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Statistical models for concrete containing wood chipping as partial replacement to fine aggregate

Bashar S. Mohammed [a,*], M. Abdullahi [b], C.K. Hoong [c]

[a] Civil Engineering Department, Universiti Teknologi PETRONAS, Bandar Seri Iskandar, 31750 Tronoh, Perak Darul Ridzuan, Malaysia
[b] Civil Engineering Department, Federal University of Technology, Minna, Nigeria
[c] Civil Engineering Department, Universiti Tenaga Nasional, Malaysia

HIGHLIGHTS

- Wood chipping can be used as lightweight aggregate for the production of lightweight concrete.
- Utilization of wood chipping as partial replacement to sand in concrete is feasible and appropriate.
- Different wood chipping percentages in concrete were studied and evaluated.
- Statistical models were developed and validated to provide a design mix aid of concrete containing wood chipping.

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ABSTRACT

The properties of concrete containing wood chippings as partial replacement to fine aggregate are presented in this paper. Wood chipping was treated by water before mixing to prevent it from soaking the water meant for cement hydration. Fifteen trial mixes were prepared and cast using three water–cement ratios (0.37, 0.41 and 0.57) at different replacement levels of wood chippings. Fresh concrete properties tested included slump, unit weight and air content. Hardened concrete properties tested included compressive strength, splitting tensile strength, flexural strength, modulus of elasticity, rebound hammer (RH) and ultrasonic pulse velocity (UPV). Several statistical models were developed to show the relationships between measured responses and variables and among measured responses. These models were validated using various model statistics. Test results show that disposal of wood chipping in concrete is feasible and appropriate. These models are providing a design mix aid of concrete containing wood chipping as partial replacement of fine aggregate.

1. Introduction

Increase in population has created greater demand on construction material which leads to a chronic shortage of building materials and thereby increases the construction cost. To alleviate this problem, engineers are not only challenged with the future home-building in terms of construction cost control but also the need to convert the industrial wastes to useful construction and building materials. One of such ways is to introduce industrial waste material into concrete. Such waste materials are wood chipping, paper mill, crumb rubber and palm oil clinker. The utilization of these waste reduce the use of aggregate from natural sources and ensures sustainability [1,2].

Concrete containing waste wood product as aggregates is one kind of lightweight concrete. The advantages of lightweight concrete are higher strength-to-weight ratio, better tensile strain capacity, lower coefficient of thermal expansion, and superior heat and sound insulation [3–5]. In addition, the using of lightweight concrete will cause a reduction in the building cost, ease the construction and has the advantage of being a relatively 'green' building material [6]. However, lightweight concrete has its associated disadvantages, such as low workability and lower indirect tensile strength. The problems arising from these shortcomings have been dealt with through adding of mineral admixtures and superplastizer to concrete mixture to obtain higher workability [4,7].

Several researches have studied the utilization of waste wood product as lightweight aggregates [5,8–12]. It has been reported that concrete containing wood waste can be produced as structural lightweight concrete with a good thermal conductivities compared to sand concrete without wood waste [10]. Besides, concrete containing wood waste displays a reasonable strength and durability and complies with class III RILEM specification for lightweight concrete [11]. Though, adverse effects of inclusion of waste wood in concrete such as reductions in the strengths of the hardened

* Corresponding author. Tel.: +60 53687305, +60 135882880; fax: +60 53656716.
E-mail addresses: bashar.mohammed@petronas.com.my, bashar_sami@hotmail.com (B.S. Mohammed).

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concrete have also been reported [5,11], however, suggestions on treatment of waste wood before inclusion in concrete to overcome the strength reductions have been made [6,11,12].

Although many experimental works have been carried out to establish the fresh and hardened properties of the concrete containing waste wood as aggregate, yet no models have been introduced to predict the properties of such concrete. Therefore, the main aim of the work presented in this paper is to establish statistical models to predict the properties of concrete containing wood chipping as a partial replacement to fine aggregate.

2. Materials

2.1. Portland cement, fine and coarse aggregates

The cement used in all mixtures was Portland cement (PC) type I, which conform to the requirement of ASTM C150. The coarse aggregate used were crushed stone graded as a 9.5 mm nominal maximum size, with a bulk density of 1571 kg/m^3, a specific gravity of 2.28, and 0.81% absorption. The fine aggregate (river sand) had a bulk density of 1573.6 kg/m^3, a specific gravity of 2.34, 7.88% absorption, and a fineness modulus of 2.45. Physical properties of coarse and fine aggregate were performed according to ASTM C127 and ASTM C128, respectively.

