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THE INFLUENCE OF BUILDING AGE ON THE FORMULATION OF CONCRETE COMPRESSIVE STRENGTH USING NON-DESTRUCTIVE TESTING

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Abstract: In the assessment of existing reinforced concrete buildings, the compressive strength of concrete, fc', is a key parameter for performance assessment. The most accurate way to identify it is by conducting compressive strength tests on core concrete samples from structural elements obtained through drilling. The more samples taken, the more accurate the determination of fc' for structural modeling will be. However, sampling in buildings certainly disrupts activities within the building, compounded by drilling marks that leave traces even after repairs. Therefore, sample collection must be selective, yet the results must still provide confidence as input for structural analysis. A method for estimating fc' using the ultrasonic pulse velocity test, *UPVT*, categorized as a Nondestructive Test, *NDT*, has long been used and continues to be developed. Various building regulations state that *NDT* for estimating fc' should be paired with the results of compressive strength tests on core concrete samples to obtain correlation between them. The relationship equation between wave propagation velocity, V, and fc' varies between studies, indicating that besides V, there are other influencing factors. In this study, samples were taken from 5 (five) buildings of different ages. In addition to V, the effects of density, ρ, and age, α, were examined. The results of the study indicate that ρ has no effect, while α influences the relationship between V and fc' according to the equation $fc' = 2.07932e^{0.64959V}\alpha^{0.07926}$ with $r^2 = 0{,}714$.

Keywords: building age, compressive strength, density, non-destructive test,

1. INTRODUCTION

Concrete is the most commonly used structural material due to its easy availability and its ease of shaping when fresh, adapting to architectural and structural designs. As buildings age, reinforced concrete may suffer damage due to improper construction techniques, excessive loads, aging, steel corrosion, chemical reactions, natural disasters, and other factors. The spread of damage is a time-dependent process affecting the capacity and resilience of the structure. When visible signs of damage such as concrete cracks or significant deflection appear, it indicates that the concrete elements may have experienced significant damage. Therefore, early detection of concrete capacity deterioration before visible damage occurs will reduce repair costs and increase the service life of the structure.

In buildings where the main structure is reinforced concrete, the strength and durability of the concrete are crucial aspects to be examined. Standards and regulations provide rules for assessing the actual compressive strength of concrete compared to its design strength (Garcez, Rohden, & Graupner de Godoy, 2018). The most accurate assessment for compressive strength is to perform compression tests on samples obtained from concrete

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core drilling. The more samples taken, the higher the level of accuracy in determining the concrete quality used in structural analysis. However, sample collection is sometimes limited by buildings that are still in operation during structural inspections, so the use of non-destructive testing (NDT) alternatives such as ultrasonic pulse velocity tests is an option.

From the principle of elastic wave propagation, the wave velocity correlates with the square root of the elastic modulus (American Concrete Institute., 2013). Because the elastic modulus and specific concrete strength increase with age, it can be inferred that wave velocity can be a means to estimate concrete strength, although there is no direct physical relationship between these two properties. However, as concrete ages, the elastic modulus and compressive strength increase at different rates. Initially, the elastic modulus increases at a higher rate than strength, but as concrete ages, the elastic modulus increases at a lower rate. Consequently, over a wide range of concrete ages, the relationship between compressive strength and wave velocity becomes highly nonlinear (American Concrete Institute., 2013). Figure 1 illustrates a typical relationship between concrete compressive strength and wave velocity, with the actual relationship depending on the specific concrete mix.

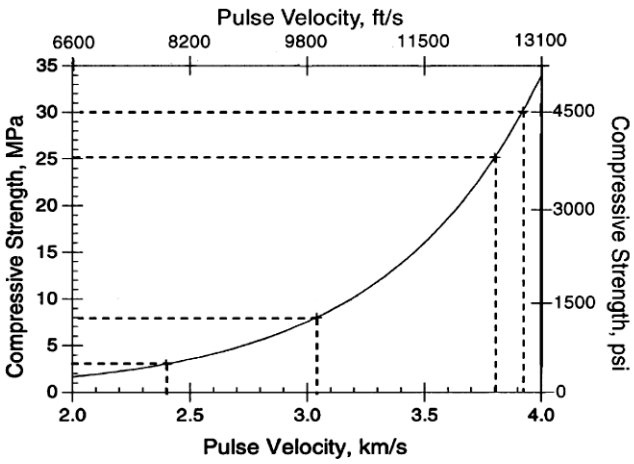

Fig. 1 A typical relationship between ultrasonic wave propagation velocity and concrete compressive strength (American Concrete Institute., 2013).

