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Development of 3d-Printable Concrete

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Abstract: *3D- printable concrete technology is an emerging technology that builds the digital model to a real structure through layer-by-layer printing process. The whole construction of the 3D-object is done automatically by a printer. When compared with conventional construction processes, the application of 3D printing techniques in concrete construction offers, Reduction of construction costs by eliminating formwork. The concrete mix mentioned in this journal consist of the materials such as Cement, Quarry dust, Metakaolin, Polypropylene fiber, PCE based superplasticizer and Viscosity Modifying Agent (VMA). In this study a mathematical model is proposed and developed using multivariate regression equation for the prediction of concrete compressive strength & flexural strength at different ages. The variables used in the prediction models were from the knowledge of the mix itself, i.e., mix proportion elements (cement, water, sand, and density. This paper also describes the development of 3D-printable concrete by doing certain material characterizations and an attempt is made to develop a relationship between concrete strength and its constituents and express this relationship with a mathematical model which can be simple to implement. The data of concrete compressive strength from a concrete ready-mix plant was employed in the development of the analytical models; these were validated using the strength results from the presented study and those available in the literature. Attempts were made to keep the models simple so that these could be conveniently used by the professionals and practitioners. The use of models avoids waiting for 28 days to determine the concrete strength.*

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I. INTRODUCTION

Three-dimensional printing (3DP) technology is a manufacturing technique used to create objects based on 3D computer models. Since it is an automated digital construction, it displays advantages over traditional construction method. The main advantages of concrete 3D printing technology are it offers, Reduction of construction costs by eliminating formwork. The cost of printing construction elements of houses is much lower than traditional construction methods. Also, material transportation and storage on sites is limited, Reduction of on-site construction time by operating at a constant rate. Printers can operate 24x7, Reduction of injury rates by eliminating dangerous jobs (e.g., working at heights), which would result in an increased level of safety in construction, Creation of high-end technology-based jobs, creation of complex shapes, less consumption of time, minimum generation of waste, and high productivity.

Concrete has an extremely versatile use in construction due to its availability, flexibility of handling, giving shape to any desired form and as such is the most widely used construction material in use today. Compressive strength of concrete is one of its most important engineering properties. Designing a concrete structure requires the concrete compressive strength to be used. Characteristic strength of the concrete is designated as the compressive strength of a concrete sample that has been cured for 28 days and is determined by the standard cylinder crushing test. In construction works 28 days is a considerable time to wait, while it is essential for quality assurance of concrete and cannot be avoided. Therefore waiting 28 days is mandatory for the confirmation of the quality control process of concrete and the desired strength.

Mathematical models evaluated on the basis of test data of concrete mixes. They allow rapid and reliable prediction of concrete strength without the full-scale testing by reducing the chances of failures. Prediction of concrete strengths, therefore, has been an active area of research and a considerable number of studies have been carried out. In this paper, an attempt is made to develop a relationship between concrete strength and its constituents and express this relationship with a mathematical model which can be simple to implement.

II. MATERIAL AND METHODS

Materials

Materials required for the concrete mix are Portland cement, Quarry dust, VMA (Viscosity modifying agent), Polypropylene fibers, Metakaolin & Superplasticizer.

- Portland cement is the most common type of cement in general use around the world as a basic ingredient of concrete, mortar, stucco, and non-specialty grout. It was developed from other types of hydraulic lime and usually originates from limestone Rapid Hardening Cement (RHC) are also called high early strength cement. The prime difference between the rapid hardening cement and ordinary Portland cement is the lime content. RHC is used where the formwork needs to be removed early for reuse. It is also used on those circumstances where sufficient strength for further construction is wanted as quickly as practicable
- Quarry dust is a waste from the crushing unit which accounts 25%-30% of the final product from stone crushing unit and a reason to cause environmental pollution. Quarry dust can be used as an admixture in concrete efficiently to lessen its impact on environment and human. It can also be used as partial replacement of cement in concrete. The maximum size should be less than or equal to 2 mm for attaining better printing quality. and the size might vary on the type of the printer used.
- The main function of viscosity modifying admixture in a concrete mix is to alter the rheological properties of concrete- especially the plastic viscosity of fresh concrete. Addition of VMA to concrete mix increases the plastic viscosity of concrete and leaves a slight increase in yield point.
- Metakaolin is a high quality pozzolanic material, which when blended with Portland cement improves the strength and durability of concrete and mortars. Metakaolin removes chemically reactive calcium hydroxide from the hardened cement paste. It reduces the porosity of hardened concrete.
- Superplasticizers (SP's), also known as high range water reducers, are additives used in making high strength concrete. Plasticizers are chemical compounds that enable the production of concrete with approximately 15% less water content. Superplasticizers allow reduction in water content by 30% or more.
- polypropylene fiber additions are that cement hydration will be improved, separation of aggregate will be reduced and the flow of water through concrete that causes deterioration from freeze/ thaw action and rebar corrosion will be reduced, creating an environment in which enhanced durability may take place.

