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Original Research Article

An Optimized Superplasticized Microsilica Concrete for Flexible Highway Pavement

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ABSTRACT

Microsilica is a by-product of silicon from an electric arc furnace. Mitigating the consequences of microsilica effect, lead to using same in concrete production to better highway pavements. In this study, microsilica has been used with Conplast SP 430 superplasticizer to produce high strength superplasticized microsilica concrete whilst employing lagoon and river sands independently. Using 3:1 aggregates cement relationship for lagoon and river sands individually, a normal and three types of superplasticized microsilica concretes (SMC) were produced. From each type of concrete produced, cube models were made to simulate rigid pavement while I-shape, Z-shape and rectangular shape paver samples were made for flexible pavement. For the superplasticized microsilica concrete produced, the amount of microsilica used was constant for each mix at 3% whereas superplasticizer used was varied as 1.5%, 2%, 2.5% and 3%. Under same condition of concrete mix of using river sand, it was SMC of 2.5% superplasticizer that gave highest value of compressive strength. However, SMC with 2% using lagoon sand gave higher values of compressive strength than those with 2.5% while using river sand.

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1. INTRODUCTION

Highway pavements have been observed to be in deplorable conditions in many locations (Forman, 2005). The growth of traffic on roads has led to more damages to the highway pavements in particular those that had substandard materials used for their construction (Mugdha, 2015). Highway pavement such as road, tunnel, airstrip, railway, parking lots and other similar areas must have surfacing with durable materials.

A highway pavement has different types of layers and of materials from top to bottom. The surface layer has maximum stiffness as measured by resilient modulus and contributes mostly to pavement strength (Chandra 2017). Flexible pavement has bituminous surface course that takes load directly by the wearing course. Flexible pavement with paving blocks as surface course takes load directly by the pavers (Mudiyono et al., 2007). According to Chandra (2017) rigid pavement is of cement concrete or reinforced concrete slab over laid on a low strength concrete layer or on a well compacted aggregate or both. The concrete slab usually lies on a compacted granular or treated subbase which is supported in turn by a compacted subgrade that forms the foundation (Anupoju, 2011).

Superplasticizer is an admixture of chemical compounds and of high range water reducer that can be at 30% or more and also which could be used in making high strength concrete (Bye et al., 2011). Plasticizers also enable the production of concrete with approximately 15% less water content (Bye et al., 2011).

According to Dunuweera and Rajapakse (2018) cement is a powdery substance made with calcined lime and clay as major ingredients of which the former provides calcium oxide and the latter provides silica, alumina, and iron oxide. They also asserted that an ordinary Portland cement concrete life span increases by 4-5 times whenever microsilica is used as part of its constituents.

According to Gite et al. (2018) microsilica consists of spherical particles with an average particle size of 150 nm and a specific surface area typically 20 m^3/g. Microsilica is a mineral compound and which in concrete contributes to strength and durability (Umesh et al., 2014; Gite et al., 2018). Aggregates are essential ingredients in concrete that are inert granular materials which are fine such as sand and coarse that is of gravel, granite or crushed stone (Akiije, 2017).

Many researchers have reported the possibilities of getting fresh workable and high strength harden concrete using superplasticizer or together with microsilica (Mohamed, 2011; Akiije, 2019). However, much has to be done while considering their influence on the use of lagoon sand and river sand in Nigerian environment with comparison. Addition of a by-product of silicon called microsilica and superplasticizer into pavement concrete constituents is considered in this study as a potential for economic capacity development in highway construction. Thus, this study aimed at investigating the worth of lagoon sand and river sand when used independently in the production of superplasticized microsilica concrete. The justification for this research work is in the economic prudence realized upon producing high-strength concrete with low permeability for highway pavements. Also, this study is of interest in the prevention of early road damage in all ramifications of highway pavement construction for traffic safety.

2. MATERIALS AND METHODS

2.1. Concrete Material Constituents

Concrete material constituents employed in this study included water, Conplast SP 430 superplasticizer, microsilica, cement, sand and granite. The constituents were tested appropriately for physical and chemical properties according to related standard specification methods.

