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Technical Note

Flexural strength and cost performance of tuffcrete concrete

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Abstract

This study investigated the flexural strength of tuffcrete concrete in relation to nominal concrete. Tuffcrete concrete (TC) was made from Portland cement (PC), tuffcrete white powder (TWP), river sand, granite chippings, tuffcrete liquid polymer (TLP), and water. A prescribed mix of 1:2:2 (binder: sand: granite) with a diluted polymer-binder ratio of 0.6 was adopted. TWP replaced PC in percentages of 0%, 5%, 10%, 15%, 20%, and 30%. 10 liters of TLP were diluted in 200 liters of water to make the water for mixing the concrete. 12 concrete standard beams of size 100mm x 100mm x 400mm were generated and hardened in water at ambient temperature for 28 days before being laid open for flexural testing. A comparative cost analysis was also carried out on the TC with respect to regular concrete. The workability of the fresh TC was highly enhanced due to the addition of the TWP. A 69.57% increase in slump was obtained by replacing PC with just 5% TWP. Slump values kept on getting bigger as the percentage of TWP incorporation grew. However, the flexural strength of TC reduced as more and more TWP was added to the mix. Flexural strength results ranged from 9.38 N/mm^2 at 0% inclusion of TWP to 4.38 N/mm^2 at 30% introduction of TWP. The best substitution of PC with TWP was at 5% with a flexural strength value of 7.22 N/mm^2. Cost analysis revealed that the amount for making TC is greater than that of normal concrete, mainly due to the addition of the TLP, and this does not impact positively on the flexural strengths achieved. Nevertheless, PC replacement with TWP reduced the cost of binding material. In conclusion, the use of tuffcrete concrete based on flexural strength alone may be discouraged due to cost. But improved strength properties could still be achieved with better mix designs.

1. Introduction

Concrete, which is a universally accepted material used for construction purposes, is produced primarily by mixing Portland cement, sand, gravel, or granite chippings with water in prearranged quantities in order to reach preferred properties. The mixture is usually allowed to gain strength before it can adequately carry a load. The combination of the cement and water forms a paste that aids in bonding the aggregates in the mixture. The use of concrete for construction works in Nigeria is on the rise as more developmental facilities are put up to meet the pressing basic needs of an increasing population.

However, the continuous collapse of these concrete structures is becoming very worrisome. Between October 1974 and November 2022, Nigeria documented about 541 building collapse incidences, and 61 of these happened in 2022 [1]. According to [2], an extraordinary degree of collapse occurred in 2014, while the greatest number of deaths recorded was in 2016 under the review period. The outcomes of these building collapses are seen in the loss of money invested and lives, the wastage of materials, the contractor's influence being badly affected, higher maintenance costs, the deterrent beauty of the building, and the bad reputation of the owners [3].

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In summary, the major cause of building and structural collapses in Nigeria is corrupt practices in the construction industry. This is seen in the use of non-professionals in construction work, the use of sub-standard materials, shoddy work, and the non-compliance and enforcement of building code specifications by clients, contractors, and regulatory bodies for selfish reasons. [4]. Therefore, in order to alleviate the frequent occurrence of collapse of concrete structures, new materials with enhanced load-bearing and weathering properties are being investigated. This study seeks to investigate the flexural strength performance of Tuffcrete concrete since this type of concrete is gaining more and more popularity as an alternative to nominal concrete in Nigeria and is mostly applied in concrete pavement construction [5].

Tuffcrete concrete is a mixture of PC, Axion TWP, Axion TLP, water, rivers sand and crushed granite. The Axion tuffcrete white powder and liquid polymer are products of Axion Global Engineering Limited which is a subsidiary of Axion Canada. Their use in concreting is believed to have a lot of advantages over the use of conventional concrete. In 2022, approval was given by the Nigerian Federal Capital Development Authority (FDCA) for the employment of the Canadian-made Axion tuffcrete lightweight concrete system in the development of feasible building projects in Abuja [6]. The body also gave instructions to ministries responsible for road construction in the country to partner with research and tertiary institutions towards the application of research data in line with the use of tuffcrete in concrete making.

