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Effects of acid attack and cassava flour dosage on the interfacial transition zone thickness, durability and mechanical characteristics of high-strength (HS) concrete

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ABSTRACT

Due to its higher porosity, the interfacial transition zone (ITZ), that is, the zone between the hardened cement paste (HCP) and the aggregate, is the weakest point in concrete. It is less resistant to cracking than both HCP and aggregate, and microcracks begin in this zone when the load is applied and propagates into the mass of concrete. The goal of this research is to investigate how various dosages of cassava flour (CF) addition affect the ITZ and how this is related to the mechanical properties of concrete, including its resistance to sulfuric acid. CF is added as a percentage of Portland pozzolanic cement (PPC) used as a binder, with dosages of 1, 2, 3, 4, and 5%. The morphology of CF and PPC was studied using x-ray diffraction (XRD) and x-ray fluorescent (XRF) techniques. Changes in the thickness of the ITZ were observed using a scanning electron microscope (SEM). The effect of sulfuric acid was observed by immersing samples of concrete in a 2% sulfuric acid solution. The results show that adding CF up to 3% progressively reduced the thickness of ITZ and improved the densification of concrete. As more CF was added, the ITZ began to widen again, but even at 5% CF addition, the thickness of the ITZ remained well below that of the control. The workability of fresh concrete decreased with an increase in CF dosage, but CF addition increased the compressive, tensile, and flexural strengths of hardened concrete. The greatest compression resistance was achieved at a 3% cassava flour addition level, which was 83.8 MPa after 180 days of curing and 8.9 MPa, 4.7 MPa for flexural and splitting strengths, respectively, after 90 days of curing. All the concrete samples containing CF had lower strengths than the control after immersion in sulfuric acid, with the concrete with 3% CF performing better than the others. The research concludes that CF used as an additive to concrete in dosages up to 5% improves the ITZ zone, leading to improved mechanical properties. However, resistance to sulfuric acid attacks is reduced. In all tests, it has been shown that a CF dosage of 3% gives the best results.

1. Introduction

As a result of urbanization, concrete has been extensively used in the past decades. Agricultural admixtures and other cementitious materials are being used as additions to concrete at an increasing rate because their use complements environmental conservation [1–4]. Both concrete manufacture and earthen building use agricultural admixtures, with the majority of attention going to concrete production [5–7]. The main benefit of agricultural SCMs is that these materials are readily accessible in many countries. Agricultural additive developments are generally focused on enhancing the effectiveness of mortar, cement paste, concrete properties, and earth blocks [8–11]. According to the composition of the materials, the inclusion of admixtures in the creation of concrete has been reported to be crucial [12]. Concrete is constructed to achieve excellent strength and resistance properties, like strong compression and bending strengths, and is frequently very robust [13]. It is typically

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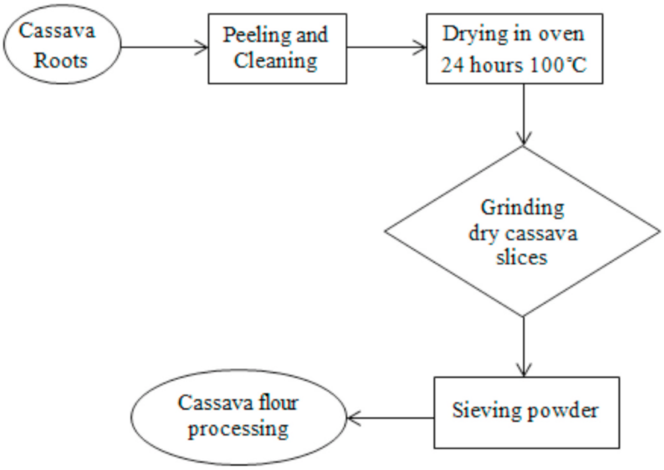


Fig. 1. A diagram depicting the cassava flour processing.

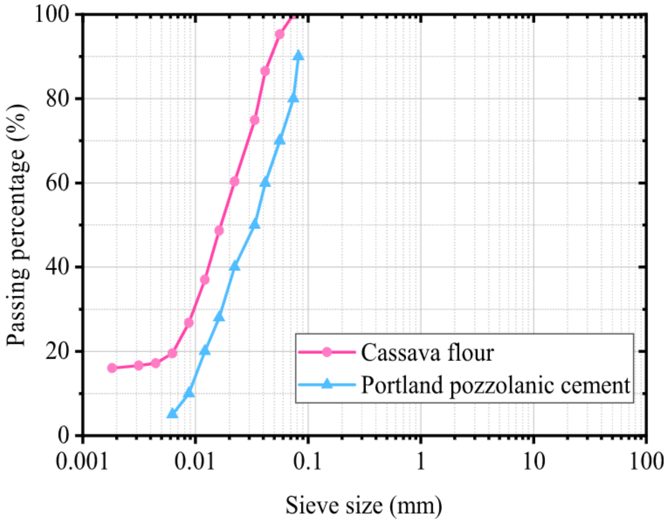


Fig. 2. PSD curves of CF and PPC.

made proportionally by mixing cement with fine, coarse aggregates, and water [14–16]. Concrete can be made using various agricultural, mineral, and chemical additives [7,17,18]. As is well recognized, concrete degrades when subjected to chemical attacks in acidic environments [19–22]. The onslaught could last for a short while or for years [13]. Sulfuric acid can cause rapid deterioration of cement composites due to its corrosive nature. The hardened binder matrix disintegrates when the cement composites are attacked by acid, resulting in the deterioration of the surface. The hardened binder matrix disintegrates when the cement composites are attacked by acid, resulting in the deterioration of the surface. $CaSO_4$, which is formed when the acid reacts with $Ca(OH)_2$, a component of cement, has the potential to damage the cement matrix. Because calcium hydroxide combines with sulphate ions, gypsum is produced as the primary byproduct of sulfuric acid. In addition, sulfuric acid can also react with calcium aluminate, another cement component, to form aluminium sulphate and calcium sulphate, further weakening the cement matrix [23]. Equations (1)–(3) below show how sulfuric acid attacks cement composites, leading to their deterioration.

$$Ca(OH)_2 + H_2SO_4 = CaSO_4 + 2H_2O \tag{1}$$

$$3(CaSO_4 \cdot 2H_2O) + 3CaO + AL_2O_3 \cdot 12H_2O + 14H2O = 3CaO \cdot AL_2O_3 \cdot 3CaSO_4 \cdot 32H_2O \tag{2}$$

$$CaO \cdot SiO_2 \cdot 2H_2O + H_2SO_4 = CaSO_4 + Si(OH)_4 + H_2O \tag{3}$$

Strength, durability, and cost-effectiveness are three important factors of concrete characteristics [23]. The cement acts as glue in the concrete, binding the particles together, and the percentage of cement in concrete significantly impacts the mechanical properties [24–26]. Portland pozzolanic cement (PPC) is frequently used because it has significant advantages over ordinary Portland cement (OPC) alone [27–29]. PPC benefits include increased long-term strength as a result of the interaction that occurs between pozzolana and $Ca(OH)_2$ produced during cement hydration, significantly reduced degree of hydrating,

Table 1
Aggregate sieve analysis to ASTM C33/C33-18, 2010.

opening of the sieves	Accumulated Weight (g)	C.R (g)	C.R (%)	C·P (%)	Lower Limit	Upper Limit
C.A						
12.5	0	0	0	100.0	90	100
9.5	812.3	812.3	40.6	59.4	40	70
4.75	1078.7	1891.0	94.6	5.4	0	15
2.36	106.3	1997.3	99.9	0.1	0	5
Pan	1.7	1999.0	100.0			
Total	1999.0					
F.A						
4.75	0.0	0.0	0.0	100	95	100
2.36	144.7	144.7	14.5	86	80	100
1.25	258.0	402.7	40.3	60	50	85
0.6	120.3	523.0	52.3	48	25	60
0.3	207.3	730.3	73.1	27	5	30
0.18	171.7	902.0	90.3	10	0	10
Pan	97.3	999.3	100.0			
Total	999.3					
FM = 2.70						

Fig. 3. Concrete workability test.