Water used was obtained from the laboratory in the Department of Civil and Environmental Engineering, University of Lagos, Lagos, Nigeria. Purechem Manufacturing Limited supplied both Conplast SP430 superplasticizer and microsilica. The Conplast SP430 superplasticizer used in this study was tested for physical and chemical composition in accordance with the specifications as stipulated by BS EN 934 (2018). Chemical and physical properties of the microsilica used in this study were tested according to ASTM C1240 (2020) on specification for silica fume.

The cement used was purchased in 50 kg per bag from a store at Akoka area of Lagos, Nigeria. The brand of cement used was tested for properties such as bulk density, specific gravity, fineness, initial setting time, final setting time, chemical and compound composition according to standard methods (ASTM C114 2018; ASTM C191 2019). The chemical analysis of the cement was tested in accordance to ASTM C114 (2018).

Granite and sand aggregates were obtained from a construction materials market at Bariga tipper garage, Bariga, Lagos and were separately air dried in bits inside the laboratory before use. Both granite and sand aggregates were subjected to gradation, coefficient of uniformity and curvature through laboratory tests according to AASHTO T 27 (2014). Also, according to ASTM C128 (2015) the two types of sand used were separately tested for moisture content, relative density, dry density and absorption values. Fine and coarse aggregates were separately tested for bulk densities in accordance to AASHTO T 19 (2014). In accordance to ASTM C127 (2015), the moisture content, specific gravity, dry density and absorption of the coarse aggregates used were determined. Los Angeles abrasion test as a standard specification methodology was employed in the laboratory to determine granite abrasion value as describe in ASTM C 131 (2016). Crushing and impact values were determined in accordance to ASTM C33/C33M (2018).

2.2. Concrete Constituents Proportioning

Both normal concrete that served as control and superplasticized microsilica concrete materials proportioning as employed in this study are presented in Table 1.

Table 1: Concrete constituents by weight using lagoon and river sand separately

S/No	Specimen label	W/C	Water (kg)	Conplast SP 430	Microsilica	Cement (kg)	Fine aggregate lagoon (kg)	Coarse aggregate (kg)
1	LAG1 or RIV1	0.40	20.00	0.00 (0%)	0 (0%)	50.0	100	50
2	LAG2 or RIV2	0.30	14.25	0.75 (1.5%)	1.5 (3%)	48.5	100	50
3	LAG3 or RIV3	0.30	14.00	1.00 (2%)	1.5 (3%)	48.5	100	50
4	LAG4 or RIV4	0.30	13.75	1.25 (2.5%)	1.5 (3%)	48.5	100	50
5	LAG5 or RIV5	0.30	13.50	1.50 (3%)	1.5 (3%)	48.5	100	50

W/C= Water cement ratio

2.3. Concrete Production and Testing

Both fresh normal and superplasticized microsilica concrete production was carried out using machine operated mixer per separate mixture as shown in Table 1. Each batch of either normal or superplasticized microsilica fresh concrete produced was tested for both slump and compacting factor tests. Production of concrete specimens was carried out immediately after the batch production of concrete mixtures. Specimen dimensions include pavers of I section (220 × 110 × 80) mm, rectangular section (200 × 100 × 80) mm, Z section (240 × 120 × 80) mm and concrete cubes (150 × 150 × 150) mm. Total concrete specimens produced were 480 numbers.

2.4. Concrete Specimens Curing and Compression Tests

For each batch, after 24 hours of casting, the hardened specimens were demoulded and cured inside clean clear water pond pending the various testing days. Specimens cast were subjected to compression test individually based upon schedule of water curing by 7, 28, 56 and 91 days. Both cube models and paver samples were individually tested using hydraulic compression testing machine powered with electricity to determine their compressive strengths. The value of the average compressive strengths of three specimens was determined based on the scheduled testing day.

3. RESULTS AND DISCUSSION

3.1. Superplasticizer Properties

Table 2 shows the results of physical and chemical composition of the Conplast SP430 superplasticizer used in this study. For confirming the suitability of the Conplast SP430 superplasticizer used, the results obtained were compared with the BS EN 934 (2018) specification requirements on admixtures for concrete, mortar and grout. They were found to be similar and therefore suitable for the production of the superplasticized microsilica concrete.

