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Strength Characteristics of Concrete with Waste Polypropylene as Modifier for Pavement Construction

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ABSTRACT

The demand for a better performing pavement and the need to convert the ever-growing polymer waste into beneficial use necessitated the need to develop and characterize a polypropylene modified concrete for use in pavement construction. This research focuses on characterizing the strength of concrete produced with waste polypropylene waste as modifiers for pavement construction. The materials used in this research are fine and coarse aggregates, cement and polypropylene waste chairs (PWC). Tests were performed on the aggregate and fresh concrete to determine their suitability and characteristics for use in concrete for pavement. Two concrete grades 1:2:4 and 1:3:6 was produced into 200 mm, 400 mm and 500 mm long paving stones on which compressive and flexural tests were performed. Results obtained showed that 400 mm 1:2:4 grade concrete has the highest compressive strength of 27.36 N/mm^2 at 10% polypropylene composition. The 200 mm 1:2:4 concrete grade paving stone with 10% polyprpopylene composition has the highest flexural strength of 12.90 N/mm^2. The 200 mm at 10% polypropylene composition correlation coefficient has that the highest value of 0.98 which better explains the compression-flexural strength relationship and validates the 200 mm length at 10% polypropylene composition paving stone as the most adequate length of paving stone for pavement construction. It was concluded that the 200 mm long 1:2:4 concrete grade paving stone at 10% polypropylene composition is the best length of paving stone that can give an adequate flexural strength which is the most important requirent in concrete pavement requirement.

Keywords: Waste Polypropylene, Concrete, Compressive Strength, Flexural Strength, Paving Stones, Pavement

INTRODUCTION

One of the solid wastes generated in large quantities and being of a high threat to the sustainability of our planet is plastic wastes. It has been reported that damage occurs to ecology, economy, and aesthetics when plastic debris enters into oceans (Jambeck, et al., 2018). Singh and Sharma (2016) confirmed that about 300 million metric tons of plastic wastes have been estimated to be generated annually worldwide. A report by the Environmental Protection Agency (EPA, 2015) has shown that out of several tons of plastic wastes generated annually, only 7% is recycled, about 8% incinerated and the remaining are landfilled. Lazarevic et al. (2010) postulated that the low biodegradability of plastic poses a huge limitation on its recyclability and disposal into the environment. Furthermore, the prospects and retrospects of the use of plastic in flexible pavements was studied by Bhardwaj et al. (2020) and Saberian et al. (2021) conducted a resrach on repurposing of COVID-19 single-use face masks for pavements base/subbase. The study revealed that introduction of the shredded face mask not only increased the strength and stiffness but also improved the ductility and flexibility of recycled concrete aggregate and shredded face mask blends.

In recent years, studies have focused concrete production with waste glass, recycled crushed glass, steel slag, steel fiber, tyres and plastics eliminate plastic's disposal problems and develop the mechanical features of concrete (Shah and Pitroda, 2013). However, due to the lack of superior strength and durability in conventional concrete pavement, material engineering has focused on its physical, structural and mechanical features development. Also, considering the concrete pavement's voids and porosity (Ramadhansyah et al., 2014), obtaining great strength through ordinary materials and their mixtures is almost impossible. Consequently, adding materials such as admixture and superplasticizer cement or aggregates replacements besides few waste materials and Nano-materials have been applied to increase the

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properties of concrete used in pavement (Huang et al., 2007). Therefore, finding applications where plastic wastes are useful will proffer a sustainable way to its management.

MATERIALS AND METHODS

Materials

The materials used for this research work were of high quality and were carefully selected and sourced locally in Akure, Nigeria to meet standard requirements. The materials are:

i. Fine aggregates: Fine aggregates are natural sand or crushed stone that are less than 5 mm in diameter. The fine aggregate is crushed grave, rock sand blended sand and fines which mainly passes through a 5.0 mm BS 410 sieve and containing no more coarser material than is permitted for the various gradings in the specifications for aggregates from natural sources for concrete (BS EN 12620:2002+A1:2008).

ii. Coarse aggregates: Coarse aggregates are naturally occurring uncrushed, crushed or partially crushed gravel that are less than 5 mm in diameter. The coarse aggregate is mainly retained on a 5.0 mm BS 410 sieve and containing no more finer material than is permitted for the various sizes in the specifications for aggregates s for concrete (BS EN 12620:2002+A1:2008).

iii. Ordinary Portland Cement: Cement is a hydraulic binder, it is a finely ground inorganic material which when mixed with water, forms a paste which sets and harden by means of hydration reactions and processes and which, after hardening, retains its strength and stability even under water according to composition, specification and conformity criteria for common cement (BS EN 197-1: 2011).

iv. Waste Polypropylene chair: The waste polypropylene chair or waste polyprop is a waste of a chair manufactured in an injection moulding process using polypropylene, it is a plastic polymer of the chemical designation C_3H_6.