Fig. 4. Concrete compressive strength test.

Table 2
Concrete mix ratios with cassava flour (kg/m^3).

Mix	C.A			F.A	Cement	Water	w/b ratio	S·P	C·F (%)	C·F
	6.35–12.7	3.18–6.35	1.58–3.18							
Mix 0	405	538	53	530	500	170	0.35	4	0	0
Mix 1	405	538	53	530	500	170	0.35	4.041	1	5
Mix 2	405	538	53	530	500	170	0.35	4.081	2	10
Mix 3	405	538	53	530	500	170	0.4	4.121	3	15
Mix 4	405	538	53	530	500	170	0.4	4.161	4	20
Mix 5	405	538	53	530	500	170	0.4	4.201	5	25

Fig. 5. Concrete splitting tensile strength test.

Fig. 6. Concrete flexural strength test.

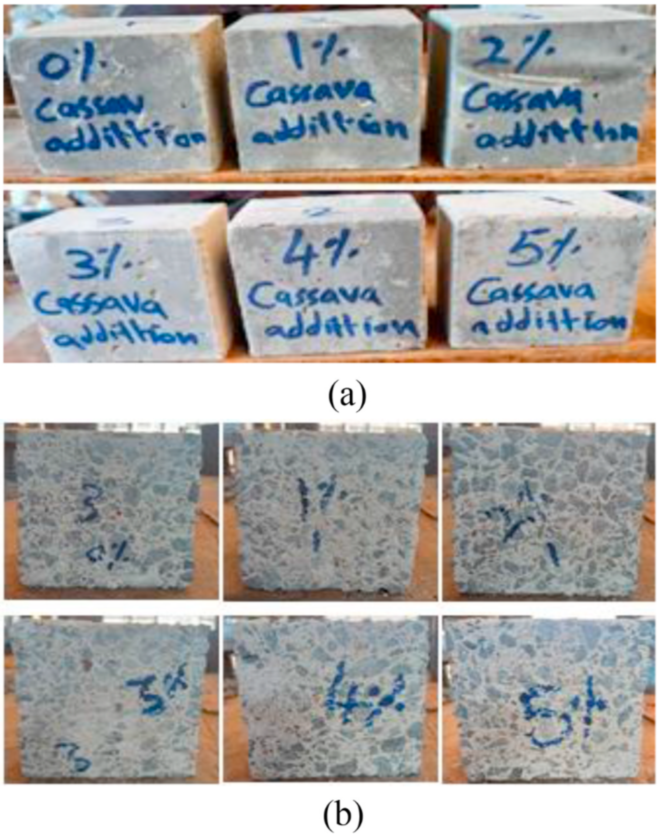


Fig. 7. Samples after curing in sulfuric acid.

strengthened chemical stability, and low permeability [30–33]. Equations (4) and (5) provide a summary of the pozzolanic reaction and cement hydration [30].

$$CS + H2O = C\text{–}S\text{–}H + Ca\ (OH)\ 2 \qquad (4)$$

$$Ca\ (OH)\ 2 + SiO2 + H2O = C\text{–}S\text{–}H \qquad (5)$$

A significant contribution to global CO_2 emissions and over-exploitation of limestone is mainly related to OPC production [34–37]. Increasing the use of SCM in concrete is necessary to achieve a suitable level of clinker replacement to match the rapidly expanding cement production industry. Using supplementary cementitious materials (SCMs), industrial by-products, or naturally occurring minerals can reduce the amount of cement in HSC [38]. Concrete at the macroscopic level is interpreted as a homogeneous mixture composed of a transition zone, mortar paste, and coarse aggregate that introduces first-level heterogeneities at the mesoscale level [39–41]. The ITZ is a thin layer of increased porosity mortar that forms primarily as a result of the wall effects of cement particles pressing up against the surface of the aggregate [42–44]. The so-called "wall effect" is a result of the unequal distribution of cement particles caused by the difference in particle size, which makes each block act as a small wall. As a result, the dense dough is pushed away, and a more porous paste is produced near to the aggregate [45–47]. ITZ has a significant impact on the determination of the strengths of concrete [48,49]. In contrast to the adjacent mortar, the ITZ is more permeable and weaker [50,51]. The ITZ layer is composed of $Ca(OH)_2$ on the aggregate side and *C*–S–H gel on the paste side [52]. If there is less residual calcium hydroxide, the interfacial transition zone can resist serious chemical attack, and ITZs with higher porosities can also give the sulphate a path for diffusion [16]. The mix proportion, w/c ratio, cement type, size of aggregates specifically its porosity and water absorption, curing conditions, and degree of hydration, significantly impact the forms of the ITZ microstructure and thickness [53–55].

Modifying the particle size distribution of cementitious material can improve the microstructure of ITZ while minimizing the thickness by lowering the porosity of cement paste and the water/cement gradient [45]. It must be minimized to ensure high strength, low permeability, and durability in concrete [56]. With a rise in design complexity, the cost of building supplies, the use of new building methods and sensitivity to local and environmental concerns, there is a growing need for modifications to certain qualities of construction materials [57]. Certain qualities of concrete mixtures can occasionally be changed by adding additives, such as increased flow for the same water-cement ratio, greater strength, and durability resulting from the cement paste's reduced porosity [58,59]. Natural materials as admixtures to improve the quality of concrete have become necessary and reduce reliance on chemical admixtures [60]. Researchers have focused on adopting naturally occurring admixtures since they are widely available, economical, eco-friendly, and can be processed locally. This has helped lessen dependence on chemical admixtures. Several local alternatives have been investigated, including sorghum flour [61], cassava starch and rice husk ash [62], arrowroots as bio admixture in concrete [63], Corn starch [64], Gum Arabic Karoo [65], okra extract [66], and mineral admixtures like silica fume, fly ash, blast furnace slag, and nano-materials to create a brand-new generation of custom, multipurpose cementitious composites with improved mechanical performance and endurance. These materials may have special qualities like low electrical resistance, high ductility, self-healing, self-cleaning, and self-control of cracks [67–69]. Previous studies have been carried out on adding cassava flour to concrete mortar to examine the physical and mechanical properties. Cassava flour is a viable natural substitute in concrete due to its viscosity characteristics, thickening quality, particle size, shape, and surface area, which improve the cementitious composite strength. Cassava flour is created by crushed dry cassava slices [70].

However, knowledge of what exactly occurs in the concrete microstructure and thickness of the interfacial transition zone to evaluate the adhesion characteristics at the interface needs to be considered and assessed. For example, Okafor, 2010 [71], who examined the results of the effectiveness of cassava flour as an additive in concrete to minimize water content. The investigation was conducted on the improvement of workability and compressive strength at 90 days for concrete by using 0.45, 0.50, 0.60, and 0.70 water-cement ratios and cassava flour dosages up to 3%. The results indicated that adding more cassava flour to the concrete mixture improved the workability of the concrete. The increase in flowability was caused by the presence of high-activity components on the surface of the admixture, which interacted with the cement particles and generated negative charges that caused the cement particles to repel each other. On the other hand, Akindahunsi and Uzoegbo, 2015 [72] investigated the concrete characteristics by using plant starches such as maize and cassava flour. The researchers found that the use of these starches increased the concrete's ultimate strength and durability but reduced the setting time of cement paste. Other researchers, S. H. Chu et al., 2015 [59] used an admixture of maize flour and tapioca to estimate the performance of the concrete. They found that the performance with various percentages of maize flour up to 1.5% performed better than the concrete with various concentrations of tapioca starch up to 2.5%. Other studies were conducted by Akindahunsi and Schmidt, 2019 [73] who investigated the shrinkage characteristics of concrete using up to 2% cassava flour by weight of cement. The findings indicated that CS increased the compression resistance of concrete and made it stiffer by making it more stable and cohesive, resulting in reduced shrinkage.

