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Modified Power Law Formula for the Characterization of Dispersions of Collagen Nanofibrils

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***Abstract*— The United States patent, USP #6660829, pertains to the production of collagen-based products in the form of dispersions and macroporous structures using untreated raw fibrillar type I bovine corium as the starting material. The resulting dispersions have improved characteristics making them ideal for use in environmental applications as a settling aid, a filtration aid, a fractionation medium, an oil droplet stabilizer, a water purification aid, and a water siphoning aid. The dispersions may be further treated in accordance with the methods described in the patent to form macroporous structures suitable for biotechnological applications including use as a cell culturing substrate and non-biotechnological applications including use as an organic aerogel. Analysis of the admixtures produced by blending standard formulations of collagen dispersions with metal dust, inerts or metallic particles indicate that the collagen matrix may be used as a sacrificial scaffold. In this analysis, physical properties and microscopy were used to assess the quality of the dispersion. Statistical analyses were used to identify the potential for characterization using dynamic power law parameters, hysteresis, pore size, density, morphology, number and nature of crosslinks, and the possibility of connecting channels and flow-through. A modified power law formula and calculation technique is suggested for the characterization of the shear stress-shear rate description of the rheology of the collagen dispersion. Experimental data and analyses are presented.**

Keywords*— *nanofibrils, power law, shear stress, shear rate, kurtosis

I. INTRODUCTION

Collagen is a biodegradable polymeric fibrous protein found in all animals. In a series of steps, the collagen molecule assembles into a fiber that has the appearance of a rope. The material is insoluble in water, but can retain many times its own mass in water near its charged surface. This and the ability to unravel the fiber thus maximizing the surface area is the key physical property that leads to numerous environmental and biotechnological applications[1],[2],[3],[4],[5]. With regard to environmental applications, when added to sludge or any material with suspended solids, a collagen dispersion causes agglomeration, the formation of large flocs, and settling, all at a very rapid rate. The material has proven to be effective in the rapid agglomeration of fine solids in all types of sludge: industrial, water treatment, wastewater, inert suspensions, and kaolin.

It has been discovered that collagen dispersions may also be used in other environmental applications such as, as an aid to filtration, separation of pollutants (including metals and soluble organic molecules) from aqueous streams, selective fractionation of molecules, and oil droplet stabilization. Moreover, because treated collagen can hold hundreds of times its mass in water, its use in water purification (with minimal energy consumption) and in water siphoning has been discovered and quantified. All of these applications are based on the affinity of the activated surface of collagen, carrying positive charges, for the negative end of the polar water molecule.

Further processing of the dispersions yields products suitable for biotechnological applications[6],[7]. When the collagen dispersion is frozen and then freeze dried, the resulting material retains the overall dimensions of the original frozen material. However, over 99% of the volume is empty and the structure of the protein is a spongy organic aerogel with controllable pore size, good mechanical properties and a density of one thousandth of water. This solid material can be cross-linked to anchor or memorize its shape, pore size and morphology.

Covalent bonds, between adjacent collagen molecules, are formed during crosslinking; thus the resulting material will no longer disperse or retain water. When placed in water, the cross-linked collagen sinks because the specific gravity is slightly higher than that of water. During the process of crosslinking, the material that is produced is also sterile. This material has enormous potential in biotechnology especially in the area of cell culture. Some of the cell culture applications include substrates for: a) achieving high cell density in bioreactors leading to increased productivity and reduced reactor sizes; b) hosting unusual and hard-to-culture cells that are used for a variety of applications including biosensors; c) organ and tissue technology that have medical implications (examples are organ regrowth, skin replacement, coating of prostheses and implants, etc.); d) coating of cell culture devices such as roller bottles or glass beads; e) collagen membranes for cell culture and biomolecule delivery; and f) controlled release of pharmaceuticals. In non-biotechnology applications the freeze dried, cross-linked collagen matrix can serve as an organic aerogel. Other possible uses for this material include encapsulation of a wide variety of organisms, enzymes and synthetic material.