Fig.1: Ordinary Portland

Fig.2: Quarry Dust

Fig.3: Polypropylene

Fig.4: Viscosity Modifying Agent

Fig.5: Superplasticizer

Fig.6: Metakaolin

Material Characterizations

- *Consistency Test of cement (IS: 4031 Part 4)*

The standard consistency of cement is that consistency, which permit the Vicat plunger to penetrate to a point 5 to 7mm from the bottom of the Vicat mold when tested. The vicat apparatus showed 6 mm reading at 33.75% water content.

Fig.7: Testing of cement consistency

- *Sieve Analysis (IS: 2720 Part 4-1985)*

The quarry dust is sieved with sieve shaker and aggregate passed through 2.36 mm sieve is used for making the special concrete. The table [1] shows the obtained data got from the test, and certain graphs were plotted with the data. Then the graphs were compared with the values of table [2] then came into the conclusion that the sand belong to the zone ll.

Fig.8: Sieve Shaker

Table 1: Observation of Sieve analysis

Sieve size	Weight retained	% Weight retained	%Cumulative weight retained	% Passing
10 mm	0	0	0	100
4.75 mm	12	1.2	1.2	98.8
2.36 mm	150	15	16.2	83.8
1.18 mm	190	19	35.2	64.8
600 microns	141	14.1	49.3	50.7
425 microns	76	7.6	56.9	43.1
300 microns	71	7.1	64	36
150 microns	140	14	78	22
90 microns	94	9.4	87.4	12.6
Pan	126	12.6	100	0

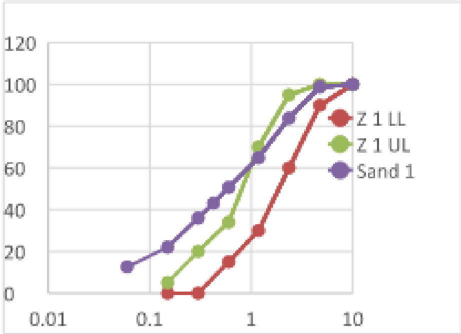


Fig.9: Graph of Zone of Sand 1

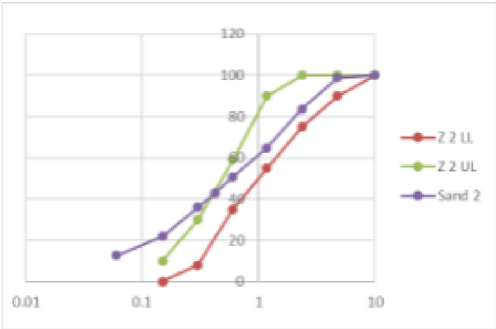


Fig.10: Graph of Zone of Sand 2.

(Sieve size on x-axis and percentage passing on y-axis).

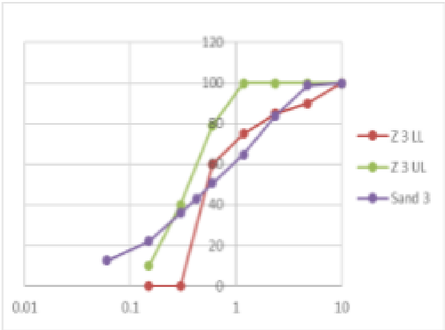


Fig.11: Graph of Zone of Sand 3

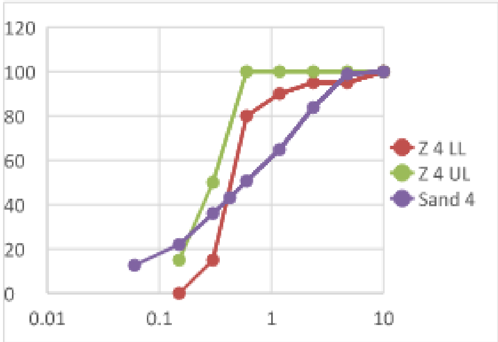


Fig.12: Graph of Zone of Sand 4

Table 2: Fine Aggregate Zone Classification

IS Sieve Designation	Percentage passing by Weight			
	Grading Zone I	Grading Zone II	Grading Zone III	Grading Zone IV
4.75 mm	100	100	100	100
2.36 mm	90-100	90-100	90-100	95-100
1.18 mm	60-95	75-100	85-100	95-100
600 microns	30-70	55-90	75-100	90-100
425 microns	15-34	35-59	60-79	80-100
300 microns	5-20	8-30	12-40	15-50
150 microns	0-10	0-10	0-10	0-15

