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Design of Green Hybrid Cementitious Composite for Sustainability Enhancement

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Abstract: Built environment sustainability is progressively coming to the upfront in the design of infrastructure as well as in the process of decision making for maintenance work. In confronting this, there is a need for the development of innovative green cement-based materials. These materials should be invented based on the needs of the final application in which they will be implemented. The actions of ignoring the connection between the developments of material, design of structures and sustainability objectives which can result to expensive, short life span, and resource-intensive structures that will need a higher cost of maintenance in a short while are becoming obsolete. This study presents the development of a design framework which was used to produce green hybrid cementitious composites for infrastructure implementation. By means of intentional and careful control of composites constituents and the tailoring of the materials similar to engineer cementitious composites, cement-based hybrid cementitious composites were developed and the mechanical properties are presented. Metakaolin, (MK) and nano-silica (nSi) in colloid form, as well as epoxy, were used as partial replacement of cement content at 12%. Fibers, oil palm, coconuts and artificial barchip were used at 2%. The impact of all these hybrid materials was tested at certain ages of 7, 28 and 90 days. The result shows that despite the replacement, the hybrid cementitious composites performed better in terms of mechanical properties than the same control sample without Metakaolin, nano-silica and epoxy.

Keywords: Cementitious composites, Metakaolin, Nano silica, Fibers

1. Introduction

The issue of sustainability in the construction industry is one of the major factors in the developing world due to the fact that the increasing reduction in the available natural resources and ever-increasing CO_2 emissions brought about by the large production of cement and concrete. The annual production of concrete was estimated to be approximately 10 billion cubic meters. Cement is the most significant and expensive constituents of concrete and it remain the main binding material. According to the report released by the United States Geological Survey, about 4180 million tons of cement was produced globally in 2014. Cement production alone causes 7% of the carbon dioxide emissions globally, as the production of a ton of cement releases a ton of carbon dioxide. Going by this, if a part of cement contents can be substituted by any supplementary cementitious materials which can either be natural, factory by-products or waste products, then, the emission of greenhouse gases can be minimized as it is linked with cement production (Hendrik, 2015, Siddique et al.,2015; Thomas & Gupta, 2015, 2016). Hence, the objective of this research is

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to minimize the CO_2 emission and to use of the natural and chemical admixture as a cement replacement. On the other hand, the most widely and frequently utilized construction material for different kind of infrastructures is cementitious materials but the materials are generally very brittle with low strength and low strain to failure (Tyson, 2013) hence the needs for fibers and mineral admixtures.

Sustainable research for materials in the construction industry has triggered the hunt for substitute materials that can replace cement. Many natural and chemical mineral additives such as ash, condensed silica fume, blast furnace, stone wastes, copper slag, steel scrap, tire ash, blast furnace slag, Metakaolin, nano-silica, carbon nanotube, fibers etc and some agriculture products as well, like palm oil shells, elephant grass, wood waste ash, Coconut shell and fiber, bagasse ash, corn cob, tobacco waste, and rice husk ash, have been verified and adjudged useful substitute as addition or substitutions to cement or the aggregates (Kumar et al.,2016, Mehra et al.,2016 and Thomas et al.,2013,2014 & 2016). The use of many of these natural, chemical and factory waste mineral additives, offer many benefits like enhanced mechanical and durability properties, minimize cost of construction, minimize CO_2 emission, reduction of pollution and enhance environmental sustainability (Kamiya et al., 2000, Saraswathy & Song, 2007 and Thomas et al., 2015a,b).

Metakaolin, as one of the natural mineral additives, possesses a particle size that is finer than cement, although not equally fine as silica fumes. Based on this special and unique feature, it offers enhanced workability and entails a smaller quantity of high-range water-reducing admixture to achieve slump that is comparable to SF concrete (Pacheco-Torgal & Jalali, 2011). In that respect, there are other benefits as well, which includes a creamier texture, less bleed water is involved and better surface finishes compared to concrete with SF (Chandrasekhar et al., 2002).

