nm	*NIR 700 -200 nm*	*UV 280-400 nm*	*Vis 380-780 nm*	
CPB_{Ref}	45.38	48.32	44.88	43.14	1.22
CPB_{10}	42.75	45.15	36.65	40.87	1.13
CPB_{20}	35.45	37.38	31.95	33.76	0.95

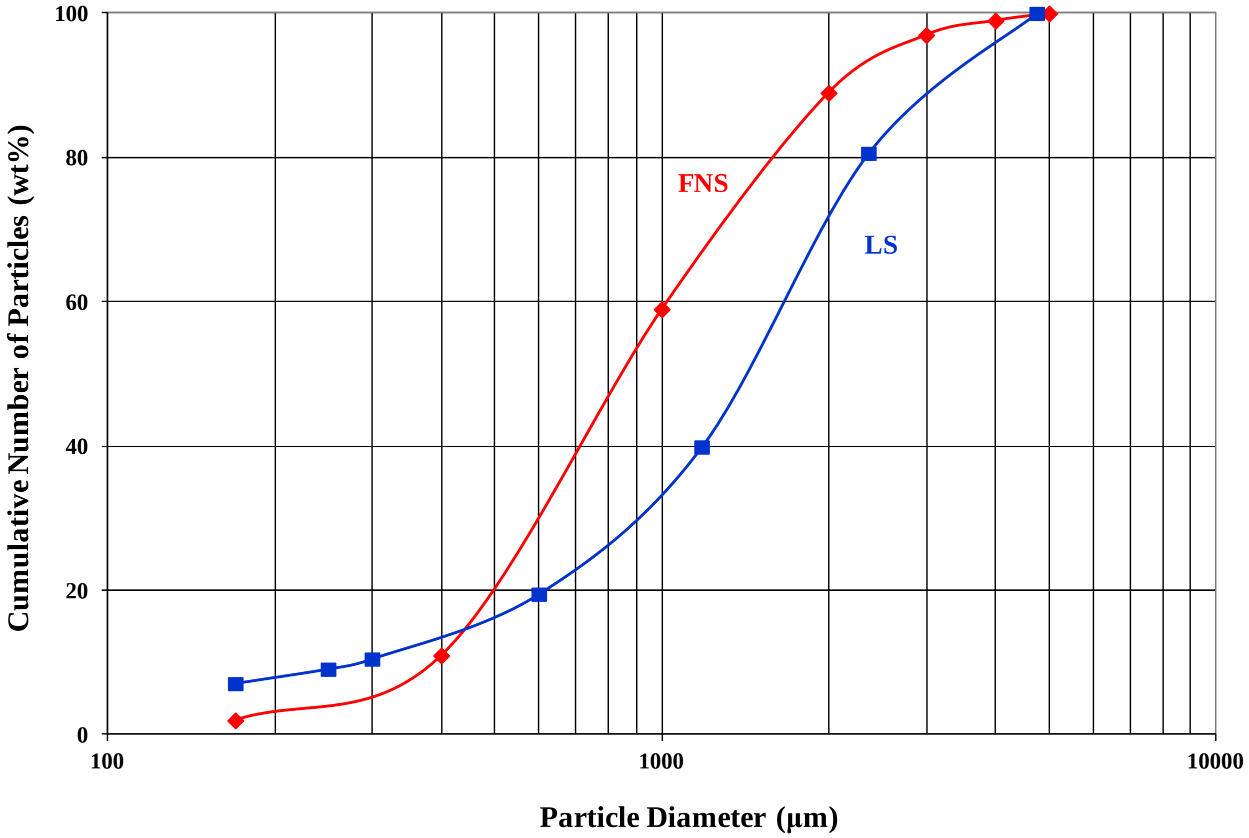

Figure 1: Particle size distribution of FNS and LS used

