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Article

Development of Strength Model of Lateritic Soil-Cement

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Abstract. Since the shortage of crushed rock as base course in some regions of Thailand, the improvement of the lateritic soil-cement as pavement base course has been evaluated. Soil cement improvement has been used for many years because of the significant improvement in soil properties. The objective of the research effort is to investigate performance of Lateritic soil cement mixtures using experimental study. The experimental results in terms of unconfined compressive strength and elasticity modulus were improved significantly as the cement content is increased. The multiple regression models based on cement content and curing time parameters were proposed to predict the unconfined strength (UCS) and elastic modulus of Lateritic soil-cement. The proposed prediction models providing good correlations with the experimental data are presented in this study.

Keywords: Lateritic, soil, cement, pavement, materials, multiple regression.

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1. Introduction

Lateritic soil is one of local materials extensively formed in the southern of Thailand. In general, the strength of lateritic soil excavated from the upper profile is quite low. However, the strength of lateritic soil will increase significantly by stabilizing with low contents of cement. Thus, the lateritic soil stabilized with cement can be widely utilized as a low-cost pavement base of roads particularly in available areas of lateritic soil. Soil stabilization with original Portland cement is one of various soil improvement methods in road geotechnical engineering. This technique has been economical compared with other soil improvement methods.

The cement stabilized base is produced by mixing In-situ cement with lateritic soil to improve shear strength and elastic modulus. The shear strength of soil samples can be experimentally evaluated using unconfined compression tests. The upper limit of unconfined compressive strength of 2000 kPa (20.13 ksc) after 7 days cured was introduced to prevent the excessive use of cement [1]. In addition, many soil cement samples collected from existing roads and prepared in laboratory were test. Unconfined compressive strength of the cored samples is far beyond the design unconfined compressive strength at 7 days cured (1724 kPa or 17.5 ksc). Surface crack highways on soil cement base with highway crack seal and chip seal maintenances were performed very well [2-4].

The chief factors affecting the quality of soil-cement are content of SO_3, pH, salt content, soil type, cement content, compaction and method of mixing. Of these the soil type is by far the most important factor since, if it is unsuitable, little can be done to make the soil-cement satisfactory. If the content of SO_3 in the soil is greater than 0.2% or SO_4 content is greater than 0.5%, or if the SO_3 content in the groundwater exceeds 300 mg/l, the strength of the cement mix will be reduced [5, 6]. Anon reports that soils with pH values of less than 5 are unsuitable for economic stabilization [7]. Kawasaki *et al.* points out that the stabilization effect will greatly deteriorate, when the pH value drops below 5 [8]. A soil with low pH is usually associated with high organic content. This type of soil is unsuitable for cement treatment. There is very little gain in strength even mixing with large quantities of cement. High salt content, especially sulphates, can retard hydration of cement in soil-cement mixtures [7]. Greater strength is obtained if distilled water is used rather than sea water. Results have shown that strength will be as much as 30% lower when using sea water [9].

In terms of effectiveness of cement treatment, Winterkorn and Fang divide the soil into three groups [10]: 1) Sandy and gravely soils with 10-35% silt and clay content. This group of soil can be easily pulverized and mixed and used under a wide range of weather conditions. These soils usually require the least amount of cement for adequate hardening. 2) Sandy soils deficient in fines. This group of soil requires a slightly more cement content than the soils in the first group for comparable results in hardening. 3) Silty and clayey soils. This group of soil can produce a satisfactory soil-cement mix. Those with high clay content are difficult to pulverize and may result in a product that has excessive shrinkage properties. Weather conditions affect this group more than the previous two groups, whose granular skeletons are not affected by moisture content.

The unconfined compressive strength of the treated soil may be as low as 1,380 kPa for fine-grained soils with 16% cement and more than 10,000 kPa for granular soil-cement with 3% cement [11]. Bell found that granular soils mix more easily than fined-grained soils and they require less cement [12]. The individual grains are coated with cement paste and bonded at their points of contact as the grain size of granular soils is larger than that of cement. Anon pointed out that the cement requirements for various soil types are quite different [7]. Under the same curing conditions, soils with higher cement content will be stronger than soils with lower cement content. Bergado *et al.* shows that the strength is a direct function of cement content [13]. Mitchell suggested that for fine grained soil the unconfined compressive strength (UCS) is a linear function of cement content [11].