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II. MATERIALS AND METHODS – POWER LAW PARAMETER

A. *Method to Develop Collagen Nanofibrils*

1. Weighed approximately 1kg of the Raw Bovine Dermis collagen sheets
2. Placed into ball mill with zirconia beads
3. Filled mill with deionized water until it covered the collagen and beads
4. Closed, sealed, and let run for approximately 2 days
5. Collected milled collagen and placed equally into 4 centrifuge bottles
6. Ran centrifuge at 5°C for 15 minutes to separate the water from the collagen nanofibrils
7. Top liquid was discarded and centrifuge bottles were filled with clean DI water
8. Ran centrifuge twice more until top liquid looked clean
9. Collagen paste was ready to use and stored in the refrigerator

B. *Method of Formulating 1% Collagen Dispersion*

1. Added acetic acid and deionized water by weight to pre-weighed amount of collagen nanofibrils produced above
2. Blended for approximately 5 minutes or until dispersion became thicker and homogenous
3. Stored in refrigerator for later use

C. *Method of Experimental Tests*

1. Previously made 1% and 2% collagen dispersions were taken out of refrigerator and left out for an hour
2. These samples were analyzed by a Viscometer that collected the viscosity, shear stress, shear rate, and pressure
3. Each day, four replicated and two treatments (increase and decrease of shear rate) were performed using Viscometer
4. Viscosity, shear stress, shear rate and pressure data was monitored and recorded
5. These tests ran for a total of 11 days until the shear stress became steady
6. Data was collected and analyzed by excel

D. *Summary of the Dispersion Process*

Raw collagen from a variety of sources is the starting material in the manufacture and modification of collagen nanofibrils. The raw material has the appearance of white ground protein as shown in Fig. 1.

Fig. 1. A collagen molecule after a series of steps assembled into the fiber that has the appearance of rope

It has been discovered that the above described existing collagen-based applications are enhanced, and novel applications possible, using raw fibrillar type I bovine corium as the starting material. Corium is the dermis layer of the hide and is rich in collagen-based connective tissue. While corium has been indicated as a preferred source of collagen for at least some applications, the applicant has discovered that use of a heterogeneous solution of corium as the starting material, as opposed to purified collagen derived from corium, produces superior end-products including new applications and results not heretofore observed.

Previously, corium was pre-treated to remove fats, triglycerides, and other soluble compounds. The resulting raw collagen was then conventionally dried and milled in a knife mill. In the present invention, a dilute solution of the corium itself is milled in a ball mill containing zirconia media for one to two weeks. The pretreatment steps are avoided. Once milling is completed, the resulting material is strained, washed, and then subjected to low temperature centrifugation and the supernatant decanted. This process is repeated several times until no fats or other soluble materials appear in the upper phase and the supernatant is clear. The lower phase containing collagen is then blended in a solution containing an organic acid to form a dispersion and allowed to thicken. The resulting dispersion has improved physical properties and results in enhanced performance when used in various environmental applications.

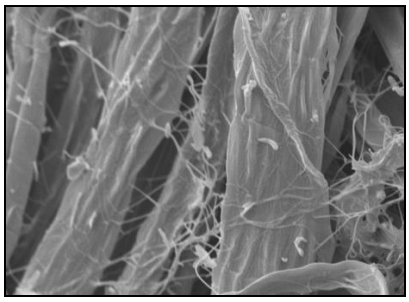

Fig. 2. Starting material fibers at 5 microns

The above dispersion may be further processed to form physically improved collagen macroporous structures or substrates capable of utilization in various biotechnological applications. During the blending stage any material for encapsulation or controlled release is added.

