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Predicting compressive strength of concrete using impact modulus of toughness

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ABSTRACT

Nondestructive testing (NDT) has wide spread application in construction industry. Existing structures are tested to establish their in-place strength when any alteration in the structural components or usage of the structure is required. Sometimes, NDT is also needed to assess the condition of a structure hit by natural disasters like an earthquake or hurricane. Core test is a one such popular NDT method which is used to determine the concrete strength. Common size of core ranges from 75 mm to 100 mm. Extracting the core, however, becomes challenging when steel bars are very closely spaced. Such situation happens frequently in columns and walls. This research work proposes to extract 25 mm∅ cylindrical specimens from the concrete and test them for impact modulus of toughness (MoT) to indirectly predict the compressive strength. Experimental work was carried out in three phases. Phase 1 consisted of testing mortar specimens whereas phase 2 and 3 comprised of testing concrete specimens. Based on the results, a relationship between compressive strength and impact-MoT has been proposed, which may be used to predict the compressive strength if impact-MoT is known. Statistical analysis of result also suggests that a strong relationship exists between the compressive strength and impact-MoT.

1. Introduction

Nondestructive testing (NDT) is frequently performed on structures to evaluate their existing condition. Nondestructive methods are preferred to avoid any further damage to an already struggling structure. Such methods save both time and money. Traditional methods of NDT include rebound hammer test; ultrasonic pulse velocity tests; core test; pullout test; penetration resistance test and load test. Modern testing methods include Ground Penetration Radar (GPR), laser based methods, infrared testing and digital image correlation method [1,2]. ACI 228.2R - 13 [3] provides comprehensive guidelines on NDT methods for the evaluation of concrete structures. Compression test on concrete core is considered the most suitable traditional method to determine the compressive strength. Extraction of cores, however, may be challenging in terms of deciding their locations and quantities. Also, it is not always possible to avoid reinforcement during extraction of the core (Fig. 1). Avoiding the reinforcement becomes much more crucial when extracting cores from columns or walls, for these being the most important load carrying members. Frequently, the reinforcement is very closely spaced in columns and walls,

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Fig. 1. Concrete Core with Steel Reinforcement.

and it becomes impossible to avoid it during core extraction (Fig. 2). This research proposes to use Charpy impact test to indirectly determine the compressive strength of concrete when extraction of traditional cores is not possible due to congestion of reinforcement. The main objective was to propose a relationship between the compressive strength and Impact modulus of toughness (impact energy absorbed per unit volume) of concrete. Charpy impact test can be performed on specimens with small diameter (25 mm or less) and is therefore suitable for the above mentioned scenario. Very limited literature is available which relates the concrete compressive strength with impact toughness of cementitious materials. One such work is reported by Al-Sarfin [4] in which linear logarithmic relationships were developed between 28 days average compressive strength at various strain rates and average impact toughness of high strength cementitious mix (HSCM) prepared with quartz and silica sand. Two impact velocities including 3.3 and 5.1 m/s were used. It was reported that the correlation coefficient is very scattered with no discernable pattern. The correlation in the data set ranged, mostly, from *weak* to *no correlation*, which may be attributed to specimen size, variability in lab conditions and material quality. More test results were recommended to reduce standard deviation and obtain better correlations.

2. Charpy impact test

Chapry impact test uses potential energy of a falling pendulum to fracture the specimens. It is frequently used to characterize metals and plastics [5,6]. It was standardized by the American Society of Testing and Materials in 1933 [7]. To perform the test, the pendulum is first given a free fall and it moves on a circular path before attaining a certain height, which can be indirectly measured from the angle traversed by the pendulum and read on a circular scale. Now the specimen is placed in the path of the pendulum and the pendulum is released. The pendulum breaks the specimen and again reaches to a height, which is naturally lower than the free fall scenario. The difference in the potential energy of the two scenarios is the energy absorbed by the specimen and if divided by the volume of the specimen it provides impact modulus of toughness (MoT).

No such standard exists which provides reliable recommendations for performing Chapry impact test on cementitious materials. Although several researchers have performed this test on mortar, concrete, ultra-high performance concrete and fiber-reinforced cementitious materials but there is no consistency in specimens' size and shape; method; and results [8]. Thomas and Sorensen [8] summarized more than fifteen studies reporting Charpy impact test on cementitious materials and all of them used specimens with square or rectangular cross-sections. The study suggested having minimum specimen dimension to be no less than five times the characteristic size of the largest constituent. In the current study, however, the specimen could only have circular cross-section with small diameter because this is proposed as an extracted core from an existing structure having congested reinforcement.