2. Methodology

Before starting sample preparation, the moisture density relationship was determined and prepared for each cement content. The cement used in the study was ordinary Portland cement (OPC or Type I). Compaction was achieved by the modified Proctor procedure (ASTM D-1557). The cement content used in this investigation was 3%, 5%, 7% and 9% with respect to the dry weight of the lateritic soil to investigate the methods in stabilizing lateritic soil samples. The effect of cement content, curing time and unit weight on the strength and stiffness characteristics of the lateritic soil-cement mix has been investigated.

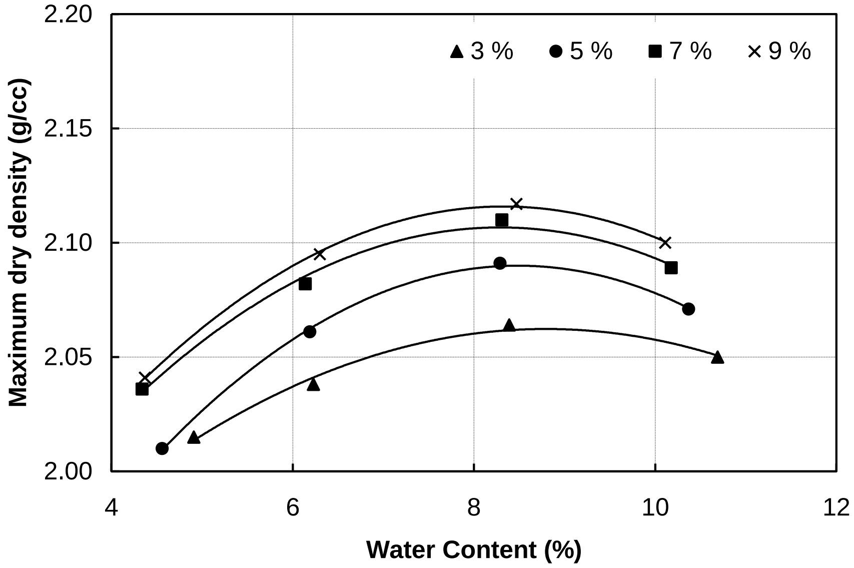

Fig. 1. The water content-density relationship of cement stabilized.

As shown in Fig. 1, there is no significant change in the optimum water content of the lateritic soil-cement mixtures with the increase in cement content. A compaction test is to re-arrange soil particles. Soil can reach it maximum dry density by wetting and re-arrange the soil particles by water molecules and compaction. For these soils with cement mixtures, the maximum dry density is between 2.06 and 2.12 g/cm^3. The optimum water content is between 8.2% and 8.4% for different amounts of cement added to soil. Therefore, the peaks of each compaction curves for different cements are recommended to improve the interlocking force among soil particles.

Firstly, mixed lateritic soil with cement according to design mixing ratio by hand for about 15 minutes and admixed them with water at amount of optimum water content according to Fig. 1. Each specimen was prepared using cylindrical mold having inner diameter of 101.6 mm and height of 116.8 mm. The prepared soil was placed in the cylindrical mold in five layers and each layer was compacted according to the procedure of modified Proctor compaction. After compaction, the specimens were wrapped with plastic sheet and cured at room temperature of about 28^{o}C and submerged under water for 2 hours before testing. Unconfined compression tests were conducted at the curing time, which are summarized in Table 1. The increase of the shear strength of the stabilized soil was determined after 3, 7, 14 and 28 days after the mixing. Laboratory tests were conducted to access the strength and stiffness of the lateritic soil-cement mixture. The statistical method was adopted to evaluate the sensitivity of various factors.

Table 1. Details of test series.

Cement Content (%)	**Curing Times (days)**			
	3	**7**	**14**	**28**
3	C3T3	C3T7	C3T14	C3T28
5	C5T3	C5T7	C5T14	C5T28
7	C7T3	C7T7	C7T14	C7T28
9	C9T3	C9T7	C9T14	C9T28

3. Soil Property Test Results

3.1. Index Properties

Lateritic soil was collected from a site at Hatyai in Thailand about 0.5-2.0 m depth below the ground surface. The lateritic soil was sealed in the air tight plastic containers and transported to the laboratory for testing. The soil properties before mixing, such as, sieve analysis, the Atterberg's limit test, water content, unit weight and CBR are shown in Table 2. Table 3 shows the particle size distribution of these soils.

