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Sustainable Water Management in Construction: Application of Natural Coagulant-Treated Greywater for Interlocking Paving Stones

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Abstract

With the rapid urbanisation, the demand for potable water has increased and sustainable alternative water sources are needed for construction. This study aimed to assess the feasibility of using greywater (GW) with four natural coagulants treatment (NCT) from *Moringa oleifera* (MO) seeds, *Cucumis limetta* (CL) seeds, *Musa sapientum* (MS) peels and *Carica papaya* (CP) seeds for the production of interlocking paving stones (IPS). The specimens of IPS were prepared in the ratio of 1:2:4 (cement:sand:stone) dust and water–cement ratio of 0.6 with dimensions of 200 × 100 × 80 mm. Greywater and NCT greywater were used as the experimental mixture while the control was potable water. The Scanning Electron Microscopy-Energy Dispersive X-Ray (SEM-EDX) Spectroscopy of IPS, compressive strength, water absorption of the IPS were determined. In addition, the physicochemical characteristics of the mixing waters such as pH, total dissolved solids, sulphate, chloride and turbidity were evaluated. The results indicated that the NCT water had an impact on the physicochemical properties of the greywater and resulted in different effects on the IPS performance. The compressive strength of CP treated greywater was 11.20 MPa, which was about 49% higher than the control (potable water) with a value of 7.53 MPa, whereas the MO treated greywater had a compressive strength of 9.70 MPa. The 28-day strengths of untreated greywater, CL-treated and MS-treated greywater were lower than the control. In addition, the CP treated greywater had a relatively low water absorption, 9.84% compared to the potable-water control (10.00%). The results showed that the NCT greywater can be used as an alternative mixing water for IPS production in general, and specifically, CP and MO-treated water. The approach promotes water savings, sustainable urban infrastructure and contributes towards Sustainable Development Goals 6 and 11.

Keywords: Greywater, Natural Coagulants, Interlocking Paving Stones, Compressive Strength, Water Absorption, Sustainable Construction

1. Introduction

Water remains an essential necessity in construction. As the demand for potable water increase in construction, it is necessary to treat greywater with natural coagulate for reuse. Water plays a vital role in the construction industry serving as source for hydration, setting and curing of cement based products [1, 2]. Potable water is under increasing strain due to the increasing demand in urbanisation, industrialization, population growth, energy, and transportation. United Nations [3] states that industrial action accounts for 22 % water usage global, while construction industries are accountable for 3 % freshwater consumption.

Cement-based materials (CBM) such as concrete and interlocking paving stone are worldwide produced with 30 billion tonnes, demanding high water consumption in its production, approximately 16.6×10^9 cubic metres of potable water per year [4, 5]. In 2012, water consumed for cement-based materials production was estimated to be 9 % of the total water used globally, representing 1.7 % of total global water use [2]. Therefore, the rise in demand for freshwater, along with the effects of climate change and urban development, highlights the need to minimize the consumption of potable water and identify sustainable fresh water sources in a proper way for construction uses.

In recent years, there has been growing research interest in the application of alternative water sources such as greywater and treated wastewater (TWW) for the production and curing of cement-based materials as a means to decrease the use of freshwater and to promote circular water management [4-7]. Feasibility of using treated wastewater for producing concrete has been proven in previous studies, but it is highly dependent on the physicochemical properties of wastewater and the degree of treatment [8-10]. Dissolved and suspended solids, organic matter and other contaminants in alternative water sources can affect the properties of the workability, setting behaviour, strength, durability and microstructure of cement-based materials [6]. Therefore, it is necessary to consider the treatment and characterisation of the alternative water sources before using them as construction materials.

Greywater (GW) is a significant share of household wastewater that is generated by a variety of uses and activities, including bathing, laundry and other domestic activities, but not toilet flows [8]. Greywater is less polluted than blackwater, but can contain suspended solid particles, surfactant, dissolved organic matter, salts and other substances that could affect the hydration and properties of cement-based products. Therefore, it may be detrimental to the quality and longevity of construction materials if it is directly used as mixing water without proper treatment [10]. Reusing greywater after treatment can help decontaminate the water and make it a potential construction resource. A conventional water-treatment process can be effective, but requires relatively high operational costs, energy requirements, and application of chemical reagents [11]. The natural coagulants (plant base) are an alternative of greywater conditioning that potentially gives the advantage of low cost and environmental protection [12].

The use of plant derived materials has received a lot of attention due to their coagulation and flocculation properties of the suspended and colloidal particles [12, 13]. For instance, water soluble cationic proteins from *Moringa oleifera* seeds have the potential to neutralise negatively charged suspended particles [12], whereas the polysaccharides, pectin, cellulose and proteolytic enzymes in *Carica papaya* seeds might play a role in coagulation and adsorption processes [13]. It could be possible, then, to use locally available plant-based materials for greywater treatment in order to improve the water quality before reusing for construction. The interlocking paving stones (IPS) are popular for walkways, driveways, pedestrian walkways and urban streets due to ease of installation, durability and versatility [14]. They use water in their production for hydration of cement and the curing process, giving an opportunity to replace potable water with appropriated treated alternative water. Reuse of treated greywater for IPS production may lead to the conservation of fresh water and at the same time offer a productive route for greywater management. This is in line with the concept of resource efficiency and circular economy, where wastewater is not just considered a waste stream, but also a potential resource [4]. The use of treated wastewater in cement-based materials has

demonstrated that it is possible to use alternative water successfully in these products, but that different treated waters and levels of treatment may lead to a difference in material performance [14-17].

