ELASTIC AND MECHANICAL PROPERTIES OF HUMAN DENTIN

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THE elastic and mechanical properties of dentin were studied as early as 1895 by Black[1] who measured the compressive strengths of cubes of dentin and reported that a cube, 0.08 inch square, had an average compressive strength of 37,200 psi and an elastic deformation of 2.09 per cent when subjected to a load of 100 pounds (elastic modulus $\sim$ 0.8 $\times 10^6$ psi). Peyton, Mahler, and Hershenov[2] reported average values of 23,400 psi, 36,100 psi, and 1.67 $\times 10^6$ psi for the proportional limit, compressive strength, and elastic modulus, respectively. Stanford, Paffenbarger, and Kumpula[3] reported average values for these properties of 25,100 psi, 50,400 psi, and 4.1 $\times 10^6$ psi, respectively. Neumann and Di Salvo[4] reported values from 1.1 to 1.7 $\times 10^6$ psi for the elastic modulus using large transverse sections of teeth. The values for the proportional limit and compressive strengths of dentin were in reasonable agreement, but those for the elastic modulus differed widely.

The difficulties involved in handling small specimens of dentin and the problems connected with correcting the deformation used in the calculation of the elastic modulus values possibly account for the differences obtained in the various studies. It was felt that a critical re-evaluation of the technics and procedures used to obtain the elastic modulus, with particular emphasis on flow properties, would help to establish a better experimental value for the elastic modulus as well as the other physical properties of dentin.

EXPERIMENTAL

Equipment.—The equipment used to measure the elastic properties of dentin was the same as that described by Peyton, Mahler, and Hershenov,[2] except for the compression testing machine and the type of steel plungers used. The stress was applied to the samples by a Riehle testing machine. The load scales of the testing machine were calibrated for loads in compression with a recently calibrated dynamometer ring. The calibration data for the 250 lb. scale, which was used for most of the measurements, showed that the load indicator was accurate to ± 0.5 per cent at the low end of the scale and to ± 0.1 per cent for the high portion of the scale. The actual error was generally ± 0.2 lb. over the entire scale. The accuracy on this and higher scales was greater than reading errors, and, therefore, the recorded scale readings were used directly in the calculation of the stress.

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The steel plungers were prepared from cylindrical rods with half of the rod shaped to form a bar, 0.175 inch square. The square end was ground smooth, and 2 of these plungers, supported by a steel frame, were placed end to end with the specimen between them to form the compression unit. Prior to making any compression measurements the two steel ends were placed together and a stress applied. The stress was increased to a point just below the proportional limit of the steel plungers (2,500 lb.) and then relieved. This operation was repeated several times, and for all subsequent measurements the plungers were always used in the same relative position.

Specimen Preparation.—Blanks, in the shape of triangular prisms, were prepared from human first and second molars by sectioning and grinding. These blanks were then placed in a machine lathe and turned down into the shape of a cylinder. The ends of the specimens were finished flat and parallel by placing the cylinders in a hole in the center of a split brass disk, ¾ inch in diameter, and polishing with 240A, 400A, and 600A Norton Tufbak Speed wet paper supported on a plate glass slab. Compression specimens 0.100 inch in diameter and 0.100 to 0.400 inch long were prepared in this manner.

Compression specimens of steel (SAE 1020), aluminum (24 S-T), and polystyrene (Jectron) were also prepared on the machine lathe, their dimensions being 0.170 inch in diameter and 0.250 to 0.300 inch long. In addition, standard ¼ inch diameter tensile specimens were prepared from the 3 materials listed above.

Procedures.—The elastic moduli in compression of the various materials were determined from the slopes of the stress-strain curves within the elastic region. The necessary stress-strain curves were obtained by taking simultaneous readings of the stress, recorded on the testing machine, and of the strain, indicated on the Tuckerman Optical strain gauges. The loading was not interrupted during the experiment, and the stress and strain measurements were taken during loading. The rate of load application was usually 3,400 psi per minute, but several experiments were conducted at 34,000 psi per minute (see Table II).