Table 2. Summary of basic properties of the laterite soil sample at Songkhla, Thailand.

Soil Properties	Value
Liquid limit	50%
Plastic limit	34.2%
PI	15.8%
Water content	26.72%
Unit weight (ton/m^3)	2.076
Specific Gravity	2.69
CBR dry	118%
Unified Classification	A-2-7
AASHTO Classification	SC

Table 3. Particle size distribution for soil used.

Sieve	% passing
2"	100
1"	91.7
3/8"	72.1
#4	51.8
#10	30.1
#40	14.7
#200	10.6
Pan	

4. Soil-Cement Mixing Test Results

Results of all tests are summarized in Table 4. Some failure mechanisms of the tested samples are shown in Fig. 2. It also revealed that more brittle type of failure were observed with curing period of 7 days.

Table 4. Results of test series.

Test #	C_C	T	D_D	UCS	ES
C3T3	3	3	2.133	18.97	3548
C5T3	5	3	2.133	34.77	6400
C7T3	7	3	2.212	51.85	9010
C9T3	9	3	2.152	61.14	12014
C3T7	3	7	2.132	22.65	4332
C5T7	5	7	2.195	39.19	6900
C7T7	7	7	2.194	54.66	9710
C9T7	9	7	2.141	66.75	12838
C3T14	3	14	2.150	24.69	4963
C5T14	5	14	2.184	45.73	8100
C7T14	7	14	2.230	61.61	11515
C9T14	9	14	2.139	73.69	14716
C3T28	3	28	2.175	34.57	6680
C5T28	5	28	2.184	54.68	9702
C7T28	7	28	2.203	69.06	12690
C9T28	9	28	2.154	83.30	15544

Note: C_C = the cement content, T = the curing time, D_D = dry density (ton/m^3), UCS = unconfined compressive strength (ksc), and ES = Modulus of elasticity (ksc).

(a) The 3% cement (b) The 5% cement

Fig. 2. The samples of the 3% and 5% cement mixing at 7 days.

4.1. Effect of Cement Content on Unconfined Compressive Strength

Typical cement content used in soil stabilization varies from 3% to 9%. If the lateritic soil-cement is too dry, it is hard to mix evenly and may result in shrinkage cracks; but if it is too wet, it may result in low strength after mixing. The relationship between cement content, time and unconfined compressive strength of the cement treated soil is shown in Fig. 3. The strength increases proportionally with increasing cement content. It appears that the 28 days strength can be estimated using the following equation proposed by Mitchell [11] as shown in Eq. (1). It is evident that predicted values of strength determined by this equation are much higher than the experimental values.

$$UCS = (300 \; to \; 600) C_C \tag{1}$$

where C_C is the cement content (%).

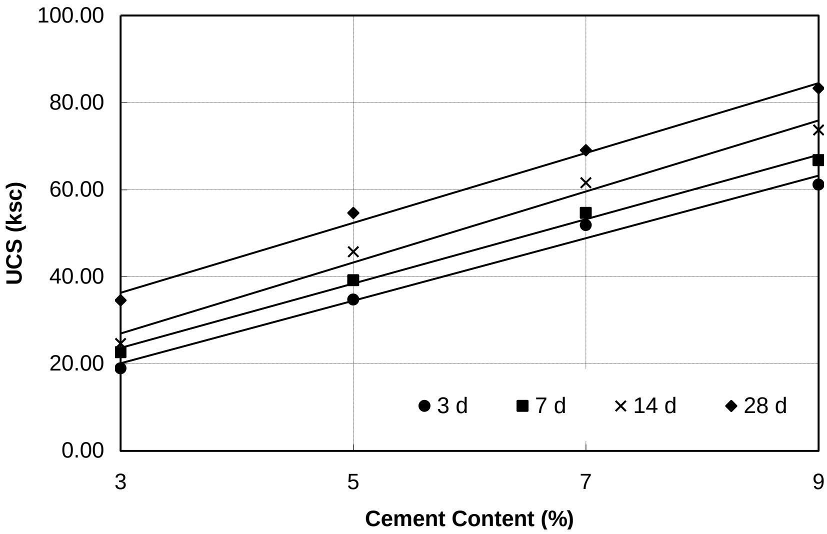

Fig. 3. Effect of cement content and curing time (UC test).

