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Microstructural characteristics, porosity and strength development in ceramic-laterized concrete

P.O. Awoyera [a, b, *], J.O. Akinmusuru [a], A.R. Dawson [b], J.M. Ndambuki [c], N.H. Thom [b]

[a] Department of Civil Engineering, Covenant University, PMB 1023 Ota, Nigeria
[b] Department of Civil Engineering, University of Nottingham, University Park, NG7 2RD Nottingham, UK
[c] Department of Civil Engineering, Tshwane University of Technology, Pretoria, South Africa

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ABSTRACT

Interfacial bonding between constituent materials and pore sizes in a concrete matrix are major contributors to enhancing the strength of concrete. In a bid to examine how this phenomenon affects a laterized concrete, this study explored the relationship between the morphological changes, porosity, phase change, compressive, and split tensile strength development in a ceramic-laterized concrete. Varying proportions of ceramic aggregates, sorted from construction and demolition wastes, and lateritic soil were used as substitutes for natural aggregates. Strength properties of the concrete specimens were evaluated after 7, 14, 28 and 91 days curing, but morphological features, using secondary electron mode, were examined only at 7 and 28 days on cured specimens, using Scanning electron microscope (SEM). From all the mixes, selected samples with higher 28 day crushing strength, and the reference mix, were further characterized with more advanced analysis techniques, using the mercury intrusion porosimetry (MIP), thermogravimetric analysis (TGA), X-ray Diffractometer, and SEM (backscatter electron mode-for assessment of the interfacial transition properties between aggregates and paste).

The reference mix yielded higher mechanical properties than the concrete containing secondary aggregates, this was traced to be as a result of higher peaks of hydration minerals of the concrete, coupled with its low tortuosity and compactness. However, a laterized concrete mix containing both 90% of ceramic fine and 10% of laterite as fine aggregate provided the optimal strength out of all the modified mixes. Although, the strength reduction was about 9% when compared with the reference case, however, this reduction in strength is acceptable, and does not compromise the use of these alternative aggregates in structural concrete.

1. Introduction

The persistent call for recycling and reuse of construction and demolition wastes currently is driven by the desire to reduce the impact of waste disposal into landfills and at the same time to mitigate depletion of natural resources. Many industrial and construction wastes are toxic and harmful [1,2], and one of these harmful construction wastes is ceramics.

Ceramic products are important components of modern construction being found in sanitary ware and tiling. Increasing urbanization has contributed immensely to the large volume of ceramics produced yearly. Records show that Spain is currently the world market leader in production and exportation of ceramic sanitary ware [3], producing approximately 7 million ceramic ware products annually. Usually during production of ceramic products, wastes are generated which represent about one third of the total volume of materials.

At present, ceramic wastes are mostly not recyclable and, consequently, these materials report to landfill [4]. Its deposition into landfills challenges the environment [5,6] and its handling can incur health and safety issues due to the very sharp edges often occurring on broken faces. However, it is interesting that some experimental studies have indicated that ceramic wastes are adequate as partial replacement for cement and natural aggregates [7–11].

In developing sub-Saharan African countries (and in other places), the wide availability of laterite has helped local communities

* Corresponding author. Department of Civil Engineering, Covenant University, PMB 1023 Ota, Nigeria.
E-mail address: paul.awoyera@covenantuniversity.edu.ng (P.O. Awoyera).

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build their houses using laterite for brick making. Such bricks are usually stabilized using cement or lime so as to increase their strength. However, a few studies [12–14], have suggested the use of laterite as a partial replacement for sand in making laterized concrete. A recent investigation [15], showcased the suitability of crushed ceramic floor and wall tiles as aggregates in laterized concrete. In that study, both the compressive and tensile strengths of concrete made with laterite and ceramic wastes were evaluated. However, the mechanical behaviour of concrete materials mostly depends on its intrinsic microstructure [16], therefore it is vital to also investigate the microstructural morphology of such modified concrete so as to understand how the components affect the concrete strength.

Concrete's strength, particularly its compressive strength, is considered to be its most important property, although other properties relating to deformability and durability cannot be ignored. Various microstructural changes occur when concrete hardens [17–19], mostly as a result of hydration of calcium and aluminate compounds in the presence of water. Consequently, the microstructure of cemented materials is essentially determined by the compounds formed during the hydration reactions of the clinker's constituents [20], while, in turn, this microstructure is one of the factors controlling compressive strength [21].

Some studies have evaluated how different factors affect both the microstructure and strength properties of recycled concrete [3,22,23]. These have shown that materials such as powdered glass and crushed ceramics from sanitary ware can affect the microstructure of concrete. However, the investigation reported in this paper aims to understand the intrinsic microscale changes in laterized concrete made with ceramics and how this addition affects compressive strength.

