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Certification of SRM 2493: Standard Reference Mortar for Rheological Measurements

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Abstract

Rheological measurements are often performed using a rotational rheometer. In this type of rheometer, the tested fluid is sheared between two surfaces, one of which acts as the rotating surface [1]. Usually, the rotational velocity is imposed and the response of the material is monitored by the measurement of the torque. Typically, manufacturers of rheometers recommend using a standard oil of known viscosity to verify that the instrument is operating correctly. However, these oils are expensive, and they cannot be used for the large volumes employed in concrete rheometers. Furthermore, the oils do not contain aggregates and may not offer a valid representation of concrete since concrete is a suspension with solid particulates and display non-Newtonian behavior. Therefore, a relatively inexpensive, accurate standard reference material (SRM) for concrete rheometers is needed. The development of this new SRM is based on a multiphase approach: (1) the first phase established the SRM 2492 for cementitious paste mixtures [2], (2) the second phase developed and certified the mortar phase SRM 2493, and (3) the completion of an SRM 2497 for concrete mixtures will mark the third stage. This third stage is currently in progress.

The purpose of this report is to describe the process used to certify SRM 2493, a "Standard Reference Mortar for Rheological Measurements". The results of the rheological testing used to determine the rheological characteristics of SRM 2493 are discussed, along with the corresponding statistical analyses that was conducted to certify that the proposed models and reference values are valid.

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Notations:

SD: Standard Deviation

SRM: Standard Reference Material

$\dot{\gamma}$: Shear rate *[s^{-1}]*

τ: Shear stress *[Pa]*

τ_0: Yield stress *[Pa]*

N: Rotational speed *[rad/s]* or *[rpm]*

Γ: Measured torque *[N·m]*

μ: Viscosity *[Pa·s]*

μ_B: plastic viscosity (Bingham model) [Pa·s]

μ_R: Relative viscosity *[-]*

μ_{R20}: Relative viscosity for 20% mortar *[-]*

μ_{R40}: Relative viscosity for 40% mortar *[-]*

μ_{sc} : Viscosity scaling factor *[-]*

$\dot{\gamma}_{sc}$: Shear rate scaling factor *[-]*

K_τ: Shear stress calibration factor based on Bingham parameters *[Pa/(N·m)]*

K_μ: Viscosity calibration factor based on Bingham parameters *[Pa·s/(N·m·s)]*

K_γ: Shear rate calibration factor based on Bingham parameters *[-]*

L_τ: Shear stress calibration factor based on viscosity curves *[Pa/(N·m)]*

L_μ: Viscosity calibration factor based on viscosity curves *[Pa·s/(N·m·s)]*

L_γ: Shear rate calibration factor based on viscosity curves *[-]*

1 Introduction

A National Institute of Standards and Technology (NIST) Standard Reference Material® (SRM) meets specific certification criteria [https://www.nist.gov/srm/srm-definitions] and is issued with a certificate of analysis that reports the results of its characterization and provides information regarding the appropriate use(s) of the material. An SRM is prepared and used for three main purposes: 1) to help develop accurate methods of analysis; 2) to calibrate measurement systems used to facilitate exchange of goods, institute quality control, determine performance characteristics, or measure a property at the state-of-the-art limit; and 3) to ensure the long-term adequacy and integrity of measurement quality assurance programs. NIST provides over 1300 different SRMs to industry and academia. Every NIST SRM is provided with a certificate of analysis that gives the official characterization of the material's properties and and provides information regarding the appropriate use(s) of the SRM. In addition, supplementary documentation, such as this report, describing the development, analysis, and use of SRMs, is also often provided to ensure effective use of the SRM.

Rheological measurements are commonly performed using a rotational rheometer. In this type of rheometer, the test fluid is sheared between two surfaces: one surface is rotating while the other is stationary [3]. The rate of the rotating surface is precisely controlled by a computer, while measuring the torque resulting from the material response. Laboratory rheometers are mainly designed for homogeneous liquids containing no particles, such as oils. After completing two inter-laboratory studies related to rheological properties of concrete, it was determined that the use of expensive oils was not suitable for calibrating concrete rheometers [4] [5]. Thus, as requested by the industry, a need exists for a granular reference material specifically designed for concrete rheometers. The first step to fulfilling that need was the development of SRM 2492, a cement paste reference material. The second step is a mortar reference material, SRM 2493. To created SRM 2493, the operator needs to mix the SRM 2492 as certified [1] [2] with the addition of 1 mm glass spheres as the fine aggregate component. Once mixed, the shelf life of the mixture is 7 d.

In this report, the simulation results of flow in an ideal Couette system are provided to determine the certified data for the rheological properties of the SRM 2493. Reported values obtained through rheological testing performed at NIST using a double spiral, a coaxial, and a vane spindles are also provided for comparision purposes. In addition, NIST is working on developing a concrete SRM, which would involve adding 10 mm beads to SRM 2493.

The objective of this report is to describe the mortar reference material, SRM 2493, and its rheological properties. A description of the methodology and all measurements used are provided, along with the statistical analysis.

2 Materials

2.1 Limestone and Corn Syrup

The SRM 2492 paste, which serves as a matrix for the SRM mortar, consists of a limestone powder, corn syrup and distilled water mixture. The limestone is referred to as a micro-limestone flour with an average particle size of 45 µm and a density of 2724 kg/m^3 ± 15 kg/m^3. The corn syrup used was specified, by the manufacturer, as a 100 % glucose corn syrup with no additives and verified via NIST testing. Analyses were conducted at NIST on samples of the limestone powder to determine its mineralogical, chemical, and physical properties, as well as its particle size distribution and density. This limestone powder and corn syrup were the same as those used for the certification of SRM 2492; refer to [1] [2] for more details about these materials.

2.2 Glass Beads

To produce SRM 2493, 1 mm glass beads were added to SRM 2492 to transform it into a suspension representative of a mortar. The glass beads were received in 5-gal buckets that were labelled from A to G. The beads from each bucket were subsequently distributed in 1.5 L plastic bottles (See Section 2.4).

The density of the glass beads was found to be 2465 kg/m^3 ± 3 kg/m^3 at NIST by using ASTM C188-09 [6]. The sphericity and size distribution of the 1 mm beads were verified as described in Sections 2.2.1 to 2.2.6 using light microscope analysis, and computed tomography scan analysis.

2.2.1 Sample Selection and Analysis Schedule

As stated in Section 2.2, the beads were received in several 5-gal buckets and then portioned into plastic bottles. To ensure a statistical representation of the bottles of beads, a pseudo-random number generator was used to randomly select two bottles from each bucket (see section 2.4). **Table 1** lists the bottles selected for analysis and their corresponding buckets. These bottles contained enough beads to be used during both the bead analysis and the subsequent rheological testing.

The order in which these bottles were analyzed was also randomized, resulting in the schedule displayed in **Table 2.** The schedule took into consideration the operator's availability and the required equipment time needed for test completion. For the bead shape analysis, only a small portion of the total beads (less than 5 %) in each bottle was used for testing. Therefore, the remaining beads were used for the rheological testing.

Table 1: Randomly selected bottles for bead analysis

	Random Bottle Selection	
Bucket A	3	10
Bucket B	2	11
Bucket C	9	14
Bucket D	7	5
Bucket E	7	10
Bucket F	5	14
Bucket G	4	8

Table 2: Schedule for bead analysis.

Bead Analysis Schedule					
	M	T	W	T	F
Week 1 3/31/2014					G4
Week 2 4/14/2014		D7		F5	
Week 3 4/21/2014	B2		C9		B11
Week 4 4/28/2014		C14		A10	
Week 5 5/5/2014	G8		F14		A3
Week 6 5/12/2014	E10		E7		D5

2.2.2 Specimen Set-up for Shape Analysis

The method for holding the beads needed to be usable for both analysis tests. This required that the specimen holder have transparency for the light microscope and flexibility for the X-ray computed tomography (CT) scan. The size of the specimen was specified to be a 76 mm x 178 mm (3 in x 7 in) piece of self-adhesive laminated sheet. This size was governed by the required sample size for the X-ray CT test.

The first step in setting up the specimen was removing the protective cover from the adhesive sheet, and placing it on a flat surface such that the adhesive side was facing up. Then, the beads that were to be analyzed were hand stirred in a cup to ensure a random particle distribution. Finally, the beads were evenly sprinkled across the adhesive sheet with the help of a scoop. Typically, the goal was to obtain a uniform distribution in which the beads were not touching each other, i.e., not very dense in terms of number of beads per unit area. This goal was necessary to avoid the appearance of beads touching in the X-ray CT reconstruction process. A total sample of around 2000 to 3000 beads was considered adequate for statistical shape analysis [7].

2.2.3 Light Microscope

This step of the bead analysis process required a microscope with adjustable lighting (Figure 1). The microscope in conjunction with an image analysis software, ImagePro, enabled capturing images of the specimen during analysis. The specimen set-up, as described in **Section 2.2.2,** was placed onto an analysis template and the lighting was adjusted to minimize shadows or any other factors that affected image visibility.

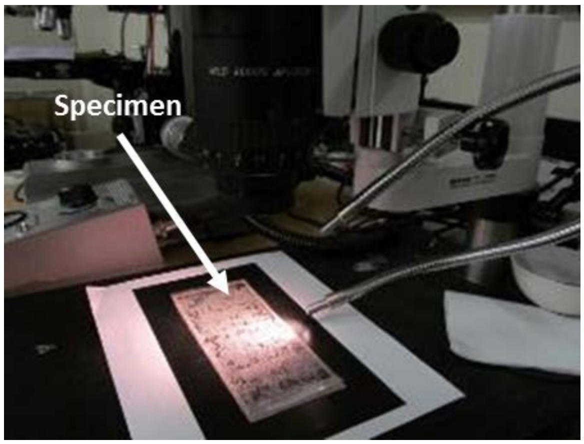
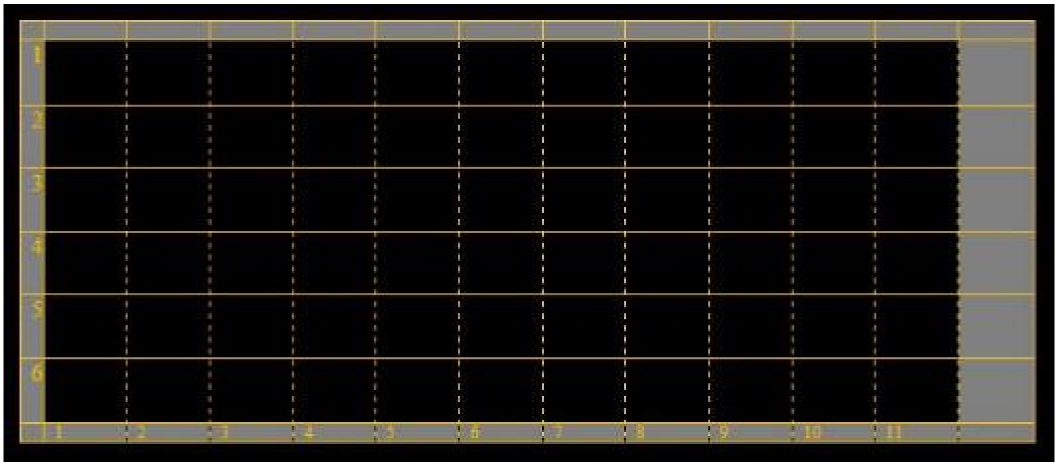


Figure 1: Light microscope with adjustable lighting of the specimen. The black area under the specimen is the grid system shown in Figure 2.

A grid template was developed to place under the specimen in order to construct a grid system that would guide the operator when using the microscope, see Figure 2. ImagePro's "video mode" enabled seeing the specimen in real-time, and the grid system enabled easy identification of the grid boxed for analysis. The system was designed to have grids (6 x 11= 66 total) of dimensions equal to the best window size that provided clear microscope images. Measurements of this window size using a metric ruler concluded that the individual grids should measure 11.5 mm x 15 mm, since this ratio developed an image of the beads at a clear size for human eye analysis, as seen in Figure 3. A black background was selected for the template to increase the contrast of the glass beads under light. The grey areas that made up the perimeter of this base template allow the operator to handle the sheet without altering the number of beads under analysis.

A total of 10 grid boxes were chosen as the standard number to analyze, and were randomly selected. This generator was modified to retrieve random selections with a fairer weight balance, as described in Section 2.2.6. The areas selected can be found in Table 3. Once the images were stored, the total number of beads and deformities in each grid box image were counted and recorded by the operator. Deformities were defined as either double beads (i.e., two or more beads that were physically attached to each other) or distorted beads (i.e., single beads that were visually non-spherical). This methodology gathered an average count per grid box image, and estimates the total number of beads and deformities in the entire specimen. This number was then compared to the bead count calculated using the X-ray CT spherical harmonic analysis, in Section 2.2.5.

Figure 2: Grid system placed under specimen allows easy selection of analysis areas. The



grid system creates *(row, col)* coordinates for random selection analysis.

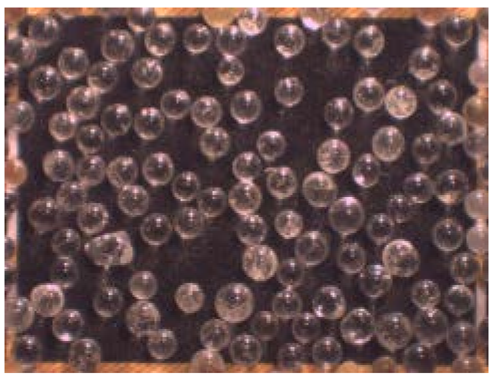


Figure 3: Snap shot image taken with the light microscope.

Table 3: Grid boxes randomly selected for analysis. The coordinates *(row, col)* indicate to the operator which grid box to scan. The most-right column "testing order" was also randomized.

Random Selection of Grids To Scan													
Bucket	Bottle #		*Grid Box Selected*										***Testing Order***
			1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th	
A	3	*Row*	3	4	4	6	4	1	6	2	5	4	*11*
		Col	5	11	1	2	5	4	5	8	3	6	
	10	*Row*	2	5	3	6	2	1	2	3	1	3	*8*
		Col	3	8	8	1	9	2	7	1	7	1	
B	2	*Row*	1	1	2	3	5	5	3	3	2	6	*4*
		Col	7	2	7	2	9	10	8	6	6	3	
	11	*Row*	3	6	3	2	1	6	3	5	5	2	*6*
		Col	7	4	6	10	7	8	8	6	1	2	
C	9	*Row*	1	3	6	3	2	3	2	4	1	4	*5*
		Col	2	6	2	7	6	8	6	9	7	4	
	14	*Row*	2	3	1	2	2	1	4	1	6	4	*7*
		Col	6	11	4	9	5	3	9	9	5	2	
D	7	*Row*	1	2	1	3	6	3	2	2	6	6	*2*
		Col	5	5	1	3	7	5	1	1	5	3	
	5	*Row*	1	4	3	2	5	5	5	2	6	3	*14*
		Col	6	4	6	11	6	9	5	10	6	10	
E	7	*Row*	5	6	3	6	3	6	6	4	5	1	*13*
		Col	11	2	4	9	6	11	5	2	1	2	
	10	*Row*	6	1	6	5	1	3	5	3	2	5	*12*
		Col	5	4	3	7	7	3	8	9	2	6	
F	5	*Row*	5	3	4	1	3	3	3	6	5	1	*3*
		Col	7	9	10	7	11	1	8	3	4	6	
	14	*Row*	2	3	1	5	6	5	6	4	6	5	*10*
		Col	4	11	4	6	5	5	4	1	8	7	
G	4	*Row*	2	2	6	2	3	1	5	4	6	3	*1*
		Col	5	3	10	6	11	10	11	8	11	3	
	8	*Row*	4	5	5	2	4	1	1	1	5	2	*9*
		Col	5	1	5	2	5	2	11	9	8	4	

2.2.4 X-ray Computed Tomography and Spherical Harmonic Analysis

The final step in the bead shape analysis process consisted of an X-ray computed tomography (CT) analysis, which uses X-ray technology and a reconstruction algorithm [7] to acquire the 3-D particle shapes, which are then analyzed by a spherical harmonic process. The specimen used for the light microscope was also used for this final step. The CT scans were performed using a Skyscan 1172 instrument (see Figure 4). To begin this analysis process, the flat specimen, from the previous step (Section 2.2.3), was first rolled into a cylindrical shape, and fit into a sample support that was placed upright into the Skyscan.

Figure 4: X-ray CT instrument.

The X-ray CT instrument takes X-ray absorption images as the sample is rotated. The reconstruction algorithm takes this image data and constructs accurate 2D slices orthogonal to the cylindrical axis of the specimen [7]. A typical slice, for the D7 sample, is shown in Figure 5. In this image, a double particle, several quite non-spherical particles, and some internal porosity can be clearly seen (marked with white circles). These slices were thresholded so that the particles were white and the background is black. By stacking the slices on top of each other computationally the result was a 3D model of the specimen. A FORTRAN program scanned each 3D structure, extracted the particles and fit them with a 3D spherical harmonic series. Any internal porosity was removed before this mathematical fit, since the only interest was in the shape of the outer envelope, which would affect suspension rheology physics. Then, it automatically computed various geometrical parameters of each bead, such as volume, surface area, and dimensions of a box that minimally surrounds the beads (length (*L)*, width (*W)*, and thickness (*T*)). The volume equivalent spherical diameter (VESD), the mean curvature integrated over the surface, and other factors were also included in these automatic calculations [8].

