An Evaluation of Three Methods to Measure the Dynamic Elastic Modulus of Steel

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Abstract

A evaluation is made of three methods used to determine the dynamic elastic modulus of steel. The three methods make use of the Grindo-Sonic machine, the Modul-$\bar{r}$ machine, and the Piezoelectric Ultrasonic Composite Oscillator Technique. Testing of specimens, all from the same piece of stock, was done using each method and a comparison was performed. Since the assumption that all specimens had the same elastic modulus was not valid, a comprehensive statistical comparison could not be done. Still, all methods produced results that were highly repeatable. In addition, it was determined that long thin specimens did not vibrate in their fundamental mode when tested with the Grindo-Sonic machine and that testing specimens with the Modul-$\bar{r}$ machine heats the internal coils of the machine which affects the determined modulus values. The width tolerance needed for the Modul-$\bar{r}$ specimens could not be maintained, and the results of tests on these specimens are not completely valid. The overall mean elastic modulus was 207.1 GPa with a standard deviation of 2.75 GPa.

Key Words: Elastic modulus, Young's modulus, flexural modulus, steel, dynamic impulse excitation, magnetic, piezoelectric, ultrasonic, density

Introduction

The elastic modulus of a material is a very important property to scientists and engineers. It is useful for applications in areas such as load deflection calculations, buckling calculations, fracture mechanics, elastic instability determinations, creep studies, and many other areas. Because of its importance, several standards organizations around the world have formulated procedures to determine the elastic modulus of many materials. However, no procedure has been standardized for the determination of the dynamic elastic modulus of steel. Efforts within ASTM [1,2] are underway to try to establish standard methods for measuring dynamic Young's and shear moduli in non-viscoelastic solids. This paper results from research that was done to assess three current methods of determining the dynamic elastic modulus of steel.

The three methods discussed are the use of the Grindo-Sonic machine, the use of the Modul-$\bar{r}$ machine, and the Piezoelectric Ultrasonic Composite Oscillator Technique (PUCOT). The last two methods determine the elastic modulus by creating longitudinal vibrations in the specimen, while the first method determines the elastic modulus by creating flexural vibrations in the specimen. In all three methods, vibrations were induced in the specimens, the frequencies of these vibrations were measured, and these frequencies along with other parameters were used in a wave equation to determine the dynamic elastic modulus.

For longitudinal vibrations, the wave equation is given by:

$$E = \rho v^2 / n^2 \qquad (1)$$

where E is the elastic modulus, ρ is the specimen density, v is the wave propagation speed, and n is the mode of vibration. The wave speed can be further reduced with the equation:

$$v = f\lambda \qquad (2)$$

where f is the frequency of vibration and λ is the wavelength. All the specimens used in the PUCOT and Modul-$\bar{r}$ methods could be forced to vibrate in their fundamental mode (n=1), and the wavelength for this mode is twice the length (L) of the specimen. Considering all of this, the equation that relates the measured frequency to the dynamic modulus for the PUCOT and the Modul-$\bar{r}$ is:

$$E = 4\rho L^2 f^2. \qquad (3)$$

For flexural vibration, the wave equation can be written as follows:

$$E = (\rho f^2 \pi^2 L^4)/(2\alpha^4 \zeta^2) \qquad (4)$$

where ρ is the density, f is the frequency, L is the specimen length, and α is a term dependent on the mode of vibration. The term ζ is calculated from the equation:

$$\frac{\zeta^2}{\rho} = \frac{I_{bending}}{\mu} \qquad (5)$$

where μ is the mass per unit length of specimen, and $I_{bending}$ is the area moment of inertia about the neutral axis with respect to bending. For the first mode of vibration, the flexural wave equation simplifies to:

$$E = \frac{0.94642 \rho f^2 l^4}{t^2} \qquad (6)$$

where t is the specimen thickness. A geometric correction factor was provided in the Grindo-Sonic literature. This correction was implemented in every test. All correction factors were very nearly unity.

The first testing method discussed is the use of the Grindo-Sonic machine. In this method, the specimen is supported at its nodal points, and a slight impact is delivered near the mid-length of the specimen. This impact starts the flexural vibrations. A piezoelectric transducer located between the specimen supports detects sound waves emanating from the specimen and sends signals to the machine. The machine itself displays a number that is proportional to the fundamental frequency. Knowing the proportionality constant, one can obtain the frequency and, with the other necessary properties, the flexural modulus.

The second testing method discussed is the Modul-$\bar{r}$. This method uses induction coils to change the magnetic permeability of the specimen material which causes strain in the longitudinal length of the specimen. Within the Modul-$\bar{r}$ machine, the specimen is supported by three coils: a drive coil, a bias coil, and a pick-up coil. A magnetic impulse is sent to the bias coil which produces a field on the specimen. In the presence of this field, the specimen strains changing the field where the specimen is supported by the pick-up coil. The pick-up coil senses this change and sends a signal which is amplified and sent to the drive coil. The changing magnetic fields create cycles of tension and compression in the specimen, and because these strains affect the magnetic fields in the coils, the specimen itself is the frequency controlling device. The Modul-$\bar{r}$ displays the frequency at which the specimen vibrates, and this can be used to determine the modulus from the longitudinal wave equation.

The dimensional tolerances on specimens tested with the Modul-$\bar{r}$ machine are very tight. The tolerances are given as:

length	104.6302 mm
width	6.3500±0.0254 mm
thickness	0.2032-2.0320 mm.