Similarly, Kone, Mwero, and Ronoh, 2022 [62] used RHA and cassava starch to evaluate the mechanical properties of concrete. The researchers added 2% cassava starch by cement weight together with 20% RHA. According to the results, the compressive and splitting tensile strengths were increased compared with the control mix. The durability, physical, and mechanical properties of high-strength concrete with CS addition were researched by Gumma et al., 2022 [74]. The study

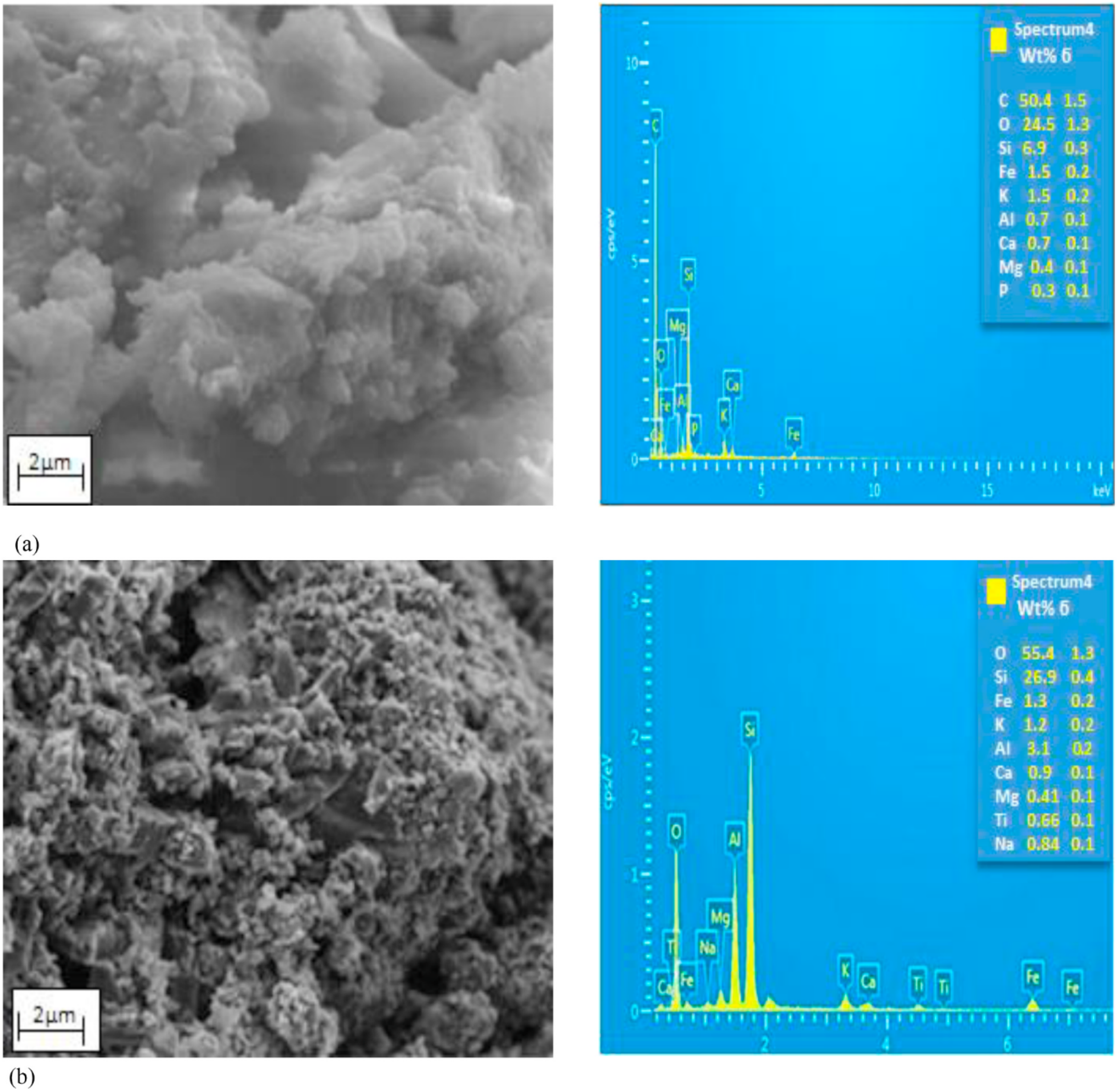


Fig. 8. SEM/EDS analysis of CF and type II cement.

analyzed the influence of CF on the fresh and hardened properties of high-strength concrete using up to 5% cassava flour by weight of Portland pozzolanic cement. The researchers found that adding up to 3% cassava flour improved concrete properties. The authors found that for cassava flour addition up to 3%, the porosity, void space volume, and bulk dry density were reduced. Other researchers, Syamani et al., 2020 [75] used cassava starch in a manufacturing process to produce bio-plastic. The findings indicated that the bio-plastic made of CS had a higher tensile strength and was more thermally stable. On the other hand, Q. Xu et al., 2016 [76] used cassava and corn starches to produce wood adhesive materials. The results showed that the adhesive material produced from cassava starch was higher stability than cornstarch-based wood adhesive, and it had excellent bonding performance even after 90 days of storage. In a separate research, Oni et al., 2020 [6] studied the impact of CS on the durability of concrete. The study focused on the effect of CS on sorptivity, including water absorption, and sodium hydroxides and chloride penetration. The slump values of concrete reduced and in the hardened state, the concrete resisted sulphate and chloride ion attacks when cassava starch increased.

The literature review shows that there are not many publications that have studied the influence of sulfuric acid on Portland pozzolanic cement concrete containing cassava flour. The aim of this study is to evaluate the microstructure and thickness of ITZ, as well as durability and mechanical characteristics of HSC, by adding a weighted admixture of cassava flour to Portland pozzolanic cement. No study of the effect of cassava flour under these conditions of use was found.

2. Research significance

Due to significant environmental issues associated with chemical materials, there have been significant advances in the use of sustainable and environmentally friendly materials during the last few years. Development must be both sustainable and sufficient to satisfy the requirements of a growing population. The foundation of sustainability is an appropriate balance between technical performance and consequences to the economy, society, and environment. Decreased clinker-based cement output is necessary as a result. The excellent chemical resistance, crack resistance, and reduced process heating of Portland pozzolanic cement makes it a good choice for concrete production. Additionally, it reduces the expenditure of some critical natural

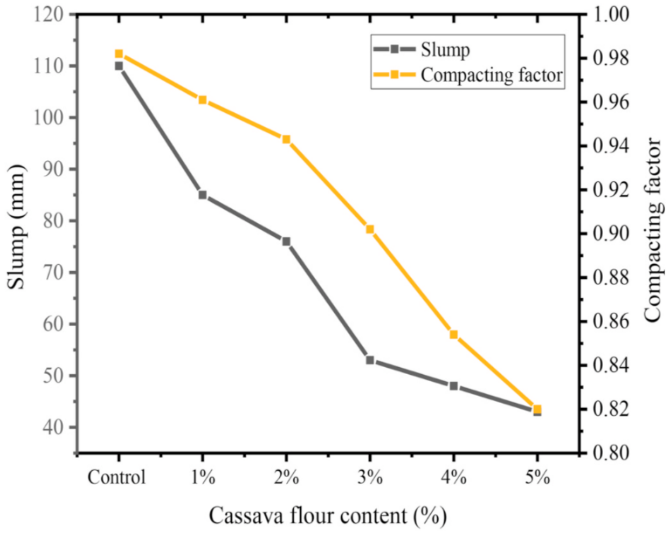


Fig. 9. Influence of cassava flour on the concrete's workability.

