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Concrete Made with Alternative Fine Aggregates: The Reuse of Porcelain Electrical Insulators

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Abstract. The use of alternative materials as substitutes for ordinary aggregates, mainly in concrete and mortar, has been common in recent decades in Brazil. Due to its physical and chemical similarities to common aggregates, ceramic waste, when coupled with a granulometric control, is suitable for use as an aggregate in concrete. Brazil has been estimated to dispose of approximately 25,000 tons of porcelain insulators annually, which are insulators that are often discarded along with other debris and harm the environment. This study examined the grinding methodology for and subsequent use of porcelain to replace fine aggregates in concrete and verified the improvement this substitution provided by evaluating the mechanical properties and durability of the concrete under study and examining scanning electron microscope images.

Introduction

Because Brazil produces an estimated 25,000 tons of porcelain electrical insulator waste annually, which accumulates on the grounds of ceramic factories or among open debris, this study proposed a methodology for the reuse of this porcelain, given that the literature has indicated the potential for its use in concrete and mortars as a substitute for common fine and coarse aggregates.

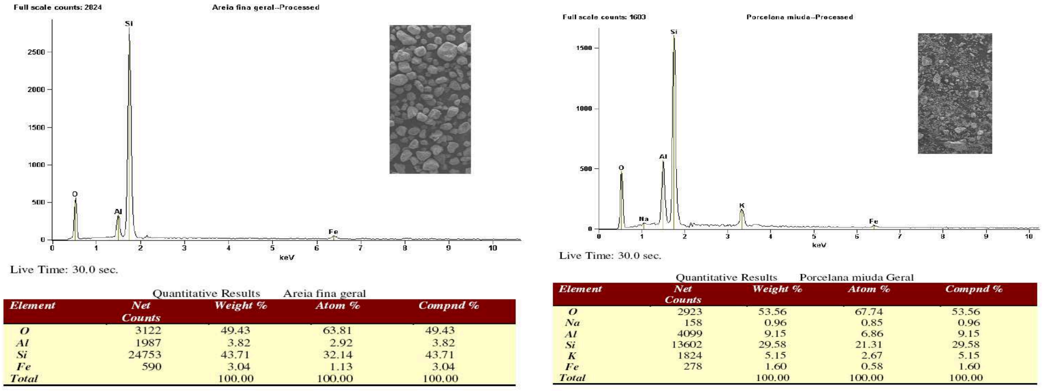
The main objective of this study was to determine a method of recycling porcelain electrical insulators to allow their use as a replacement for the common aggregate sand in concrete by comparing concrete mixtures containing different amounts of porcelain to a reference mixture based on the following properties: workability, consistency, compressive strength, tensile strength in diametral compression, at different ages. In addition, the behavior of the interfacial transition zone (ITZ) between the aggregate and cement paste was studied by analyzing scanning electron microscopy (SEM) images.

Materials and Methods

The materials used to create the concrete samples in this study were: Portland cement (CP V ARI - High Initial Strength); Common fine aggregate common (sand); Alternative fine aggregate (porcelain electrical insulators); Common coarse aggregate (gravel); and Hyperplasticizer additive.

The pozzolanic activity of this porcelain, tested according to the technical standard NBR 5752 [1], reached a pozzolanic activity index of 0.75, which was attributed to the thermal activation of the insulator's clay. The porcelain was characterized as an alternative aggregate according to the NBR 15116 [2].

Fig. 1(a) shows the results of the energy-dispersive X-ray spectrometry (EDS) tests performed on the fine common aggregate (sand), the components of which were remarkably similar to those of porcelain, Fig. 1(b) especially the silicon (*Si*), aluminum (*Al*), and iron (*Fe*), and it forms SiO_2 and Al_2O_3 compounds with potential hydraulicity and thermally activated pozzolanic activity. Also indicates the presence of potassium (*K*), which, along with the silica, can cause efflorescence or alkali-aggregate reaction due to its solubility [3].



Live Time: 30.0 sec.

Quantitative Results Areia fina geral

Element	*Net Counts*	*Weight %*	*Atom %*	*Compnd %*
O	3122	49.43	63.81	49.43
Al	1987	3.82	2.92	3.82
Si	24753	43.71	32.14	43.71
Fe	590	3.04	1.13	3.04
Total		100.00	100.00	100.00

(a)

Live Time: 30.0 sec.

