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Kenaf Fibre-RHA Biocomposite: A 'Green' Substitute to Asbestos in Sustainable Eco-Construction

Ofoegbu, O.
National Research Institute for Chemical Technology,
P.M.B. 1052, Zaria, Kaduna, Nigeria
obinnafor@yahoo.co.uk

Victor, O.
National Research Institute for Chemical Technology,
P.M.B. 1052, Zaria, Kaduna, Nigeria

Alisa, C.O.
School of Chemical Sciences,
Novena University,
Ogume, Delta State

Abstract

With the damaging impact of asbestos to health and the environment, search for substitutes with equal or better properties have led to trials involving select bio materials. This work presents the result of combinatory use of bast and core fibers from local cultivar of Kenaf plant as reinforcement and Rice Husk Ash (RHA) as asbestos substitute in the production of insulation material. The fibers were used at varied blend ratios with rice husk ash as partial substitute Portland cement binder material. The strength of material test results showed the products to have the same (tensile strength greater than 262.31 MPa, Young's modulus of not less than 22.94 and failure strain (%) of 2.62 and above) for samples of same dimensions as conventional sheets. Friedman statistical analysis showed that an increase or addition of the Kenaf core enhances the compact nature and consequent strength of the material. This substitution with Kenaf fiber and RHA embraces four out of the five key areas of sustainable human and environmental health target: sustainable site, energy efficiency, material selection and indoor environmental quality. Kenaf plant serves as a good carbon sink source with consequent environmental detoxification.

Introduction

The general concept of sustainable urban housing revolves around the integration of energy and environmental issues in housing programmes/projects. It is important to note that this integration takes place in all aspects of the housing process and when extrapolated yields a low cost housing initiative. Definitively, low-cost (housing) is relative to the socio-economic aptitude of target group. Job creating activities such as labour-intensive construction methods and the creation of small workshops could present another way of obtaining local socio-economic sustainability and the use of renewable, good building materials is of immense importance.

Traditional materials often have relatively minor or negative impact on environment than modern materials such as bricks, concrete, corrugated iron roofing sheets and ceiling materials. Generally environmental sustainability is a matter of minimizing the pollution from the consumption of energy, water, materials and land, and maximizing the use of renewable and or recyclable materials (Christel and Bjarke, 2000).

The use of natural fibers as reinforcements in cement composites as substitute for asbestos in insulating materials has huge prospect in the field of recycling materials for construction. Aside being a cheap material resource it gives an environmental friendly alternative. Conventional synthetic materials (glass fibre, carbon fibre, etc.) which are good reinforcing materials for construction though available are costly and therefore, predominately used for high-tech applications in transport, building and construction industries (Beaudoin, 1990).

Sisal, coconut, jute, bamboo and wood fibres, are a few examples of reinforcing materials that have both renewable and recyclability attributes and their use before this period has been more experiential than technological (Persson, 1980). Vegetable fibre-cement composites production comes with inherent challenges despite it being the solution for combining unconventional building materials with traditional construction methods. The incorporation of natural fibers in cement matrix has resulted in post fiber debonding and material failure due to high alkali content of the matrix but the part substitution with Rice husk ash is envisaged to be the solution to the challenge; hence the target of this research.

Utility potentials of kenaf plant

A cousin of cotton and a potentially new crop, kenaf, has in recent time found a strategic position as the choice forest conservation and eco-detoxifying crop. The potentials inherent in a kenaf sustainable raw material feed include and not limited to the fact that:

1. Kenaf plant absorbs CO_2 from the atmosphere more than any other crop - about 1.5 tons of CO_2 is needed for a production of 1 ton of dry matter of Kenaf. It means that every hectare of kenaf consumes 30-40 tons of CO_2 for each growing cycle, translating to each hectare of kenaf consuming the amount of CO_2 that exhaust from 20 cars in whole year emits. Kenaf plant can absorb toxic elements, such as heavy metals from the soil. Kenaf core can be applied as soil remediation in case of hydro carbonates infestations.

2. Dissolved kenaf lignin (black liquor) from the pulping process can be turned into a solid cake in the presence of chitosan, producing an animal feed binder. The remaining soluble black liquor can be

converted to a low-sodium, dry fertilizer containing about 22 percent nitrogen.

3. Kenaf incorporated into fiber composite board may effectively replace use of fiberglass. Kenaf's strength and low weight make it less likely to shatter or warp under extreme temperatures.