Sample preparation

Polypropylene based plastic waste chair was pulverized with ball milling machine, it was then sieved with a 0.075 µmm sieve, this was used as an additive in concrete in this research work. Paving stones of varying lengths of 200 mm, 400 mm and 500 mm were produced with polypropylene wastes chair (PWC) added in varying proportion of 2%, 4%, 6%, 8% and 10% by weight. The paving stones were produced using 1:2:4 and 1:3:6 concrete mix ratios, for each percentage replacement and concrete grades, three samples were produced to test for flexural and compressive tests. The paving stones were cured for 7, 14, 21 and 28 days before they were tested for compression and flexure. Table 1 contains the mix ratios, percentage polypropylene waste chair content, mix ratios, number of curing days and the total number of paving stones produced for flexural and compressive tests. A total of 720 paving stones were produced.

Table 1. PWC Composition, paving stone (PS) sizes, concrete grades and number of PS produced

PWC (%)/ Days	Paving Stone Sizes	1:2:4				1:3:6				
		7	14	21	28	7	14	21	28	Total
2	200 x 100 x 100	6	6	6	6	6	6	6	6	240
4		6	6	6	6	6	6	6	6	
6		6	6	6	6	6	6	6	6	
8		6	6	6	6	6	6	6	6	
10		6	6	6	6	6	6	6	6	
2	400 x 100 x 100	6	6	6	6	6	6	6	6	240
4		6	6	6	6	6	6	6	6	
6		6	6	6	6	6	6	6	6	
8		6	6	6	6	6	6	6	6	
10		6	6	6	6	6	6	6	6	
2	500 x 100 x 100	6	6	6	6	6	6	6	6	240
4		6	6	6	6	6	6	6	6	
6		6	6	6	6	6	6	6	6	
8		6	6	6	6	6	6	6	6	
10		6	6	6	6	6	6	6	6	

Method

Physical properties. The physical properties of aggregates used in this research work were determined and confirmed suitable for production of concrete for paving stones by carrying out the following tests:

i. Aggregate Impact Value test (BS EN 1097-2:2020)
ii. Aggregate Crushing Value test (BS EN 1097-2:2020)
iii. Moisture content Test (BS 812-109:1990)
iv. Particle size distribution test (BS ISO 11277:2020)

Properties of fresh concrete. The properties of fresh concrete produced for casting of the paving stone were investigated by conducting the following tests:

i. Slump test (BS EN 12350-2:2019)
ii. Compacting factor test (BS EN 12350-4:2019)

The strength properties of hardened concrete were investigated by performing the following tests:

i. Compressive test (BS EN 12390-3:2019)
ii. Flexural test (BS EN 12390-5:2019)

RESULT AND DISCUSSION

Aggregate crushing value (ACV)

The result of aggregate crushing value (ACV) test carried out on the coarse aggregate used in this research work is presented in Table 2, it can be seen that the average ACV value obtained is 27.71%. This indicates that shows that aggregates are strong enough to withstand crushing due to rolling and traffic loads.

Aggregate impact value (AIV)

The result of aggregate impact value (AIV) test carried out on the coarse aggregate to determine its toughness is presented in Table 3. It can be seen that the average AIV value obtained is 20.24% which is a good measure of toughness and resistance against any impact load.

Particle size distribution

This test was performed to determine the particle grading of the fine aggregates used in this research. Figure 1 shows the plot of the particle grading curve of the fine aggregated used. From the result, it can be the seen that the soil is well graded.

Moisture content

The moisture content test result performed on the fine aggregate in Table 4 showed that the average moisture is 2.75% which is within the tolerable maximum limit of 5%.