Table 2: Physical and chemical composition of the Conplast SP430 superplasticizer

Property	Value	BS EN 934 (2018) specification
Specific gravity	1.18	1.15
Chloride content (kg/m^3)	0.000	Free

3.2. Microsilica Properties

The results of chemical and physical properties of the microsilica used in this study based on silica fume specification according to ASTM C1240 (2020) are presented in Table 3. It could be seen in Table 3 that with the exception of specific gravity and bulk density having values higher than the required specifications, all other chemical and physical composition of the microsilica conformed.

Table 3: Chemical and physical composition of the microsilica

Chemical compound	Value	ASTM C1240 (2020) specification
Silicon dioxide (SiO_2), (%)	92.6	85-97
Aluminum oxide (Al_2O_3), (%)	0.6	0.4-0.9
Iron oxide (Fe_2O_3) (%)	1.65	1-2
Calcium Oxide (CaO) (%)	0.55	0.2-0.7
Magnesium Oxide (MgO) %	0.38	< 1
Potassium oxide (K_2O) (%)	0.68	< 1
Sodium oxide (Na_2O) (%)	0.3	< 1
Silicon dioxide (SO_2) (%)	0.15	< 1
Loss on ignition (%)	2.1	6
Specific gravity	2.24	2.2 – 2.3
Bulk density (kg/m^3)	619	130-600
Surface area (m^2/kg)	20,000	15,000 – 30,000

3.3. Cement Properties

Results of the chemical analysis of the cement used in this study are presented in Tables 4 and also related to ASTM C114 (2018) standard specifications for chemical analysis of hydraulic cement. In Table 4, it is revealed that aluminum oxide value is higher than the specification standard value while other chemical compositions conformed. Table 5 shows results of the compound composition of the cement as carried out in the laboratory according to ASTM C1356 (2020) specification standard. Tricalcium silicate $(CaO)_3.SiO_2$ and dicalcium silicate $(CaO)_2.SiO_2$ were not in conformity to the standard specification as shown in Table 5. However, as also seen in Table 5, tricalcium aluminate and tetracalcium aluminoferrite conformed to the standard specification. Table 6 also shows physical properties of the cement values as obtained in the laboratory. As exhibited in Table 6, the values of physical properties of the cement used were in conformity to their related standard specifications.

Table 4: Chemical composition of the cement

Chemical compound	Value (%)	ASTM C114 (2018) specification (%)
Silicon dioxide (SiO_2)	21.0	18.7 – 22.0
Aluminum oxide (Al_2O_3)	6.5	4.7 – 6.3
Iron oxide (Fe_2O_3)	2.9	1.6 – 4.4
Calcium oxide (CaO)	65.2	60.6 -66.3
Magnesium oxide (MgO)	1.5	0.7 – 4.2
Sulphur trioxide (SO_3)	2.8	1.8 – 4.6
Sodium oxide (Na_2O)	0.3	0.11 -1.2
Potassium oxide (K_2O)	0.7	0.11 -1.2

Table 5: Compound composition of the cement

Chemical compound	Cement chemist notation (CCN)	Value (%)	ASTM C1356 (2020) specification (%)
Tricalcium Silicate ($(CaO)_3.SiO_2$)	C_3S	76.56	45 - 75
Dicalcium Silicate ($(CaO)_2.SiO_2$)	C_2S	4.17	7 - 32
Tricalcium Aluminate ($(CaO)_3.Al_2O_3$)	C_3A	9.91	0 - 13
Tetracalcium Aluminoferrite ($(CaO)_4.Al_2O_3$ $Fe_2O)_3$	C_4AF	8.2	0 - 18

Table 6: Physical properties of the cement

Standard	Physical properties	Value	Specification	Standard
ASTM C786 (2017)	Fineness (% retained on 45 μm)	3	10	ASTM C786 (2017)
ASTM C188 (2017)	Specific gravity	3.15	3.13-3.15	ASTM C188 (2017)
IS 875 (2013)	Bulk density (kg/m³)	1440	1440	IS 875 (2013)
ASTM C187 (2011)	Standard consistency (%)	28	25-35	ASTM C187 (2011)
ASTM C191 (2019)	Initial setting time (min)	122	≥ 30	ASTM C191 (2019)
ASTM C191 (2019)	Final setting time (min)	258	≤ 600	ASTM C191 (2019)
ASTM D7348 (2013)	Loss on ignition (%)	0.05	0.04-0.05	ASTM D7348 (2013)
ASTM C465 (2019)	Insoluble residue (%)	0.03	0.02-0.04	ASTM C465 (2019)