- *Specific Gravity of Quarry dust, Metakaolin & Cement*

Specific gravity of quarry dust is done using Pycnometer according to IS: 720 Part 3-1980
Specific gravity of metakaolin is done using density bottle according to IS: 2386 (Part II) - 1963
Specific gravity of cement is obtained by Le Chatelier' s flask according to IS: 2720 Part 3

The results are summarized in the table [3] given below,

Table 3: specific gravity of quarry dust, metakaolin, and cement

Components	Specific gravity
Quarry dust	2.88
Metakaolin	2.727
Cement	2.91

Fig.13: Pycnometer

Fig.14: Metakaolin in density bottle

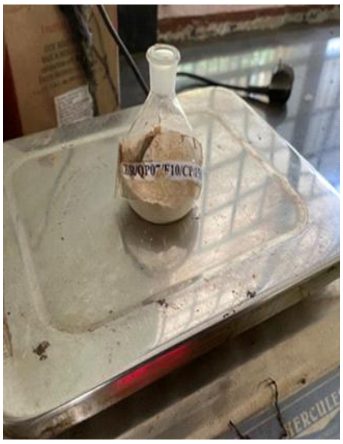


Fig.15: Le Chatelier's flask

Casting of Mortar Cubes

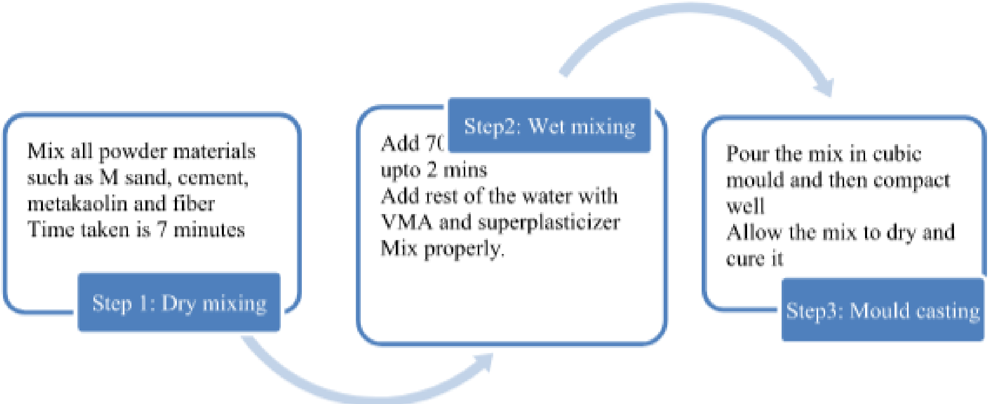


Fig.16: Flow

Fig.17: Casting of mortar cubes

Mix Design

Table 4: Mix design

Mix Components	Mix Design (total weight – 2 kg)			
	Mix 1(gm)	Mix 2(gm)	Mix 3(gm)	Mix 4(gm)
Cement	470	500	515	530
M sand (Quarry Dust)	1300	1172.25	1062.25	1010
Water	195	195	195	195
Metakaolin	82	100	120	135
Superplasticizer	15	15	15	15
VMA	1.5	1.5	1.5	1.5
Polypropylene fiber	1.25	1.25	1.25	1.25
Water/cement ratio	0.41	0.39	0.37	0.36
Density	2047	1967.25	1892.25	1870

Experiments

- *Compressive Strength*

A property-specified mortar needs first to be developed in the laboratory, through a trial-and-error procedure, to determine a mix that meets the property specification of ASTM C270. Trial mixes must be made from the materials to be used at the construction site as specified in the project specifications and be prepared according to the strict specifications outlined in ASTM C270. Higher water content results in lower compressive strength.