Quantitative Results Porcelana miuda Geral

Element	*Net Counts*	*Weight %*	*Atom %*	*Compnd %*
O	2923	53.56	67.74	53.56
Na	158	0.96	0.85	0.96
Al	4099	9.15	6.86	9.15
Si	13602	29.58	21.31	29.58
K	1824	5.15	2.67	5.15
Fe	278	1.60	0.58	1.60
Total		100.00	100.00	100.00

(b)

Fig.1 – EDS of the common fine aggregate (sand) (a), alternative fine aggregate (fine porcelain) (b).

Test Methodology

The proportions of materials in each mix were calculated according to the IPT-Modified method 23 and determined to be 1:2:3:0.40:0.0064 (cement: fine aggregate: coarse aggregate: water: hyperplasticizer additive), with a cement consumption of approximately 375 kg/m³ of concrete. The quantities of material necessary to mold 1.0 m³ of each concrete mix are shown in Table 1.

Table 1 – Material quantities for concrete mixes containing porcelain.

Material quantities (kg / m³ concrete) for a 1:2:3:0.40:0.0064 mix							
Mix	**Cement**	**Fine aggregate**		**Coarse aggregate**	**Water**	**Additive**	**Replacement content (%)**
		Common	**Porcelain**				
Ref C	375.0	750.0	-	1125.0	150.0	2.4	**Reference**
25 C	375.0	562.5	187.5	1125.0	150.0	2.4	**25**
50 C	375.0	375.0	375.0	1125.0	150.0	2.4	**50**
75 C	375.0	187.5	562.5	1125.0	150.0	2.4	**75**
100 C	375.0	-	750.0	1125.0	150.0	2.4	**100**

The water/hyperplasticizer additive ratio was fixed at 1.6% because the preliminary hypothesis was that this ratio assisted in maintaining a slump of 6.0 ± 2.0 cm for both the reference mix and the mixes with higher aggregate substitution levels, a slump that is common in typical non-pumpable concrete projects.

The process of molding and curing the concrete samples was performed in compliance with NBR 5738 [4]. Separate concrete samples were molded for the imaging (SEM) tests instead of reusing samples from the other tests. The samples used in the SEM tests had their tops cut off, after which a section was taken from the sample with a thickness varying between 0.5 and 1.0 cm.

These samples were sent to the Laboratory of Electron Microscopy at the Analytical Center of the Institute of Chemistry at Campinas State University (Universidade Estadual de Campinas – Unicamp) and tested on JSM 6360-LV equipment with an acceleration of 30 KeV, resolution of 3 nm, and a Noran System Six EDS.

Results and Discussion

Fresh concrete mixtures were slump tested according to NBR NM 67 [5]. A hyperplasticizer additive was used in the concrete to reduce its water/cement ratio and obtain a slump similar to that of conventional concrete, 6.0 ± 2.0 cm. The reference concrete mix showed a slump of 7.0 cm, while the other mixes, independent of their porcelain content, had slumps of 8.0 cm. Thus, all mixes fell within the established limits. The porcelain content did not influence the slump [6].

Simple Compression Strength – NBR 5739 [7]. Tests of the samples compressive strengths were conducted at 3, 7, 28, 56, 112, 180, and 365 days, and the average results of are shown in Fig. 2. The use of porcelain insulators to replace the common fine aggregate was determined to be beneficial from the initial time tested onward.

The strength increase of mixture C 50 at 3 and 7 days was 21% and 26%, respectively. After 28 days, a higher porcelain content corresponded to higher strengths, with increases in compressive strength over the reference concrete for the 100% ceramic aggregate mixture, C 100, of 34% at 28 and 56 days, 30% at 112 days, 40% at 180 days and 53% at 365 days.