4. Kenaf is used in the pulp, paper and cardboard industry -from wet way process sulphate pulp (Kraft) from the whole kenaf stem and from separated fibers, lining for roofs in felt paper, cellulose for chemical uses, e.t.c.

5. For a dry process pathway (dry processes using moldable fibre mattresses), panels for interior panels for cars and planes, furniture and construction industries, rigid molded products (boxes, trays, drums, pallets etc. for the packing, stowage and shipment of industrial products), e.t.c.
6. Kenaf provides mass uses as absorbent agent (cleaning up of liquid leakages from spill areas), additive for drilling muds in oil wells, animal litter and other products.

7. Processing of kenaf yields packing materials such as inert, natural and biodegradable filler, used instead of polystyrene foam, e.t.c

8. Kenaf plant can, if desired, serve as raw material for natural fuels routed as biomass for burning in various forms (powder, core fiber and waste in general), production of ethyl alcohol and other chemical products from kenaf animal litter using ligno-cellulose conversion technologies.

9. Kenaf seeds yields a 21-22% oil content product with cake that is suitable for animal feed production.

Chemical composition

Retted kenaf fiber is chemically composed of, -cellulose, hemicelluloses, and lignin. The lignin if desired can be almost completely removed. Average fiber length of the bast is 2.6mm, and the core is 6mm. The lignin percent of the bast is 7.7% and the core is 17.4%. This lower lignin content accounts for the lower chemical and energy need in pulping. The average cellulose content for the whole stalk kenaf is Crude=54% and Alpha 37.4% (Thomas, 1999).

Acetyl content

The acetyl content offers a means of differentiating between jute and kenaf. Kenaf, like most vegetable fibers, contain a proportion of acetyl groups that are readily hydrolyzed by dilute alkali to acetic acid. Estimation of the quantity of acetic acid produced per unit weight of fiber gives an index of the acetyl content. (Soutar and Brydon,1990), reported acetyl contents averaging 110 for *Hibiscus*, expressed in milli equivalents of acetic acid per 100 g of dry fiber (Virta, 2000). In a recent study, Han and Rowell reported changes in kenaf as a function of the growing season. They found that the average length of a bast and core (stick) fiber increased as the plant aged. Protein content went from 1.48% at 48 days to 1.84% at 70 days. Lignin content went from 5.4% at 48 days to 10.5 at 70 days. Solvent extractive content increased from 2 % to 13% in the same length of time. Arabinose, rharmnose, galactose, and manose content decreased from day 48 to day 70 while glucose and xylose content increased over this same period.

Chemical modification for property improvement

Agro-based composites change dimensions, burn and are degraded by organisms and ultraviolet radiation with change in moisture content because the cell wall polymers having hydroxyl and other oxygen-containing groups, attract moisture through hydrogen bonding. Properties such as dimensional instability, flammability, biodegradability, and degradation caused by acids, bases, and ultraviolet radiation are environmentally influenced (carbon dioxide and water) (Otouma and Take,.....). Fibers are degraded biologically by specific enzyme systems capable of hydrolyzing these polymers into digestible units[9]. Strength is lost as the cellulose polymer undergoes degradation through oxidation, hydrolysis, and dehydration reactions. The same types of reactions take place in the presence of acids and bases (A. Europaeus-Ayrapaa, 1930).

Fibers exposed outdoors to ultraviolet light undergo photochemical degradation. Because the properties of the agro-based fiber are influenced by the chemistry between the cell wall components, the basic properties of a fiber can be changed by modifying the basic chemistry of the cell wall polymers (Skinner *et al*.; 1988). Many chemical-reaction systems have been published for the modification of agro fibers (Alleman and Mossman, 1997; Bentur and Mindess, 1990).

Asbestos fiber

Asbestos fiber exhibit high tensile strengths, high length: diameter (aspect) ratios of 20 and up to 1000 are sufficiently flexible to be spun; and macroscopically resemble organic fibers like cellulose. Early uses of asbestos were due to the reinforcement and thermal properties of the fibers. The first recorded application can be traced to Finland (approximately 2500 B.C.) (Bowles, 1946). The use of asbestos fibers on a true industrial scale began in Italy early in the nineteenth century with the development of asbestos textiles (Bernard, 1990; Virta, 2006 and Roberta, 2004) and in particular for thermal insulation (Paul, 1985). During the late 1960s and 1970s, the finding of health problems associated with long-term heavy exposure to airborne asbestos fibers led to a large reduction in the use of asbestos fibers. In most of the current applications, asbestos fibers are contained within a matrix, typically cement or organic resins. Consequent to the health issues the search for alternative to asbestos started and is the basis of this work.