According to [7], the use of tuffcrete concrete in pavement construction is expected to improve the waterproofing effect of the pavement, reduce its rate of contraction and expansion, and enable the pavement to attain more load-bearing capacity than nominal concrete, depending on the mix design. This will make the road pavement last longer and live out its intended useful life without failing. In addition, tuffcrete concrete is expected to eliminate the use of damp-proof courses in foundation construction, is good for repairing damaged and old concrete, and results in a lighter-weight concrete than normal concrete. [6] stated that the product saves time and money and can reduce material and labor costs by 4%.

The rise in the use of these products for concrete production, especially in the construction of pavements, has necessitated the need to study the concrete material. However, it was observed from the literature review that very few scientific investigations on this product have been published online, making it very difficult to access information on previous related studies. So, the present study is intended to fill this knowledge gap.

The flexural strength of concrete is its capacity to withstand collapse via bending. This mechanical strength is the basis for the design of concrete roads. According to [8], the design of concrete pavement is done with a 4.5 MPa flexural strength at 28 days, based on third-point loading. Thus, the use of Tuffcrete concrete in the construction of Nigeran roads has made it very important to study the flexural strength property of the material. This will enable concrete designers to know how well the concrete is performing under flexure.

As earlier noted, not many researchers have published online materials on the use of Tuffcrete concrete in construction work. Nevertheless, only a very few published articles on TC were accessed via the internet. Some unpublished materials were also accessed from the Port-Harcourt warehouse of the Axion company in Rivers State, Nigeria. [9], in their study on the strength of steel-fibro tuffcrete element, observed a flexural strength range of 9MPa to 14MPa for tuffcrete concrete. These values expanded by 37% when the concrete was tested with the fibers, reinforcing rods and form work in place. [10], considered the inclusion of volcanic tuff as a substitute for Portland cement and tuff sand in mortar production, and recorded the best 28-day flexural strength result of 12.5 MPa at 50% replacement of Portland cement. At 28 days, strength readings of 5.7 MPa, 3.7 MPa, and 2.3 MPa were obtained with 25%, 75%, and 100% inclusions, respectively.

[11] worked with the addition of lava tuffs to implement concrete behavior. In concrete production, they replaced Portland pozzolan cement with 0%, 5%, 10%, 15% and 20% volcanic tuff and reported that the flexural strength of the concrete decreased as the percentage of the tuff increased. The maximum flexural strength of about 3.1MPa was established at 0% and, with 20% inclusion, a minimum flexural strength of 1.3MPa was obtained. As more volcanic tuff is added to the concrete mixture, it has been demonstrated that the amount of cement will decrease and thus hamper the hydration process leading to reduction in the generation of the strength gaining compounds such as C_2S and C_3S. [11] also observed that as the percentage of substitutable value was increasing, the slump of the concrete began to decrease. This was due to the high porous nature of volcanic tuff that make it able to suck up mixing water from the concrete.

[12] reported that a common problem for polymer-cement mixtures is that their compressive strength is generally modest because of a lack of joint bonding between two dissimilar phases in the concrete structure. However, the concrete showed improvements in all areas of performance. Studies by [13] showed that the durability and adhesion strength of cementitious materials are enhanced by including a very low amount of water-soluble polymer, thereby enabling them to be used as repair materials. An increase in workability as a result of polymer plasticizing and the effect of air entrainment was observed. It was noted that, compared to conventional concrete, a greater retention of water had been observed which led to more flowing mortar. This was effective in reducing the mortar's bleeding and, therefore, increasing concrete homogeneity by regulating segregation of new mixes. However, due to the increased entrained air, the mechanical properties of the concrete have been reduced.

