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RESEARCH ARTICLE

Performance Evaluation of Uncertainty in Measurement for Dynamic Young's Modules of Elasticity

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Abstract

Background: In construction field, to check the quality of the developed concrete, material testing methods plays a very vital role. As the testing gives measurements therefore maintaining the accuracy and precision of measurement is very essential for producing higher quality concrete. But always uncertainties in measurement is inevitable in every measurement. **Methods**: The effects of qualitative factors which contributes in uncertainty are considered largely in case of measuring instrument but very less attention is given on impact of these parameters on test specimen. It is necessary to integrate both the instrument and test specimen related parameters to get satisfactory results. This paper focuses on the measurement uncertainty calculation in dynamics Young's modules of elasticity obtained from ultrasonic pulse velocity tester. **Findings**: In most of the studies on non-destructive methods propagation of uncertainty is largely dependent on repeatability of measurement results, but we need to focus on all parameters associated with particular measurement process which may contribute in final uncertainty value. To evaluate the measurement uncertainty of dynamic young's modules of elasticity, two major factors are considered one is uncertainty in velocity and another is uncertainty of density. **Novelty**: The calculation of uncertainty in velocity is calculated from the measurement of uncertainties from time (ultrasonic pulse velocity test) and phase length of concrete block. Whereas the uncertainty of density is done from the calculation of uncertainty with mass and volume of the concrete block.

Keywords: Ultrasonic Pulse Velocity Test (UPV); Measurement; Uncertainty; Dynamic Young's Modules of Elasticity; Propagation

1 Introduction

A measurement's result is merely an approximation of the measurand's value, and it is completed only after combining the uncertainty with final result. Because all measurements are subject to errors, it is frequently claimed that a measurement result is only complete if it is accompanied by a quantitative description of its uncertainty [1,2]. Measurement uncertainty describes how well the true value of the measurand is thought to be known, assuming that no undiscovered systematic errors impacts the measurement [3]. Calculating the test result from gathered data is simple; however, calculating the uncertainty related with the particular test result needs more thought and work. The uncertainty evaluation procedure will take into account a number of variables that have an impact on the measurement result. To measure the uncertainty, all factors that potentially influence the outcome must be considered, such as (repeatability, testing speed, temperature, etc.). Because measurement professionals must explain the worth of their work, including its constraints [4,5].

In general, a measurement result is influenced by a large number of influence quantities. While it is hard to identify all of them, the most important ones can be identified and the size of their impacts on the measurement result approximated. Furthermore, they may be mathematically represented in terms of how they affect the measurement outcome. In this research, a technique for determining measurement results in the field of non-destructive testing methods and their related uncertainties is established. This process for determining measurement uncertainty could be used in a variety of fields, including metrological measurement. To reduce measurement uncertainty and increase the accuracy of data, the methodology can be implemented for various testing instruments in laboratories [6]. In most of the studies on non-destructive methods propagation of uncertainty is largely dependent on repeatability of measurement results, but we need to focus on all parameters associated with particular measurement process which may contribute in final uncertainty value. The effects of qualitative factors which contributes in uncertainty are considered largely in case of measuring instrument but very less attention is given on impact of these parameters on test specimen. It is necessary to integrate both the instrument and test specimen related parameters to get satisfactory results.

As the tolerances used in industrial production become more stringent, the function of measurement uncertainty in assessing adherence to these tolerances becomes increasingly essential [7–9]. The accuracy of measurement results is determined by a certain set of parameters. One organization may require low accuracy, whereas another may require high accuracy in measurements. Every instrument has a limited lifespan that is determined by the failure rate. Failures may be linked to a constant over a short period of time. Maintenance plans or strategies may have an impact on failure rates, but they only work in the context of an economic portfolio. The measurement was not always taken in the most convenient position [10–12]. As a result, if measurement is critical, measurement uncertainty is critical as well. The process for uncertainty evaluation can be easily understood from Figure 1 which shows the generalized flowchart from carrying out the measurement to reporting the measurement result with related uncertainty.