The substitution of asbestos fibers by other types of fibers or minerals must, in principle, comply with three types of criteria (Harrision *et al*.; 1999): the technical feasibility of the substitution; the gain in the safety of the asbestos-free product relative to the asbestos-containing product; and the availability of the substitute and its comparative cost. In some applications, particularly those that rely on several characteristic features of asbestos fibers, the substitution has presented a significant challenge. For example, in fiber-cement composites, the fibers must exhibit high tensile strength, good dispersion in Portland cement pastes, and high resistance to alkaline environments. In such applications, the replacement of asbestos fibers has required a combination of several materials. In fiber-cement construction materials, several alternatives are being practised, either using cellulosic fibrous products or synthetic organic fibers such as polypropylene (PP) or polyacrylonitrile or alternative products such as cast iron, PVC, or PP pipe.

The representative mean chemical composition of amphibole minerals (Asbestos) is:

$A_{0-1}, B_2C_5T_8O_{22}(OH, O, F, Cl)_2$

Where:

A = Na, K,

B = Na, Ca, Mg, Fe^{+2}, Mn, Li

C= Al, Fe^{+2}, Fe^{+3}, Ti, Mg, Mn, Cr

T = Si, Al

A, B, C each represent cationic sites within the crystal structure (Stern and Stout, 1954; Stern, 1957 and Singh, 1985).

The two most important amphibole asbestos minerals are amosite and crocidolite, and both are hydrated silicates of iron, magnesium and sodium (crocidolite only).

Portland cement

Portland cement (Dangote brand) has the generic composition:

Cement Compound	Weight Percentage	Chemical Formula
Tricalcium silicate	50 %	Ca_3SiO_5 or $3CaO\cdot SiO_2$
Dicalcium silicate	25 %	Ca_2SiO_4 or $2CaO\cdot SiO_2$
Tricalcium aluminate	10 %	$Ca_3Al_2O_6$ or $3CaO\cdot Al_2O_3$
Tetracalcium aluminoferrite	10 %	$Ca_4Al_2Fe_2O_{10}$ or $4CaO\cdot Al_2O_3\cdot Fe_2O_3$
Gypsum	5 %	$CaSO_4\cdot 2H_2O$

Experimental

Materials

a) Ordinary Portland cement

b) rice husk ash

c) kenaf bast fiber

d) kenaf stem core

e) borax

Materials pretreatment methods

a) Bast fiber from kenaf were extracted as long strands then cut to average lengths of 10mm and conditioned by alkali treatment. The cut fibers were dried and kept for use.

b) The stem core of kenaf was extracted, dried and conditioned to constant moisture content.

c) Rice husk was first burned in the open then transferred to a furnace and ashed at a temperature of 550^{o}C for 2hrs.

Sample production

From literature and practice the production technologies available for making cement-matrix composites include: (i) combining fibres with matrix in a pan mixer as if the fibres were an extra ingredient in the common method of producing a cementitious mix; (ii) simultaneously spraying fibres and cement slurry onto the forming surface to produce thin products; (iii) fibre-reinforced concrete; (iv) dispersal of fibres in a cement slurry which is then dewatered to produce thin products; (v) hand-laying fibres, in the form of mats or fabrics, in moulds, impregnating them with a cement slurry and then vibrating or compressing the mix to produce a dense material with high fibre content; and (vi) impregnating continuous fibre mats and fabrics with a cement slurry by passing them through a cement bath in a continuous process(Bentur and Mindess, 1990). For the purpose of this work with the intent of local adaptation, the boards were produced by first dry blending the materials in a laboratory mixer after obtaining a homogenized blend, water was added. The formed slurry was transferred to flat moulds and compacted using a hydraulic press. The products were removed from the mould, cured and conditioned at ambient temperature for 7days then in a water through for twenty four hours to effect proper curing/setting (figs 1-8). Flat rectangular and dump bell shapes were obtained and used for test analysis. The blend formulation is as shown in table 1 below:

Table I: Formulation of sample boards used.