In the modern construction world, UPVT (Ultrasonic Pulse Velocity Test) has become an integral part of estimating the quality of concrete structures ((Herki, Khatib, Ramadhan, & Hamadameen, 2023),(Choi, Kang, Hwang, & Cho, 2021), (Hong et al., 2020), (Handika, Norita, Tjahjono, & Arijoeni, 2020), (Sertçelik, Kurtuluş, Sertçelik, Pekşen, & Aşçı, 2018), (Ali-Benyahia, Sbartaï, Breysse, Kenai, & Ghrici, 2017), (Ridho & Khoeri, 2015), (Khoeri, 2016), (Lopes, Vanalli, & Ferrari, 2016)) dan lainnya). Several previous research findings on the relationship between the propagation speed of ultrasonic waves and the compressive strength of concrete are summarized in the Table 1 below:

Table 1 Some previous research findings regarding the relationship between ultrasonic pulse velocity and concrete compressive strength

No	Equations	Units	r^2	Refference
1	$fc' = 2.1557e^{0.6248V}$	fc'[MPa]; V [km/sec]	0.619	(Herki et al., 2023)
2	$\mathrm{fc}' = 0.0066\mathrm{V} - 2.12$	fc'[MPa]; V [m/sec]	0.823	(Choi et al., 2021)
3	$fc' = 832{,}75ln(V) + 844{,}9$	fc'[MPa]; V [m/sec]	0.94	(Hong et al., 2020)
4	$V = 0.015e^{1.728fc'}$	fc'[MPa]; V [km/sec]	0.75	(Handika et al., 2020)
5	$fc' = 0.008V - 14.882$	fc'[MPa]; V [m/sec]	0.94	(Sertçelik et al., 2018)
6	$fc' = 1.2288e^{0.726V}$	fc'[MPa]; V [km/sec]	0.72	(Ali-Benyahia et al., 2017)
7	$fc' = 2{,}0355V^{2{,}120906}$	fc'[MPa]; V [km/sec]	0.77	(Khoeri, 2016)
8	$fc' = 3 \cdot 10^{-14}V^{4.1488}$	fc'[MPa]; V [m/sec]	0.717	(Lopes et al., 2016)

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However, ultrasonic wave propagation velocity measurements are influenced by the characteristics of the concrete mix, which can complicate interpretation (Saint-Pierre, Philibert, Giroux, & Rivard, 2016), (Karaiskos, Deraemaeker, Aggelis, & Hemelrijck, 2015). Therefore, this study conducted tests on several buildings with different ages and varying sample sizes to obtain a realistic relationship that can be applied to estimate concrete compressive strength from UPV testing.

2. METHOD

Concrete samples were taken from 5 (five) buildings in DKI Jakarta, in the year 2022, with the number of samples in each building as shown in Table 2 below:

Table 2 Concrete sample information

ID	Sampling Locations	Construction Year	Sampling Time	Sample Quantity
G1	36-storey Pejompongan Building	2015	November 2022	72
G2	5-storey Pejompongan Plaza	2015	October 2022	25
G3	2-storey Warehouse	2021	August 2022	35
G4	Gambir Station	1986	July 2022	10
G5	DJKN Headquarters	1970	June 2022	12

The stages of the research conducted are as follows:

1. Concrete sample collection from structural elements: Concrete samples were collected using a concrete coredrilling machine. Before drilling, a rebar scanning was performed around the location using the Hilti PS200 2D and PS1000 3D rebar scanners to avoid hitting the reinforcement bars with the drill. Documentation during the drilling process at one of the test locations is provided in Fig. 2.

Fig. 2 Rebar scanning (left) and concrete core sample collection (right)

2. Ultrasonic wave velocity data collection: Ultrasonic wave velocity data collection on the concrete core samples was conducted using the Proceq PL200PE, with the direct method according to ACI 228.1R-19 (ACI, 2019). Documentation during the ultrasonic wave velocity data collection on one of the concrete core samples is provided in Fig. 3.