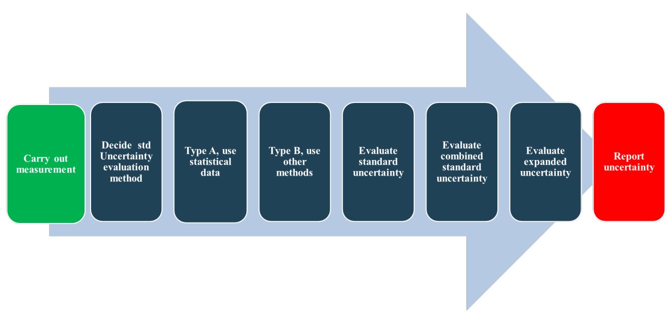

Fig 1. Flowchart of Uncertainty Evaluation Process

Most ultrasonic tests shows variation in readings because of temperature fluctuations between the calibration and testing phases. Several measurements are taken on the instrument in a continuous fashion without re-calibration, which can lead to considerable temperature-related uncertainties. The density and Young's modulus of test specimen changes with change in temperature, thus a theoretical calculation can be employed to calculate the wave velocity for a wide range of temperatures [13–18].

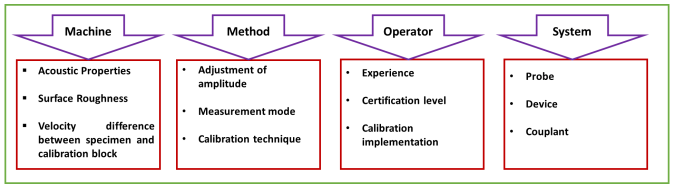

Fig 2. Sources of uncertainty in ultrasonic wall thickness measurements

2 Methodology

2.1 Experimental Setup

The ultrasonic pulse velocity (UPV) test is a nondestructive testing method used to determine the homogeneity and quality of concrete in relation with desired standards by calculating dynamic Young's modulus of elasticity (DME). The ultrasonic pulse is generated by a pulse generator transmits in the body of concrete via transducer. It is reflected multiple times at the interfaces between the various concrete phases. There are three distinct stress wave types that are accounted for in this system: longitudinal, shear, and surface. These three waves travel at different speeds. The longitudinal wave travel s through the solid body of concrete at double speed as compare to shear and surface waves, therefore the receiver transducer identifies the appearance of the longitudinal waves immediately[(19)]. As the velocity of the ultrasonic pulses are dependent elastic properties instead of geometry of the concrete structure, UPV test is an advantageous method for examining structural concrete. As shown in Figure 3. The UPV test setup consist of

- Pulse generating device
- Two transducers (Transmitter and Receiver)
- Timing device (Time Measuring Circuit & Time-Display unit)
- Receiver Amplifier

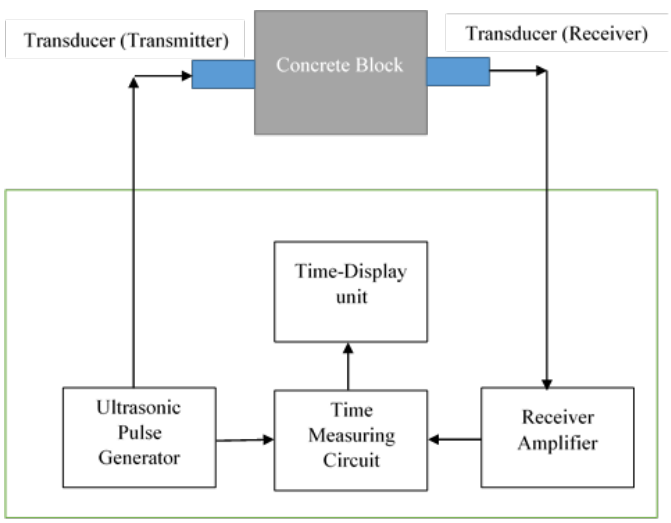

Fig 3. Ultrasonic Pulse Velocity Test Set-up

In this test, a specific transducer is used that works between 20 kHz and 150 kHz. Normally they may be either Piezoelectric or magneto-strictive type. Table 1 shows the frequency of transducers for different phase lengths[(20)].

The electronic timing device can determine how long it takes for a pulse to travel from the source transducer to the point where it is first detected at the destination transducer. Normally two different types of electronic timing apparatus are available one employs a CRT to show the pulse's leading edge with reference to a suitable time scale, while the second one makes use of an interval timer with digital display. It's easier to make sense of the data if we have access to both kinds of timing equipment[(21,22)] . From the obtained time value velocity is calculated and which is used along with density value to calculate dynamic Young's modulus of elasticity.