Sample ID	Kenaf Fiber(g)	Portland Cement(g)	Rice Husk Ash(g)	Kenaf Core(g)	Water (ml)
A	3.00	50.00	0.00	1.00	250.0
B	3.00	45.00	5.00	2.00	250.0
C	3.00	40.00	10.00	3.00	250.0
D	3.00	35.00	15.00	4.00	250.0
E	3.00	30.00	20.00	5.00	250.0
F	3.00	25.00	25.00	6.00	250.0
G	3.00	20.00	30.00	7.00	250.0
H	3.00	15.00	35.00	8.00	250.0
I	3.00	10.00	40.00	9.00	250.0
J	3.00	5.00	45.00	10.00	250.0

Figure1: kenaf core extracted from stem Figure2: kenaf core being ground to powder

Figure3: Cut kenaf stem fibre   Figure4: Rice husk (Ash and precarbonized)

Fig 5: Hydraullic pressing of the sheets

Fig 6

Fig 7

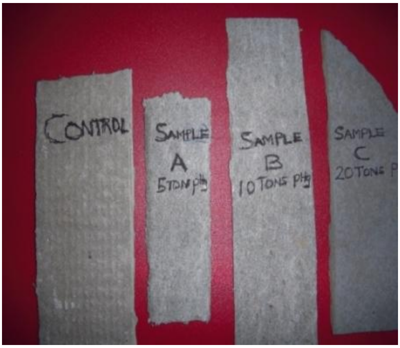

Fig 8

Fig 9

Fig 10

Fig 11

The analysis carried out are, three-point static bending and tensile strength tests (9-11), degree of moisture absorption. Other tests are density and linear expansion after soak.

Results and discussion

The results of the analysis are presented in figures 12, 13, 14 and table I and II.

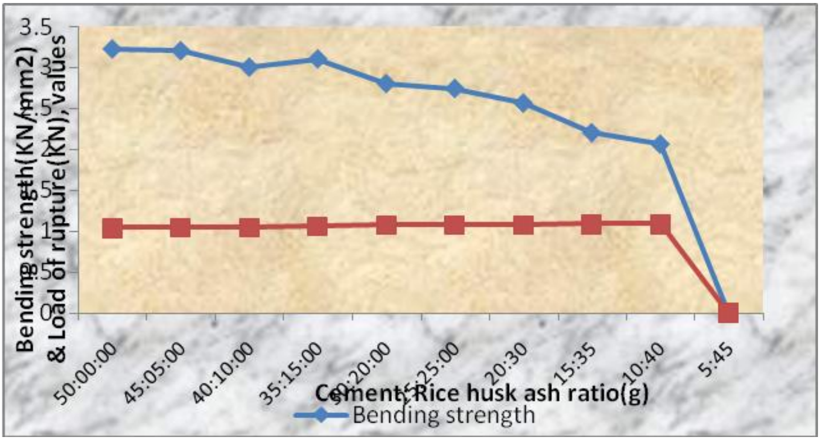

Fig 12: Plot of cement: RHA ratios against breaking load and load of rupture

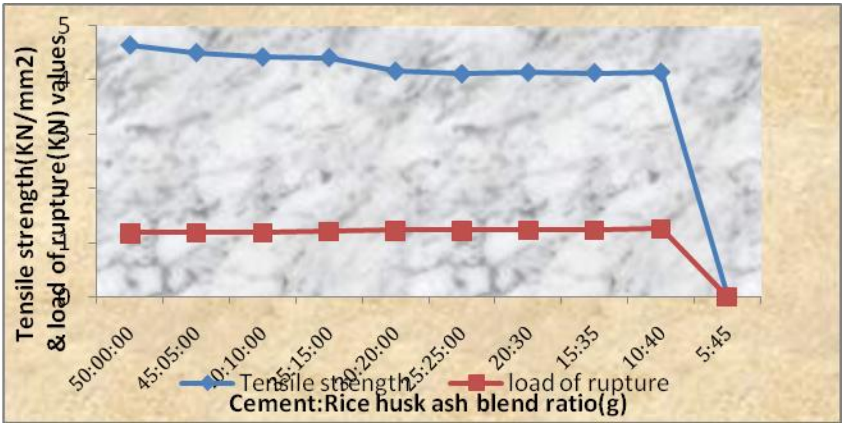

Fig 13: Plot of Cement: RHA ratios against tensile strength and corresponding load of rupture