2. Materials and Methods

The materials and methods adopted in this study are discussed as follows:

2.1. Materials

The following materials were used for producing the tuffcrete concrete: Portland cement (PC), tuffcrete white powder (TWP), river sand, granite chippings, tuffcrete liquid polymer (TLP), and water. The 42.5N grade of Dangote 3X brand portland cement was used. It meets the requirements of the specification for cement [14]. Axion tuffcrete white powder and liquid polymer were purchased from the Axion Chemical warehouse located along Aba Express-way, Iriebe, Port-Harcourt, Rivers State Nigeria. According to [15], the TWP is a product marketed under and protected by a registered trade name. It acts as a molecular binding agent which meets the specifications of chemical resistance and durability. The TLP plays the role of a molecular activator that provides high resistance to aggressive liquids and chemicals in concrete. It is a water-soluble polymer. The chemical and physical property test results for the TWP and TLP are presented in Table 3 and Table 4.

At the Choba campus of the University of Port Harcourt, water (free of dirt and organic matter) was obtained. From a construction site on the university's campus, river sand was purchased. Granite-crushed rocks with nominal sizes of 19mm were used as coarse aggregate. The sieve analysis tests on the aggregate, according to [16], displayed that aggregates were uniformly graded accordingly.

2.1.1 Mix proportioning

Standard concrete beams of 100mm x 100mm x 400mm were prepared according to [17] and cured in water for 28 days, as illustrated in Figure 1 and Figure 2 accordingly. A prescribed mix of 1:2:2 (binder: sand: granite) at a 0.6 diluted polymer/cement ratio was investigated. Water for mixing concrete was prepared by diluting 10 liters of polymer in 200 liters of water. Portland cement was replaced by tuffcrete white powder in percentages of 0%, 5%, 10%, 15%, 20%, and 30%, respectively. Two specimens were made for each mix ratio, leading to a total of 12 concrete beams. The mix proportions of the tuffcrete concrete are shown in Table 1.

Table 1. Concrete mix proportion of tuffcrete concrete

Mix proportions of concrete						Mix proportioning by weight of one concrete beam of size 100mmx100mmx400mm (kg/m³)					
Mix No.	PC	TWP	Sand	Granite	Dil. poly-cement ratio	PC	TWP	Sand	Granite	Water	Liquid polymer
F1	1	0	2	2		480	0	960	960	288	14.4
F2	0.95	0.05	2	2		456	24	960	960	288	14.4
F3	0.90	0.10	2	2	0.60	432	48	960	960	288	14.4
F4	0.85	0.15	2	2		408	72	960	960	288	14.4
F5	0.80	0.20	2	2		384	96	960	960	288	14.4
F6	0.70	0.30	2	2		336	144	960	960	288	14.4

Fig. 1 Concrete beams

Fig. 2 Curing of beams by total immersion in water

2.2 Methods

Methods applied in the study of tuffcrete concrete include chemical and physical property tests on the TWP and TLP, slump tests of fresh concrete, flexural strength tests on hardened concrete, and a cost analysis of the use of tuffcrete in concrete production.

2.2.1 Physical and chemical Property Tests on the TWP and TLP

The chemical composition of the TWP and TLP was obtained in accordance with [18] using the X-Ray Fluorescence (XRF) method. Results obtained are shown in Tables 3 and 4. The physical properties of the materials were also measured, and the values determined are presented in the same tables.

2.2.2 Slump Test

The workability of the fresh concrete paste was accessed using the slump test in accordance with [19], as depicted in Figure 3. The values obtained are presented in Figure 5.

Fig. 3 Slump test on fresh concrete

2.2.3 Flexural Strength Test

The flexural strength of the hardened concrete was ascertained by testing the specimen under flexure using a universal testing machine in accordance with [20]. The equation (1) was used to calculate the flexural strength of the concrete. While, Figure 4 shows the experimental procedure carried out in the laboratory.

$$\text{Flexural strength } (N/mm^2) = 3PL/2bd^2 \qquad (1)$$

Where, P is the fracture load (N); b is the average specimen width at fracture (mm); D is the average specimen depth at fracture (mm).