3.4. Aggregate Properties

Properties of fine and coarse aggregates used were determined upon specifications based on AASHTO T 27 (2020), AASHTO T 19 (2014), ASTM C128 (2015 and ASTM C127 (2015) through laboratory tests of which the results are presented in Table 7. The values of fineness modulus, specific gravity, coefficient of uniformity, coefficient of curvature and percentage voids of lagoon sand were higher than those of river sand. For this reason, lagoon sand is of coarser sand material than that of river sand. Although the values of percentage void of both sand are similar but they are so small to that of granite which made same coarse material. Figure 1 and Figure 2 show the aggregate gradation charts of fine aggregates respectively for lagoon sand and river sand. In comparing Figure 1 and Figure 2, lagoon sand conformed better than river sand. Also, Figure 3 shows the coarse aggregate gradation chart for granite used. The gradation graph for granite spread better than the lagoon and river sands graduation chart.

Table 7: Properties of fine and coarse aggregates

Properties	Fine aggregates		Coarse aggregates
Aggregates	Lagoon sand	River sand	Granite
Maximum size of the aggregate (mm)	4.75	4.75	9.5
Fineness modulus (%)	2.62	2.54	2.03
Specific gravity	2.67	2.64	2.70
Bulk density (kg/m^3)	1670	1670	1700
Coefficient of uniformity (Cu)	7.06	2.4	1.5
Coefficient of curvature (Cc)	1.76	1.35	0.96
Percentage voids (%)	57.24	54.56	83.45
Maximum percentage of bulking (%)	18.8	20.56	-
Corresponding moisture content (%)	2.2	2.43	-
Water absorption (%)	2.11	2.45	0.06