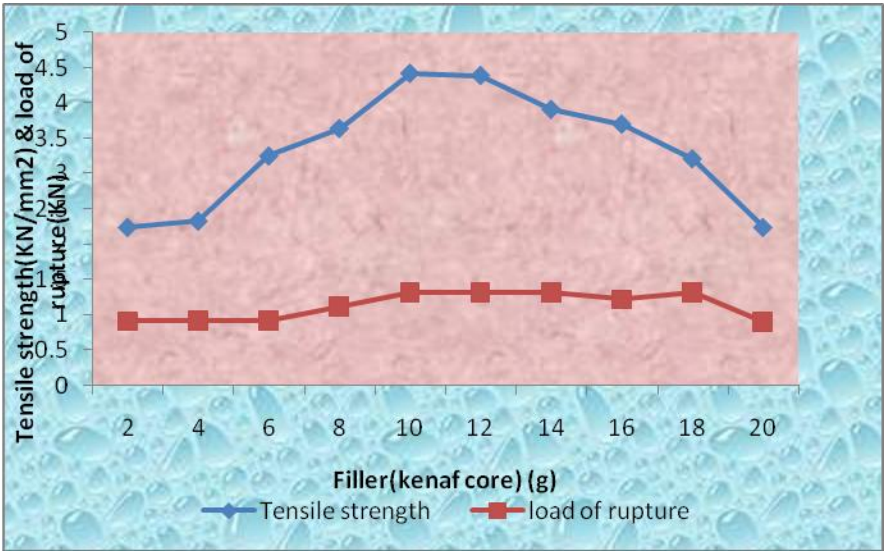

Fig 14: Plot of filler loading against tensile strength and load of rupture for fixed Cement: Rice husk ash blend binder ratio of 35:15

Discussion

Tensile Strength dropped (fig 13) from 4.65KN/mm2 at Cement: RHA substitution of 50:0 till it got to 4.42KN/mm2 at Cement: RHA of 35:15. Beyond this point there became significant decrease in tensile strength with corresponding RHA substitution which is mechanically disadvantageous with respect to desired strength of material. A sharp dip was observed between the values obtained from cement: RHA substitution of 10:40 and that of 5:45(4.5 to 0) which indicates rapid loss of binder strength clearly proving that RHA substitution is not targeted at binder strength enhancement but for matrix's alkalinity reduction. Striking a bargain between RHA substitution and strength of material desired, binder ratio of 35:15(cement: RHA) was selected as most appropriate binder composition for optimization i.e. within the scope of this research.

A close study of the load of rupture shows a gradual but steady rise in value from 1.18KN for 50:0 Cement: RHA substitution to 1.26KN for 10:40 cement: RHA substitution. The observed difference of 0.05KN between 35:15 cement: RHA binder and10:40 ratio though remarkable, can be accommodated due to the incorporation of the fibre reinforcement. The fibre imparts effective resistance to separation at failure of material as a result of elongation under strain.

Elongation Effect

Kenaf fibre posses a degree of extensibility with resultant strong fibres property but marred by a level of brittleness. The elongation at which a fibre breaks is a more invariant and fundamental property than the load at which it breaks. Length of test specimens does have an effect, however, as irregularities in diameter prevent all sections of a long fibre from being elongated equally. For test lengths of 100 mm, the elongation is generally between 1% and 2% of the initial length, but is difficult to measure accurately such short lengths. It may be noted that 1.6% elongation corresponds to a spiral angle of 10°12', which, although slightly greater than the Hermans angle reported, is still within the uncertainty of the comparison.