Slump test

The result of slump test conducted on the 1:2:4 and 1:3:6 concrete grades with 0–10% polypropylene composition to determine their consistencies are presented in Table 5. The slump values obtained as shown in Table 4, the slump values are less than 100 mm maximum slump values required for concrete for road pavements.

Table 2. Aggregate crushing value (ACV) of coarse aggregate

	Sample 1	Sample 2	Sample 3
Weight of sample before Test (kg)	536.30	541.30	529.20
Weight of sample after Test (kg)	145.30	152.30	147.70
ACV (%)	27.09	28.14	27.91
Average ACV (%)		27.71	

Table 3. Aggregate impact value (ACV) of coarse aggregate

	Sample 1	Sample 2	Sample 3
Weight of sample before Test (kg)	437.20	425.00	440.30
Weight of sample after Test (kg)	85.20	87.30	91.10
ACV (%)	19.49	20.54	20.69
Average ACV (%)		20.24	

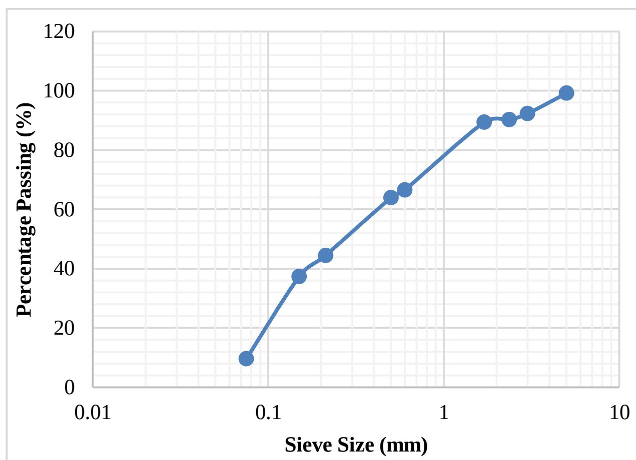

Figure 1. Particle grading of fine aggregate curve

Table 4. Moisture content of fine aggregate

	Sample 1	Sample 2	Sample 3
Wt of Can	4.80	4.80	4.80
Wt of Can + Wet Sample (g)	57.30	63.30	55.20
Wt of Wet Sample (g)	52.50	58.50	50.40
Wt of Can + Dry Sample (g)	56.80	63.10	54.80
Wt of Dry Sample (g)	52.00	58.30	49.30
Moisture Content (%)	0.96	0.34	0.80
Average Moisture Content (%)		0.70	

The average moisture content of 0.70% is very small, therefore water has no effect on the quality of the concrete produced.

Table 5. Slump values of concrete grades 1:2:4 and 1:3:6

Polypropylene Composition (%)	1:2:4 Concrete Grade	1:3:6 Concrete Grade
	Slump (mm)	Slump (mm)
0	19.00	65.00
2	18.50	70.00
4	16.00	70.00
6	15.50	72.00
8	14.00	75.00
10	9.50	75.00

The slump values obtained are less than 50 mm maximum slump values required for concrete for road pavements.

Compacting factor test

The result of compacting factor test conducted on the 1:2:4 and 1:3:6 concrete grades with 0–10% poly propylene composition to determine their workability are presented in Table 6. The compacting factors obtained indicated that they are all more than 0.95 which is the minimum requirement for a good compacting factor.

Compressive strength for 1:2:4 paving stone

Concrete road pavements are usually specified and designed using the characteristic compressive strength at 28 days. This refers to the strength value which 95% of samples will exceed after 28 days curing in laboratory conditions. The compressive strength is not important for road pavement design, but is used as a proxy for flexural strength. For this reason, characteristic 28-day compressive strength of the concrete is used along with a defined relationship between compressive strength and flexural strength for this particular concrete mix. The compressive strength for 200 mm, 400 mm and 500 mm paving stone with concrete grade 1:2:4 is presented in Tables 7 - 9.

The result showed an increasing trend in the compressive strengths of the paving stones from 7 days to 28 days for all the percentage compositions. 10% polypropylene composition has 26.03 N/mm^2 which is the highest at 28 days. Compressive strength requirements for paving concrete are generally specified at 20.7 MPa (3,000 psi) at 28 days in BS EN 1338:2013. The repair concrete should develop an equal or greater strength by the time it receives traffic loadings. The result showed an increasing trend in the compressive strengths of the paving stones from 7 days to 28 days for all the percentage compositions. 10% polypropylene composition has 26.03 N/mm^2 which is the highest at 28 days. The result meets the requirement on the strength to be attained at 28 days before a concrete pavement is opened to traffic.