The third method discussed is the PUCOT. This method uses piezoelectric crystals subjected to an alternating voltage to create the vibration of the specimen. In the initial step of a PUCOT test, an alternating voltage is sent to a drive crystal which compresses and extends. A gauge crystal, which is glued to the drive crystal, is subjected to this same motion and returns an alternating voltage accordingly. From these cycles, the frequency of the system can be determined. In the second step of a PUCOT test, a specimen is glued to the drive crystal-gauge crystal system and is subjected to longitudinal cycles of strain. The frequency of this new system is slightly different from the frequency of the original system. The frequency of the new system is determined, and, from an energy analysis of the two separate systems, the frequency at which the specimen is vibrating (which is different from the frequency of the entire system) can be determined. This frequency is used to determine the modulus.

Goal

The goal of this research was to determine the elastic modulus of steel according to the three methods discussed. The values produced using each method were compared statistically using the comparison of means test.

After background testing on the Grindo-Sonic machine, a 9.525 mm square stock of 1018 steel was chosen as the specimen material. All specimens were machined from one length of this material. The specimen material for the Modul-$\bar{r}$ must be ferromagnetic, and 1018 steel fits this requirement.

Because all specimens were made from the same bar stock, it was envisaged that they would have the same elastic modulus. A statistical comparison was made to consider whether the three methods produced the same value of elastic modulus. Therefore, the precision and repeatability of each method were considered as the characteristics to be compared.

Procedure and Results

The first step in carrying out this research was to determine appropriate sizes of the steel specimens for testing. Initially, long, thin sheet metal specimens were chosen in order to meet the Modul-$\bar{r}$ tolerance requirements. However, these specimens yielded poor results when tested with the Grindo-Sonic machine either because the slight impact loads moved the specimens from their structural supports or because they would not vibrate in their fundamental mode. A section of 12.700 mm square stock was then tested. This yielded very repeatable and reasonable values of elastic modulus. However, a 9.525 mm square stock was chosen in order to minimize machining time in producing specimens for the Modul-$\bar{r}$. Specimens of these sizes were machined: 104.6 x 2.0 x 6.3 mm (Modul-$\bar{r}$) and 102.0 x 9.5 x 9.5 mm (Grindo-Sonic). Five specimens for each of these two methods were produced. PUCOT specimens were machined from these ten specimens later after Modul-$\bar{r}$ and Grindo-Sonic testing had been concluded.

Testing with the Grindo-Sonic method was begun. Each specimen was tested twenty five times: five series of tests were done, each series consisting of five individual tests. Test readings were recorded, and the vibration frequencies were determined from this. Specimen lengths and widths were determined from an average of three measurements done with digital calipers for each dimension. A constant density was used, and this was determined from an average of individual densities calculated by dividing the specimen mass by the dimensional volume.

With all of these data recorded, elastic modulus values were calculated and compared to each other with the comparison of means test. For each specimen tested, the Grindo-Sonic method produced highly repeatable measurements with standard deviations for measurements on individual specimens ranging from 0.40 GPa and 0.77 GPa. However, the calculated mean elastic moduli for the individual specimens did not compare well, and, for this reason, all the sets of calculated elastic moduli were considered to be statistically different.

The decision was then made to acquire better measures of specimen density to obtain better comparisons between the mean elastic moduli of the specimens. The Archimedes method was used to determine the density of all the specimens. The density of each specimen was measured twice, and an average of these two values was taken as the density of each specimen. A comparison of means test for these values is provided in the Appendix. Because few of the measured values of density compared well with other values, it was decided to treat density as a variable in the wave equations and use the value of density that corresponded to the specimen being tested.

With the density of each specimen determined, the previously recorded Grindo-Sonic test readings were used to recalculate the elastic moduli of the specimens. These values were compared using the comparison of means test. The results of these tests are displayed in the Appendix. These results show that, of the ten possible comparison combinations, only one combination contained two specimens that had the same elastic modulus value. Mean elastic moduli and standard deviations are displayed in the Appendix. These range from 207.2 GPa to 209.1 GPa and from 0.40 GPa to 0.77 GPa, respectively (See Figure 1). The determined mean values differed from each other by slightly less than 1% of the elastic modulus value. The very low standard deviations (less than 1% of the modulus value) indicate that measurements for each specimen are highly repeatable. Considering all Grindo-Sonic tests of the five specimens, a mean modulus value was calculated at 208.1 GPa with a standard deviation of 0.86 GPa (See Figure 2). This was the lowest overall standard deviation produced by any of the methods. Therefore, it was concluded that the Grindo-Sonic method has the least systematic error of the three methods.

Testing was then begun on the Modul-$\bar{r}$ specimens. Specimens were tested, and the vibrational frequency for each was recorded. Elastic moduli values were determined, and the values were compared to each other with the comparison of means test. Again, five series of five individual tests were done on each specimen. Of the ten possible comparison combinations, no two specimens had the same elastic modulus. The statistical test results are presented in the Appendix. Calculated means for the individual specimens ranged from 201.3 GPa to 210.6 GPa with standard deviations ranging from 0.07 GPa to 0.09 GPa (See Figure 3). The very low standard deviations indicated that measurements on each specimen were highly repeatable. A mean elastic modulus value for all specimens tested with the Modul-$\bar{r}$ machine was 205.8 GPa with a corresponding standard deviation of 3.40 GPa (See Figure 2).

At this point, testing of some of the specimens using the PUCOT method was begun. However, it was decided to attempt to test the Modul-$\bar{r}$ specimens with the Grindo-Sonic machine. Only the second specimen tested with the Modul-$\bar{r}$ had been cut to produce PUCOT specimens. Still, all five specimens were tested with appropriate distances between the specimen supports corresponding to positions of the nodal points for each specimen.