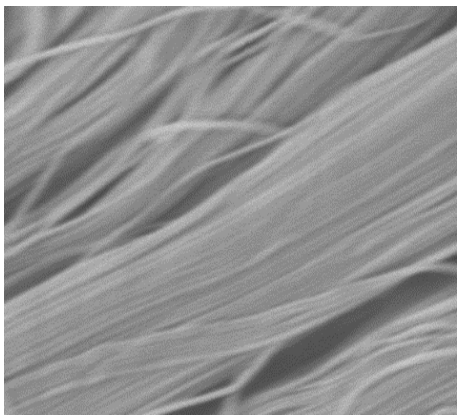

Fig. 3. Collagen nanofibrils before being unraveled in the ball mill

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There has thus been outlined, rather broadly, some important features of the invention in order that the detailed description thereof that follows may be better understood, and in order that the present contribution to the art may be better appreciated. There are, of course, additional features of the invention that will be described hereinafter and which will form the subject matter of the claims appended hereto. In this respect, before explaining at least one embodiment of the invention in detail, it is to be understood that the invention is not limited in its application to the details of construction and to the arrangements of the components set forth in the following description or illustrated in the drawings.

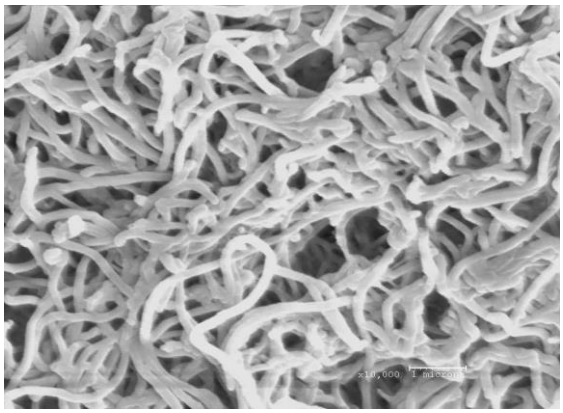

Fig. 4. Final Bovine Nanofibrils[8]

This invention is capable of other embodiments as presented and of being practiced and carried out in various ways, biomedical and environmental. Also, it is to be understood that the phraseology and terminology employed herein are for the purpose of description and should not be regarded as limiting. As such, those scientists and engineers working in protein technology will appreciate that the conception, upon which this research is based, may readily be utilized as a basis for the designing of other structures, methods and systems for carrying out the several purposes of the present invention[9],[10],[11],[12].

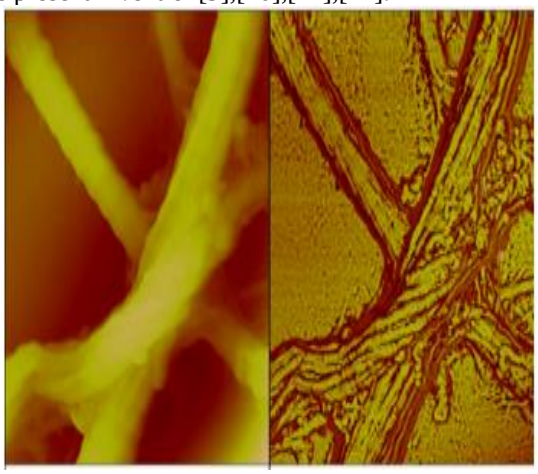

Fig. 5. Atomic force microscope (AFM) micrograph of collagen nanofibrils. Note the visible d-spacing.

III. DATA: ANALYSIS OF RESULTS

A. *ANOVA TEST – F Distribution and t-Distribution*

TABLE I. DAY 2 DATA FROM 3.57% COLLAGEN PASTE

Day 2 : Data From 3.75% Collagen Paste			
	Parameter(a)	*Parameter(b)*	*Directions*
Trial 1	7.2218	0.1978	Increase
	4.8652	0.2750	decrease
Trial 2	5.1141	0.2389	increase
	5.0947	0.2360	decrease
Trial 3	5.1732	0.2321	increase
	5.0405	0.2357	decrease
Trial 4	5.1732	0.2244	increase
	5.0385	0.2318	decrease
average a	5.3401		
std. dev. a	0.7666		
average b	0.2340		
std. dev. b	0.0211		

Table 1 shows the average value of parameter(a) and Parameter(b) in different treatments (increase/ decrease the shear rate) for day 2, and also the average value and standard deviation of parameter (a) and parameter (b) for all four trials.

