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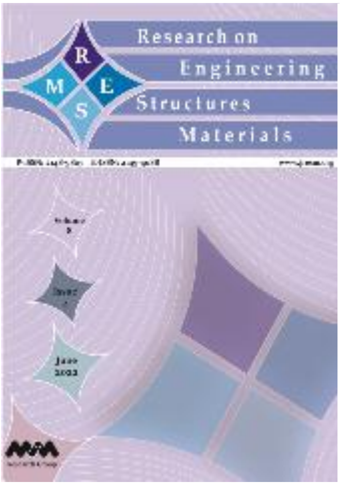

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Research Article

Mix ratio design assessment of interlocking paving stone using both destructive and non-destructive methods

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Abstract

Interlocking paving stones have been produced in most developing countries with no specific method for testing the strength before use. This study presented the mix ratio design assessment of interlocking paving stone strength properties using both destructive and non-destructive methods. Six mix ratios were used to produce the interlocks and tests such as skid resistance, flexural strength, compressive strength and rebound hammer were conducted on 7, 14, 28, 56 and 90 days. All the skid resistance tests had British Pendulum Number (BPN) values greater than 75 specified in Table NA.2 of BS 1338:2003, the interlocking paving stone potential for skid is extremely low. The flexural strength was conducted following IS 15658:2006 and the result ranges from 1.34 – 5.38 N/mm2. The compressive strength result for the mix ratios ranges from 6.20 – 21.78 N/mm2 and mix ratio 1:3 had the highest compressive strength of 19.34, 21.78 N/mm2 at 56 and 90 days respectively. Table 1 of IS 15658:2006 is used to classify the paving stone for use in non-traffic areas based on the compressive strength results. A correlation model was developed combining all the mix ratio average rebound values and compressive strength, the regression equation was produced and an accuracy test was performed to check the regression formula estimates. This study validates the use of a rebound hammer as a non-destructive method on interlocks to predict the compressive strength with 79 % accuracy. Mix ratio 1:3, 1:2 is recommended for use in producing interlocks based on higher compressive and flexural strength.

1. Introduction

Cutting edge interlocking paving stones (IPS) are assuming an imperative role in our transportation industry and construction world as a whole. Paving stones are answers for outdoor application considering their quality, aesthetics and toughness, it is generally favoured in any environmental condition and areas like pedestrian walkways, road surfaces, yards and intersections among other types of pavement design (1–4). IPS requires high compressive strength and efforts have been taken to increase the compressive strength of the paving blocks. The IPS compressive strength can be investigated either by destructive means using the compression testing machine or the non-destructive test means using several methods like the rebound hammer, ultrasonic pulse velocity etc. (3). Paving stones have numerous advantages over asphaltic and concrete pavement such as the engineering durability properties, aesthetically pleasing surfaces, cost-effective maintenance and economical characteristics (5). Like other types of pavements, the design of the IPS will depend on the ecological, traffic movement, subgrade support and the IPS materials (6,7).

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Despite the good engineering properties that IPS possess, it can still fail in cracking, deflection etc. when not properly produced following standard requirements and specification which would need a lot of financial resources from the maintenance budget to replace the failed interlocks. In Nigeria, IPS are used a great deal most especially in areas with high water tables such as the Island areas of Lagos state. IPS are observed to be in their worst conditions after a short period of usage due to factors like the poor condition of the manufacturing process, inadequate sub-base, use of substandard materials, the wide profit margin on the part of the manufacturers causing low quality, low water-cement ratio etc (3). Most of these factors exist because there is no specific standard for the mix designs for IPS and also no specific method to check the strength of IPS produced. Manufacturers in Nigeria resolve to batch by a range to be produced from a bag of Cement. Quality/strength check of concrete is done with the use of destructive tests and the advancement of non-destructive tests. The latter are the tests which are carried out without impairing the present state of the structural element while the formal causes total damage to the tested element. Some examples of non-destructive tests equipment are the rebound hammer (8), Ultrasonic Pulse Velocity (9,10), Infrared thermography (11) etc

Being quick, cheap and non-destructive, the Schmidt rebound hammer test is a method used for the assessment of concrete compressive strength in terms of surface rebound hardness in buildings, rocks etc (12,13). The relationship between the rebound index and the compressive strength of structural elements has relied in the past on empirical relationships using regression analysis (14–19). Past researchers had reason to evaluate the concrete itself to understand the uncertainties surrounding the rebound hammer testing method (15,18–20). The standard process for testing and the association between concrete cube crushing and strength rebound number was established by Indian standards (21). Several factors influence the rebound values, such as the type of cement and aggregate used, the surface condition and moisture content of the concrete, the age of the concrete, and the level of carbonation. The compressive strength of 150mm standard cubes and the rebound number were developed into a correlation, which was included with the device. However, as additional researchers began to explore connections between strength and rebound number, it became clear that strength and rebound number did not have a unique relationship (22). The current recommended approach [18] depicts the strength connection using the same concrete and shaping materials that will be utilized in the construction process. The rebound hammer is only useful for identifying large changes in concrete quality throughout a structure if there is no such association. Numerous researchers have worked on the comparison of compressive strength and rebound hammer values for concrete (14,16-19,23-29). Only a few past works on the comparison of compressive strength and rebound values have been done on IPS (30), which only considered one mix ratio. This research work looked at the relationship between the strengths and rebound values with different mix ratios in the production of IPS, creating a strength template for the quality assessment of IPS with the use of a rebound hammer.