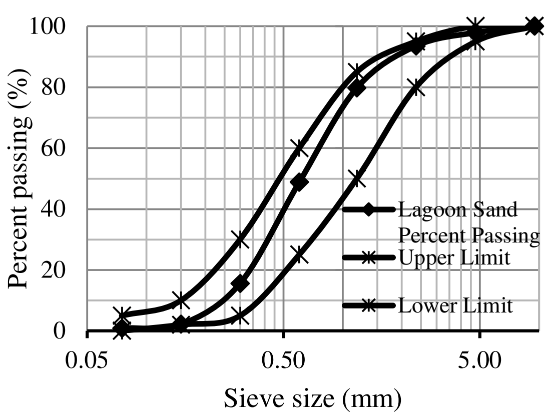

Figure 1: Lagoon sand fine aggregate gradation chart

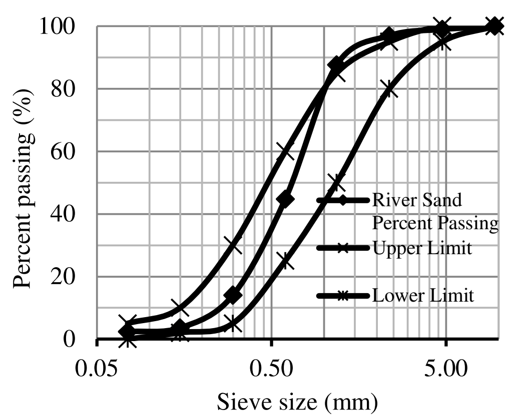

Figure 2: River sand fine aggr. gradation chart

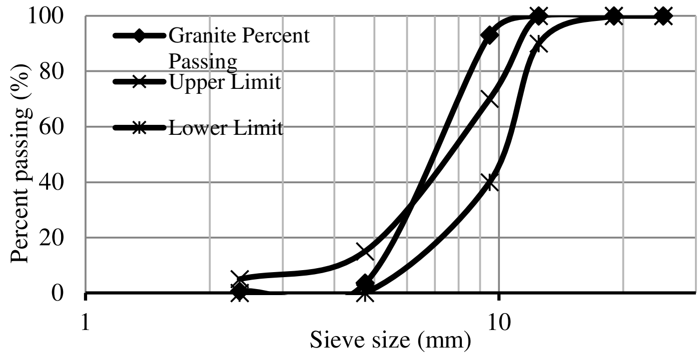

Figure 3: Granite coarse aggregate gradation chart

3.5. Fresh Concrete Properties

Table 8 shows that LAG1 and LAG2 fresh concretes have the same slump and compaction factor values although the former is normal concrete while latter is superplasticized microsilica concrete. The slump values of superplasticized microsilica concretes of LAG3, LAG4 and LAG5 increased as the superplasticizer amount increased. However, superplasticized microsilica fresh concrete of LAG3 gave the lowest value of compaction factor. Also, in Table 8 the slump values of superplasticized microsilica concretes increased as the superplasticizer amount increased. Fresh superplasticized microsilica concrete RIV4 had the lowest compacting factor value while RIV5 had the highest amount. Superplasticizers are used to increase the fluidity of concrete whilst producing flowing concrete with very high slump at reduced water cement ratio (Akiije, 2019).

Table 8: Fresh concrete levels of workability per sand type

Specimen label lagoon sand	Slump values (mm)	Compaction factor	Specimen label river Sand	Slump values (mm)	Compaction factor
LAG1	10	0.89	RIV1	13	0.89
LAG2	10	0.89	RIV2	17	0.90
LAG3	12	0.86	RIV3	20	0.89
LAG4	15	0.92	RIV4	22	0.86
LAG5	20	0.96	RIV5	25	0.96

3.6. Hardened Concrete Properties

Results of both normal and superplasticized microsilica concretes compressive strengths using both lagoon and river sands separately are shown in Figures 4 to 8 based on water curing. In each figure, the trend of the compressive strength is such that the higher the curing day the higher the strength with variation in the rate of development. The rate of compressive strength development between day 7 and day 28 is the highest and followed with lower rate for the other subsequent day's strength values. These figures also indicate that the compressive strength of lagoon sand concrete is higher than that of river sand concrete when subjected to the same concrete mix proportioning. More so, cube models gave the highest values of compressive strength when compared with the paver samples as shown in Figures 4 to 8. Correspondingly, Z-paver gave the highest compressive strength value while comparing same with the other rectangular and I-paver samples appropriately as shown in Figures 4 to 8. The cube model concrete compressive strength values obtained for lagoon (LAG) and river (RIV) sands separately are shown in Figure 9. Also, Z-paver being the optimal of paving block regarding comprehensive strength is shown in Figure 10 along with cube model of Figure 9. For both cube and Z-paver concrete compressive strengths using lagoon sand, the concrete strength increases as the superplasticizer amount is increasing up to 2% of cement at optimal. However, the subsequent increase of superplasticizer amount after the optimal gave reduced strength of the specimens. While using river sand, both cube and Z-paver concrete compressive strength, increases as the superplasticizer amount was increasing up to 2.5% of cement as optimum. However, subsequent increase of superplasticizer amount after the optimum gave reduced strength of the specimens. Table 9 shows the increment in percentage of concrete compressive strength at optimal for RIV3 to LAG3 and RIV4 to LAG3 of which it could be confirmed that lagoon sand performed better than river sand. Table 10 gives comparison of compressive strength of type LAG3 and RIV4 at optimum usage of lagoon sand and river sand respectively for highway suitability compliance. The results show that using Conplast SP 430 at 2% and microsilica at 3% with lagoon sand to produce superplasticized microsilica concrete tagged LAG3 gave the best results of compressive strength in this study. The values of concrete compressive strength in this case of LAG3 is higher than that of RIV4 of using Conplast SP 430 at 2.5% and microsilica at 3% using lagoon sand to produce superplasticized microsilica concrete. Only rectangular and Z-shaped pavers as produced by LAG3 of using lagoon sand that are suitable for medium traffic category of flexible pavement. However, upon similar condition of LAG3, it is only Z-shaped pavers that are suitable for heavy to very heavy traffic category flexible pavement highway. It should also be noted that only Z-shaped pavers produced by RIV4 of river sand that are suitable for both medium traffic and heavy to very heavy traffic categories for flexible pavement highway. On the other hand, cubes produced by both LAG3 and RIV4 are suitable for both medium traffic and heavy to very heavy traffic categories intended for rigid pavement highway.