The highest compressive strength for 400 mm paving stone is 27.36 N/mm^2 obtained in 28 days at 10% polypropylene composition; this value meets the compressive strength requirement for concrete pavement at 28 days. Furthermore, the 500 mm 1:2:4 paving stone has its compressive strength increasing with increase in the age of the concrete as presented in Table 3. The highest compressive strength of 26.27 N/mm^2 for 500 mm 1:2:4 concrete was obtained after 28 days of curing. The result meets the minimum requirement of 20 N/mm^2 for concrete pavement.

Compressive strength for 1:3:6 paving stone

The 28 days compressive strength for 200 mm, 400 mm and 500 mm paving stone with concrete grade 1:3:6 is presented in Table 10. The compressive strength of 200 mm, 400 mm and 600 mm 1:3:6 concrete presented in Table 4 showed that none of length of the paving stones meets minimum requirement of 20 N/mm^2 for 28 days to open the concrete pavement for traffic.

Flexural strength of paving stones

The flexural strength also known as the modulus of rupture is a measure of the tensile strength of concrete. It is a measure of an unreinforced concrete beam or slab to resist failure in bending. Concrete pavements are currently designed using a mean 28-day flexural strength of 4.5 N/mm^2 (650 psi) based on the third point loading and a flexural strength of 4.1 N/mm^2 (600 psi) is required to open pavement to traffic prior to 14 days after placement according to the concrete paving blocks requirements and test method (BS EN 1338:2003). – 21). The 14 days flexural strength test result of 200 mm, 400 mm and 500 mm long 1:3:6 paving stones with varying polypropylene composition used in this research is presented in Table 11.

It can be seen from the result that the 14 days flexural strength criteria of 4.1 N/mm^2 (600 psi) required to open pavement to traffic is met by all the paving stone lengths from 0 to 10% polypropylene composition; the highest flexural strength of 7.50 N/mm^2 was obtained after 14 days at 10% polypropylene composition for 200 mm length. The 28 days flexural strength test result of 200 mm, 400 mm and 500 mm long 1:3:6 paving stones with varying polypropylene composition used in this research is presented in Table 12.

The result showed that the 200 mm long paving stone with 10% polyprpopylene composition has the highest flexural strength of 12.90 N/mm^2 which meets the flexural strength design critreria of mean 28-day flexural strength of 4.5 N/mm^2. Other percentage compositions and lengths of 200 mm, 400 mm and 600 mm also meet the criteria.

Table 6. Compacting factor of concrete grades 1:2:4 and 1:3:6

Polypropylene Composition (%)	1:2:4 Concrete Grade			1:3:6 Concrete Grade		
	Full	**Part**	**Compacting Factor**	**Full**	**Part**	**Compacting Factor**
0	18.0	17.60	0.98	17.80	17.50	0.98
2	17.70	17.10	0.97	18.10	17.80	0.98
4	18.20	17.00	0.93	17.80	17.30	0.97
6	18.20	17.10	0.94	17.90	17.20	0.96
8	18.30	17.50	0.96	18.00	17.60	0.97
10	18.30	17.80	0.97	17.90	17.20	0.96

Table 7. Compressive strength for 200 mm paving stone

Polypropylene Composition (%)	Compressive Strengths (N/mm^2)			
	7 days	**14 Days**	**21 Days**	**28 Days**
10	9.87	12.50	16.13	26.03
8	9.30	12.43	14.90	25.80
6	9.30	11.40	13.30	24.87
4	8.37	11.50	13.57	24.45
2	7.97	11.43	13.00	24.25
0	7.23	11.27	12.70	24.02

Table 8. Compressive strength for 400 mm 1:2:4 paving stone

Polypropylene Composition (%)	Compressive Strengths (N/mm^2)			
	7 days	**14 Days**	**21 Days**	**28 Days**
10	10.53	14.50	17.37	27.36
8	10.03	14.49	16.97	26.23
6	9.27	14.08	15.77	25.76
4	9.23	13.78	15.13	25.26
2	8.80	13.70	14.87	25.20
0	8.27	13.52	14.70	24.60