Some research have examined the use of treated waste or grey water in production of CBM. CBM produced with treated wastewater or grey water parameters are governed by several standards in construction such as EN 1008 [18], ASTM C1602 [19] and NBR 15900 [20]. Morgado *et al* [2] assessed the performance of concrete with treated wastewater and recycled aggregates, the study observed the maximum mechanical and durability properties of concrete at 50% replacement. Ghrair *et al* [6] investigated the influence of grey water on physical and mechanical properties of mortar and concrete. The study record no physical or mechanical change in the use of treated grey water on both the mortar and the concrete mix. Babu *et al* [21], Almeida and Tonetti [22] shows that concrete made and cured with treated wastewater has no significant effect on its physical and mechanical properties. Asadollahfardi and Mahdavi [11] also conducted a test on the performance of compressive strength of concrete with 100% treated wastewater over time. The study observed that the strength of concrete produced exceeded 90 % of the control sample. The factors, which lead to the loss of strength was recorded to be presence of solid particles and other contaminants, also transformation of ettringite into monosulphate aluminate [23, 24]. The increase in thickness of the duplex layer surrounding the aggregate surface within the interfacial transition zone can also lead to the reduction of bond between aggregate and cement paste [25]. This presence of solid particles also influenced the loss of tensile strength [26]. Fact shows that, if wastewater or grey undergoes demanding treatment processes, this reduction in strength may not occur [27-30]. These innovation orders to move towards sustainable water management in construction.

Although, alternative water resources are being explored and evaluated for use in construction, there has been little attention to the use of naturally coagulated treated greywater as mixing water for the production of IPS, especially utilizing locally available plant coagulants. Moreover, the comparative effect of various natural coagulants on greywater quality in terms of its physicochemical characteristics and the resulting mechanical, physical and microstructural properties of IPS are not yet well understood. The knowledge gap is relevant because there are different types of natural coagulants that can be used and the quality of greywater produced could affect the quality of the hardened paving stones and their pore structure and strengths.

Hence, this study determines the suitability of the greywater treated with four natural coagulants, namely *Moringa oleifera* (MO), *Cucumis limetta* (CL), *Musa sapientum* (MS) and *Carica papaya* (CP) as mixing water in the production of interlocking paving stones. The study compares the physicochemical parameters of greywater before and after treatment, produced IPS with potable water as control, untreated greywater and naturally coagulated treated greywater. Water absorption, compression strength, and scanning electron microscope (SEM) coupled with energy-dispersive X-ray spectroscopy (EDX) were used to evaluate the physical, mechanical and microstructural characteristics of the paving stones produced.

2. Materials and Methods

2.1 Materials

The materials used were three (3) water types; Potable water from the university borehole, Grey water from the University student hostels and treated grey water from natural coagulants. The fine aggregates used were sharp sand and the coarse aggregates used were stone dust as medium aggregates. Portland Limestone Cement (Grade 42.5) as the binder. The four (4) natural coagulants used as treatment for the greywater are *Moringa oleifera* (MO) seeds, *Cucumis limetta* (CL) seeds, *Musa sapientum* (MS) peels and seeds of *Carica papaya* (CP). Fig. 1 shows the image of the four natural coagulants used. All materials were sourced locally.



(a) MO seeds

(b) CL seeds

(c) MS peels

(d) CP seeds

Fig. 1: Selected Natural Coagulants [31]

2.2 Materials Characterization

The materials used in the production of IPS were characterized to determine their physical and chemical properties. The physicochemical properties of the raw greywater and the Natural Coagulant treated (NCT) water were assessed for pH, total dissolved solids (TDS), sulphate, chloride and turbidity, following the guideline procedure of World Health Organization [32]. Sieve analysis were carried out on the natural aggregate to determine their particle sizes. The setting characteristics of the cement also were obtained using Vicat apparatus as specified in BS EN 196-3 [33]. The test was performed to determine the setting properties of the cement employed in the manufacture of the IPS, and to serve as a reference to evaluate the effect of the various water types on the cement hydration and setting behaviour [23, 24].

2.2 Sample Preparation, Curing and Testing of IPS

2.2.1 Greywater Treatment and Coagulant Application

Greywater was filtered using a filtration system composed of sharp sand, gravel and a polyethylene mesh net, and then treated in batches using aqueous extracts of each coagulant. The coagulated flocs were allowed to settle before the clarified water was decanted and filtered through Whatman No. 42 paper to get the coagulated water, which was used for the mix.

The conformation of grey water depends largely on its treatment processes; either primary or tertiary treatment ensures that the water produce meets the minimum requirements applicable to reclaimed water intended for green spaces and street cleaning [2, 6]. Fig. 2 shows a schematic illustration of wastewater treatment as described by Morgado et al [2].

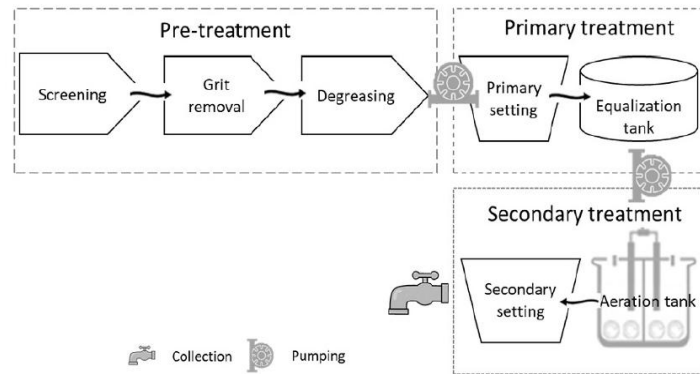


Fig. 2: Schematic image of wastewater treatment with secondary treatment [2]