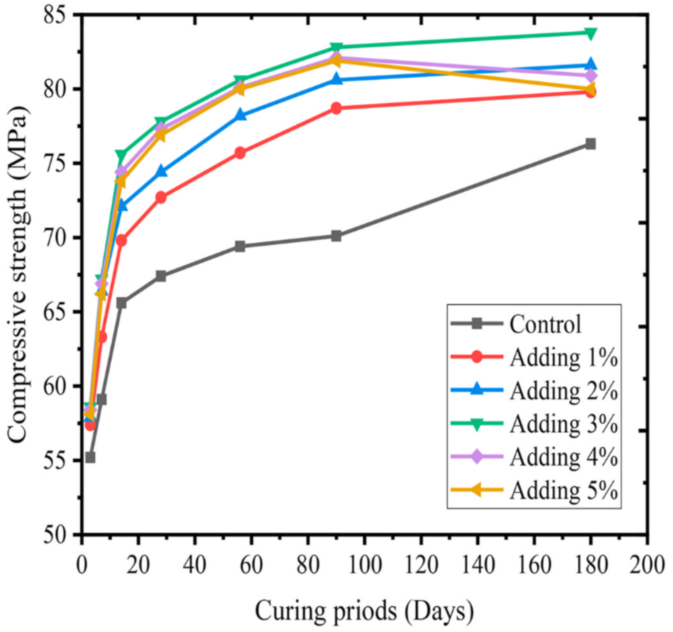


Fig. 10. Impact of CF on the compression resistance of concrete.

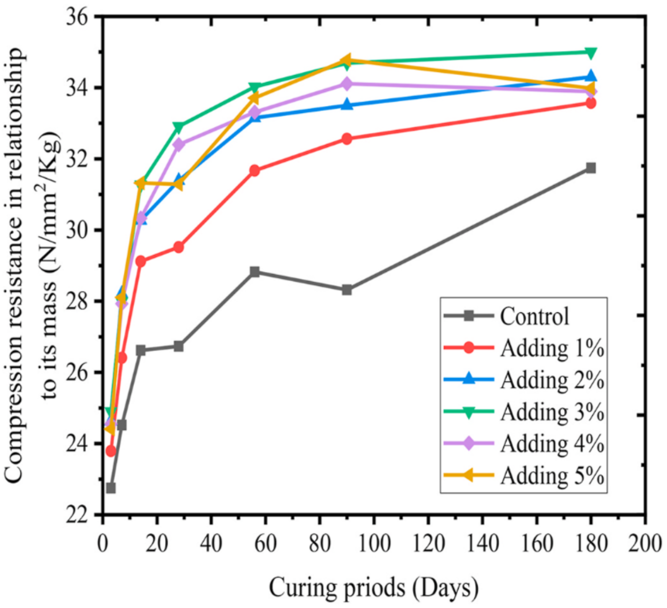


Fig. 11. Performance of CF on compression resistance in relation to weight.

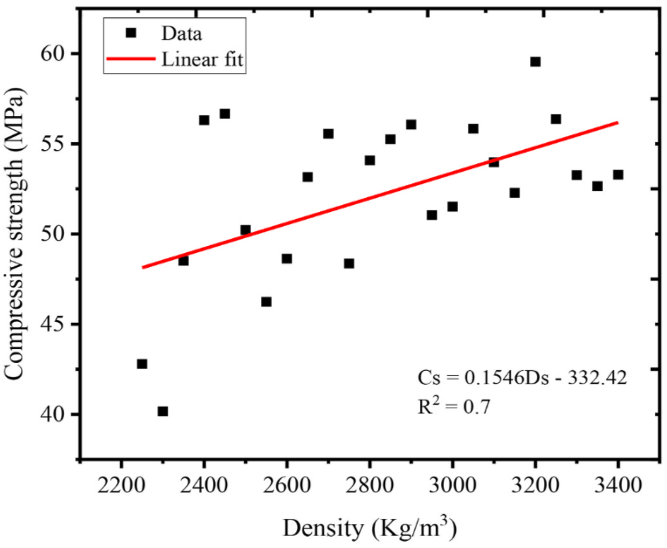


Fig. 12. Compressive strength and density relationship.

resources used in the production of cement. When cassava flour is added to concrete as an admixture, it encourages the use of locally available building materials and solves the problem of cost and availability of chemical admixtures in less industrialized countries.

3. Experimental program

3.1. Materials utilized

3.1.1. Portland pozzolanic cement and cassava flour

The steps used in this study included purchasing cassava roots from the Juja village market. The cassava roots were peeled, cleaned, sliced, and dried in a 100 °C oven. Then the dried cassava slices were ground and sieved through ASTM sieve #200, as shown in Fig. 1. Fig. 2 depicts the PSD of Portland pozzolanic cement and cassava flour. To determine the mineral composition and elements of cassava flour and Portland pozzolanic cement, the XRF, XRD, and EDS/SEM tests were used. Finally, Type II (PPC) cement was applied as a binder (see Fig. 3).

3.1.2. Superplasticizer

The superplasticizer used in this research was Sika Viscoflow-615 KE. It has a yellowish color, a property density (kg/L) of 1.08 kg/L (at +20 °C), and a 34% solid content.

3.1.3. Aggregates

The coarse aggregate used was a type of crushed granite rock with a specific gravity (SG) of 2.66 and a maximum aggregate size (MAS) of 12.5 mm. The coarse aggregate was pre-treated by being washed and sun-dried before being used in concrete mixtures. The fine aggregate (FA) utilized had a fineness modulus (FM) of 2.7 and a specific gravity (SG) of 2.61. Table 1 outlines the PSD from sieve analysis of the coarse and fine aggregates in comparison with the standards set by ASTM C33/C33-18, 2010 (see Fig. 4).

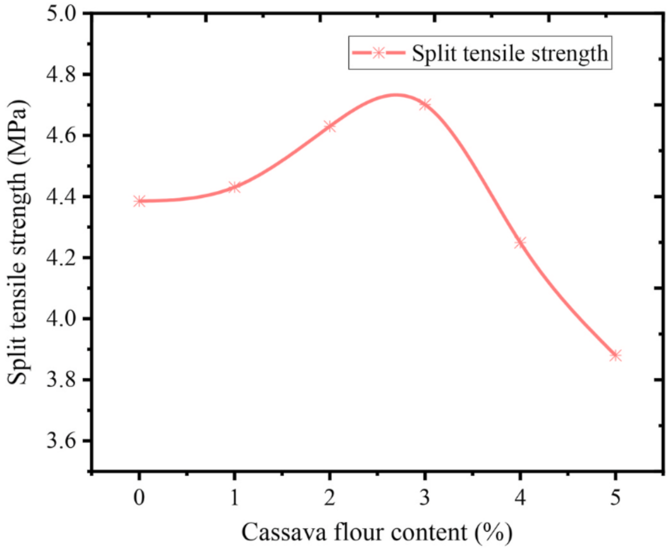


Fig. 13. Effect of cassava flour on tension strength.

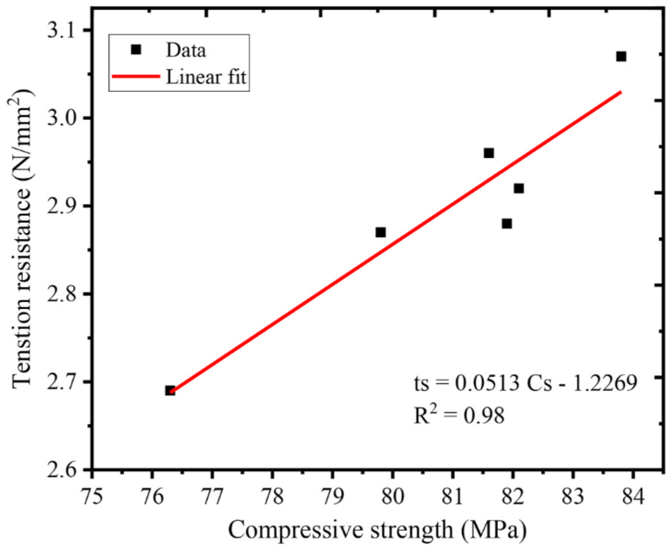


Fig. 14. Split tensile and compressive strength relationship.