Grindo-Sonic tests were carried out, vibrational frequencies were determined, and the elastic moduli were calculated. These results are presented in the Appendix. The mean elastic moduli for the individual specimens ranged from 200.4 GPa to 212.3 GPa with standard deviations ranging from 0.4 GPa to 2.4 GPa. The highest standard deviation for tests done on an individual specimen was about 1% of the calculated mean elastic modulus indicating a high level of repeatability for tests on individual specimens. A mean value was calculated using all tests on these five specimens. This value was 205.2 GPa with a corresponding standard deviation of 4.29 GPa.

An interesting note which was observed while testing these five specimens was that they did not vibrate at their fundamental frequency. With the unmachined square stock specimens originally tested with the Grindo-Sonic machine, all of these originals vibrated in their fundamental mode. Of the Modul-$\bar{r}$ specimens, the four longer specimens vibrated in their fifth mode, while the second specimen, which had been cut to produce a PUCOT specimen, vibrated in its third mode during testing.

The wave equation for flexural vibration is dependent on the thickness of the test specimen through the term ζ. However, it was very difficult to maintain constant specimen thicknesses or widths when machining the thin, narrow Modul-$\bar{r}$ specimens. Consequently, these specimens, over their length, varied somewhat in width and thickness.

The obtained values of the elastic moduli could be manipulated by choosing any value of thickness found anywhere along the length of each specimen. It was impossible to determine the thickness value which could be used to obtain a true representation of the specimen's elastic modulus. For this reason, no comparison of means tests are provided for elastic moduli of these five specimens obtained with the Grindo-Sonic machine. Using a thickness calculated from an average of three measurements, individual elastic moduli of all specimens were calculated to be less than 200 GPa. Using a minimum value of specimen thickness, one obtains the above mentioned results.

The last method used was the PUCOT. Because of the time duration of each PUCOT test, it was not feasible to test all specimens with this method. Five specimens were chosen, and these were tested five times each. The fifth specimen tested with the Grindo-Sonic method and the second specimen tested with the Modul-$\bar{r}$ method were chosen because their calculated mean elastic moduli agreed well (208.3 GPa and 208.7 GPa, respectively). In addition, the second specimen tested with the Grindo-Sonic was chosen because its calculated mean elastic modulus (207.6 GPa) agreed well with that of the other two specimens. Later, the first and the fourth specimens tested with the Modul-$\bar{r}$ were chosen since their calculated means were the highest and lowest values encountered. It was important to determine how these would compare with other specimens whose mean moduli were more near the overall mean elastic modulus.

PUCOT tests were carried out, and the measured elastic modulus of each specimen was compared with all of the others determined in a similar way. The results of these tests are presented in the Appendix. Of all possible comparison combinations, no combination had two specimens which had the same elastic modulus. The calculated mean elastic modulus for individual specimens ranged from 204.1 GPa to 211.8 GPa with standard deviations ranging from 0.01 GPa to 0.10 GPa (See Figure 4). These were the lowest standard deviations for individual specimens produced at this stage in testing. These low values indicate a very high level of repeatability. A calculated mean using all values obtained from specimens tested with the PUCOT was 207.9 GPa with a standard deviation of 2.8 GPa (See Figure 2).

The last stage of the research concerned the results of the Modul-$\bar{r}$ test method. The difference between high and low values of calculated mean elastic moduli of individual specimens was 9.3 GPa. Similar differences for the other methods were 1.9 GPa (Grindo-Sonic) and 7.8 GPa (PUCOT). This difference seemed high, and it was decided to search for a reason.

During testing with the Modul-$\bar{r}$ machine, a strange trend was noticed. In almost every series of tests on individual specimens, frequency readings became consecutively lower. Because of this and because of the large difference in calculated mean elastic moduli of individual specimens, the manufacturer of the Modul-$\bar{r}$ machine was contacted.

A spokesperson for this manufacturer pointed out two important notes. First, the process of magnetically exciting the specimen heated the coils within the machine. This internal heating caused the consecutive decrease in frequency values put forth by the Modul-$\bar{r}$ machine. Second, the elastic moduli determined by using the Modul-$\bar{r}$ method were not completely valid because the specimens did not meet the width requirements quoted. In machining, it was attempted to maintain the 6.350 mm width. However, the complexities in machining parts with small widths and thicknesses caused variations in specimen width and thickness, as mentioned above.

A few more tests were made to assess the above factors. First, one of the specimens which was not used to make PUCOT specimens was tested with significant time intervals between tests to allow the Modul-$\bar{r}$ machine to cool. The results of these tests are displayed in the Appendix. Fifteen tests were done with approximately five to fifteen minute intervals between tests with the machine off. The mean elastic moduli determined from these tests was 203.7 GPa with a standard deviation of 0.006 GPa. In thirteen of the fifteen tests, the Modul-$\bar{r}$ detected and displayed the same frequency. This is near the lowest standard deviation calculated for any of the methods. This may indicate that the Modul-$\bar{r}$ is capable of producing results with the highest level of repeatability. More tests should be done to substantiate this.

Measurements were done also to determine the affect of specimen width on elastic modulus values for the Modul-$\bar{r}$ method. However, only two specimens were available.

Once testing with these three methods was completed, it was decided to determine the static elastic modulus of specimens from the same stock and compare this with the values of dynamic elastic modulus previously determined with the three methods. Two specimens were machined to approximately 6.35 mm in diameter. These specimens were loaded in tension while force and strain data were recorded. The specimens were not loaded to the yield point so that all strain was in the elastic range. Each specimen was subjected to five cycles of loading and unloading. The elastic modulus was determined for each situation, and a mean of these elastic moduli was calculated for each specimen. The determined mean elastic modulus of the first specimen was 202.8 GPa with a standard deviation of 2.9 GPa. The determined mean elastic modulus of the second specimen was 202.8 GPa with a standard deviation of 3.1 GPa. These mean static elastic moduli each represented a 2.1% difference from the overall mean dynamic elastic modulus calculated from all the results of the three methods.

