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The Effect of Compressive Stress on Ultrasonic Pulse Velocity in Concrete for Compressive Strength Prediction

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Abstract

Ultrasonic pulse velocity (UPV) has been a popular non-destructive testing method for prediction of concrete strength. This leads to development of two major types of concrete compressive strength prediction models using measured UPV values, namely the exponential function and the power function. A simpler exponential function, recognised as one of the earliest, has proven to be more accurate in predicting the concrete compressive strength. From this study, it was observed that measured UPV increases with the increase in stress-to-strength ratio of up to 0.25, and the measured UPV decreases thereafter. The increase in UPV will lead to overestimation of concrete compressive strength by up to 15%. However, if ⅓ of compressive strength is considered as service stress, then the overestimation of concrete compressive strength will be lower at about 8%, and may even register a slight underestimation occasionally; due to the decrease in measured UPV values beyond stress-to-strength ratio of 0.25.

1. Introduction

Ultrasonic pulse velocity (UPV) has been used in various types of concrete for correlation of UPV with compressive strength [1]-[12]. Although UPV in concrete is dependent of many parameters such as aggregate content [13]-[15], density [16], moisture content [17], etc., the relationship between UPV and concrete compressive strength remains robust, leading to standard testing procedure using UPV such as seen in BS EN 12504-4 [18].

The most common form of relationship between concrete compressive strength and UPV proposed by various research studies is an exponential function as follows:

$$f_{\mathrm{ck}} = Ae^{BV_{\mathrm{up}}} \tag{1}$$

where f_{ck} = compressive strength of concrete (normally at the age of 28 days); A, B = coefficients; and V_{up} = ultrasonic pulse velocity (in km/s). A pair of coefficients A and B are suggested by various researches [4], [19]-[25] as shown in Table 1. It is important to note that different shape of specimen was used in each research and it influences the value of compressive strength. It is also worthy to note that the equation proposed by Popovics et al. [22] is used for concrete at the age of 7 days whilst the other equations are for concrete at the age of 28 days or above.

Table 1 *Coefficients A and B in Eq. (1) as reported by various research studies*

Research \ Coefficient	Shape of Specimen	*A*	*B*
Jones [19]	Cube	2.8	0.53
Elvery & lbrahim [20]	Cube	0.0012	2.27
Raouf & Ali [21]	Cube	2.01	0.61
Popovics et al. [22]	Cylinder	0.0028	2.1
Nash't et al. [23]	Cube	1.19	0.715
Trtnik et al. [4]	Cylinder	0.854	1.2882
Atici [24]	Cylinder	0.0316	1.3
Ali-Benyahia et al. [25]	Cylinder	1.2288	0.726

In order to incorporate the effect of coarse aggregate (CA) content, Lin et al. [13] proposed two pairs of coefficients *A* and *B*; one pair for coarse aggregate content of 1000 kg/m^3, and the other pair for coarse aggregate content of 1100 kg/m^3 as shown in Table 2. Al-Nu'Man et al. [14], [15] extended the investigation and proposed the pairs of coefficients *A* and *B* for coarse aggregate content of 1000 kg/m^3, 1200 kg/m^3, 1300 kg/m^3 and 1400 kg/m^3, respectively as shown in Table 2.

Table 2 *Coefficients A and B in Eq. (1) as reported by various research studies considering CA content*

Research \ Coefficient	Shape of Specimen	CA Content (kg/m^3)	*A*	*B*
Lin et al. [13]	Cylinder	1000	0.00106	2.37
		1100	0.00055	2.5
Al-Nu'Man et al. [14], [15]	Cube	1000	8.8793	0.4247
		1200	0.0574	1.6013
		1300	1.0332	0.8674
		1400	1.3908	0.7806

In addition, Al-Aasm [16] incorporated the effect of density and coarse aggregate content by setting *A* as a variable dependent of both parameters given as:

$$A = 0.11 - 0.019\left(\frac{\frac{\text{Aggregate Content}}{\text{Cement Content}}}{\rho}\right) \tag{2}$$

where ρ = density of concrete in g/cm^3. The value of *B* is still a coefficient which is set to 1.3.