3.1.4. Mixture proportions

The American Concrete Institute's 211.4R-2008 technique was used to generate a total of six different concrete mixes. There was zero percent cassava flour in the control mixture, denoted by CM. The other five mixes were prepared by adding varying amounts of cassava flour to Portland pozzolanic cement in percentages of 1, 2, 3, 4, and 5%, respectively. Table 2 demonstrates all the particulars of the cassava flour concrete mixture.

3.2. Testing procedures

3.2.1. Flowability test

The compacting factor and slump tests were made for all mixtures made according to ASTM C143/C143M – 10 to see how well freshly mixed cassava flour concrete could be worked.

3.2.2. Compressing test

Number of 126 samples, 100-mm cube size were prepared to BS EN 12390–03 and compression strength tests were carried out at 3, 7, 14, 28, 56, 90, and 180 days. A universal compression testing machine of 150 KN load capacity was used to load each cube to failure and the maximum load was recorded. Three cubes were tested to obtain an average failure load for each mix at the specified age.

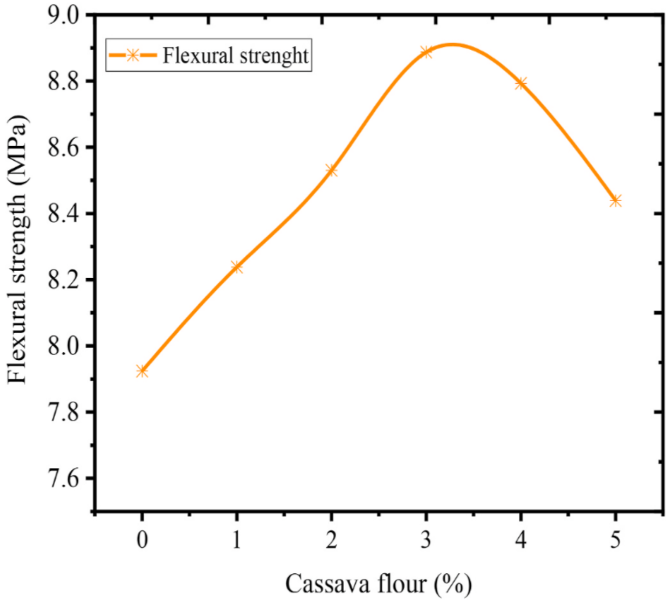


Fig. 15. Cassava flour's influence on the flexural strength at 90 days.

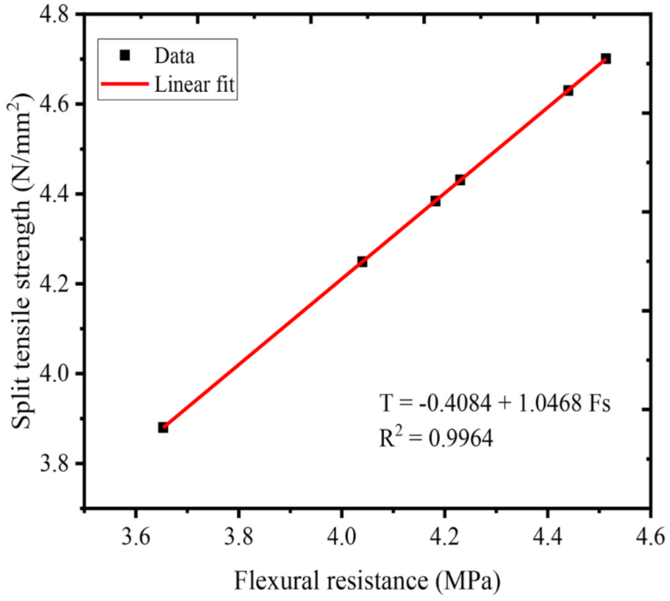


Fig. 16. Correlation between flexural and split tensile strengths.

3.2.3. Concrete tensile strength test

18 specimens with a 150 mm diameter and 300 mm length were tested at 90 days for each mix to obtain an average record.

3.2.4. Flexural strength test

A test of flexural strength was performed on 18 beams with a 100 mm depth and 350 mm length. BS EN 12390 (2009) [77] was adopted to carry out the flexural strength test at 90 days. The average value was recorded for three beams for each mix.

3.2.5. Sulfuric acid attack test

A number of 54 cubes of 100 mm were manufactured. To test the

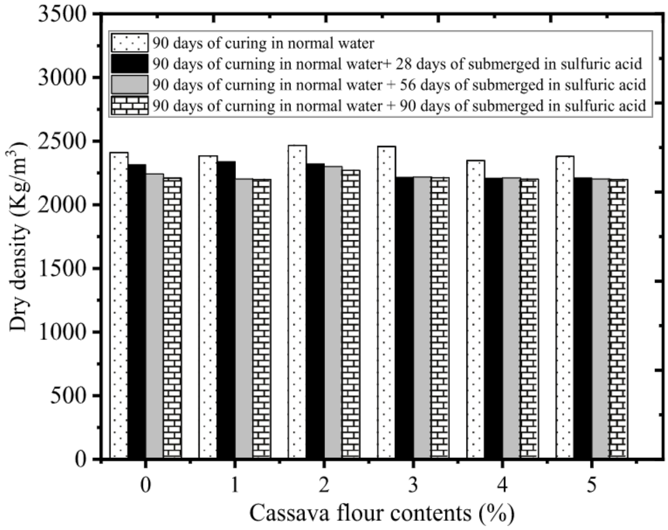


Fig. 17. Effect of sulfuric acid on dry density of concrete.

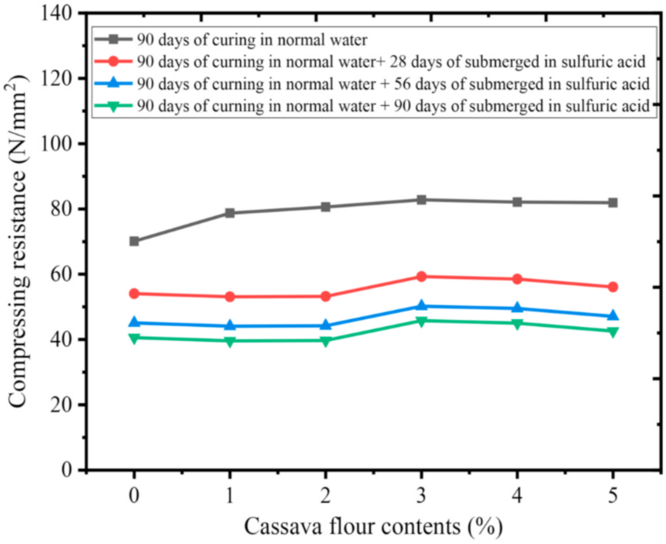


Fig. 18. Influence of acid attack on compressive strength.

opposition to the entry of sulphate ions into cassava flour concrete, the mass of the samples was measured after the curing period. They have also been immersed for 28, 56, and 90 days, respectively, using acid sulfuric solutions with a pH of 3.0. The losses in compressive strength and mass were then calculated. Fig. 7a, b display the samples that have undergone sulfuric acid curing.

3.2.6. Interfacial transition zone (ITZ)

Using scanning electron microscopy, the microstructure and thickness of the ITZ of all 6 mixes were examined. A tiny cylindrical core from the concrete cube was extracted for this test, and a thin slice measuring about 3–4 mm was then cut by a diamond cutter and polished by an electrical polisher for imaging. At the same magnification, the ITZ was photographed and its thickness was measured.