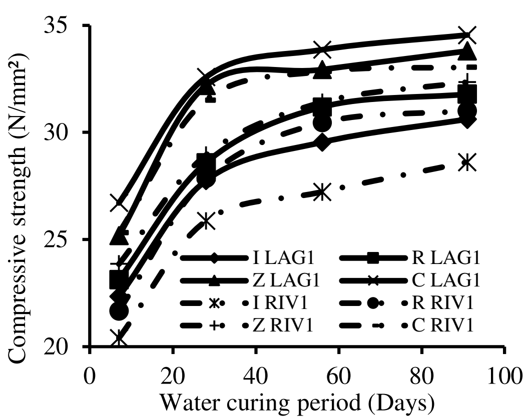

Figure 4: Effect of curing on concrete compressive strength for 0% superplasticizer and 0% microsilica

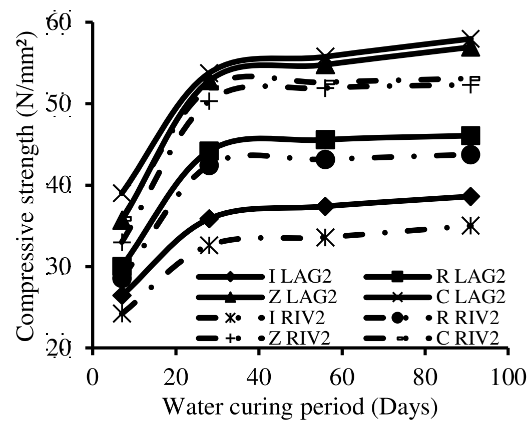

Figure 5: Effect of curing on concrete compressive strength for 1.5% superplasticizer and 3% microsilica

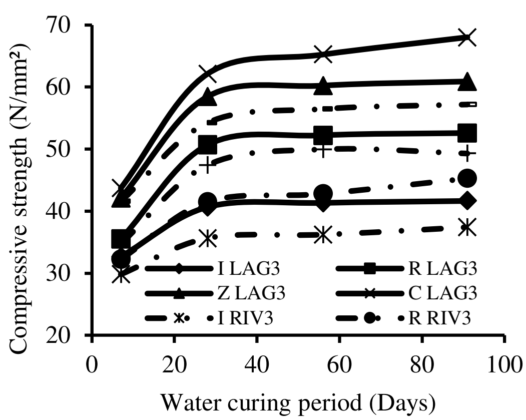

Figure 6: Effect of curing on concrete compressive strength for 2% superplasticizer and 3% microsilica

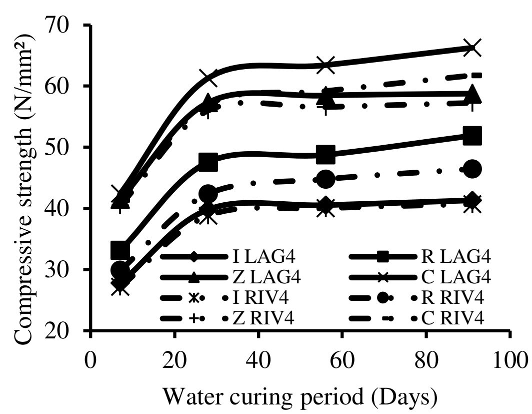

Figure 7: Effect of curing on concrete compressive strength for 2.5% superplasticizer and 3% microsilica

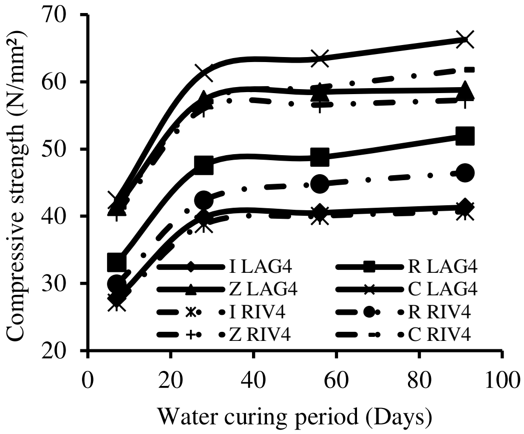

Figure 8: Effect of curing on concrete compressive strength for 3% superplasticizer and 3% microsilica