Discussion

Two hundred and seventy six measurements were taken in all, not counting tests on the Modul-$\bar{r}$ specimens by the Grindo-Sonic method. Compiling all of these values, the overall mean elastic modulus calculated was 207.1 GPa with a standard deviation of 2.75 GPa. The highest obtained elastic modulus value was 211.8 GPa, and the lowest obtained value was 201.3 GPa. These values have percent differences from the overall mean of 2.3% and 2.8%, respectively. From each other, the high and low values have a 5.2% difference (with respect to the lowest value).

Of the elastic modulus values compared against others obtained using the same method, there were thirty possible test combinations. This number neglects the tests done on the Modul-$\bar{r}$ specimens using the Grindo-Sonic machine. In the thirty possible comparison cases, only one combination paired two specimens whose set of measured elastic moduli could be said to be statistically the same. This means that statistically almost all of the specimens have a different elastic modulus. The major initial assumption for the statistical comparison was that all specimens have the same elastic modulus. Therefore, comprehensive comparisons could not be carried out among the three methods.

Conclusions

The overall mean elastic modulus of all the specimens tested was calculated to be 207.1 GPa. This agrees well with the industry accepted elastic modulus of steel. The mean modulus measured for all specimens tested with the Grindo-Sonic method was 208.1 GPa with a standard deviation of 0.86 GPa. This represents a 0.5% difference from the overall mean. The mean elastic modulus calculated for all specimens tested with the Modul-$\bar{r}$ was 205.8 GPa with a standard deviation of 3.4 GPa. This represents a 0.6% difference from the overall mean. The mean elastic modulus measured for all specimens tested with the PUCOT was 207.9 GPa with a standard deviation of 2.8 GPa. This represents a 0.4% difference from the overall mean.

The initial assumption that all specimens statistically have the same elastic modulus is invalid. Therefore, a comprehensive statistical comparison cannot be done among the three methods.

All methods produce very repeatable results. The highest standard deviation of a set of elastic modulus values of an individual specimen was 0.8 GPa (not including tests on Modul-$\bar{r}$ specimens by the Grindo-Sonic machine). This is approximately 0.4% of the overall mean. For any one method, the highest overall standard deviation was 3.4 GPa. This was 1.6% of the overall mean. The Grindo-Sonic method produced results with the lowest standard deviation. For this reason, we conclude that this method produces the least systematic error in its measurements. The standard deviation of the total set of 276 tests was 2.8 GPa. This was 1.4% of the overall mean. These low standard deviations indicate a high level of repeatability in the measurements.

The long, thin Modul-$\bar{r}$ specimens did not vibrate at their fundamental frequency when tested with the Grindo-Sonic machine. All of the heavier, thicker specimens tested with this method vibrated at their fundamental frequency. Because of the variations in thickness of the lighter specimens, it was impossible to determine a thickness value that would yield a true representation of the elastic modulus of each Modul-$\bar{r}$ specimen tested in this fashion.

Each test done with the Modul-$\bar{r}$ machine heats the internal coils of the machine. Therefore, a sufficient cooling time should be allowed between tests. Fifteen tests were done using five to fifteen minute intervals with the machine off. The resulting data yielded the third lowest standard deviation determined in the study. Thirteen of the fifteen tests resulted in exactly equal values. Because of this extremely low standard deviation, it seemed that enough cooling time was allowed between tests and that the Modul-$\bar{r}$ method may produce results with the highest level of repeatability. Further tests should be done to determine if this method actually does produce the highest level of repeatability.

Additionally, it was determined that maintaining the width tolerance on specimens tested with the Modul-$\bar{r}$ method is critical. Insufficient tests were done to quantify this effect.

GrindoSonic Method

	Mean Modulus (GPa)	Standard Deviation (GPa)	Number of Tests
Specimen 1	208.5	0.43	25
Specimen 2	207.6	0.40	25
Specimen 3	209.1	0.47	25
Specimen 4	207.2	0.56	25
Specimen 5	208.3	0.77	25