4.2. Effect of Curing Time on Strength and Stiffness

The tests were to investigate the increase of the unconfined compressive strength and the effect of aging on the stabilized soil. Fig. 3 shows the unconfined compressive strength of the cement treated lateritic soil as determined by unconfined compression tests. It can be seen that the compressive strength increased with increasing cement content as well as with increasing time of the curing. It increased to 22.65 ksc, 39.19 ksc, 54.66 ksc and 66.75 ksc after 7 days with 3%, 5%, 7% and 9% cement, respectively. The increase of the compressive strength was thus large when the cement content was high.

The mix contained 3% cement, 7 and 28 days unconfined compressive strength test samples gave strength of 22.65 ksc and 39.19 ksc, respectively. It was also noted that laboratory prepared samples produce a 7 days strength over 17.5 ksc following specification of Highway Department for base course materials. The initial increase of the compressive strength of the cement treated soil was mainly caused by a reduction of the water content due to hydration. The increase of the compressive strength was still large even after 28 days due to ion exchange and cementation. It can be seen that the effect of the cementation increases rapidly with increases with time for the cement treated lateritic soil. The increases of the compressive strength due to a reduction of the water content are proportional to the cement content. It was observed that the reduction of the water content decreased with time. The reduction of the water content contributed substantially to the short term improvement of the compressive strength while the long term improvement was mainly caused by cementation.

Using the 3 days strength as a reference, the strength at 7 days varies from 1.11 to 1.17 of the 3 days strength with an average value of 1.14. The strength at 14 days varies from 1.11 to 1.17 of the strength at 7 days with an average value of 1.14. The strength at 28 days varies from 1.07 to 1.19 of the strength at 14 days with an average value of 1.13. Results show that the optimum curing time for all specimens is 14 days. The variation of strength with curing time is shown in Fig. 4.

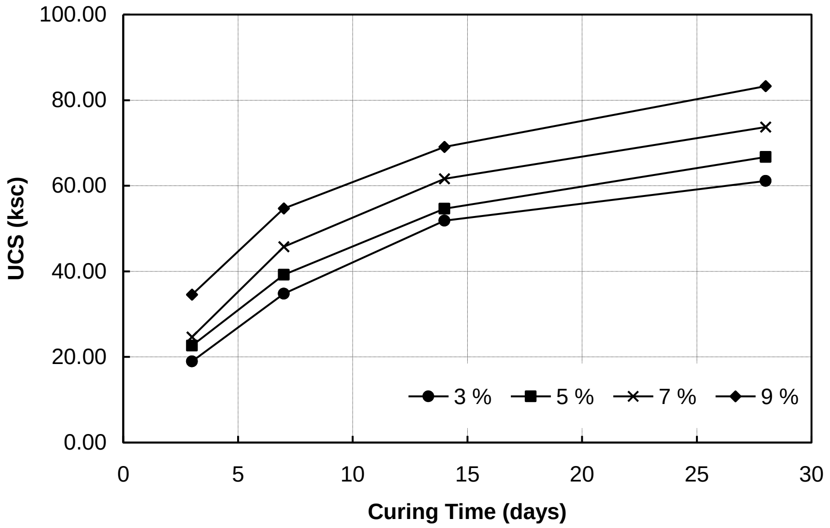

Fig. 4. The variation of strength with curing time.

The initial increase of the unconfined compressive strength of the cement treated soil was mainly caused by a reduction of the water content due to hydration. The increase of the compressive strength was still large even after 28 days due to ion exchange and cementation. Figure 4 illustrates the relative improvement of the compressive strength with cement. It can be seen that the effect of the cementation increases rapidly with increases with time for the cement treated lateritic soil. The increases of the compressive strength due to a reduction of the water content are proportional to the cement content. It was observed that the reduction of the water content decreased with time. The reduction of the water content contributed substantially to the short term improvement of the compressive strength while the long term improvement was mainly caused by cementation. The strength varies linearly with the logarithmic time as can be seen in Fig. 5.