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Fig. 3 Ultrasonic pulse velocity data collection on concrete core sample

3. Concrete compressive strength testing: Concrete core samples were tested according to SNI 2492:2018 (BSN, 2018). Testing was conducted at the PT. Hesa Laras Cemerlang concrete laboratory in Jakarta, 7 (seven) days after sample collection. The obtained data from the testing include the size, density, and compressive strength of the concrete. Documentation during the testing of one of the concrete core samples is provided in Fig. 4.

Fig. 4 Documentation of testing one of the concrete core samples

4. Data analysis:
   - Regression analysis to establish the relationship between ultrasonic pulse velocity, V (km/second), and concrete compressive strength, fc' (MPa), for each building, with fc' as the dependent variable and V as the independent variable. Regression analysis was performed using linear, exponential, and power regressions. The best relationship, producing the determination factor closest to 1, was selected from these.
   - Regression analysis to establish the relationship between ultrasonic wave velocity, V (km/second), and concrete compressive strength, fc' (MPa), for all data. Regression analysis was performed using

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linear, exponential, and power regressions. The best relationship, producing the determination factor closest to 1, was selected from these.

- Addition of variables age, α (years), and density, ρ (kN/m^3), as independent variables, and comparison of the redundancy factor values obtained between regression with multiple independent variables and previous single independent variable regression.

3. RESULT AND DISCUSSION

Results of compressive strength test, ultrasonic pulse velocity test, density test, and building age for 5 buildings G1, G2, G3, G4, and G5 as shown in the Table 3.

Table 3 Compressive strength (fc'), Ultrasonic wave propagation velocity (V), Density (ρ), and Building age (α)

No	G1			G2			G3			G4			G5		
	fc'	V	ρ	fc'	V	ρ	fc'	V	ρ	fc'	V	ρ	fc'	V	ρ
1	22.25	3.36	19.07	20.93	3.43	22.01	41.60	4.35	22.21	33.31	4.03	24.44	35.36	3.63	23.02
2	23.62	3.28	19.58	34.02	4.30	23.02	27.00	4.20	22.32	28.64	3.89	22.97	20.21	3.10	21.02
3	24.85	3.31	20.08	40.66	4.47	23.61	25.65	4.20	22.27	27.77	3.79	22.84	12.38	2.65	21.51
4	42.66	4.20	21.33	35.10	4.29	22.73	52.65	4.64	22.40	24.98	3.87	23.37	17.68	3.12	22.65
5	38.80	4.05	21.64	25.01	3.73	23.18	51.30	4.75	22.74	25.17	3.76	22.67	20.61	2.66	21.35
6	30.18	3.67	21.20	24.35	3.53	22.65	45.90	4.41	22.76	30.42	3.79	23.04	28.49	3.14	22.67
7	29.32	3.61	20.80	27.96	3.67	22.97	41.85	4.59	22.38	37.07	4.22	25.41	16.97	2.93	21.20
8	26.30	3.53	20.60	27.50	3.51	22.80	29.70	4.11	21.58	32.81	4.01	22.84	33.95	3.44	23.38
9	30.04	3.67	20.50	24.75	3.51	22.80	35.10	4.55	22.39	32.76	4.17	23.04	23.07	2.88	22.65
10	27.73	3.59	21.63	30.57	4.00	22.94	45.90	4.61	22.69	28.42	3.97	21.86	16.27	2.62	22.86
11	34.83	4.02	21.31	27.73	4.05	22.65	47.25	4.98	23.03				27.78	3.19	22.65
12	33.50	4.14	21.99	24.54	3.62	22.06	47.25	4.55	22.49				16.48	2.70	21.93
13	25.72	3.74	22.83	32.80	3.85	23.28	51.30	4.66	22.79						
14	29.76	4.04	22.70	32.91	3.99	23.45	34.89	4.39	22.27						
15	34.01	3.96	22.89	24.52	3.43	22.41	33.55	4.31	22.55						
16	31.44	4.07	22.70	24.08	3.67	22.28	42.94	4.48	22.70						
17	50.51	4.26	23.22	27.60	3.67	22.13	41.21	4.45	22.66						
18	31.05	3.73	21.79	38.97	4.17	23.46	41.21	4.40	22.54						
19	29.24	3.78	21.50	29.02	4.03	23.13	22.49	4.01	22.37						
20	27.76	3.91	21.60	22.61	3.73	23.13	38.12	4.36	21.75						
21	18.08	3.55	20.93	33.47	3.99	23.30	14.37	3.81	21.45						
22	21.26	3.49	20.93	34.87	4.30	23.49	19.99	4.04	22.60						
23	47.75	4.17	22.96	35.72	3.99	23.03	34.37	4.44	22.74						
24	39.27	4.14	22.89	26.53	3.81	23.34	37.49	4.37	22.73						
25	29.05	3.88	20.52	26.08	3.99	22.65	30.62	4.22	22.64						
26	27.86	3.73	21.33	20.93	3.43	22.01	38.12	4.48	22.83						
27	46.13	4.40	22.57				40.61	4.46	22.66						
28	37.96	4.40	22.18				41.24	4.65	22.44						
29	28.15	3.57	21.22				32.49	4.43	22.25						
30	28.64	3.82	21.76				42.49	4.66	22.70						
31	21.39	3.62	20.25				24.99	4.17	21.58						
32	27.74	3.58	20.12				23.12	4.18	22.19						
33	52.25	4.26	23.22				29.99	4.11	22.39						
34	52.16	4.39	23.22				40.49	4.41	22.02						
35	53.30	4.40	22.28				30.62	3.85	21.35						
36	49.75	4.26	23.73												
37	45.17	4.26	23.26												
38	30.69	3.88	22.01												
39	36.82	4.17	21.70												
40	28.91	3.88	21.60												
41	41.38	4.44	23.64												
42	36.81	4.30	22.51												
43	29.91	3.85	22.11												
44	28.33	3.74	20.83												
45	34.13	4.09	20.73												
46	38.49	4.17	23.53												
47	30.75	3.82	22.18												