Figure 2: Paving block production

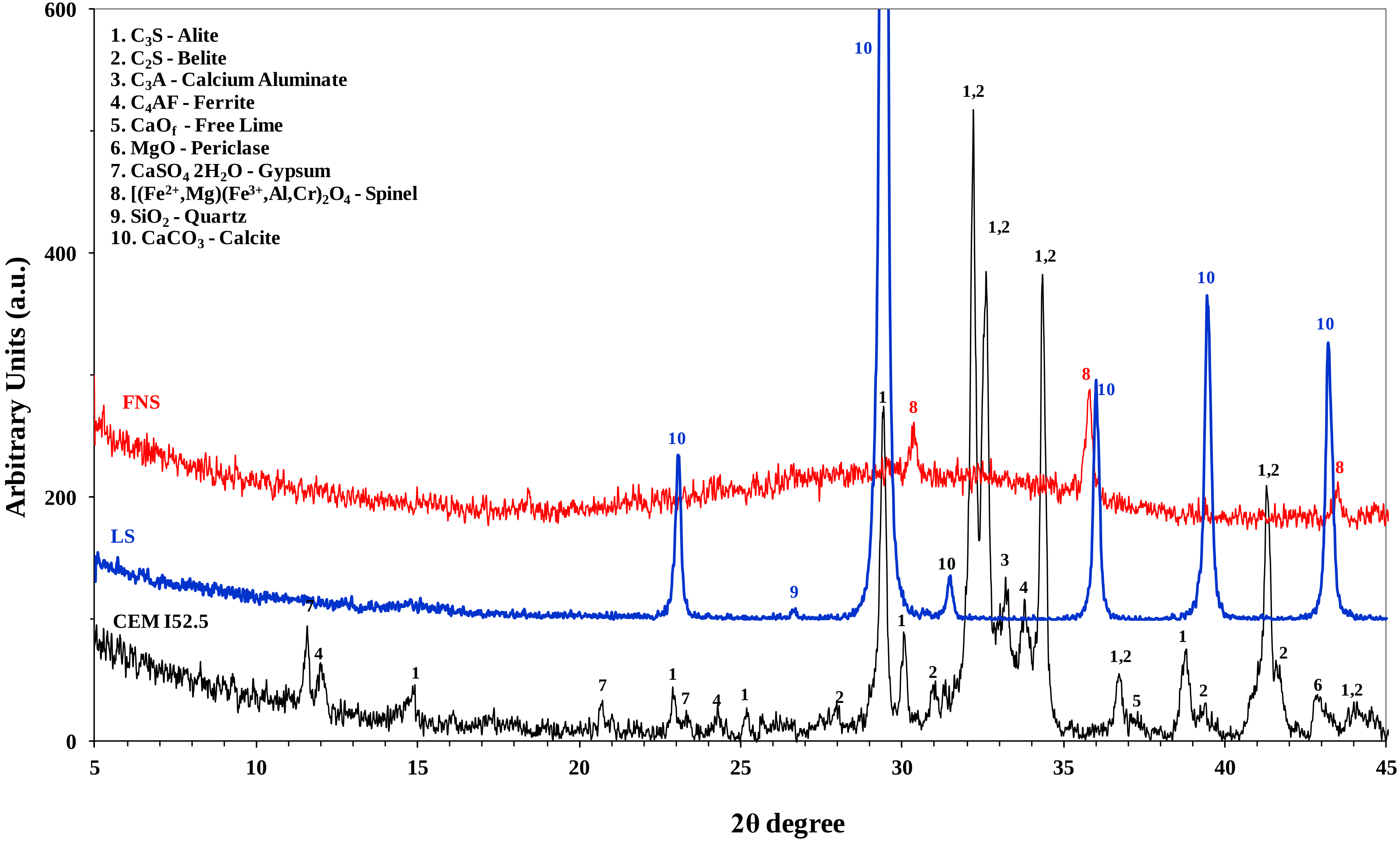

Figure 3: X-ray diffraction analysis of CEM I52.5, FNS and LS used

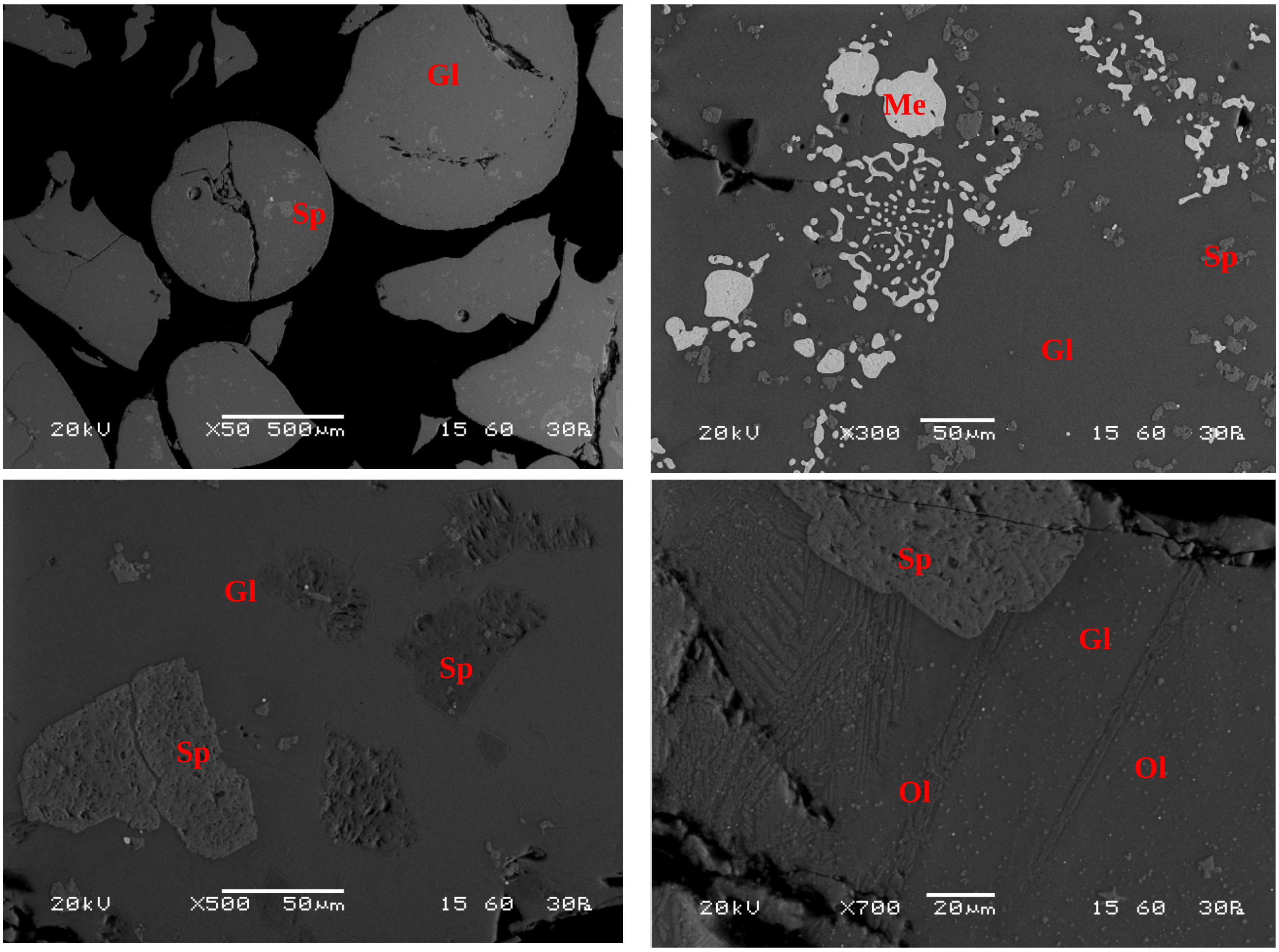

Figure 4: Backscattered electron micrographs of the as received FeNi slag polished sections. Fine to coarse-sized euhedral crystals of spinel (Sp) embedded in glassy matrix (Gl). Parallel growths of columnar elongated olivine-group crystals (Ol) and drop-like metallic particles composed of FeNi (Me).