Likewise, nano-silica, been a chemical mineral additive, has the potential enhancement ability which is through two major mechanisms. The first of the mechanism is that the ultrafine particles of nano-silica have the ability to fill - up the microscopic voids that exist within cement particles, thereby enhancing the cementing properties and as well establish a less permeable structure. Also, the curing procedure permits the reaction between $Ca(OH)_2$ and nano-silica in the course of hydration of cement to yield supplementary calcium silicate hydrate (Sobolev & Gutiérrez, 2005). In addition to this, the evenly mixed nano-silica particles could serve as the centre for nucleation of cement hydrates, a stimulant factor that can bring about the acceleration of the hydration process. The nanoparticles enhance the configuration of cluster small-sized and uniform C-S-H. As well, they could the structure of the aggregate contact zone which brings about strong bonds between cement pastes and aggregates (Sanchez & Sobolev, 2010). Epoxy resins are a class of thermosetting polymers with special resistance and mechanical properties. They are usually the end product of the chemical reaction of the curing system of hardeners or curing agents. Substances, such as polyamines, phenolic and aminoamides compounds can be used as hardeners. According to Ferdous et al., (2016), epoxy resin and polyester resin are the most frequently used class of resin and this is because of the high strength and chemical deterioration resistance. Epoxy resin was chosen in this study because of its mechanical and durability properties. It has strong chemical resistance, reduced shrinkage in the course of curing, excellent structural capability, low water absorption and excellent resistance to fatigue Ferdous et al., (2016).

Based on these, this research aim at developing green hybrid cementitious composites (HCC) targeting reduction of the cement contents and test the mechanical properties at the early age. The HCC was produced utilizing 10% MK, 1% colloidal nano-silica (CNS) and 1% epoxy resin without hardener, as partial replacement of the binder.

2. Constituent materials

2.1 Cement

This study used a type I Portland cement having a median particle size of 6.14 µm, specific surface area of 1123.3 m^2/kg and the specific gravity of 3.02. The cement has a setting time of 115 and 310 minutes, respectively, for the initial and final setting time. The physical and chemical properties of the cement are in line with the guideline of ASTM Standard C150 (Ma et al., 2018).

2.2 Metakaolin

The Metakaolin (MK) used in this study was produced from raw Kaolin which locally sourced and was calcined in the laboratory. The calcination process was as detailed in another publication (Sanchez & Sobolev, 2010). MK is having particle size diameter (d_{50}) of 2.80 µm and a specific gravity of 2.6. It has 0.015 m^2/kg of specific surface area and mean size of between 1 to 2 µm. The chemical composition of the MK is highlighted in Table 1.

Table 1 - Chemical composition of metakaolin produced in the laboratory (% weight)

Oxides	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI*
MK (%)	53.03	0.93	35.63	1.81	0.02	0.57	0.04	0.04	1.88	0.06	1.99

* Lost on ignition is 1.99%, in compliance with BS EN 15935 (2009)

2.3 Nanosilica and Epoxy resin

The colloidal silica used was supplied by Sigma- Aldrich and the brand type is Ludox AS- 40 colloidal silica. It is 40 wt. % suspensions in water. Meanwhile, Epoxy resin (CP 370A) model of bisphenol A was utilized in the study. It was used as cementitious material, as well as a bonding agent.

2.4 Fine Aggregates (natural sand)

Locally sourced natural fine aggregates were used. It has a fineness modulus of 0.99 measured according to ASTM C33. The particles of the sand were retained by 0.60 mm sieve aperture having a maximum particle size of 600 µm. The sand has a specific gravity of 2.62 and water absorption of 2.1%.

2.5 Fibers

Locally supplied coconut fiber and oil palm fiber were chopped to length. The properties are 1.13 and 1.24 respectively. Water absorption of the two fibers is 7.2% and 0.6% respectively for hours between 24-48 hours. The tensile strength is 120-200; 240-260 N/mm^2 respectively.