Hermans Rms spiral angle

The importance of the spiral angle measurements lies in the control which the spiral structure exercises on the extension that the fibre can withstand before breaking. A wide range of base and leaf fibres have been examined using the analysis of the intensity distribution which allows calculation of the Hermans RMS spiral angle (Stern and Stout 1954), with results showing the Hermans angle to range from about 80 for jute and kenaf to 23° for sisal. Coir fiber, *Cocos nuciferos*, is exceptional in having a Hermans angle of about 45°. secondary bast fibres, the cell dimensions show little variation among plant species, but the number of spiral turns per unit length of cell averages only about 4/mm, (appreciably fewer than for the leaf fibres). Regarding the structure as a helical spring, by calculation, a 10° spring will extend by 1.54%, a 20° spring by 6.4%, and a 30° spring by 15.5%. Coconut fibre, coir, has a spiral of about 45°, and a helical spring extension of 41.4%. Such a large extension is easily measured and has been shown to be reasonably correct. X-ray measurements showed the angle to decrease with the extension, as predicted by the spring structure, and it was concluded that the extensibility of fibre is due almost entirely to the spiral structure of the ultimate cells (Stern, 1957) It is difficult to measure the extension/spiral angle relationship for low angle fibres such as jute and kenaf due to the changes in angle being small, Consequently using the coir results as a reference to fibre cells, the helical spring theory could be used to calculate the order of magnitude of the extensibility of the fibre and to rank fibres accordingly. Jute and kenaf are strong fibres but exhibits brittle fracture and yields a small extension at break. They have a high initial modulus, but show very little recoverable elasticity.

Flexural (breaking) load:

The flexural strength of the board as depicted by the breaking load values (fig 12), shows a downward slide as the amount of rice husk ash increased. Remarkable difference in value is observed between the 50:0 binder ratio and those from 30:20 ratios with increasing amount of rice husk ash. That between 35:15 and 50:0(3.10 and 3.22) can be adduced to be close, unlike the 3.22 (50:0) and 2.80 (30:20), 2.74 (25:25), 2.56(20:30), 2.20 (15:35) and 2.06 (10:40). Consequently the choice and selection of binder ratio of 35:15(cement: RHA) being substantiated as from the tensile strength values. The load of rupture gave a least value of 1.04KN with (50:0) binder ratio and highest value of 1.09KN with (10:40). A plateau (1.08) was obtained from 30:20 to 20:30 ratios. 35:15 ratio gave a value of 1.06KN which is within the highest and the plateau showing relative good and acceptable value.

Optimal filler loading:

With the choice of binder ratio of 35:15(cement: RHA), the optimum filler loading of the Kenaf core was determined (Fig 14). A gradual rise was obtained from filler loading of 2g to 10g with a peak tensile strength value of 4.42KN/mm2. A gradual dip occurred from filler load of 12g to 20g with the least tensile strength value of 2.24KN/mm2. The load of rupture peaked from 2g(0.90KN) to 10g (1.31KN) where a plateau occurred till 14g(1.31KN) the a dip from 16g(1.21KN) to 20g (0.89KN).

Alkalinity of matrix

The equation for the hydration of tricalcium silicate is given by:

(A) Tricalcium silicate + Water--->Calcium silicate hydrate+ Calcium hydroxide + heat

$$2\ Ca_3SiO_5 + 7\ H_2O \text{ ---> } 3\ CaO^{\cdot}2SiO_2{}^{\cdot}4H_2O + 3\ Ca(OH)_2 + 173.6Kj$$

(B) Dicalcium silicate + Water--->Calcium silicate hydrate + Calcium hydroxide +heat

$$2\ Ca_2SiO_4 + 5\ H_2O\text{---> } 3\ CaO^{\cdot}2SiO_2{}^{\cdot}4H_2O + Ca(OH)_2 + 58.6\ Kj$$

On addition of water to cement, each of the compounds undergoes hydration and contributes to the final concrete product. Only the calcium silicates contribute to strength. Tricalcium silicate is responsible for most of the early strength i.e. first week. Dicalcium silicate reacts more slowly and is responsible for the strength at later times. Tricalcium silicate rapidly reacts to liberate calcium ions, hydroxide ions, and a huge quantity of heat. The pH swiftly rises to over 12 (the release of alkaline hydroxide [OH^-] ions). This preliminary hydrolysis slows down rapidly after resulting in a decrease in heat evolved producing calcium and hydroxide ions until the system becomes saturated. At this point, the calcium hydroxide starts crystallizing. Concurrently, calcium silicate hydrate begins to form. Ions precipitate out of solution accelerating the reaction of tricalcium silicate to calcium and hydroxide ions. The substitution with rice husk ash reduces the amount of calcium hydroxide in the cement matrix without adversely affecting the binding strength of the cement. The lower amount of CaO (1.36%) from the ash effectively ensures a minimal resultant calcium hydroxide formation during the curing process which consequently reduces the incident of adhesion failure and fiber debonding.