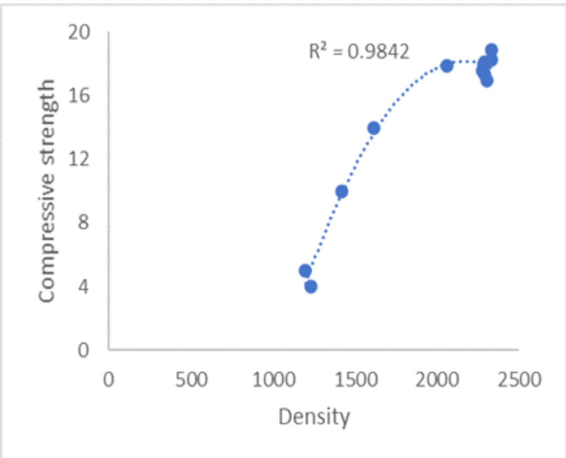
- *Flexural strength*

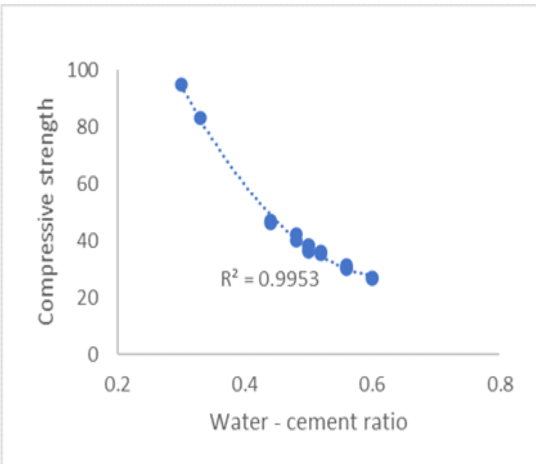
Flexural stress is as important as the compressive strength of concrete. To know the Flexural strength of concrete, the flexural test is performed by both types 3-point load test & center point load. In 3-point load test, the stress goes on the entire middle 1/3th portion uniformly and beam fails at the weakest point in the middle 1/3 portion of the beam. The flexural strength was generally higher at a lower W/C ratio,

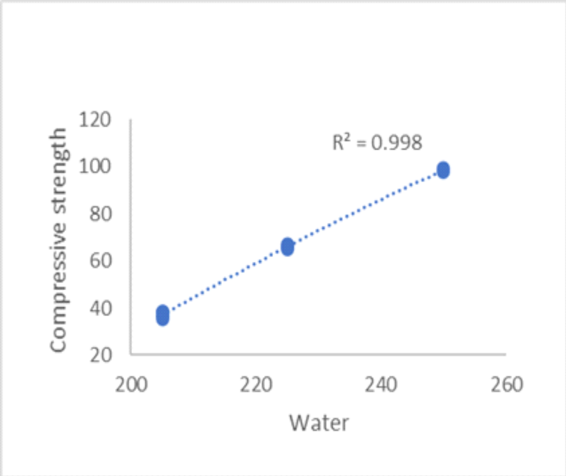
The data used for this study was obtained by conducting certain material characterizations and tests in the laboratory. The data of mix and testing results pertaining to the various grades of concrete ranging in specified are summarized in the table below as well as the correlation of the independent variables to the 28 day compressive strength.

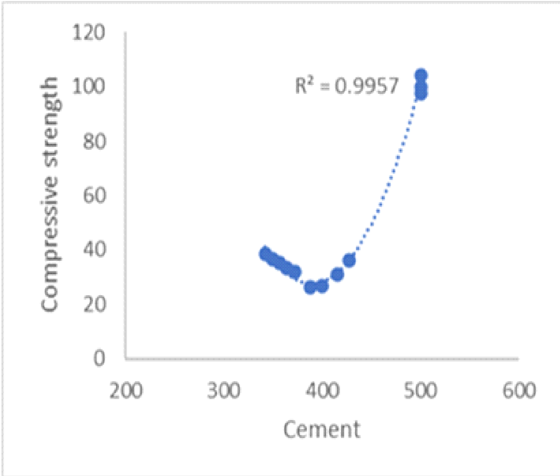
The following figure shows the independent variable parameter correlation (R) with 28 days strengths graphically.