Table 1. Frequency of Transducers

Sr. No	Phase Lengths of Concrete (mm)	Frequency of Transducers (kHz)
1	Up to 500	150
2	500-700	> 60
3	700-1500	> 40
4	Above 1500	> 20

Test Procedure

1. A specific acoustic lubricant like glycerin or petroleum jelly is applied on the contact surface of concrete and face of both transducer.
2. As shown in Figure 4 these two transducers are held in touch with two faces of the concrete block under test.
3. The first transducer generates the ultrasonic pulse.
4. This pulse is turned into an electrical signal by the second transducer which is in contact with the other face of the test specimen after travelling a complete phase length.
5. The transit duration of the pulse is quantified using an electronic timing circuit
6. Finally as shown in Figure 5 the display unit shows the reading of time in μs.

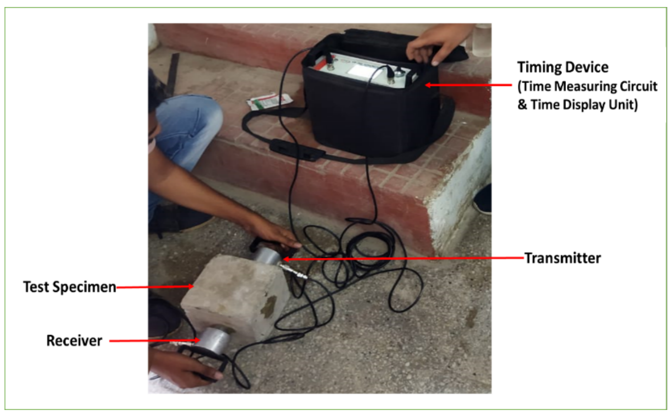

Fig 4. UPV Test Setup

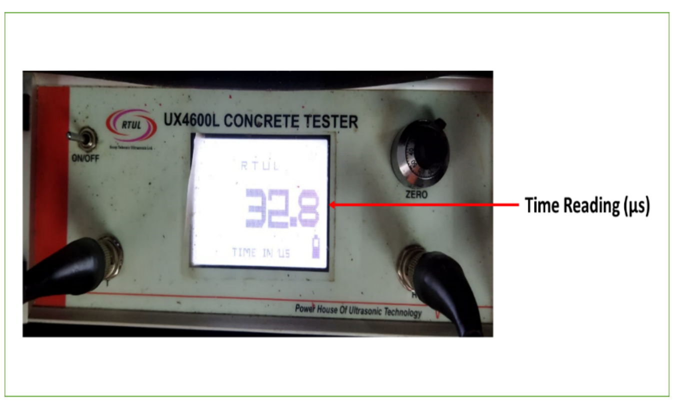

Fig 5. Display of UPV test set up

When the density, homogeneity, and uniformity of the concrete are all high, the resulting velocities are comparatively higher. When the quality is lower, the velocities that can be achieved are also lower. If there is any imperfection inside the body that prevents the propagation of the pulses, the strength of the pulse is diminished, and it travels around the void space, which results in the path length becoming longer. The overall pulse velocity that is obtained is primarily dependent on the density of the specimen, while the specimen's modulus of elasticity also significantly affect the pulse velocity[23–25]. The UPV test is used to measure a number of different parameters, including:

- The uniformity of the concrete specimen under test
- The possibility of the presence of imperfections like cracks
- To determine the quality of the aggregate

3 Result and Discussion

The uncertainty evaluation process for UPV test is carried out as per the flow chart shown in Figure 6. In this process the final uncertainty in the value of DME is dependent on two main components velocity and density. Further each of these component having their own two subcomponents. Uncertainty in measurement of velocity is dependent on transit time and phase length, while mass of and volume of test specimen contributes in measurement uncertainty of density[23–25].