4. Results and discussions

4.1. X-ray fluorescence, x-ray diffraction analysis, and physical properties

For the determination of the various elements in a variety of materials, x-ray fluorescence spectrometry (XRF) has been extensively used. It is observed that the major compounds found in cassava flour were (SiO_2), which comprised 20.16% of the total. Together with Al_2O_3, which was 3.51%, and CaO, which was 8.28%, when exposed to water, can react to form cementitious hydrated calcium silicates and aluminates, which make the concrete stronger. Although higher than for cement, loss on igniting for CF was still within the ASTM C-618-specified range of 12%. Additionally, it was established that the cassava flour had a specific gravity of 1.49 g/cm^3. The test results showed that processed cassava flour and Portland pozzolanic cement had a lot of quartz in them, which was also recognized by Gumma et al. [74], Syafri, Kasim, Abral, and Asben, 2017 [78], Zainuddin et al., 2013 [79], and Narattha, Thongsaitgarn, and Chaipanich, 2015 [80].

4.2. X-ray spectroscopy analysis and optical scan microscope

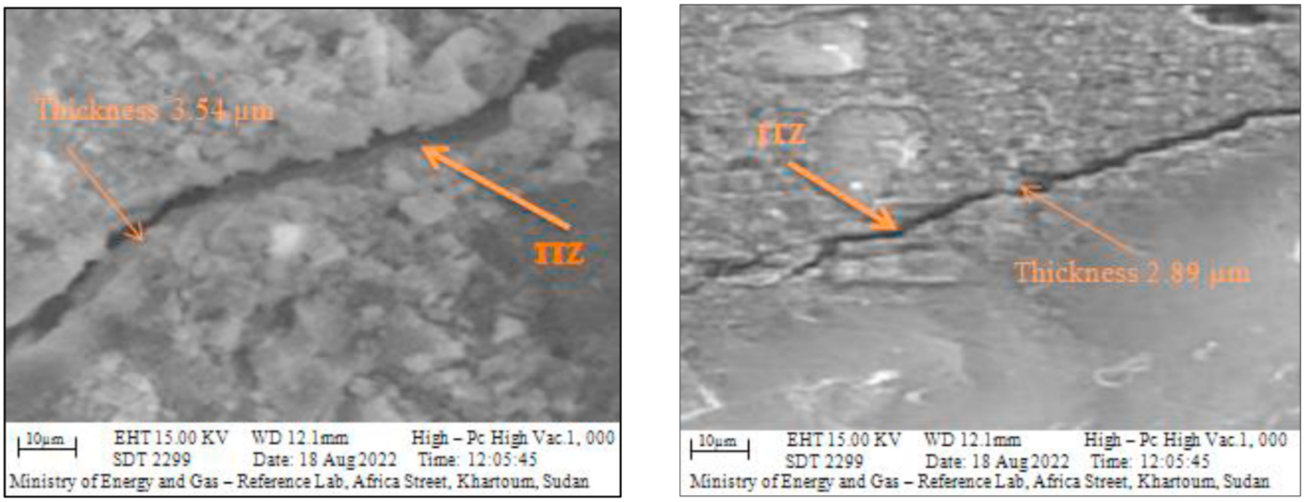
To analyze the surface structure, size, and shapes of the elements, OSM was used to produce micrographs [81–83]. The results demonstrated that the surface of the fibrous, irregular flakes that make up cassava flour have circular capillary holes. Since the majority of the granules are cylindrical, they fill any spaces inside cassava flour concrete, increasing its density as well as compressive strength same found in study by Gumma et al. [74],. However, due to the fibrous nature of the cassava flour particles, adding them to the cementitious matrix increased the demand for water and made the concrete flexible. To determine the elements in the cassava flour and the cement, ED's analytical method was used. Samples of cassava flour and Portland cement were taken randomly, and ED's analysis was performed to identify the elemental structure. The elemental structures of cassava flour and Portland pozzolanic cement are shown in Fig. 8a and (b). Carbon, oxygen, silicon, aluminum, calcium, iron, potassium, magnesium, and phosphorous were all found in different amounts in samples of cassava flour.

4.3. Flowability

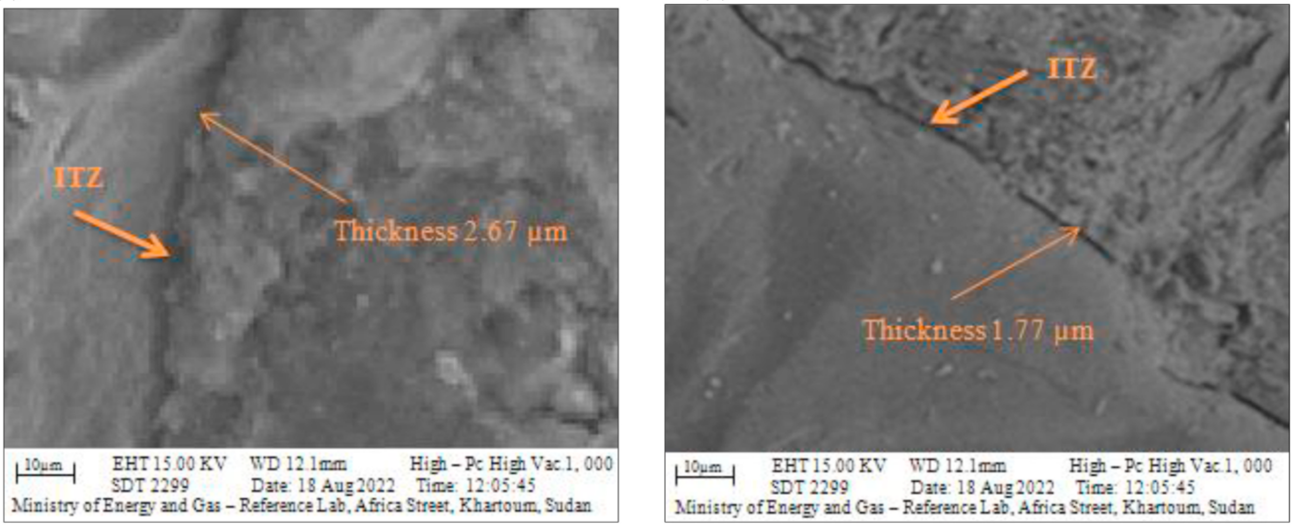
Fig. 9 shows the slump and compacting factor values for all concrete mixtures at various levels of cassava flour addition in a gradual by-millimeter decrease (see Fig. 5). Data plainly indicates that workability decreased as the percentage of cassava flour increased. For mixtures containing 1, 2, 3, 4, and 5% cassava flour, the slump and compacting factor were gradually reduced by 22.73, 30.91, 51.82, 56.36, and 60.91% compared to the workability values for the reference mix. In addition, starch in concrete reduces workability due to its viscosity properties and thickening power, as clearly presented in Fig. 6a, which increases the requirement for water. The fibrous, asymmetrical granules and pores that cover cassava flour are to blame for the loss in workability. These results match those of Okafor 2010 (Okafor, 2010) and Joseph and Xavier 2019 (Chu, 2019), who also found that with a higher amount of cassava flour, the concrete's workability declined.