3. Experiments and results

3.1. Phase 1

Objective to this phase was to discover if a reliable relationship exists between the impact-MoT and the compressive strength of cement mortar. It consisted of performing impact test in bending on the cement-sand mortar thin cylindrical specimens, referred as pencils. Pencils of size 16 mm∅ x90 mm were prepared with various cement:sand (C:S) ratios along

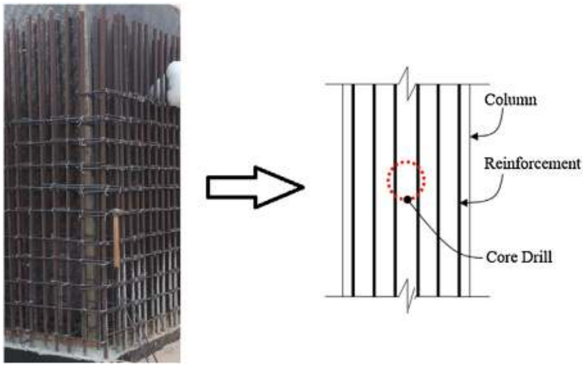

Fig. 2. Core Drill Interfering with Column Reinforcement.

with 50 mm cube companions to be tested in compression. The C:S ratios of 1:0, 1:2, 1:3 and 1:4 were used. For each C:S ratio, three pencils and cubes were tested. These mortar specimens broke with very little impact resistance, as also observed by Lu et al. [9]. Fig. 3 presents the relationship between impact-MoT and compressive strength. This should be considered as crude because it is based on a small set of specimens.

3.2. Phase 2

For phase 2, pencils and cylinders were prepared with plain cement concrete using cement:sand:aggregate (C:S:A) proportions of 1:1.25:2.5, 1:1.5:3, 1:1.75:3.5, 1:2:4 and 1:2:3. For each proportion, 25 pencils and 10 cylinders were prepared. Each pencil had a diameter of 25 mm and length of 100 mm while the cylinders were 100 wide and 200 mm long. Aggregates used to prepare concrete were passed through 50 mm sieve size. Fig. 4 presents the relationship between impact-MoT and compressive strength. Results of specimens with proportion 1:2:3 were outliers and were therefore excluded from the plot. Each dot on Fig. 4 represents the average values of impact-MoT and compressive strength. Only those values were considered to take averages which were within one standard deviation on the either side of the mean.

3.3. Phase 3

Phase 3 was very detailed and it covered four different C:S:A proportions along with four different W/C ratios for each C:S:A proportion. Considerably large number of pencils and cylinders for each batch were prepared to ensure the reliability of the experimental results. In total, 16 different recipes were cast. For each combination of C:S:A and W/C ratio, 15 cylinders (75 mm∅ × 150 mm) and 30 pencils (25 mm∅ × 100 mm) were prepared. Unplasticised polyvinyl chloride (UPVC) pipes were used as molds for preparing the pencils and cylinders. Silicon was used to seal the molds to avoid any bleeding. Pencils molds were arranged in wooden box to ensure straight edges (Fig. 5). Having straight edges is important for accurate calculation of the volume. Table 1 presents the test matrix for this phase. Ordinary Portland cement (*Fauji*®), *Lawrencepur* sand and *Royi* coarse aggregate were selected for preparing the specimens. Common properties of these materials were determined and are

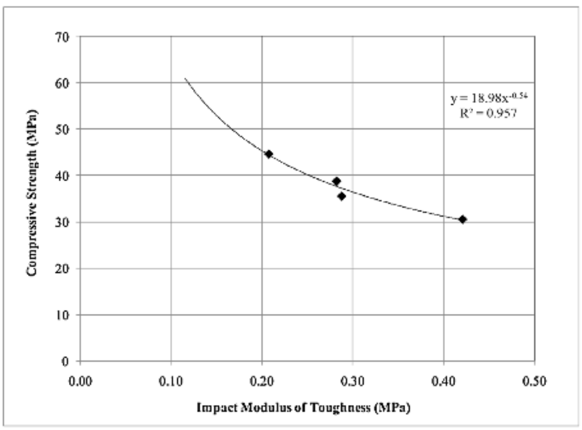

Fig. 3. Relationship between Compressive Strength and Impact-MoT for Mortar (Phase 1).