The toughness is between 3,000-3,200 and 2,000-2,200 N/ mm^2 respectively. The synthetic fiber used was Barchip 54 chopped to length like the other natural fibers. The specification is base resin with polyolefin property and the specific gravity is 0.95 while the tensile strength is 40 N/ mm^2.

2.6 Mixing water and Superplasticiser

Type F sulfonated melamine formaldehyde superplasticiser was used at a certain dosage to attain the target workability. The mixing water was locally supplied portable water.

3. Experimental programme

3.1 Mixture proportioning and mixing procedure

The mix design was adopted from ECC 45 as proposed by Professor Li of the University of Michigan (Li, 2003 and Ramli et al., 2016). The original mix proportion was modified in composition which consists of binder, sand and water in the ratio of 0.8:1:0.30, respectively, for all the HCC specimens. Table 2 shows the mix proportion for all mixes. Meanwhile, C represents control specimen, BM is the base mix, OPFBF is the oil palm fruit brunch fiber, CF is coconut fiber and BF is barchip fiber.

The preparation of the fresh HCC specimens involves a systematic mix of all the constituents and the uniform dispersion of different fibers in the matrix. The dry particles like cement, MK, fine aggregates were blended in the 75-litre capacity Hobart tilting drum mixer, having a planetary rotating blade for 2 minutes. Thereafter, 10% of water with plasticizers was added in the mix, while the blending continues for another 2 minutes. The remaining water was added and then the fibers manually so as to ensure the even distribution of the fibers in the matrix.

Table 2 - Mix proportion

Mix	PC (Kg/m^3)	MK (Kg/m^3)	Nso (Kg/m)	Epoxy (Kg/m^3)	Fine agg (Kg/m^3)	Water (Kg/m)	SP (Kg/m)
C	66.4	7.47	0.01	0.01	83.0	24.9	0.82
BM	66.4	7.47	0.01	0.01	74.7	24.9	0.82
OPFBF	66.4	7.47	0.01	0.01	74.7	24.9	0.82
CF	66.4	7.47	0.01	0.01	74.7	24.9	0.82
BF	66.4	7.47	0.01	0.01	74.7	24.9	0.82

The OPFBF, CF and BF are at 2% each in specimens that contain fibers.

3.2 HCC mixing and Exposure regime

The HCC mixing process was done using a laboratory size mixer in accordance with ASTM Standard C305 (Ma et al., 2018). The mixing process took between 10-15 min. After the mixing, the workability test was done, and the fresh density was measured accordingly. The specimens were cast and later exposed to seawater and portable water regime until the dates of tests to assess different environmental impacts on their properties.

4. Mechanical properties of HCC

4.1 Slump test

Slump test to ascertain the workability of the mix was conducted on the fresh HCC mixes with the use of flow table in compliance with BS 1881: Part 102 (ASTM, 1997).While the fresh density of the HCC was measured according to ASTM C1611.

4.2 Bulk density and Mechanical strength tests

The bulk densities of HCC mixes were accessed in conformity with BS 1881: Part 114 (Ramli et al., 2016). The compressive strength test of HCC samples was conducted according to ASTM Standard C109 (ASTM, 1994) using 50mm cube sizes at different ages. Meanwhile, prism specimen of 40 x 40 x 160 mm dimensions was used for the flexural strength test of the HCC mixes at different ages in compliance with ASTM Standard 348 (Brooks et al., 2000). The results of the compressive and flexural strengths at any each age are the mean of three numbers of the samples of HCC tested.