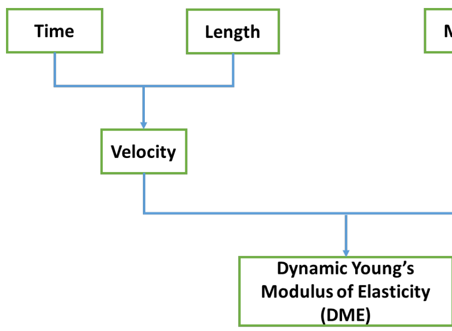

Fig 6. Flowchart of uncertainty components in UPV

In this test total 15 test readings are taken on test specimen made up of concrete. Table 2 shows the observations of UPV test in which transit time measurement is done with the help of UPV test setup while phase length of test specimen is measured using Vernier caliper.

Table 2. Observations of UPV test

Sr. No	Transit Time (μs)	Distance (mm)	Sr. No	Transit Time (μs)	Distance (mm)	Sr. No	Transit Time (μs)	Distance (mm)
1	32.7	149.8	6	32.4	150.34	11	33.2	151.54
2	32.7	151.14	7	32.6	150.2	12	33.4	150.5
3	33	150.24	8	33.2	149.78	13	32.3	150.64
4	32.8	150.68	9	32.8	149.66	14	32.9	149.56
5	32	149.6	10	32.9	150.6	15	33.3	150.82

3.1 Evaluation of measurement uncertainty in pulse velocity

The pulse velocity (V) is given by:

$$V = \frac{L}{T} = 4.58167\ Km/s \tag{1}$$

Where L, is the average distance between two apposite surfaces of concrete cube and T, is the average transit time.

3.1.1 Standard uncertainty of time measurement:

The Type A standard uncertainty, arising from repeated measurements on the concrete block is determined by[14]

$$U_{rm} = \frac{Sd}{\sqrt{n}} = 0.0999\ \times 10^{-6}\ s \tag{2}$$

Where, Sd is Standard deviation of transit time measurements made on concrete cube =0.3871, n is number of transit time measurements made on concrete cube = 15

Degree of freedom, $V_{rm} = 15 - 1 = 14$

From the calibration report, calibration block (40μs) is used with calibration accuracy of $\pm$ 0.2μs.Hence uncertainty of calibration block is calculated by[15]

$$U_{cb} = \frac{0.2}{\sqrt{3}} = 0.1155\ \mu s = 0.1155\ \times 10^{-6}\ s \tag{3}$$

Degree of freedom, $V_{cb} = \infty$

As per the user manual and calibration certificate resolution of display unit of ultrasonic pulse velocity tester is $\pm$ 0.1μs.for digital scale uncertainty due to resolution is calculated by

$$U_{res} = \frac{0.1}{\sqrt{3}} = 0.05774\ \mu s = \ 0.05774 \times 10^{-6}\ s \tag{4}$$

Degree of freedom, $V_{res} = \infty$

Combined standard uncertainty of time measurement [15]

$$UC_T = \sqrt{U_{rm}^2 + U_{cb}^2 + U_{res}^2} = 0.16326\ \times 10^{-6}\ s \tag{5}$$

Effective degree of freedom of time measurement $V_{eff(T)}$ [15,16]

$$V_{eff(T)} = \frac{UC_T^4}{\frac{U_{rm}^4}{V_{rm}} + \frac{U_{cb}^4}{V_{cb}} + \frac{U_{res}^4}{V_{res}}} = 99.71 \tag{6}$$

3.1.2 Standard uncertainty of length measurement

Number of readings for length = 15, Standard Deviation of reading for length = 0.5893 mm Standard Uncertainty of length

$$U_l = \frac{0.5893}{\sqrt{15}} = 0.1522 \text{ mm} = 0.1522 \times 10^{-6}\text{Km} \tag{7}$$

Degree of freedom $V_l = 15 - 1 = 14$

Uncertainty of accuracy of reading of Vernier caliper

Minimum reading (from the equipment manual) = $\pm$ 0.02 mm, Uncertainty of reading = $\pm$ 0.02 mm

Standard uncertainty of a length measurement,

$$U_{vernier} = \frac{0.02}{\sqrt{3}} = 0.0116\ mm \tag{8}$$

Degree of freedom, $V_{vernier} = \infty$

Combined standard uncertainty of dimensional measurement

$$UC_L = \sqrt{U_l^2 + U_{vernier}^2} = \ 0.1526\ \times 10^{-6}\ Km \tag{9}$$

Effective degree of freedom of length measurement $V_{eff(L)}$

$$V_{eff(L)} = \frac{UC_L^4}{\frac{U_l^4}{V_l} + \frac{U_{vernier}^4}{V_{vernier}}} = 14.16 \tag{10}$$