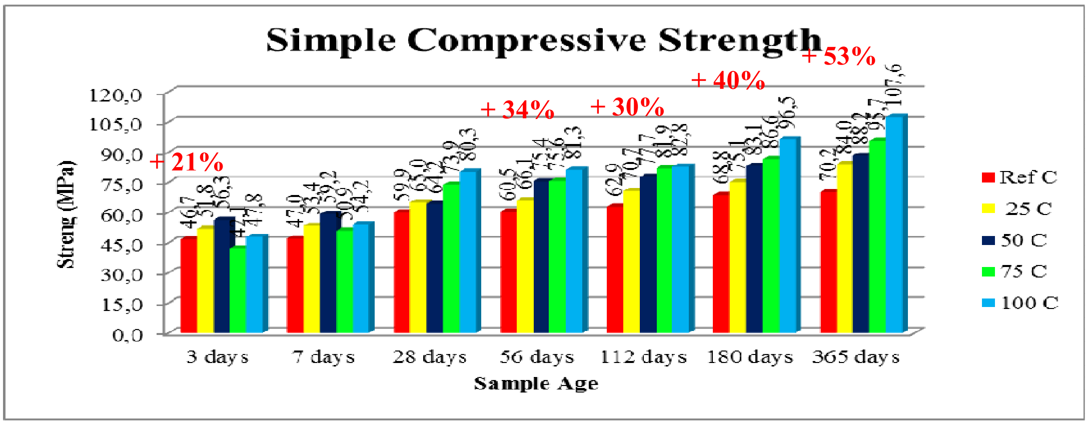


Fig. 2 – Simple compressive strength results.

This trend of increased strength compared to the reference mix has also been noted, but with smaller increases. Among other factors, this discrepancy can be explained by those authors not using additives and using porcelain aggregate that was larger than that used in the present study [8].

Several factors gave the porcelain concrete in this study greater density and a higher pozzolanic effect, including the porcelain's pozzolanic activity index of 0.75, the fact that it was free of organic materials, a controlled particle size because its production was the result of the insulator grinding process and because it contained a large proportion of material with particle sizes of less than 75 microns, and a low water absorption capacity. These factors resulted in the higher compressive strength of concrete samples containing porcelain.

Tensile Strength by Diametral Compression – NBR 7222 [9]. The results of the tests measuring the concrete mixes tensile strength by diametral compression are shown in Fig. 3. The diametral compression increased in the mixes containing fine porcelain at all ages, and the maximum strength increases in concrete C 100 were approximately 60% at all ages tested.

The increase in diametral compression strength observed was less intense than that obtained in the present study [8]. The higher strengths in this study's results were associated with smaller porcelain and common coarse aggregate particle sizes, resulting in greater tensile strength against the forces to which the sample was submitted, and were also the result of the additive that improved the concrete's compaction.

The fine ceramic aggregate had better tensile strength by diametral compression than the common fine aggregate (sand) due to the ceramic aggregate's more uniform particle size and similar grain shapes. The diametral compressive performances of all the concretes containing porcelain were better than that of the reference mixture regardless of sample age, proving that the use of porcelain also improved this property of the concrete samples.

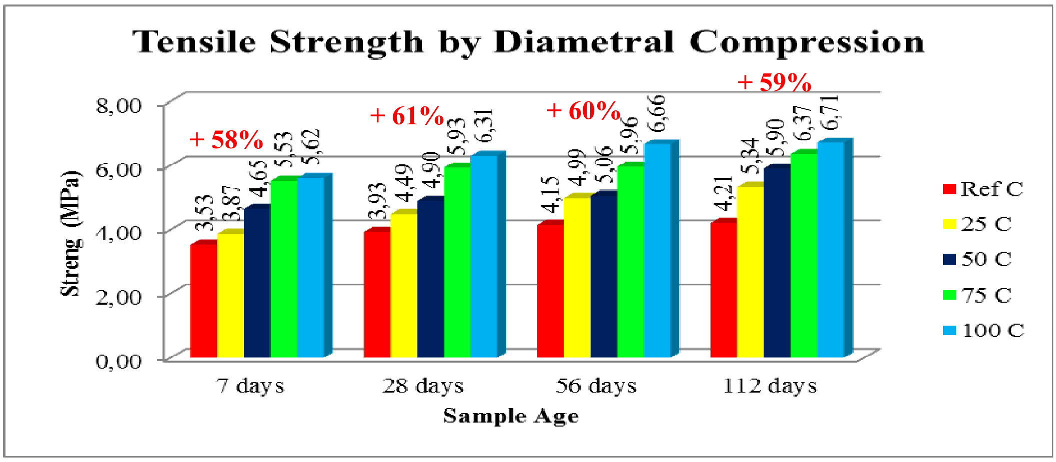
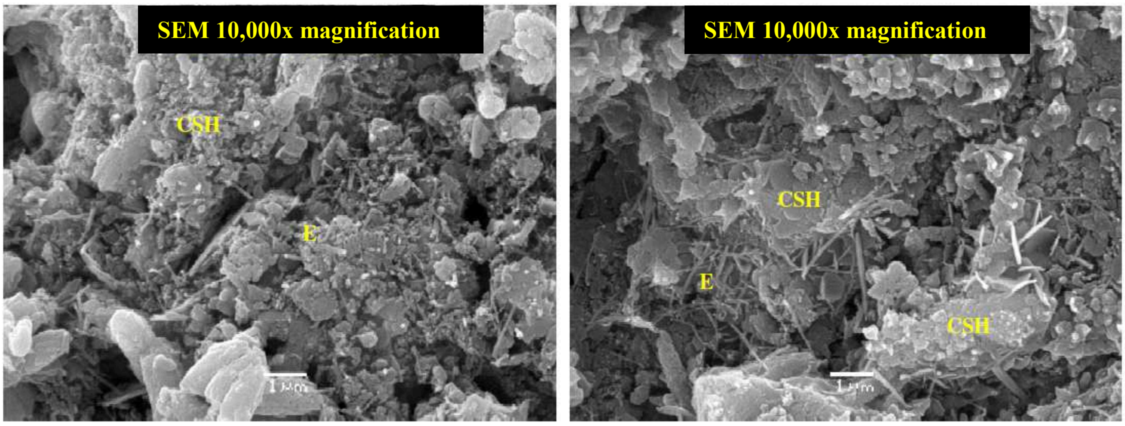