2.2. Wood chippings

The wood chipping used in this study is generated in the factory from the mechanical processing of raw wood in the sawing process, with bulk density of 257.7 kg/m^3, a specific gravity of 0.288, and 290.2% absorption.

3. Mixture proportions

The mixture proportions and fresh properties of the concrete mixtures produced in the laboratory are shown in Table 1. A total of 15 concrete mixtures were produced. Three water cement ratio had been used, 0.37, 0.41, and 0.57. Four levels of wood chipping partially replaced to fine aggregate by volume, 10%, 15%, 20% and 30% for each water cement ratio. Additional water at each specified water cement ratio required due to higher water absorption of wood chipping (290.2%) to produce workable concrete mixtures. Table 2 shows the amount of additional water needed. Eq. (1) used to calculate the additional water added.

$$Mass\,of\,additional\,water = \frac{Difference\,in\,absorption}{100} \times mass\,of\,wood\,chipping \quad (1)$$

where difference in absorption = absorption of wood chipping – absorption of sand.

Table 2
Amount of additional water at various water–cement ratio and percentage replacement of sand by wood chipping.

w/c Ratio	Wood chipping replacement by volume (%)	Wood chipping replacement (kg/m^3)	Mass of additional water (kg/m^3)
0.37	0	0	0
	10	4.857	13.72
	15	7.288	20.58
	20	9.715	27.44
	30	14.57	41.15
0.41	0	0	0
	10	12.71	35.89
	15	19.01	53.68
	20	25.41	71.45
	30	38.11	107.61
0.57	0	0	0
	10	14.17	40.01
	15	21.26	60.03
	20	28.32	79.96
	30	42.50	120.00

4. Experimental program

After mixing and before the concrete were poured into the mould, slump, unit weight and air content tests were conducted. From each concrete mixture, 100 mm cubic specimens were cast to determine the compressive strength, 150 × 300 mm cylinders were cast for the compressive strength, splitting tensile strength, modulus elasticity, and non-destructive tests, 100 × 100 × 500 mm prisms were cast for the flexural strength tests. Table 3 shows the number of specimens and test standards.

4.1. Fresh concrete tests

The slump tests were performed according to ASTM C143 on all the concrete mixtures to determine the consistency and workability. The air content and unit weight tests were performed using gravimetric methods according to ASTM C138.

4.2. Hardened concrete tests

Mechanical properties were investigated to determine the compressive, splitting tensile, flexural and static modulus of elasticity. Non-destructive tests (Rebound hammer and ultrasonic pulse velocity tests) were also carried out. The mechanical

Table 1
Mix proportion at different water–cement ratio.

w/c Ratio	Wood chipping replacement		Cement (kg/m^3)	Fine aggregates (kg/m^3)	Coarse aggregates (kg/m^3)	Water (kg/m^3)	Air content (%)	Slump (mm)	Unit weight (kg/m^3)
	%	kg/m^3							
0.37	0	0	656.76	297.18	801.21	243	7	30	1915.43
	10	4.857	656.76	267.43	801.21	243	10.1	110	1808.00
	15	7.288	656.76	252.12	801.21	243	11.7	150	1754.64
	20	9.715	656.76	237.30	801.21	243	14	180	1687.84
	30	14.57	656.76	207.64	801.21	243	19	210	1554.15
0.41	0	0	592.68	775.96	673.35	243	9.1	50	1889.96
	10	12.71	592.68	698.36	673.35	243	12.3	135	1733.99
	15	19.01	592.68	659.50	673.35	243	14.3	175	1649.64
	20	25.41	592.68	620.79	673.35	243	16.7	210	1562.11
	30	38.11	592.68	543.21	673.35	243	21.3	240	1402.16
0.57	0	0	426.32	865.00	750.65	243	11.3	72	1836.65
	10	14.17	426.32	778.46	750.65	243	14.8	175	1660.78
	15	21.26	426.32	735.19	750.65	243	17.4	220	1563.70
	20	28.32	426.32	692.07	750.65	243	19.7	245	1476.96
	30	42.50	426.32	605.52	750.65	243	23.6	260	1328.15

Table 3
Number of specimens and standard test methods.