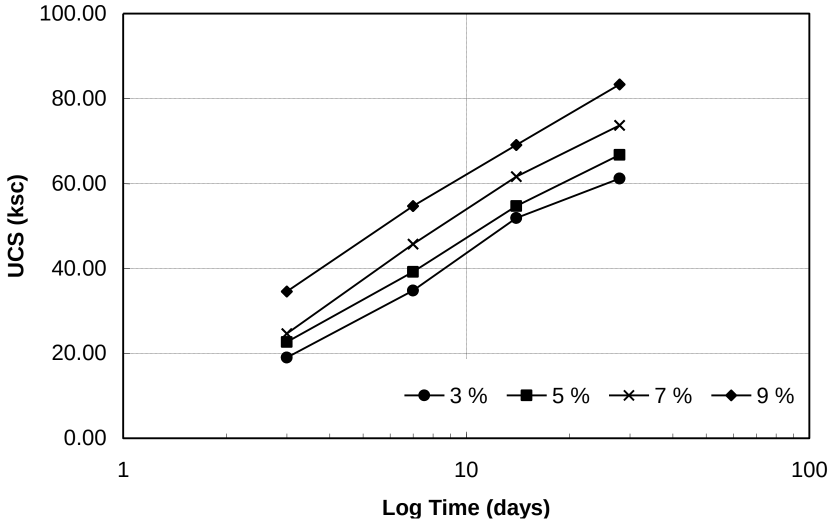

Fig. 5. The strength varies linearly with the logarithmic time.

5. Analysis

From experimental data, the results for soil-cement mixing are presented in Table 4. The experimental results with 16 tests represent the unconfined compressive strength and modulus of elasticity during the 28 days after addition of water. The cement content (C_C), curing time (T) and dry density (D_D) are linearly dependent predictors of the cement content, the curing time and the dry density of soil. Variable (UCS) and (ES) are the unconfined compressive strength and the modulus of elasticity, respectively. The multiple regression model [14] was proven to have a good fit with inclusion of all the two predictors (UCS and ES) presented as given in Eq. (2).

$$y_i = \beta_0 + \beta_1 x_{i1} + \beta_2 x_{i2} + \beta_3 x_{i3},\ i = 1, 2, ..., n \tag{2}$$

where, y_i is the predictors (UCS and ES), β_i is numerical constants and x_{ii} is soil cement parameters. In this model, multiple regression analysis is applied to all data. The resulting regression is as follows:

For unconfined compressive strength:

$$UCS = -6.045 + 7.685 C_C + 0.713T \qquad [\ R^2 = 0.971\ ] \tag{3}$$

$$UCS = -108.468 + 7.607 C_C + 0.674T + 47.656 D_D \qquad [\ R^2 = 0.976\ ] \tag{4}$$

For modulus of elasticity:

$$ES = -1298.470 + 1467.375 C_C + 131.584T \qquad [\ R^2 = 0.974\ ] \tag{5}$$

$$ES = -1873.914 + 1466.938 C_C + 131.367T + 267.747 D_D \qquad [\ R^2 = 0.974\ ] \tag{6}$$

where, unconfined compressive strength (UCS) unit: kg/cm^2, cement content (C_C) unit: % by weight, curing time (T) unit: days, dry density (D_D) unit: ton/m^3, modulus of elasticity (ES) unit: kg/cm^2.

It should be noted that the modulus of elasticity in this study represents the modulus of elasticity at 50% of ultimate load. To determine the static modulus of elasticity, the slope based on the two linear points of stress-strain relation: 1) the first point at longitudinal strain 50 $\mu\varepsilon$ and 2) the second point at compressive stress corresponding to 50% of ultimate load was used for this purpose. Comparison between the experimental data and predicted values obtained from Eq. (4) and Eq. (6) were presented in Fig. 6. The maximum absolute error percentage of unconfined compressive strength and modulus of elasticity were found to be 11 and 12%, respectively.