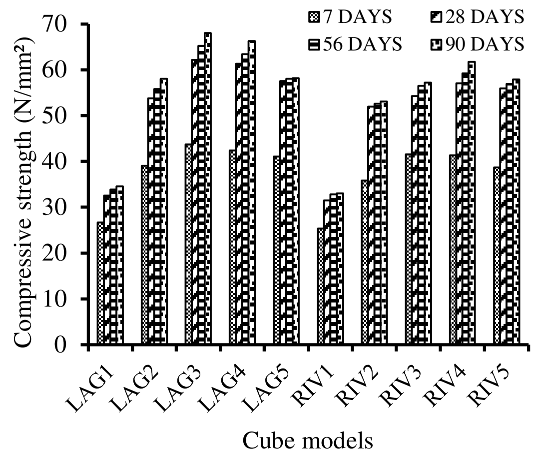

Figure 9: Cube models compressive strengths compared

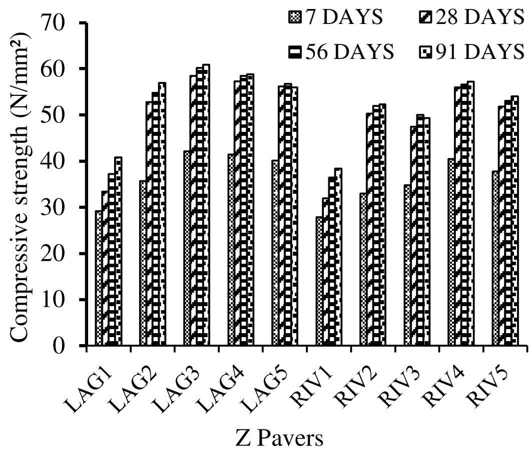

Figure 10: Z-Pavers compressive strengths compared

Table 9: Increment percentage of concrete compressive strength at optimal

Type of specimens	LAG3 28 days compressive strength (N/mm²)	RIV3 28 days compressive strength (N/mm²)	RIV4 28 days compressive strength (N/mm²)	Increment percentage RIV3 to LAG3 (%)	Increment percentage RIV4 to LAG3 (%)
I- shape	41	36	39	14	5
Rect.- shape	51	41	42	24	21
Z- shape	58	47	56	23	4
Cube	62	54	57	15	9

Table 10: Comparison of compressive strength of type LAG3 and RIV4 for highway suitability compliance

Specified grade of concrete	Required compressive strength (N/mm²)	Type of specimens	LAG3 28 days compressive strength (N/mm²)	Highway suitability compliance	RIV4 28 days compressive strength (N/mm²)	Highway suitability compliance
C35 medium traffic category	45	I- shape	41	Unsatisfactory	39	Unsatisfactory
		Rect.- shape	51	Satisfactory	42	Unsatisfactory
		Z- shape	58	Satisfactory	56	Satisfactory
		Cube	62	Satisfactory	57	Satisfactory
C45 heavy to very heavy traffic category	55	I- shape	41	Unsatisfactory	39	Unsatisfactory
		Rect.- shape	51	Unsatisfactory	42	Unsatisfactory
		Z- shape	58	Satisfactory	56	Satisfactory
		Cube	62	Satisfactory	57	Satisfactory

4. CONCLUSIONS

A laboratory experimental study describing the characterization of normal and superplasticized microsilica concretes compressive strengths for highway pavement using lagoon and river sands separately is presented. Normal concrete gave the lowest compressive strength in this study and in particular concrete with lagoon sand has higher value than that of river sand ones. For superplasticized microsilica concretes, the higher the value of superplasticizer the higher the value of compressive strength while using the lagoon sand up to the optimum at 2% (LAG3) but 2.5% of superplasticizer for the river sand concrete (RIV4). The highest value of compressive strength obtained from specimens cured in water for 28 days as per standard specification for highway rigid pavement was obtained for cube model by LAG3. The highest value of compressive strength obtained from specimens cured in water for 28 days as per standard specification for highway flexible pavement is obtained through Z- shape paver by LAG3.

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6. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

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