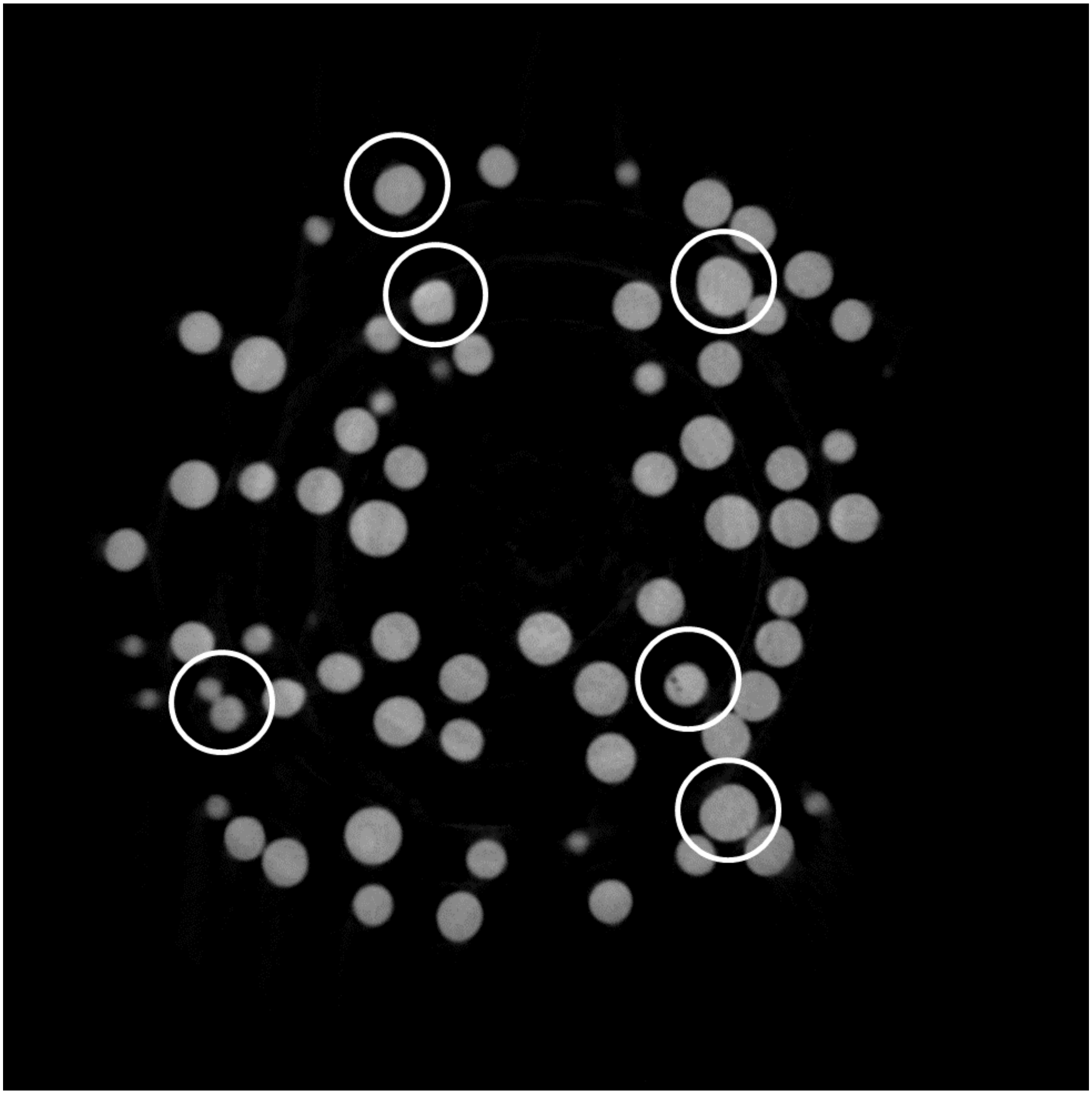


Figure 5: A typical reconstructed slice from the X-ray CT results for bead sample D7. The image is 1000 x 1000 pixels, and the length per pixel is approximately 20.9 µm. Note the several non-spherical particles, one double particle, and one particle with internal porosity (marked with white circles).

The dimensional data of the beads were analyzed to verify that most were indeed very close to being 1 mm spheres (L = W = T = 1 mm). To analyze non-sphericity, consider ratios of these dimensions. A sphere has L/T = W/T = 1. A double sphere (or two identical spheres glued lightly together) has L/T = 2, and W/T = 1, since by definition, L > W > T. Any particle that had values of L/T and W/T outside what was considered to be the spherical range (see section 2.2.5 for details) were considered to be distorted, and were compared to the number developed from the light microscope analysis for confirmation.

2.2.5 Bead Analysis Results

The analysis of the two tests showed similar characteristics but differed slightly due to distinct parameters between the two methods. The analyses did confirm the existence of deformed beads, which were categorized as either distorted or double-spheres. These deformities taint 1 % to 4 % of the sample population, by number, according to the light microscope (LM) and X-ray CT scan tests. Table 4 represents the total amount of deformed beads for each sample analyzed from both methods, but doesn't highlight which are distorted or double-spheres. The individual percent of distorted or double-spheres for both analysis methods can be found in Table 5. The "total beads estimate" and "deformed beads estimate" from the LM method were calculated by taking the average count of the ten grid boxes analyzed, and proportionally estimating the count for the total specimen area. The CT scan method numbers come from the automatic calculations described in Section 2.2.4.

The deformed beads were categorized as either double-spheres or distorted as shown in Table 5. These values were obtained from the CT scan data, which gives the dimensions of each reconstructed sphere. A perfect sphere will have an L/T ratio of 1, thus doubling that value would signify a double sphere. Therefore, the number of double spheres was calculated by counting the beads with length/thickness ratios greater than 1.8, to allow for some size variation in the spheres. Two unequal spheres, with diameters D_1 and D_2, $D_2 > D_1$, will have $L = D_2+D_1$ but $T = D_2$, so that $L/T = 1 + D_1/D_2 < 2$. The remaining deformed beads were classified as distorted, if the L/T ratio was between 1.3 and 1.8, which would indicate a non-spherical single particle. A value of L/T below about 1.3 was considered close to being spherical, hence was not counted as distorted or as a double particle. These approximate cutoff values of L/T were confirmed by a visual study of randomly-selected particles. The uncertainty was estimated at 10 % based on previous data using the same instrument [7].

The deformed bead count presented for the LM method is an estimate calculated via operator visual analysis of 10 randomly selected grid boxes. This attaches an uncertainty to the LM estimated deformed count, as shown in Figure 6, since the 10 selected grid boxes could have missed better representations of deformed beads. Furthermore, the LM method is a basic 2D analysis while the X-ray CT is a true 3D method. The CT method computes its numbers from reconstructed models, which can over count the deformed percentage by considering two neighboring, non-connected spheres that are too close together as double-spheres. The reconstruction process can blend two particles together that were geometrically very close in the original sample. The CT scan can be safely assumed to be the more accurate representation since it is actually analyzing every single bead in the specimen, and at worst it will over count as previously mentioned. The main uncertainty in the CT data comes from the segmentation of the CT images into particles (white) and background (black), and this mostly affects the volume determination [7]. The shape analysis is quite insensitive to the exact segmentation, so we estimate the uncertainty in the CT shape analysis, determining which spheres are irregular or double, to be about 1 %, which is almost certainly an upper bound.

Table 4: Total and deformed bead count for the LM and CT analysis methods. The LM method counts are estimates, while the CT counts are calculated via computer. Samples are listed in alphabetical order by bucket bottle #.

Light Microscope				
Sample #	**Bucket Bottle #**	**Total Beads Estimate**	**Deformed Beads Estimate**	*Deformed Ratio* [%]
11	**A 3**	3729	34	0.91
8	**A 10**	3518	27	0.77
4	**B 2**	3802	6	0.16
6	**B 11**	3788	34	0.90
5	**C 9**	3610	47	1.30
7	**C 14**	3656	42	1.15
2	**D 7**	3201	41	1.28
14	**D 5**	4376	19	0.43
13	**E 7**	3755	48	1.28
12	**E 10**	3445	35	1.02
3	**F 5**	3821	36	0.94
10	**F 14**	3927	36	0.92
1	**G 4**	4666	51	1.09
9	**G 8**	3775	30	0.79
	Average	**3791**	**35**	**0.92**
	SD	**351**	**11**	**0.31**

CT Scan				
Sample #	**Bucket Bottle #**	**Total Beads**	**Deformed Beads**	*Deformed Ratio* [%]
11	**A3**	2969	152	5.12
8	**A10**	3082	150	4.87
4	**B2**	3053	177	5.80
6	**B11**	2986	160	5.36
5	**C9**	2380	120	5.04
7	**C14**	2925	174	5.95
2	**D7**	2688	188	6.99
14	**D5**	3564	149	4.18
13	**E7**	3418	204	5.97
12	**E10**	2903	193	6.65
3	**F5**	2945	175	5.94
10	**F14**	3077	163	5.30
1	**G4**	4105	249	6.07
9	**G8**	3026	134	4.43
	Average	**3080**	**171**	**5.55**
	SD	**391**	**31**	**0.77**

Table 5: Deformed ratio separated into percentage of either distorted or double sphere category. All percentages are respective to the total amount of beads in each sample.

Light Microscope		Deformed Beads	Double Sphere	Distorted
Sample #	**Bucket Bottle #**	[%]	[%]	[%]
11	**A 3**	0.91	0.20	0.71
8	**A 10**	0.77	0.17	0.60
4	**B 2**	0.16	0.03	0.12
6	**B 11**	0.90	0.20	0.70
5	**C 9**	1.30	0.29	1.02
7	**C 14**	1.15	0.25	0.90
2	**D 7**	1.28	0.28	1.00
14	**D 5**	0.43	0.10	0.34
13	**E 7**	1.28	0.28	1.00
12	**E 10**	1.02	0.22	0.79
3	**F 5**	0.94	0.21	0.73
10	**F 14**	0.92	0.20	0.72
1	**G 4**	1.09	0.24	0.85
9	**G 8**	0.79	0.17	0.62
	Average	**0.92**	**0.20**	**0.72**
	SD	**0.31**	**0.07**	**0.24**

CT Scan		Deformed Beads	Double Sphere	Distorted
Sample #	**Bucket Bottle #**	[%]	[%]	[%]
11	**A 3**	5.12	2.63	2.49
8	**A 10**	4.87	2.76	2.11
4	**B 2**	5.80	2.69	3.11
6	**B 11**	5.36	2.95	2.41
5	**C 9**	5.04	1.93	3.11
7	**C 14**	5.95	3.04	2.91
2	**D 7**	6.99	3.98	3.01
14	**D 5**	4.18	1.74	2.44
13	**E 7**	5.97	3.10	2.87
12	**E 10**	6.65	3.69	2.96
3	**F 5**	5.94	3.43	2.51
10	**F 14**	5.30	2.86	2.44
1	**G 4**	6.07	3.58	2.48
9	**G 8**	4.43	2.18	2.25
	Average	**5.55**	**2.90**	**2.65**
	SD	**0.77**	**0.63**	**0.32**

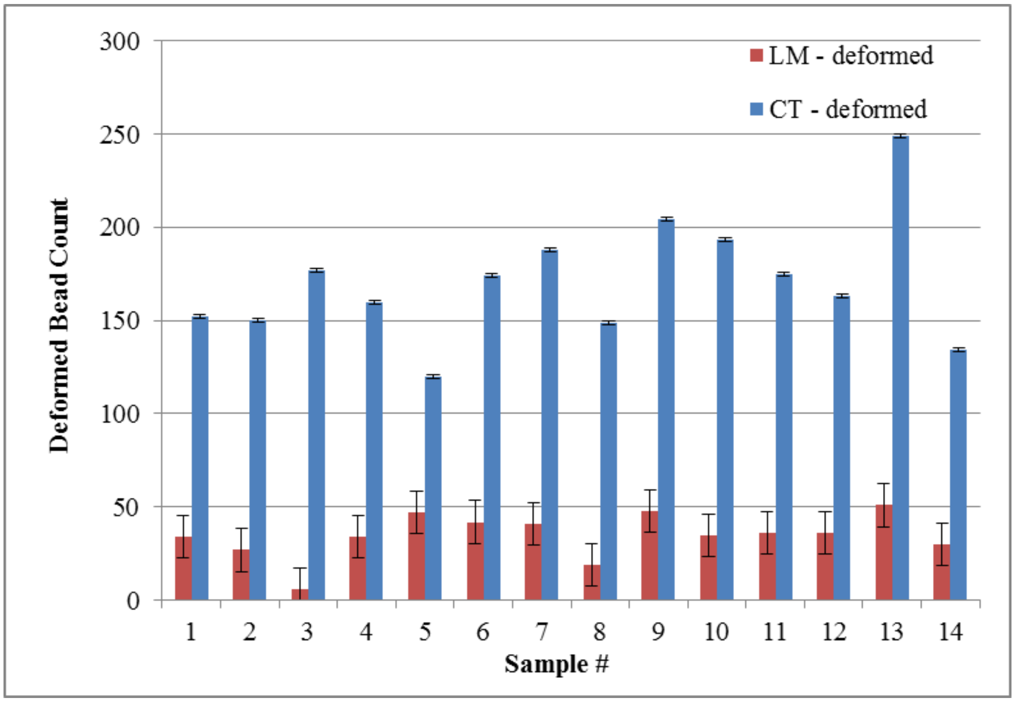


Figure 6: Deformed beads from the two analysis methods. The LM method provided an uncertainty due to estimation, shown by error bars. The uncertainty for the CT data was estimated at 1 %.

2.3 Mixing and Composition

The SRM paste portion for SRM 2493 was mixed according to ASTM C1738, as described in the previous reports [1] [2]. Once the SRM paste was mixed, it was stored in a polypropylene sealed container for one night. The following day, the beads were mixed into the SRM paste using a high-speed plunger blender at 31.42 rad/s (300 RPM) for 5 min to reach homogeneity. The lag for the addition of beads was due to the fact that SRM 2492 paste was measured in the rheometer the day before the beads were added.

The initial step of the mixing procedure is dependent on the composition of the mortar. For mortar mixes with a high percentage of bead composition, the initial mixing time may take longer than mortars with low bead percentages (<25% by vol.) due to the slow addition of the beads (longer if more beads). This suggestion allows the blender to mix a portion of the added beads without clogging during blending. It is also recommended to mix for at least 2 additional min (i.e., 7 min total) after all the beads have been introduced in order to give the SRM mortar enough time to homogenize. The shelf life of the mortar is 6 d (limited by the shelf life of the paste [9]). If the SRM mortar will be stored and reused some other day after mixing (but less than 7 d), it is recommended to verify that no changes have occurred to the mortar's composition. The user should measure the bead concentration by volume. To avoid issues with assuring that the SRM was stored and its composition was not altered during future reuse, the certification values were only recorded at an age of one day and the material was not reused.

During this study, two compositions of the mortar were measured, with the glass beads having a volume fraction of 20 % and 40 %. Pre-certification testing showed that the mortar becomes too stiff as the mortar composition approaches the maximum packing fraction for spherical monosize particles, 64 % by volume. In fact, compositions higher than 50 % caused our rheometer to exceed its maximum torque limit. Considering these observations, a 40 % by volume mortar was concluded to be a good representation of a concentrated bead percentage. Furthermore, for future interpolations and model comparisons, a 20 % composition was also tested to portray semi-concentrated mortars. The experimental results of this study (in Section 4) were drawn from samples of compositions as discussed in this section.

2.3.1 Instruction for the Certificate to Prepare the Mixture

Follow the instructions below. The mixture's composition is:

- Corn syrup: 200.00 g
- Distilled water: 63.16 g
- Limestone: 458.10 g
- Glass beads (Asuming a total paste volume of 320 cm^3 or see calculation below):

20 % volume fraction	196.8 g
40 % volume fraction	524.8 g

Mixing the material is a two phase process by first preparing the paste as for SRM 2492 and then adding the beads. The whole process is described here. The water baths of the high shear blender and the rheometer should be maintained at 23 °C ± 1 °C.

Phase 1: Preparation of the paste fraction (limestone, corn syrup and water). The equipment and the method are described in ASTM C1738 [3], with the following sequence to introduce the ingredients. Pour the correct amount of distilled water in a jar that already contains the correct mass of corn syrup, and mix with a spatula until homogeneous. On average, it will take 5 min of mixing to dilute the visible glucose chains in the corn syrup. Note that assuring the syrup is diluted prior to adding it into the high shear blender results in a more effective transfer of the corn syrup into the mixture. Then, add all of the mixture into the high shear blender that conforms to the specifications detailed in ASTM C1738 and proceed as described in ASTM C1738 to introduce the limestone and mix. (note, the limestone is taking the place of the cement in ASTM C1738).

Phase 2: Addition of the beads

- Tare a plastic container preferably made of polypropylene [9] and pour the mixed paste into it. Make sure that the container has a lid. Measure the mass of the paste, Pm.
- Calculate the mass of beads needed for the mixture using the formula below:

20 % beads	Mass beads = 0.329*Pm
40 % beads	Mass beads = 0.877*Pm

Note: the density of the paste is (1.87 ± 0.01) g/cm^3 and the glass beads densities is 2.46 g/cm^3

- After the mass of beads is determined, the best method to mix the beads into the paste is to use a plunger mixer (rotation speed of 31.4 rad/s (300 rpm)). Add the calculated amount of beads and mix for 5 min using the plunger mixer (See Figure 7). It is recommended to use a plunger mixer (rotation speed of 31.4 rad/s (300 rpm)) for 30 s to remix the prepared SRM before each use, especially after a few days of rest.

Figure 7: An example of plunger mixer

2.4 Packaging

The corn syrup and the limestone used were taken from SRM 2492 supplies [1]. The beads were purchased in one lot and were delivered in 5-gal buckets. The seven buckets were labelled from A to G. The beads were then packaged in 500 mL plastic bottles (100 bottles in total) each containing about 1500 g. About 14 bottles were obtained from each bucket.

The final packaging was in single boxes, each containing:

- 2 containers of limestone (600 g each)
- 1 container of corn syrup (500 g)
- 1 container of 1-mm beads (1500 g)

Each box contains enough material to make two batches of SRM 2493 at 40 % beads by volume.

3 Definitions

Here some definitions of terminology used throughout this report are provided for more detailed discussion on rheological properties of fluid review ref [3].

Viscosity of a fluid, μ, is the shear stress, τ, divided by the shear rate, $\dot{\gamma}$.

Bingham equation is a linear relationship between shear stress and shear rate

$$\boldsymbol{\tau = \mu_B \dot{\gamma} + \tau_0}$$

where τ is the shear stress, μ_B, is the plastic viscosity and, τ_0 is the yield stress.
The Bingham equation is a two parameter model used for describing viscoplastic fluid exhibiting a yield response. The ideal Bingham material is an elastic solid at low shear stress values and a Newtonian fluid above a critical value called the yield stress. The plastic viscosity region exhibit a differential viscosity called the plastic viscosity.

Pseudo-viscosity, Γ/N, is defined as the ratio of the measured torque and the applied rotational speed. This value is related to the viscosity.

