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Optimization of Banana Fiber Reinforced Fly Ash Based Geopolymer Mortar

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From past decades since Joseph Davidovits introduced geopolymer, this innovative green technology as alternative for cement mortar have been studied and proven its strength, effectiveness, and potential to many applications. Likewise, crack proneness due to lack of reinforcement, occurrence of efflorescence and curing methods are issues on geopolymer. This paper focused on the effects of treated banana fibres (BF) using 4 % sodium hydroxide (NaOH) soaked within 2, 4 and 6 h which served as reinforcement on the geopolymer mortar with different parameters to eliminate macro cracks and two curing methods were used to address efflorescence. Fiber reinforced geopolymer mortar (FRGM) can lessen the massive utilization of conventional construction materials due to sustainability of geopolymer and provide crack bridging in the matrix. Compressive and split tensile strength test of geopolymer cube and cylinder samples for burlap and saran wrapped method of ambient curing were determined using universal testing machine (UTM). The flowability, weight loss of samples during curing period and the occurrence of efflorescence were observed as well. In Design Mixture - 1 (DM1), there are 13-design mixtures (DM) with 5 - 50x50x50 mm cubes and 5 -100x200 mm cylinder specimens each reinforced with BF while 8 DMs for DM1 are plain geopolymer mortar (PGM) to obtain the mixture with the highest compressive and split tensile strength for both FRGM and PGM. FRGM and PGM with the highest mechanical strength are further explored reinforcing with treated and untreated BFs. Mechanical strengths, flowability, efflorescence and weight loss of samples were recorded. The optimum FRGM shows that there is no significant difference in compressive and split tensile strength when reinforced with 4 % NaOH treated within 2 and 6 h compared to 4 h of treatment which has the highest strengths. Finally, the governing BF with 4 % NAOH treated within 4 h was used to reinforce the PGM to investigate the strength variation provided by BFs which gave up to 22.43 % increment in terms of compressive strength.

1. Introduction

Geopolymer mortar is a promising innovative and sustainable construction material that can be an alternative or replacement of Ordinary Portland Cement (OPC) mortar. Geopolymer was developed by Prof. Davidovits to lessen the use of OPC (Provis and Deventer, 2009). The process of geopolymerization also produced significant reduction in carbon dioxide (CO_2) emission compared to OPC manufacturing alone (Pilien et al., 2022). Since OPC are being used for more than two centuries now (Mohamad et al., 2022) which generates four times higher than geopolymer in terms of CO_2 emissions (Huseien et al., 2017). The building industry utilises 50 % of the world's limited resources which needs to be address towards materials sustainability without depleting natural resources (Ongpeng et al., 2021). Likewise, the projected global need for OPC in 2050’s will be about 200 % of today’s consumption (Xie and Ozbakkaloglu, 2015). These projections and environmental concerns that researchers are currently facing are the opportunities to widen up the call for more sustainable and alternative construction materials.

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In this study, an optimization of geopolymer mortar were conducted to maximize the investigation and produce a high quality and more environmentally friendly mortar by utilizing banana fibres as reinforcement and fly ash as binder on the geopolymer mortar. Like OPC mortar, PGM are also naturally brittle which produces cracks that can weaken the composite. This weakness of the geopolymer can be prevented by using BF as reinforcement. The strength variation of reinforcing the PGM with BF is also investigated. NFs are locally available, renewable, biodegradable and non-toxic and through alkali treatment, the hydrophilicity of BF can be modified (Camargo et al., 2020). Akinyemi and Dai (2021) used short BFs to reinforce the mortar with wood bottom ash that provided an increase in split tensile strength from 19 to 33 % provided by BF alone. The utilization of BFs as reinforcement for concrete and other cementitious composites are proven to be effective and can increase the compressive strength significantly up to 18.18 % with 0.5 % BF incorporation according to Ali et al. (2021) while a 51 % increase in compressive strength when used in concrete mixture with 1 % of BFs as reinforcement was obtained in the study of Bharathi et al. (2021). To avoid the development of efflorescence which is a major drawback for geopolymer that can weaken the mortar, samples were wrapped with saran wrap during ambient curing to avoid spilling of chemicals of the geopolymer (Pilien et al., 2022).