2. Materials and Methods

2.1. Materials

The materials for concrete mix used in the production of IPS for this research work are Dangote 3X Grade 42.5R Portland cement, Quarry dust, Granite chippings, Potable water and engine oil. In the manufacture of the IPS, cement is utilized as a binder. The Dangote 3X cement was gotten in Omu-Aran, Kwara state Nigeria and manufactured by the Dangote group of companies, Nigeria. The 3X depicts extra strength, extra life and extra yield. Dangote cement contains a wide range of qualities that are equivalent to all varieties of cement. It had the lowest proportion of CaO in its composition and the highest amount of Fe2O3 in its composition. The SiO2 percentage value corresponded to the Ordinary Cement of (31). The Al2O3 composition of around 1% corresponded to type IV (32). The MgO and SiO2 values are of type I and its CaO and SO3 percentage composition are of type IV of (32). It has the highest proportion of uncombined lime, resulting in a low CaO. Its C3S and C3A belonged to type I of (32) while its C2S and C4AF were type IV and type V, respectively, based on their mineralogical composition (Table 1). C4AF was found to be low as a result of the substitution of ferric oxide for alumina, resulting in a rise in C3A and a decrease in C4AF (33).

Table 1. Mineral percentage composition of dangote 3X portland cement

C_3S (%)	C_2S (%)	C_3A (%)	C_4AF (%)	Total Sum (Σ) (%)
33.33	26.47	14.33	4.77	78.9

Quarry dust with fractions of 90 microns as fine aggregate in different mix ratios. The quarry dust was gotten in Omu-Aran Kwara State, Nigeria. The chemical compositions of quarry dust for this research are illustrated in table 2.

Table 2. Chemical composition of quarry dust

SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	CaO (%)	MgO (%)	Na_2O (%)	K_2O (%)	TiO_2 (%)	LOI (%)
86.03	17.81	6.44	4.71	2.65	1.47	3.15	0.27	1.09

Granite chippings: Granite chippings with fractions 4-6mm, served as the coarse aggregate in different mix ratios. Portable water for concrete mixing. Engine oil was used as a lubricant on the internal surfaces of the interlock moulds for easy de-moulding of the stones. The interlock moulds (double Tee design interlocking moulds) (figure 1). The depth of the double Tee design interlocking moulds is 60mm which produces a paving stone of 221mm×137mm×60mm

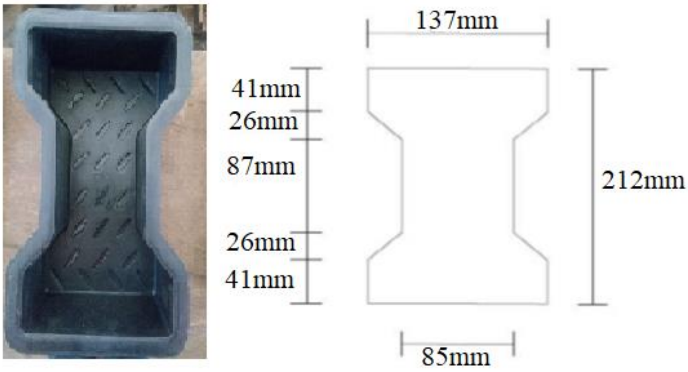

Fig. 1 Double Tee design interlocking moulds

2.2. Experimental Design

Six (6) different mix proportions were considered based on the different sampling of construction sites across the country, IPS manufacturers use different mix designs based on personal gains and material availability. The mix proportions used in this research are borne out of the objective to develop a defined mix proportion for IPS (Table 3). Quarry dust and Granite chippings were varied and used as aggregates, the water-cement ratio of 0.8 was used for the production. The material quantities measured by weight are presented in Table 3.

After mould lubrication, a mixture of cement, quarry dust, granite chippings and water were placed in the moulds following the mix proportions. The cast interlocks were covered with polythene and left for 24 hours at room temperature 20±5°C before being demoulded. The interlocks were cured in water for 7, 14, 28, 56, and 90 days at a temperature of 20±5°C and relative air humidity of (95 ± 5) % to achieve acceptable strength before the physical and mechanical tests were performed on the interlocks. A total number of 180 interlocking blocks were produced and cured.