4 Modeling Approach

A two-step approach was used to predict the viscosity of the mortar SRM. First, a direct numerical simulation was used that incorporates the paste SRM rheological properties in a hard sphere suspension computational model. Once the viscosity was calculated for a finite set of shear rates, two scaling parameters were determined that map the viscosity vs. shear rate data of the suspension to the viscosity vs. shear rate data of the matrix fluid (SRM paste). By performing the inverse of this transformation to the matrix viscosity vs. shear rate curve, the full viscosity vs shear rate curve is obtained for the suspension. The full description and validation of this scaling ansatz is given in [10].

The computational approach used in this work for modeling suspension is based on Smooth Particle Hydrodynamics (SPH) [11]. SPH is a Lagrangian formulation of the Navier-Stokes equations that has been adapted to model non-Newtonian fluids containing solid inclusions. While a full description of this approach is beyond the scope of this work, it is worth mentioning a few features of this simulation. A Lees-Edwards boundary condition is used to model Couette flow in the simulation cell [12]. This approach allows for the establishment of a Couette-like velocity profile in an infinite quasi-periodic system. As a result, wall effects, which might produce an inhomogeneous density variation or slip effects, are avoided. For an applied rate of strain, the volume average stress is calculated. The viscosity is then determined by dividing the volume averaged stress by the shear rate. An additional feature in this simulation is that lubrication forces are included to properly model the interactions between solid inclusions when they are in close proximity, as the numerical resolution needed to model such effects is too demanding computationally to accomplish using SPH alone. The approach utilized for this work has been validated for a variety of flow scenarios where excellent agreement with analytic solutions of flow fields for non-Newtonian continuum fluids in channel tube geometries and in experimental measurements of suspensions composed of micrometer sized spheres with different power-law matrix fluids in a Couette geometry [10, 13].

SRM 2493 (mortar) utilized SRM 2492 (paste) to serve as the matrix fluid of a suspension composed of mono-sized glass bead inclusions. Due to the different power law behavior of the viscosity vs. shear rate in low and high shear rate, the data were divided into two regions. The division between low and high shear rate was selected to be at a shear rate of 1 s^{-1}. The high shear portion could be approximated with the Bingham equation or linear behavior of shear stress vs. shear rate. The data in each region was fitted to functions f_1 and f_2 (see equation 2 and 3 respectively). Function f_1 fit the viscosity vs. shear rate curve with $\dot{\gamma} < 1$ and function f_2 fit for $\dot{\gamma} > 1$. To represent the full dataset with a single function, equation 1 was developed, which seamlessly combines the two functions without any significant deviations from f_1 and f_2,

	$$\boldsymbol{\mu} = [(\boldsymbol{tanh}(-\boldsymbol{a}(\dot{\boldsymbol{\gamma}} - \mathbf{1})) + \mathbf{1})\boldsymbol{f_1}(\dot{\boldsymbol{\gamma}}) + (\boldsymbol{tanh}(\boldsymbol{a}(\dot{\boldsymbol{\gamma}} - \mathbf{1})) + \mathbf{1})\boldsymbol{f_2}(\dot{\boldsymbol{\gamma}})]/\mathbf{2}$$	*[1]*
	where $$f_1(\dot{\gamma}) = \frac{A_1}{\dot{\gamma}^{B_1}} + C_1$$	*[2]*
	$$f_2(\dot{\gamma}) = \frac{A_2}{\dot{\gamma}^{B_2}} + C_2$$	*[3]*

where

$\dot{\gamma}$ = Shear rate at the outer rim of the plate
μ = Viscosity
A_i, B_i, *and* C_i *(i= 1,2)* = Coefficients to fit the curve
a = Fitting parameter to smoothly combine curves f_1 and f_2.

The coefficients were determined by a least square fit to the paste SRM 2492 data obtained with the parallel plate geometry. The difference was estimated at less than 3 % of the experimental values. The viscosity (μ) can be calculated at any given shear rate with equation (1) (uncertainity discussion on Section 7):

A_1=16.411; B_1=0.988; C_1=9.641
A_2=19.178; B_2=0.727; C_2=7.116
a = 4

The viscosity from equation (1) was input into the simulation code to serve as the matrix fluid. The glass beads were modeled as spherical inclusions with 472 spheres and 944 spheres used to model the 20 % and 40 % suspensions, respectively. The uncertainty of the simulated suspension viscosity was derived from calculating the standard deviation of the stress values, which was proportional to viscosity, over several strains (usually strains values of approximately 5 to 10). Four different shear rates were used in the simulation and the viscosity at each shear rate was determined (Table 6**).** When suitably rescaled [10], the simulation data falls on top of the viscosity vs. shear rate curve of the matrix fluid. The scaling parameters, shown in Table 7**,** are then used to generate predictive curves of the suspension's viscosity vs shear-rate, as shown in Figure 8 for the 20% and 40% volume fraction suspensions. In other words, to produce the scaled predictive curves, the μ_{sc} scaling parameter was factored into the viscosity variable, μ, in equation (1). Similarly, the γ_{sc} scaling parameter was factored into the shear rate variable, $\dot{\gamma}$, in equation (1).

In Figure 8, the SRM 2492 (paste) certified data baseline is shown as a solid black line, along with the simulation data for 20 % volume fraction (O's) and 40 % volume fraction (X's). From the data obtained using equation 1 and the scaling parameters of Table 7, it is possible to generate Table 8 using arbitrary shear rates for the paste and then calculate the plastic viscosity and yield stress, i.e., the Bingham parameters.

Table 6: Rheological values estimated from numerical simulation model for SRM2492 paste containg 0%, 20% and 40% spherical inclusions. Simulation data portrayed as *X*'s and *O*'s in Figure 8. The uncertainty in values of viscosity, based on the standard deviation, is 10 % or lower.

Shear Rate [1/s]	0 % Simulated Viscosity [Pa-s]	20 % Simulated Viscosity [Pa-s]	40 % Simulated Viscosity [Pa-s]
0.1	175.0	214.0	297
1	27.4	39.4	85
10	10.6	18.1	66
100	7.76	14.1	59

Table 7: Scaling parameters to factor the SRM2492 curve to a mortar curve with known concentration. The uncertainty in scaling parameters, based on a least square fit of simulation data to equation (1), is 10 % or less

Concentration [%]	μ_{sc} factor	$\dot{\gamma}_{sc}$ factor
20	1.85	0.66
40	7.20	0.23

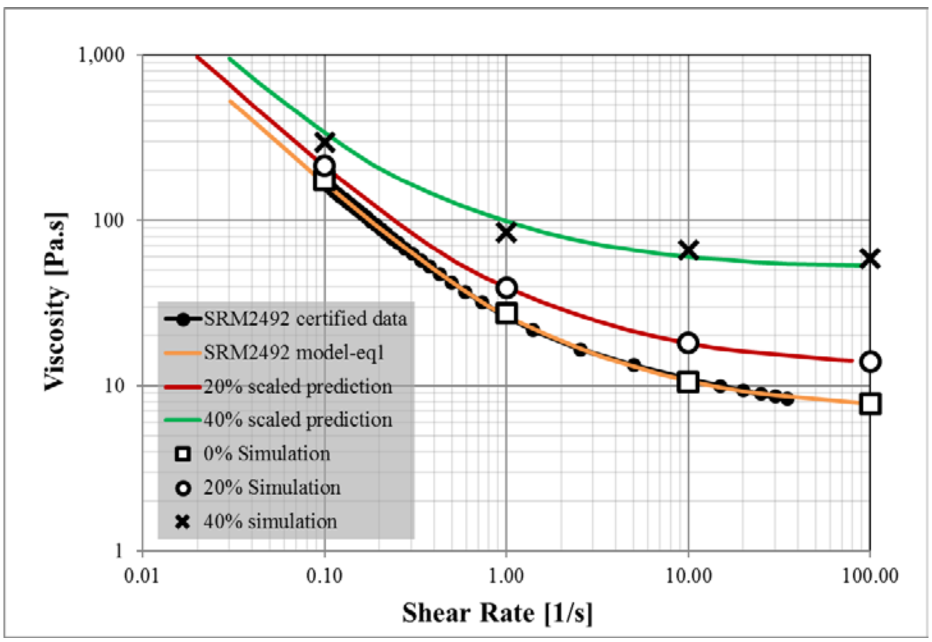


Figure 8: Numerical model simulation model data and predicted data from scaling parameters are compared to experimental data results (see Table 6 for values). The uncertainty is about 10 % (see text)

Table 8: Values for model with uncertainties provided in fundamental units (data were rounded to nearest hundreth). The shear rates for the 0% were arbitrary selected while the shear stress and viscosity were calculated using equation 1. The 20 % and 40 % were determined using the scaling factors of Table 7.

Model														
0% Model					20% Model					40% Model				
Shear Rate [1/s]	**Shear Stress [Pa]**	**Shear Stress Expanded uncertainity [Pa]**	**Viscosity** [Pa·s]	**Viscosity Expanded uncertainity [Pa]**	**Shear Rate** [1/s]	**Shear Stress [Pa]**	**Shear Stress Expanded uncertainity [Pa]**	**Viscosity** [Pa·s]	**Viscosity Expanded uncertainity [Pa]**	**Shear Rate** [1/s]	**Shear Stress [Pa]**	**Shear Stress Expanded uncertainity [Pa]**	**Viscosity** [Pa·s]	**Viscosity Expanded uncertainity [Pa]**
30	262	26	8.7	0.9	20.0	323	32	16	2	6.90	454	45	63	6
21	193	19	9.2	0.9	13.9	223	22	17	2	4.83	332	33	66	7
14	139	14	9.9	1.0	9.7	167	17	18	2	3.22	247	25	72	7
10	107	11	10.7	1.1	6.7	128	13	20	2	2.30	186	19	77	8
7	82	8	11.8	1.2	4.7	99	10	22	2	1.61	142	14	85	8
5	65	7	13.1	1.3	3.2	78	8	24	2	1.15	110	11	94	9
3	47	5	15.7	1.6	2.3	63	6	29	3	0.69	87	9	113	11
2.3	40	4	17.6	1.8	1.6	51	5	33	3	0.53	70	7	127	13
1.6	33	3	20.7	2.1	1.1	42	4	38	4	0.37	57	6	149	15
1.1	28	3	25.0	2.5	0.8	36	4	46	5	0.25	47	5	180	18
0.8	24.1	2.4	30	3	0.53	32	3	56	6	0.18	41	4	217	22
0.5	21.1	2.1	42	4	0.36	29	3	78	8	0.12	36	4	304	30
0.4	20.1	2.0	50	5	0.26	27	3	93	9	0.09	33	3	362	36
0.3	19.1	1.9	64	6	0.18	26	3	118	12	0.07	31	3	458	46
0.2	18.0	1.8	90	9	0.13	25	3	167	17	0.05	30	3	649	65
0.1	16.9	1.7	169	17	0.09	24	2	313	31	0.023	29	3	1219	122
0.09	16.8	1.7	187	19	0.06	24	2	346	35	0.021	28	3	1345	134
0.06	16.4	1.6	274	27	0.04	23	2	507	51	0.014	27	3	1973	197
0.04	16.2	1.6	404	40	0.03	23	2	748	75	0.009	26.9	3	2911	291
0.03	16.0	1.6	534	53	0.02	23	2	988	99	0.007	26.6	3	3846	385

Table 9: Bingham parameters extracted from the model data displayed in Table 8.

		Bingham Parameters	
		Yield Stress, τ_0 [Pa]	Plastic Viscosity, μ_B [Pa·s]
Model	*0 %*	23.1	8.07
	Std. Unc.	*1.8*	*0.8*
	20 %	31.0	14.9
	Std. Unc.	*3.6*	*2.3*
	40 %	38.8	57.9
	Std. Unc.	*5.2*	*8.7*

5 Rheological Measurements

5.1 Rheometer Set-up

Many industrial rheometers available today allow the users to test a variety of configurations of containers and spindles. In this study, the container is a cylindrical steel cup with a height of 80 mm and a diameter of 43 mm, with serrated ribs. Various spindle designs were used. A computer controls the rotational speed of the spindle and measures the torque, while the container is stationary.

Three types of spindles were used for this certification study, selected to represent spindle families: six-blade vane (vane-type), a serrated coaxial cylinder (cylindrical-type) and a double helical spiral (sometimes referred to as helical ribbon mixer or mixer-type). See Figure 9 for spindles' dimensions.

A coaxial rheometer with a smooth or serrated surface of the spindle is the most widely used design. The serration is needed to reduce slippage of the suspension. The modified spindle with a serrated surface is shown in *Fig. 9a*.

The vane spindle (*Fig. 9b*) provides a shearing plane made from the material in shear itself. As the vane spins, it is generally assumed that a cylindrical wall of the material is formed on the perimeter of the blades, thus the material shears on a wall made of itself. This shearing scenario, presumably, increases the frictional force, therefore reducing slippage.

The third type of spindle tested in this study is the mixer-type or impeller spindle, known as the double spiral (*Fig. 9c*). This spindle type is useful due to its capability to mix the material during testing. By mixing during the testing, any sedimentation or migration issues are minimized.

***Fig. 9a:** Serrated coaxial cylinder.*
D = 18 mm
H = 55 mm

***Fig. 9b:** Six-blade vane.*
D = 18 mm
H = 55 mm

***Fig. 9c:** Double helical spiral.*
D = 35 mm
H = 50 mm

Figure 9: Three spindle types were used for testing, each representing a different family

5.2 Experimental Design

Rheological testing was performed on a MARS III rheometer in conjunction with the spindle geometries described in the previous section. The certification of SRM 2492 [2] used one batch from 11 units (or boxes). The second batch from these same units were used for the certification of SRM 2493 along with 11 randomly selected container of beads[1]. The first batch of 11 was incorrectly tested and was consequentl not considered for the certification. See Appendices A and B for the data obtained from the 10 mixtures used for certification.

All 10 mixtures used for the certification were tested at an age of one day after mixing the paste portion of the SRM. Each reported value was the average of three consecutive tests run back-to-back with a 5 min rest in between each test. The test protocol consisted of ramping 15 steps up from 0.1 rpm (0.01047 rad/s) to 100 rpm (10.47 rad/s) and 20 steps back down to 0.1 rpm (0.01047 rad/s) to capture any hysteresis. Schedule codes for testing were assigned and represented in the schedule shown in Table 10 and complemented by the legend on the side**.** The pseudo-random generator was used to establish the order in which the spindles were tested each day. The gray row in the schedule refers to the time period it takes the rheometer to complete its readings. This waiting period was used to create the mixture samples as scheduled.

The testing model was developed to observe three concentrations of beads in the amounts of 0 %, 20 % and 40 % by volume. The amount of material developed by one batch of SRM was sufficient enough to yield two containers of SRM that overfilled the rheometer’s holding container. Therefore, half of the 10 usable batches were used to test SRM compositions of 0 % and 20 % beads by volume, while the other half tested compositions of 0 % and 40 %. Ultimately, the results will report five values for 20 %, five for 40 % and 10 values for 0 % concentrations.

[1] Eventually a portion of the SRM 2492 units (or boxes) were repackaged to include the beads container and re-labelled SRM 2493

Table 10: Testing schedule complemented by the key on the right side. The waiting periods were used to create the mixes listed along the gray rows.

		Full Testing Schedule				
8:00 AM		M	T	W	T	F
9:30 AM	Week 1	Columbus Day		1B	2A	
11:00 AM				1C	2B	
12:30 PM				1A	2C	
3:00 PM	10/13/2015			1B	2A	
4:30 PM				1C	2B	
6:00 PM				1A	2C	
Waiting Period			Mix 1	Mix 2		
	Week 3		3B	4A		
			3A	4C		
			3C	4B		
	10/20/2015		3B	4A		
			3A	4C		
			3C	4B		
Waiting Period		Mix 3	Mix 4			
	Week 4 10/27/2015	ACI Convention				
	Week 5			5B	6B	
				5A	6C	
				5C	6A	
	11/3/2015			5B	6B	
				5A	6C	
				5C	6A	
Waiting Period				Mix 5	Mix 6	
	Week 6		Veterans Day		7B	8C
					7A	8B
					7C	8A
	11/10/2015				7B	8C
					7A	8B
					7C	8A
Waiting Period				Mix 7	Mix 8	
	Week 7		9B	10B	11B	
			9A	10C	11A	
			9C	10A	11C	
	11/17/2015		9B	10B	11B	
			9A	10C	11A	
			9C	10A	11C	
Waiting Period		Mix 9	Mix 10	Mix 11		

Schedule Key	
Testing Parameters	
All Mixes tested at 1 day.	Mixing Day
	Test 0% (11)
	Test 20% (5)
	Test 40% (6)
Schedule Code	Spindle
A	RHN-83A *Double Spiral*
B	RHN-83C *Six Blade Vane*
C	SS18 *Serr. Coaxial Cylinder*

5.3 Rheometer Data Calibration

To calibrate a rheometer using the data developed in this report, two methods are suggested: 1) using the approximation of the Bingham equation and 2) using a method based on the viscosity vs. shear rate curve and the model described in Section 4. Here, step by step instruction will be provided on how to proceed using these two suggested methods.

The first step with either method is to prepare the SRM 2493 mortar mixture and to load it in the rheometer to be calibrated. Run at least three tests and use the average to extract the raw data, which consists of the measured torque (Γ) [N·m] and rotational speed (N) [rad/s] for at least 10 points in the decreasing rotations speed curve (down-curve). The next goal is to convert this values in fundamental units of Pa and s^{-1}, respectively, by using one of the two suggested methods. Either methods are acceptable, the method based on Bingham parameters (Section 4.3.1) is faster and easy to implement, but the method based on viscosity vs. shear rate (Section 4.3.2) could be more accurate as it takes into account the whole curve measured not just the linear portion.

The certified values for SRM 2492 tested in a parallel plate rheometer are used here as reference points. It should be noted that the SRM 2492 paste materials are the same as the SRM 2493 matrix materials. Ideally, the results of any other spindle that is used to test the SRM 2492 or paste part of SRM 2493 should reproduce the certified values. Using such criteria, the raw data simply needs to be calibrated to the SRM 2492 certified values. Thus, the next step would be to convert the data obtained with the different tools (Section 5.2) into fundamental units by using SRM 2492 or paste SRM 2493. The next two sections, 5.3.1 and 4.3.2, will describe how this is done.

The same process described in two Sections 5.3.1 and 4.3.2 could be used to calibrate any rheometer by the user of SRM 2493, by selecting either method as described in the certificate for SRM 2493[2]. A web based software and a spreadsheet are posted on the NIST website that should help the user to calculate the necessary calibration factors.