Since most of the dentin specimens were approximately 0.20 inch long and the strain gauges, as normally used, were 1 inch in length, the deformation recorded included the deformation for about 0.80 by 0.175 by 0.175 inch of steel. Of course, corrections were made in the calculations for this contribution. The Tuckerman Optical strain gauges are designed so that they can also be used as ¼ inch gauges.[5] In several instances, dentin specimens longer than 0.25 inch were obtained, and in these cases the ¼ inch gauge length was used which spanned a continuous cylinder of dentin. In these cases no correction for the deformation of steel was required.

The elastic moduli in tension for steel, aluminum, and polystyrene were determined on the standard tensile specimens using a 1 inch gauge. The strain gauge extended across a continuous section of material, again making corrections to the deformation values unnecessary.

RESULTS AND DISCUSSION

In order to establish the reliability of the modulus of elasticity obtained in compression with small samples of dentin, small cylinders of steel, aluminum, and polystyrene were prepared and the elastic moduli were determined. The accuracy of these measurements was established by comparing them with experimentally determined elastic moduli values in tension and with accepted published values for these materials.

Table I contains average experimental values for the elastic moduli of steel, aluminum, and polystyrene determined both in compression and in tension. These values are in good agreement with each other and are also in accord with published results. Thus, the elastic modulus values of dentin determined in compression should represent experimentally satisfactory results. This is not to imply that the elastic modulus of dentin in compression will equal the elastic modulus in tension since this is only true for isotropic solids, and differences in these values can exist in the case of laminated structures.

TABLE I
MODULUS OF ELASTICITY VALUES DETERMINED IN COMPRESSION AND TENSION

MATERIAL	EXPTL. ELASTIC MODULUS, COMPRESSION $\times 10^6$ PSI	EXPTL. ELASTIC MODULUS, TENSION $\times 10^6$ PSI	ACCEPTED ELASTIC MODULUS,* TENSION $\times 10^6$ PSI
Steel (SAE 1020)	29.7	29.4	29.0
Aluminum (24 S-T)	10.2	10.5	10.3
Polystyrene (Jectron)	0.53	0.54	---

*Values taken from Hoyt, S. L., *Metals and Alloys Data Book,* New York, 1943, Reinhold Publishing Corporation.

The values recorded in the first column of Table II represent the various experimental elastic moduli for dentin specimens determined with a 1 inch strain gauge and corrected for the effect of the elastic modulus of steel. The values ranged from 1.84 to 2.41 $\times 10^6$ psi, resulting in an average value of 2.10 $\pm$ 0.18 $\times 10^6$ psi. The reproducibility of a single measurement was checked by making two separate determinations of the elastic modulus on a single sample. In each case a value of 2.02 $\times 10^6$ psi was obtained.

Since the ends of the dentin specimens were smaller than the square ends of the compression plungers, the surface of the plungers will deform to some extent when stress is applied, and this will result in a false strain reading. A correction for this effect has been proposed by Stanford, Paffenbarger, and Kumpula,[3] and the second column in Table II lists the elastic modulus values with this type of correction applied. The correction amounted to approximately 0.18 $\times 10^6$ psi for the size specimens and plungers used in this research.

The direction of the dentin specimen in relationship to the tooth, the rate of loading on the dentin specimens (from 3,400 to 34,000 psi/min.), and the dryness of the dentin did not have any measurable effect on the elastic modulus. The length/diameter ratio of the dentin specimens, however, did appear to have some effect on the elastic modulus but, in general, it was independent of the length/diameter ratio in the range from 1/1 to 2.5/1. For ratios between 1/1 and 0.5/1, the elastic modulus values were lower and appeared to be a direct function of the length. Two reasons for this observation are: (1) an actual decrease in the elastic modulus as the specimen shape changes from a cylinder to a plate, and (2) a lower slope of the stress-strain plot (lower modulus) caused by non-parallel ends of the specimen. This second factor would become more important the shorter the specimen, since the error introduced into the strain measurement would then be a larger percentage of the total strain. Thus, in the low length/diameter range of 0.5/1 to 1/1 it is felt that the second factor is the major reason for the low elastic modulus values.