In some other research studies on the relationship of compressive strength of concrete to UPV [25], [26], it is proposed to have a power function as follows:

$$f_{\text{ck}} = CV_{\text{up}}^{D} \tag{3}$$

in which *C* and *D* are coefficients as shown in Table 3.

Table 3 *Coefficients C and D in Eq. (3) as reported by various researches*

Research \ Coefficient	Shape of Specimen	*C*	*D*
Ali-Benyahia et al. [25]	Cylinder	0.6401	2.5654
Lee et al. [26]	Cylinder	0.0952 (normal strength concrete) 0.0028 (high strength concrete)	3.5 (normal strength concrete) 6.1 (high strength concrete)

Huang et al. [27] utilises UPV combined with rebound hammer test, referred to as SonReb [28], to predict the in-situ value of compressive strength through a probabilistic multivariable linear regression model. Ju et al. [29]

also adopted the SonReb model to further the research on high-strength concrete and acquired the following equation for prediction of concrete compressive strength:

$$f_{ck} = 38.7055 - 9.5194 \times V_{up} + 1.6678 \times R_0 \quad (4)$$

where R_0 = rebound hammer value. Hernández Oroza & Cuetara Ricardo [30] conducted an evaluation of SonReb models for estimating compressive strength and found that the RILEM model [28] shows less than 4% error, indicating that this model is relevant for this purpose.

It is interesting to note that all the literatures mentioned in the aforementioned discussion reported on stress-free concrete, i.e., the concrete samples that are not subjected to any stress. It was also reported by Popovics & Popovics [31] that stress in concrete does not affect the value of ultrasonic pulse velocity. However, with the compaction action due to compression, it is anticipated that the concrete density is slightly increased. According to ACI 228 [32], ultrasonic or longitudinal waves travel faster in denser medium. Therefore, the increase in density may affect UPV value, and subsequently, the predicted compressive strength. Furthermore, with the behaviour and mechanism of microcracking under load [33], [34], the value of UPV may also be affected. Therefore, the effect of compressive stress on ultrasonic pulse velocity in concrete is further investigated herein, with extended consideration on predicted concrete compressive strength.

2. Test Program

2.1 Concrete Specimen

The concrete mixes for the two grades of concrete used are shown in Table 4. The mix selections were based on the British method [35]. The first value of the concrete grade indicates the cylinder strength and the latter value the cube strength [36].

Table 4 *Concrete mix proportion by weight of cement*

Concrete Grade, f_{ck} (MPa)	Cement	Fine Aggregate	Coarse Aggregate	Water
25/30	1	1.97	2.48	0.46
28/35	1	1.88	2.39	0.43

For each grade of concrete, cubes and prisms with 100 mm square cross section were cast in accordance with guidelines in BS EN 12390-1 [37] and BS EN 12390-2 [38]. The prisms were cast with aspect ratios of 2, 4 and 5. The compressive strength was determined by averaging the results from three 100 mm test cubes for each grade at the age of 28 days in accordance with BS EN 12390-3 [39]. The UPV values were also measured on all test cubes in accordance with BS EN 12504-4 [18] and the average value was recorded for each grade of concrete.

2.2 Test Procedure

The tested compressive strength for each grade of concrete was used to calculate the level of stress at each stress-to-strength ratio at intervals of 0.05, which was the applied load step on each specimen. The maximum stress-to-strength ratio is limited to 0.5 in this study as lab safety measure. In view that the level of stress under service conditions is usually ⅓ of compressive strength [40] and level of stress at ½ compressive strength is a typical permissible working stress in concrete in accordance with Eurocode 2 [36] and ACI 318 [41], it is deemed not necessary to test the specimens beyond the stress-to-strength ratio of 0.5.

Each of the test specimen was then placed in the testing frame and loaded with the load steps calculated from the stress-to-strength ratios using manual hydraulic jack. The UPV at each load step was measured with direct method at mid-height of the specimen using a calibrated portable ultrasonic non-destructive digital indicating tester (PUNDIT) at 54 kHz frequency.