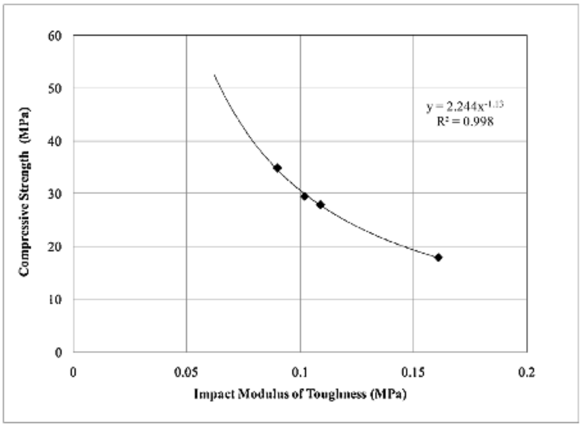

Fig. 4. Relationship between Compressive Strength and Impact-MoT for Concrete (Phase 2).

Fig. 5. UPVC Molds and Wooden Boxes (Phase 3).

listed in Table 2. Inner surfaces of the molds were oiled to ease the extraction of the specimens. Concrete was filled in three equal layers. After filling each layer, external vibrations were induced to ensure compaction. Specimens were extracted after 24 h. Few of the pencils broke during de-molding. Specimens were then immersed in water for 28 days. Compression testing was performed on a traditional compression machine while the impact-MoT was determined using Charpy impact testing machine, shown in Fig. 6. Assuming friction and drag to be negligible - around 1% of the total impact energy- [10], following equation was used to calculate the Impact-MoT:

$$MoT = mgR(\text{Cos}(\theta_2) - \text{Cos}(\theta_1)) \quad (1)$$

Where, *m* (22.9 kg) is the mass of the arm, *R (700 mm)* is the radius of the arm, θ_1 and θ_2 are the angles achieved by the arm in the free fall and when the specimen is tested, respectively. Fig. 7 presents the pencil specimens before and after the testing.

Table 3 presents the summary results of compression and impact-MoT tests. Each of the values mentioned in the Table 3 is an average of 15 tests. Fig. 8 graphically presents the relationship between compressive strength and Impact-MoT. Similar to the results of phase 1 and 2, in general, the compressive strength of concrete decreases in non-linear manner with the increase in impact MoT. With the decrease in cement content the compressive strength of concrete decreases and concrete exhibits relatively more ductile behavior, which in turns causes more energy absorption resulting in higher impact-MoT. Similarly, with the increase in W/C ratio the compressive strength decreases and the impact-MoT increases. Yalçınkaya et al. [11] reported for the reactive powder concrete that the impact energy absorbed is independent of its W/C ratio. Limited literature is available to verify these observed relations between the cement content, W/C ratio and impact-MoT. The relationships developed by Al-Sarfin [4] for HSCM also showed decreasing trend of compressive strength of concrete with

Table 1
Test Matrix for Phase 3.

Batch No.	Proportion	W/C Ratio	No. of Cylinders	No. of Pencils
1	1:1:2	0.55	15	30
2		0.5	15	30
3		0.45	15	30
4		0.4	15	30
5	1:1.5:3	0.55	15	30
6		0.5	15	30
7		0.45	15	30
8		0.4	15	30
9	1:2:3	0.55	15	30
10		0.5	15	30
11		0.45	15	30
12		0.4	15	30
13	1:2:4	0.55	15	30
14		0.5	15	30
15		0.45	15	30
16		0.4	15	30

Table 2
Properties of Materials used in Phase 3.