4.4. Compressing test

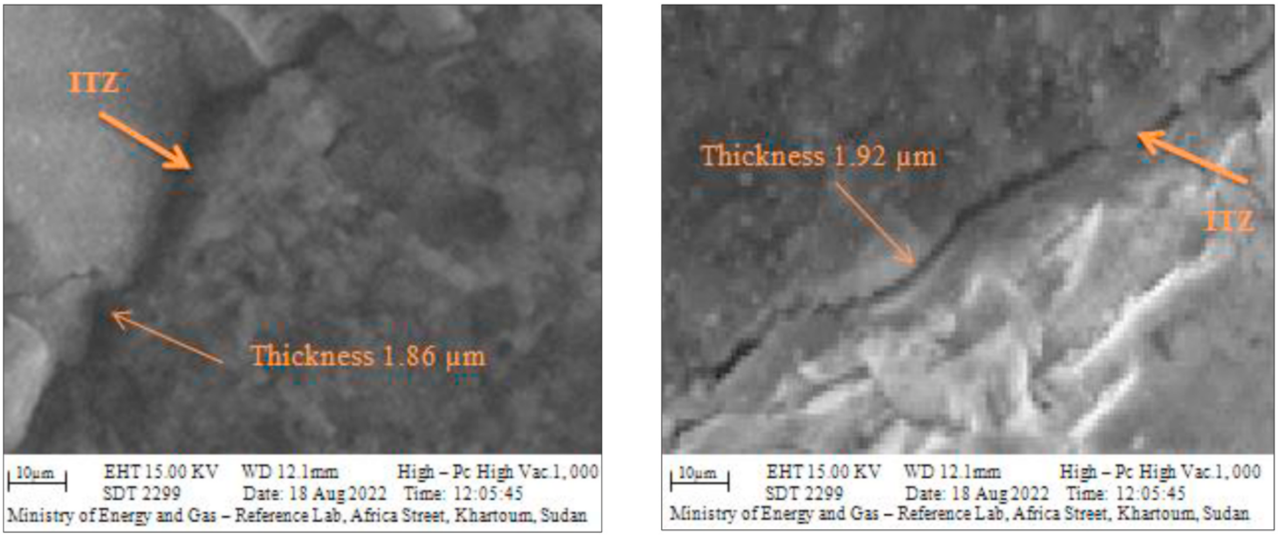
Compression testing of Portland pozzolanic cement concrete mixed with cassava flour is shown in Fig. 10 for varied curing periods. The compressive strengths at 180 days ranged from 55.2 to 83.8 MPa. Compressive strength increased with extended curing times. Portland pozzolanic cement gains strength as a result of the existence of a percentage of pozzolana that reacts slowly with $Ca(OH)_2$ over an extended period of curing. It can be observed that, when compared to the other mixes, the 3% cassava flour addition had the highest strength. The high silica content of Portland pozzolanic cement and the percentage found in cassava flour react in the mix to produce additional C–S–H gel, which can be attributed to the increase in strength with extended curing times. The same findings were noted by Kone, Mwero, and Ronoh, 2022 [62]. These phenomena may be connected to the delayed reactivity of



(a) Normal concrete (b) 1% cassava flour addition



(c) 2% cassava flour addition (d) 3% cassava flour additions



(e) 4% cassava flour additions (f) 5% cassava flour additions

Fig. 19. Interfacial transition zone thickness of cassava flour addition levels.

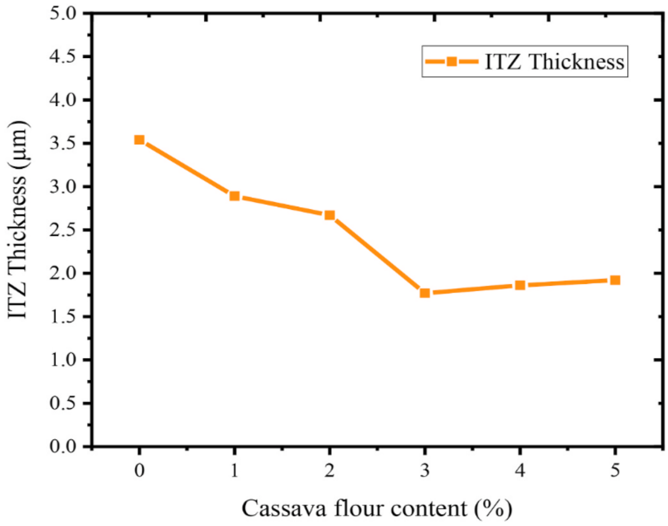


Fig. 20. Influence of cassava flour on ITZ thickness.

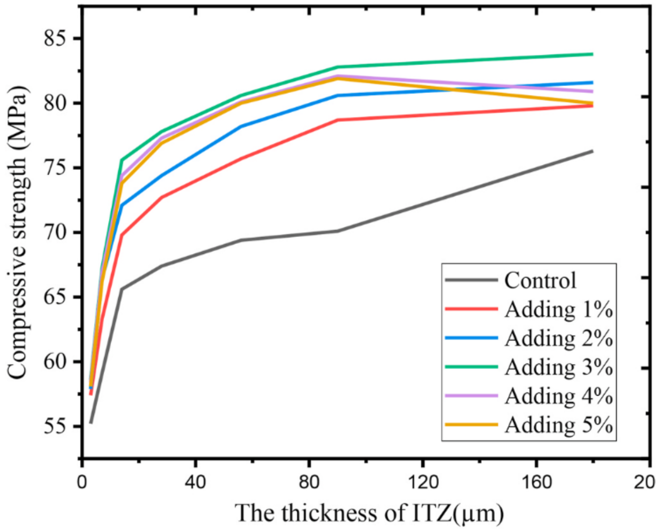


Fig. 21. The relation between ITZ thickness and compressive strength.

Portland pozzolanic cement, as reported by A.A. Akindahunsi and Uzoegbo, 2015 [72], Siqueira and Cordeiro, 2022 [84]. Furthermore, the high porosity of the materials presented in Fig. 6a, as evidenced by the high water consumption, can be attributed to a compression strength decline with increasing cassava flour percentages up to 5%. Similar results were presented by Sindh et al., 2012 [85] and Ma et al., 2022 [86].

Additionally, Fig. 11 gives the compression resistance per unit mass. This is due to the fact that cassava flour, compared to cement, has a smaller unit weight, leading to a reduced concrete density. Mixes 2 and 3, which have 1% and 3% of cassava flour, do better than the control mix 1.

The test findings for concrete made with cassava flour led to the development of a link between compressive strength and density. Fig. 12 shows the density line that most accurately corresponds to the information obtained for samples with various compressive strengths. Eq. (6) demonstrates the connection between compression resistance and density. The linear relationship between density and strength allows concrete density to be predicted for a given compressive strength even when density testing does not take place. Eq. (6) is used to determine the coefficient of determination (R^2), which comes out to 0.7 for concrete made using cassava flour. When the results are at equal distances from the mean value and the largest number of samples has a value equal to the mean, then the distribution is normal and is known as the curve of the normal frequency distribution, and its properties depend on the values of the mean and the standard deviation.

$$Cs = 0.1546\ Ds - 332.42 \tag{6}$$

$$F_{(\max,\min)} = F_m \pm K\partial \tag{7}$$

$$\partial = \sqrt{\sum\left(\frac{(X - X^{-})^2}{n-1}\right)} \quad n > 20 \tag{8}$$

Where;

n = number of values.

K = Probability coefficient and expresses the probability of a sample occurring out the ($F_m \pm k\partial$) bounds

F_m = The mean value

∂ = The stander deviation

C_S = concrete compressive strength in MPa.

D_S = concrete density in kg/m.^{3}

4.5. *Tensile strength*

Concrete's ability to crack under tension is used to identify the crack in the elements. Fig. 13 displays the tensile strength findings after 90 days curing. With an increase of 7.21% over the control mix, the 3% cassava flour addition produced the greatest value of tension, while the 1% addition was extremely near the control mixture. Tension strength decreased with additions of 2%, 4%, and 5%, respectively, by 5.59%, 3.102%, and 11.52%. When contrasted with the control combination, the tension strength increasing by up to 3% cassava flour percentage in Portland pozzolanic cement paste may result in additional cementitious *C*–S–H gel produced which reduces the size of capillary pores and improves the bond strength. The pozzolanic reaction with a small percentage of SiO_2 in cassava flour generates more cementitious *C*–S–H gel because Portland pozzolanic cement's hydration produces non-cementing $Ca(OH)_2$, which is converted into a more useful form, Berra, Mangialardi, and Paolini, 2018 [87].