3. Results and Discussion

3.1 Compressive Strength Prediction on Stress-free Concrete

The exponential and power functions of Eq. (1) and Eq. (3), respectively, were used to predict the compressive strength of stress-free concrete, i.e., the average value of the three 100 mm test cubes. Table 5 shows the results of prediction by various exponential and power functions proposed by various research studies. It is noted that for those functions providing values of cylinder strength, the results have been converted to cube strength values using factors of 30/25 and 35/28 for concrete grades of 25/30 and 28/35, respectively. Positive error indicates overestimation and vice versa.

For concrete grade 25/30, the tested compressive strength is 31.7 MPa with a measured UPV value of 4.74 km/s. Almost all the exponential and power functions over- or underestimated the concrete strength by more than 10% except for Jones [19] which has the exponential function with an error of only 8.93%. As for the higher concrete grade of 28/35, the tested concrete strength is 34.5 MPa with measured UPV of 4.78 km/s, and there are only three functions overestimated the compressive strength by under 10%, i.e., Jones [19], Raouf & Ali [21] and Nash't et al. [23] exponential functions. However, Jones [19] shows the best prediction at an error of only 2.23%.

It is noteworthy that Jones [19] exponential function; being the earliest amongst the proposed equations, provides the best prediction of compressive strength in stress-free concrete for both grades of concrete in this study. This is probably due to the simplicity of the equation that had been developed for normal concrete. Therefore, this function will be used to calculate the concrete compressive strength values in the impending discussion on the effect of stress in concrete on the prediction of concrete strength.

Table 5 *Predicted concrete compressive strength*

Concrete Grade, f_{ck} (MPa)	Tested Compressive Strength (MPa)	Function Type	Research	Predicted Compressive Strength (MPa)	Error (%)
25/30	31.7	Exponential	Jones [19]	34.5	8.93
			Elvery & lbrahim [20]	56.5	78.3
			Raouf & Ali [21]	36.2	14.2
			Nash't et al. [23]	35.3	11.3
			Lin et al. [13]	96.2	204
			Trtnik et al. [4]	383	1108
			Atici [24]	18.0	−43.3
			Al-Nu'Man et al. [14]	66.5	110
			Ali-Benyahia et al. [25]	46.0	45.2
		Power	Lee et al. [26]	26.5	−16.4
			Ali-Benyahia et al. [25]	41.6	31.2
28/35	34.5	Exponential	Jones [19]	35.3	2.23
			Elvery & lbrahim [20]	61.9	79.4
			Raouf & Ali [21]	37.1	7.57
			Nash't et al. [23]	36.3	5.20
			Lin et al. [13]	110	219
			Trtnik et al. [4]	403	1069
			Atici [24]	19.7	−42.8
			Al-Nu'Man et al. [14]	67.6	96.0
			Ali-Benyahia et al. [25]	49.4	43.1
		Power	Lee et al. [26]	28.4	−17.6
			Ali-Benyahia et al. [25]	42.5	23.2

3.2 Effect of Compressive Stress on Ultrasonic Pulse Velocity

The test results of the effect of compressive stress on the measured values of UPV are shown in Fig. 1 and Fig. 2 for concrete grades of 25/30 and 28/35, respectively. It is shown in Fig. 1 and Fig. 2 that the UPV values increase by about 1 to 2% when the stress-to-strength ratio is increased from 0 to 0.10 for the test specimens. Under this state of stress, the specimens might be compacted in which the volume of the voids in the concrete specimens were reduced, resulting in a denser concrete. According to ACI 228 [32], ultrasonic or longitudinal waves travel faster in denser medium. Therefore, the phenomenon of increase in the measured UPV values at this state of stress may be justified. However, the increase in UPV values under this lower range of stress-to-strength ratio is not that significant. As the state of stress in the concrete specimens is increased from 0.10 to 0.25 stress-to-strength ratio,

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the UPV values increased by another 1 to 2%, resulting in a total increase in UPV values of 3 to 5%. The aspect ratio was found to be insignificant on the test results, but the specimen with the smallest aspect ratio of 1:1 showed slightly more significant effect.