Table 3. Mix ratios and material proportions

Mix Ratios	Cement (kg)	Quarry dust (kg)	Granite chippings (kg)	Water (kg)
1:4	13.91	64.93	-	11.13
1:3	17.39	60.87	-	13.91
1:2	23.19	54.11	-	18.55
1:1:2	17.39	40.58	32.61	13.91
1:2:4	9.94	46.38	37.27	7.95
1:1.5:3	12.65	44.27	35.58	10.12

2.3. Experimental Test Procedures

The specimens at the specific curing days were subjected to different tests namely compressive strength test, flexural strength test, skid resistance and Schmidt rebound hammer test. Experimental investigations of IPS on compression and flexure were conducted on an ELE Compression machine with model no 36-3090/01 machine.

2.3.1. Compressive Strength Test

This is the ability of a material to withstand stress without failing determines its strength (34). Failure due to cracking and disintegration is common to interlocks during compression (3). The area (24400mm2) and rate (25Kpa/sec) are set (Figure 2) when the machine is turned on, and the machine's condition is examined. The paving stones are fed into the machine, which subsequently crushes them.

Fig. 2 Compressive strength setup

2.3.2. Flexural Strength Test

The behaviour of materials subjected to basic bending loads is measured using this mechanical testing method. To assess the link between bending stress and deflection, flexural testing involves bending a material rather than pushing or pulling it (35,36). The paving stones and steel rods representing the point loads are inserted into the machine using a predefined value and condition for the machine.

2.3.3. Schmidt Rebound Hammer

The Schmidt rebound hammer test was carried out on the IPS to determine the rebound hammer values used to develop a correlation with the compressive strength to predict the compressive strength of the interlocks. IPS were held in position by the compressive testing machine under a fixed load of 7N/mm2 and measurements of the rebound hammer values were done following BS 1881 (37). The hammer was held horizontally to test opposite sides of the cube after which the values were recorded. An average of 10 readings was taken on each test sample on points 25mm apart.

2.3.4. Skid Resistance Test

The skid-resistance test is used to verify the properties of concrete paving blocks and whether a specific surface finish is suitable for use in anti-skid applications. Skid resistance can be measured in two ways: static and dynamic. The British Pendulum Skid Resistance Tester is a standard device for static measurements. Paving blocks of size 221mm×137mm×60mm were tested (Figure 3). To perform the test, both dry and wet surface measurement is taken, The shoe is rubbed against the surface as the pendulum is drawn back. The British Pendulum Number (BPN) is a read scale reading on the machine depicting friction resistance.

Fig. 3 Skid resistance test setup

3. Result and Discussion

For the destructive tests, the Strength values of the IPS samples were recorded at the failure point. The failure pattern for all samples is almost the same (Figure 4).

3.1. Skid Resistance Test

The skid Resistance test was carried out on the IPS following (38) to determine the British Pendulum numbers. The results obtained on days 7, 14, 28, 56 and 90 are presented in table 4.

Table 4 shows the summary of the average British Pendulum numbers recorded after carrying the skid resistance test in the laboratory on each curing day. Referring to the standard value given in BS 1338, 2006 (38), the specimen potential for slip is extremely low with all the BPN values greater than 75 specified in the code. On average, IPS samples with no granite chippings gave better skid resistance results compared to the samples with granite chippings. Comparing the skid resistance values in Table NA.2 of (39) with the results in Table 4, it can be concluded that the interlock potential for slip is extremely low.

Fig. 4 Strength tests failure mode

Table 4. Average British pendulum numbers

Mix Ratios	7 days		14 days		28 days		56 days		90 days	
	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
1:4	122.2	114	100	95.83	119.8	110.8	118.7	110.2	105	99.8
1:3	134.5	120.2	122.7	111.2	135.5	126.8	120.3	108.3	122.7	111.2
1:2	127.5	121.7	116.7	108.8	130.5	122.7	122.7	114.6	116.7	108.8
1:1:2	129.5	125.3	112.2	106.3	129	123.7	133.5	126.7	112.2	106.3
1:2:4	124.3	117	111.2	106	128.5	118.3	122.7	117	111.2	106
1:1.5:3	104.7	101	113.8	109.3	119.7	112.8	115	107.7	113.8	109.3

3.2. Rebound Hammer Test

A rebound hammer test was carried out on the IPS to determine the rebound hammer values. The result obtained from the test at 7, 14, 28, 56 and 90 days are presented in table 5.

Table 5. Average rebound hammer values

Mix ratios	7 days	14 days	28 days	56 days	90 days
1:4	-	10.56	13.08	13.92	14.4
1:3	-	17.45	20.2	22.23	22.57
1:2	-	16.27	17.27	18.77	19.55
1:1:2	-	13.68	14.87	16.05	16.67
1:2:4	-	13.8	13.52	13.02	13.25
1:1.5:3	-	13.75	15.65	14.95	15.55

No rebound hammer value was recorded on the 7th day for all the samples because the rebound hammer values could not be read from the equipment as the values were below the scale reading of 10 on the equipment, this is due to the low strength which is attained after 7 days of curing. The control mix ratio 1:4 and 1:2:4 have the least rebound hammer values on each curing day compared to other mix ratios. Mix ratios 1:3 and 1:2 have the highest average rebound values. The average rebound hammer values for the mix ratios with granite chippings used as coarse aggregate is greater than the control mix on each curing day except for ratio 1:2:4 rebound hammer values that are lesser on the 56th and 90th day. The average rebound hammer values increased on each curing day.