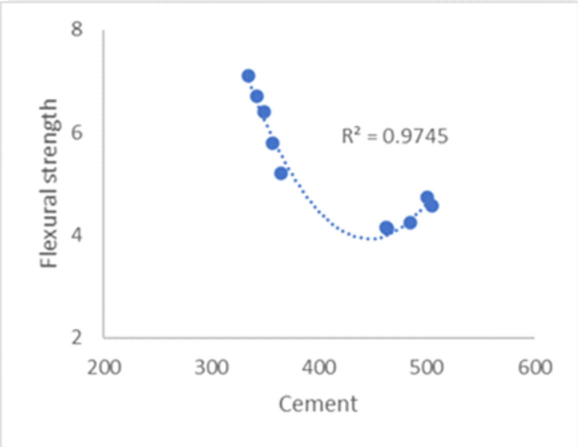
Compressive strength and flexural strength of concrete mortar is calculated in 28 days after curing periods were investigated using regression analysis. Different values of materials and properties were used to compare compressive and flexural strengths. Regression analysis method is used to determine the strengths and each graph are shown below for understanding the effects of each material on compressive strength and flexural strength. They were modeled by linear regression and after the analysis, different R^2 values, P values and equations were obtained are shown in Table 6.

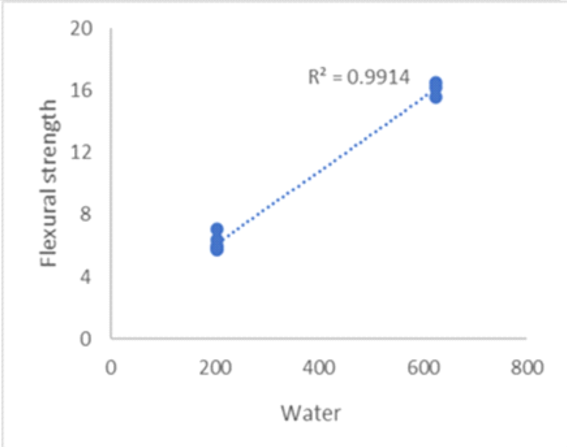












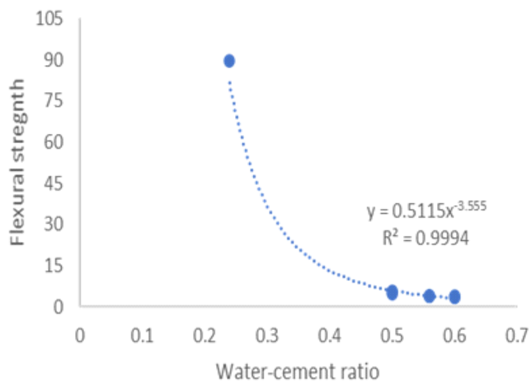


Table 5: Regression analysis outputs

Relation	R^2 Value	P Value
Cement vs Compressive strength	0.9957	0.000185
Cement vs Flexural strength	0.9745	0.00077
W/C ratio vs Compressive strength	0.9953	1.84E - 09
W/C ration vs Flexural strength	0.9994	8.12E - 05
Water vs Compressive strength	0.998	2.27E - 11
Water vs Flexural strength	0.9914	1.75E - 08
Density vs Compressive strength	0.9842	1.48E - 06

R-squared value which is less than 50% is not acceptable and above 50% is acceptable. The R-squared value above 70% have very good measurements and good analysis of physical process. The smaller the p-value, the stronger the evidence that should reject the null hypothesis.

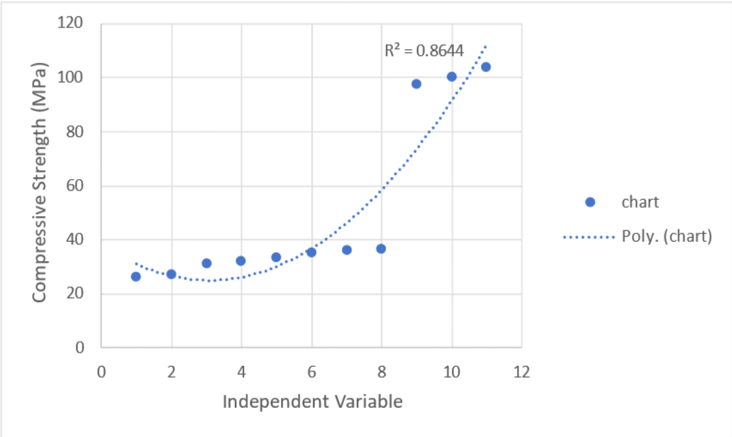
Multiple linear regression is one of the most widely used methods for expressing the dependence between a response (dependent variable) Y, influenced by a set of independent variables X1, X2…...Xm. Often the model parameters or coefficients are predicted by using least squares method. A linear relationship between these variables can be identified as:

$$Y = b0 + b1X1 + b2X2 + \cdots + bmXm$$

III. RESULT & DISCUSSION

The adjusted R^2 is a modified version of R^2 that has been adjusted for the number of predictors in the model. The adjusted R^2 increases only if the new term improves the model more than would be expected by chance. It decreases when a predictor improves the model by less than expected by chance. It is always lower than the R^2. The model with the highest adjusted R^2 and only statistically significant independent variables, P-value < 0.05 was chosen. The MLR 28-day strength prediction model gives an excellent agreement on the unseen validation/testing data. The residual (28-day strength observed - predicted) plots were also employed for model assessment.