TABLE II. DATA ANALYSIS FROM DAY 2 RESULTS

Day 2: t – Distribution			
Testing of Means	*Observations*		
Do increase first	H0: b=0.22	t_0	0.3666
	H1: b ≠ 0.22	absolute(t_0)	0.3666
	t(0.05,3)	3.1824	
	If t_0 >t, reject	Fail to reject, therefore, b=0.22	
Do decrease second	H0: b=0.24	t_0	0.4548
	H1: b ≠ 0.24	absolute(t_0)	0.4548
	t(0.05,3)	3.1824	
	If t_0 >t, reject	Fail to reject, therefore, b=0.24	

Table 2 is the t-Distribution for day 2, from the t-distrubution, one can conclde that the increase and decrease treatments don't matter for the value of parameter(b), where increase means increase the shear rate, and decrease means decrease shear rate to return to original shear rate.The purpose of the treatment is to test the hysteresis.

TABLE III. DAY 2 SS ANALYSIS

Day 2: SS Analysis				
Trial	*Increase*	*Decrease*		
1	0.1978	0.2750		
2	0.2389	0.2360		
3	0.2321	0.2357		
4	0.2244	0.2318		
Average	0.2233	0.2446		
std deviation	0.0180	0.0203		
Observations				
Total	0.8932	0.9785	1.8717	
Average	0.2233	0.2446	0.2340	0.2340
ss treatments	0.000910			
Trial 1	0.000650	0.000923		
Trial 2	0.000243	0.000074		
Trial 3	0.000077	0.000080		
Trial 4	0.000001	0.000164		
Total	0.000972	0.001241		
ss error	0.002213			
ss total	0.003123			

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Table 3 is the data analysis for One-Way ANOVA for the error and total Sum of Square for day 2.

TABLE IV. DAY 2 DATA ANALYSIS FOR TREATMENT

Day 2: ANOVA				
Between treatments	ss	DOF	Mean square	F0
ss treatments	0.000910	1	0.000910	2.4654
ss errors	0.002213	6	0.000369	
ss Total	0.003123	7		
F(0.05,1,6)	5.9874			
H0:	Treatments(increase, decrease) don't matter			
H1:	treatments matter			
If F_0>F, reject H0	fail to reject, therefore, treatments don't matter			

Table 4 is the Test on Means of Normal Distribution-Variance Known Analysis for Day 2.

TABLE V. DAY 6 DATA FROM 3.57% COLLAGEN PASTE

Day 6: Data From 3.75% Collagen Paste			
	Parameter(a)	*Parameter(b)*	*Directions*
Trial 1	7.3082	0.2023	increase
	5.7185	0.2477	decrease
Trial 2	5.8183	0.2385	increase
	5.6019	0.2411	decrease
Trial 3	5.6763	0.2321	increase
	5.4866	0.2375	decrease
Trial 4	5.5823	0.2316	increase
	5.4390	0.2365	decrease
average a	5.8289		
std. dev. a	0.6101		
average b	0.2334		
std. dev. b	0.0136		

Table 5 shows the average value of parameter(a) and Parameter(b) in different treatments (increase/ decrease shear rate) for day 6, and the average value and standard deviation of parameter (a) and parameter (b) for all four trials.