Test	Number	Standard
Compressive strength – Cube	45	BS EN 12390-3
Compressive strength – Cylinder	45	ASTM C39
Splitting tensile strength	45	ASTM C496
Flexural strength	45	ASTM C293
Static modulus elasticity	45	ASTM C469
Pulse velocity	15	ASTM C597
Rebound hammer	15	ASTM C805

and non-destructive tests results reported are average of three tested specimens in the respective tests.

100 mm Cube specimens were used to determine the compressive strengths at 28 days in accordance with the requirements of BS EN 12390-3. Compressive strength, splitting tensile strength and static modulus of elasticity on 150 × 300 mm cylinders were carried out at 28 days according to the requirements of ASTM C39, ASTM C496 and ASTM C469, respectively. Prisms specimens (100 × 100 × 500 mm) used for flexural strength tests carried out at 28 days curing age whereas centre-point loading method conforming to ASTM C293 was employed.

Non-destructive tests, rebound hammer and ultrasonic pulse velocity tests, were carried out using the method described in the ASTM C805 and ASTM C597, respectively.

4.3. Model development

Models were developed from the experimental data to show the relationships between measured responses and variables, and among measured responses. These models are indicated on the figures in this work. Microsoft Excel package was used for the model development since all the models considered here is one parameter model. Linear transformations of the variable were done where the models are non-linear. This is to allow validation of the models through statistical analysis since the excel package can only perform linear regression. The regression was done at 95% confidence interval.

5. Results and discussions

5.1. Fresh concrete containing wood chipping

The slump test results are presented in Table 1. The slump increased when the wood chipping content and water/cement ratio increased as shown in Fig. 1. The wood chipping absorbs higher water compared to fine aggregates. The increase in slump was due to the additional water added into the concrete mixtures. With added water, the wood chipping has the tendency to have the sponge characteristic. The bunch of saturated surface dry wood chipping easily looses its water content during mixing thereby leading to increase in slump of the mixture.

The unit weight of concrete mixtures containing wood chipping decreased compared to the control specimens presented in Table 1. Test result also showed reduction in unit weight as the wood chipping replacement increased as shown in Fig. 2. The reduction in unit weight was because the replaced wood chipping (specific gravity = 0.288) is lighter than fine aggregate (specific gravity = 2.34).

The air content of concrete containing wood chipping is presented in Table 1 and Fig. 3. Air content increased as the replacement of wood chipping increased. During the compaction, the water squeezed out from the wood chipping, leaving an unoccupied void inside the wood chipping. These voids are occupied by air.

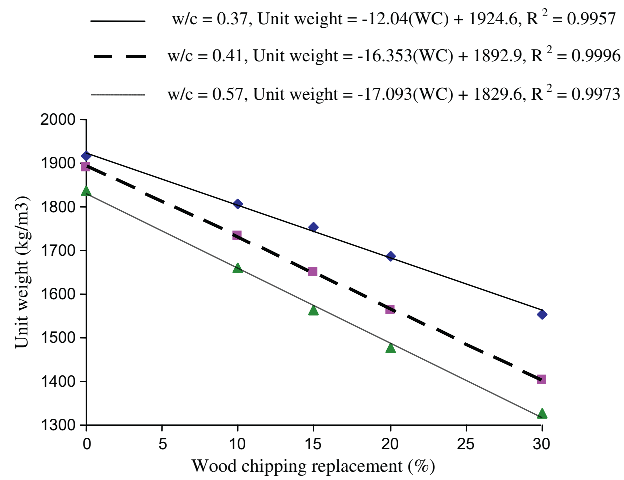

Fig. 2. Unit weight versus percentage of wood chipping replacement.

5.2. Hardened concrete containing wood chipping

The results for compressive, splitting tensile, flexural strength and static modulus elasticity are given in Table 4. The compressive strength, splitting tensile strength, flexural strength and static modulus of elasticity of concrete containing wood chipping decreased as the wood chipping replacement increased. Meanwhile, as the water–cement ratio increased also contributed to the reduction in overall strength. Wood chipping possesses a spongy characteristic when in contact with water and compresses easily. This is

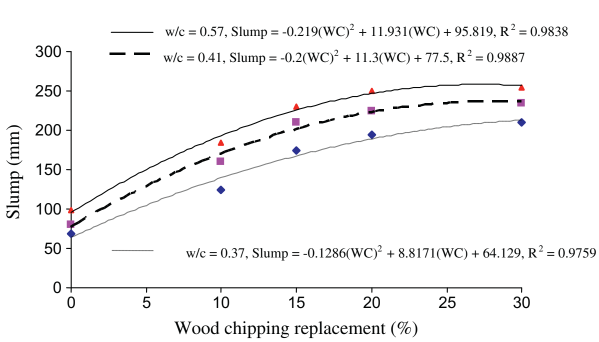

Fig. 1. Slump versus percentage of wood chipping replacement.