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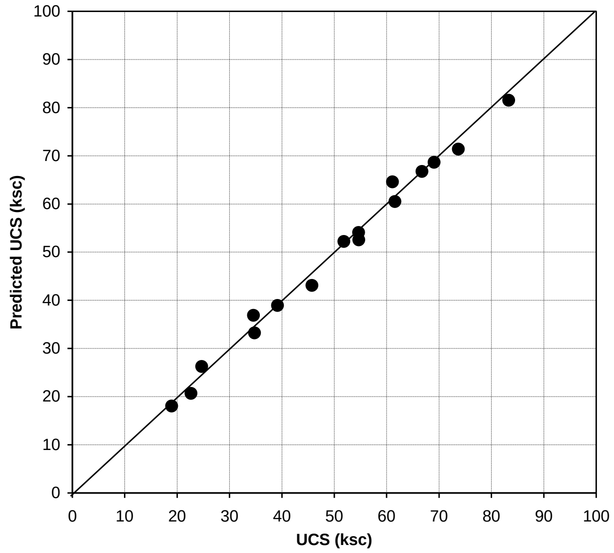
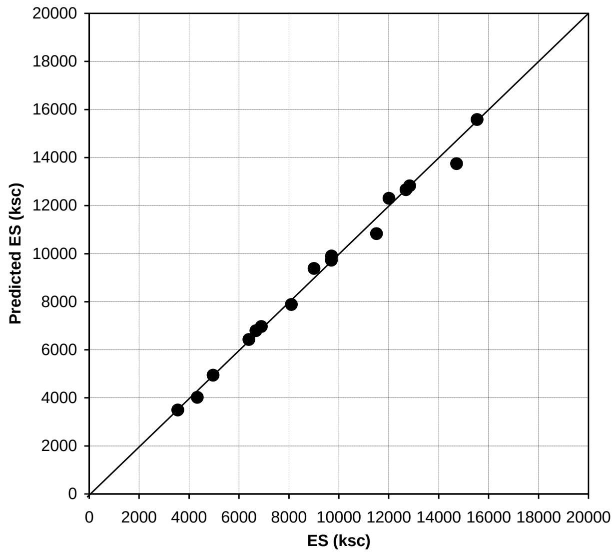
At low cement contents ductile stress-strain relationships were observed though brittle behavior appeared with increasing strength. The modulus of elasticity of the lateritic soil-cement also increases with increasing strength. Approximate ratios of the elastic modulus to unconfined compressive strength of cement treated lateritic soils varied between 100 and 200. Therefore unconfined compressive strength and the modulus of elasticity can be stated by Eq. (4) and Eq. (6), respectively. In addition, the relationship between the modulus of elasticity and unconfined compressive strength tend to from the linear model as given in Eq. (7).

$$ES = -71.83 + 188.28UCS \qquad [\ R^2 = 0.984\ ] \tag{7}$$



(a) Unconfined compressive strength.



(b) Modulus of elasticity.

Fig. 6. Comparison of Experimental data and predicted values.

6. Conclusions

The improved strength of the lateritic soil-cement depends on many factors such as the type of soils, cement content, water content ratio and curing time. The strength increases proportionally with increasing cement content. The strength increased about 10 ksc for every 2% increase in cement content. The average

ES/UCS ratio is about 200 regardless of the cement content. The strength of soil-cement increases linearly with the logarithmic of time. The optimum curing time for soil-cement mixing is 14 days. The strength at 7 days varies from 1.11 to 1.17 of the 3 days strength with an average value of 1.14. There is an overall improvement in the strength characteristics of the lateritic soil and this behavior has been confirmed from unconfined compression tests. This can be realized with increase in the induced UCS and ES values. There is an increase in the strength of the lateritic soil by about 4 times for 5% cement weight by soil weight when compared to the untreated soil. Based on the results of the study, the following conclusions can be drawn:

- Multiple regression models can be used to predict the strength and modulus of lateritic soil-cement more easily and efficiently since it is more user-friendly.
- The higher the percentage of cement added the higher the increment in the strength and modulus of treated soil.
- Unconfined compressive strength and modulus of elasticity (ES) are improved significantly as the cement content is increased.
- Cement content (CC) and curing time (T) have major effects on the strength and modulus of lateritic soil-cement in flexible pavement.
- On the basis of the results, 3% cement content is the optimum for use as a base course in highway pavements.
- The performance evaluations showed that the multiple regression model predictions are very satisfactory in estimating unconfined compressive strength and modulus of elasticity.

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