2.2.2 Mix design of samples and Curing

IPS mix was designed and produced following the British/European standard BS EN 1338. Six different mixing-water types were used: potable water (control), untreated greywater (GW) and natural coagulant treated (NCT) with plants such as *Moringa oleifera* (MO), *Cucumis limetta* (CL), *Musa sapientum* (MS), and *Carica papaya* (CP). The samples were made with a fixed ratio of sharp sand to stone dust of 2:4 and a fixed water-to-cement ratio (w/c) of 0.60. The constituent materials were taken at the mix proportion of 1:2:4 and mixed properly to get homogeneous mix (Table 1). The different quantities of the materials cement, sharp sand, stone dust and mixing water were retained the same for all batches and the type of mixing water changed as the main experimental variable. The specimens were produced with the interlock mould size of 200 mm×100 mm×80 mm and compacted to provide good compaction and reduce air entrainment. For each water type, four specimens were produced for a total of 24 IPS specimens. The reason that this approach was chosen was to assess the effect of water quality and natural coagulation treatment on the IPS performance.

The specimens were demoulded and then cured in water of the same type as used in the production of the specimen. The specimens were cured for 7 and 28 days prior to testing. The temperature of the room was kept constant during the curing period. All the specimens were immersed consistently in the same type of water so that the experimental procedure would be uniform.

Table 1: IPS Mix Design

% replacement Water type	Cement (kg)	Fine aggregate (kg)	Coarse Aggregate (kg)	w/c	Replicate
100	350	700	1400	0.6	4

2.2.3 Test Methods

The physical and mechanical properties of the cured IPS made using the various types of mixing-water were tested in terms of water absorption and compressive strength. The microstructural and elemental composition of the hardened IPS was also examined.

After the above cure periods, the water absorption of the cured IPS specimens was measured. This test was performed in order to measure the amount of water absorbed by the set-up paving stones and to give an indication of the level of compaction and the pore structure of the stones [28]. The same test procedure was used for the specimens created using potable water, untreated greywater, and treated greywater with MO, CL, MS and CP. The compressive strength of the IPS specimens was measured by a Universal Testing Machine (UTM) after 7 days and 28 days curing. The specimens were set up in the machine and compressed continuously without impact or shock load until it failed. The peak load applied to each specimen at failure was noted and the compressive strength of the specimen was computed using Equation 1. The tests were carried out on samples made using the six types of mixing water to compare the development of their strength at 7 and 28 days [30, 35].

$$F_c = \frac{f}{A} \quad (1)$$

Where: F_c is Compressive strength (N/mm²), F is Maximum load at failure (N), A is the concrete cross-sectional area of specimen (mm²).

The microstructural and elemental analysis with Scanning Electron Microscopy – Energy Dispersive X-ray Spectroscopy (SEM-EDX) was conducted on the IPS at 28days. The specimens were broken down to obtain suitable hardened residues for examination. The SEM images were used to determine the differences in morphology and compactness of the hardened matrix whereas EDX was used to identify the elemental components related to the various water mixing types. The SEM-EDX analysis was carried out according to the method described by Goldstein et al., [12].

The outcomes of the various tests were analyzed and compared with each of the 6 types of mixing water (treated and naturally coagulated greywater) to determine how the use of untreated and naturally coagulated greywater affects the performance and microstructural characteristics of the interlocking paving stones. Fig. 3 shows the experimental procedure of the sample preparation, curing and testing of the IPS.



Fig. 3: Site process photographs (a) flocculated greywater after 5-day settling in the filtration tank, (b) harvesting of filtered water via sand–gravel filtration, (c) curing of cast interlocking paving stone specimens, (d) compressive strength test setup after 28 days of curing

3. Results and Discussion

3.1 Water Characterization

The physicochemical properties of the untreated greywater and NCT greywater with the four natural coagulants are shown in Table 2. The parameters taken into consideration were: pH, total dissolved solids (TDS), sulphate, chloride and turbidity. During the manufacture of cement-based products, the quality of the mixing water is a key factor as it may contain dissolved and suspended materials that can affect the processes of cement hydration, setting and subsequent physical and mechanical characteristics of the set material [6, 27]. Fig.4 compares the parameters to the acceptable value of WHO [32] and BS EN196-3 [33] cement-based water for construction. Previous studies have also shown that unsuitable for drinking water may be acceptable for concrete production, if physicochemical properties are within acceptable limits and do not have a negative impact on the properties of the concrete [2,6, 36]. The pH value recorded in the untreated greywater was near neutral (6.95). The value of TDS, sulphate, chloride and turbidity in the untreated water were 140, 125.6, 68.4 and 3.06 mg/L (NTU for turbidity), respectively. Significant differences were found between the four coagulants after the treatment. The pH was raised slightly after treatment with *Moringa oleifera* (MO) to 7.55, which is about 8.6% higher than the untreated greywater. However, the pH level dropped to 5.64, 5.64 and 5.75 after being treated with CL, MS and CP respectively. The pH decrease for the NCT suggest the treatment process changed the acid-base behavior of the greywater, which is related to the release or interaction with soluble organic components of the natural coagulants [37]. The pH values were still in a moderate acid pH to near neutral.

Treatment of all four natural coagulants resulted in an increase in the TDS values. The values gone up from 140 mg/L from untreated greywater to 230, 175, 200 and 180 mg/L for MO, CL, MS and CP, respectively. The TDS of MO-treated water was TDS max at about 64.3% which was higher, whereas the increases in TDS were about 25.0%, 42.9% and 28.6% for CL, MS and CP, respectively. This increase could be related to the dissolution of soluble components of the coagulants during treatment. The increase in TDS does not necessarily mean that coagulation did not reduce all dissolved constituents. This is significant as the behaviour of dissolved constituents and suspended particles may differ. Past studies have also defined constituents in the mixing water that are classified as dissolved and suspended as having a significant impact on the characteristics of the concrete [6, 38].