5. Results and Observation

5.1 Slump value of HCC specimens

The results of the slump test of all specimens of HCC are presented in Table 3. It is observed that the slump result for BM, that is, the base mix is lower in value when compared to the control mix C, it is almost 3.25%. This may probably be as a result of the presence of MK in the mix. MK has been observed to absorbed more water because of its high reactivity, the surface area and fine particles. This corroborates the result published by Brooks et al. (2000), where it was explained and confirmed that paste with Metakaolin needs more water for workability and consistency.

Likewise, the utilization of colloid nano-silica, CNS, was observed to bring about reduction in the workability value and this was also confirmed in the study conducted by Singh et al.,(2013), where it was analysed that the nano-features of nano-silica with the surface area caused high water absorption (ASTM,1998). All other HCC specimens that contain fibers have a consistency value ranging between 140mm and 146mm. These are lower than control specimen, C, and the base mixes in percentages ranging between 5% and 9 %. This may be probably because of the friction between the paste and the fibers. According to the study, the presence of fibers in a mixture brings about extra coherency within the cementitious paste as the specific surface area of the fibers stimulates the influence of the friction. Since the absorption properties differ from one fiber to another hence the differences in the values in the slump measurement.

Going by each fiber, coconut oil fibers recorded the other fibers. This is closely followed by oil palm fruit bunch highest value because of the highest absorption tendency than fibers specimens, while barchip fibers specimens have the least slump value. The coconut fiber specimens recorded 143mm slump value which is 7.14% lower than the control specimen and also 4.03% lower than BM. This is observed to be as a result of the high absorbent properties of the fibers and this finding is in tune with past experimental studies (ASTM, 1997 and Singh et al., 2013). Studies shows that the main factors for slump value relies on water and binder ratio, w/b, superplasticiser and binder ratio, sp/b and sand and binder ratio,s/b but the most significant out of all is the superplasticiser and binder ratio, sp/b.(Ramli & Hoe,2010).

Table 3 - Slump flow of the HCC mixes with superplastizer dosage

SCC mix design	Superplasticiser Dosage (kg/m^3)	Slump flow (mm)
C	0.062	154
BM	0.062	149
CF	0.062	143
OPFBF	0.062	145
BF	0.062	148

5.2 Density

Fig. 1 shows the result of the bulk density of all samples. It shows that the density of all specimens increases with ages. This may be because of the continuous hydration process which can occur in the presence of continuous water because of the curing regime. The density recorded at all ages ranges from 2204 Kg/m^3- 2249 kg/m^3 at age of 7days, 2212kg/m^3-2253 kg/m^3 for the age of 28days and 2218 kg/m3-2255 kg/m3 at the age of 90days. But at all ages, it was observed that control specimens, C, has the highest density of 2260 kg/m^3 - 2294 kg/m^3. The result complies with the result of other researchers like Sahmaran et al. (2013) where it was confirmed that cementitious composites with or without fibers increase with ages irrespective of the exposures.