Hsu et al. [33] reported that very fine cracks at the interface between coarse aggregate and cement paste exist prior to application of load on the concrete. These microcracks are stable up to the state of stress of 0.30 stress-to-strength ratio, after which they begin to increase in length, width and number [42]. These observations on the behaviour and mechanism of microcracking are in accordance with the test results reported in this study, in which the reduction in UPV values at more than 0.25 stress-to-strength ratio may be attributed to the propagation of microcracks. And this resulted in longer path length of the ultrasonic wave travelling around cracks, thus velocity reduction.

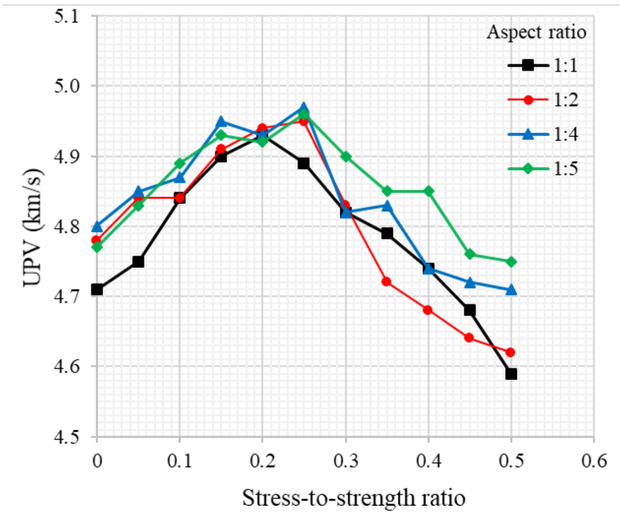

Fig. 1 *Effect of compressive stress on UPV of grade 25/30 concrete*

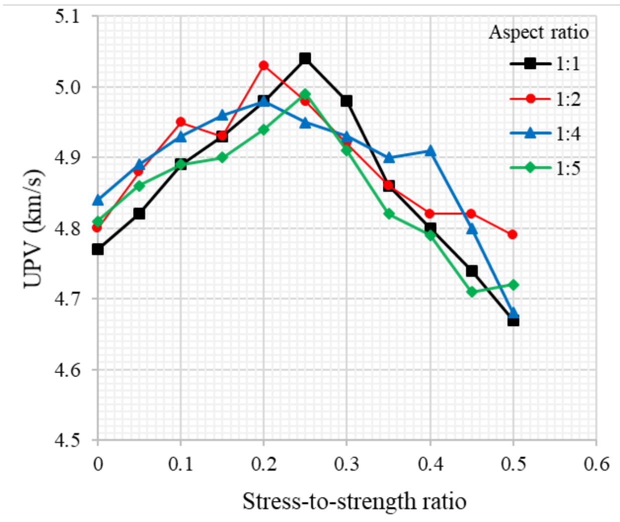

Fig. 2 *Effect of compressive stress on UPV of grade 28/35 concrete*

3.3 Effect of Compressive Stress in Concrete on Compressive Strength Prediction Using UPV

When UPV is utilised to predict the compressive strength of the concrete under investigation, any change in UPV value will affect the prediction. In the preceding discussion, it was found that the state of compressive stress affects the measured UPV values. Therefore, it leads to the error in predicted concrete compressive strength using UPV values.

Fig. 3 and Fig. 4 show the predicted concrete compressive strength using Jones [19] exponential function for concrete grades of 25/30 and 28/35, respectively. Similar to the trend in measured UPV values, the predicted concrete compressive strength increases for stress-to-strength ratio of up to 0.25. The predicted concrete compressive strength decreases thereafter, following the decrease in measured UPV values.