5.3.1 Calibration Based on the Bingham Parameters

To transform the data generated in this report using the Bingham approach, the SRM 2492 certified values were used as the base line. The Bingham parameters of the SRM 2492 paste were extracted from the certificate and compared to the parameters calculated from the experimental or model data, using only the linear part of the curve (torque vs. rotational speed). The schematic shown in Figure 10 explains the calibration process in a sequential form. A spreadsheet was developed for this procedure, and is posted on the SRM 2493 website[2]. This file can be used by following a "how to" fact sheet, which will be available on the same spreadsheet.

The calibration process begins by running at least three tests with a geometry of choice on a sample of SRM 2493, and finding the average values from the produced torque and respective rotational speed. Since the raw data should match the SRM 2493 certified values either for the paste or the model data, then the torque and rotational speed can be scaled to match the known

[2] www.nist.gov under "Standard Reference Materials"

certified viscosity and shear rate. This implies that the shear stress (τ), shear rate ($\dot{\gamma}$), and apparent viscosity (μ) are proportional to the torque (Γ), rotational speed (N), and angular momentum (Γ/N), respectively. In other words, the *(Γ vs. N)* results from the new geometry are scaled to match the *(τ vs. $\dot{\gamma}$)* certified SRM 2493 paste values by calculating scaling factors K_τ and K_μ. Figure 9 provides a schematic of the procedure. The calibration factors convert the two raw variables into fundamental rheology units by using proportionality relationships. Also, if preferable, the two calibration factors listed are able to produce a direct shear rate scaling factor, K_γ, by means of *equation (5)* which is derived from the known relationship shown in *equation (4):*

$$\mu = \tau / \dot{\boldsymbol{\gamma}} \quad \text{[Pa·s]}. \qquad [4]$$

Thus, the shear rate calibration factor would be:

$$K_\gamma = K_\tau / K_\mu. \qquad [5]$$

The best results using this method are obtained when the shear rate is larger than 1 s^{-1} or when using the linear portion of the curve. The flow curve of shear stress vs. shear rate is clearly not linear for shear rates lower than 1 s^{-1}, while the Bingham model implies that the relationship remains linear. The factors K represent the influence of the rheometer geometry on the results.

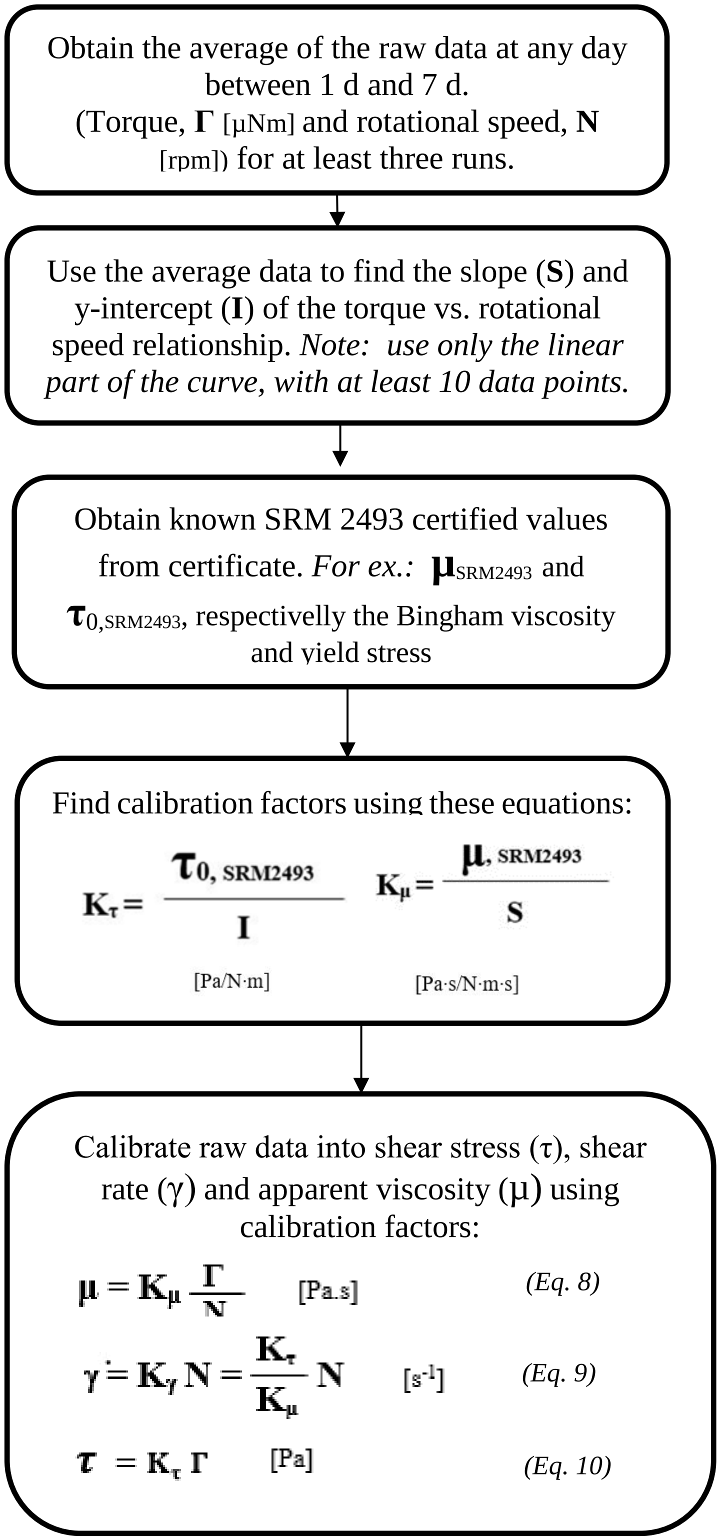


Figure 10: Schematic for the calibration of rheometer data from raw torque and rotational speed to fundamental rheological variables, viscosity and shear rate.
Note: a) This process is applied for calibration of any spindle used in coaxial rheometer.
b) The conversion from rpm to rad/s requires multiplication by 2π/60.

5.3.2 Calibration Using the Viscosity vs. Shear Rate Curve

The second method proposed is to use the viscosity vs. shear rate curve, as represented by equation (1) and compared with the data measured using the same material (i.e., same beads concentration). This comparison can be achieved by calculating two scaling factors, L_μ and L_γ, that will be used for all future calculation to convert torque to shear rate when measuring unknown materials. See Figure 12 for a scheme of the calibration process.

$$\boldsymbol{\mu = L_\mu \frac{\Gamma}{N}} \quad [\,Pa{\cdot}s] \qquad [\,11]$$

$$\dot{\gamma} = L_\gamma N \quad [s^{-1}] \qquad [\,12]$$

$$\tau = L_\mu L_\gamma \Gamma \quad [Pa]. \qquad [13]$$

To calculate the factors L, the measured curve needs to be rescaled both along the Y and X axes, until it matches the reference curve (SRM 2492 paste or the model curve). An algorithm could be developed to fit by least square regression, to equation (1). This equation can be simplified by simple algebra , using the same parameters as equation (1):

$$\boldsymbol{\mu = \frac{\left(C_2 + \frac{A_2}{\dot{\gamma}^{B_2}}\right) + \left(C_1 + \frac{A_1}{\dot{\gamma}^{B_1}}\right) e^{2a(\dot{\gamma}-1)}}{1 + e^{2a(\dot{\gamma}-1)}}} \qquad [\,14]$$

The computation of the L factors can be accomplished as follows:

1. Define a statistical model for the n measurement pairs (N_i, Γ_i) based on the SRM 2493 paste as:

$$\dot{\gamma}_i = \boldsymbol{L_\gamma} \cdot N_i, \quad i = 1, \dots, n$$
$$\tau_i \sim Gaussian(\mu_i, \sigma^2), i = 1, \dots, n$$

where

$$\mu_i = \boldsymbol{L_\mu} \cdot \frac{\left(C_2 + \frac{A_2}{\dot{\gamma}_i^{B_2}}\right) + \left(C_1 + \frac{A_1}{\dot{\gamma}_i^{B_1}}\right) e^{2a(\dot{\gamma}_i - 1)}}{1 + e^{2a(\dot{\gamma}_i - 1)}}, \quad i = 1, \dots, n,$$

A_1=16.411; B_1=0.988; C_1=9.641
A_2=19.178; B_2=0.727; C_2=7.116
a = 4

Prior distributions:

$$\sigma \sim Gamma(1.0E-5, 1.0E-5)$$
$$\boldsymbol{L_\gamma} \sim Uniform(1,8)$$
$$\boldsymbol{L_\mu} \sim Uniform(10,10000)$$

2. Compute the values of $\boldsymbol{L_\gamma}$ and $\boldsymbol{L_\mu}$ using a Markov Chain Monte Carlo method [14] implemented in OpenBUGS [15], executed using the following R code [16].

The code requires that both R and OpenBUGS be installed, both are free to download. R can be obtained at http://www.R-project.org/ , OpenBUGS at http://www.openbugs.net/w/Downloads . The only input to the program that is needed are the values N and Γ, and the sample size n. Pasting the entire program below into an R window will produce the estimates of the L factors as well as a plot which shows the fit to the SRM 2492 function.

Here is an example using the measurement data for SRM 2493 with six-blade vane configuration (Figure 11). This software will also be available from the SRM 2493 website[2].

In the program below X = N in rad/s, and Y = Γ in μNm

```
#####################################################################################
library(R2OpenBUGS)

############## type data X, Y, n here:

linedata<-list(y=c(7246.99,5435.07,4136.84,3203.2,2528.2,2035.31,1672.22,1399.73,
1190,1031.01,907.89,812.84,740.87),
x=c(10.472,7.278,5.058,3.519,2.45,1.696,1.183,0.822,0.571,0.397,0.276,0.192,0.133), n=13)

###############

####SRM 2492 curve for comparison to see the fit
visc92<-c(8.72,9.21,9.84,10.66,11.73,13.15,14.94,17.33,20.44,24.44,30.1,
39.27,51.25,69.47,94.31,132.83, 186.79,274.08,404.37,534.13)

sr92<-c(30.32,21.07,14.64,10.19,7.09,4.91,3.43,2.38,1.65,1.15,0.8,
0.55,0.39,0.27,0.19,0.13,0.09,0.06,0.04,0.03)
#####
##### OpenBUGS code and inits

lineinits<-function(){list(sig=1)}
linemodel <- function() {sig~dgamma(1.0E-5,1.0E-5)
Lg~dunif(1,8)
Lm~dunif(10,10000)
Lmu<-1/Lm
Ltau<-Lg/Lm

a1n<-16.411
a1sig<-1/(0.64*0.64)
b1n<-0.988
b1sig<-1/(0.018*0.018)
c1n<-9.641
```

```
c1sig<-1/(0.98*0.98)
a2n<-19.178
a2sig<-1/(0.61*0.61)
b2n<-0.727
b2sig<-1/(0.09*0.09)
c2n<-7.116
c2sig<-1/(0.78*0.78)

a1~dnorm(a1n,a1sig)
b1 ~dnorm(b1n,b1sig)
c1 ~dnorm(c1n,c1sig)
a2 ~dnorm(a2n,a2sig)
b2 ~dnorm(b2n,b2sig)
c2 ~dnorm(c2n,c2sig)
a<-8
  for (i in 1:n){ srd[i]<-x[i]*Lg
            num[i]<-a*srd[i]
            top[i]<-a*(srd[i]-1)
  mu[i]<-
Lm*(c2*exp(a)+c1*exp(num[i])+a1*exp(num[i])/pow(srd[i],b1)+a2*exp(a)/pow(srd[i],b2))/(e
xp(a)+exp(num[i]))
            gon[i]<-y[i]/x[i]
            gon[i]~dnorm(mu[i],sig)
           }
}
######
###### run the OpenBUGS

lineout<-bugs(data=linedata,inits=lineinits,parameters=c("Lg","Lmu","Ltau"),
model.file=linemodel,n.chains=1,n.iter=10000,n.burnin=5000,n.thin=10)

#####print the values of the L factors
print(lineout, digits=7)
######

##### compute the calibrated curve
Lg<-lineout$mean["Lg"]
Lmu<-lineout$mean["Lmu"]
viscnew<-linedata$y/linedata$x*Lmu$Lmu
srnew<-linedata$x*Lg$Lg

### plot the SRM 2492 curve and the calibrated curve
plot(visc92~sr92,type="l",col="blue", lwd=3, xlab="shear rate (1/s)", ylab =" viscosity (Pa s)",
log="x")
title("Viscosity vs. Shear rate ",  sub="blue line is SRM 2492, cyan line new material")
lines(viscnew~srnew, type="l",col="Cyan",log="x")
```

##
#######

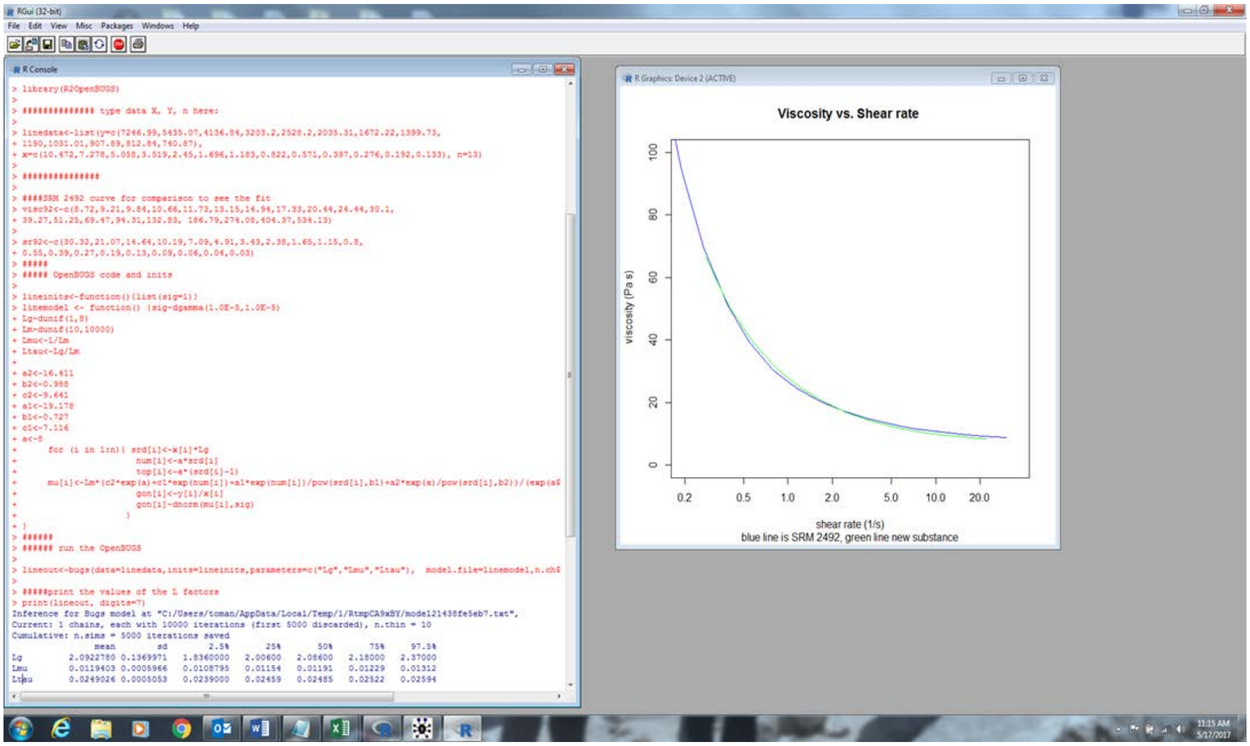


Figure 11: Screenshot of the running of the above software code and of the results for the SRM 2493 six-blade vane data using the method for fitting equation (1).

Obtain the average of the raw data (Torque, **Γ** [μNm] and rotational speed, **N** [rpm]) for at least three runs using an SRM 2493 mixture
Convert **N** *units to [rad/s] and **Γ** to [Nm]*.

↓

Use the average data to calculate the ratio (**Γ** / **N** [Nm/(rad/s)]) for each **N** [rad/s].

↓

Fit the data to model curve equation (1), scaled with the coefficient of Table 4 with the same concentration used for the tests and obtain two factors $\mathbf{L_\mu}$ and $\mathbf{L\gamma}$ (See methodology above)

↓

Calibrate raw data into shear stress (τ), shear rate ($\dot{\gamma}$) and viscosity (μ) using scaling factors:

$$\boldsymbol{\mu = L_\mu \frac{\Gamma}{N}} \quad [\text{Pa·s}] \quad \textit{(Eq.14)}$$

$$\boldsymbol{\dot{\gamma} = L_\gamma N} \quad [\text{s}^{-1}] \quad \textit{(Eq. 15)}$$

$$\boldsymbol{\tau = L_\mu L_\gamma \Gamma} \quad [\text{Pa}] \quad \textit{(Eq.16)}$$

Figure 12: Schematic for the calibration of rheometer data from raw torque and rotational speed to fundamental rheological variables, viscosity and shear rate, applicable only to the linear portion of the curve.

Note: a) This process is applied for calibration of any spindle used in coaxial rheometer.
b) The conversion from rpm to rad/s requires multiplication by 2π/60.

5.4 Experimental Results

Rheological data represented in the form of flow curves were obtained for three different spindles, as mentioned in Section 4.1. The flow curves portray the flow behavior of the material as a simple continuum fluid without needing to regard the existence of the complex inter-particle flow [10]. The flow curves are useful representations because they help compare the flow behavior of two different materials, or two different spindles, so long as the testing shear rates are similar. In addition, flow curve data is typically represented by the data acquired during the downward ramp (decreasing shear rate) which is why the protocol contains more steps for the down ramp compared to the up ramp, see protocol in Section 4.2. Therefore, flow curve comparisons will use only down curve data in the rest of this report. These results were expected to match the behavior from the simulation models described in Section 3.

As explained in the rheometer calibration process in Section 4.3 for the reference curves developed in this report, testing requires that the SRM paste (0 % beads) be tested when introducing a new spindle geometry. Therefore, every batch used for SRM mortar testing was divided into two containers prior to testing on the rheometer. In doing so, half the batch is used to complete the required calibration step where the operator performs the test on the SRM paste (0 % beads). Since this step is required for data calibration, the calibrated 0 % values for any new geometry is expected to match the SRM 2492 certified values using a parallel plate.