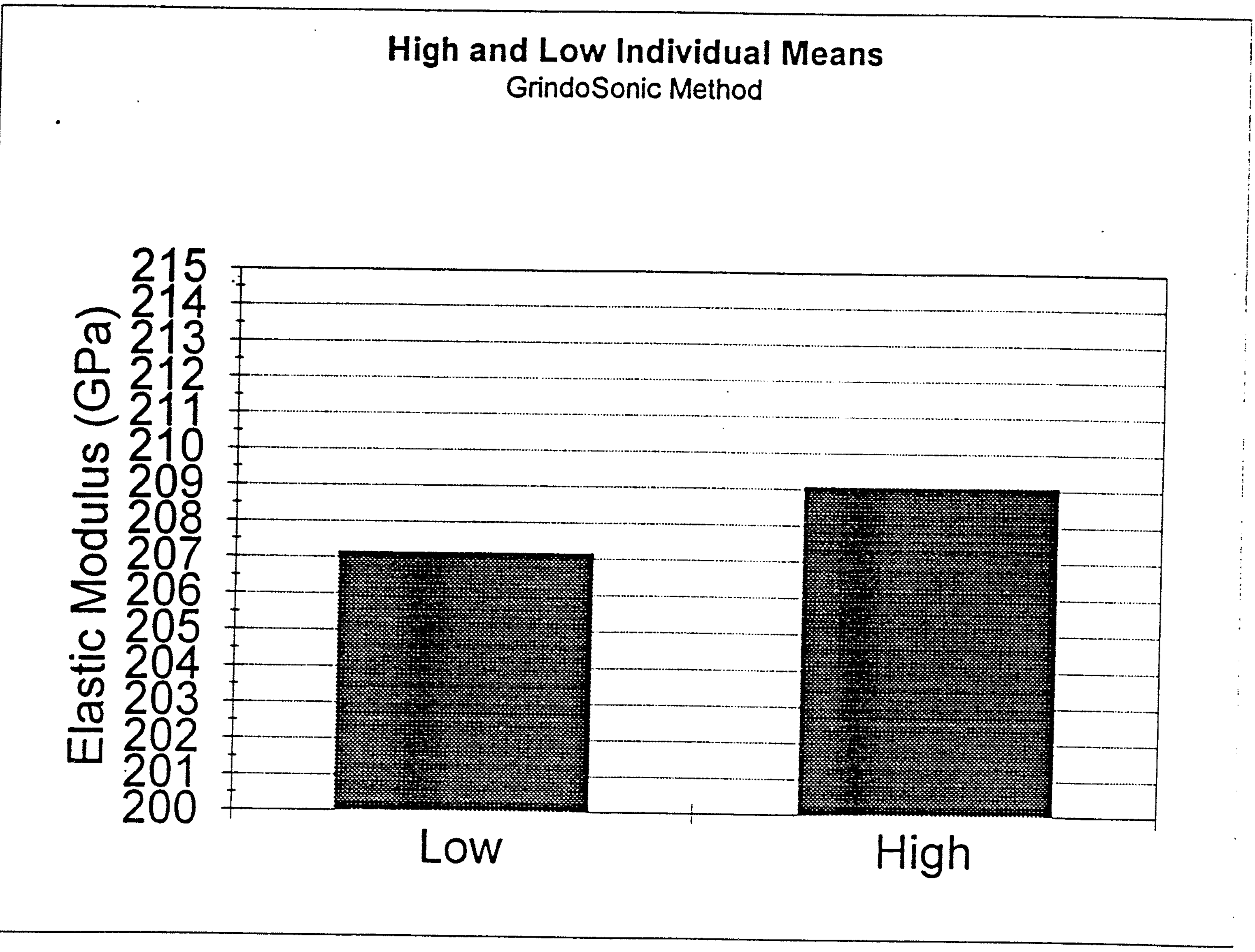

Fig. 1 Summary of Grindo-Sonic Tests

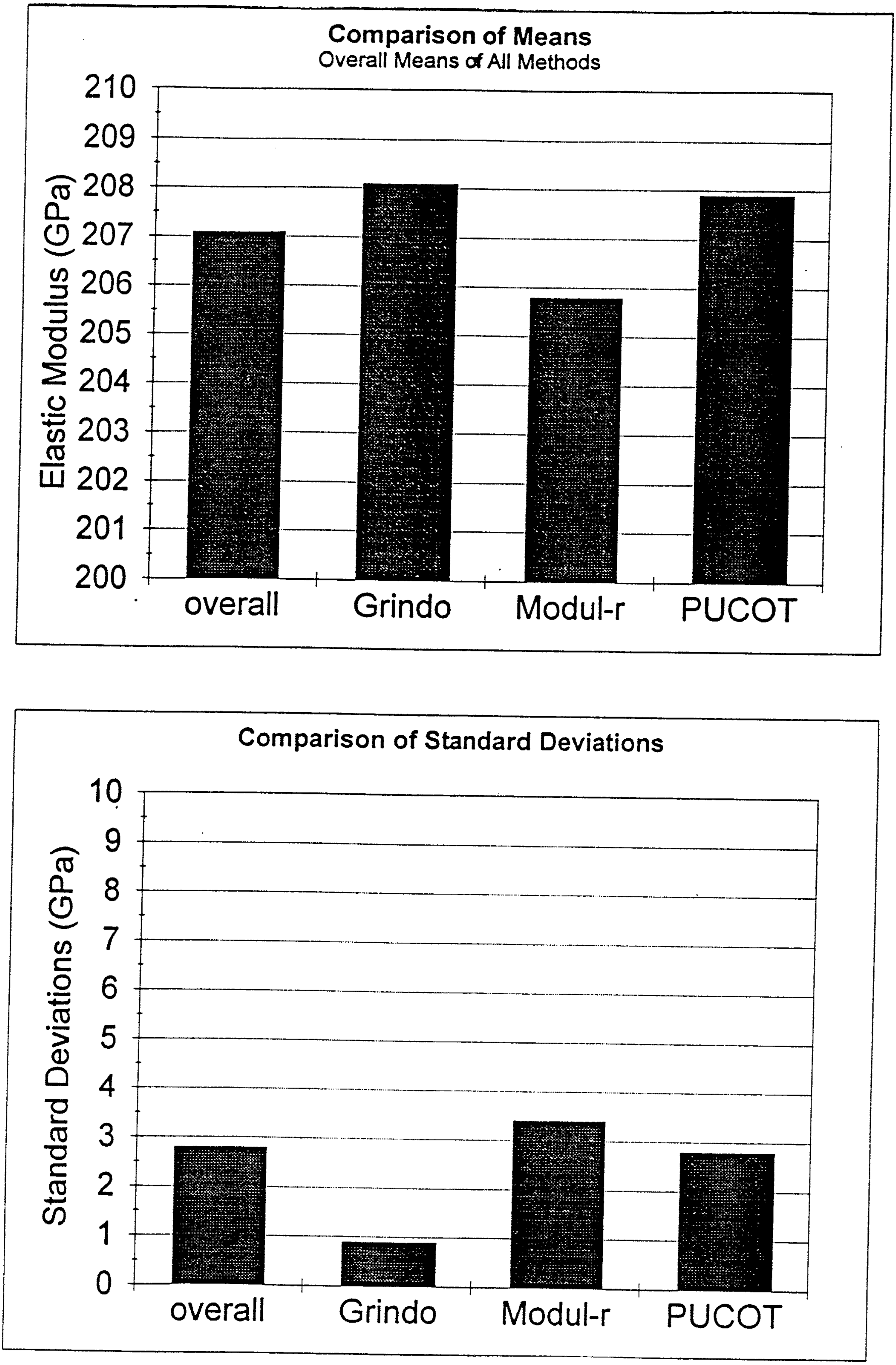

Fig. 2 Cumulative Summary of Tests

Modul-r Method

	Mean Modulus (GPa)	Standard Deviation (GPa)	Number of Tests
Specimen 1	210.6	0.07	25
Specimen 2	208.7	0.08	25
Specimen 3	203.6	0.08	25
Specimen 4	201.3	0.09	25
Specimen 5	204.9	0.09	25