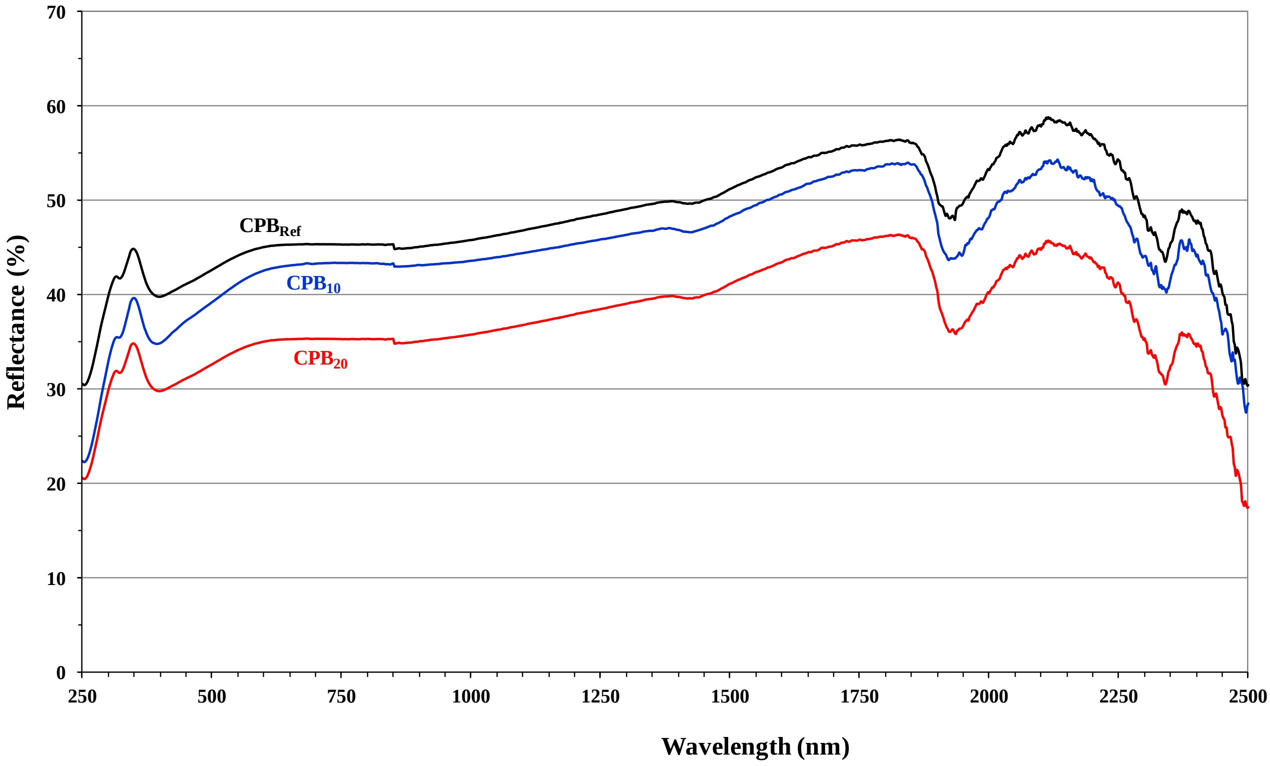

Figure 5: Reflectance spectra of the produced concrete paving blocks