3.1.3 Uncertainty due to temperature and moisture content of concrete

Due to temperatures and moisture deviation of 0.32072 obtained. Hence, assuming rectangular distribution, the standard uncertainty due to temperature and moisture content of concrete is,

$$U_{tm} = \frac{0.32072}{\sqrt{3}} = 0.18517\ Km/s \tag{11}$$

Degree of freedom, $V_{tm} = \infty$

3.1.4 Estimation of combined uncertainty

The combined standard uncertainty of pulse velocity

$$UCV = \sqrt{C_T^2\, UC_T^2 + C_L^2\, UC_L^2 + U_{tm}^2} = 0.18662\ Km/s \tag{12}$$

Where C$_T$ = Sensitivity coefficient of time = $\frac{\partial V}{\partial T}$;

C$_L$ = Sensitivity coefficient of length = $\frac{\partial V}{\partial L}$

Effective degree of freedom of pulse velocity measurement $V_{eff(V)}$

$$V_{eff(V)} = \frac{UV^4}{\frac{C_T^4\, UC_T^4}{V_{eff(T)}} + \frac{C_L^4\, UC_L^4}{V_{eff(L)}} + \frac{U_{tm}^4}{V_{tm}}} = 442509.63 \approx \infty \tag{13}$$

3.2 Evaluation of measurement uncertainty in density of concrete cube

Density of concrete cube is given by,

$$\rho = \frac{m}{v} = 2533.849\ Kg/m^3 \tag{14}$$

Where, m is mass of the concrete cube is 8.61 Kg and v is the calculated volume of the concrete cube based on measured dimensions length (Lx), width (Ly) and height (Lz)

3.2.1 Standard Uncertainty of Mass measurement:

As the expanded Uncertainty in weighing balance, is $\pm$ 0.001 Kg

Standard uncertainty of weighing balance,

$$U_b = \frac{0.001}{2} = 0.0005\ Kg \tag{15}$$

Degree of freedom, V$_b$ = 60

3.2.2 Standard Uncertainty of measurements used to compute volume of concrete block

By calculating the sensitivity coefficient and standard uncertainty of length, Lx, Ly and Lz

The combined standard uncertainty of the density, ρ

$$UC\rho = \sqrt{C_m^2\, U_b^2 + C_{Lx}^2\, UL_x^2 + C_{Ly}^2\, UL_y^2 + C_{Lz}^2\, UL_z^2} == 7.7558\ Kg/m^3 \tag{16}$$

Effective degree of freedom of density measurement $V_{eff(\rho)}$

$$V_{eff(\rho)} = \frac{UC\rho^4}{\frac{C_m^4\, U_b^4}{V_b} + \frac{CL_x^4\, UL_x^4}{VL_x} + \frac{CL_y^4\, UL_y^4}{VL_y} + \frac{CL_z^4\, UL_z^4}{VL_z}} = 10.234 \tag{17}$$

3.3 Measurement uncertainty in dynamic Young's modulus of elasticity

The dynamic Young's modulus of elasticity (E) of the concrete determined from the pulse velocity, density and the Poisson's ratio, using the following relationship [17]

$$E = \frac{\rho\, V^2(1+\mu)(1-2\mu)}{(1-\mu)} = 45.12743\ GPa \tag{18}$$

Where, ρ is density of concrete block, V is pulse velocity and μ is Poisson's ratio= 0.24

The combined standard uncertainty of dynamic Young's modulus of elasticity (E) is calculated by,

$$UCE = \sqrt{C_\rho^2 U\ C\rho^2 + C_V^2 U\ CV^2} = 0.1381379GPa \tag{19}$$

Where C_ρ is sensitivity coefficient of density $= \frac{\partial E}{\partial \rho}$;