3.3. Flexural Strength Test

To determine the flexural strength of the IPS, a flexural strength test was performed. The outcome at 7, 14, 28, 56 and 90 days are shown in table 6 and figure 5.

Table 6. Average flexural strength

Mix ratios	7 days (N/mm^2)	14 days (N/mm^2)	28 days (N/mm^2)	56 days (N/mm^2)	90 days (N/mm^2)
1:4	1.79	2.02	2.02	2.69	2.69
1:3	3.58	4.03	4.71	5.38	5.38
1:2	2.24	3.14	3.36	4.03	4.49
1:1:2	2.02	2.69	2.91	3.36	3.36
1:2:4	1.34	2.02	2.02	2.47	2.69
1:1.5:3	2.47	2.69	2.69	2.91	3.63

The flexural strength test was performed according to (40) and the average flexural strength values are shown in Table 6, ranging from 1.34 – 5.38 N/mm2. All of the interlocks' flexural strength increased with age, and the maximum flexural strengths were reached after 90 days. In comparison to the control mix ratio and others, the mix ratios 1:3 and 1:2 had the maximum flexural strength, indicating that they would be ideal for the construction of interlocks.

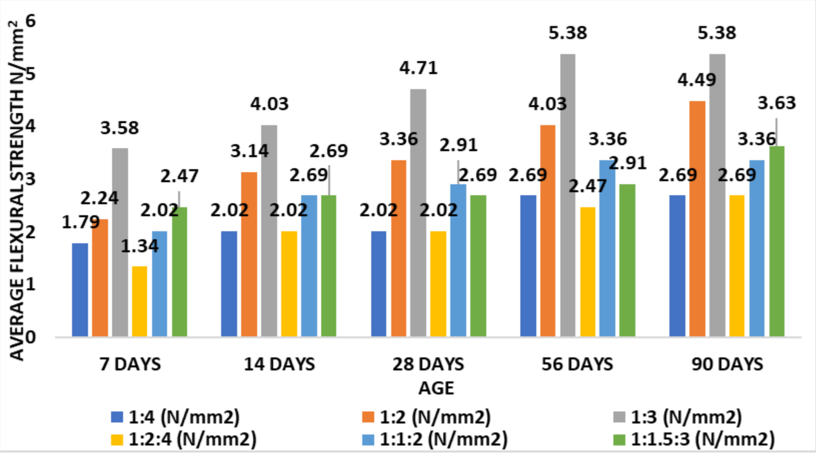

Fig. 5 Average flexural strength with age

The mix ratio with quarry dust had a flexural strength of 5.38 N/(mm)^2 (1:3), 4.49 N/(mm)^2 (1:2) greater than the control mix flexural strength of 1:4 (2.69 N/(mm)^2) on the 90th day (Figure 6). All the mix ratios with granite chippings had a flexural strength of 3.36 N/(mm)^2 (1:1:2), 3.63 N/(mm)^2 (1:1.5:3) greater than the flexural strength of the control mix 1:4 (2.69 N/(mm)^2) except mix ratio 1:2:4 (2.69 N/(mm)^2) that had the same value on the 90th day.

3.4. Compressive Strength Test

The compressive strength result obtained at 7 days, 14 days, 28 days, 56 days and 90 days are shown below in table 7 and figure 7.