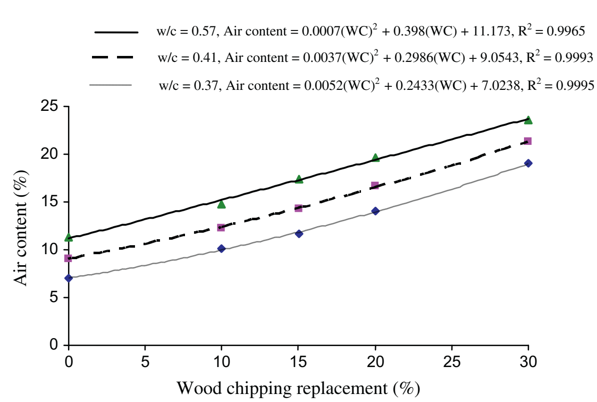

Fig. 3. Air content versus percentage of wood chipping replacement.

Table 4
Mechanical properties of wood chipping concrete.

w/*c* Ratio	Replacement percentage by volume (%)	Compressive strength – Cube (MPa)	Compressive strength – Cylinder (MPa)	Splitting tensile strength (MPa)	Flexural strength (MPa)	Static modulus of elasticity (Gpa)
0.37	0	50.45	40.3	3.58	7.03	22.59
	10	46.40	36.5	3.26	6.39	19.99
	15	39.67	33.2	3.15	5.91	18.38
	20	34.68	28.6	3.04	5.04	17.37
	30	31.61	17.3	2.41	4.78	14.26
0.41	0	47.28	32.5	3.30	6.47	18.58
	10	40.55	28.3	2.91	5.70	16.04
	15	35.16	25.4	2.79	5.04	14.27
	20	30.96	21.1	2.59	4.51	13.40
	30	26.48	10.6	2.15	4.30	10.34
0.57	0	42.92	23.7	2.86	6.10	15.23
	10	37.52	19.4	2.65	5.02	12.73
	15	29.86	16.0	2.33	4.72	10.72
	20	25.16	13.2	2.16	4.25	9.58
	30	23.32	6.1	1.86	3.87	7.16

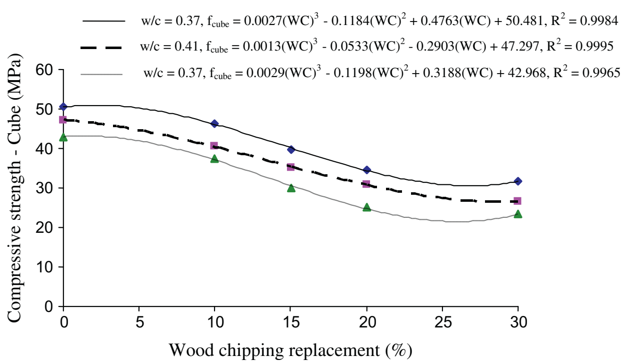

Fig. 4. Compressive strength (cube) versus percentage of wood chipping replacement.

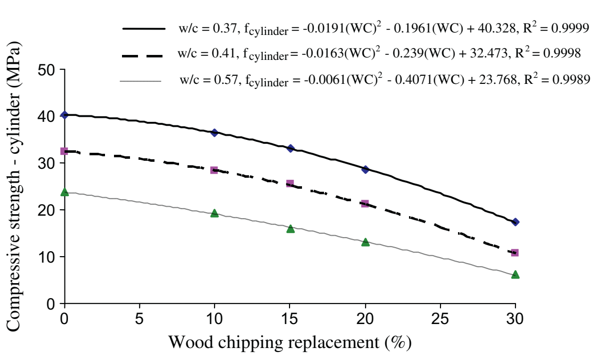

Fig. 5. Compressive strength (cylinder) versus percentage of wood chipping replacement.

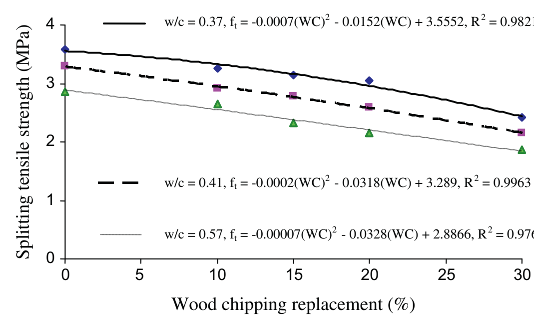

Fig. 6. Splitting tensile strength versus percentage of wood chipping replacement.