C_V is Sensitivity coefficient of velocity $= \frac{\partial E}{\partial V}$

Effective degree of freedom $V_{eff(E)}$

$$V_{eff(E)} = \frac{UCE^{\,4}}{\frac{C_\rho^4\ UC\rho^{\,4}}{V_{eff(\rho)}} + \frac{C_V^4\ UCV^{\,4}}{V_{eff(V)}}} = 10.2364 \tag{20}$$

Since, $V_{eff(E)}$ is not an integer, we can use equation given below to estimate more accurate coverage factor [16]

$$K = \left[\left(n+1-V_{\text{eff}\,(E)}\right) t_{0.975}(n)\right] + \left[\left(V_{eff(E)}-n\right) t_{0.975}(n+1)\right] = 2.2216 \tag{21}$$

Expanded Uncertainty (U) [4, 15, 16]

$$U = K \times UCE = \ 0.306887\ GPa \tag{22}$$

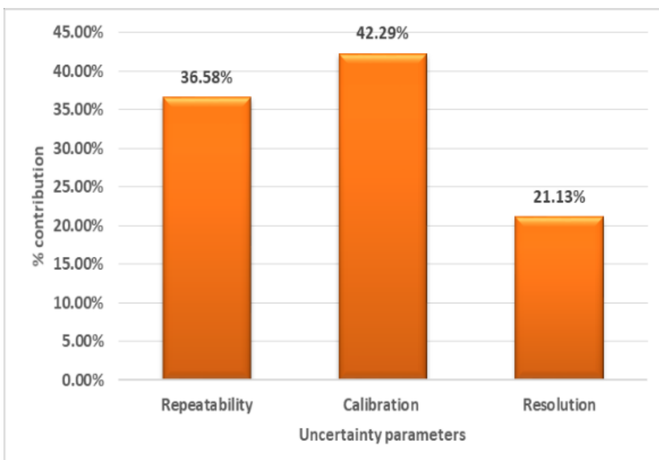

Fig 7. Impact of various parameters on time measurement

The most important aspect of ultrasonic pulse velocity tester is the time measurement, in this study it is observed that in case of uncertainty in time measurement is affected by repeatability transit time measurements, calibration and resolution of instrument. Influence of these parameters is shown in Figure 7. During analysis of density of test specimen as shown in Figure 8, it is observed that volume of the test specimen contributes very largely in uncertainty value as compare to its mass. Similarly, repeatability and test specimen uncertainty have major impact on overall uncertainty value whereas impact of instrument uncertainty is less than 1%.

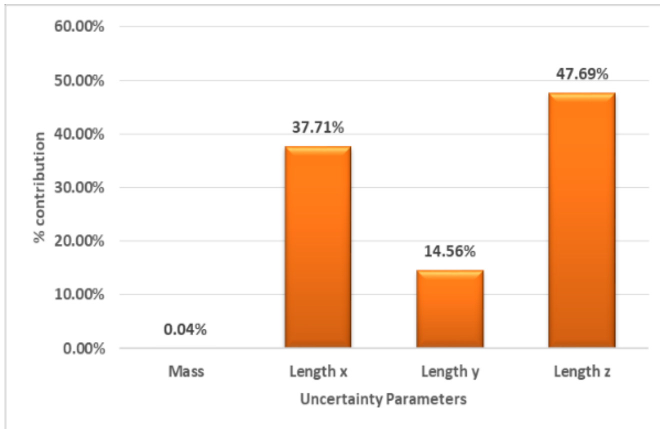

Fig 8. Impact of various parameters on density measurement

4 Conclusion

For the evaluation of dynamic Young's modulus of elasticity of concrete cube, using ultrasonic pulse velocity tester, the expanded uncertainty associated with the result is 0.68% at 95% level of confidence and coverage factor of 2.2216. Hence, the value of dynamic Young's modulus of elasticity of concrete cube is 45.12743 $\pm$ 0.306887 GPa. The ultrasonic pulse velocity test is a good method for analyzing the homogeneity of concrete by determining the dynamic Young's modulus of elasticity. Due to the fact that it has a straightforward testing technique therefore after analyzing the correct value of uncertainty it is possible to conduct tests in laboratories as we as directly on the structures on site. It is observed that density parameters contributes around 98.96% in overall uncertainty whereas contribution of velocity parameters is very less. Based on the current results, it is very easy concentrate on the parameters which are having major impact on the final result, which will help to improve the testing procedure.

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