As stated in Section 4.2, half of the mixtures analyzed during this study represent a concentrated mortar composition of 40 % monosized beads by volume. Half of the batches were used to analyze a concentrated mortar composition of 20 % beads by volume. After the calibration step was taken, the same testing procedure was conducted on both the 20 % and 40 % mortars.

Then two processes were applied to the raw data of torque and rotational velocity to convert the data into fundamental units: either by using the Bingham approximation (Section 4.4.1) or by rescaling the viscosity curves (Section 4.4.2) as described in the calibration Section 5.3.

5.4.1 Bingham Parameters

As mentioned in Section 4.3, the calibration factors are calculated in order to convert the rheometer's raw data into fundamental rheological units. A different calibration factor is calculated for each test since each set of tests data is independent of the other tests. The three calibration factors (K_γ, K_τ, K_μ) were calculated for each mixture, and were found not to change with the beads concentration. Thus, they were averaged to represent the geometry being used (Table 9), along with the standard uncertainty, calculated from one standard deviation of all the values obtained. The calculation of such factors are produced when testing the SRM paste without beads. The table shows the calibration factors operators could use to calibrate their experimental data if using the same exact spindles as were used in this study.

The resulting flow curves of the calibrated data for both mortar types and the paste without beads (0 %) can be found in Figure 13 to Figure 16. The figures compare the results of the 0 % paste (Figure 13) to the certified SRM 2492 values, as well as the changes in the flow curve behavior when 20 % or 40 % beads by volume are added to the paste. As shown, the 20 % and 40

% mortars increase the viscosity of the mixtures, as expected when increasing the concentration of particles in a suspended fluid. The flow curves shown in Figure 13 track each other closely, within the uncertainity of the measurements, providing confidence in the calibration process of the SRM 2493 mortars.

The torque and rotational speed, obtained from the set of raw data in this study showed that the SRM 2493 materials acted like Bingham materials. Bingham materials are known for having a linear shear stress vs. shear rate relationship, which makes the Bingham parameters, yield stress and plastic viscosity, simple to calculate, where the plastic viscosity is the slope of the linear relationship and the yield stress is its y-intercept. The similarity in behavior found in the raw data encouraged the calculation of a “yield stress” and “plastic viscosity” based on the torque vs. rotational speed relationship. These values were calculated for all three spindles discussed in this study at 0 %, 20 % and 40 % bead concentrations and are summarized in Table 12.

The accuracy of this calibration process is shown in Figure 13**,** which compares the calibrated data after testing SRM paste (no beads) with the three spindles observed in this study. As shown, using any of the three spindles allows the experimental curves to be shifted on top of the certified SRM 2492 values (shown in black) especially in the range of equal shear rates. Equal shear rates refer to those that were applied during the SRM 2492 certification testing. A larger range of shear rates was used in this study to observe the behavior at lower shear rates.

Table 11: Calibration factors for experimental data of each spindle tested in this study.

	Data Calibration Factors		
	Serrated Coaxial Cylinder	Six Blade Vane	Double Spiral
Kτ [Pa/N·m]	**29951.7**	**28470.5**	**11,540.5**
Std. Unc.	*927.8*	*657.7*	*282.4*
Kγ [-]	**2.66**	**2.29**	**3.63**
Std. Unc.	*0.16*	*0.11*	*0.19*
Kμ [Pa·s/N·m·s]	**11,307.6**	**12,485.0**	**3,185.2**
Std. Unc.	*574.4*	*555.3*	*146.9*

Table 12: Plastic viscosity and yield stress at 0 %, 20 % and 40 % bead volume concentrations for all three spindles. See *Section 7.1* for standard uncertainties. Note that the values for 0% are all identical as all curves were calibrated against the 0 % data of SRM 2492.

		Bingham Parameters			
		Plastic Viscosity, μ_B [Pa·s]		Yield Stress, τ_0 [Pa]	
		value	Std. uncertainty	value	Std. uncertainty
Double Spiral	*0%*	7.7	0.4	25.6	0.8
	20%	14.3	0.7	37.2	1.4
	40%	30.4	3.1	80.7	3.9
6 Blade Vane	*0%*	7.7	0.6	25.6	1.3
	20%	13.8	1.3	35.9	1.4
	40%	27.2	2.1	63.4	5.0
Serr. Coaxial Cylinder	*0%*	7.7	0.6	25.6	0.8
	20%	13.2	0.9	38.2	1.8
	40%	22.8	1.7	69.2	4.9

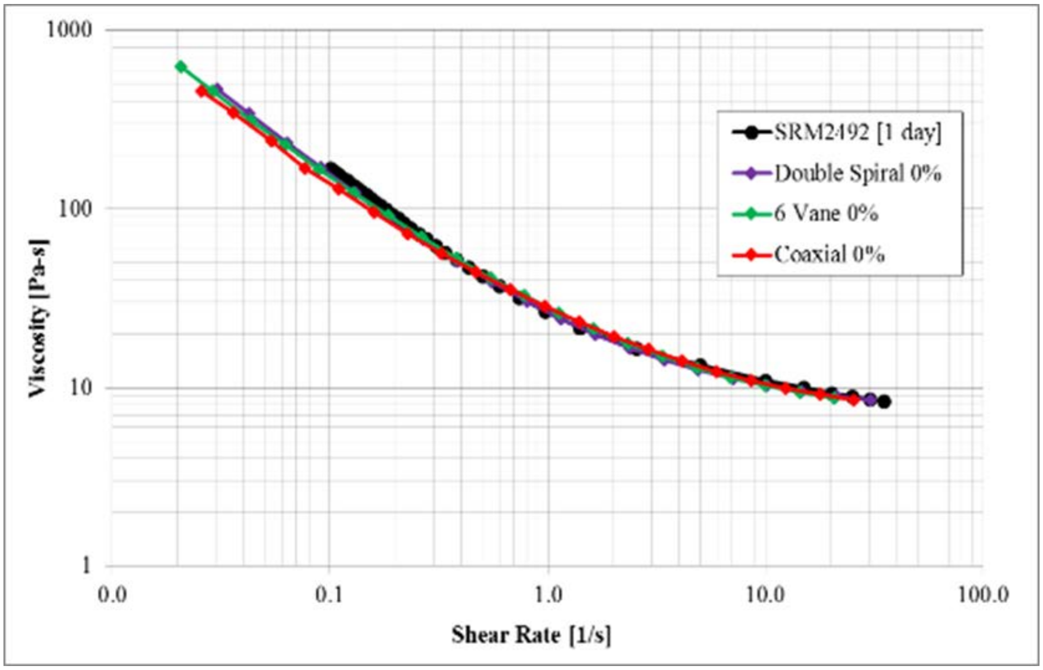


Figure 13: Flow curve comparison of the calibrated experimental data for SRM 2492 paste (0% beads) for all three spindles. The flow curves are compared to their reference curve shown in black, SRM2492 certified values. Uncertainities are analyzed in Section 6.

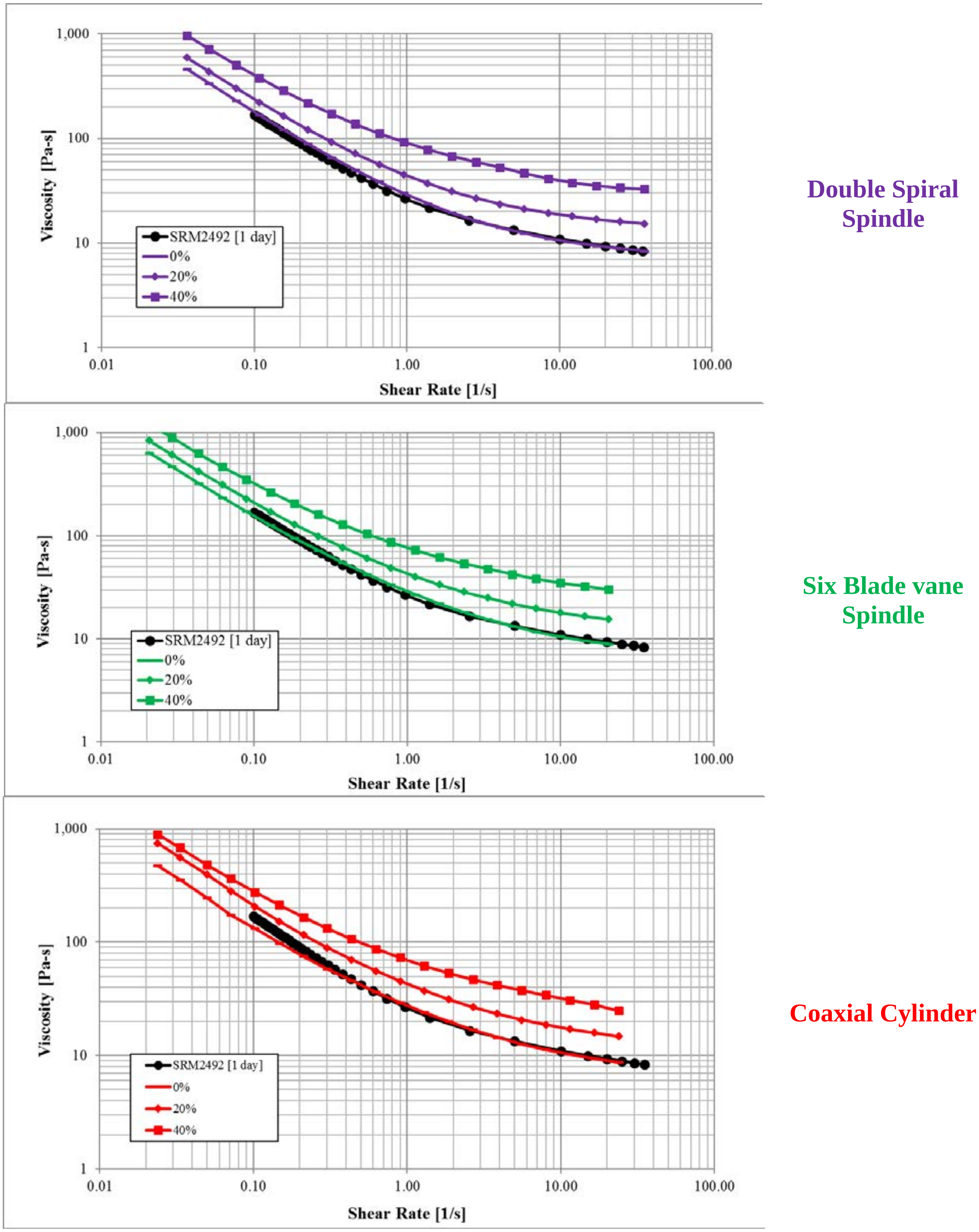


Figure 14: Calibrated, by Bingham parameters, experimental flow curves for different geometries of spindles at bead volume concentrations of 0 %, 20 % and 40 %. The 0 % curve (black) represents the certified SRM2492 flow curve values. Uncertainities are analyzed in Section 7.

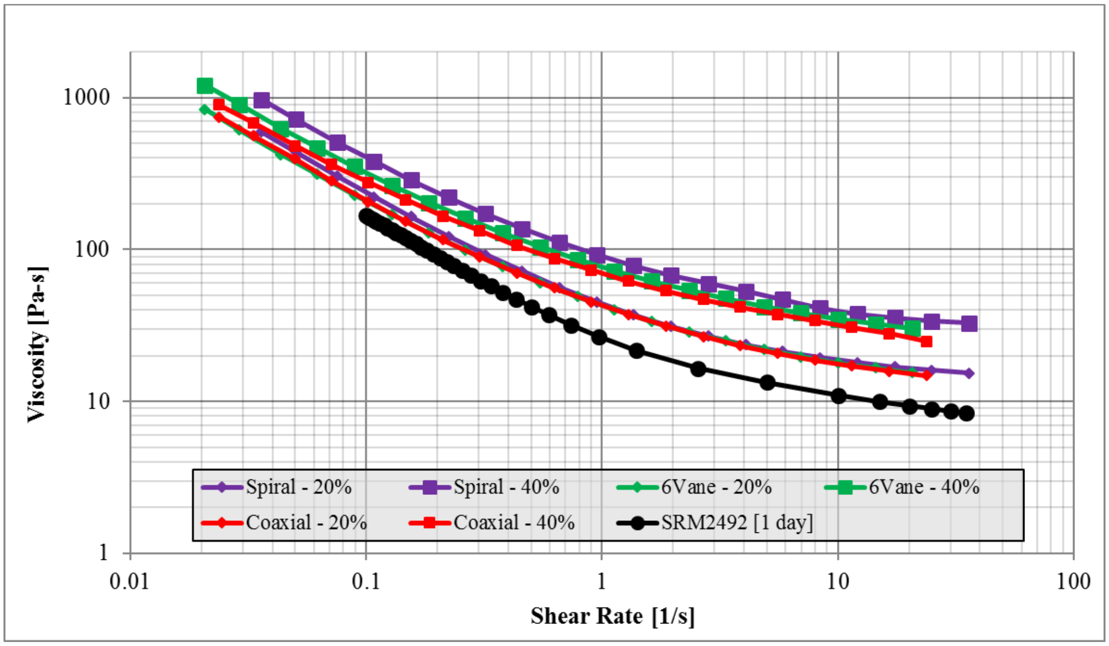


Figure 15: Viscosity curve at concentrations of 20 % and 40 % by volume of glass beads. The uncertainty is estimated to be 10 % of the viscosity. The 0 % curves are omitted for clarity. Full discussion of the uncertainties can be found in Section 6.

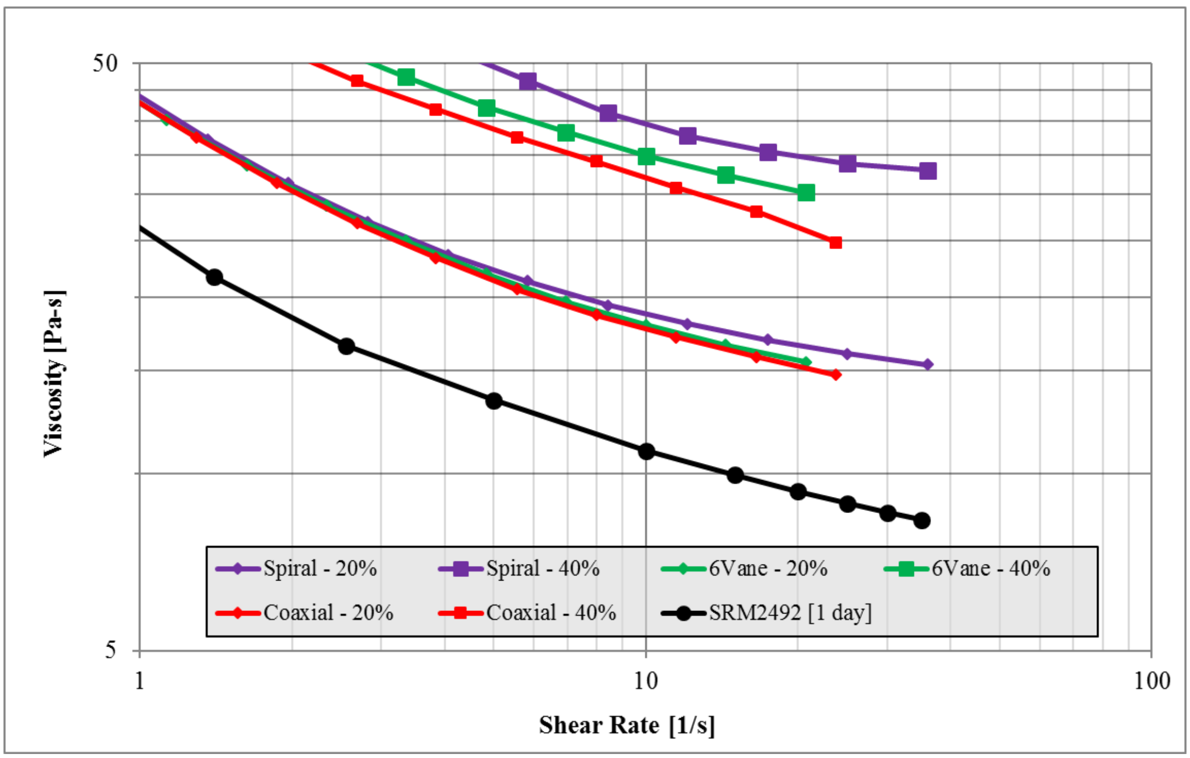


Figure 16: An enlargement of Figure 15 for the higher shear rates to better show the difference in viscosity depending on the spindle used. The 0 % curves are omitted for clarity. Full discussion of the uncertainties can be found in Section 6.

5.4.2 Viscosity Curves Method

As mentioned in Section 4.3 the calibration factors are calculated in order to convert the rheometer's raw data into fundamental rheological units. The three calibration factors (L_γ, L_τ, L_μ) were calculated by rescaling the measured curves of the paste (0 % beads) to the reference curve found for SRM 2492. The values obtained are shown in Table 13, along with the standard uncertainty. These L factors could be used to calibrate new experimental data if using the exact spindles as in this study. Uncertainty in the L factors was estimated using the method as described in Section 6.1.3 for the coefficients of Equation 1. This means that the L factor values were produced by a ordinary least squares procedure (OLS) and also by a Bayesian hierarchical model (BHM). The uncertainties are square roots of sums of squared uncertainties of the BHM and the squared bias.

The resulting flow curves of the calibrated data for both mortar types and the paste without beads (0 %) can be found in Figure 17. Figure 18 compares the results of the 0 % paste to the certified SRM2492 values, as well as the changes in the flow curve behavior when 20 % or 40 % beads by volume are added to the paste. As expected again, the 20 % and 40 % mortars increase the viscosity of the mixtures. The calibrated data that compose the viscosity curves can be found Table 36 to Table 38**.** The agreement of the flow curves shown in Figure 19 with each other provided reliability in the calibration process which was enacted on the study subjects, the SRM mortars, when compared with the SRM 2492 as measured using a parallel plate rheometer. Figure 18 shows all the curves in one graph. It highlights the higher viscosity measured using the spiral spindle compared with the vane or coaxial spindles.

Table 13: Calibration factors for experimental data of each spindle tested in this study.