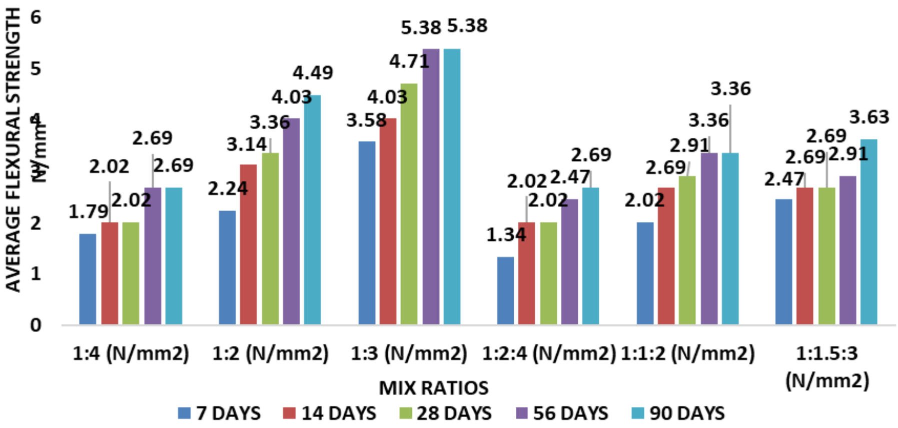

Fig. 6 Average flexural strength with mix ratio

Table 7. Compressive strength result for the different mix ratios

Mix Ratios	7 days (N/mm^2)	14 days (N/mm^2)	28 days (N/mm^2)	56 days (N/mm^2)	90 days (N/mm^2)
1:4	6.20	8.29	9.02	11.23	11.38
1:3	10.37	17.7	16.59	19.34	21.78
1:2	10.92	12.72	15.63	17.71	18.25
1:1:2	10.44	13.75	16.2	16.44	17.40
1:2:4	7.85	11.67	11.55	12.57	13.02
1:1.5:3	12.25	12.77	15.62	17.02	17.30

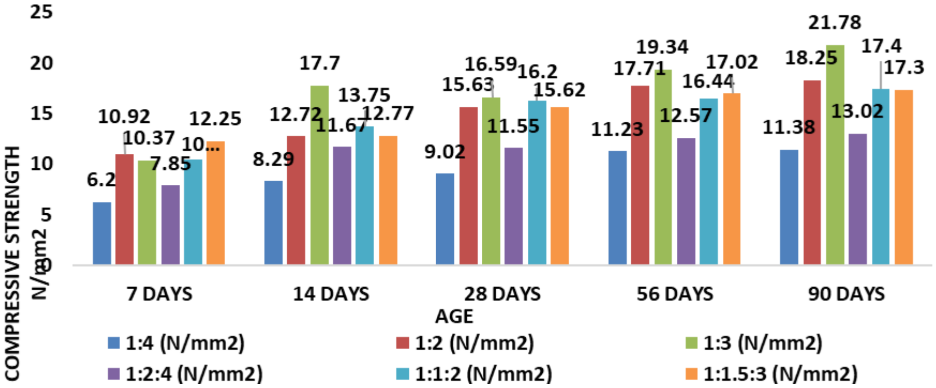

Fig. 7 Average compressive strength with age

The compressive strength test was carried out according to (38), and the average compressive strength values are shown in Table 7, ranging from 6.20 to 21.78 N//(mm)^2. As seen in figure 8, the compressive strength of all interlocks increased with age, with maximum compressive strengths reached on the 90th day. They are would be suitable for the construction of interlocks for use in non-traffic areas based on the classification in Table 1 of (40). Mix ratio 1:3 had the highest compressive strength of 21.78 N//(mm)^2 and followed closely by (1:2) with a compressive strength of 18.25 N//(mm)^2 compared to the control mix (1:4) with a compressive strength of 11.38 N//(mm)^2 on the 90th day. All the mix ratios with granite chippings had compressive strength of 17.4 N//(mm)^2 (1:1:2), 13.02 N//(mm)^2 (1:2:4) and 17.3 N//(mm)^2 (1:1.5:3) greater than the control mix strength of 11.38 N//(mm)^2 (1:4) on the 90th day,

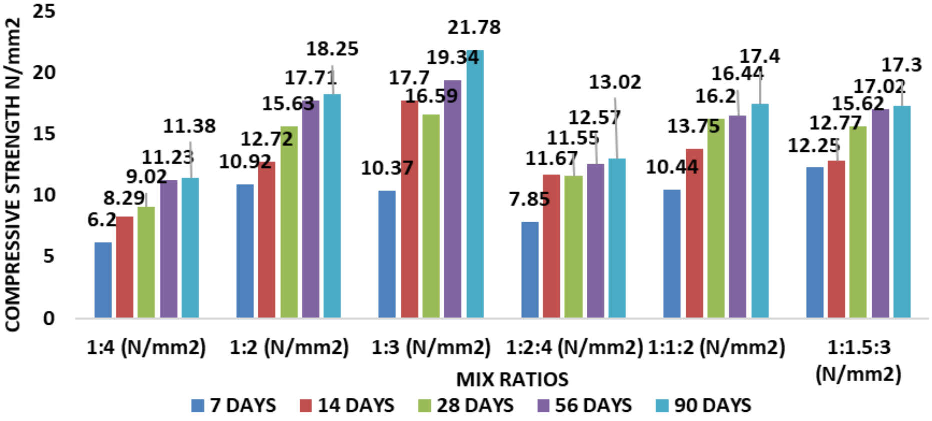

Fig. 8 Average compressive strength with mix ratio

3.5. Correlation Between Compressive Strength and Rebound Hammer Values

One of the objectives of this research work is to develop a correlation model to be used in the fabrication yard and by Engineers on-site to predict the compressive strength of the interlocks using the rebound hammer values gotten after carrying out a non-destructive test using the Schmidt rebound hammer. The average rebound hammer values and the compressive strength values recorded on the 14th, 28th, 56th and 90th day respectively shown in Table 8 were used to develop the correlation in Figure 9.