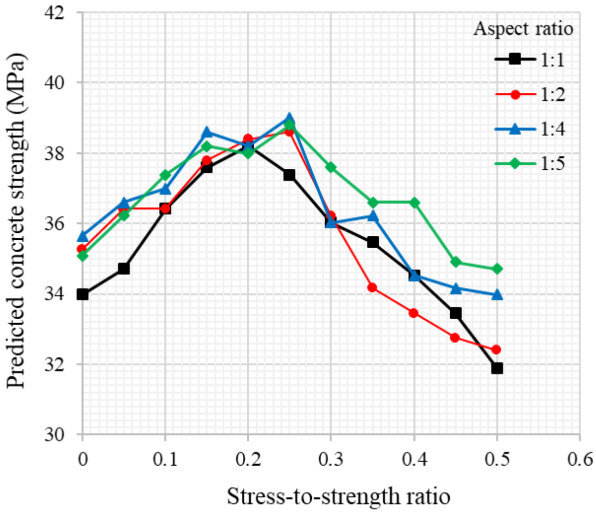

Fig. 3 *Predicted concrete compressive strength using UPV values for grade 25/30 concrete*

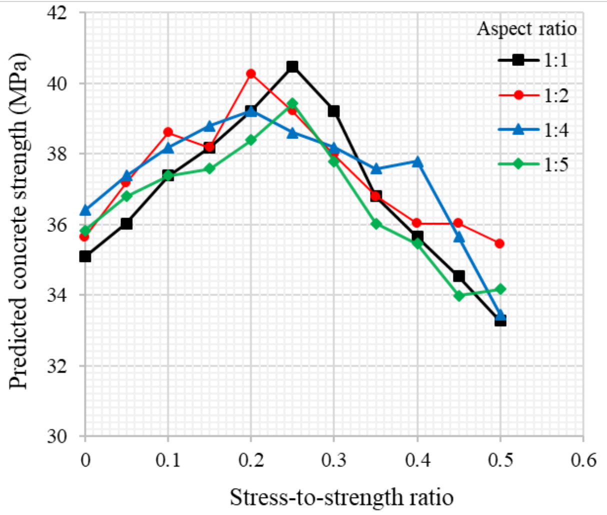

Fig. 4 *Predicted concrete compressive strength using UPV values for grade 28/35 concrete*

In order to observe the effect more rigorously, the errors in estimating concrete compressive strength using UPV values are presented in Fig. 5 and Fig. 6 for concrete grades of 25/30 and 28/35, respectively. The error in each sample was calculated with reference to the predicted concrete compressive strength using the measured UPV of each sample at zero stress-to-strength ratio. Positive error denotes overestimation and vice versa.

It is observed that the maximum error occurs at stress-to-strength ratios of 0.2 to 0.25 in general. The error approaches null at stress-to-strength ratios of 0.3 to 0.4, and the samples registered negative error thereafter. There is no noteworthy effect observed in the samples with different aspect ratios, therefore this parameter is deemed insignificant in this study. From these results, there is considerable overestimation of concrete strength from stress-to-strength ratios of 0 to 0.25, due to the increase in UPV values; with the peak of overestimation occurring at stress-to-strength ratios of 0.2 to 0.25. This overestimation will slowly be counterbalanced by the decrease in UPV values from stress-to-strength ratios of 0.3 to 0.4.

If ⅓ of compressive strength is designated as the service stress [40], the error in concrete compressive strength demarcated in Fig. 5 and Fig. 6 ranges from about –1 to 8%. These results indicate that the state of stress at service conditions will not record the maximum predicted concrete compressive strength based on measured UPV on site. It may lead to a slight underestimation sometimes.