	Data Calibration Factors based on		
	Serrated Coaxial Cylinder	Six Blade Vane	Double Spiral
Lτ [Pa/N·m]	**32,000**	**26,000**	**9,700**
Std. Unc.	*6,280*	*4,970*	*1,050*
Lγ [-]	**3.24**	**2.28**	**3.09**
Std. Unc.	*0.56*	*0.42*	*0.26*
Lμ [Pa·s/N·m·s]	**9,718**	**11,419**	**3,145**
Std. Unc.	*954*	*558*	*214*

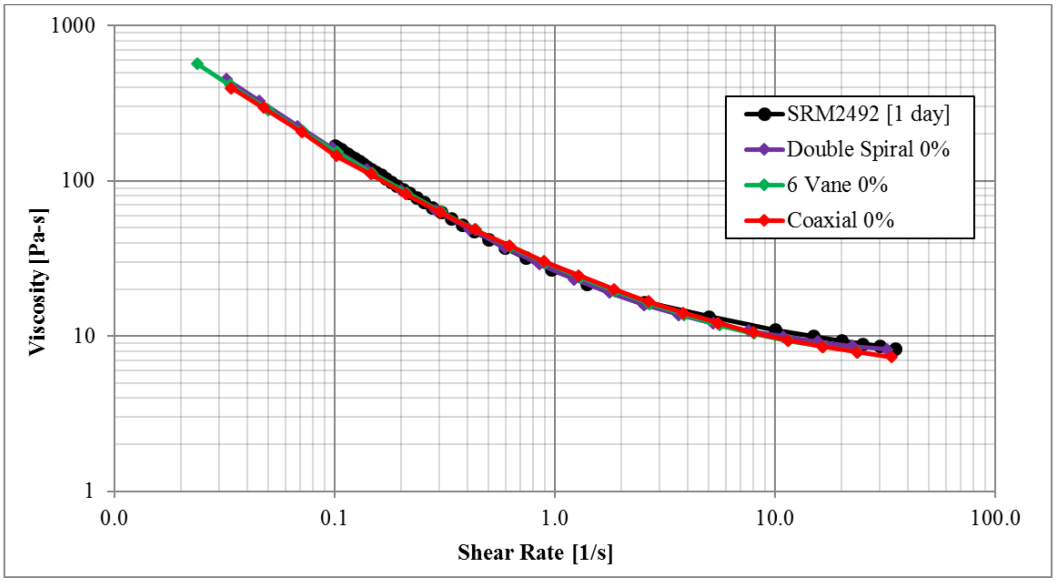


Figure 17: Flow curve comparison of the calibrated experimental data for SRM 2492 paste (0% beads) for all three spindles. The flow curves are compared to their reference curve shown in black, SRM2492 certified values, using the L factors shown in Table 11. Uncertainities are analyzed in Section 6.

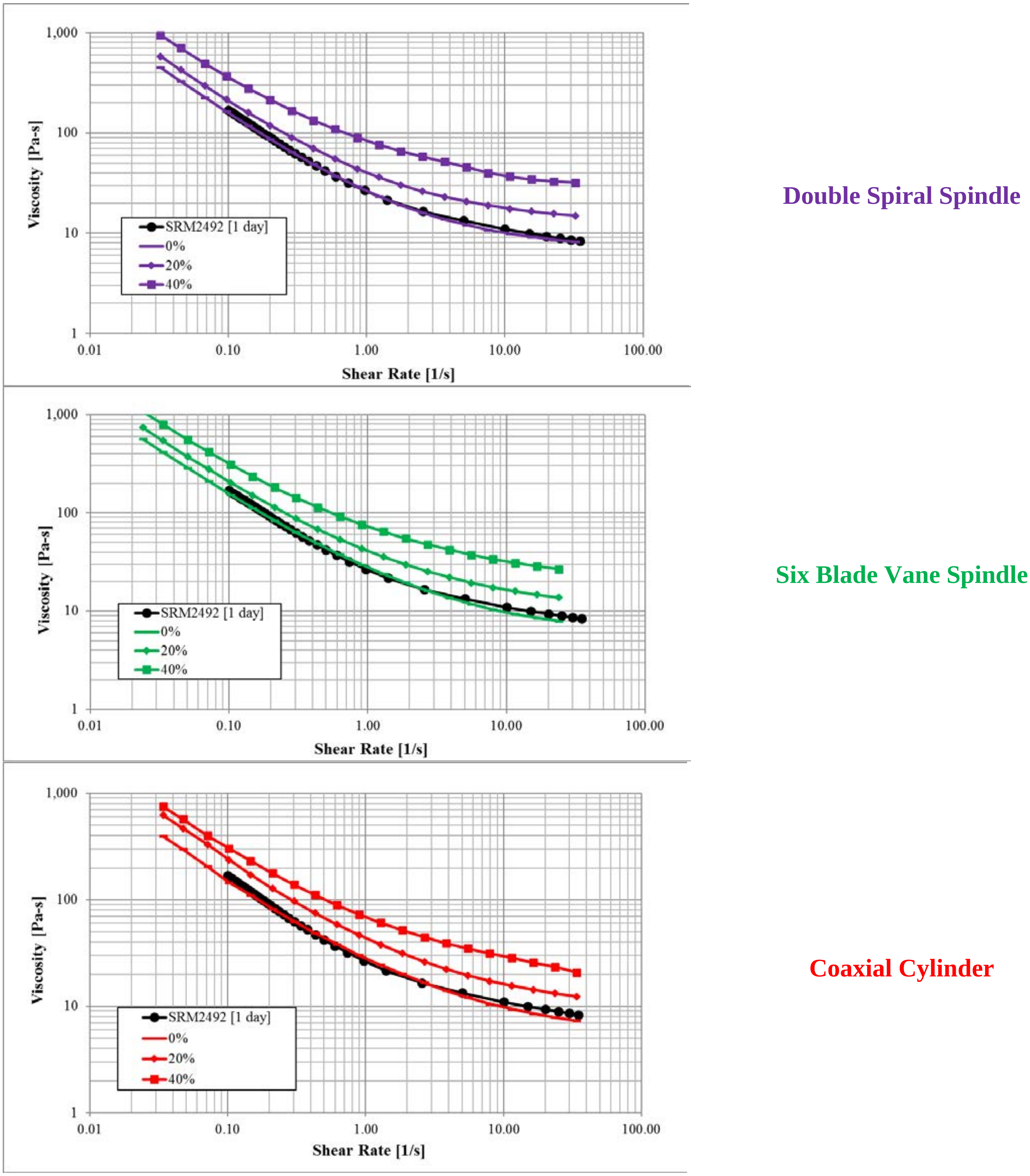


Figure 18: Calibrated, by viscosity curve method, experimental flow curves for each spindle at bead volume concentrations of 0 %, 20 % and 40 %. The 0 % curve (black) represents the certified SRM2492 flow curve values. Uncertainities are analyzed in Section 6.

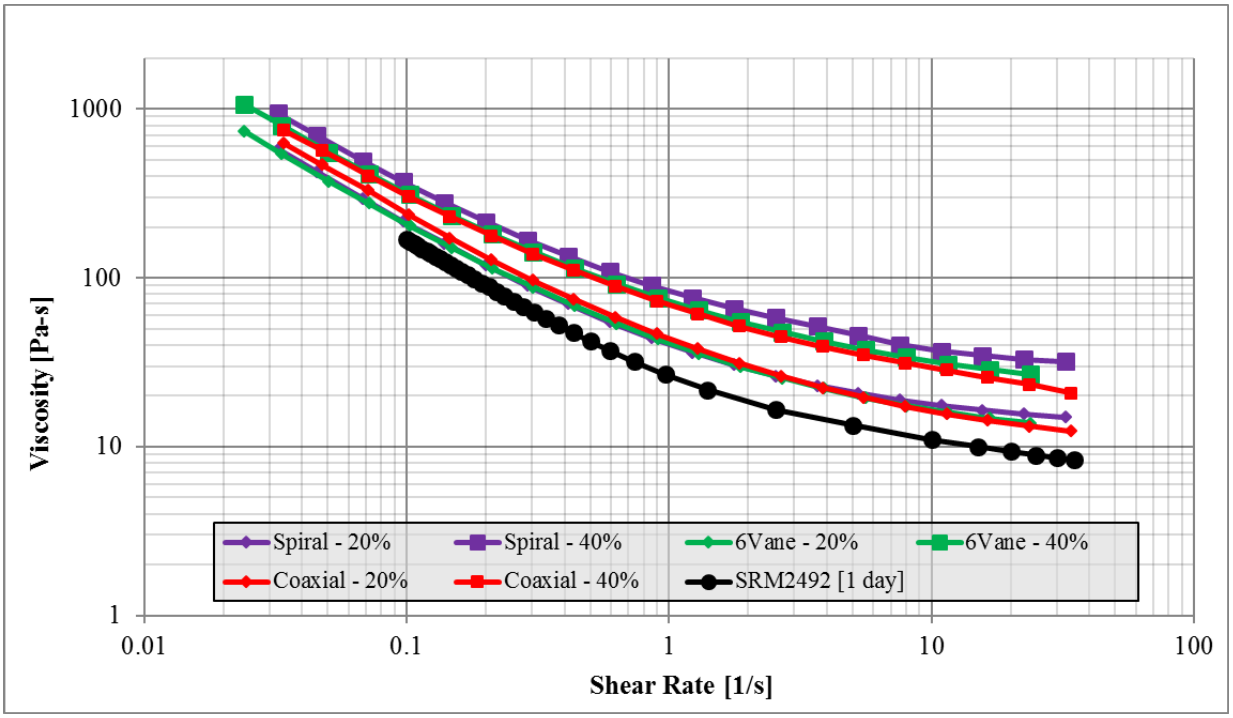


Figure 19: Viscosity curve at concentrations of 20 % and 40 % by volume of glass beads. The uncertainty is estimated to be 10 % of the viscosity. Full discussion on the uncertainties can be found in Section 7.

5.4.3 Comparison of Two Calibration Methods: Bingham or Viscosity Curves Fit

It is important to check how much the choice of either method of calibration influences the results obtained. As all the data were first calibrated on the SRM 2492 (paste or 0% beads), the fit there should be optimal as shown in Figure 13 and Figure 17. The differences should be more evident on the mixtures of 20 % and 40 % beads concentration. Figure 20 show the curves for each of the spindles used and calculated using either the K (Bingham method) or the L factors (viscosity fit). The visual differences from the figures are clearly small. To quantify the differences Table 14 was prepared. It is clear that the differences between the two methods are within the uncertainity of the measurements, or less than 10 % of the viscosity values. Thus the two methods are considered equivalent. The advantage of the Bingham method is that it also produces the yield stress, while the viscosity fit does not.

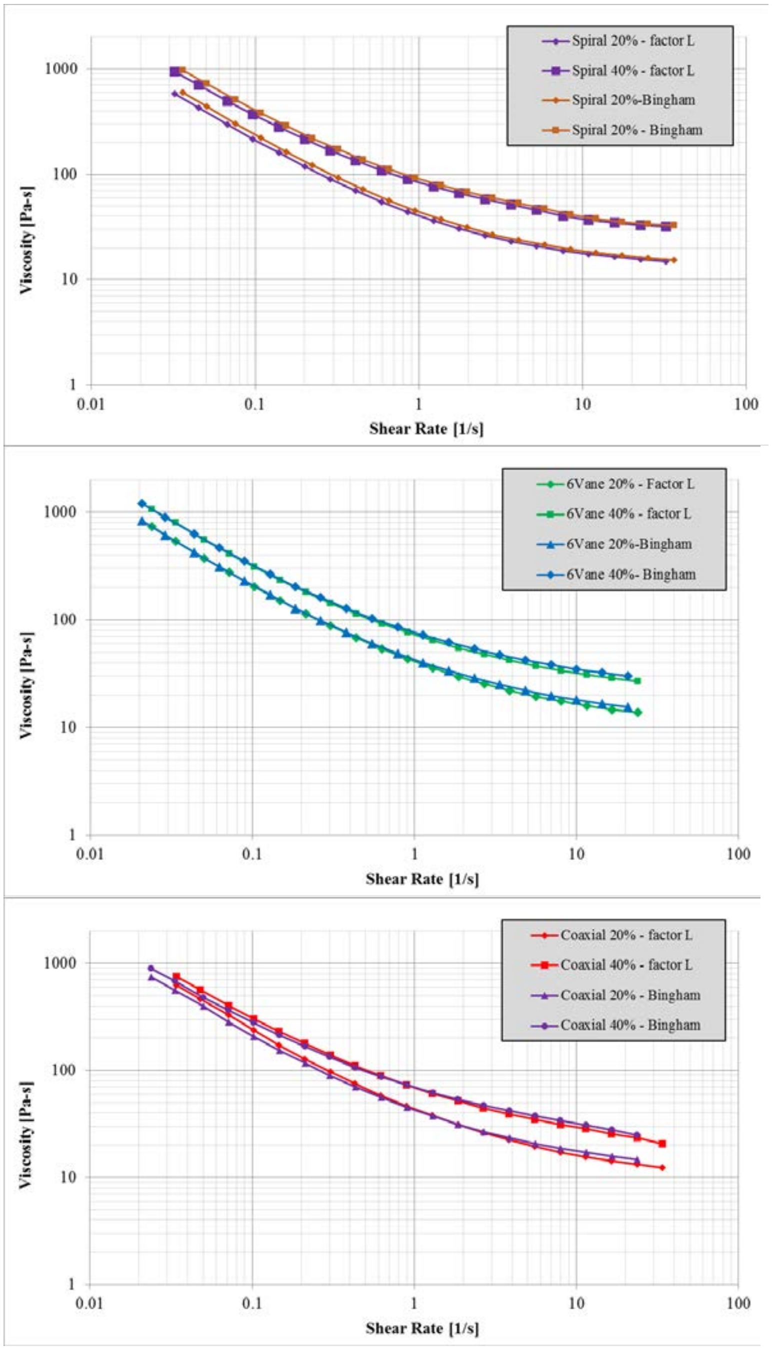


Figure 20: Graphic comparison between the curves obtained by Bingham (K factors) or by the viscosity curves (L factors). Uncertainities are analyzed in Section 6.

Table 14: The differences between viscosity calculated using Bingham equation and viscosity fits are shown for three shear rates. The differences was calculated by (Values by Bingham – Value by viscosity fit). The uncertainity is estimated to be less than 10 % of the measured viscosity.

	Volume fraction of glass beads	Viscosity Difference [Pa·s]			
		0.1 s^{-1}	1 s^{-1}	20 s^{-1}	
Double Spiral	**0%**	20.1	2.3	0.4	Pa.s
	20%	25.8	3.3	0.7	Pa.s
	40%	41.1	6.1	1.4	Pa.s
6 Blade Vane	**0%**	6.9	1.1	0.7	Pa.s
	20%	9.9	1.9	1.3	Pa.s
	40%	16.0	4.1	2.4	Pa.s
Coaxial Cylinder	**0%**	-12.2	-0.7	0.9	Pa.s
	20%	-30.6	-1.0	1.6	Pa.s
	40%	-26.2	0.5	1.9	Pa.s

Another concept that should be introduced now to compare the various methods is the relative viscosity (μ_R). The definition of the relative viscosity is the ratio of the viscosity of a mortar (with beads) to the viscosity of the paste at the same shear rate. Table 15 and Table 16 show the calculated relative viscosities at selected shear rates. Table 15 used the data calibrated using the Bingham method, while Table 16 used the data from the viscosity fit. Figure 21 shows the data from Table 15. Only the data from Table 15 is represented for clarity of the figure, as it can be seen from the two tables that the difference between the two methods is very small: the highest difference is 0.2 within the uncertainty. It can be seen that for 20 % mortar, the relative viscosity is within the uncertainty for all the spindles used. On the other hand for the 40 % mortar, a wide spread occurs with the spiral having always the highest relative viscosity. In Section 6, an attempted explanation for this difference will be offered.

Table 15: Relative viscosity (μ_R) values based on the calibrated experimental data at concentrations of 20 % and 40 % by volume, labeled μ_{R20} and μ_{R40}, respectively. These were calculated using the Bingham method of conversion.

		Shear Rate [1/s]		
		0.1	1	20
Double Spiral	μ_{R20}	**1.3**	**1.6**	**1.8**
	Std. Unc.	*0.04*	*0.06*	*0.09*
	μ_{R40}	**2.3**	**3.3**	**3.8**
	Std. Unc.	*0.12*	*0.21*	*0.34*
6 Blade Vane	μ_{R20}	**1.3**	**1.5**	**1.7**
	Std. Unc.	*0.03*	*0.03*	*0.05*
	μ_{R40}	**2.0**	**2.7**	**3.4**
	Std. Unc.	*0.11*	*0.17*	*0.24*
Coaxial Cylinder	μ_{R20}	**1.6**	**1.5**	**1.7**
	Std. Unc.	*0.08*	*0.06*	*0.08*
	μ_{R40}	**2.1**	**2.5**	**2.8**
	Std. Unc.	*0.10*	*0.10*	*0.19*
Model	μ_{R20}	**1.3**	**1.5**	**1.7**
	μ_{R40}	**2.0**	**3.8**	**6.1**

Std. Unc. = Standard Uncertatinty
(multiply by 1.96 to obtain expanded values)

Table 16: Relative viscosity (μ_R) values based on the calibrated experimental data at concentrations of 20 % and 40 % by volume, labeled μ_{R20} and μ_{R40}, respectively. These are calculated using the viscosity curve approach.