TABLE VI. DATA ANALYSIS FROM DAY 6 RESULTS

Day 6: t – Distribution			
Testing of Means	*Observations*		
Do increase first	H0: b=0.23	t_0	-0.4787
	H1: b ≠ 0.23	absolute(t_0)	0.4787
	t(0.05,3)	3.1824	
	If t_0 >t, reject	Fail to reject, therefore, b=0.23	
Do decrease second	H0: b=0.24	t_0	0.2763
	H1: b ≠ 0.24	absolute(t_0)	0.2763
	t(0.05,3)	3.1824	
	If t_0 >t, reject	Fail to reject, therefore, b=0.24	

Table 6 is the t-Distribution for day 6, from the t-distrubution, one can conclde that treatments(increase and decrease shear rate) don't matter for the value of parameter(b).

TABLE VII. DAY 6 SS ANALYSIS

Day 6: SS Analysis				
Trial	*Increase*	*Decrease*		
1	0.2023	0.2477		
2	0.2385	0.2411		
3	0.2321	0.2375		
4	0.2316	0.2365		
Average	0.2261	0.2407		
std. dev.	0.0162	0.0051		
Observations				
Total	0.9045	0.9628	1.8673	
Average	0.2261	0.2407	0.2334	0.2334

ss treatments	0.000425	
Trial 1	0.000568	0.000049
Trial 2	0.000153	0.000000
Trial 3	0.000036	0.000010
Trial 4	0.000030	0.000018
Total	0.000786	0.000077
ss error	0.000863	
ss Total	0.001288	

Table 7 is the data analysis for One-Way ANOVA for the error and total Sum of Squares for Day 6.

TABLE VIII. DAY 6 DATA ANALYSIS FOR TREATMENT

Day 6 : ANOVA				
Between treatments	ss	DOF	Mean square	F0
ss treatments	0.000425	1	0.000425	2.9522
ss errors	0.000863	6	0.000144	
ss Total	0.001288	7		
F(0.05,1,6)	5.9874			
H0:	Treatments(increase, decrease) don't matter			
H1:	treatments matter			
If F_0>F, reject H0	fail to reject, therefore, treatments don't matter			

Table 8 is the Test on Means of Normal Distribution-Variance Known Analysis for Day 6.

TABLE IX. DAY 11 DATA FROM 3.57% COLLAGEN PASTE

Day 11: Data From 3.75% Collagen Paste			
	Parameter(a)	*Parameter(b)*	*Directions*
Trial 1	6.6619	0.2036	increase
	5.1192	0.2569	decrease
Trial 2	5.0820	0.2530	increase
	5.1213	0.2466	decrease
Trial 3	5.2425	0.2434	increase
	5.2783	0.2391	decrease
Trial 4	5.2904	0.2355	increase
	5.2683	0.2376	decrease
average a	5.3830		
std. dev. a	0.5233		
average b	0.2395		
std. dev. b	0.0163		

Table 9 Shows the average value of parameter (a) and parameter (b) in Different treatments(increase/ decrease) for day 11, and the average value and standard deviation of parameter (a) and parameter (b) for all four trials

TABLE X. DATA ANALYSIS FROM DAY 11 RESULTS

DAY 11: t – Distribution			
Testing of Means	*Observations*		
Do increase first	H0: b=0.23	t_0	0.3619
	H1: b ≠ 0.23	absolute(t_0)	0.3619
	t(0.05,3)	3.1824	
	If t_0 >t, reject	Fail to reject, therefore, b=0.23	
Do decrease second	H0: b=0.25	t_0	-1.1216
	H1: b ≠ 0.25	absolute(t_0)	1.1216
	t(0.05,3)	3.1824	
	If t_0 >t, reject	Fail to reject, therefore, b=0.25	

Table 10 is the t-Distribution for day 11, from the t-Distrubution, one can conclde that the increase and decrease treatments don't matter for the value of parameter(b).