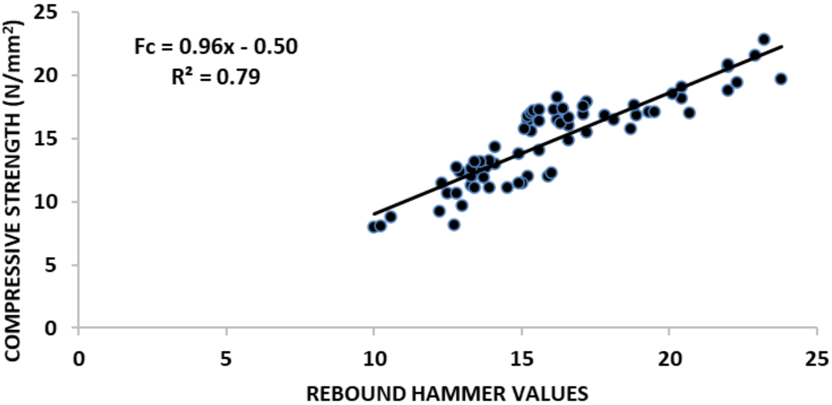

Fig. 9 Correlation graph between compressive strength and average rebound hammer values

Table 8. Compressive strength and average rebound hammer values

S/N	Average Rebound Hammer Values	Average Compressive Strength	Regression Formula Estimates
1	10.56	8.77	9.58
2	10.00	8.03	9.06
3	10.23	8.07	9.28
4	17.80	16.84	16.27
5	15.30	15.57	13.96
6	22.00	20.70	20.14
7	14.90	13.81	13.59
8	15.90	12.05	14.51
9	16.00	12.30	14.60
10	14.10	14.39	12.85
11	15.60	14.10	14.23
12	13.70	12.75	12.48
13	14.10	12.99	12.85
14	12.50	10.70	11.37
15	13.30	11.31	12.11
16	13.40	12.25	12.20
17	13.80	12.79	12.57
18	13.90	13.28	12.66
19	12.20	9.22	11.09
20	12.70	8.16	11.56
21	13.00	9.67	11.83
22	20.70	17.05	18.94
23	18.70	15.82	17.10
24	18.90	16.89	17.28
25	16.60	14.88	15.16
26	17.20	15.53	15.71
27	18.10	16.48	16.54
28	15.60	16.39	14.23
29	15.20	16.39	13.86
30	15.10	15.82	13.77
31	12.30	11.48	11.19
32	13.30	12.01	12.11
33	13.40	11.15	12.20
34	16.20	18.32	14.79
35	15.20	12.01	13.86
36	16.20	16.52	14.79
37	12.80	10.66	11.65
38	13.70	11.93	12.48
39	13.90	11.11	12.66
40	22.00	18.81	20.14
41	23.80	19.75	21.81
42	22.30	19.47	20.42
43	18.80	17.71	17.19
44	20.40	18.24	18.67
45	19.30	17.17	17.65
46	16.60	16.08	15.16
47	17.10	16.97	15.62
48	16.30	16.27	14.88
49	13.60	12.71	12.39

Table 8 (Con). Compressive strength and average rebound hammer values

50	13.30	12.62	12.11
51	12.90	12.38	11.74
52	15.20	16.76	13.86
53	15.30	17.00	13.96
54	16.10	17.30	14.70
55	14.50	11.15	13.22
56	15.00	11.52	13.68
57	14.90	11.48	13.59
58	23.20	22.83	21.25
59	22.90	21.60	20.98
60	22.00	20.90	20.14
61	20.40	19.06	18.67
62	20.10	18.53	18.39
63	19.50	17.17	17.84
64	17.20	17.95	15.71
65	17.10	17.54	15.62
66	16.60	16.72	15.16
67	13.60	13.20	12.39
68	13.40	13.15	12.20
69	12.80	12.71	11.65
70	15.40	17.20	14.05
71	16.40	17.40	14.97
72	15.60	17.30	14.23

4. Conclusion

The study aims at evaluating the mix ratio design assessment of IPS using both destructive and non-destructive methods. The following conclusions are based on the analyses and discussions.

- For improved compressive and flexural strength, less material usage and reduced cost of production, the use of mix ratios 1:3 and 1:2 are recommended for use in the production of IPS with ratio 1:3 giving the best strength. However, in places where granite chippings are readily available and the cost of production would not affect profit, mix ratios 1:1:2 and 1:1.5:3 can be utilized for interlock production.
- The correlation model developed from this research should be utilized both on-site and in the production yard for quality control of the interlocks after the production stage to investigate the compressive strength by the quality control unit before supply and usage of the interlocks.
- The following design strength for IPS is recommended;

Table 9. Recommended design strength for interlocks

Mix ratios	Design strength (N/mm^2)
1:4	10
1:2	17.5
1:3	20
1:1:2	16
1:2:4	12.5
1:1.5:3	17