		Shear Rate [1/s]		
		0.1	1	20
Double Spiral	μ_{R20}	**1.3**	**1.5**	**1.8**
	Std. Unc.	*0.04*	*0.06*	*0.09*
	μ_{R40}	**2.3**	**3.2**	**3.8**
	Std. Unc.	*0.12*	*0.21*	*0.34*
6 Blade Vane	μ_{R20}	**1.3**	**1.5**	**1.7**
	Std. Unc.	*0.03*	*0.03*	*0.05*
	μ_{R40}	**2.0**	**2.7**	**3.4**
	Std. Unc.	*0.11*	*0.17*	*0.24*
Coaxial Cylinder	μ_{R20}	**1.6**	**1.5**	**1.7**
	Std. Unc.	*0.08*	*0.06*	*0.08*
	μ_{R40}	**2.1**	**2.4**	**3.0**
	Std. Unc.	*0.10*	*0.10*	*0.19*

Std. Unc. = Standard Uncertainty
(multiply by 1.96 to obtain the expanded value)

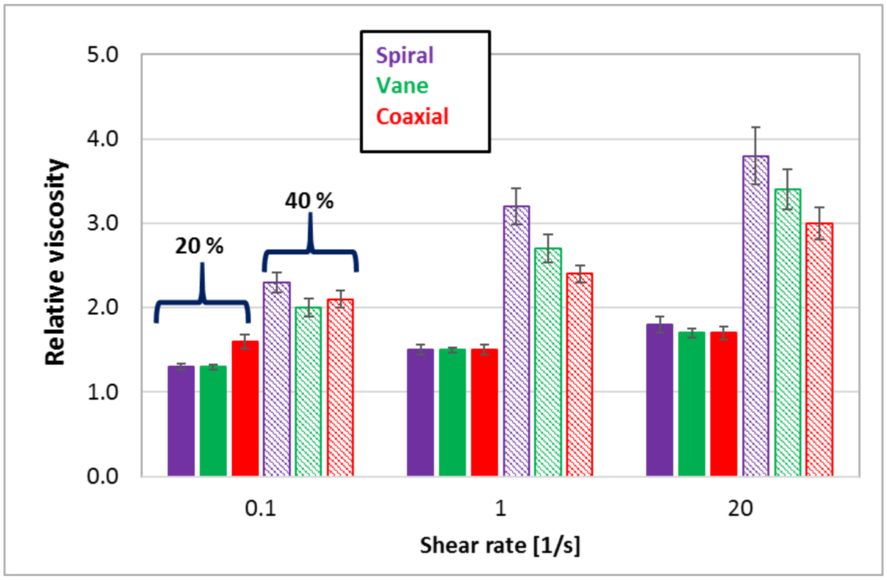


Figure 21: Graphical representation of the data in Table 15 representing the relative viscosity as a function of the beads volume concentration and the spindle used. The uncertainity is as listed in the Tables 15.

6 Comparison Between Model and Experimental

Figure 22 shows the average curves for all type of spindles and concentrations used in this study. The three spindel geometries (see Section 5.1) used on a mortar reference material (SRM2493) of 20 % and 40% volume concentrations are shown. In Figure 23, the model results (see Section 0) were added to the data from Figure 22. The graphs compare all the experimental viscosity curves to the certified SRM2492 curve (black), which is the reference baseline for this study. The difference in viscosities between the baseline and any other viscosity curve of interest is considered the relative viscosity (μR), as stated above. The relative viscosity is a factor that represents the effects on viscous behavior of a material caused by using different rheometers geometries and the addition of beads to the matrix (i.e. bead concentration).

As shown previously (Section 5.3), the viscosity depends on the spindle used for performing the rheological measurement. For 40 % beads concentration the model values are higher than the measured one. The different rheometer spindles vary in effectiveness of shearing. This effectiveness can be correlated to how well the shearing walls are actually able to grasp the material and shear it without slippage. Any slippage (non-effective shearing) results in lower readings of viscosity. This issue is more evident at higher bead concentrations, which is shown when comparing the 40 % curves with the SRM 2492 paste (shown in black) in Figure 22 or Figure 23.

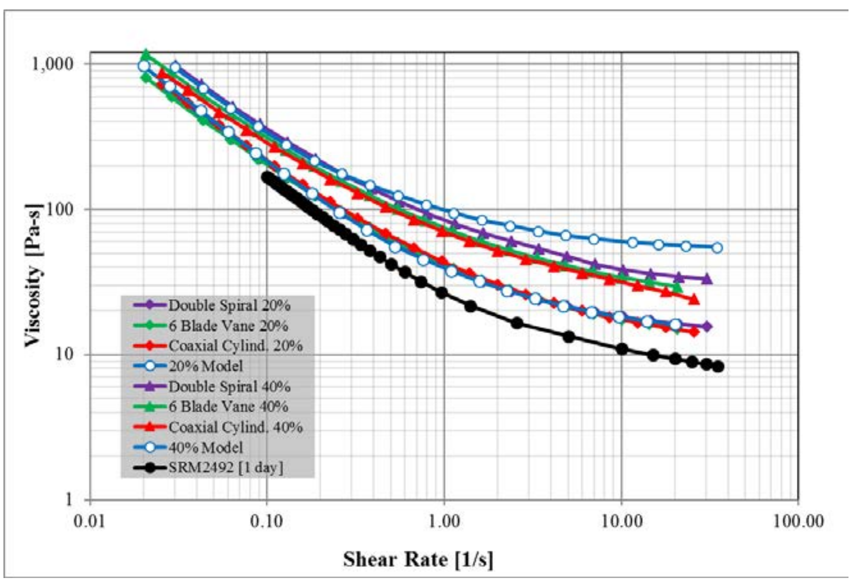
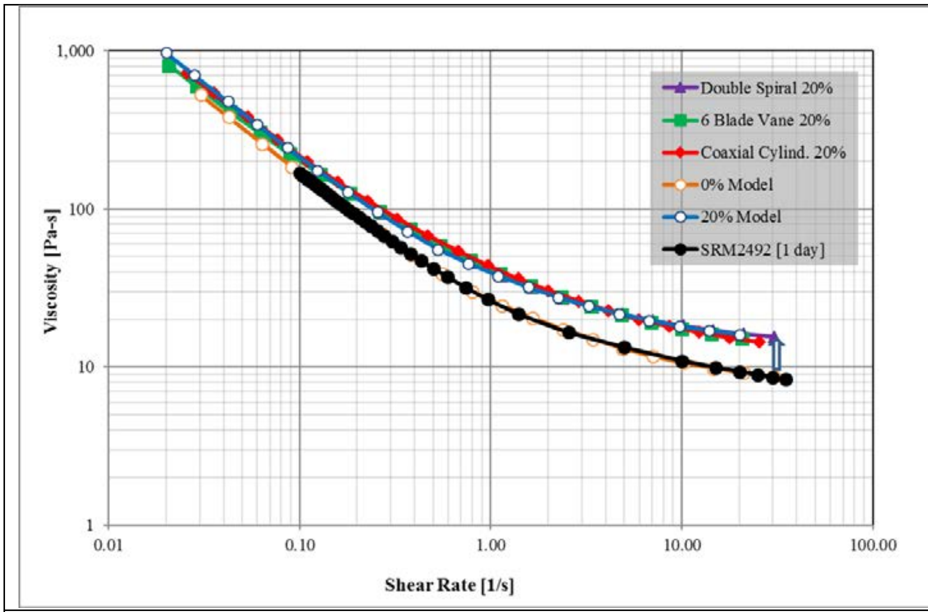
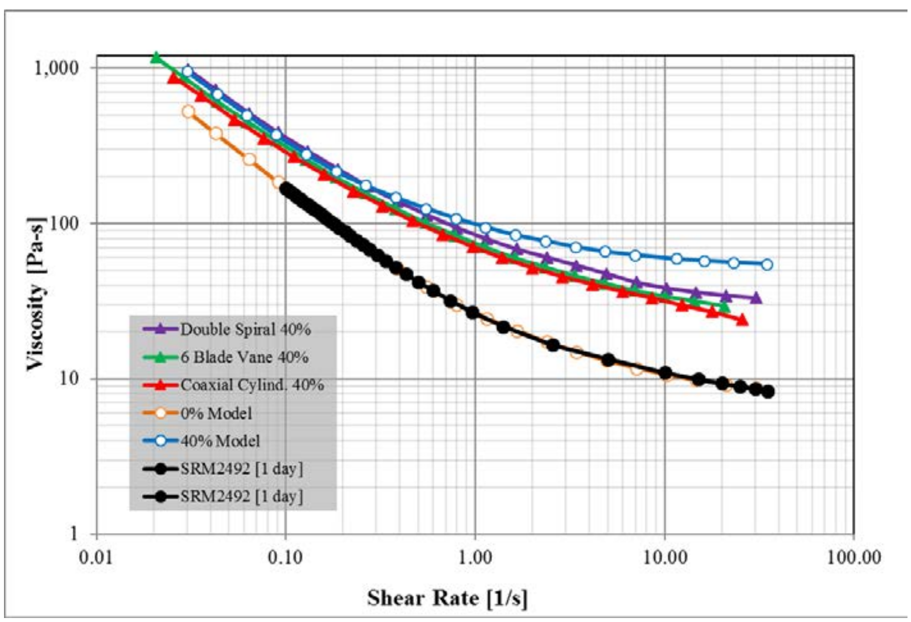


Figure 22: Viscosity vs. shear rate (using the Viscosity fit method) for all data collected including the scaled prediction values determined from the numerical simulation model. The 0% data for the measurements were omitted for clarity. The uncertainties are discussed in Section 6.



A)
20 % mortar



B)
40 % mortar

Figure 23: Comparison of model vs experimental viscosity curves (obtained using the viscosity fit method) for A) 20 % and B) 40% glass beads volume fraction mortar mixture. Relative viscosity, μ_R, was modeled with respect to the SRM 2492 (1 day) baseline curve at 20 s^{-1}. The uncertainties are discussed in Section 6.

Table 17: Relative viscosity (μ_R) values for the scaled prediction numerical model. Standard uncertainties are estimated at 10 %.

		Shear Rate [1/s]		
		0.1	1	20
Model	μ_{R20}	**1.3**	**1.5**	**1.7**
	μ_{R40}	**2.0**	**3.8**	**6.1**

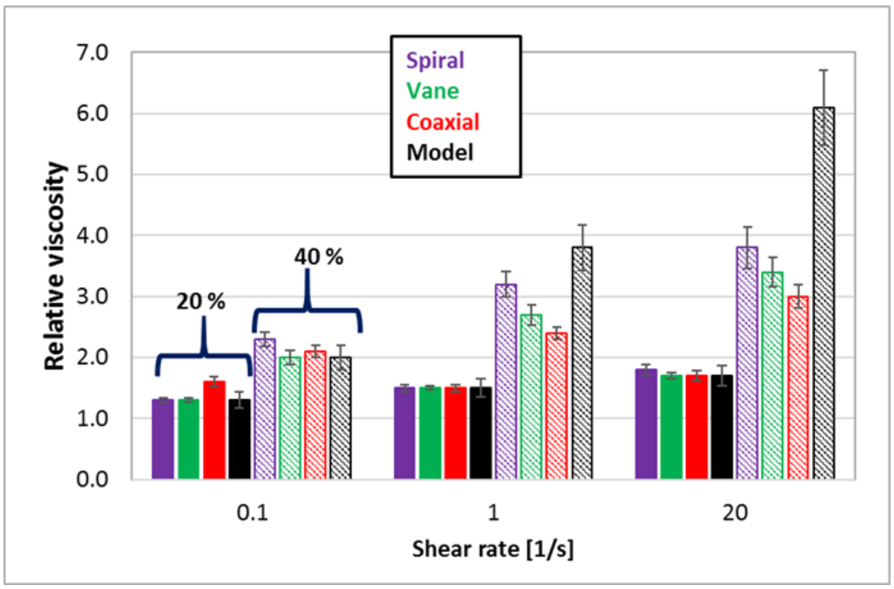


Figure 24: Graphic representation of the relative viscosity from Table 15 and Table 16, with the values for the model added. The uncertainities are also from these two tables with the model assigned an uncertainity of 10 %

The relative viscosity for all spindle/material combinations are displayed in Table 15, Table 16 and Table 17 at three shear rates and represented graphically in The three shear rates were selected to portray the relative viscosity at low, medium and high measured shear rates. It is evident from these tables and Figure 24 that major differences in μ_R values are caused by two factors: shear rate and bead concentration. First, when the mortar tested has a high volume fraction of glass beads (40 %) the relative viscosity (μ_{R40}) differs greatly depending on the spindle used and the model; however, when testing the 20 % mortar the relative viscosities (μ_{R20}) don't differ nearly as much (see discussion below). The second noticeable trend is caused by the shear rate, at high shear rates major differences also exist based on the spindle used, yet at low shear rates the relative viscosities are identical regardless of spindle.

The model is, ideally, a prediction for the experimental results, but experimental results and theory don't always match perfectly. Figure 23*a* portrays the 20 % predicted (computer modeled) viscosity curve and its relative viscosity (μ_R) in order to compare with the experimental relative viscosities discussed formerly. Similarly, the 40 % curves are shown in Figure 23*b*. The relative viscosities at the high shear rates are good comparison points for a quantitative analysis between experimental vs. model curves. However, Table 16 and Table 17 display the μ_R at low, medium and high shear rates for the experimental and compares them to the predicted μ_R values from the model. As shown, the model predicted the viscosity to be higher than the resulting experimental data for all three spindles types, with the difference more evident for μ_{R40} than μ_{R20}. It should be noted that once again, a trend exists between the three types of spindle which highlights the double spiral being the most accurate when compared to the prediction model at high shear rates and 40 % beads. High shear, 40% conditions are the least accurate for the serrated coaxial cylinder. The reason for the model and experimental relative viscosity discrepancy is possibly due to several possible explanations, which can be present in experiments but are not present in the model:

- Slippage of the material on the spindle or the cup. The spiral tool provides a higher connection between the material and the spindle thus has a higher torque or shear stress than measured with the other spindles at the same shear rate.
- The model is an ideal couette flow with no walls and no changes in the material composition, while the experimental measurement could have also particle migration away from the spindle and also vertically on the open surface.
- The open surface at the top allows material to dilate and thus create an artificial reduction in particle concentration that would tend to reduce the viscosity.

More detailed analysis of the discrepancies between the model and the experimental data are provided in Ref. [17].

7 Statistical Analysis

7.1 Flow Curves

7.1.1 Uncertainty Calculation

As stated above, for each of the three spindles: double spiral, 6 blade vane and serrated coaxial cylinder, and different bead volume fractions, 0 %, 20 % and 40 %, five different batches (See Section 5.2) were measured for torque Γ [μNm] at 35 different rotational speed N [1/min]. The shear rate increased from 0.1 to 100 [1/min] and then decreased back down to 0.1.

The five mixtures were treated as independent replicates of the flow curves for each geometry and bead volume fraction. Only the "down curve" data was used, that is, the torques for the 20 shear rates starting at 100 s^{-1} and decreasing to 0.1 s^{-1}. For 0 % beads the curves were computed individually for 0 % pre 20 % and 0 % pre 40 % and also combined. Pre 20 % or pre 40 % represent the paste measured before the beads were added in the volume concentration indicated. They represent repeats of paste measurements (see Section 4.2).

For each of the shear rates, a consensus torque was computed together with an uncertainty value using the model

$$\Gamma_{ij} = \theta_i + \varepsilon_{ij}, i = 1, \ldots, 20, j = 1, \ldots, 5 \qquad [17]$$

where θ_i were the consensus torque values for the 5 replicates.

Estimation was performed via Markov Chain Monte Carlo methods [14] (which require prior distributions on the parameters of the model) with

$$\theta_i \sim N(0, 1.0E5), \varepsilon_{ij} \sim N\left(0, \sigma_i^2\right), \sigma_i^2 \sim Gamma(1.0E5, 1.0E5), i = 1, \ldots, 20\ . \qquad [18]$$

The computations were done using the software OpenBUGS [15] using the code given in Section 6.4. The posterior mean, standard deviation, and 95 % highest posterior density interval at each shear rate were used for the estimate (Γ), standard ($u(\Gamma)$) and expanded uncertainty. These estimates were very stable with respect to the Gaussian and Gamma distributions of the parameters. The following tables contain the results.

Table 18: Torque and rotational speed with the calculated uncertainity for the double Spiral spindle with 0 % beads

	0 % pre 40 %				**0 % pre 20 %**				**0 % combined**		
N 1/min	Γ μNm	U(Γ) μNm	expanded U(Γ)		Γ μNm	U(Γ) μNm	expanded U(Γ)		Γ μNm	U(Γ) μNm	expanded U(Γ)
100	26920.36	781.44	1531.63		27766.15	1194.69	2341.59		27347.39	525.87	1030.71
69.5	19691.11	516.52	1012.39		20292.41	787.99	1544.47		19997.13	383.05	750.78
48.3	14570.1	389.66	763.73		15024.64	607.37	1190.45		14789.76	279.16	547.15
33.6	10903.95	282.69	554.07		11252.44	438.87	860.19		11068.28	213.07	417.62
23.4	8296.96	217.09	425.49		8546.34	337.43	661.35		8420.6	156.62	306.9
16.2	6428.55	159.78	313.17		6612.42	243.16	476.60		6522.95	118.41	232.06
11.3	5085.59	123.58	242.22		5228.63	185.78	364.12		5159.47	90.9	178.16
7.85	4121.02	101.99	199.89		4229.29	148.83	291.70		4174.73	72.55	142.20
5.45	3417.81	86.5	169.53		3502.89	120.90	236.96		3461.13	56.69	111.11
3.79	2908.17	71.35	139.83		2978.17	95.00	186.21		2943.22	46.99	92.10
2.64	2534.37	61.8	121.11		2590.92	81.59	159.91		2561.62	39.82	78.05
1.83	2257.35	55.33	108.43		2304.34	69.47	136.16		2280.26	34.1	66.84
1.27	2048.01	50.13	98.25		2090.88	60.53	118.65		2070.09	30.53	59.84
0.89	1891.55	46.73	91.59		1931.35	56.21	110.16		1911.94	28.62	56.09
0.62	1772.84	41.09	80.53		1808.58	48.53	95.11		1789.91	25.03	49.06
0.43	1687.08	41.19	80.71		1718.48	44.04	86.33		1702.75	23.15	45.38
0.3	1614.25	40.21	78.80		1647.44	43.07	84.43		1631.25	22.83	44.75
0.21	1558.58	40.73	79.83		1591.92	41.27	80.88		1575.38	21.78	42.7
0.14	1515.53	37.03	72.59		1546.64	40.82	80.02		1531.65	21.86	42.9
0.1	1481.95	39.03	76.49		1511.95	43.28	84.83		1496.99	20.97	41.11

Table 19: Torque and rotational speed with the calculated uncertainity for the double Spiral spindle with 20 % beads

N 1/min	Γ μNm	U(Γ) μNm	expanded U(Γ)
100	49833.47	2318.27	4543.82
69.5	36132.02	1606.74	3149.21
48.3	26493.03	1174.34	2301.70
33.6	19615.71	861.06	1687.67
23.4	14721.38	642.11	1258.54
16.2	11191.44	453.54	888.94
11.3	8661.45	341.25	668.86
7.85	6840.30	265.94	521.24
5.45	5526.94	204.34	400.51
3.79	4570.18	158.89	311.42
2.64	3865.92	129.02	252.89
1.83	3351.13	106.17	208.10
1.27	2963.43	89.93	176.26
0.89	2674.21	79.32	155.47
0.62	2456.19	68.63	134.51
0.43	2286.19	61.16	119.87
0.3	2161	57.11	111.94
0.21	2064.17	53.30	104.46
0.14	1987.19	50.42	98.82
0.1	1931.65	53.27	104.41