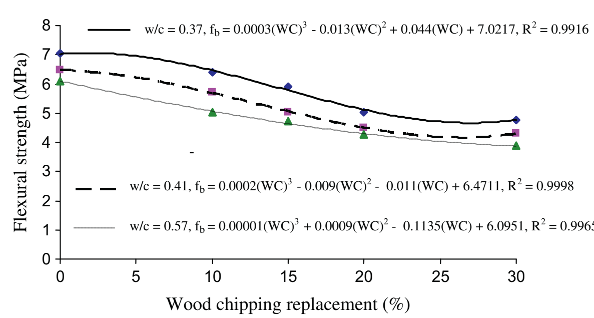

Fig. 7. Flexural strength versus percentage of wood chipping replacement.

responsible for the earlier crack formation between the weak bonding of concrete matrix and wood chipping upon application of load. It is believed that air content within the concrete matrix is responsible for reduce in overall specific surface bonding of the concrete and act as stress concentration [13]. Increase in water–cement ratio tends to lower the cement content of the mixtures leading to a decrease in strength. Figs. 4–8 shows the relationships of compressive-cube, compressive-cylinder, splitting tensile, flexural and static modulus elasticity versus wood chipping replacement.

Fig. 9 shows the relationship between compressive strength (cylinder) and flexural strength for wood chipping concrete. Equation relating compressive strength, f_c and flexural strength, f_f for conventional concrete used in ACI is $f_f = 0.62\sqrt{f_c}$. For concrete containing wood chipping concrete similar equation derived in this work is $f_f = 1.0992\sqrt{f_c}$, $R^2 = 0.9902$. Fig. 10 shows the relationship between compressive strength and splitting tensile strength for conventional and wood chipping concrete. According to ACI, $f_t = 0.55\sqrt{f_c}$. For wood chipping concrete the equation relating compressive strength and splitting tensile strength was found to be $f_t = 0.9191 f_c^{0.3524}$, $R^2 = 0.9553$.

5.3. Non-destructive tests wood chipping concrete

The results for non-destructive tests are shown in Table 5. The rebound number (RN) and ultrasonic pulse velocity (UPV) decreased as the percentage of wood chipping replacement increased. Wood chipping is a highly compressible material that resisted the impact of rebound hammer, resulting in a reduction

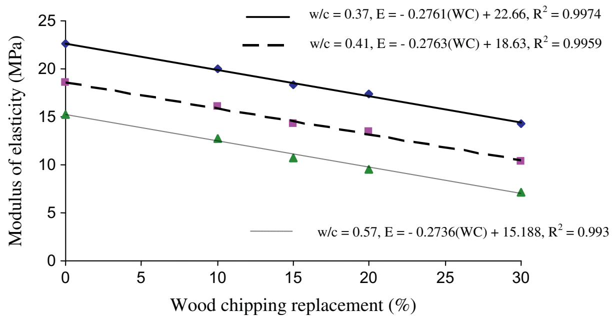

Fig. 8. Modulus of elasticity versus percentage of wood chipping replacement.

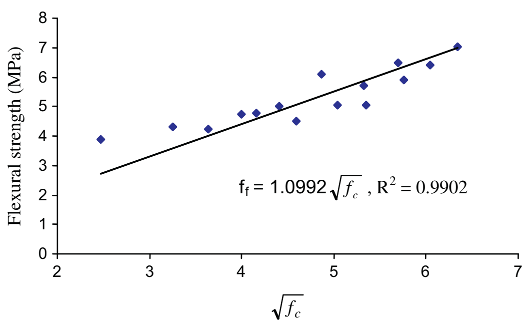

Fig. 9. Flexural strength versus compressive strength (cylinder) of concrete.

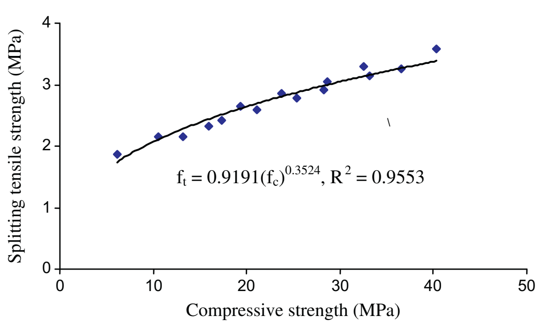

Fig. 10. Splitting tensile strength versus compressive strength (cylinder) of concrete.