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References

[1] Djamaluddin AR, Caronge MA, Tjaronge MW, Lando AT, Irmawaty R. Evaluation of sustainable concrete paving blocks incorporating processed waste tea ash. Case Stud Constr Mater [Internet]. 2020;12:e00325. https://doi.org/10.1016/j.cscm.2019.e00325

[2] Gencel O, Ozel C, Koksal F, Erdogmus E, Martínez-Barrera G, Brostow W. Properties of concrete paving blocks made with waste marble. J Clean Prod [Internet]. 2012;21(1):62-70. https://doi.org/10.1016/j.jclepro.2011.08.023

[3] Atoyebi OD, Ikubanni PP, Adesina A, Araoye O V, Davies IEE. Effect of curing methods on the strength of interlocking paving blocks. Cacciola P, editor. Cogent Eng [Internet]. 2020 Jan 1;7(1):1770914. https://doi.org/10.1080/23311916.2020.1770914

[4] Rath B. Effect of asphalt pavement construction on the environment of Ethiopia. Res Eng Struct Mater. 2022;x(xxxx):1-18. https://doi.org/10.17515/resm2022.352ma1010

[5] Ojuri OO. Interlocking Paving Stones Pavement as a Solution to Marshy Roads. Mod Appl Sci. 2012;6(5):91-9. https://doi.org/10.5539/mas.v6n5p91

[6] Jamshidi A, Kurumisawa K, White G, Nishizawa T, Igarashi T, Nawa T, et al. State-of-the-art of interlocking concrete block pavement technology in Japan as a post-modern pavement. Constr Build Mater [Internet]. 2019;200:713-55. https://doi.org/10.1016/j.conbuildmat.2018.11.286

[7] Uygunoğlu T, Topcu IB, Gencel O, Brostow W. The effect of fly ash content and types of aggregates on the properties of pre-fabricated concrete interlocking blocks (PCIBs). Constr Build Mater [Internet]. 2012;30:180-7. https://doi.org/10.1016/j.conbuildmat.2011.12.020

[8] Saha AS, Amanat KM. Rebound hammer test to predict in-situ strength of concrete using recycled concrete aggregates, brick chips and stone chips. Constr Build Mater [Internet]. 2021;268:121088. https://doi.org/10.1016/j.conbuildmat.2020.121088

[9] Parihar HS, Shanker R, Singh V. Effect of variation of steel reinforcement on ultrasonic pulse velocity prediction in concrete beam. Mater Today Proc [Internet]. 2022. https://doi.org/10.1016/j.matpr.2022.04.468

[10] Almasaeid HH, Suleiman A, Alawneh R. Assessment of high-temperature damaged concrete using non-destructive tests and artificial neural network modelling. Case Stud Constr Mater [Internet]. 2022;16:e01080. https://doi.org/10.1016/j.cscm.2022.e01080

[11] Wang S, Sui X, Leng Z, Jiang J, Lu G. Asphalt pavement density measurement using non-destructive testing methods: current practices, challenges, and future vision. Constr Build Mater [Internet]. 2022;344:128154. https://doi.org/10.1016/j.conbuildmat.2022.128154

[12] Basu A, Aydin A. A method for normalization of Schmidt hammer rebound values. Int J Rock Mech Min Sci. 2004;41(7):1211-4. https://doi.org/10.1016/j.ijrmms.2004.05.001

[13] Atoyebi OD, Afolayan JO, Arum C. Analyses and Interpretations of Structural Health Monitoring Data on Reinforced Concrete Buildings: A Critical Review. J Eng Appl Sci. 2019;14(24):9657-66. https://doi.org/10.36478/jeasci.2019.9657.9666

[14] Szilágyi K, Borosnyói A, Zsigovics I. Rebound surface hardness of concrete: Introduction of an empirical constitutive model. Constr Build Mater [Internet]. 2011;25(5):2480-7. https://doi.org/10.1016/j.conbuildmat.2010.11.070

[15] Alwash M, Breysse D, Sbartaï ZM. Non-destructive strength evaluation of concrete: Analysis of some key factors using synthetic simulations. Constr Build Mater [Internet]. 2015;99:235-45. https://doi.org/10.1016/j.conbuildmat.2015.09.023

[16] Tsioulou O, Lampropoulos A, Paschalis S. Combined Non-Destructive Testing (NDT) method for the evaluation of the mechanical characteristics of Ultra High Performance

Fibre Reinforced Concrete (UHPFRC). Constr Build Mater [Internet]. 2017;131:66-77. https://doi.org/10.1016/j.conbuildmat.2016.11.068

[17] Atoyebi OD, Ayanrinde OP, Oluwafemi J. Reliability Comparison of Schmidt Rebound Hammer as a Non-Destructive Test with Compressive Strength Tests for different Concrete Mix. J Phys Conf Ser. 2019;1378(3):1-9. https://doi.org/10.1088/1742-6596/1378/3/032096