Table 9. Compressive strength for 500 mm 1:2:4 paving stone

Polypropylene Composition (%)	Compressive Strengths (N/mm^2)			
	7 days	**14 Days**	**21 Days**	**28 Days**
10	10.93	15.02	18.00	26.27
8	9.30	14.87	17.83	25.27
6	8.63	14.68	17.23	24.39
4	8.37	14.61	17.10	24.33
2	8.17	14.54	16.00	24.30
0	7.97	14.51	15.33	24.01

Table 10. Compressive strength for 200 mm, 400 mm and 500 mm 1:3:6 paving stone

Polypropylene Composition (%)	Compressive Strengths at 28 days (N/mm^2)		
	200 mm	**400 mm**	**500 mm**
10	17.70	17.10	16.77
8	17.16	16.23	16.33
6	16.87	15.70	15.17
4	15.87	14.70	14.77
2	15.10	14.23	14.43
0	14.77	13.73	14.03

Table 11. Flexural strength for 200 mm, 400 mm and 500 mm 1:3:6 paving stone

Polypropylene Composition (%)	Flexural Strengths at 14 days (N/mm^2)		
	200 mm	400 mm	500 mm
10	7.50	5.64	5.05
8	6.86	5.25	4.76
6	6.56	4.80	4.49
4	6.00	4.65	4.24
2	5.86	4.46	4.17
0	5.54	4.14	4.14

Table 12. Flexural strength for 200 mm, 400 mm and 500 mm 1:3:6 paving stone

Polypropylene Composition (%)	Flexural Strengths at 28 days (N/mm^2)		
	200 mm	400 mm	500 mm
10	12.90	9.60	8.10
8	12.90	9.43	7.37
6	11.57	9.13	6.80
4	10.93	8.97	6.30
2	10.67	8.33	5.23
0	10.03	7.93	4.83

Compression-flexural strength relationship

The comparison between the compressive Strengths and the rupture modulus (flexural strengths) of the 200 mm 1:2:4 concrete with different percentage polypropylene composition can be seen in Figure 2.

The relationship between the compressive strength (independent variable) based on BS EN 12390-3:2019 standard to the flexural strength (dependent variable) based on the BS EN 12390-5:2019 yielded a correlation coefficient (*r*) of 0.92 and this regression is statistically significant at 95 percent confidence level. From this regression, flexural strength for a 200 mm 1:2:4 concrete can be predicted from compressive strength using equation 1.

$$y = 1.4136x - 23.704 \quad (1)$$

where

y is the flexural strength of a 200 mm 1:2:4 concrete; and

x is the compressive strength 200 mm 1:2:4 concrete

Similarly, the comparison between the compressive strengths and flexural strengths of the 400 mm 1:2:4 concrete with different percentage polypropylene composition is presented in Figure 3. The relationship between the compressive strength and the flexural strength yielded a correlation coefficient (*r*) of 0.89 and this regression is statistically significant at 95 percent confidence level.

Form the analysis, the flexural strength for a 400 mm 1:2:4 concrete can be predicted from compressive strength using equation 2.

$$y = 0.5928x - 6.3554 \quad (2)$$

where

y is the flexural strength of a 400 mm 1:2:4 concrete; and

x is the compressive strength 400 mm 1:2:4 concrete

Furthermore, the comparison between the compressive strengths and the rupture modulus of the 500 mm 1:2:4 concrete with different percentage polypropylene composition in Figure 4 yielded a correlation coefficient (*r*) of 0.88 and this regression is statistically significant at 95 percent confidence level.

Form the regression analysis, the flexural strength for a 500 mm 1:2:4 concrete can be predicted from Compressive strength using equation 3.

$$y = 1.2849x - 25.37 \quad (3)$$

where y is the flexural strength of a 500 mm 1:2:4 concrete;

and

x is the compressive strength 500 mm 1:2:4 concrete.