Table 5
Rebound number and ultrasonic pulse velocity.

w/c Ratio	Percentage replacement by volume (%)	Rebound number	Ultrasonic pulse velocity (m/s)
0.37	0	43.5	4452.7
	10	37.3	4193.6
	15	36.2	4100.9
	20	34.8	4061.8
	30	30.2	3959.4
0.41	0	35.1	4229.7
	10	30.1	3946.1
	15	26.7	3851.1
	20	24.2	3775.8
	30	21.3	3628.0
0.57	0	28.5	3912.5
	10	24.7	3602.7
	15	22.1	3511.2
	20	20.9	3434.1
	30	17.1	3294.3

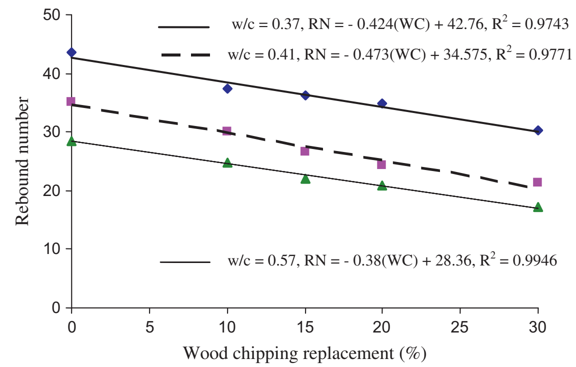

Fig. 11. Rebound number versus percentage of wood chipping replacement.

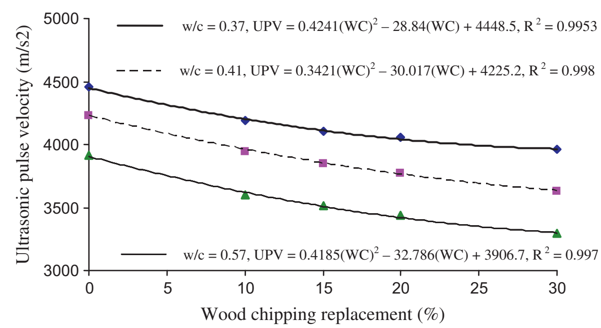

Fig. 12. Ultrasonic pulse velocity versus percentage of wood chipping replacement.

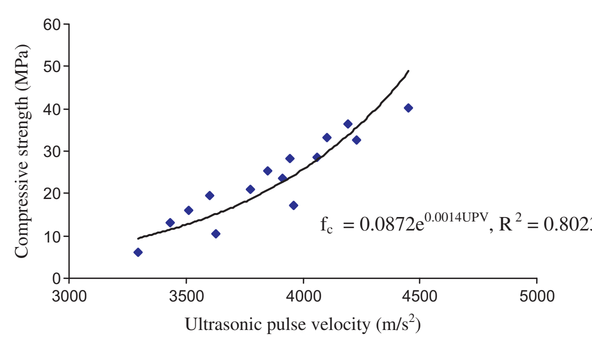

Fig. 13. Compressive strength versus ultrasonic pulse velocity.

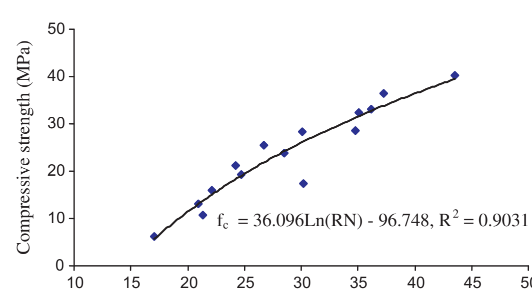

Fig. 14. Compressive strength versus rebound number.

in RN. The RN decreased as the water/cement ratio increased as shown in Fig. 11. This is due to the surface hardness, directly affected by the concrete strength. The UPV decreased as wood chipping content increased as shows in Fig. 12. The air content in the concrete matrix is responsible for the reduction in UPV in the sense that the UPV travels faster in air than in solid.

5.4. Models for RN versus wood chipping replacement

The models relating RN to wood chipping replacement is shown in Fig. 11. For all water–cement ratios, the linear models show that RN decreases as the percentage of wood chipping replacement increases. Wood chipping is softer than sand and weakens the concrete as it replaces sand. This reduces the hardness of the concrete surface. This has the effect of reducing the RN of the concrete.