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To establish the relationship between the independent variable of ultrasonic wave velocity, V (km/second), and the dependent variable of concrete compressive strength, fc' (MPa), regression analysis was conducted. The results of linear, exponential, and power regression analyses for the pairs of data V and fc' are provided in Table 4 below:

Table 4 Regression equations for linear, exponential, and power fc' and V from data samples of each building

No	Linear Regression		Exponential Regression		Power Regression	
	Equation	r^2	Equation	r^2	Equation	r^2
G1	$fc' = 24.297x - 61.463$	0.736	$fc' = 1.9789e^{0.7153V}$	0.768	$fc' = 0.763V^{2.757}$	0.758
G2	$fc' = 15.109x - 29.158$	0.703	$fc' = 4.0723e^{0.5061V}$	0.711	$fc' = 2.039V^{1.963}$	0.707
G3	$fc' = 32.103x - 104.07$	0.729	$fc' = 0.4639e^{0.9883V}$	0.731	$fc' = 0.061V^{4.312}$	0.734
G4	$fc' = 20.19x - 49.628$	0.696	$fc' = 2.2265e^{0.6576V}$	0.675	$fc' = 0.829V^{2.611}$	0.672
G5	$fc' = 19.642x - 36.6$	0.744	$fc' = 1.7237e^{0.8376V}$	0.701	$fc' = 1.320V^{2.542}$	0.694

From the regression equations obtained, both linear, exponential, and power regressions have the lowest determination factor r^2 of 0.672. If the building with the highest determination factor is selected for each, the relationship between fc' and V is obtained as shown in Table 5 below:

Table 5 Regression equations for fc' and V with the highest determination factor for each building

No	The regression equation	Coefficient of Determination
G1	$fc' = 1.9789e^{0.7153V}$	With an influence of V at 76.8% and other factors at 25.2%
G2	$fc' = 4.0723e^{0.5061V}$	With an influence of V at 71,1% and other factors at 28,9%
G3	$fc' = 0.061V^{4.312}$	With an influence of V at 73,4% and other factors at 26,6%
G4	$fc' = 20.19x - 49.628$	With an influence of V at 69,6% and other factors at 69,4%
G5	$fc' = 19.642x - 36.6$	With an influence of V at 74,4% and other factors at 25,6%

The regression equation for the relationship between fc' and V in Table 3 and the raw data are depicted in Figure 5 below:

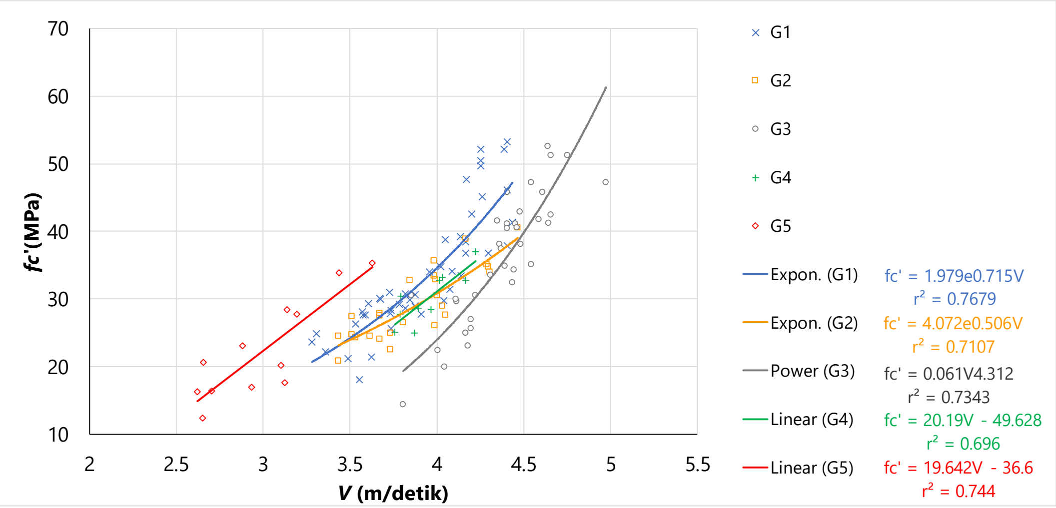

Fig. 5 Data testing and regression equation for the relationship between between fc' and V for each building

Next, to obtain the general relationship between fc' and V, all data were combined, and the regression equation was obtained as follows:

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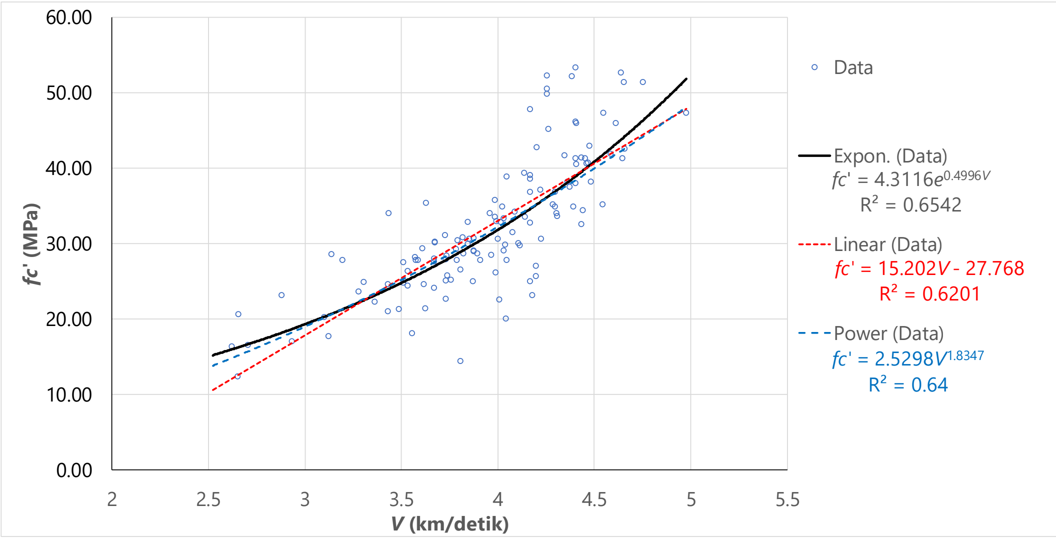

Fig. 6 Data testing and regression equation for the relationship between fc' and V from all data]

From Figure 6, the regression equation with the highest determination factor, r^2, of 0.6542 is obtained as follows:

$$fc' = 4{,}3116e^{0{,}4996V} \qquad (1)$$

The r^2=0.6542 in the equation indicates that V influences $\ln(fc')$ by 65.42%, while the remaining 34.58% is influenced by other variables. In this study, there are additional data obtained, namely density, ρ (kN/m^3), and building age, α (years). By performing regression analysis with $\ln(fc')$ as the dependent variable and V, ρ, and α as independent variables, the regression statistical parameters are obtained as shown in Table 6 below:

Table 6 Regression statistical parameters for multiple regression of $\ln(fc')$ against the independent variables V, ρ, and α

Regression Statistics	
Multiple R	0.823626057
R Square	0.678359882
Adjusted R Square	0.670640519
Standard Error	0.164787211
Observations	129