Fig. 4 Flexural strength test of concrete beam

2.2.3 Cost Analysis of Producing TC

Costing to determine and compare the total amount of money for producing a cubic meter of tuffcrete concrete beam as well as conventional concrete was done. Table 2 shows the current values of the constituents of tuffcrete concrete that were used in carrying out the analysis. The results of this analysis are given in Table 5.

3. Results and Discussions

3.1 Chemical and Physical Properties of TWP and TLP

The results of the chemical and physical property test conducted on TWP and TLP are depicted in Table 3 and Table 4 as follows:

Table 2. Current market prices of Tuffcrete concrete components

S/No.	Constituents	Market procurement pattern	Unit cost (₦ per Kg)
1.	Cement	₦4,500 per 50kg bag	90.00
2.	Granite	₦420,000 per 30ton (30,000kg)	14.00
3.	Sand	₦43,000 per 30ton (30,000kg)	1.43
4.	Water	₦3,500 per 1000kg	3.50
5.	Tuffcrete white powder	₦2,500 per 50kg	50.00
6.	Tuffcrete liquid polymer	₦25,000 per 10kg	2500

Table 3. Chemical property test for TWP and TLP

S/N	OXIDES	TWP (%)	TLP (%)
1.	CaO	4.83	1.58
2.	SiO_2	68.24	0.73
3.	AL_2O_3	5.37	2.69
4.	Fe_2O_3	3.74	0.31
5.	MgO	2.60	0.84
6.	Na_2O	0.23	0.03
7.	K_2O	3.69	0.29
8.	SO_3	0.72	0.17
9.	TiO_2	0.42	0.02
10.	ZnO	0.08	1.34

Table 4. Physical property test for TWP and TLP

S/N	Properties	TWP	TLP
1.	Bulk density	10. 28KN/m^3	1.088g/ml
2.	pH	7.98	5.78
3.	Color	White	Black
4.	Electrical conductivity	-	136.6μS/cm
5.	Porosity	68%	-
6.	Particle size	43.2μm	-
7.	WHC	55.76%	

The combination of the oxides of aluminum, iron, and silicon gave a total percentage of 77.35%. This exceeded the specification given by [21] that states that the summation of these three oxides in a binding material for concrete production must not be less than 70%. AL_2O_3 was at 5.37%, SiO_2 at 68.24%, and Fe_2O_3 at 3.74%.

3.2 Slump

Fig. 5 reveals that the replacement of PC with TWP improved the workability of the fresh concrete. A drastic rise in this property of the concrete was observed from 0% to 5% replacement. Slump values rose from 5.09mm to 40.5mm at these points accordingly. Values kept increasing steadily from 5% up till 30% substitution. Slump value at 30% inclusion was 80.5mm. Therefore, a percentage increase in slump of 1481.53% was observed between 0% to 30% TWP addition. Due to the high porosity of the TWP (68%), it is expected that the workability of the concrete should reduce as the content of TWP increased. This is because, there are much voids that could assimilate mixing water from the fresh concrete. But this was not the case. According to [9], the use of water-soluble polymer in concrete making creates an air entrainment and plasticizing effect in the concrete leading to more water being retained in the mix. This makes concrete to be more flowable.

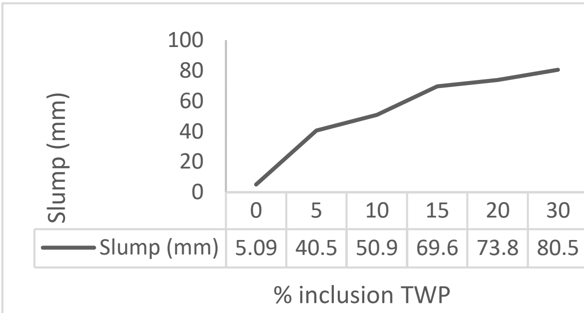

Fig. 5 Slump (mm) vs. % inclusion of TW

3.3. Flexural Strength

Fig. 6 shows the behavior of the flexural strength of the TC as the content of TWP increased. A boost in the amount of TWP lowered the flexural strength of the concrete. Nominal concrete had the largest value at 9.38 N/mm^2. This dropped to 7.22 N/mm^2 at 5% replacement, which was quite a significant drop. A very slight reduction in strength was observed between 5% and 10% as the flexural strength value dropped further to 7.20 N/mm^2. At 15% substitution, a remarkable reduction in strength was seen as values reduced further to 5.84 N/mm^2. Steady lessening of strength continued up to 30% replacement. Strength at this point was 4.38 N/mm^2. An optimal percentage replacement of 5% was achieved in the study, leading to a percentage strength reduction of 23.03% at that point.