TABLE II
ELASTIC MODULUS OF DENTIN

1 INCH STRAIN GAUGE*			¼ INCH STRAIN GAUGE†	
ELASTIC MODULUS, E_y, CORRECTED FOR E_s OF STEEL PLUNGERS $\times 10^6$	ELASTIC MODULUS CORRECTED FOR E_s AND FOUNDATION EFFECTS $\times 10^6$	ELASTIC MODULUS CORRECTED FOR E_s AND F.E. AND CALC. FROM DECOMPRESSION CURVE $\times 10^6$	ELASTIC MODULUS $\times 10^6$	ELASTIC MODULUS CORRECTED FOR RETARDED ELASTIC DEFORMATION $\times 10^6$
1.93‡	2.13		2.20‖	2.57
2.41§	2.58		2.20‖	2.57
2.02‖	2.20		2.52	2.85
2.02‖	2.20		2.41	2.70
1.97	2.15			
2.39	2.57			
1.90‡, §	2.08	2.41		
1.84	2.02	2.35		
2.38¶	2.56			
2.10 ± 0.18 Avg.	2.28 ± 0.18 Avg.		2.33 Avg.	2.67 Avg.

*The specimens were 0.20-0.25 inch long and therefore 0.75-0.80 inch of the length of the strain gauge was steel.

†The specimens were 0.35-0.40 inch long and therefore the entire length of the 0.25 inch strain gauge was a continuous specimen of dentin.

‡The long axis of the specimen was perpendicular to the occlusal surface; in the remaining specimens the long axis was parallel to the occlusal surface.

§The rate of loading was 34,000 psi/min.; the rate of loading for the remaining specimens was 3,400 psi/min.

‖These values represent separate determinations of the elastic modulus on identical specimens.

¶Specimen was dried for 30 hours at 105° C. prior to determining E_y.

The elastic modulus values reported in the fourth column of Table II were obtained on a continuous piece of dentin using a ¼ inch strain gauge. The need of correcting for the elastic modulus of the steel plungers and foundation effects was, therefore, avoided. The values varied from 2.20 to 2.52 $\times 10^6$ psi, resulting in an average value of 2.33 $\times 10^6$ psi which is in good agreement with 2.28 $\times 10^6$ psi, the average obtained using specimens less than ¼ inch long and a 1 inch strain gauge. The remaining 2 columns of Table II (3 and 5) represent elastic modulus values corrected for the retarded elastic deformation or recoverable flow of dentin. This correction increases the elastic modulus values approximately 0.34 $\times 10^6$ psi. Since this phenomenon will be treated in greater detail later in this section, the discussion of these results will be deferred until that time.

Peyton, Mahler, and Hershenov[2] previously published a value of 1.67 $\times 10^6$ psi for dentin and Stanford, Paffenbarger, and Kumpula[3] reported a value of 4.1 $\times 10^6$ psi. No corrections were made on the former value and, thus, this value would be increased to approximately 2.3 $\times 10^6$ by applying the average corrections for the elastic modulus of steel, foundation effects, and recoverable flow. This corrected value is then in fair agreement with the average value of approximately 2.7 $\times 10^6$ psi, which will be reported later in detail. The disagreement with the value reported by Stanford, Paffenbarger, and Kumpula may be due to their empirical method for correcting the experimental compression modulus values.

The proportional limit, defined as the stress at the point where the stress-strain curve ceases to be linear, and the ultimate compressive strength of a number of dentin specimens are tabulated in Table III. The proportional limit for dentin varied from 20,200 to 30,100 psi, the average value being 24,200 ± 2,900 psi. The ultimate compressive strength values ranged from 38,100 to 49,400 psi, yielding an average value of 43,100 ± 3,600 psi; these results did not show any correlation with the corresponding proportional limits. Black,[1] Peyton, Mahler, and Hershenov,[2] and Stanford, Paffenbarger, and Kumpula[3] have reported average values of 37,200, 36,100, and 50,400 psi, respectively, for the compressive strength of dentin and the latter two groups have published average values of 23,400 and 25,100 psi, respectively, for the proportional limit of dentin. Considering the wide range of compressive strengths obtained in any one investigation, the average values are in reasonable agreement. No absolute basis for a choice between these values is possible; however, it is more difficult to discount high than low results since errors in compressive strength measurements are most likely to be caused by faulty specimen preparation and these errors would yield low rather than high values. The rate of load application used in the various researches would also have an effect on the compressive strength of dentin. The higher averages of 50,400 and 43,100 psi are probably closer, therefore, to the true figure for dentin than values of 36,100 and 37,200 psi. The average proportional limit of 24,200 psi obtained in this research compares well with, and is about midway between, the literature values of 23,400 and 25,100 psi.