Fig. 3 – Tensile strength by diametral compression results.

SEM Image Tests. There was formation of compounds in the transition zone between the aggregate and cement paste in the concrete according to the quantities of these compounds used in the studies [10], [11]. Ettringite (E) and calcium silicate hydrate (CSH) were observed in mix C 50, Fig. 4(a), and mix C 75, Fig. 4(b), which were both photographed at 28 days.



(a) (b)

Fig. 4 – Transition zones in mixes (a) C 50 and (b) C 75 at 28 days.

Analyzing the SEM images highlighted the initial presence of empty capillaries (VC) formed in the aggregate-paste transition zone, consisting of aggregate (Ag) and paste (Pa), which was more common in mixes with higher concentrations of porcelain than the reference mix. As the concrete hardened, these voids in the aggregate-paste transition zone were filled with the products of cement hydration, as observed in Fig. 5 for mix C 50 at 56 days.

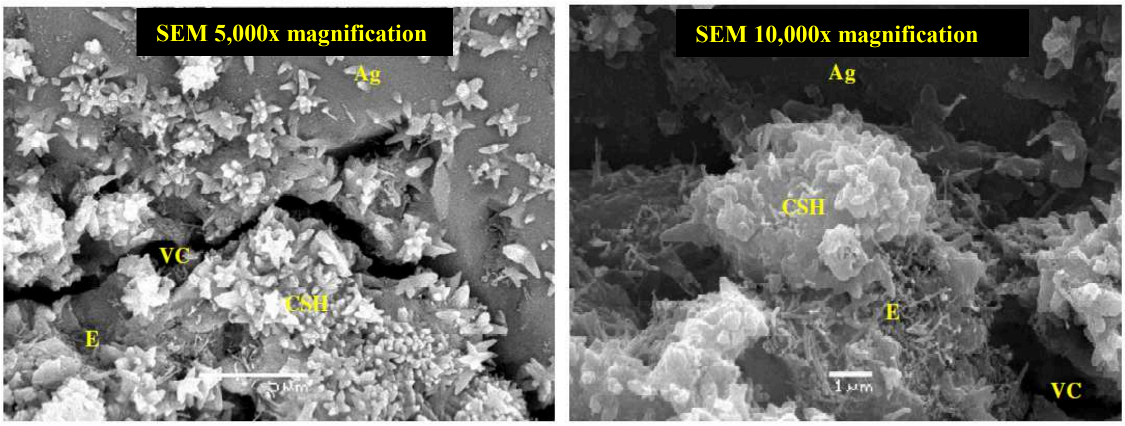
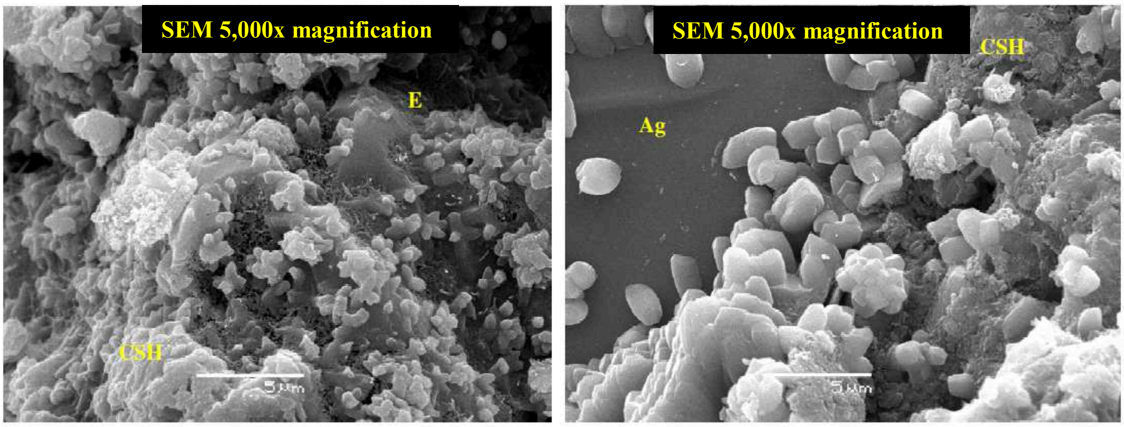