The decrease in strength as more TWP was added into the concrete mix is due to the fact that lesser quantities of the strength giving compounds (i.e., the tricalcium silicate and the dicalcium silicate) were produced. This occurred because the addition of TWP in the cement slowed down the process of cement hydration that forms these compounds. As earlier observed, the inclusion of the TWP improved the workability of the fresh concrete due to polymer plasticization and air entrainment [13]. But, as the workability improved, the flexural strength of the concrete decreased.

3.4 Cost Analysis of Tuffcrete Concrete to Conventional Concrete

Table 5 illustrates the cost of each item for making concrete in Nigerian naira (₦) per cubic meter. Considering Table 5, the cost of producing a cubic meter of tuffcrete concrete increased far more than that of conventional concrete for all percentage replacements studied. A sudden increase in cost of production of 59.4% was witnessed between 0% and 5% incorporation. However, this rise was a result of the addition of TLP to the mixture and not due to the replacement of PC with TWP. In fact, the replacement of PC with TWP led to a gradual and overall cost reduction of about 9.76% from 0% to 30% replacement when the cost of TLP was excluded from the analysis, as presented in Figure 8. This means that the main source of the high cost of tuffcrete concrete production when compared to nominal concrete is the incorporation of the TLP in the mixture. As the amount of TWP substitution increased above 5%, the cost of producing TC began to drop gradually as shown in Figure 7.

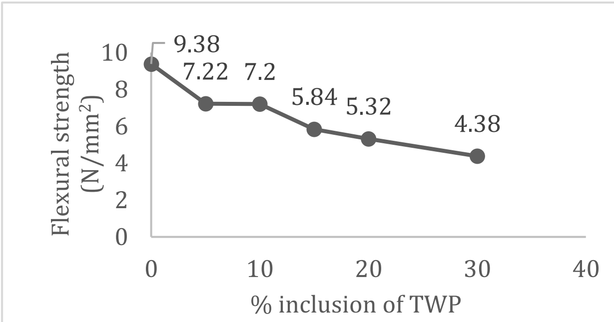

Fig. 6 Relationship between flexural strength (N/mm^2) and % inclusion of TWP

Table 5. Cost of concrete constituent materials

S/ No	% repl.	Cement	Granite	Sand	Water	TWP	TLP	Total cost of TC	Total cost of TC- cost of TLP	% Diff. of cost
1	0	43,200	13,440	1,372.80	1008	0	0	59,021	59,021	0
2	5	41,040	13,440	1,372.80	1008	1200	36000	94,061	58,061	38
3	10	38,880	13,440	1,372.80	1008	2400	36000	93,101	57,101	39
4	15	36,720	13,440	1,372.80	1008	3600	36000	92,141	56,141	39
5	20	34,560	13,440	1,372.80	1008	4800	36000	91,181	55,181	39
6	30	30,240	13,440	1,372.80	1008	7200	36000	89,261	53,261	40
									Average =	39

4. Conclusions

In this work, the flexural strength of tuffcrete concrete and its cost implications were investigated compared to conventional concrete. A specified mix ratio of 1:2:2 (binder:sand:granite chipping) at a 0.6 diluted polymer/cement ratio was studied. The binders, which were PC and TWP, were combined in such a way that they replaced PC with 0% to 30% of TWP one after the other. This study revealed that this substitution greatly improved the workability of the fresh concrete, making the concrete a very flowable one that can be finished very smoothly. The concrete produced can be classified as having medium workability and is suitable for normal reinforced concrete works with manual compaction, and heavy reinforced concrete works with vibration as the mode of compaction. Since the TWP content has a great impact on the workability of the concrete, the mix design of tuffcrete concrete should be done considering that the water-cement ratio must be minimal. This is expected to improve the strength of the concrete. Although, the effect of the TLP in the concrete was not specifically studied in this work, the presence of polymers in fresh concrete have been proven to improve workability as a result of the entrainment of air and plasticization of the concrete. This may have been one of the reasons why the fluidity of the concrete was greatly improved.