There was a large variation between the treated waters with regard to sulphate content. The untreated greywater had a sulphate concentration of 125.6 mg/L and MO-treated water had a concentration of 132.6 mg/L, which is about 5.6% higher. The CL, MS and CP treatments, on the other hand, achieved significant reduction of the sulphate concentration, with values of 1.1, 52.6 and 111.0 mg/L, respectively. These are equivalent to 99.1%, 58.1% and 11.6% decreases. The significant decrease achieved by CL shows that this treatment has a high efficiency to decrease the measured sulphate concentration. The effect of natural coagulants is also dependent on the composition and characteristics of the treatment material, which again reflected in the contrasting response of MO, which showed a slight increase [26, 38].

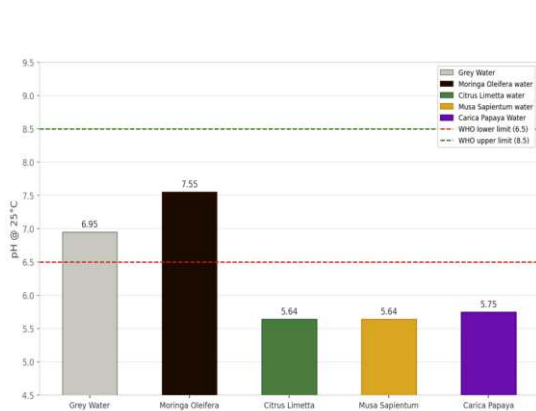
For chloride, the untreated concentration of the greywater was 68.4 mg/L and the concentration after treatment with MO was 78.3 mg/L; which is around 14.5% higher. However, CL, MS and CP lowered the chloride concentration to 2.5, 48.1 and 29.1 mg/L, which is about 96.3%, 29.7% and 57.5% respectively. CL had the highest decrease in both sulphate and chloride levels of the four treatments. The results indicate that the CL treatment performed especially well at removing the inorganic constituents measured in the greywater.

Results of turbidities are the best indications of the coagulation performance of the natural materials. The original turbidity of the greywater was 3.06 NTU. After treatment, turbidity has dropped to 1.28, 0.68, 0.37 and 2.30 NTU for MO, CL, MS and CP, respectively. Therefore, the removal efficiencies of turbidity were about 58.2%, 77.8%, 87.9 % and 24.8 % for MO, CL, MS and CP, respectively. The superior performance of MS shows that the material was highly effective in destabilising and removing suspended particles from the greywater, under the experimental conditions.

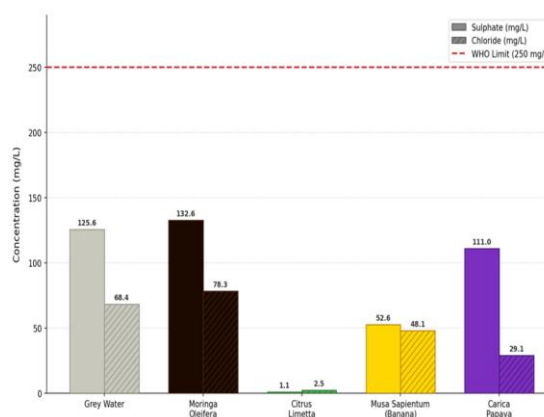
The action of natural coagulants is based on the principles of charge neutralisation, adsorption and bridging. Therefore, the effectiveness differs depending on the nature and the quantity of active biomolecules that are released into the water and the initial nature of the greywater. The results corroborate with the earlier report that the quality of greywater and the treatment process can significantly impact the water quality and its application for the production of cement-based materials [36-40].

Table 2: Physicochemical Characteristics of the Water Samples

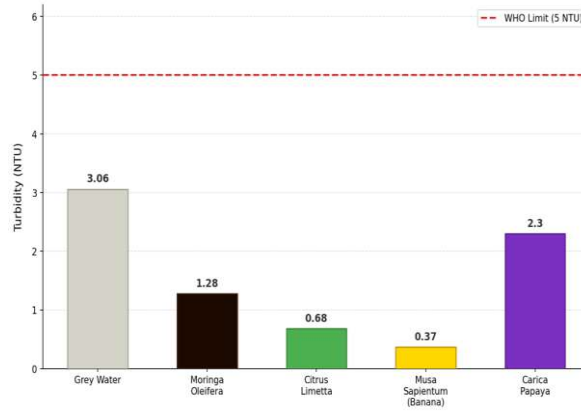
Sample	pH	TDS (mg/L)	Sulphate (mg/L)	Chloride (mg/L)	Turbidity (NTU)
GW (untreated)	6.95	140	125.6	68.4	3.06
MO	7.55	230	132.6	78.3	1.28
CL	5.64	175	1.1	2.5	0.68
MS	5.64	200	52.6	48.1	0.37
CP	5.75	180	111.0	29.1	2.30



(a)



(b)



(c)