[18] Alwash M, Breysse D, Sbartaï ZM, Szilágyi K, Borosnyói A. Factors affecting the reliability of assessing the concrete strength by rebound hammer and cores. Constr Build Mater [Internet]. 2017;140:354-63. https://doi.org/10.1016/j.conbuildmat.2017.02.129

[19] El Mir A, Nehme SG. Repeatability of the rebound surface hardness of concrete with alteration of concrete parameters. Constr Build Mater [Internet]. 2017;131:317-26. https://doi.org/10.1016/j.conbuildmat.2016.11.085

[20] Breysse D. Nondestructive evaluation of concrete strength: An historical review and a new perspective by combining NDT methods. Constr Build Mater [Internet]. 2012;33:139-63. https://doi.org/10.1016/j.conbuildmat.2011.12.103

[21] IS 13311-1 : 1992. Non-Destructive Testing of Concrete - Part 1: Ultrasonic Pulse Velocity. New Delhi; 2004.

[22] Nawy EG. Concrete Construction Engineering Handbook. Second. CRC Press; 2008. https://doi.org/10.1201/9781420007657.ch17

[23] Malhotra VM, Carino NJ. Handbook on Nondestructive Testing of Concrete [Internet]. CRC Press; 2004. (Civil engineering). https://doi.org/10.1201/9781420040050

[24] Carette GG, Malhotra VM. In Situ Tests: Variability and Strength Prediction of Concrete at Early Ages. ACI Symp Publ. 2014;82:114-42.

[25] Ali-Benyahia K, Sbartaï ZM, Breysse D, Kenai S, Ghrici M. Analysis of the single and combined non-destructive test approaches for on-site concrete strength assessment: General statements based on a real case-study. Case Stud Constr Mater [Internet]. 2017;6:109-19. https://doi.org/10.1016/j.cscm.2017.01.004

[26] Jain A, Kathuria A, Kumar A, Verma Y, Murari K. Combined use of non-destructive tests for assessment of strength of concrete in structure. Procedia Eng [Internet]. 2013;54:241-51. https://doi.org/10.1016/j.proeng.2013.03.022

[27] Bilgin N, Copur H, Balci C. Use of Schmidt Hammer with special reference to strength reduction factor related to cleat presence in a coal mine. Int J Rock Mech Min Sci. 2016;84:25-33. https://doi.org/10.1016/j.ijrmms.2016.01.016

[28] Demirdag S, Yavuz H, Altindag R. The effect of sample size on Schmidt rebound hardness value of rocks. Int J Rock Mech Min Sci. 2009;46(4):725-30. https://doi.org/10.1016/j.ijrmms.2008.09.004

[29] Kim J-K, Kim C-Y, Yi S-T, Lee Y. Effect of carbonation on the rebound number and compressive strength of concrete. Cem Concr Compos [Internet]. 2009;31(2):139-44. https://doi.org/10.1016/j.cemconcomp.2008.10.001

[30] Brožovský J, Matejka O, Martinec P. Concrete Interlocking Paving Blocks Compressive Strength Determination Using Non-destructive Methods. In: The 8th International Conference of the Slovenian Society for Non-Destructive Testing. Portoroz, Slovenia; 2005. p. 91-7.

[31] BS 4550-3.1. British Standard Methods of testing cement - Part 3: Physical Tests. Vol. 3. London; 1978.

[32] ASTM C150/C150M-18. Standard Specification for Portland Cement [Internet]. West Conshohocken, PA; 2018. Available from: www.astm.org

[33] Volzenski AV. Mineral binding materials. 4th ed. Stroyizdat, Moscow, Russia; 1986.

[34] Odeyemi SO, Adisa MO, Atoyebi OD, Wilson UN, Odeyemi OT. Optimal water-cement ratio and volume of superplasticizers for blended cement-bamboo leaf ash high-performance concrete. Res Eng Struct Mater. 2022;x(xxxx):1-13. https://doi.org/10.17515/resm2022.382ma0108

[35] Sadiq OM, Atoyebi OD. Flexural Strength Determination of Reinforced Concrete Elements with Waste Glass as Partial Replacement for Fine Aggregate. NSE Tech Trans J Niger Soc Eng. 2015;49(2):74-81.

[36] Atoyebi OD, Sadiq OM. Experimental data on flexural strength of reinforced concrete elements with waste glass particles as partial replacement for fine aggregate. Data Br [Internet]. 2018;18:846-59. https://doi.org/10.1016/j.dib.2018.03.104

[37] BS1881-116. BS 1881 Part 116-1983. Testing Concrete: Method for determination of compressive strength of cubes. UK; 1983.

[38] BS EN 1338. British Standard Testing Concrete paving blocks. Requirements and test methods. West Conshohocken, PA, USA:; 2006.

[39] BS 7941-2:2000. Methods for measuring the skid resistance of pavement surfaces. UK; 2000.

[40] IS 15658:2006. Precast Concrete blocks for paving - Specification. New Delhi; 2006.]