Fig. 5 – Filling of an empty capillary in mix C 50 at 56 days.

The filling of voids in the aggregate-paste transition zone by CSH crystals was observed in all concrete mixes and increased with age. The CSH in the mixtures at 56 days is shown in Fig. 6(a) for mix 25 C and Fig. 6 (b) for mix C 75.



(a) (b)

Fig. 6 – Filling of voids by CSH in mixes (a) C 25 and (b) C 75 at 56 days.

Conclusions

The grinding process to which porcelain electrical insulators are subjected before being reused in civil construction enables their use as an alternative aggregate with similar particle sizes to common aggregates. Simple adjustments to the hammer mill and subsequent sieving result in a material with properties that facilitate the molding and compaction of concrete, which can then be pumped or released, among other actions.

This study assessed an alternative aggregate created from this waste material with a controlled particle size that improved the compaction of concrete and enhanced the filling of molds. The porcelain did not contain any potentially harmful organic materials. Due to the porcelain insulator manufacturing process, grinding the material into particles greater than 9.5 mm in diameter gave them a more lamellar aggregate form, and correction was possible only by reducing their maximum size because the material's application improved with smaller particle sizes.

Increasing the fine material content resulted in improved concrete mechanical properties because the finer material had a better pozzolanic activity than coarser material. The milling process also gave the material a more matte texture than a sand surface. This matte surface facilitated the filling of voids with cement hydration products in the aggregate-paste transition zone.

An EDS assay demonstrated that the porcelain had a chemical composition similar to that of the common aggregate. However, the presence of soluble potassium and silica could cause problems such as efflorescence or alkali-aggregate reactions, which have been described in the literature but were not tested in the present study.

When performing concrete slump tests on the samples, the incorporation of a hyperplasticizer additive allowed for the control of this slump to keep it similar to that of typical projects at 6.0 ± 2.0 cm. Because porcelain had no influence on the slump, regardless of the degree of grinding, other additives could also be added to concrete containing this type of porcelain in a fresh or hardened state to improve its properties.

Simple compressive strength testing showed that increasing the porcelain content and sample age resulted in an increase in compressive strength. The concrete containing 100% porcelain replacement, C 100, reached an average strength of 107.6 MPa at 365 days, which was 53% higher than that of the reference mixture. The tensile strength by diametral compression increased in concrete containing porcelain relative to the reference concrete at a minimum of 7 days, and the increased strength was proportional to the replacement level. These increases over the value for the reference mixture were as high as 59%, which was found for mix C 100 at 112 days, which reached an average strength of 6.71 MPa.

SEM images made it possible to observe capillary voids that were filled by cement hydration products during the curing process. It was also possible to visualize formations similar to those described in the literature for compounds in the transition zone between the aggregate and cement paste matrix. Over time, these hydration products, in addition to filling such voids, begin to form even on the coarse aggregate, thereby providing greater strength to the concrete, and the similarity of its compounds, as demonstrated by SEM imaging, to the compounds formed in the literature and reference mix confirmed the potential to use porcelain electrical insulators to replace the fine aggregates in concrete.

The physical and chemical characterization of porcelain aggregates, when compared to those of common aggregates, indicated that their use in concrete would be feasible. In conclusion, the methodology presented in this study can be a resource for future studies aimed at the use of porcelain electrical insulators in concrete and mortar. The porcelain should be combined with other alternative materials to reduce the extraction of common aggregates required for civil construction.

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