Fig. 4: (a) pH (b) Sulphate and chloride (c) Turbidity of water samples

3.2 Cement Properties

The characteristics of the cement and its setting effect with different water type is shown in Table 3. The specific gravity and fineness modulus are 2.85, 2.25 respectively, which indicated consistency in the measured characteristics for the experimental mixtures. The results for penetration and setting-time, however, were quite inconsistent with the different types of water used. The non-treated greywater had a penetration value of 40 mm, initial setting time of 40 min and final setting time of 360 min. The initial setting times of the treated greywater samples were mostly longer than that of untreated greywater, whereas the final setting times were mostly shorter for the treated greywater samples. The water treated by MO showed the highest penetration value of 60 mm and the initial setting time of 60 min, but the final setting time was reduced to 250 min. The CL treated water had a penetration of 55 mm and initial setting time of 55 min followed by final setting time of 225 min. This is the lowest final settling time of the water types investigated and is a 37.5% improvement compared to untreated greywater. Both MS and CP treatments had 39 mm of penetration and 45 min of initial setting time. The final setting time was 300 and 265 min for their samples respectively. Studies reveals that dissolved salts can increase the initial setting time of cement paste up to +70 min when using treated domestic greywater [6, 9, 41]. The results suggest that treatment of greywater with the natural coagulants modified the setting characteristics of the cement paste. These results are consistent with ASTM C94 [42] requirements of initial setting time, which elucidates that the initial setting time of cement paste made with questionable water must not be more than 60 min earlier nor more 90 min later than that made with the same cement using distilled water [6].

Table 3: Cement Properties

Water type	Penetration (mm)	Initial Setting Time (min)	Final Setting Time (min)
GW (untreated)	40	40	360
MO	40	60	250
CL	40	55	225
MS	39	45	300
CP	39	45	265

3.3 Aggregate Properties

The Specific gravity, fineness modulus and particle-size distribution of the aggregates used in the manufacture of the IPS are shown Fig. 5. Specific gravity of fine aggregate was determined as 2.50 while the coarse aggregate had a specific gravity of 2.85. The fine aggregate and coarse aggregate had fineness moduli of 2.96 and 3.96 respectively. The higher fineness modulus of the coarse aggregate shows that the distribution of its particles was relatively coarse in comparison with the fine aggregate. The particle size distribution curves indicate that the fine and coarse aggregates have different gradation characteristics. The distribution of the fine aggregate was more widely spread over a smaller particle size range while the coarse aggregate was more spread over a larger particle size range [19]. The contrasting gradations of the two aggregates can be beneficial when used in the production of cement-based paving stones since the smaller size aggregates can fill the voids between the larger size aggregates, increasing the particle packing and decreasing the potential void volume of the aggregate mixture [25, 38].

The fine aggregate has a coefficient of uniformity (Cu) of 6.90 and coefficient of curvature (Cc) of 0.96. The Cu value meets the criterion for a well-graded sand. The coarse aggregate Cu is 39.22 and Cc of 2.33. The values meet the numerical requirements for a well-graded sand. The results show that the particle-size distribution of the two aggregates is complementary. This could aid in particle packing and affect the density, water absorption and compressive strength of interlocking paving stones produced [12, 29].

The aggregate gradation is an important factor governing the physical and mechanical performance of interlocking paving stones. The optimum packing of particles can increase the density of the matrix and decrease the interconnected voids, which may lead to better compressive strength and water absorption properties [26-28].

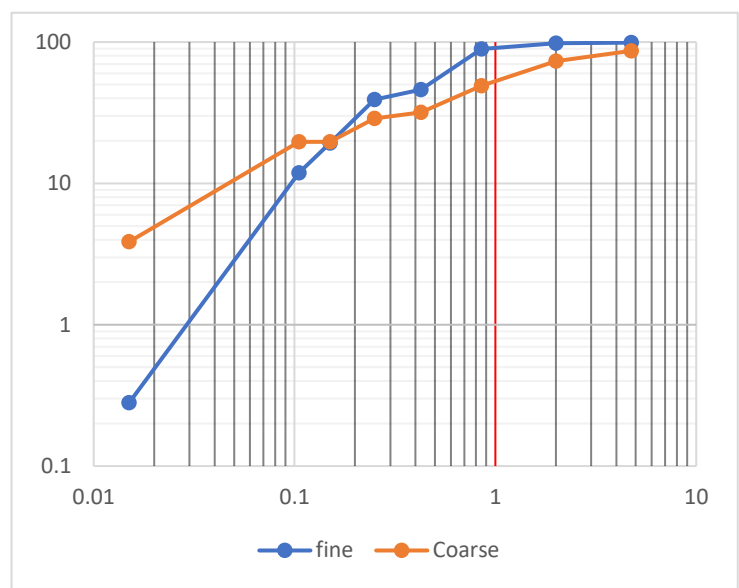


Fig. 5: Particle size distribution Curve of aggregates

3.4 Water Absorption of the Interlocking Paving Stones

Table 4 shows the water absorption results for the interlocking paving stones (IPS) made using the different mixing-water types. The absorption of water measures the permeability and pore structure of cement-based materials, higher water absorption generally relates to higher porosity and permeability and may lead to durability reduction [28, 42]. Water absorption of

10 % was recorded for the potable-water control. The IPS made from untreated greywater had the lowest absorption (9.52%) with a marginal reduction of around 4.8 % from the control. The result in this case, suggests that there was no increase in water uptake when using untreated greywater in the conditions investigated. The moderate difference between greywater and control specimens shows good agreement with the past results were treated wastewater may be used to produce the water absorption value similar to the conventional control concrete [6, 43]. The highest absorption of water was observed in the MO- IPS with 15.79 %, which is about 57.9 % higher compared to the control. CL and MS specimens recorded 13.11 %, which were increases of about 31.1 % when compared to the control. The higher absorption values for these mixtures indicate that there has been the development of a relatively more porous or interconnected pore structure, which permit greater penetration of water into the hardened paving stones. CP sample, on the other hand, absorbed 9.84 %, just about 1.6 % less than the potable-water sample. This relatively low absorption is not detrimental to the water absorption property of the IPS, and can help to form a comparatively dense cementitious matrix. The results show that the water absorption behaviour of IPS can be different depending on the nature of the alternative mixing water treatment, but the difference varies depending on the treatment [44 - 45].