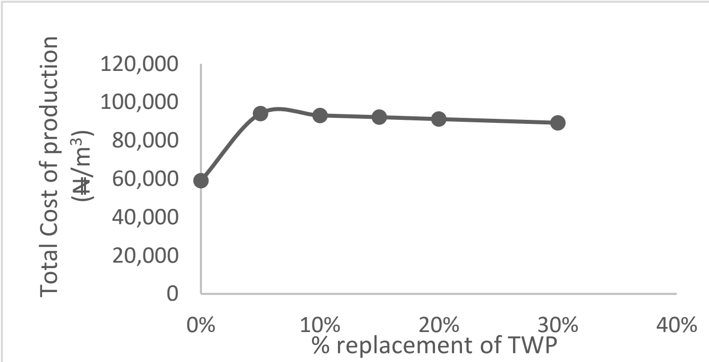

Fig. 7 Relationship between total cost of production vs. % replacement

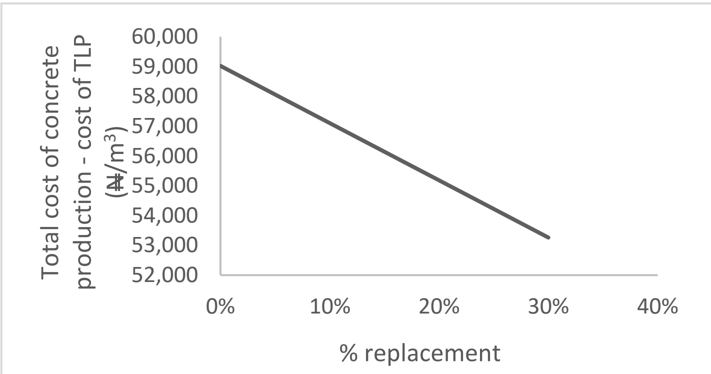

Fig. 8 Relationship between total cost of concrete production less cost of TLP (₦) vs. % replacement

Introduction of the TWP into the concrete mix lessened the flexural strength of the concrete. 0% inclusion of TWP gave the greatest flexural strength result, while 5% addition of TWP was seen as the best percentage insertion for the attainment of the finest strength of 7.22N/mm^2. 30% replacement generated a strength value of 4.38N/mm^2. There was no significant drop in strength between 5% and 10% replacements. The drop in strength could be attributed to the decrease in the content of cement in the concrete, effect of air entrainment, and plasticizing of the polymer within the cement matrix. However, strength is expected to increase at older age.

The cost of producing tuffcrete concrete was way higher than that of nominal concrete by reason of the insertion of TLP into the mix. The addition of TWP resulted in cost savings with regards to cement consumption. But this advantage was overtaken by the increased cost of the TLP. A 59.4% increase in cost was observed between 0% and 5%. However, after the 5% substitution, the cost kept decreasing slightly. At intervals of 5% and 10%, the cost dropped by 1.02%. Between 5% and 15%, a cost reduction of 2.04% was obtained. Between 5% and 20%, the cost was reduced by 3.1%, and a drop of 5.10% was observed between 5% and 30%.

A future examination of the effect of TLP in the concrete should be carried out so as to ascertain its advantage in the production of the tuffcrete concrete. There is also a need to study the microstructure of tuffcrete concrete in order to gain a better understanding of its makeup. This will enable the mix designer to understand the parameters to improve upon so as to have a very strong and durable concrete with properties that counter the higher cost of its production over that of conventional concrete.

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