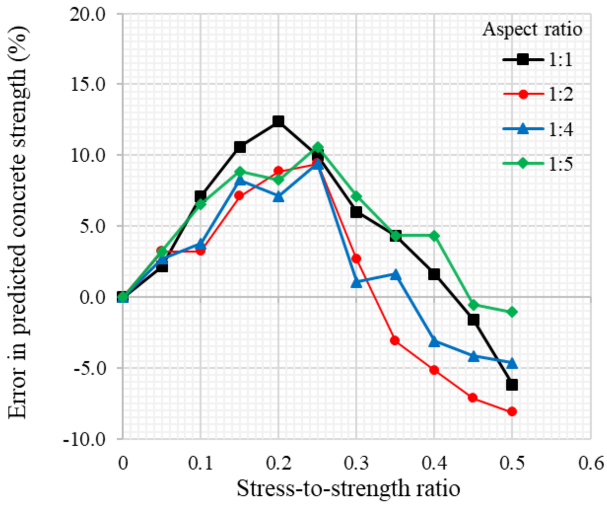

Fig. 5 *Error in predicted concrete compressive strength using UPV values for grade 25/30 concrete*

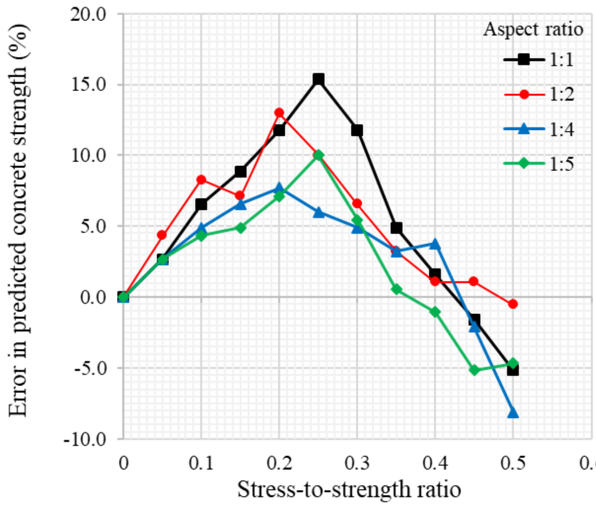

Fig. 6 *Error in predicted concrete compressive strength using UPV values for grade 28/35 concrete*

Table 6 shows the maximum predicted concrete compressive strength in each sample with the corresponding error. It is shown that the overestimation of concrete compressive strength ranges from about 8 to 15% at stress-to-strength ratios of 0.2 to 0.25. These results indicate that the maximum error in predicted concrete compressive strength from measured UPV on site will occur when the service stress in the concrete is about 20 to 25% of the compressive strength.

Table 6 *Maximum predicted concrete compressive strength and the corresponding error*

Concrete Grade, f_{ck} (MPa)	Aspect Ratio	Maximum Predicted Compressive Strength (MPa)	Error (%)
25/30	1:1	38.2	12.4
	1:2	38.6	9.4
	1:4	39.0	9.4
	1:5	38.8	10.6
28/35	1:1	40.5	15.4
	1:2	40.3	13.0
	1:4	39.2	7.7
	1:5	39.4	10.0

4. Conclusions

There are two major types of concrete compressive strength prediction models using measured UPV values, namely the exponential function and the power function. It was found that one of the simpler exponential functions, which is the also the earliest, is better in predicting the normal concrete compressive strength based on measured UPV with errors of 8.93% and 2.23% for concrete grades of 25/30 and 28/35, respectively.

From this study, it was observed that UPV values increase with the increase in stress-to-strength ratio of up to 0.25. The measured UPV will decrease thereafter when the stress-to-strength ratio is increased. The increase in UPV will lead to overestimation of concrete compressive strength by up to 15% based on the test samples. However, if ⅓ of compressive strength is designated as service stress, then the overestimation of concrete compressive strength will be lower at about 8%, and may also register a slight underestimation occasionally; due to the decrease in measured UPV values beyond stress-to-strength ratio of 0.25.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Chee Khoon Ng, Sim Nee Ting, Hoo Tien Nicholas Kuan;* ***data collection:*** *Peng How Chai;* ***analysis and interpretation of results:*** *Chee Khoon Ng, Sim Nee Ting, Hoo Tien Nicholas Kuan;* ***draft manuscript preparation:*** *Chee Khoon Ng, Peng How Chai, Hoo Tien Nicholas Kuan. All authors reviewed the results and approved the final version of the manuscript.*

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