TABLE III
PROPORTIONAL LIMIT AND ULTIMATE COMPRESSIVE STRENGTH OF DENTIN

PROPORTIONAL LIMIT (PSI)	ULTIMATE COMPRESSIVE STRENGTH (PSI)
23,000	38,100
20,200	40,000
24,600	41,800
30,100	44,600
24,400	43,800
22,800	49,400
26,000	41,800
20,200	43,300
26,300	45,000
26,400*	52,000*
24,200 Average	43,100 Average

*Specimen was dried for 30 hours at 105° C. prior to making measurements and values were not included in the average.

In the process of determining the stress-strain plots for dentin, it was observed that, if the stress was maintained at a constant value, the strain would continue to increase. It was of interest to study this effect further and to establish whether this flow represented permanent deformation and what effect the flow would have on the calculated elastic modulus.

Fig. 1 shows the effect of loads below and above the proportional limit on the flow properties of dentin. In the first case, the load of 110 lb. was applied to the specimen as rapidly as possible, and the autocollimator reading was determined at various times (the autocollimator readings were not converted to strain since only relative values were needed to study the flow properties; to convert to strain the autocollimator reading should be multiplied by 0.0013 inch/inch). As shown in the graph, the strain increased with time when the load was maintained at 110 lb. After 20 minutes the load was relieved and the major portion of the deformation, the Hookian elastic deformation (ϵ_h), was recovered immediately. The remaining deformation, the retarded elastic

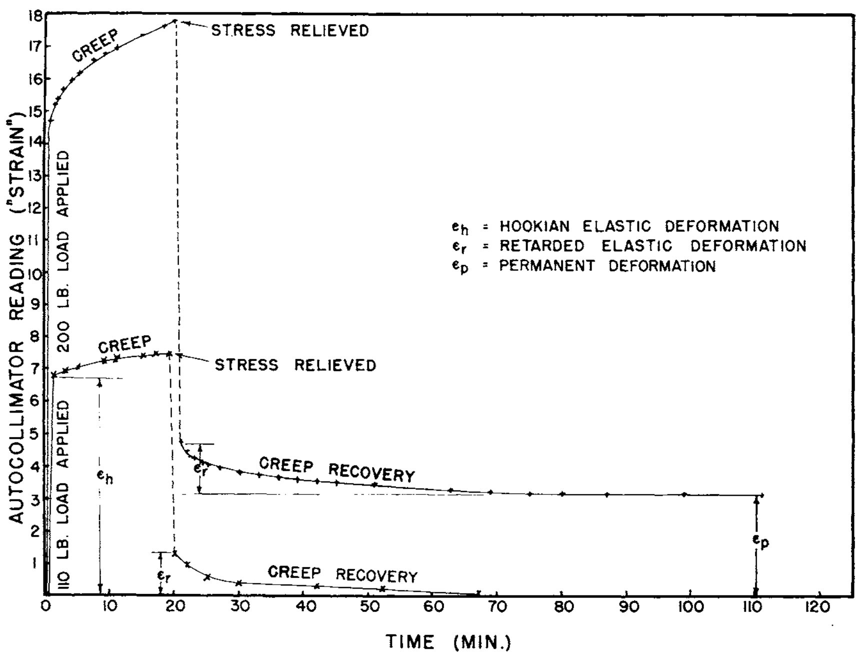

Fig. 1.—Deformation of dentin under stress above and below the proportional limit.

deformation (ϵ_r), however, was not completely recovered until 50 minutes later. The same load cycle was used with a 200 lb. load applied on the dentin specimen and a similar shaped curve was obtained (the stress in this case was above the proportional limit). A correspondingly larger value for ϵ_h was obtained and, although the value for ϵ_r was somewhat larger than for the lower load, the relation of the values indicates that the retarded elastic deformation was load, as well as time, dependent. After the load was relieved, however, a portion of the deformation was not recovered, and ϵ_p represents this permanent deformation.

In order to establish clearly the fact that the flow observed in dentin was true flow and not caused by instrumental difficulties, a compression specimen of aluminum was subjected to compression and decompression. A single stress-strain curve was obtained from the compression and decompression values, thus establishing the validity of the results on dentin.