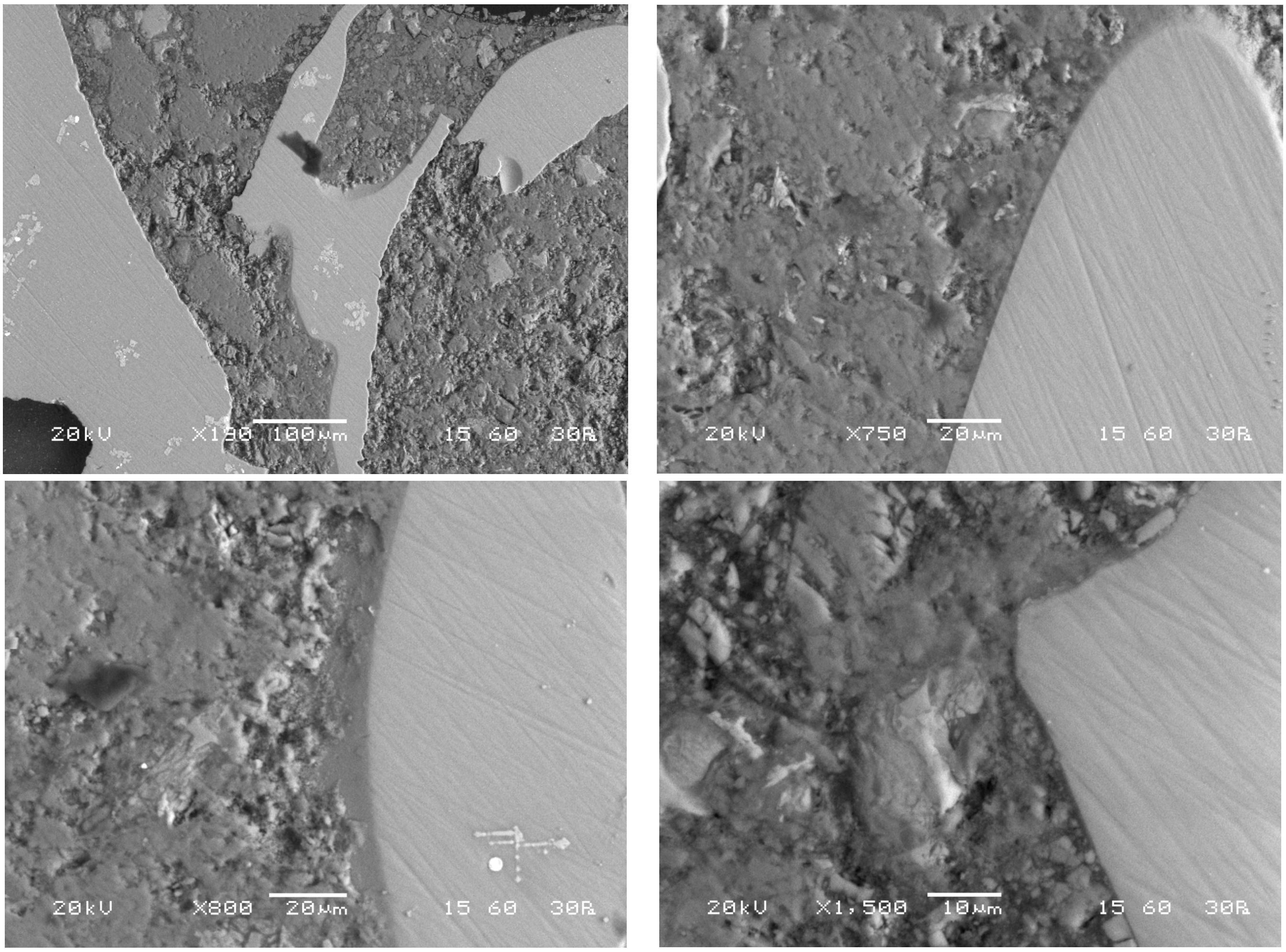

Figure 6: Backscattered electron micrographs of CPB_{10} after 28 days of curing.