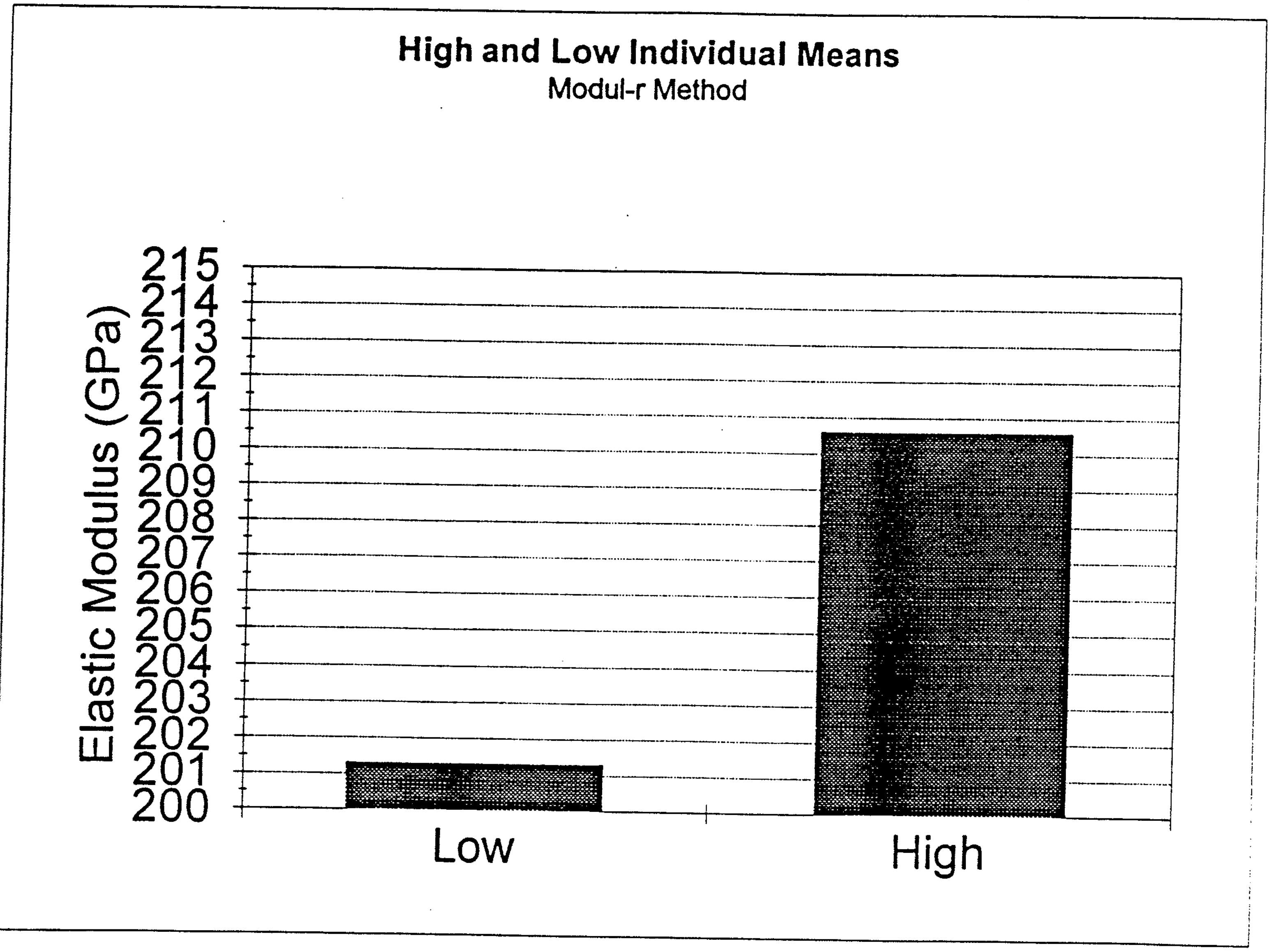

Fig. 3 Summary of Modul-$\bar{r}$ Tests

PUCOT Method

	Mean Modulus (GPa)	Standard Deviation (GPa)	Number of Tests
Modul-r 2	211.8	0.10	6
Grindo 2	209.5	0.05	5
Grindo 5	205.7	0.01	5
Modul-r 4	207.5	0.02	5
Modul-r 1	204.0	0.05	5