Rice husk ash

Rice husk ash from analysis has the composition:

Fe_2O_3	0.95%
SiO_2	67.30%
CaO	1.36%
Al_2O_3	4.90%
MgO	1.81%
Total	76.32%

The rice husk ash not only reduces the cost of the cement while maintaining the quality by its supplementary inclusion, but partly replaces lime, or calcium hydroxide. Lime is the product to which natural fibers like sisal reacts to, which weakens the cementation. The silica in pozzolana can only combine with calcium hydroxide when it is in a finely divided state. Pozzolana in this state has uniform particles which cannot be packed very closely which is why RHA composites give compact bulk density.

Friedman Test

The Friedman test is a non-parametric alternative to the one way ANOVA with repeated measures. It is used test for difference between groups when the dependent variable being measured is ordinal. It is also used for continuous data that has violated the assumptions necessary to run the one-way ANOVA with repeated measures.

The Friedman test compares the mean ranks between the related groups and indicates how the groups differed as seen in the ranks table and the test statistics table is the table which actually informs the result of the Friedman test and whether there was an overall statistically significant difference between the mean ranks of the related groups. It is thus important to note that the Friedman test is an omnibus test like its parametric alternative, that is, it tells you whether there are overall difference but does not pinpoint which group in particular differ from each other. Thus to do this, you need to run a post-hoc test such as the wilcoxon signed rank test on the different combinations of related groups to examine where the differences actually occur.

This test is necessary here since we are interested in observing the interdependence of PC to RHA and to KC by assessing their significant status. A statistically significant result indicates the interdependence and a non-significant result indicates ceasure of such interdependence.

Friedman test result ranks

Test statistics

	Mean Ranks
PC	2.45
RHA	2.35
KC	1.20

N	10
Chi Square	9.897
Df	2
Asym. Sig	0.007

Descriptive statistics

		Percentiles		
	N	25th	50th (Median)	75th
PC	10	13.7500	27.5000	41.2500
RHA	10	8.7500	22.5000	36.2500
KC	10	2.7500	5.5000	8.2500

Wilcoxon signed-rank test

Test statistics

	RHA – PC	KC – PC	KC – RHA
Z	-0.535[a]	-2.599[a]	-2.701[a]

Asymp. Sig. (2 tailed)	0.593	0.009	0.007

a. Based on positive ranks.
b. Wilcoxan signed ranks test.

KEY

PC – Portland cement

RHA – Rice Husk Ash

KC – Kenaf Core

There was a statistically significant difference in the cement product depending on the additive (RHA) and the binder (KC), χ^2 (2)=9.897, P=0.007. post-hoc analysis with Wilcoxin signed-rank Test was conducted with a bonferroni correction applied, thus, the Bonferroni adjusted significance level is at P<0.017. Median value (IQR) for PC, RHA and KC trial were 27.5000, 22.5000 and 5.5000 respectively. There were no significant differences between RHA and PC trial (Z=0.535, P=0.593). However, there were a statistically significant diffence between KC and PC trial (Z=-2.599, P=0.009) as well as between KC and RHA trial (Z=-2.701, P=0.007).

The analysis buttresses the fact that substituting the Portland cement (PC) with the Rice husk ash (RHA), does not affect the binding strength of the binder negatively. On the same vein an increase or addition of the Kenaf core enhances the compact nature and consequent strength of the material, implying that the addition of the core material apart from giving it a light weight attribute, also contributes to the overall strength of the product.

Conclusion

Thin sheets of insulation material have been produced using kenaf core as filler and the bast fibre as the reinforcement.

Rice husk ash has been used to substitute complimentarily the amount of Portland cement binder in the production of insulation boards as substitute to Asbestos sheets.

Within the scope of this research, the optimal material requirement with respect to filler loading and binder blend ratio are 10g and 35:15(Cement: RHA) respectively.

The compositional make up of the rice husk ash falls above the minimum 70% for pozzolana therefore its good performance as a compatible cementations material.

The composition of the ash ensures that the amount of free calcium hydroxide from the cement is effectively reduced to a tolerable minimum consequently preventing the adverse effect on fibre material in the matrix. This ensures that the problem of binder failure and debonding within matrix of the fibre does not occur.

The incorporation of fibre into matrices like Portland cement has the advantage of increasing the tensile strain value at rupture which results into a tough material with high resistance to impact loading (Singh, 1985) .

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