Three phases were performed to optimize the best design mix that produced high mechanical properties and addressed the brittleness and efflorescence of geopolymer. Phase 1 is the BF treatment using 30 g of solution for every gram of fibre. The solution contained 4 % of NaOH and 96 % of water within 2, 4 and 6 h. The fibre with highest mechanical and physical properties were adopted with 1 cm length to reinforce the geopolymer mortar containing class F fly ash (FA), microsilica (MS), sand and alkali activator. For the phase 2, a total of 21 DMs were used (105-cubes and 105-cylinder samples), 13 FRGM and 8 PGM. Each design mix have 5-cylinder samples (100mm×200mm) and 5-cube samples each (50×50×50mm cube). Samples were wrapped with plastic (saran-wrapped) for ambient curing and after 44-days geopolymer mortars were tested. The PGM and FRGM samples with highest mechanical properties are used for the application of all treated and untreated BFs to investigate the effects of BFs on the geopolymer matrix. The phase 3 (Design Mixture – 2) used the optimum PGM and FRGM from phase 2 and reinforced with the BFs from phase 1. Five design mixes with 5-cylinder samples and 6-cube samples were made, 5 samples each for split and tensile strength test using Universal testing Machine (UTM). While the extra cube sample in excess to the five samples required for testing were used to observe the effects of curing using burlap wrapping. The weight loss and occurrence of efflorescence during curing time of the geopolymer and the flowability of the mixtures were observed, recorded and compared.

2. Materials and Methods

2.1 Materials

The materials used in this study are fine sand as filler, microsilica (MS) and low calcium Class F fly ash as binders and NaOH and Sodium Silicate (Na_2SiO_3) or waterglass (WG) as activator. There is also additional water (+Water) due to Fly ash and BF content to maintain a good workability of the design mixtures. The reinforcement used is the banana fiber (BF) extracted through small-scale fiber decorticator and portable hand mixer was used to consistently mix the geopolymer and BFs.

2.2 Banana Fiber Extraction and Treatment

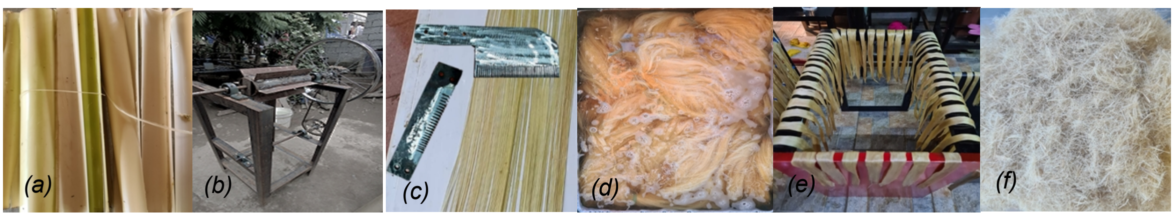

Figure 1: BF Extraction and Treatment Flow (a) Banana pseudostem, (b) decorticator (c) BF stripping tool (d) NaOH Treatment (e) Drying of treated BFs (f) 1cm short BFs