If the elastic modulus is considered to be represented by the ratio of the stress to the Hookian elastic deformation, then some means of correcting for the retarded elastic deformation should be used. Two methods for practically eliminating the contribution of the retarded elastic deformation were to calculate the elastic modulus from: (1) the stress-strain curve obtained on relieving the compressive stress on a dentin specimen, or from (2) the stress-strain curve obtained on the second or higher compression cycle. These procedures are illustrated in Fig. 2. The stress-strain curves were obtained on a dentin specimen less than 0.25 inch long, for which reason 1 inch strain

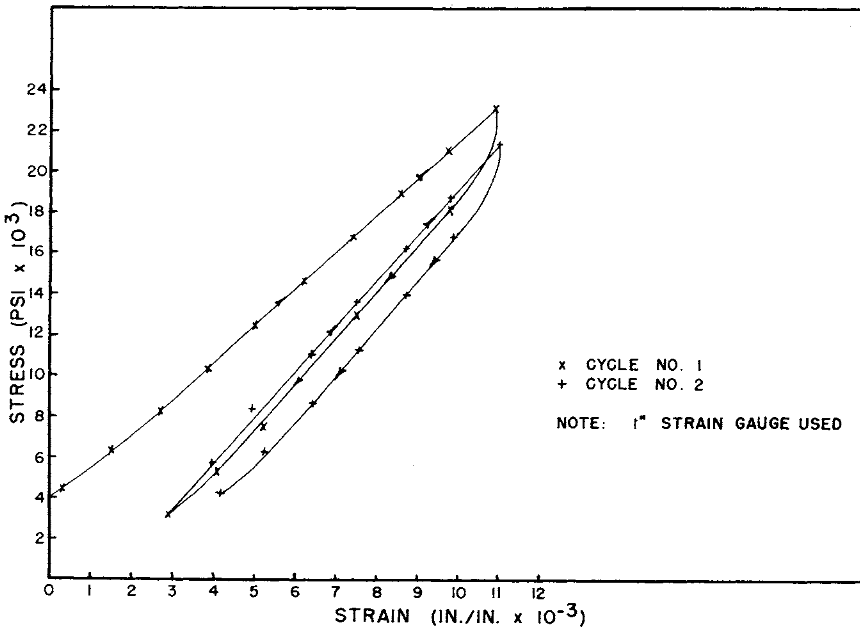

Fig. 2.—Stress-strain curves of dentin for two compression-decompression cycles.

gauges were used. The stress was increased from an initial stress of 4,000 psi to about 23,000 psi, which was below the proportional limit for this specimen; the stress was then decreased to approximately 3,000 psi, increased to 22,000 psi, and decreased again to about 4,000 psi. During these cycles, simultaneous readings of load and deformation were taken, permitting the calculation of the stress-strain curves in compression and decompression.

It can be observed that the compression curve for cycle 1 was not linear below a stress of 7,000 psi (Fig. 2). Also the slope of the linear portion of the compression curves for cycle 1 was less than the slope of the compression curve for cycle 2 or the decompression curves for cycle 1 or 2. The decompression curves for cycle 1 or 2, likewise, did not coincide with the compression curves for cycle 1 or 2, respectively. The compression curve for cycle 2 did not coincide with the decompression curve of cycle 1, with the former having higher stress values for corresponding strain values. The slopes of the compression curve for cycle 2 and the decompression curves for both cycles 1 and 2 were equal.

These five observations from Fig. 2 may be explained in the following manner: (1) The non-linearity of the first stress-strain curve was due to not having the ends of the dentin specimen exactly parallel. (2) The slope was lower for the first compression cycle because of the contribution to the strain of the retarded elastic deformation, and to some extent the non-parallel ends of the specimen. (3) The decompression curves did not coincide with the compression curves because the retarded elastic deformation did not have sufficient time to recover in the 6 to 8 minutes required to traverse the decompression range, as revealed by the curve. (4) The compression curve for cycle 2 did not coincide with the decompression curve of cycle 1 because some of the retarded elastic deformation was being recovered even though the stress was increasing. (5) The slopes of the compression curves for cycle 2 and the decompression curves for cycles 1 and 2 were equal because the effects of non-parallel ends and retarded elastic deformation had been largely avoided as influencing factors.