5.5. Models for UPV versus wood chipping replacement

The models relating UPV to wood chipping replacement is shown in Fig. 12. The quadratic model shows that UPV decreases as the wood chipping replacement increases. As the wood chipping increases, the density of concrete decreases and allows more air voids in the hardened concrete. This reduces the propagation of ultrasonic pulse velocity.

5.6. Correlation between compressive strength with UPV and RN for concrete containing wood chipping

Correlations were made to determine the relationship between compressive strength with UPV and rebound number at 28 days. The correlation curves as shown in Figs. 13 and 14 were based on the results of UPV, RH and compressive strength tests obtained using w/c ratio of 0.37, 0.41 and 0.57. It can be observed that, the strength of concrete containing wood chipping increased as the UPV and rebound number increased.

The best fit lines representing the relationship between compressive strength with UPV at an age of 28 days is given as:

$$f_c = 0.0872e^{0.0014\mathrm{UPV}}, \quad R^2 = 0.8023 \tag{2}$$

where UPV and f_c are the ultrasonic pulse velocity (m/s) and compressive strength (MPa), respectively, at 28 days. The R^2 value was found to be 0.8023.

The relationship between compressive strength and RN at 28 days is shown in Fig. 14. The best fit line is given as:

$$f_c = 36.096\mathrm{Ln}(\mathrm{RN}) - 96.748, \quad R^2 = 0.9031 \tag{3}$$

where RN and f_c are the rebound number and compressive strength (MPa) at 28 days respectively. The R^2 value was found to be 0.9031.

5.7. Model statistics

The regression output for the statistical analysis is shown in Table 6. The models relating slump to percentage of wood chipping replacement is shown in Fig. 1. The regression output is shown in Table 6. For w/c = 0.57, the adjusted coefficient of determination (adjusted R^2) is very high, about 0.9917. This means that about 99.17% of the variability in slump is accounted for by the regression model. This result suggests that the developed model is adequate to explain the data. The p-value for the constant term

Table 6
Regression output.