Table 4: Water Absorption Results of the Interlocking Paving Stones

Mix Type	D.U.W. (kg)	O.U.W. (kg)	W.U.W. (kg)	Absorption (%)
PW (Control)	3.10	3.00	3.30	10.00
GW (untreated)	3.30	3.15	3.45	9.52
MO	3.10	2.85	3.30	15.79
CL	3.30	3.05	3.45	13.11
MS	3.35	3.05	3.45	13.11
CP	3.25	3.05	3.35	9.84

3.5 Compressive Strength of the Interlocking Paving Stones

The test results for 7 and 28- day compressive strength of the IPS crushed using the various mixing-water types are given in Fig. 6. The results show great variability in strength development depending on the type of water used during production, showing that the water content in the products is a crucial factor for the strength development [46, 47]. The compressive strengths measured for 7 days ranged between 3.33 and 7.67 MPa and for 28 days varied between 4.77 and 11.20 MPa. The potable-water control had 3.33 MPa compressive strength after 7 days, with a strength gain of 126% after 28 days. The increase demonstrates continued strength development with curing age, which can be attributed to the progressive hydration of cement and development of the hardened cementitious matrix [47]. The untreated greywater mixture exhibited a different trend. The compressive strength had first risen to 5.00MPa at 7 days and then slightly dropped to 4.77MPa at 28 days (i.e. 4.7 % reduction). The strength of the potable-water control was higher than the 7-day strength, but the 28-day strength was about 36.7% lower than the control. The decrease in the late-age strength could be related

to the fact that the constituents present in the untreated greywater may have affected the further development of the cementitious matrix such as the presence of surfactants and dissolved organic material in the water that affected long term formation of calcium silicate hydrate (C-S-H) gel [28, 44].

The CL water mixture gave compressive strengths of 4.08 and 5.33 MPa at 7 and 28 days, respectively, it shows strength gain of 30.6%. The mixture was stronger during curing, but the 28-day strength was about 29.2% less than that of potable-water control. Similarly, MS had a 16.2% increase from 4.33 MPa after 7 days to 5.03 MPa after 28 days. Its 28-day strength was about 33.2% less than the control. The results of cement retarding effect of CL and MS can be attributed to the present of natural sugars and starches in these extracts with citric acid nature [47, 48]. However, MO water produced significantly higher strength values. The compressive strength at 7 days was 7.67MPa, which was around 130.3% greater than the 7 days control compressive strength value of 3.33MPa. It was further strengthened to 9.70 MPa after 28 days, which is a 26.5% increase, which can be attributed to the early age particle packing benefits of the cationic polyelectrolyte proteins of Moringa Water [47, 48]. The potable-water control 28-day strength was about 28.8% lower than the potable-water control strength. The result shows that IPS obtained from MO treated greywater had a higher compressive strength than the control under the experimental conditions.

The highest strength performance was obtained with CP water. The compressive strength was increased from 6.33 MPa at 7 days to 11.20 MPa at 28 days, which means 76.8% strength gain. The 28-day strength was 48.7% greater than the potable-water control strength of 7.53 MPa. This could be related to fact that the extract CP contains proteolytic enzyme papain, which has a long-term strengthening effect [46], This finding shows that greywater treated with CP can be used as an alternative mixing water for IPS production with great potential. This enhanced performance may relate to the changes to the greywater properties after treatment, which may have helped cement hydration and the formation of a denser hardened matrix [48-50]. The findings thus show that the utilization of the selected natural coagulants can significantly affect the strength development of IPS when greywater is treated with the coagulants. The results emphasize the need to treat the greywater and compare the performance of the cement-based product after treatment, and not just the water quality [28].