Compressive Strength



Summary Output

Regression Statistics	
Multiple R	0.99520452
R Square	0.99043204
Adjusted R Square	0.9840534
Standard Error	4.05541211
Observations	11

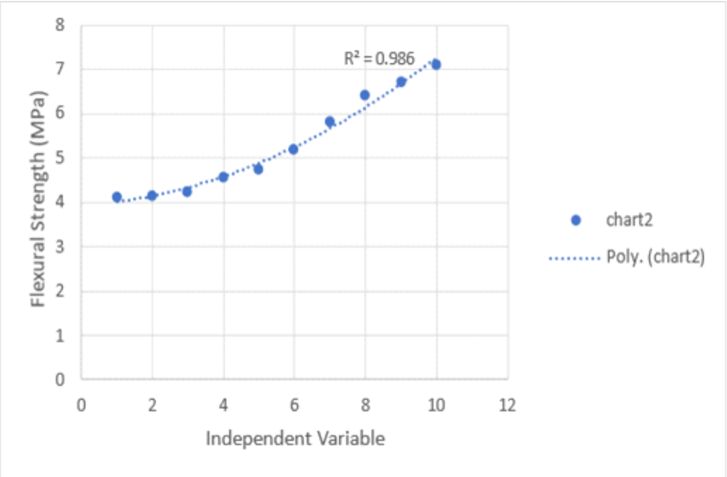
ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	4	10214.72	2553.681	155.2732	3.47849E-06
Residual	6	98.6782	16.44637		
Total	10	10313.4			

	Coefficients	*Standard*	*t Stat*	*P-value*

		Error		
Intercept	160.579835	44.54985	3.604497	0.011305
x2	-243.70281	32.68332	-7.45649	0.0003
x1	0.05218021	0.062596	0.833597	0.436429
x3	0.02277121	0.081259	0.28023	0.788712
x4	-0.0107915	0.006122	-1.76279	0.128398

Flexural Strength



Summary Output

Regression Statistics	
Multiple R	0.951837755
R Square	0.905995111
Adjusted R Square	0.858992667
Standard Error	0.422425394
Observations	10

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	3	10.31874	3.43958	19.27549	0.001752
Residual	6	1.070659	0.178443		
Total	9	11.3894			

	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	-22.60415458	21.88961	-1.03264	0.341587
water	0.160874291	0.10309	1.560523	0.169657
w/c	-3.7279089	1.75253	-2.12716	0.077513
Cement	-0.006897506	0.003139	-2.19766	0.070329

The resulting 28-day strength prediction model for this mix dataset is summarized by the following formulas**:**

28 days compressive strength = [160. + (-243.703) (w/c) 5798 + 0.05218 (cement) + 0.022771 (water) +(-0.01079) (density)]
28 days flexural strength = [-22.60415458 +(-0.006897506) (cement)+(-3.7279089) (w/c) + 0.160874291 (water)]

The results obtained for the mix composition mentioned in table 5 is summarized in the table 6 given below;

Table 6: Prediction of concrete strength of mix at 28-days

Mix	Compressive strength (MPa)	Flexural strength (MPa)
Mix 1	67.53	3.99
Mix 2	74.8	3.86
Mix 3	81.3	3.83
Mix 4	84.7	3.76

The above table shows that mix 4 shows more compression strength than other mixes and mix 1 shows more flexural strength than the other mixes. so, it shows a inverse proportion between compression and flexural strengths

IV. CONCLUSION

This paper presents a simple mathematical model to predict the concrete strengths from the early age test results. In this study, the concrete strength characteristic with age is modeled by a multiple linear regression (MLR) mathematical equation. Early age test data are being used in this case to get reliable values of the 28-day strength prediction. Here, a simple and practical approach has been described for prediction of 28-day compressive strength and flexural strength of concrete and the proposed technique can be used as a reliable tool for assessing the strength of concrete from quite early test results. This will help in making quick decision at site and reduce delay in the execution time of large civil construction projects.

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