Relationship		R^2	Adjusted R^2	F_0	Significance of regression	p-Value	
						Intercept	Variable
1. Slump versus % of wood chipping replacement	w/c = 0.57	0.9938	0.9917	480.78	2.08×10^{-04}	4.31×10^{-04}	2.08×10^{-04}
	w/c = 0.41	0.9887	0.9849	261.81	5.14×10^{-04}	1.823×10^{-03}	5.14×10^{-04}
	w/c = 0.37	0.9759	0.9679	121.73	1.595×10^{-03}	6.499×10^{-03}	1.595×10^{-03}
2. Unit weight versus % of wood chipping replacement	w/c = 0.37	0.9957	0.9943	693.33	1.2×10^{-04}	1.71×10^{-07}	1.2×10^{-04}
	w/c = 0.41	0.9996	0.9995	8346.40	2.89×10^{-06}	1.09×10^{-08}	2.89×10^{-06}
	w/c = 0.57	0.9973	0.9965	1125.80	5.82×10^{-05}	2.79×10^{-07}	5.82×10^{-05}
3. Air content versus % of wood chipping replacement	w/c = 0.57	0.9965	0.9953	854.71	8.79×10^{-05}	2.621×10^{-05}	8.79×10^{-05}
	w/c = 0.41	0.9993	0.9991	4406.13	7.53×10^{-06}	3.52×10^{-06}	7.53×10^{-06}
	w/c = 0.37	0.9995	0.9994	6551.62	4.16×10^{-06}	3.58×10^{-06}	4.16×10^{-06}
4. Compressive strength (cube) versus % of wood chipping replacement	w/c = 0.37	0.9981	0.9975	1610.28	3.41×10^{-05}	4.72×10^{-07}	3.41×10^{-05}
	w/c = 0.41	0.9991	0.9988	3207.70	1.21×10^{-05}	2.69×10^{-07}	1.21×10^{-05}
	w/c = 0.57	0.9964	0.9952	826.034	9.25×10^{-05}	2.83×10^{-06}	9.25×10^{-05}
5. Compressive strength (cylinder) versus % of wood chipping replacement	w/c = 0.37	0.9999	0.9998	21212.58	7.14×10^{-07}	1.93×10^{-08}	7.14×10^{-07}
	w/c = 0.41	0.9998	0.9997	13606.99	1.39×10^{-06}	6.37×10^{-08}	1.39×10^{-06}
	w/c = 0.57	0.9989	0.9986	2815.64	1.47×10^{-05}	1.11×10^{-06}	1.47×10^{-05}
6. Splitting tensile strength versus % of wood chipping replacement	w/c = 0.37	0.9706	0.9608	98.98	2.161×10^{-03}	8.82×10^{-06}	2.161×10^{-03}
	w/c = 0.41	0.9963	0.9951	811.439	9.5×10^{-05}	7.69×10^{-07}	9.5×10^{-05}
	w/c = 0.57	0.9760	0.9680	121.80	1.593×10^{-03}	1.64×10^{-05}	1.593×10^{-03}
7. Flexural strength versus % of wood chipping replacement	w/c = 0.37	0.9916	0.9888	354.36	3.27×10^{-04}	2.92×10^{-06}	3.27×10^{-04}
	w/c = 0.41	0.9634	0.9513	79.07	0.003	3.09×10^{-05}	0.003
	w/c = 0.57	0.9389	0.9186	46.13	0.0065	7.4×10^{-05}	0.0065
8. Modulus of elasticity versus % of wood chipping replacement	w/c = 0.37	0.9974	0.9965	1144.90	5.67×10^{-05}	6.03×10^{-07}	5.67×10^{-05}
	w/c = 0.41	0.9959	0.9945	726.109	1.12×10^{-04}	2.09×10^{-06}	1.12×10^{-04}
	w/c = 0.57	0.9930	0.9907	427.85	2.47×10^{-04}	8.53×10^{-06}	2.47×10^{-04}
9. Flexural strength versus $\sqrt{f_{cylinder}}$		0.9902	0.9188	1414.28	1.19×10^{-14}	NA	1.83×10^{-15}
10. Splitting tensile strength versus compressive strength		0.9987	0.9273	10835.33	2.23×10^{-20}	NA	1.25×10^{-21}
11. Rebound number versus % of wood chipping replacement	w/c = 0.37	0.9743	0.9657	113.69	1.763×10^{-03}	1.04×10^{-05}	1.763×10^{-03}
	w/c = 0.41	0.9771	0.9695	127.92	1.482×10^{-03}	2.28×10^{-05}	1.482×10^{-03}
	w/c = 0.57	0.9946	0.9928	552.55	1.69×10^{-04}	2.39×10^{-06}	1.69×10^{-04}
12. UPV versus % of wood chipping replacement	w/c = 0.37	0.9953	0.9938	637.63	1.36×10^{-04}	6.05×10^{-08}	1.36×10^{-04}
	w/c = 0.41	0.9980	0.9973	1460.61	3.94×10^{-05}	3.2×10^{-08}	3.94×10^{-05}
	w/c = 0.57	0.9970	0.9959	983.05	7.13×10^{-05}	8.43×10^{-08}	7.13×10^{-05}
13. Compressive strength (cylinder) versus UPV		0.9734	0.9020	512.99	7.86×10^{-12}	NA	7.86×10^{-12}
14. Compressive strength (cylinder) versus rebound number		0.9031	0.8956	121.137	5.85×10^{-08}	7.45×10^{-07}	5.85×10^{-08}

and variable are 0.000431 and 0.000208 respectively. This implies that the contribution of the constant term (intercept) and the variables in the model are significant and should be retained in the model.

From the analysis of variance (ANOVA), the *F* test for significance of regression is $F_0 = 408.78$. The calculated F_0 is compared with the theoretical value and a *p*-value for the significance of regression is obtained as 0.000208. Therefore, the hypothesis that the coefficient of the variables in the model should be zero is rejected because the *p*-value is very small (0.000208 is less that 0.05); suggesting that at least some of these parameters are nonzero and the terms contribute significantly to the model. The ANOVA test suggests that the developed model adequately explains the data. Similar explanations apply to other models using the appropriate model statistics shown in Table 6. The model statistics favour the acceptability of all the models indicated in Figs. 1–14.

6. Conclusion

Based on the results presented, the following conclusions can be drawn:

1. The workability of the wood chipping concrete increases as the wood chipping content increases.
2. The unit weight of fresh wood chipping concrete decreases and air content of fresh wood chipping concrete increases as wood chipping content increases.
3. Replacement of fine aggregate by wood chipping in concrete results in reduction of strength.
4. Increase in wood chipping content leads to reduction in ultrasonic pulse velocity and rebound number.
5. Several models have been proposed and validated to predict the properties of wood chipping concrete.
6. Utilization of wood chippings for production of concrete is feasible and appropriate.

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