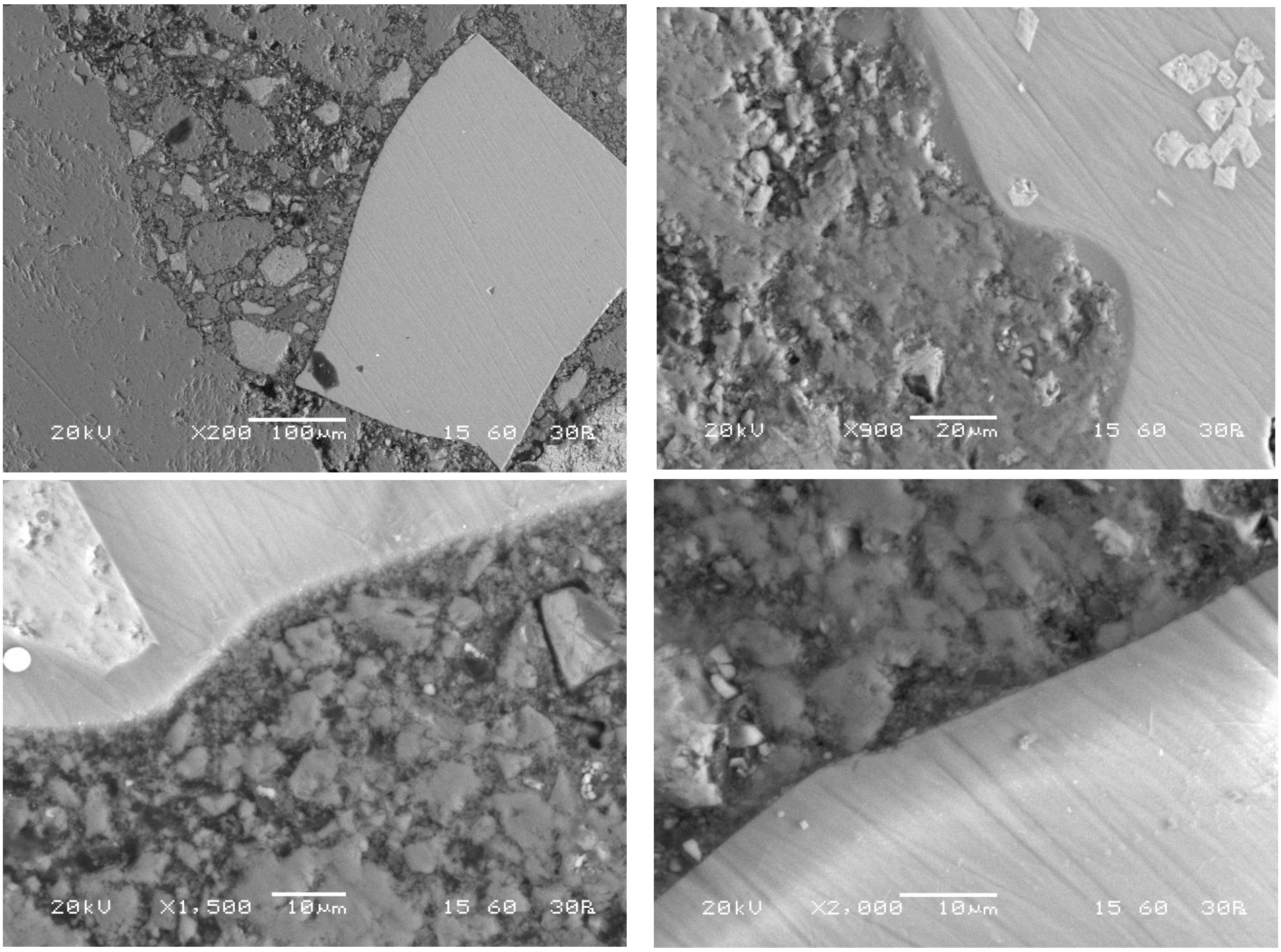

Figure 7: Backscattered electron micrographs of CPB_{20} after 28 days of curing.