Property	Test Standard	Value
Properties of Fauji Cement		
Normal Consistency	ASTM C187-16	30 %
Initial Setting Time	ASTM C191-18	2.5 h
Final Setting Time	ASTM C191-18	4.5 h
Specific Gravity	ASTM C77-40	3.15
Properties of Lawrencepur Sand		
Water Absorption	ASTM C128-15	1.97 %
Fineness Modulus	ASTM C136/136M-14	2.69
Relative Density (SSD)	ASTM C128-15	2.51
Relative Density (Oven Dry)	ASTM C128-15	2.52
Apparent Relative Density	ASTM C128-15	2.58
Properties of Royi Crush		
Aggregate Crushing Value (ACV)	BS 812: Part 110:1990	24.97 %
Water Absorption	ASTM C127-15	0.75 %
Relative Density (SSD)	ASTM C127-15	2.72
Relative Density (OD)	ASTM C127-15	2.7
Apparent Relative Density	ASTM C127-15	2.76

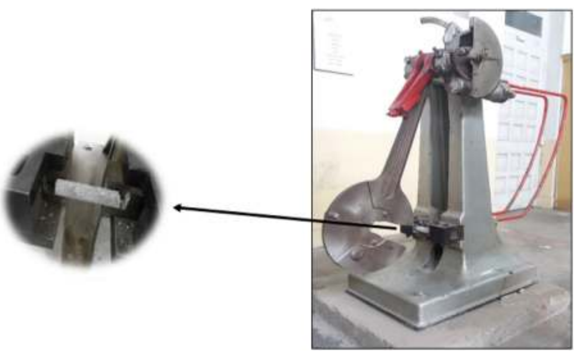

Fig. 6. Impact-MoT Testing of Concrete.

Fig. 7. Concrete Pencil Specimens before and after testing.

Table 3
Compressive Strengths and Impact-MoTs for Phase 3.

Batch #	Proportion	W/C Ratio	fc' MPa	Impact-MoT MPa
1	1 : 1 : 2	0.55	23.19	0.298
2		0.5	24.94	0.287
3		0.45	26.32	0.273
4		0.4	27.94	0.249
5	1 : 1.5 : 3	0.55	18.59	0.321
6		0.5	20.20	0.298
7		0.45	21.07	0.289
8		0.4	23.04	0.270
9	1 : 2 : 3	0.55	17.65	0.340
10		0.5	18.81	0.320
11		0.45	20.86	0.309
12		0.4	23.55	0.267
13	1 : 2 : 4	0.55	14.88	0.382
14		0.5	16.33	0.374
15		0.45	17.94	0.323
16		0.4	20.56	0.298

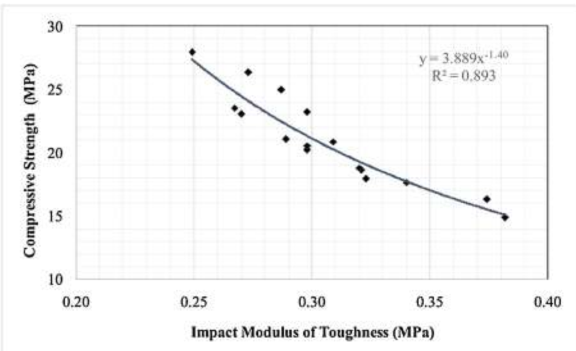

Fig. 8. Relationship between Compressive Strength and Impact-MoT for Concrete (Phase 3).

the increase in impact toughness. However, Al-Sarfin [4] did not use coarse aggregates in the mix. Zhang et al. [12] reported similar observation for high strength concrete. In that case, impact resistance increased with the increase in the coarse aggregates in the mix, which results in the decrease in the compressive strength. However, there was one condition that the workability of concrete should not be compromised.

Statistical analysis was performed on test results of phase 3 using IBM© SPSS® Statistics Version 26 to further explore the relationship between the compressive strength and the impact-MoT. As the relationship between the compressive strength and the impact-MoT of PCC is non-linear (Fig. 8), the Spearman Bivariate Correlation test (Table 4) was performed to investigate the association between them. The test results show that there exists a very strong monotonic association between the compressive strength and the impact-MoT of PCC ($r_s = -0.941$, $p = 0.000$). Various regression curve estimates are presented shown in Fig. 9 and Table 5. The significance for all curves is less than 0.001 which means that they are all

Table 4
Results of the Spearman Bivariate Correlation Test in SPSS.