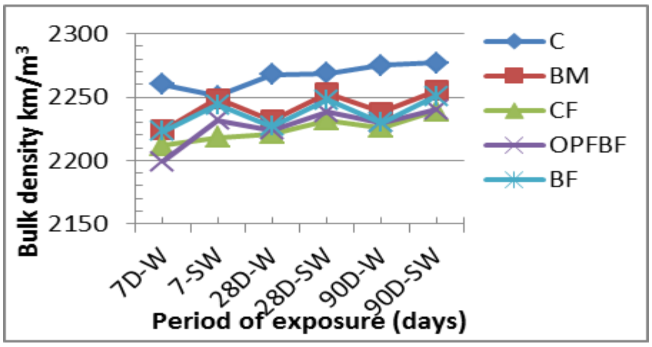


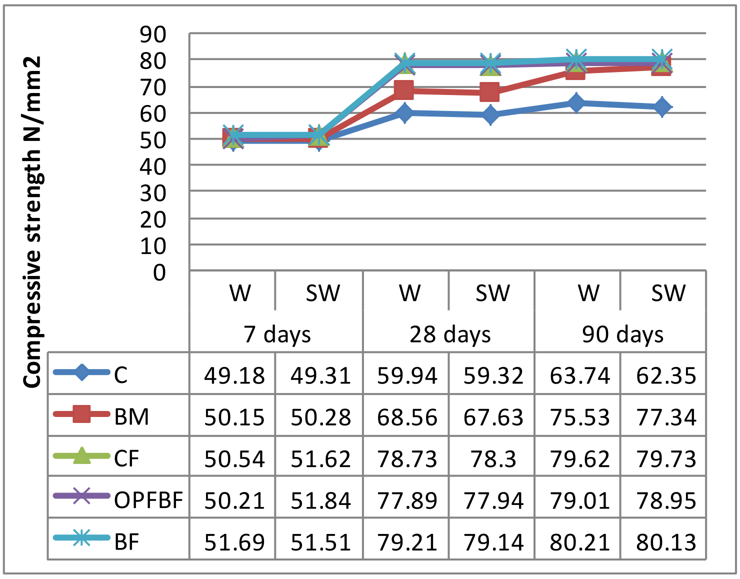
Fig. 1 - Bulk density of all HCC samples

5.3 Compressive strength

Results of HCC specimens' compressive strengths at all ages are shown in Fig. 2. The result shows that all HCC specimens developed higher strength than the control specimens at all ages. Irrespective of the exposures, the compressive strength increases at all ages. It was also noticed that the rate of strength development before the age of 28 days was higher than other ages after 28 days. The percentage of strength increase is between the ranges of 1.97 to 33.41% at the age of 7 days and 28 days respectively, above what was recorded by control specimens. The change in phenomenon could be explained by the presence of CNS in the mix, the pozzolanic reaction in the presence of calcium hydroxide formed C-S-H chain dimension and stiffness at the final phases which brought about significant strength development at the early ages of all specimens. This process and formation are faster and higher in quantity than what Metakaolin can produce. This is because of the higher surface area of CNS and because the formation works as nucleation for the precipitation of C-S-H gel (Dinakar et al., 2013). But at the later ages, the higher compressive strength of HCC can be attributed to MK particle pores filling impact and its' pozzolanic reaction with calcium hydroxide. This result corroborates the results of other past research in the literature (Sahmaran et al., 2013; Zapata et al., 2013).

As shown in Fig. 2, at the age of 28days, BF specimen was observed to have the highest strength with 33.41% higher than the control specimen and 29% higher than the strength recorded at the age of 7 days. Meanwhile, BM, CF and OPFBF have compressive strength at the age of 28 days with 12.21%, 29.93% and 26.26% respectively above what was recorded at the age of 7 days.

It was also observed that HCC specimens with higher compressive strength were those that were exposed to seawater, for instance, the compressive strength of BF specimen exposed in seawater recorded the highest compressive strength at the age of 28 days. Among all the specimens exposed to portable water, BM and CF recorded the higher compressive strength. At the age of 90 days, BF specimen still has the highest compressive strength with 80.21 N/mm^2 compared to CF specimen that recorded 79.73 N/mm^2 among the specimen exposed to seawater. Meanwhile, OPFBF specimens have 78.95 N/mm^2 and BM specimens have 77.34 N/mm^2.



	W (7 days)	SW (7 days)	W (28 days)	SW (28 days)	W (90 days)	SW (90 days)
C	49.18	49.31	59.94	59.32	63.74	62.35
BM	50.15	50.28	68.56	67.63	75.53	77.34
CF	50.54	51.62	78.73	78.3	79.62	79.73
OPFBF	50.21	51.84	77.89	77.94	79.01	78.95
BF	51.69	51.51	79.21	79.14	80.21	80.13