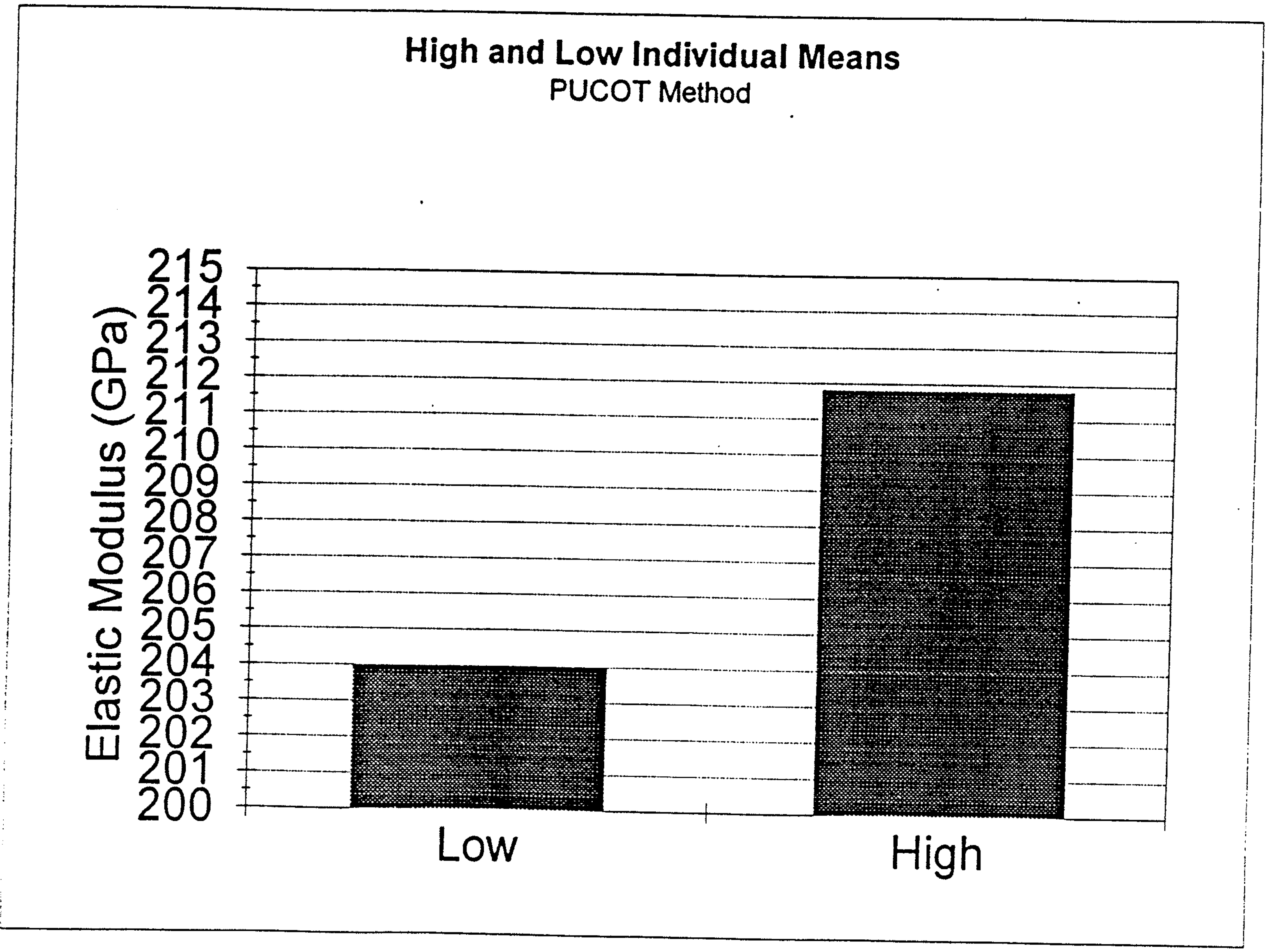

Fig. 4 Summary of PUCOT Tests

Acknowledgments

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Appendix

T Test to statistically compare the density measurements

All Methods Densities	Avg.	Std. Dev	GrindoSonic Densities	Avg.	Std. Dev.	Modul R Densities	Avg.	Std. Dev.	PUCOT Densities	Avg.	Std. Dev.
7840.3	7833.5	6.2[illegible]	7840.5	7839.2	3.10	7833.1	7828.3	3.10	7834.6	7832.5	5.2[illegible]
7834.6			7834.6			7827.4			7839.7		
7838.5			7838.5			7826.9			7836.0		
7843.5			7843.5			7827.3			7842.6		
7839.7			7839.7			7830.1			7833.1		
7833.1			7838.4			7825.1			7828.3		
7827.4			7836.0			7831.7			7825.1		
7826.9			7835.5			7827.9			7831.7		
7827.3			7843.2			7831.6			7827.4		
7830.1			7842.6			7822.0			7827.3		
7838.4						7828.3			7831.6		
7836.0											
7835.5											
7843.2											
7842.6											
7825.1											
7831.7											
7827.9											
7831.6											
7822.0											
7828.3											

Minimum number of data points	10
Degrees of Freedom	9
Confidence Level	95 percent
alpha	0.025
T critical	2.262

First Data Set	Average	Standar Deviatio	Number of Trials	Second Data Set	Average	Standard Deviation	Number of Trials	T
All	7833.5	6.2	21	Grindo	7839.2	3.1	10	3.41
All	7833.5	6.2	21	Modul R	7828.3	3.1	11	3.16
All	7833.5	6.2	21	PUCOT	7832.5	5.2	11	0.48
Grindo	7839.2	3[illegible]	10	Modul R	7828.3	3.1	11	8.05
Grindo	7839.2	3[illegible]	10	PUCOT	7832.5	5.2	11	3.62
Modul R	7828.3	3[illegible]	11	PUCOT	7832.5	5.2	11	2.30