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TABLE XI. DAY 11 SS ANALYSIS

Day 11: SS Analysis				
Trial	*Increase*	*Decrease*		
1	0.2036	0.2569		
2	0.2530	0.2466		
3	0.2434	0.2391		
4	0.2355	0.2376		
Average	0.2339	0.2451		
std. dev.	0.0214	0.0088		
Observations				
Total	0.9355	0.9802	1.9157	
Average	0.2339	0.2451	0.2395	0.2395
ss treatments	0.000250			
Trial 1	0.000917	0.000140		
Trial 2	0.000366	0.000002		
Trial 3	0.000091	0.000035		
Trial 4	0.000003	0.000056		
Total	0.001376	0.000234		
ss error	0.001609			
ss Total	0.001859			

Table 11 is the data analysis for One-Way ANOVA for the error and total Sum of Square for day 11.

TABLE XII. DAY 11 DATA ANALYSIS FOR TREATMENT

Day 11: ANOVA				
Between treatments	*ss*	*DOF*	*Mean square*	*F0*
ss treatments	0.000250	1	0.000250	0.9311
ss errors	0.001609	6	0.000268	
ss Total	0.001859	7		
F(0.05,1,6)	5.9874			
H0:	Treatments(increase, decrease) don't matter			
H1:	treatments matter			
If F_0>F, reject H0	fail to reject, treatment don't matter			

Table 12 is the Test on Means of Normal Distribution-Variance Known Analysis for Day 11.

From F-distribution and t-distribution, all of the data failed to reject. Therefore, all of the parameter(b) value from the experiments are accepted. And all the treatments include increase and decrease rotor speed don't matter.

B. Raw Data

"Kurtosis is a measurement of the probability distribution of a real-valued random variable. It is the fourth moment in statistics. It is a description of the shape of a probability distribution. A normal kurtosis value is +/- 3"[13]. "Skewness is a measurement of the asymmetry of the probability distribution of a real-valued random variable about its mean. A normal kurtosis value is +/-1"[14]. Following is the Kutosis and Skewness analysis for 1% and 2% collagen dispersion of the average parameter (a) and parameter (b) value from day 1 to day 11 as seen in Tables 13 and 14.

TABLE XIII. AVERAGE DATA OF POWER LAW PARAMETER FOR 1% COLLAGEN DISPERSION IN 11 DAYS

1% collagen from 3.57% paste		
Day	average parameter(a)	Average parameter(b)
1	4.97	0.197
2	5.34	0.23
3	5.22	0.22
4	4.92	0.23
5	6.53	0.23
6	5.83	0.23
7	5.45	0.24
8	8.63	0.18
9	5.68	0.25
10	5.5	0.24
11	5.38	0.24

Table 13 is the average data of 1% collagen dispersion made from 3.57% collagen paste for parameter(a) and parameter(b) in 11 days.

TABLE XIV. KURTOSIS AND SKEWNESS DATA OF PARAMETER A

Analysis for Average parameter(a)	
Mean	5.7682
Standard Error	0.3155
Median	5.4500
Mode	N/A
std. dev. (Standard Deviation)	1.0462
Sample Variance	1.0946
Kurtosis	6.3142
Skewness	2.3915
Range	3.7100
Minimum	4.9200
Maximum	8.6300
Sum	63.4500
Count	11.0000
Confidence Level (95.0%)	0.7029
UL (Upper Limit)	6.4711
LL (Lower Limit)	5.0653

Table 14 is the analysis for average parameter (a), the kurtosis value of 6.3142 is greater than 3. And skewness 2.3915 is greater than 1. Both data are higher than the normal kurtosis and skewness.

TABLE XV. KURTOSIS AND SKEWNESS DATA OF PARAMETER B

Analysis for Average parameter(b)	
Mean	0.2261
Standard Error	0.0062
Median	0.2300
Mode	0.2300
std. dev. (Standard Deviation)	0.0205
Sample Variance	0.0004
Kurtosis	1.6685
Skewness	-1.4204
Range	0.0700
Minimum	0.1800
Maximum	0.2500
Sum	2.4870
Count	11.0000
Confidence Level (95.0%)	0.0138
UL (Upper Limit)	0.2399
LL (Lower Limit)	0.2123

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Table 15 is the analysis for average parameter (b), the kurtosis value of 1.6685 is less than 3. And skewness -1.4204 is out of the range between -1 and 1. Kurtosis value is in the range of the normal kurtosis, but skewness value is out of the normal range.