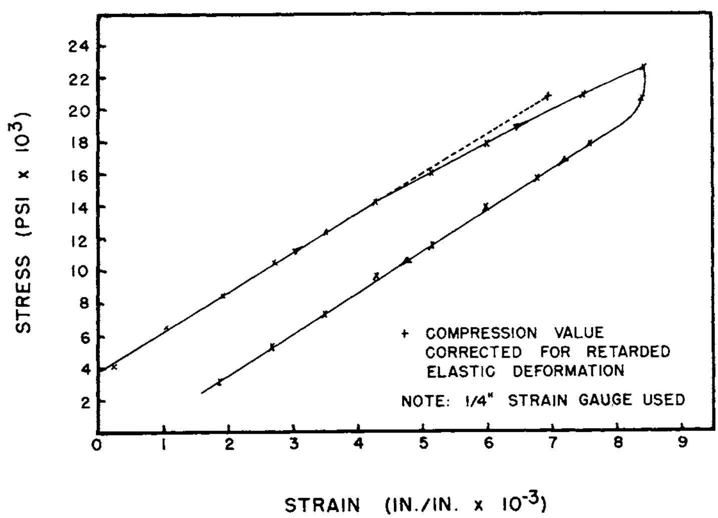

Fig. 3.—Stress-strain curves in compression and decompression for a continuous dentin specimen.

When a dentin specimen longer than 0.25 inch was used with a ¼ inch strain gauge, the effect of the specimen ends not being parallel was eliminated. The stress-strain curve in compression and decompression for this type of system is shown in Fig. 3. It is apparent that the stress-strain curve in compression at low stress values was linear and deviated from linearity at about 14,000 psi. This deviation was caused by the retarded elastic deformation. The decompression curve was linear throughout the main portion of its length and was parallel to the initial portion of the stress-strain curve in compression, again because the retarded elastic deformation did not have sufficient time to recover. It should be noted that the strain at 20,500 psi has been corrected for this retarded elastic deformation. This correction was determined by relieving the load as rapidly as possible to the original initial load and observing the value of the retarded elastic deformation included in the total deformation at 20,500 psi stress. When the early stress-strain points and the corrected value of the strain at 20,500 psi stress were used to draw the stress-strain curve in compression, a straight line was obtained which was parallel to the decompression curve. The same elastic modulus value was, therefore, obtained by either correcting the compression curve or by directly calculating the slope of the decompression curve. It should be noted that the rate of loading is unimportant if the correction for retarded elastic deformation is made.

The best values for the elastic modulus of dentin are, therefore, those listed in columns 3 and 5 of Table II. Unfortunately, stress-strain curves in decompression were determined for only 2 specimens using the 1 inch strain gauge (column 3), and they yielded an average elastic modulus of 2.38×10^6 psi. If it is assumed that the values in column 3 are on the average 0.33×10^6 psi larger than those in column 2 (as indicated by data), the average value for column 3 would be approximately 2.6×10^6 psi. Elastic modulus values determined on dentin specimens using ¼ inch strain gauges and corrected for the retarded elastic deformation ranged from 2.57 to 2.85×10^6 psi (column 5) and yielded an average value of 2.67×10^6 psi. Thus, this research indicates that a good average value for the elastic modulus of dentin is 2.65×10^6 psi.

SUMMARY AND CONCLUSIONS

The proportional limit and the ultimate compressive strength of dentin have been found to have average values of 24,200 and 43,100 psi, respectively.

The corrected elastic modulus of dentin was independent of the direction from which the specimens were taken from the teeth and from the rate of loading the specimen. The elastic modulus was also found to be independent of the length/diameter ratio for the specimen within the limits of 1/1 to 2.5/1.

Comparable values for the elastic modulus of dentin were obtained regardless of whether or not the deformation used in the calculation was determined with a strain gauge spanning a continuous dentin specimen or a combination of dentin and steel, when proper corrections were made.

The total deformation in a dentin specimen below the proportional limit consisted of pure and retarded elastic deformation. Since this latter deformation was a function of time as well as load, it must be substracted from the total deformation before a correct elastic modulus can be calculated.

The average corrected elastic modulus of dentin was found to be between 2.4 and 2.7×10^6 psi.

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