T tests

Method	First Specimen	Mean (GPa)	sigma (GPa)	Number of Tests	Second Specimen	Mean (GPa)	sigma (GPa)	Number of Tests	T	T Critical
G S	1	208.47	0.433	25	2	207.63	0.395	25	7.17	2.064
G S	1	208.47	0.433	25	3	209.08	0.469	25	4.78	2.064
G S	1	208.47	0.433	25	4	207.15	0.558	25	9.34	2.064
G S	1	208.47	0.433	25	5	208.32	0.773	25	0.85	2.064
G S	2	207.63	0.395	25	3	209.08	0.469	25	11.82	2.064
G S	2	207.63	0.395	25	4	207.15	0.558	25	3.51	2.064
G S	2	207.63	0.395	25	5	208.32	0.773	25	3.97	2.064
G S	3	209.08	0.469	25	4	207.15	0.558	25	13.24	2.064
G S	3	209.08	0.469	25	5	208.32	0.773	25	4.20	2.064
G S	4	207.15	0.558	25	5	208.32	0.773	25	6.14	2.064
Modul R	1	210.61	0.073	25	2	208.69	0.077	25	90.48	2.064
Modul R	1	210.61	0.073	25	3	203.6	0.079	25	326.85	2.064
Modul R	1	210.61	0.073	25	4	201.31	0.090	25	401.20	2.064
Modul R	1	210.61	0.073	25	5	204.85	0.088	25	251.89	2.064
Modul R	2	208.69	0.077	25	3	203.6	0.079	25	230.70	2.064
Modul R	2	208.69	0.077	25	4	201.31	0.090	25	311.54	2.064
Modul R	2	208.69	0.077	25	5	204.85	0.088	25	164.20	2.064
Modul R	3	203.60	0.079	25	4	201.31	0.090	25	95.61	2.064
Modul R	3	203.60	0.079	25	5	204.85	0.088	25	52.85	2.064
Modul R	4	201.31	0.090	25	5.	204.85	0.088	25	140.62	2.064
PUCOT	mr2	211.84	0.103	6	GS2	209.45	0.050	5	50.18	2.776
PUCOT	mr2	211.84	0.103	6	GS5	205.66	0.007	5	146.56	2.776
PUCOT	mr2	211.84	0.103	6	MR4	207.46	0.017	5	102.50	2.776
PUCOT	mr2	211.84	0.103	6	MR5	204.03	0.050	5	163.99	2.776
PUCOT	GS2	209.45	0.050	5	GS5	205.66	0.007	5	167.86	2.776
PUCOT	GS2	209.45	0.050	5	MR4	207.46	0.017	5	84.26	2.776
PUCOT	GS2	209.45	0.050	5	MR5	204.03	0.050	5	171.40	2.776
PUCOT	GS5	205.66	0.007	5	MR4	207.46	0.017	5	218.93	2.776
PUCOT	GS5	205.66	0.007	5	MR5	204.03	0.050	5	72.19	2.776
PUCOT	MR4	207.46	0.017	5	MR5	204.03	0.050	5	145.23	2.776

Grindo-Sonic Tests

	Length (mm)	Width (mm)	Density (kg/m^3)
Specimen 1	102.89	9.51	7839.45
Specimen 2	102.27	9.51	7835.30
Specimen 3	102.29	9.51	7836.99
Specimen 4	102.63	9.51	7843.33
Specimen 5	102.32	9.51	7841.16

	Elastic Modulus (GPa)	Standard Deviation (GPa)
Specimen 1	208.5	0.43
Specimen 2	207.6	0.40
Specimen 3	209.1	0.47
Specimen 4	207.2	0.56
Specimen 5	208.3	0.77

Modul-r Tests

	Length (mm)	Width (mm)	Thickness (mm)	Density (kg/m^3)
Specimen 1	104.71	6.37	1.98	7828.86
Specimen 2	104.21	6.29	1.99	7829.54
Specimen 3	103.68	6.53	1.90	7827.40
Specimen 4	102.27	6.51	1.97	7829.46
Specimen 5	100.33	6.30	1.98	7826.04

	Elastic Modulus (GPa)	Standard Deviation (GPa)
Specimen 1	210.6	0.07
Specimen 2	208.7	0.08
Specimen 3	203.6	0.08
Specimen 4	201.3	0.09
Specimen 5	204.9	0.09

Grindo-Sonic Tests on Modul-r Specimens

	Length (mm)	Width (mm)	Thickness (mm)	Density (kg/m^3)
Specimen 1	104.71	6.37	1.90	7828.86
Specimen 2	71.11	6.29	1.98	7829.54
Specimen 3	103.68	6.53	1.86	7827.40
Specimen 4	102.27	6.51	1.92	7843.33
Specimen 5	100.33	6.30	1.94	7841.16

	Elastic Modulus (GPa)	Standard Deviation (GPa)
Specimen 1	212.3	2.36
Specimen 2	204.5	0.69
Specimen 3	200.4	0.35
Specimen 4	206.4	0.39
Specimen 5	202.1	0.94

PUCOT Tests

	Length (mm)	Mass (g)	Density (kg/m^3)
Modul-r 2	32.89	3.247	7829.54
Grindo 5	31.98	22.576	7841.16
Grindo 2	32.53	22.888	7835.30
Modul-r 4	32.21	3.102	7829.46
Modul-r 1	31.73	2.991	7828.86

	Elastic Modulus (GPa)	Standard Deviation (GPa)
Modul-r 2	211.8	0.10
Grindo 5	205.7	0.01
Grindo 2	209.5	0.05
Modul-r 4	207.5	0.02
Modul-r 1	204.0	0.05

Modul-r Tests to Investigate Thermal Effects

Specimen	3		
Length mm	103.68	Mass g	9.76142
Thickness	1.9	Dens. kg/m^3	7827.40
Width	6.53		

Series 1

Frequency (Hz)	Dynamic Modulus GPa
24603	203.72
24605	203.76
24604	203.74
24604	203.74
24604	203.74
24604	203.74
24604	203.74
24604	203.74
24604	203.74
24604	203.74
24604	203.74
24604	203.74
24604	203.74
24604	203.74
24604	203.74
avg.	203.74
Std. Dev.	0.006