The ability of cassava flour to control bleeding in concrete, which reduces the number of microcracks or shrinkage cracks at the paste-aggregate interface, was attributed to the development of tensile strength of concrete containing cassava flour, as found in the study by Oluwabusayo ONI et al., 2020 [60], Kone et al., 2022 [62], and Adedokun, 2022 [88]. The same conclusions were achieved by O. Thomas et al., 2017 [89]. As demonstrated in Eq. (9), Fig. 14 shows a basic correlation between the compression and tension strengths of the experimental cassava flour concrete, with a determination coefficient ($R^2 = 0.98$), providing strong support for this relationship. According to study done by Ref. [90], the tensile force might be in the range of ts = 0.0855 Cs-0.7482 [91] According to the statement, the tension strength of cassava flour concrete is greater than the normal strength of concrete when the compression resistance in excess of 25 MPa [92].

$$ts = 0.0513\ Cs - 1.2269 \tag{9}$$

Where;

ts = tensile force.

4.6. *Flexural strength*

Fig. 15 shows the results of the three-point bending test that was done on the unreinforced concrete beam of size 100 × 100 × 350 mm after 90 days of curing to measure the flexural strength. Knew that the beams would crunch due to the cracks in the flexural zone, and the concrete would be separated in the compression zone between the loading points Arora et al., 2016 [93]. Concrete containing cassava flour as an additive follows the same pattern for compressive, splitting, and flexural strengths. The results show that the mix that contained 3% cassava had a stronger flexural resistance of 12.153% over the mixture that served as the control, due to the aptitude of cassava flour to enhance the characteristics of hardened and fresh concrete. This is because cassava flour enhances flexural strength by preventing the creation of microcracks in the phase between the aggregate and cement paste. Similarly, a study conducted by Kone, Ronoh, and Mwero, 2022 [62], Kamaruddin et al., 2022 [94], and Oluwole and Avwerosuoghene, 2015 [95]. The experimental cassava flour concrete exhibits a substantial correlation between its split tensile and flexural strengths (Fig. 16), providing strong evidence for this relationship.

4.7. *Sulfuric acid attack on cassava flour concrete*

After 28, 56, and 90 days of immersion, samples were taken out of the acid solution and dried, and using a wire brush, extra loose material was cleaned from the degraded surface. The variations in the bulk density and compression strength of the samples subjected to sulfuric acid were measured. A more obvious sign of degradation is the decrease in strength and density of the specimens, Chintalapudi and Pannem, 2022 [96]. The results show the samples submerged in sulfuric acid for 28, 56, and 90 days each lost 9.68%, 11.3%, and 12.8% of their compressive strengths compared to the control mix. This is because cassava flour can restrict the void space in hardened concrete, reducing the speed at which concrete is penetrated by water and other corrosive substances. Additionally, the retarding property of cassava flour prevents the development of mono-sulphate aluminates during cement hydration, making the concrete less resistant to acid attack, similarly noted by Oni et al., 2020 [6]. Negligible surface deterioration with increased cassava flour up to 3%, 4%, and 5% levels in Portland pozzolanic cement mortar is due to the high resistance to Portland cement bond loss in the presence of an acid attack, similarly found in studies researched by Abrao et al., 2020 (Abrão et al., 2020) and A. Khan et al., 2022 (A. Khan et al., 2022). Figs. 17 and 18 shows the effect of sulfuric acid on dry density and loss on compressive strength, respectively.

4.7.1. *ITZ thickness*

There are several ways to reduce the ITZ thickness in concrete. Using high-strength concrete with a low water-to-cement ratio is the most efficient approach. This makes the concrete less prone to cracking, which could result in a reduction in the ITZ thickness. Because the link between the cement paste and aggregate is strengthened due to the increasing cement fineness, more calcium silicate hydrate can be formed in ITZ, which can refine the pore structures and create a denser and more homogeneous microstructure of ITZ. The microstructure of hydrated cement paste next to aggregate particles is different from the microstructure of the cement paste matrix. The reason is that dry cement particles cannot get dense around reasonably large aggregate particles during the mixing process. Narrow ITZ thickness leads to increased mechanical strengths. The SEM images for each concrete mix containing cassava flour are displayed in Fig. 19(a–f) for analyzing the bond quality and morphology. The ITZ thickness is plotted in Fig. 20. The reduction of the ITZ thickness at all addition levels brought about by the addition of cassava flour to Portland pozzolanic cement mortar substantially confirmed the results for the compression, flexural, and tension strengths. Compared to the standard mix, the ratio of ITZ thickness that was reduced by 1, 2, 3, 4, and 5% cassava flour addition was approximately 22.5, 32.6, 100, 90.32, and 84.4%, respectively. Additionally, it should be noted that at 3% cassava flour addition, the gap between the aggregate and mortar was very small and the microstructure was extremely homogeneous (Fig. 21).

The size of microcracks in the ITZ area of analyzed concrete varies depending on the type of concrete and the conditions of its manufacture. Generally, microcracks in the ITZ area are small and not easily visible to the naked eye. The crack width of Portland pozzolanic cement concrete with cassava flour addition range from 3.5 to 2 μm. In general, the larger these microcracks are, the more damage they can cause to the concrete over time. For example, large microcracks can impact the durability and strength of the concrete, leading to early deterioration. Additionally, large microcracks can also lead to water seeping into the concrete, leading to further damage.

This result can be related to the pore refinement that produced a better microstructure at the interfacial transition zone. The strength of the ITZ is also related to the compression resistance of concrete. If the strength of the ITZ is higher, then the compressive strength of the concrete is also higher. Conversely, if the strength of the ITZ is lower, then the compressive strength of concrete is lower. The ITZ's porosity and strength are directly related to the compressive strength of concrete. Lower strengths in concrete are caused by a weak zone between cement paste and aggregate owing to its higher porosity. On the other hand, the connection between the aggregate and cement paste is stronger if the ITZ has a lower porosity, and the resulting concrete has a higher strength. Similarly, in the study by Gao et al., 2014 [97], A. Sadrmomtazi et al. [98], G. L. Golewski [99], and Hussein et al., 2014 [100] In situations of increasing curing age over 56–90 days, decreasing ITZ porosity was detected, and the ITZ thickness was slightly decreased. Influences of the water-to-cement ratio and aggregate content on the ITZ thickness were not taken into account. It was also observed by Okafor, 2010 [71] Adding a high volume of cassava flour to concrete improves workability by reducing the water demand by 8% and increasing the mechanical properties, this finding may help improve the ITZ microstructure in concrete mixtures containing cassava flour.

5. Conclusion

The study concentrated on performance, workability, strength, protection against an acid attack, and interfacial transition zone thickness. As the examples below show, some mixes worked well in some situations and not in others.

1 The combination of SEM and EDS parameters maximized the understanding of shape properties, morphological, and chemical compositions for cassava flour and Portland pozzolanic cement. The application of SEM and XRD analysis as presented here may help future research aimed at identifying the materials characteristics. SEM images demonstrate that cassava flour contains circular, fiber, uneven, and holes forms. Cassava flour's uneven particles made the paste more difficult to work with as the amount was increased, and the porosity raised the requirement for water.
2 The strongest results were achieved with the mixture containing 3% of concentrated cassava flour, which enhanced the microstructure of the concrete and set the minimum thickness of the transition zone.
3 The sulfuric acid attack caused the least deterioration in Mix 4 with a 3% cassava flour addition.
4 Rather than using ordinary Portland cement to make high-strength concrete, using Portland pozzolanic cement with cassava flour helps reduce the use of natural resources as little as possible, like limestone in the clinker process, harmful emissions, and concerns about global warming.
5 In concrete, cassava flour can be used as an additive material to reduce cost and dependence on chemical admixtures, especially in developing nations.
6 Since there is no previous research on this topic and this study is the first to talk about interfacial transition zone thickness by using cassava flour, more research needs to be done on ITZ microstructure of concrete.

Credit author statement

Marwa Gumma Omer Adam: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Writing – original draft, Visualization. David Otieno Koteng: Writing – Review & editing, Supervision. Joseph Ng'ang'a Thuo: Writing – Review & editing, Supervision. Mohammed Matallah: Writing – review & editing, Supervision.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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