Figure 1 shows the BF extraction and treatment flow: Figure1(a) shows the banana pseudo stem cut into 60cm for convenience in cleaning and stripping of fibers. The pseudo-stem is a component of the banana that resembles a trunk and is composed of a softer inner core and have up to 25 leaf sheaths firmly wrapped around it. The inner soft cores are eliminated which cannot be stripped due to very weak cores (Subagyo and Chafidz, 2018). Figure1(b) shows the small-scale BF decorticator, which was patterned from the work of Veera Ajay, (2021). Materials used to build the machine is from scrap materials. The purpose of this machine is just to eliminate the pulps and liquids coating the fibers only from the leaf sheath followed by hand stripping to extract the fibers. Figure 1(c) shows the tools for stripping the BFs. The extracted fibers were washed with clean water and air dried before the chemical treatment. Figure 1(d) shows the BFs soaked in the NaOH solution for treatment. Figure 1(e) shows the drying of BFs after rinsing with running water until free from chemicals and (f) shows the short banana fibers with 1 cm length. In addition to the importance and effects of chemical treatment. The study of Elbehiry and Mostafa (2020) used NaOH for chemical treatment which modified the mechanical and physical properties of banana fibers. These are due to the elimination of impurities on fiber surfaces and causing the fiber to be roughened that improves cohesive strength that improves the bonding between the matrix and the fiber.

2.3 Design Mixes and Design Parameters

Table 1 shows the 21 design mixes in the study

Table 1: Geopolymer Mortar Design Mixes - 1 (DM1)

DM1	Fly Ash (Kg)	Sand (Kg)	(MS) (Kg)	NaOH (Kg)	Water (Kg)	WG (Kg)	BF (Kg)	+Water (Kg) 10 % FA	+Water (Kg) 200 % BF	Molarity (M)
DM1-1	3.000	3.105	0.398	0.553	1.155	0.947	0.000	0.300	0.000	11.97
DM1-2	3.213	2.885	0.592	0.537	1.186	0.909	0.032	0.321	0.064	11.31
DM1-3	3.000	3.105	0.393	0.509	1.142	0.905	0.060	0.300	0.120	11.15
DM1-4	3.600	2.484	0.406	0.607	1.282	1.013	0.000	0.360	0.000	11.85
DM1-5	3.000	3.105	0.778	0.459	1.130	0.891	0.060	0.300	0.120	10.15
DM1-6	3.600	2.484	0.835	0.591	1.295	1.182	0.072	0.360	0.144	11.41
DM1-7	3.513	2.574	0.416	0.616	1.280	1.141	0.070	0.351	0.141	12.03
DM1-8	3.600	2.484	0.835	0.675	1.306	1.125	0.000	0.360	0.000	12.92
DM1-9	3.108	2.993	0.602	0.583	1.183	0.971	0.062	0.311	0.124	12.32
DM1-10	3.526	2.561	0.810	0.529	1.257	1.058	0.000	0.353	0.000	10.52
DM1-11	3.019	3.086	0.598	0.496	1.151	0.991	0.030	0.302	0.060	10.77
DM1-12	3.600	2.484	0.616	0.588	1.285	1.090	0.036	0.360	0.072	11.44
DM1-13	3.505	2.582	0.811	0.602	1.263	1.013	0.070	0.351	0.140	11.92
DM1-14	3.000	3.105	0.389	0.454	1.130	0.896	0.000	0.300	0.000	10.06
DM1-15	3.330	2.763	0.608	0.562	1.225	1.034	0.000	0.333	0.000	11.46
DM1-16	3.600	2.484	0.406	0.608	1.282	1.013	0.072	0.360	0.144	11.85
DM1-17	3.391	2.700	0.402	0.514	1.226	1.029	0.068	0.339	0.136	10.49
DM1-18	3.447	2.643	0.408	0.623	1.259	1.038	0.034	0.345	0.069	12.37
DM1-19	3.600	2.484	0.419	0.600	1.298	1.200	0.000	0.360	0.000	11.55
DM1-20	3.232	2.865	0.812	0.573	1.210	1.040	0.032	0.323	0.065	11.83
DM1-21	3.000	3.105	0.785	0.532	1.144	0.886	0.000	0.300	0.000	11.62