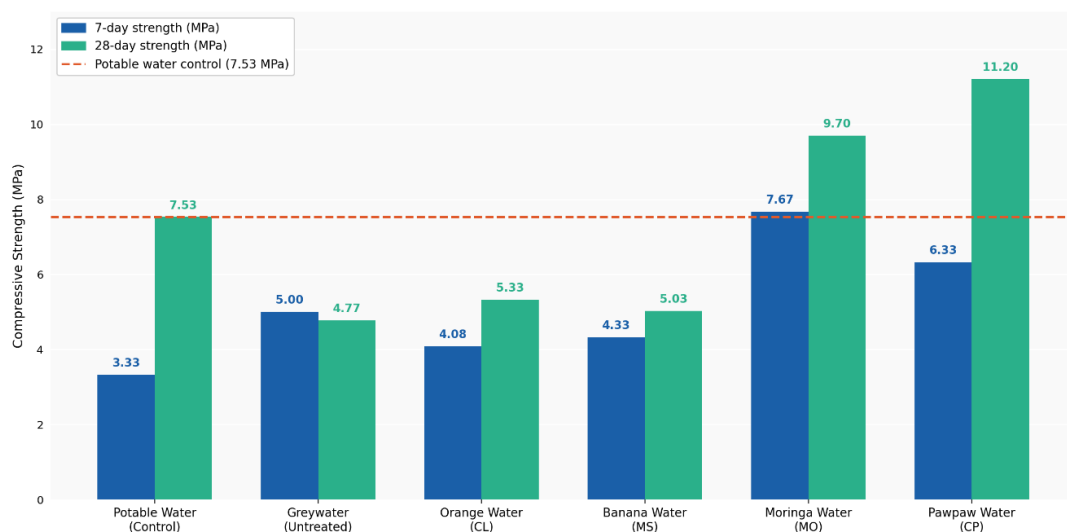


Fig. 6: 7-day and 28-day compressive strength of the interlocking paving stones

3.6 SEM-EDX Analysis of Hardened Interlock Residue

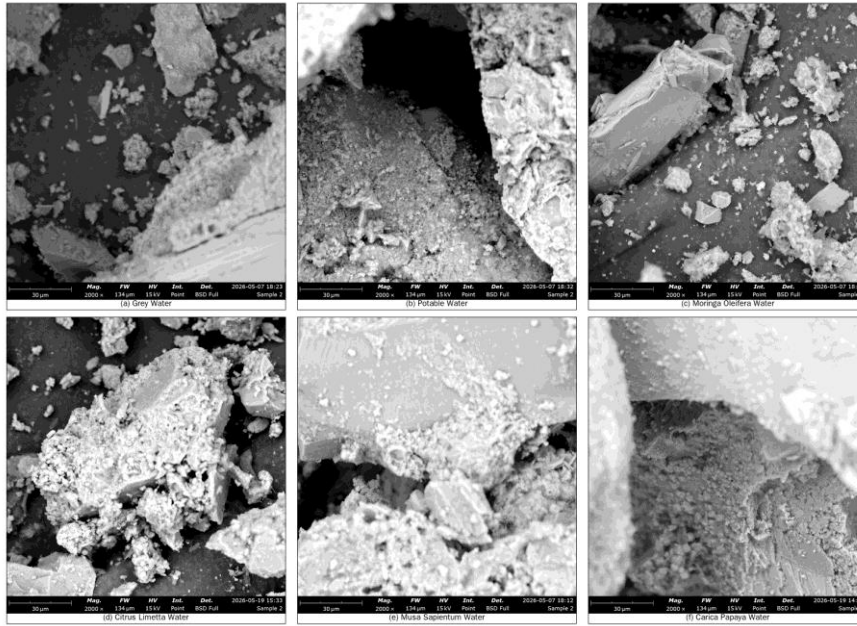
Table 5 shows the elemental composition of the hardened interlocking paving stones made with untreated greywater, potable water and naturally treated greywater. The SEM-EDX analysis showed that there was a lot of variation between the individual mixtures in terms of the proportion of oxygen, calcium, carbon, silicon and aluminium (Fig.7). The differences in the elemental composition of the hardened cementitious matrices gave rise to these variations, which were attributed to the different mixing-water sources used. The highest proportion of oxygen (70.42 %) followed by carbon (15.84 %), silicon (10.23 %) and aluminium (3.51 %) were found in the potable-water control. The analysed spectrum did not contain any calcium. A relatively high oxygen content and a silicon content suggest oxygen-bearing silicate phases in the hardened cementitious matrix. The presence of silicon and aluminium are important constituents associated with cementitious aluminosilicate phases, and carbon may be related to carbon containing constituents or surface carbonation. However, the information obtained by SEM-EDX is only elemental and not mineralogical phase information, thus the mineralogical phases are not the only information that can be obtained from these results [6, 50].

Oxygen, calcium, carbon, silicon and aluminium content of the untreated greywater sample were 63.87, 16.91, 4.78, 5.42 and 2.39, respectively. Additionally, iron (Fe) was found at 6.62%. The calcium concentration of the greywater sample was significantly greater than that of the potable-water sample, while the level of iron detected was present in the greywater sample. It is especially important to detect calcium, since it is one of the main components of cement hydration products. The difference in the elements of the untreated greywater and potable-water samples indicates that the mixing water itself may have created differences in the makeup of each hardened matrix. The elemental composition of the MO treated greywater was found to be significantly different with oxygen (92.5%) and carbon (7.5%). EDX reported: No Ca, Si and Al detected. This is the highest oxygen content of the elements of the samples investigated. The greywater specimen treated with the CL had 68.97% oxygen, 14.68% calcium, 6.70% carbon, 6.91% silicon and 2.74% aluminium. The simultaneous detection of the three elements Ca, C and Si and Al were fairly close to the untreated greywater with regard to their relative distribution. The calcium content is 14.68%, which suggests that there is a significant amount of calcium in the analyzed area, and the calcium, silicon and aluminium presence suggests the presence of constituents that could be related to the presence of a cementitious matrix.

The CP treated greywater sample had 69.22 % oxygen, 6.22 % calcium, 15.67 % silicon and 3.82 % aluminium. Another element detected was strontium (Sr) at 5.07%. In the reported spectrum, the presence of carbon was not observed, unlike the other specimens. The CP sample was most unique with its relatively high silicon content. The detection of Si, Al and Ca in the same sample suggests a chemically different hardened matrix than the other mixtures. There are also minor amounts of Sr detected in this sample, which further distinguishes this sample from the other analysed IPS specimens.

Table 5: Dominant Elements (wt%) in Hardened Interlock Residues by SEM-EDX

Sample	O	Ca	C	Si	Al	Other
GW (untreated)	63.87	16.91	4.78	5.42	2.39	Fe: 6.62
MO	70.42	15.84	—	10.23	3.51	—
CL	92.5	—	7.5	—	—	—
MS	68.97	14.68	6.7	6.91	2.74	—
CP	69.22	6.22	—	15.67	3.82	Sr: 5.07

**Fig. 7: SEM micrographs (2000×) of hardened interlock residues after 28 days – (a) GW (b) PW (c) MO (d) CL (e) MS (f) CP**

3.7 Compressive strength and SEM-EDX Relationship

The SEM-EDX results are correlated with the 28-day compressive strength results. The highest compressive strength (11.20 MPa) was found in the CP Water IPS that had a relatively high silicon content (15.67%) and aluminium (3.82%) and calcium (6.22%). The MO Water IPS had the second highest 28 day strength (9.70 MPa) with a very high oxygen content (92.5%) but Ca, Si and Al were not detected in the reported spectrum. This is a helpful supporting piece of evidence that the differences in the hardened matrix from the treated waters could be responsible for the improved mechanical performance of the CP and MO mixtures.