Fig. 2 - The Compressive strength of HCC samples at all ages

5.4 Flexural strength

The results of the flexural strength at all ages are shown in Fig. 3. The results show the same pattern as compressive strength, there is a noticeable increase in flexural strength of all specimens over the ages. This is despite the ageing effects of the natural fibers, especially OPFBF specimen. At the early age, all specimens achieve higher flexural strength than the control samples C and BM specimens. This signifies that fiber incorporation brings about an increase in flexural strength. This may be because of the impact of toughness matrix of fiber as well as their homogeneity and compactness. This result confirmed the results of research published by Felekoglu et al., (2009), where it was found that fiber, either natural or synthetic has a significant impact on the flexural strength of concrete. The result shows that BF specimens recorded the highest flexural strength with 29.58% above C specimens and 26.88% above what was recorded by BM. Meanwhile, OPFBF recorded the lowest flexural strength among all the specimens exposed in portable water with a flexural strength value of 6.36 N/mm^2. This is 3.92% above the control specimen value and 1.59% above the BM HCC specimen at the age of 7 days. At this age, it was observed that BM and CF specimens exposed to portable water recorded higher values above the seawater. At the other ages of tests, HCC specimens exposed to seawater recorded higher flexural strength values. At the age of 28 days, BF specimens exposed to portable water recorded the highest values of 52.77% above the control specimens and 27.30% above BM specimens. This signifies an increase of 23.19% and 0.42% respectively above what was recorded at the age of 7 days. It shows a significant increase above the BM and C specimens. Specimens CF recorded the second-highest value; it has 9.97 N/mm2 which indicate 40.57% above the control specimen and 18.40% above the BM specimens. Among the entire specimens that contain fiber, the OPFBF exposed to water recorded the lowest flexural strength of 9.07 N/mm^2 which indicates 28.65% above the C specimen and 8.36% above the BM specimens. At age 90 days, the BF specimen has the highest flexural strength value, and this happened at all the ages. The findings may be as a result of the high tensile ductility properties of the barchip fiber, which is a synthetic fiber and when compared to natural fibers which have lower tensile ductile properties. The result reflects the tensile ductility property of each fiber accordingly (Madandoust & Mousavi, 2012). In addition to this, the barchip fiber's mechanical and elastic property, as well as their surface structure is more influential in their performance.

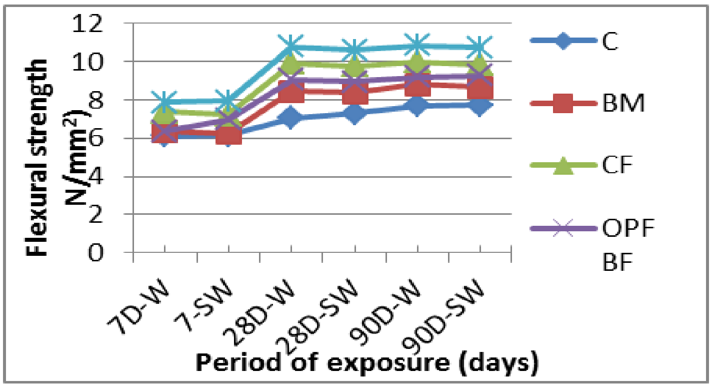


Fig. 3 - The Flexural strength of SCC at various ages

6. Conclusions

The following conclusion can be deduced from the laboratory experiment. The HCC with the incorporation of 10% MK, 1% CNS and 1% epoxy resin of the total weight of the binder reduces the slump value of the mix compared to the control specimen by 3.25%. Meanwhile, the incorporation of natural fibers causes further reduction to compare to the control specimen with about 7.14%. The density also increases with ages. Also, the compressive strength is high at the early age and increases as the age increases, higher than 38 N/mm^2 of normal concrete at 28 days and 33.41% above the control specimen. HCC with Metakaolin, CNS and epoxy causes an increase in flexural strength at all ages; it recorded 29.58% and 26.88% above the BM. The incorporation of MK and Nanosilica with epoxy at a certain percentage replacement of binder, that is the cement, contributes to the sustainability of the concrete, hence green hybrid cementitious composites.

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