C. Goal Seek Application for R^2

Goal seek is computed to further analyze the data to pick a power that is as close to 0.9999 as possible. In Table 16, these data shows the goal seek application for picked power law equation to reach the maximum R^2 value. The shear rate and shear stress data came from the 1st trial decrease, R^2 =0.9386 originally of 1% collagen dispersion made from 3.57% collagen at day 2. Following is the Power Law Equation:

$$SS = a + b\ SR^c \quad (1)$$

SS= Shear stress, Pa
SR= Shear rate, 1/s
a,b,c=modified power law parameter for non-Newtonian fluids[15].

TABLE XVI. APPLYING GOAL SEEK TO GET R^2

Day 2: Applying goal seek to get R^2		
Shear rate,1/s	Shear Stress, Pa	Shear rate^k
0.418	4.1089	0.4648
0.522	4.2125	0.5649
0.836	4.7401	0.8544
1.045	4.9533	1.0394
2.09	5.7893	1.9108
4.18	6.8134	3.5129
10.45	7.6076	7.8564
12.51	9.2199	9.2016
20.94	10.7003	14.4672
41.82	17.4808	26.5627
Goal seek approach		
slope	0.4854	
intercept	4.3378	
R2	0.9855	
pick power in power law equation	0.8784	

Table 16, these data shows the goal seek application for picked power in power law equation to reach the maximum R^2. shear rate and shear stress data came from 1st trial increase, R^2 =0.9932 originally of 1% collagen dispersion made from 3.57% collagen at day 2.

TABLE XVII. APPLYING GOAL SEEK TO GET R^2

Day 6 : Applying goal seek to get R^2		
Shear rate,1/s	Shear Stress	Shear rate^k
0.418	5.9356	0.9395
0.522	6.2640	0.9546
0.836	7.0642	0.9873
1.045	7.4300	1.0032
2.09	8.7362	1.0541
4.18	10.2410	1.1077
10.45	12.0175	1.1827
12.51	12.0096	1.1980
20.94	13.4435	1.2429
41.82	15.0134	1.3059
Goal seek approach		
slope	24.7349	
intercept	-17.3331	
R2	0.9986	
pick power in power law equation	0.0715	

In Table 17, these data shows the goal seek application for picked power in power law equation to reach the maximum R^2. shear rate and shear stress data came from 1st trial increase, R^2 =0.9932 originally of 1% collagen dispersion made from 3.57% collagen at day 6.

TABLE XVIII. APPLYING GOAL SEEK TO GET R^2

Day 11 : Applying goal seek to get R^2		
Shear rate,1/s	Shear Stress	Shear rate^k
0.418	5.4758	0.9245
0.522	5.7420	0.9432
0.836	6.4288	0.9840
1.045	6.7403	1.0040
2.09	7.9002	1.0686
4.18	9.1124	1.1373
10.45	11.0770	1.2351
12.51	11.0088	1.2552
20.94	12.4384	1.3148
41.82	13.7588	1.3992
Goal seek approach		
slope	17.6879	
intercept	-10.9590	
R2	0.9984	
pick power in power law equation	0.0900	

In Table 18, these data shows the goal seek application for picked power in power law equation to reach the maximum R^2. shear rate and shear stress data came from 1st trial increase, R^2 =0.9962 originally of 1% collagen dispersion made from 3.57% collagen at day 11.