In addition, the SEM-EDX analysis results showed that the various mixing water sources resulted in different elemental compositions in the hardened IPS specimens [51]. The untreated greywater sample contained relatively high concentration of calcium and detectable presence of iron while potable-water control sample contained higher concentration of oxygen, carbon and silicon. The MO treated specimen was an oxygen rich sample and the CL sample had a relatively balanced level of calcium, silicon and aluminium. The CP specimen exhibited the highest silicon content and also strontium was detected in this sample. Remarkably, the IPS treated with CP had the highest 28-day compressive strength of 11.20 MPa with relative silicon

and detectable calcium and aluminium. The variation of these elements might be related to variations in development and composition of the hardened cementitious matrix [52, 53].

3.8 Compressive Strength and Water Absorption Relationship

The correlation between the water absorption and compressive strength of the IPS is shown in Fig. 8. The compressive strength and absorption of IPS of different water mix correlation was fair with $R^2 = 0.4227$. It was observed that higher compressive strength generally tends to coincide with lower water absorption. The result is consistent with previous studies in which incorporation of treated greywater did not change the property by more than 2 % [52] and water absorption of cement-based material with treated greywater corresponds to approximately 50 % of the value obtained with potable water [6, 53].

The relatively weak association could be due to differences in the internal pore structure and matrix properties of the paving stones. Pore volume, pore connectivity, particle packing and the development of cement hydration products are only a few factors that influence water absorption in addition to the strength of the hardened stones [54, 55]. Therefore, the water absorptive qualities of specimens of similar compressive strength can vary. The relationship indicates that the treated greywater can slightly alter the physical and mechanical characteristics of the IPS directly, making it necessary to consider both compressive strength and water absorption as important properties of suitability of alternative mixing waters.

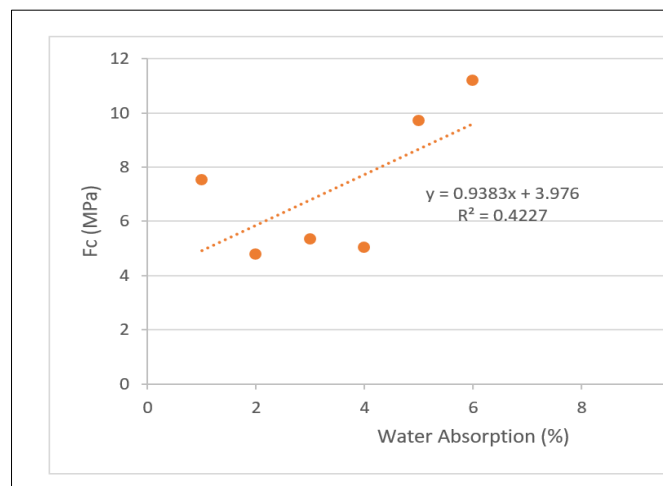


Fig. 8: Correlation between Compressive strength and water absorption at 28-day

4. Conclusion

This study aimed at evaluating the use of greywater treated with the four natural coagulants (*Moringa oleifera*, *Cucumis limetta*, *Musa sapientum* and *Carica papaya*) as alternative mixing water for production of interlocking paving stones (IPS). The outcomes illustrated the impact of the natural coagulants on the physicochemical properties of the greywater and their effect on the performance of the paving stones in the following stage. The treated water had better turbidity properties and the Total Dissolved Solid (TDS), Sulphate and Chloride concentration were within the ranges reported for non-potable reuse. The results of this study show the viability of the natural coagulants as easy and low cost pre-treatment methods for greywater use in construction projects.

Mechanical results indicated that the treatment effects were different for the various coagulants. The use of greywater produced with the CP yielded the highest overall performance with 28-day compressive strength of 11.20 MPa, which is about 49% higher than potable water control (7.53 MPa), and along with that the water absorption was comparatively low at 9.84%. The second best treatment was MO with 7.67 MPa at 7 days and 9.70 MPa at 28 days, especially at young age. The 28-day strengths for the IPS produced using untreated greywater, greywater treated with CL and MS were lower than that of the potable-water control. The differences observed indicate that water composition may impact cement hydration and formation of the hardened matrix.

The SEM-EDX results also showed different variation of the elemental composition of the hardened IPS made from the different mixing waters, which was consistent with the observed variation in the mechanical performance. Water absorption was not only inversely related to compressive strength, but also showed a weak inverse relationship ($R^2=0.0861$) indicating that the water absorption is not only dominated by compressive strength but also by other characteristics of the material and pore structure.

In summary, it can be concluded that naturally treated greywater especially the treated water by CP and MO, has potential as an alternative mixing water for IPS production, which can help to reduce the dependence of potable water in construction, promote reusing greywater and help to achieve SDG 6 (Clean Water and Sanitation) and SDG 11 (Sustainable Cities and Communities). Further studies should explore optimization of water/cement ratio, use of mixed coagulants (natural and chemical), and long-term durability, weathering, permeability and performance of IPS using naturally treated greywater.

Author contributions

Bayode O. Conceptualization of the study, Supervision, Writing and Coordination of research. Stanley I Ebirim S. I, Akande E. I, Olowomuwan S., Alao F., Olanipekun A.A, Idusuyi D.I. Findings integrity supervision, Data Validation, Editing. Agbelusi F., Ududchukwu C.O., Data collection, Data analysis, manuscript drafting.

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Ethics approval and consent to participate

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Consent for publication

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Competing interests

The authors declare no competing interests.

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