Table 1 shows the geopolymer mortar DM1 with 13 FRGM and 8 PGM. Several parameters were considered on the DMs including ratios of materials such as 0.2 for water to total weight of solids, 0.5 to 0.5 activator to FA+MS, 1 to 1.5 FA to sand and 0.5 to 0.6 NaOH to WG to produce an optimize FRGM and PGM. These range of parameters were also used by Quiatchon et al, 2021 for optimization of geopolymer. Likewise, for the FRGM, the banana fiber content ranges from 1 % to 2 % of the mass of fly ash. These percentages were also used by Bharathi et al. (2020) in reinforcing concrete, while 1 to 2 % of BF provided the highest tensile strength. The Molarity (M) is moles of solute over the liters of solution calculated as follows:

$$M = \frac{moles\ of\ solute}{liters\ of\ solution} = \frac{Mass\ of\ NaOH\ /\ 40}{liters\ of\ water\ /1000} \quad (1)$$

Eq. 1 shows the formula of the molarity (M) of NaOH. The mass of NaOH over 40 g (molar mass of NaOH) is divided by the liters of water over 1,000.

After the optimization on the Design Mix – 1, optimum FRGM and PGM were used and reinforced with the treated and untreated BFs reflected in Table 1 to study the effects of treatment. Table 2 shows five design mixes which were adopted from DM1-12 and DM1-4 and reinforced with BFs in this design mixes. DM2 was designed to observe the effects of BFs in the geopolymer mortar.

Table 2: Geopolymer Mortar Design Mixes - 2 (DM2)

DM2	Fly Ash (Kg)	Sand (Kg)	(MS) (Kg)	NaOH (Kg)	Water (Kg)	WG (Kg)	BF (Kg)	BF Treatment	+Water (Kg)	+Water (Kg) 200 % of BF
DM2-1	3.600	2.484	0.616	0.588	1.285	1.090	0.036	BF01	0.360	0.072
DM2-2	3.600	2.484	0.616	0.588	1.285	1.090	0.036	BF02	0.360	0.072
DM2-3	3.600	2.484	0.616	0.588	1.285	1.090	0.036	BF03	0.360	0.072
DM2-4	3.600	2.484	0.616	0.588	1.285	1.090	0.036	BF04	0.360	0.072
DM2-5	3.600	2.484	0.406	0.607	1.282	1.013	0.000	BF03	0.360	0.000

3. Results and Discussion

3.1 Treated and Untreated Banana Fiber Average Breaking Load and Elongation

The tensile properties of the untreated and treated fibers were tested using Istron-5966 UTM. Results of the test are shown in Table 3. The BF03 treated with 4 % NaOH within 4 h have the highest average breaking load and has mid-range maximum elongation value. With these, BF03 was used as reinforcement for the DM1 to establish the optimum FRGM.

Table 3: Average Breaking Load and Elongation of Treated Banana Fibers

BF No.	Treatment duration in 4 % NaOH, h	Average Breaking Load, N	Average Max Elongation, mm
BF01	Untreated BF	1.83	0.56
BF02	2	1.71	0.49
BF03	4	3.36	0.54
BF04	6	2.13	0.54

3.2 Mechanical Strength, Flowability, Weight Loss (WL) and Occurrence of Efflorescence

Table 4 shows the average weight loss for geopolymer mortar sealed with saran wrap taken from 5 cube samples each is 7.32 % only of the original weight. This is due to the ambient curing with average room temperature of 29.6 °C with average humidity of 78 %. According to Haoyang Su et. al. (2015), if geopolymer are exposed to elevated temperature notable weight loss will be observed.