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IV. APPENDIX 1: POWER LAW FORMULA

$\tau_{rz} = \mu\left(\frac{\partial}{\partial r}v_z\right)$; Newton's Law

$\tau_{rz} = a\left(\frac{\partial}{\partial r}v_z\right)^b$; Power Law Fluid; b > 1 dilatant; b < 1 pseudoplastic

$\frac{\Delta P}{\mu L} = \frac{1}{r}\frac{\partial}{\partial r}r\left(\frac{\partial}{\partial r}v_z\right)$; Equation of Motion for Newtonian Fluid in a Pipe

$\frac{\Delta P}{aL} = \frac{1}{r}\frac{\partial}{\partial r}r\left(\frac{\partial}{\partial r}v_z\right)^b$: Equation of Motion for Power Law Fluid in a Pipe

$\frac{\Delta P}{L} = \frac{1}{r}\frac{\partial}{\partial r}r\left(\tau_0 + a\left[\frac{\partial}{\partial r}v_z\right]^c\right)$: Equation of Motion for Collagen Dispersions

where $\tau_{rz} = \tau_0 + a\left[\frac{\partial}{\partial r}v_z\right]^c$ regressed as

$SS = \tau_0 + a\,SR^c$

where :

τ_{rz} is shear stress for flow in the z direction (Axial) with stress at a plane at r,

μ is the proportionality constant in Newton's Law, typically called viscosity,

$\frac{\Delta P}{L}$ is the pressure drop in Pa per length of pipeline in m,

a, b, c, τ_0 are the modified power law parameters for non - Newtonian fluids

Appendix 2: Sample Power Law Analysis-Figure 6

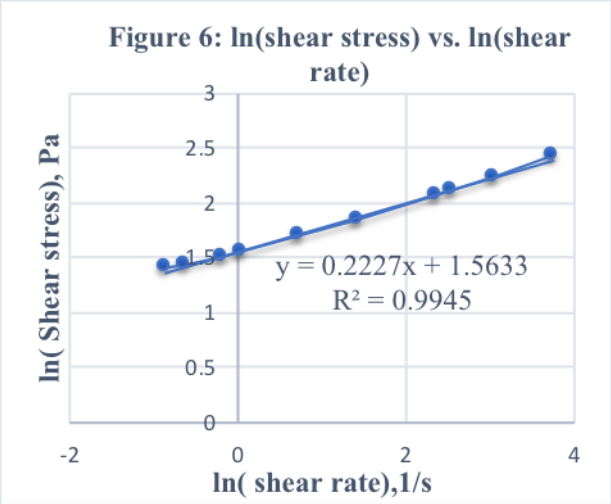

Fig. 6. Log data of both the shear stress as a function of shear rate.

Appendix 3: Sample Power Law Parameters Analysis

Day 6(1% collagen)			
	Parameter(a)	Parameter(b)	Directions
Trial 1	7.3082	0.2023	increase
	5.7185	0.2477	decrease
Trial 2	5.8183	0.2385	increase
	5.6019	0.2411	decrease
Trial 3	5.6763	0.2321	increase
	5.4866	0.2375	decrease
Trial 4	5.5823	0.2316	increase
	5.4390	0.2365	decrease
average a	5.8289		
std. dev. a	0.6101		
average b	0.2334		
std. dev. b	0.0136		

At Day 6, 1% of collagen dispersion was taken out from the refrigerate and then left for an hour. Then the 1% dispersion was analyzed by viscometer. Followed by monitoring and recording Viscosity, shear stress, Shear rate and pressure data in both increasing and decreasing shear rate directions. And then excel was used to analyze the data collected.

V. CONCLUSION

From all the data collected, power law Intercept is not zero for log equation. After series of data analysis, ln (shear stress) vs. ln (shear rate) equation are linear with non-zero intercept. Therefore, the power law formula was then Rewrite by Taking power law until it is Close to before by using Goal seek to get R^2 as close to 0.9999. In conclusion, we discovered that from day1 to day 11, it follows the Power law. As the time increased, parameter (a) kept increasing. Parameter (b) kept constant. the shear stress increased as the time increased until day 11, shear stress kept constant.

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