Correlations				
			Compressive Strength	Impact-MoT
Spearman's rho	Compressive Strength	Correlation Coefficient	1.000	−.941**
		Sig. (2-tailed)	.	.000
		N	16	16
	Impact-MoT	Correlation Coefficient	−.941**	1.000
		Sig. (2-tailed)	.000	.
		N	16	16

** Correlation is significant at the 0.01 level (2-tailed).

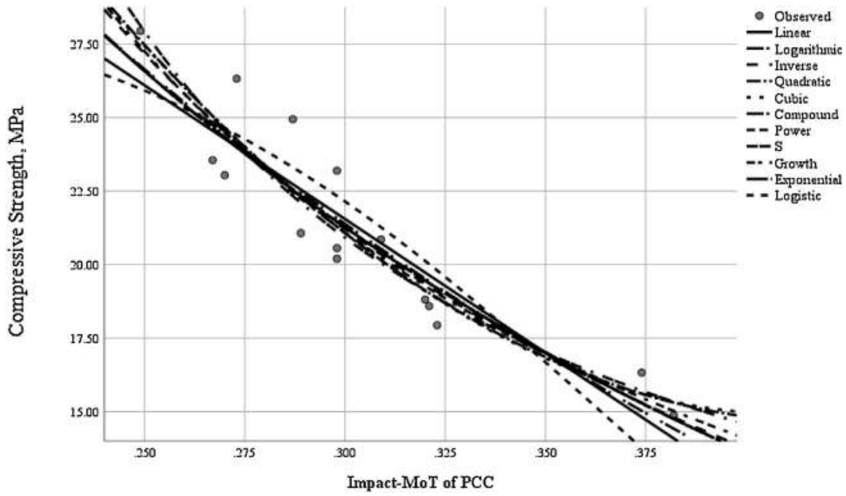

Fig. 9. Various Curves fitted between the Compressive Strength and the Impact-MoT using SPSS.

Table 5
Results of the Curve Estimation Test in SPSS.

Model Summary and Parameter Estimates									
Dependent Variable: Compressive Strength									
Equation	Model Summary					Parameter Estimates			
	R Square	F	df1	df2	Sig.	Constant	b1	b2	b3
Linear	.843	75.431	1	14	.000	48.831	−90.939		
Logarithmic	.863	87.961	1	14	.000	−13.305	−28.813		
Inverse	.874	96.967	1	14	.000	−8.611	8.946		
Quadratic	.878	46.841	2	13	.000	92.266	−368.505	437.296	
Cubic	.878	46.937	2	13	.000	78.298	−232.428	.000	463.387
Compound	.884	106.402	1	14	.000	81.058	.012		
Power	.893	116.897	1	14	.000	3.889	−1.405		
S	.894	117.693	1	14	.000	1.596	.433		
Growth	.884	106.402	1	14	.000	4.395	−4.460		
Exponential	.884	106.402	1	14	.000	81.058	−4.460		
Logistic	.747	41.381	1	14	.000	9.095E-5	11123528.983		

The independent variable is Impact-MoT.

Table 6
Inter-Correlation between Parametric Values of the Power Equation determined from the Non-Linear Regression.

Correlations of Parameter Estimates		
	A	B
A	1.000	0.996
B	0.996	1.000

applicable. The 'goodness-of-fit' of a curve to the given data is measured from R^2 value which is highest for the power equation curve (0.893), as shown in Fig. 8. Parametric values for the power equation were validated using the non-linear regression test and their inter-correlation values are shown in Table 6. Thus, the final expression for the relationship between compressive strength and impact-MoT of concrete is:

$$f_c^{'} = 3.889(\text{Impact} - \text{MoT})^{-1.405} \quad (2)$$

here, both compressive strength, f_c' and *Impact-MoT* are in MPa.

4. Summary and conclusions

This experimental work aimed at developing a relationship between compressive strength and impact-MoT of plain cement concrete. Testing was carried out in three phases: phase 1 consisted of testing cement mortar specimens whereas phase 2 and 3 comprised of testing concrete specimens. Thin cylindrical specimens, referred as pencils, were tested on Charpy impact machine to determine the impact-MoT.

1 Experimental data show that relationship between compressive strength and impact-MoT does exist and can be used to predict the compressive strength in the scenarios when traditional core testing is not possible.
2 Compressive strength was found to have non-linear inverse relation with impact-MoT. Statistical analysis also confirmed the existence of strong relationship between these two parameters.

Although, experimental results seem promising, further testing on specimens prepared with wider range of C:S:A and W/C ratios, and specimens with different slenderness ratio is recommended to enhance the reliability of the proposed relationship. Also, testing of specimens extracted from the existing concrete structures will help in understanding the effects of micro-cracking on impact-MoT.

Declaration of Competing Interest

The authors report no declarations of interest.

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