Table 7 ANOVA for the dependent variable $\ln(fc')$ against the independent variables V, ρ, and α

	df	**SS**	**MS**	**F**	**Significance F**
Regression	3	7.158910985	2.386304	87.87770384	1.20495E-30
Residual	125	3.394353114	0.027155		
Total	128	10.5532641			

Table 8 t-test statistics for the variables V, ρ, and α

	Coefficients	**Standard Error**	**t Stat**	**P-value**
Intercept	0.947626	0.343370	2.759779	0.006654
V	0.572035	0.052443	10.907802	0.000000
ρ	0.003498	0.001454	2.405172	0.017631
t	0.008370	0.019044	0.439490	0.661065

Based on Table 8, the regression equation can be written as:

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$$\ln(fc') = 0.947626 + 0.572035V + 0.003498\rho + 0.008370\alpha \quad (2)$$

Alternatively, it can be expressed differently as:

$$fc' = 2{,}57958e^{0.572035V+0.003498\rho+0.008370\propto} \quad (3)$$

From Table 4, it can be observed that r^2=0.6784r2=0.6784, which is greater than the r^2 in equation (1), which is 0.6542. This increase in the determination factor indicates that with the addition of the density and building age variables, the influence of other unknown variables in this study is reduced by 34.58% - 32.16% = 2.24%. This is further supported by Table 5, where in the F-test, the significance value $1.20495 \cdot 10^{-30} < 0{,}05$, meaning that collectively, variables V, ρ, and α affect the value of fc'. However, from the results of the t-test statistic, it is observed that the variable ρ has a P-value of $P = 0.43949 > 0{,}05$, indicating that the variable αα does not have a significant influence on fc'. Meanwhile, the other two variables, V and α, have P-values of 0.00000 and 0.017631, respectively, which are less than 0.05, indicating their significant influence on fc'.

By removing the variable ρ, the best regression equation obtained from multiple regression analysis is as follows:

$$ln(fc') = 0{,}73204 + 0{,}64959V + 0{,}07926\,ln(\alpha) \quad (4)$$

With r^2=0.714, which is greater than the r^2 values in equations (1) and (3), it indicates that with the increase in the determination factor, by removing the density variable and transforming the building age variable, αα, into $ln(\alpha)$, the influence of other unknown variables decreases to 28.6%.

Table 9 shows the ANOVA for the dependent variable $\ln(fc')$ against the independent variables V and $ln(\alpha)$.

	df	SS	MS	F	Significance F
Regression	2	7.534851	3.767425	157.2666	5.66E-35
Residual	126	3.018413	0.023956		
Total	128	10.55326			

Meanwhile, Table 7 indicates a significance value F of $5.66 \cdot 10^{-35} < 0{,}05$, meaning that collectively, variables V and $ln(\alpha)$ affect the value of fc'.

Table 10 presents the t-test statistics for the variables V and $ln(\alpha)$

	Coefficients	Standard Error	t Stat	P-value
Intercept	0.732038	0.184111	3.976064	0.000117
V	0.649588	0.04147	15.66418	2.32E-31
$\ln\alpha$	0.079256	0.015441	5.132773	1.05E-06

Similarly, the t-test results show that variable V has a P-value of $2{,}32 \cdot 10^{-31}$, and $ln(\alpha)$ has a P-value of $1{,}05 \cdot 10^{-6}$, both of which are less than 0.05, indicating that both variables have a significant influence on fc'.

Equation (4) can be written as:

$$fc' = 2.07932e^{0.64959V}\alpha^{0.07926} \quad (5)$$

Plot the 3D equation (5) as provided in Fig. 7 below:

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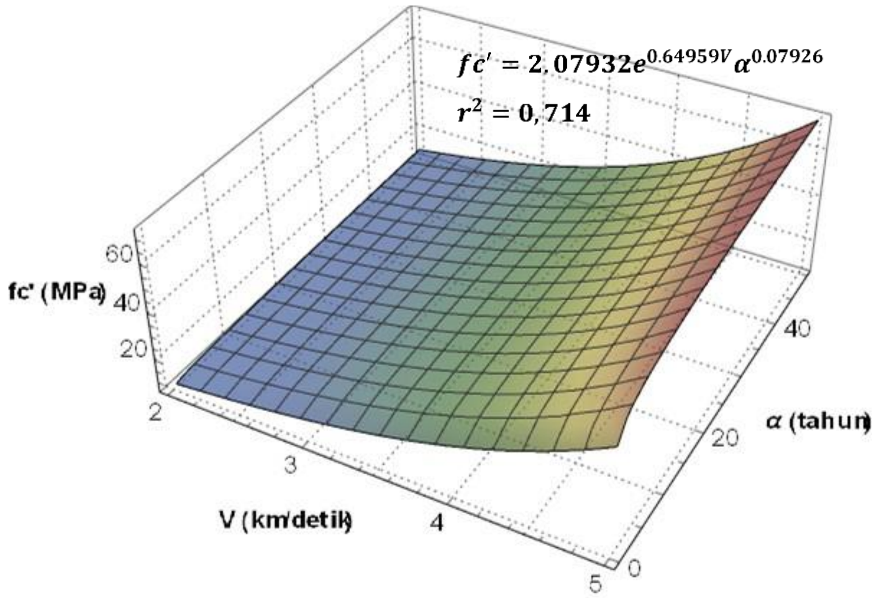

Fig. 7 Regression plot of V and α against fc'

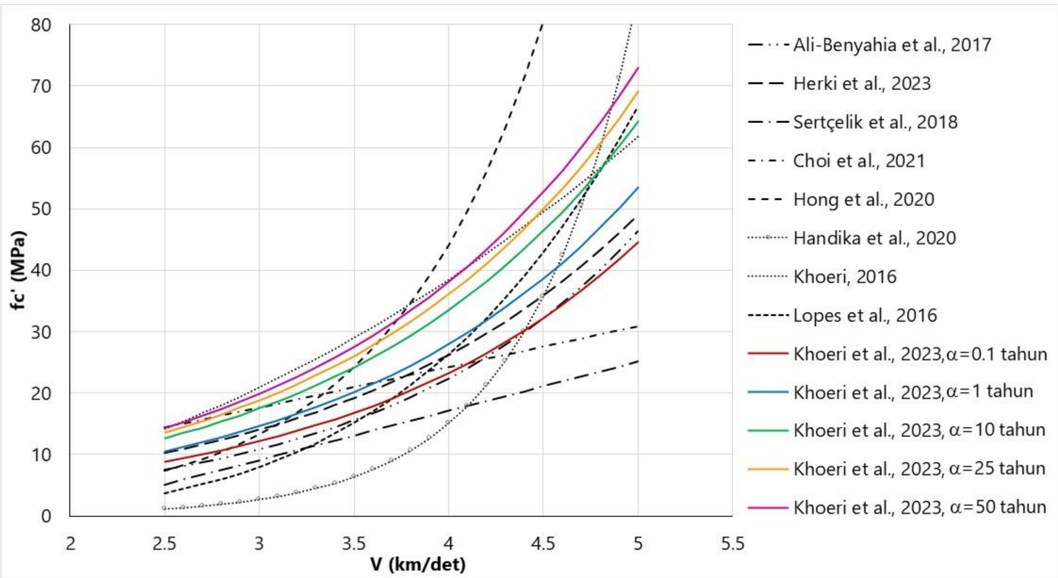

Fig. 8 Regression plot of V against fc' from various studies

Based on Fig. 7 and Fig. 8, it can be observed that there is an influence of sample age (based on building age) on the increase in fc' from V readings, but the increase is not linear; as the sample age increases, the increase will decrease. With r^2=0.714, it means that there is still 28.86% influenced by other variables not examined in this study.

4. CONCLUSION

UPVT is a reliable tool for determining concrete homogeneity and providing descriptive estimates of concrete quality. However, to predict concrete compressive strength, a number of UPVT-data pairs with concrete sample strength results within a single building structure system are still required. Based on research results from 135 core concrete samples taken from 5 building structures, 5 different equations were derived, with varying determination factors ranging from 0.696 to 0.768. This translates to error factors of 23%-30%, with a tendency for higher determination factors as more samples are taken. Combining regression analysis of all samples actually increases the error factor to 34.6%. The results of multi-regression analysis, incorporating additional factors of density, ρρ, and age, αα, show that ρρ has no effect, while αα influences the relationship between V and fc' according to the equation $fc' = 2.07932e^{0.64959V}\alpha^{0.07926}$ with $r^2 = 0.714$. By adding the factor of concrete sample age, the error factor decreases to 28.6%.

5. ACKNOWLEDGMENT

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