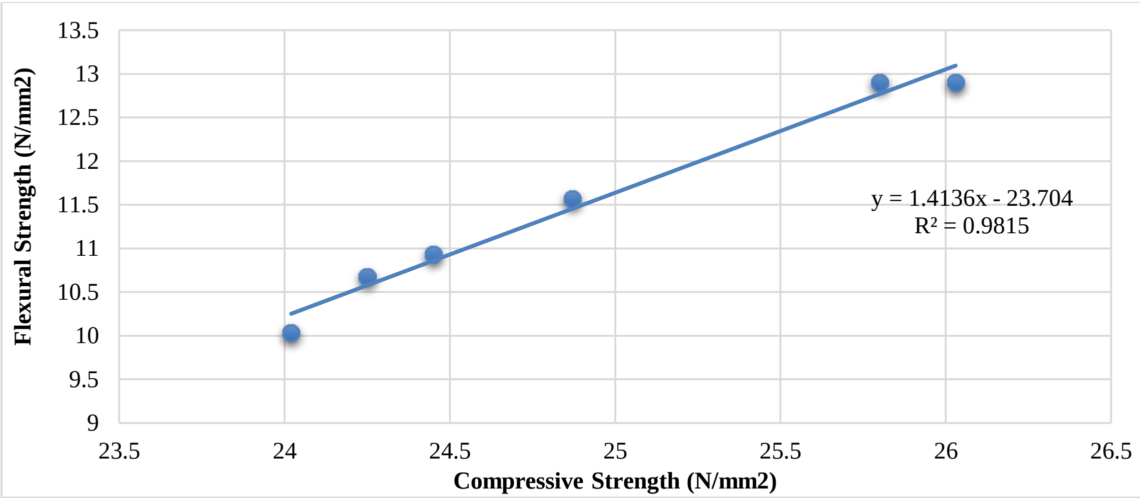

Figure 2. Flexural-compression strengths correlation diagram for 200 mm 1:2:4 concrete

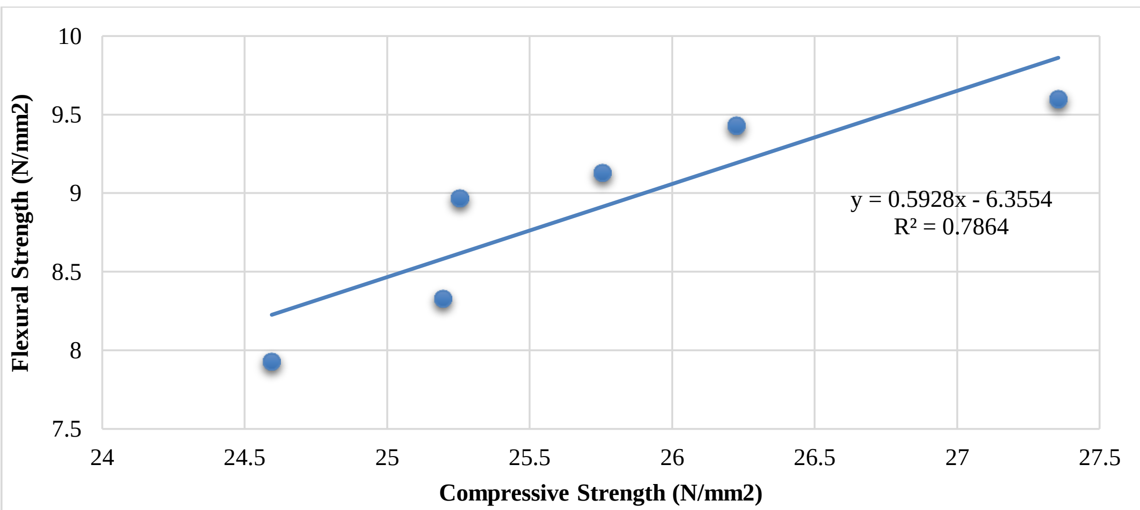

Figure 3. Flexural-compression strengths correlation diagram for 400 mm 1:2:4 concrete