Table 4: Weight Loss of Geopolymer Mortar Sealed with Saran Wrap and Burlap

Saran Wrapped	Weight: Day 1 (grams)	Weight: Day 44 (grams)	WL Due to Curing (%)	Burlap Wrapped	Weight: Day 1 (grams)	Weight: Day 44 (grams)	WL Due to Curing, %	Flow (%)	Spread Diameter (mm)
DM2-1	252.2	231.65	8.15	DM2-1	255.3	224.16	31.14	66.46	13.65
DM2-2	256.2	238.88	6.76	DM2-2	252.5	224.43	28.07	61.59	13.25
DM2-3	256.9	238	7.36	DM2-3	257.69	229.65	28.04	64.33	13.98
DM2-4	258.66	240.91	6.86	DM2-4	253.78	230.50	23.28	67.43	14.03
DM2-5	257.13	237.93	7.47	DM2-5	255.43	231.81	23.62	86.95	15.33

On the other hand, the average weight loss for geopolymer wrapped with burlap and cured using water spray just to moisten the samples once a day. The sample used in this observation is the single cube as excess of the 5-cubes required for testing. The cubes wrapped with burlap has an average weight loss of 26.83 % which is 366.53 % higher average weight loss than the samples wrapped with saran wrap. It also shows from the table the minimal variations in flowability percentage and spread diameter of the composites ranging from 61.59 % to 67.43 % and 13.25 mm to 14.03 mm for DM2-1 to DM2-4 which has the same design mixtures except of the 1 % BF content which differs in treatment method. This shows the importance of the workability of the geopolymer which gives great value of mechanical properties of the composites and specially when used as mortar for in situ application.

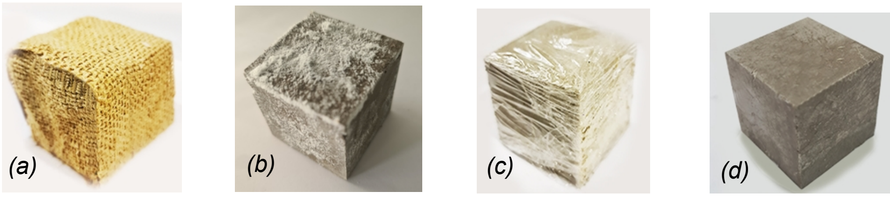

Figure 2: Geopolymer Mortar Efflorescence: (a) Geopolymer wrapped with burlap; (b) Occurrence of efflorescence; (c) Geopolymer with saran wrap; (d) Non-occurrence of efflorescence

Figure 2 shows the geopolymer mortars wrapped with burlap and saran wrapped. Efflorescence was observed when using burlap, while the samples wrapped with saran wrap has non-occurrence of efflorescence.

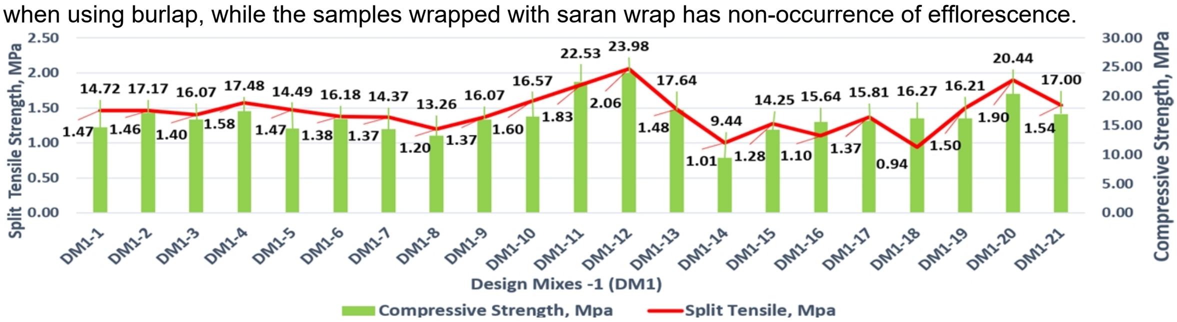

Figure 3: Design Mixes – 1 (DM1) Compressive and Split Tensile Strength Test Results

Figure 3 show the results of the split tensile and compressive strength test using UTM. The results shown that DM1-12 has the highest compressive and tensile strength with 23.98 MPa and 2.06 MPa. This DM has 0.2 water to solids ratio, 0.54 NaOH to WG ratio, 1.5 (FA+MS) to sand ratio, 5 % MS and 1 % of BF. For the PGM, DM1-04 has the highest compressive with 17.48 MPa and second highest in split tensile strength with 1.58 MPa. This DM has 0.2 water to solids ratio, 0.6 NaOH to WG ratio, 1.5 (FA+MS) to sand ratio,5 % MS.