2. Materials and method

The materials used in this study for producing the different concrete mixes were granite of 12.7 mm nominal size, river sand (≤4 mm sizes), ceramic fine and coarse aggregate processed to similar sizes as the natural aggregates, laterite and Ordinary Portland Cement (OPC). All the constituent materials were prepared in conformity with standards [24–28]. The physical properties of the materials are presented in Table 1, the test values satisfied the standard requirement for aggregates to be used in different types of concrete.

Fig. 1 shows the aggregates used for making the concrete, while their particle size distribution is presented in Fig. 2a. The chemical oxide composition of laterite, cement and ceramics, as obtained from a parallel study [29], is shown in Fig. 2 (b). The results of chemical analysis (using X-ray fluorescence (XRF) method) showed that the ceramic tile powder satisfied the condition for pozzolans [30] in that the combination of SiO_2 and Al_2O_3 (equaling 86.13 wt %) is greater than 70 wt%. The XRD spectrum showing the mineralogy of cement, ceramics and laterite are presented in Figs. 3–5 respectively.

Concrete mixing was performed for the selected laterized concrete samples, based on the mix proportion design shown in Table 2.

A characteristic compressive strength of 25 MPa was targeted, with a constant water-binder ratio of 0.6. The slump of the fresh concrete mixes was tested to evaluate its workability. For all the mixes, 150 mm dimension concrete cubes, and cylinders of 100 mm diameter and 200 mm depth were prepared in triplicate and cured in water for a maximum of ninety one (91) days at a temperature of 20 ± 1 °C. In order to achieve the desired consistency or workability in mixes with a large quantity of ceramics, 0.6 water-binder ratio was used, primarily so as to complement the water absorption (coefficient of 0.55%) of ceramic tile aggregate being more than four times as much that of the granite (0.13%).

The concrete cubes and cylinders were subjected to compressive and split tensile testing at 7, 14, 28 and 91 days curing periods, according to [31,32], using a 2000 kN compression machine. After crushing of the cubes, broken samples were machined into cubes of approximately 3 cm dimensions, for microstructural tests from the surface of the specimens. Scanning electron microscope (SEM) images and energy dispersion spectroscopy (EDS) results at 7 and 28 days of the selected mixes were obtained (in secondary electron mode) so as to identify the changes in the morphology of the samples with the intention of relating these changes to associated strength developments.

Scanning electron microscopy (SEM - Hitachi S4100 equipped with energy dispersion spectroscopy, EDS – Rontec) was used, at 5 kV and 25 kV, to investigate the microstructure of the samples. Test samples were coated with gold using 10–20 mA DC current, and afterward attached to double-sided carbon tape mounted on a brass stub.

In addition, advanced analysis techniques, mercury intrusion porosimetry, thermogravimetric analysis (TGA), X-ray diffractometer (XRD), and SEM (backscatter electron mode), were used to characterize a selected sample (having higher compressive and split-tensile strengths), alongside reference mix sample. Mortar cubes of 70 mm dimensions that had been cured in water for 28 days were used for the tests.

Fragments of mortar, obtained from the crushed concrete cubes, were used for the XRD and the TGA tests. The mortar specimen was dried completely in the oven, and afterward ground with mortal and pestle, and later sieved through a 63 μm aperture size. The resulting powder sample was used for both XRD and TGA analysis. The XRD analysis reveals the specimen mineralogical phases, while the TGA test was used to determine the amount of calcium hydroxide ($Ca(OH)_2$) derived, as a result of the dehydroxylation of the specimen. A Bruker – AXS D8 Advance equipment, having a scanning speed of 2° per minute was used for the XRD analysis. The scanning process was performed in steps of 0.05° and at a range 10 to 70°. The TGA was performed using a Q600 TGA-Differential scanning calorimeter. A ramp heating procedure was adopted in a nitrogen atmosphere, which allows for a sample to be heated uninterruptedly at different specified rates per minute. In this study, the specimens were heated, initially at 30 °C per minute up to 300 °C, and subsequently at 20 °C per minute up to 600 °C. Finally,

Table 1
Physical properties of the aggregates used.

Properties	River sand	Laterite	Ceramic fine	Ceramic coarse	Granite
Specific gravity	2.61	2.13	2.26	2.31	2.87
Water absorption (%)	2.24	4.70	2.52	0.55	0.23
Fineness modulus	2.24	1.80	2.20	6.88	6.95
Aggregate crushing value	–	–	–	20.86	34.00
Aggregate impact value	–	–	–	27.00	24.00