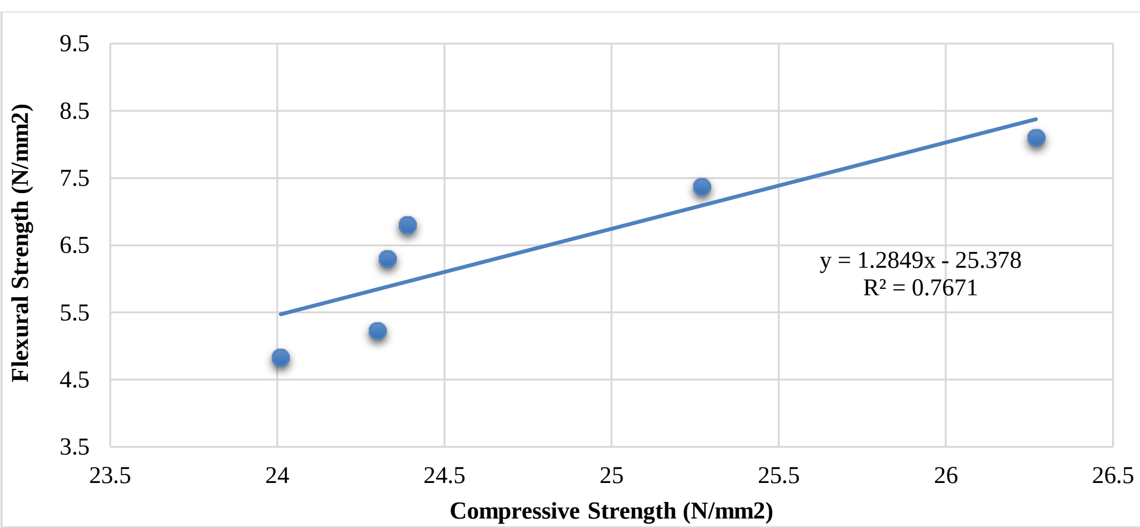

Figure 4. Flexural-compression strengths correlation diagram for 500 mm 1:2:4 concrete

CONCLUSION

This research has focused on the use of polypropylene based waste chair in different percentage compositions to modify 1:2:4 and 1:3:6 grades of concrete used to produce paving stones of different lengths (200 mm, 400 mm and 500 mm) for pavement construction. Strength tests like compressive and flexural tests have been performed to determine the strength characteristics and the correlation of these strengths. Other tests to determine the suitability of the aggregates and fresh concretes for use in the production of concrete paving stones have also been carried out.

Form this research, the highest compressive strength obtained for the 200 mm, 400 mm and 500 mm lengths paving stones are respectively 26.03 N/mm^2, 27.36 N/mm^2 and 26.27 N/mm^2 after 28 days of curing for 1:2:4 concrete at 10% polypropylene composition. However, 400 mm 1:2:4 grade concrete has the highest compressive strength of 27.36 N/mm^2 at 10% polypropylene composition. Furthermore, the compressive strengths of 200 mm, 400 and 600 mm 1:3:6 concrete does not meet the requirement of 20 N/mm^2 for 28 days to open the concrete pavement for traffic. Therefore 1:3:6 concrete is not good under any condition for producing concrete for paving stones.

The 14 days flexural strength criteria of 4.1 N/mm^2 (600 psi) required to open pavement to traffic and the flexural strength design critreria of mean 28-day flexural strength of 4.5 N/mm^2 were met by the flexural strengths all lengths and percentage compositions, while the highest flexural strength obtained after 14 days is 7.50 N/mm^2 at 10% polypropylene composition for 200 mm length. Likewise, the 200 mm long paving stone with 10% polyprpopylene composition has the highest flexural strength of 12.90 N/mm^2. In effect it can be concluded that the 200 mm long paving stone at 10% polypropylene composition is better in the consideration of the length of paving stone that can give an adequate flexural strength which is the most important requirent in concrete pavement requirement.

The correlation coefficients (*r*) obtained for the compression-flexural strength relationship for 200 mm, 400 mm and 500 mm are 0.92, 0.88 and 0.89 respectively further validate the strong positive relationship existing between the compression and flexural strengths of concrete pavement. The 200 mmm at 10% polypropylene composition correlation coefficient has that the highest value of 0.98 which better explains the compression-flexural strength relationship and validates the 200 mm length at 10% polypropylene composition paving stone as the most adequate length of paving stone for pavement construction.

DECLARATIONS

Authors' contribution

Olugbenga Joseph Oyedepo designed the experimental plan, Ebenezer Omoniyi Olukanni carried out the laboratory tests and Temitope Rufai Arowolo did analysis of results and the write up

Conflict of interest

There is no conflict of interest with any third party.

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