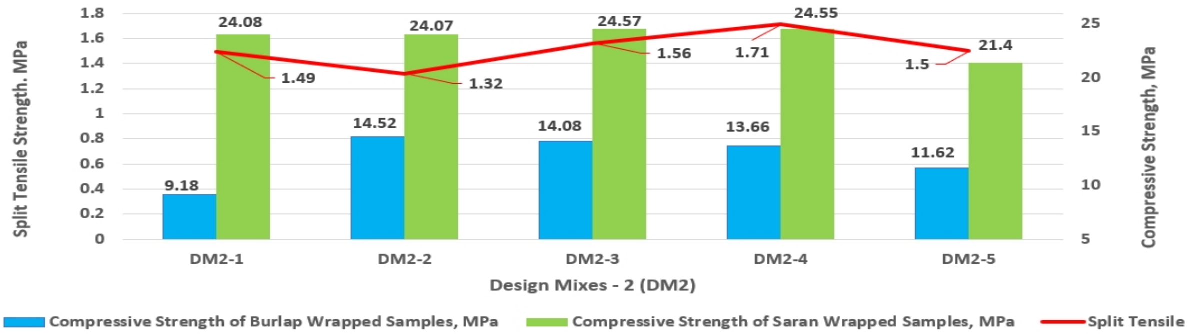

Figure 4: Correlation of Compressive and Split Tensile Strength

Figure 4 shows that the compressive and split tensile strengths of the DM2-1 to DM2-4 are almost identical in compressive strength, but the long-term benefit of the treatment were embedded within the modified BF as reinforcement. In terms of strength variations, DM2-5 from DM1-4 and reinforced with BF03 elevated from 17.48 MPa to 21.4 MPa giving 22.43 % increase in strength. In the case of DM2-1, the compressive strength of sample dropped from 24.08 (saran) to 9.18 MPa (burlap) which highlighted the benefits of saran wrap when curing.

4. Conclusions

From the different phases of the study, the following conclusions of the study are presented as follows:

1. The treatment process elevated the tensile properties of the BFs and shortened the elongation of the fiber. It elevates the average breaking load of the untreated BF from 1.83 N (BF01) to 3.36 N (BF03) which is almost twice the strength when treated.
2. The average weight loss for geopolymer mortar sealed with saran is 7.32 % only of the original weight. While the average weight loss for geopolymer wrapped with burlap has a weight loss of 26.83 % which

is 366.53 % higher weight loss than the samples wrapped with saran wrap. Likewise, efflorescence occurs on the samples wrapped with burlap while the samples wrapped with saran wrapped have non-occurrence of efflorescence.

3. The optimization of PGM and FRGM using different parameters and ratios of the binders, fillers and activators is effective and produced as low as 9.44 MPa and 17.48 MPa as the highest in terms of compressive strength for the PGM and 14.37 MPa to 23.98 MPa for the FRGM.
4. The use of treated and untreated BFs as reinforcement in geopolymer provide insignificant variations in compressive strength but the long-term protection of BFs from hydrophilic characteristics of NFs, the surface modification and the elevated tensile strength gained from BF treatment is very important.
5. The strength variations of plain geopolymer mortar when reinforced with BFs increased from 17.48 MPa to 21. 4 MPa which provided up to 22.43 % increase in compressive strength.
6. The curing method plays a major rule in the strength development of the geopolymer mortar. The results shows that saran wrapped samples obtained greater strength values and avoided the occurrence of efflorescence. The compressive strength of the single sample wrapped with burlap is 61.88 % lower than the samples wrapped with saran wrap in case of DM2-1.

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