Table 20: Torque and rotational speed with the calculated uncertainity for the double Spiral spindle with 40 % beads

N 1/min	Γ μNm	U(Γ) μNm	expanded U(Γ)
100	106683	9561.52	18740.58
69.5	76155.25	6656.63	13046.99
48.3	55491.24	4734.68	9279.97
33.6	41062.72	3314.46	6496.33
23.4	31257.54	2036.05	3990.67
16.2	24606.85	1205.36	2362.50
11.3	19427.01	1094.86	2145.93
7.85	15158.49	996.95	1954.02
5.45	11973.31	788.09	1544.65
3.79	9621.73	614.26	1203.95
2.64	7915.19	502.65	985.19
1.83	6631.62	414.27	811.97
1.27	5665.15	330.41	647.59
0.89	4954.07	277.95	544.77
0.62	4416.82	245.72	481.62
0.43	3998.80	214.90	421.20
0.3	3694.45	195.37	382.93
0.21	3445.4	176.09	345.13
0.14	3264.46	166.73	326.80
0.1	3142.72	156.89	307.51

Table 21: Torque and rotational speed with the calculated uncertainity for the six-blade vane spindle with 0 % beads

	0 % pre 40 %				0 % pre 20 %				0 % combined		
N 1/min	Γ µNm	U(Γ) µNm	expanded U(Γ)		Γ µNm	U(Γ) µNm	expanded U(Γ)		Γ µNm	U(Γ) µNm	expanded U(Γ)
100	7309.29	182.61	357.91		7185.95	195.45	383.09		7246.99	103.12	202.12
69.5	5483.12	133.88	262.40		5387.10	146.27	286.70		5435.07	75.67	148.32
48.3	4176.09	95.39	186.97		4102.92	106.86	209.44		4136.84	55.33	108.44
33.6	3228.94	73.28	143.62		3175.48	82.43	161.57		3203.20	41.76	81.85
23.4	2549.10	55.00	107.80		2507.84	64.35	126.12		2528.2	31.77	62.28
16.2	2049.33	40.63	79.63		2020.66	49.08	96.20		2035.31	24.49	48.01
11.3	1683.84	30.00	58.78		1659.8	36.54	71.62		1672.22	18.84	36.93
7.85	1409.06	25.84	50.66		1389.63	34.45	67.51		1399.73	16.28	31.90
5.45	1197.40	20.72	40.62		1182.76	26.86	52.64		1190.00	13.20	25.87
3.79	1034.64	17.44	34.19		1027.23	23.27	45.61		1031.01	11.00	21.55
2.64	910.59	14.93	29.26		904.97	20.13	39.45		907.89	9.61	18.83
1.83	814.18	13.15	25.77		811.41	17.49	34.27		812.84	8.33	16.32
1.27	738.89	11.74	23.01		742.40	17.97	35.23		740.87	8.20	16.08
0.89	681.35	10.71	20.99		685.53	15.36	30.10		683.41	7.26	14.23
0.62	633.74	10.08	19.76		639.61	12.59	24.68		636.65	6.23	12.21
0.43	597.61	10.59	20.76		605.64	13.95	27.34		601.52	6.71	13.15
0.3	566.48	9.61	18.83		583.08	10.78	21.12		574.89	6.18	12.12
0.21	543.32	10.26	20.11		558.76	12.17	23.85		551.14	6.85	13.43
0.14	525.05	11.90	23.33		542.44	8.30	16.27		533.65	6.60	12.93
0.1	508.48	9.61	18.84		530.70	11.34	22.22		519.51	7.08	13.88

Table 22: Torque and rotational speed with the calculated uncertainity for the six-blad vane spindle with 20 % beads

N 1/min	Γ μNm	U(Γ) μNm	expanded U(Γ)
100	12606.57	327.67	642.23
69.5	9373.63	230.94	452.65
48.3	7049.17	168.46	330.18
33.6	5372.77	131.21	257.17
23.4	4167.39	92.38	181.07
16.2	3285.99	65.02	127.43
11.3	2629.74	47.13	92.38
7.85	2140.88	41.93	82.18
5.45	1777.44	30.19	59.17
3.79	1506.62	26.62	52.17
2.64	1298.55	23.60	46.26
1.83	1141.87	18.93	37.10
1.27	1021.81	17.50	34.30
0.89	926.39	16.95	33.22
0.62	859.88	14.40	28.23
0.43	800.90	13.28	26.04
0.3	761.74	11.39	22.32
0.21	720.38	10.48	20.54
0.14	696.30	8.03	15.74
0.1	678.22	10.35	20.28

Table 23: Torque and rotational speed with the calculated uncertainity for the six-blade vane spindle with 40 % beads

N 1/min	Γ μNm	U(Γ) μNm	expanded U(Γ)
100	24512.57	1328.32	2603.51
69.5	18264.38	1252.74	2455.37
48.3	13673.2	894.37	1752.96
33.6	10432.25	719.23	1409.69
23.4	8018.50	576.80	1130.52
16.2	6251.92	435.50	853.57
11.3	4938.09	347.48	681.06
7.85	3947.76	270.61	530.40
5.45	3204.74	218.71	428.67
3.79	2649.68	175.61	344.20
2.64	2221.24	154.61	303.04
1.83	1903.85	118.53	232.32
1.27	1662.50	101.78	199.48
0.89	1475.63	87.58	171.65
0.62	1334.05	76.63	150.20
0.43	1226.54	71.98	141.07
0.3	1139.02	62.75	122.99
0.21	1067.44	53.08	104.03
0.14	1021.97	54.27	106.37
0.1	980.35	47.81	93.715

Table 24: Torque and rotational speed with the calculated uncertainity for the Serrated Coaxial Cylinder with 0 % beads

	0 % pre 40 %				0 % pre 20 %				0 % combined		
N 1/min	Γ μNm	U(Γ) μNm	expanded U(Γ)		Γ μNm	U(Γ) μNm	expanded U(Γ)		Γ μNm	U(Γ) μNm	expanded U(Γ)
100	7686.6	245.91	481.98		8072.5	422.36	827.83		7879.8	198.52	389.10
69.5	5765	189.55	371.52		6040.8	321.69	630.51		5903.4	147.36	288.83
48.3	4356.1	138.46	271.38		4562.1	233.25	457.17		4455.2	108.8	213.25
33.6	3335.1	106.5	208.74		3484.7	180.31	353.41		3411.8	81.95	160.62
23.4	2604.6	80.21	157.21		2719.1	136.97	268.46		2661.6	61.67	120.87
16.2	2068.7	61.76	121.06		2162	100.61	197.20		2115.6	48.44	94.95
11.3	1676.4	46.34	90.82		1751.6	76.51	149.96		1714.4	37.47	73.45
7.85	1378.2	40.22	78.82		1442.6	67.23	131.78		1411.1	31.15	61.054
5.45	1148.1	33.16	65.00		1208.9	54.39	106.61		1178.3	26.91	52.75
3.79	972.15	28.38	55.63		1028.6	47.76	93.61		1000.4	23.38	45.82
2.64	834.34	25.589	50.15		886.06	41.88	82.083		860.36	21.14	41.43
1.83	725.18	22.68	44.45		782.41	37.35	73.20		753.94	19.76	38.72
1.27	638.3	20.45	40.08		691.91	33.07	64.82		665.63	17.97	35.22
0.89	574.36	25.75	50.46		625.49	25.39	49.76		599.94	16.91	33.14
0.62	515.41	21.60	42.33		584.88	26.20	51.36		550.06	18.65	36.56
0.43	469.95	19.82	38.85		557.07	27.10	53.11		513.17	20.75	40.67
0.3	433.3	19.77	38.76		502.27	24.99	48.98		467.9	17.56	34.43
0.21	407.72	24.60	48.21		521.34	36.60	71.72		465.01	27.33	53.57
0.14	380.95	19.99	39.18		515.81	33.80	66.24		448.35	30.14	59.06
0.1	365.28	24.45	47.91		487.25	36.59	71.72		426.01	28.47	55.79

Table 25: Torque and rotational speed with the calculated uncertainity for the Serrated Coaxial Cylinder with 20 % beads

N 1/min	Γ µNm	U(Γ) µNm	expanded U(Γ)
100	13300	503.36	986.59
69.5	9908	381.61	747.96
48.3	7441.6	284.2	557.03
33.6	5642.8	221.28	433.71
23.4	4349.3	169.49	332.20
16.2	3408	125.47	245.92
11.3	2722.8	95.51	187.19
7.85	2214.5	79.91	156.62
5.45	1834.2	62.09	121.70
3.79	1548.6	52.99	103.85
2.64	1327.1	43.62	85.49
1.83	1155.1	39.07	76.57
1.27	1023.3	35.49	69.55
0.89	931.6	32.40	63.50
0.62	852.62	29.35	57.53
0.43	797.47	27.16	53.23
0.3	764.83	21.20	41.56
0.21	747.97	53.35	104.56
0.14	704.58	26.99	52.90
0.1	673.3	27.04	52.99

Table 26: Torque and rotational speed with the calculated uncertainity for the Serrated Coaxial Cylinder with 40 % beads

N 1/min	Γ µNm	U(Γ) µNm	expanded U(Γ)
100	22339	1084.4	2125.42
69.5	17512	1003.6	1967.06
48.3	13364	708.69	1389.03
33.6	10316	467.7	916.69
23.4	7897.2	326.89	640.70
16.2	6096	236.56	463.66
11.3	4756.4	177.22	347.35
7.85	3771.1	142.64	279.57
5.45	3036.4	105.82	207.41
3.79	2490.5	85.29	167.16
2.64	2071.7	66.05	129.47
1.83	1755.6	53.08	104.03
1.27	1520	43.06	84.40
0.89	1329.9	34.61	67.84
0.62	1189.4	31.72	62.16
0.43	1071.2	27.77	54.46
0.3	979.14	24.57	48.16
0.21	907.41	22.34	43.79
0.14	860.1	37.25	73.01
0.1	807.42	32.96	64.60

7.1.2 OpenBUGS Code

This program computes the yield stress (alpha) in 1000·Nm, and viscosity (betad) in 1000·Nm·s, for the cases where there are 5 replicates of 20 points each. It also computes the average torque (theta) in 10^{-2}·µNm. For alpha, beta, and theta, it also computes the standard uncertainties and 95% uncertainty intervals. The data is first reduced so that only the down-curve is included, that is, the first 25 points are eliminated. It also obtains the average curves in microNm/1000 (theta).

```
{ ## prior distributions for Bingham parameters
## dnorm represents the Gaussian distribution
## dgamma represents the Gamma distribution.
alpha~dnorm(0,1.0E-5)
beta~dnorm(0,1.0E-5)
siga~dgamma(1.0E-5,1.0E-5)
sigb~dgamma(1.0E-5,1.0E-5)
sigd~dgamma(1.0E-5,1.0E-5)
for(i in 1:5){ a[i]~dnorm(alpha,siga)
               b[i]~dnorm(beta,sigb)
}
###
## regression model for Bingham parameters
for(i in 1:100){ mean[i]<-a[mix[i]]+b[mix[i]]*sig[i]
M[i]~dnorm(mean[i],sigd)}
betad<-beta/0.105
###
## prior distributions for flow curve model
for(j in 1:20){theta[j]~dnorm(0,1.0E-5)
               sigthe[j]~dgamma(1.0E-5,1.0E-5)
}
###
## flow curves
for(i in 1:100){M2[i]~dnorm(theta[posit[i]],sigthe[posit[i]])}
##
}
## initial values
list(siga=1,sigb=1,sigd=1, sigthe=c(1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1))
```

7.1.3 Uncertainty of the Estimates of the Parameters of Equation 1

Section 3 provides an equation (Equation 1) for viscosity as a function of shear rate to be used for calibration of the user's rheometer data. This equation (1) can be written as:

$$\mu = \frac{\left(C_2+\frac{A_2}{\dot{\gamma}^{B_2}}\right)+\left(C_1+\frac{A_1}{\dot{\gamma}^{B_1}}\right)e^{a\times(\dot{\gamma}-1)}}{1+e^{a\times(\dot{\gamma}-1)}} \qquad [19]$$

where µ is viscosity, $\dot{\gamma}$ is shear rate, A_i, B_i , C_i are parameters estimated based on the SRM 2492 paste data, and a is a fitting parameter. Note that

$$\lim_{a \to -\infty} \mu = \left(C_1 + \frac{A_1}{\dot{\gamma}^{B_1}}\right), for\ \dot{\gamma} < 1\ s^{-1}, \quad \left(C_2 + \frac{A_2}{\dot{\gamma}^{B_2}}\right), for\ \dot{\gamma} > 1\ s^{-1}, \quad \frac{\left(C_1 + \frac{A_1}{\dot{\gamma}^{B_1}}\right) + \left(C_2 + \frac{A_2}{\dot{\gamma}^{B_2}}\right)}{2}, for\ \dot{\gamma} = 1 s^{-1}. \qquad [20]$$

The parameter estimates given in Section 3 were obtained using ordinary least squares (OLS) fitting separately for viscosity values where $\dot{\gamma} < 1\ s^{-1}$ and for values where $\dot{\gamma} > 1\ s^{-1}$. To obtain an estimate of total uncertainty for these coefficients, equation 1 was also fitted using a Bayesian hierarchical model (BHM) using the code given below. This model accounts for the uncertainty of the fit as well as the uncertainty in the SRM 2492 measurements. As the two sets of estimates were not identical, the uncertainty estimates based on the BHM could not be used for the OLS coefficients without accounting for the bias. This component was computed by subtracting the OLS estimate from the BHM estimate. Squaring the bias and adding it to the squared BHM standard uncertainty forms an estimate of the total uncertainty of the OLS values. Thus the expanded total uncertainty is $etu = 2\sqrt{(u^2) + bias^2}$ given below.

Coefficients	Estimate via OLS	Estimate via BHM	standard uncertainty via BHM (u)	Bias : BHM – OLS ($bias$)	Expanded total uncertainty of the OLS estimates (etu)
A_1	16.411	16.99	0.30	0.58	1.30
A_2	19.178	18.74	0.53	-0.44	1.38
B_1	0.988	0.97	0.01	-0.018	0.04
B_2	0.727	0.63	0.07	-0.097	0.24
C_1	9.641	8.79	0.54	-0.851	2.09
C_2	7.116	6.39	0.70	-0.726	2.02

OpenBUGS code:

```
{sig~dgamma(1.0E-5,1.0E-5)
a1~dunif(5,25)
b1~dunif(0,1.5)
c1~dunif(1,15)
a2~dunif(5,25)
b2~dunif(0,1.5)
c2~dunif(1,15)
for(i in 1:29){ mu[i]<-a1/pow(sr[i],b1)+c1
                visc[i]~dnorm(mu[i],sig)}

for(i in 30:38){ mu[i]<-a2/pow(sr[i],b2)+c2
                visc[i]~dnorm(mu[i],sig)}

for(i in 1:38){dif[i]<-(visc[i]-mu[i])/visc[i]}
}

list(sig=1)

sr[]        visc[]      viscu[]
0.1         168.527     11.924
0.103       163.838     11.734
0.107       159.082     11.595
0.11        154.122     11.1
0.114       149.277     10.891
0.119       144.355     10.569
```

0.123	*139.263*	*10.168*
0.129	*134.355*	*9.843*
0.134	*129.328*	*9.458*
0.14	*124.294*	*8.993*
0.147	*119.303*	*8.653*
0.154	*114.252*	*8.293*
0.162	*109.06*	*7.965*
0.171	*103.957*	*7.549*
0.181	*98.739*	*7.162*
0.192	*93.497*	*6.794*
0.205	*88.39*	*6.428*
0.219	*83.193*	*6.054*
0.235	*78.004*	*5.66*
0.255	*72.871*	*5.345*
0.277	*67.72*	*4.904*
0.305	*62.549*	*4.536*
0.338	*57.373*	*4.157*
0.379	*52.333*	*3.731*
0.431	*47.235*	*3.326*
0.5	*42.127*	*2.946*
0.596	*37.011*	*2.536*
0.737	*31.881*	*2.139*
0.966	*26.782*	*1.73*
1.402	*21.659*	*1.357*
2.55	*16.554*	*1.104*
5	*13.353*	*0.944*
10	*10.966*	*0.777*
15	*9.972*	*0.722*
20	*9.349*	*0.676*
25	*8.925*	*0.655*
30	*8.601*	*0.62*
35	*8.354*	*0.617*
END		

7.2 Bingham Parameters

Yield stress and plastic viscosity are respectively the intercept and slope of a straight line fitted to the graph of torque plotted against rotational speed (**Figure 25)**. Only the "down curve" data was used to fit the regression, that is, the torques for the 10 shear rates starting at 100 s^{-1} and decreasing to 1 s^{-1}. This is considered to use only the linear portion of the curve. A straight line model fits the flow curve data reasonably well and provides an approximation to the flow curves given in the previous section. Figure 25 shows an example.

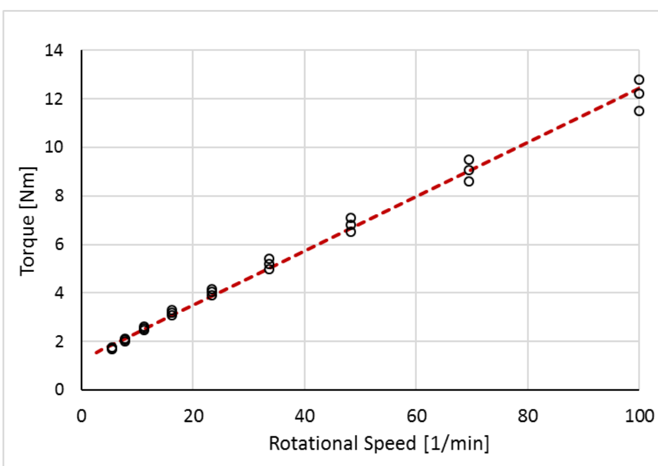


Figure 25: Example of torque vs. rotational speed for 20 % bead volume fraction using six-blade vane. The red line is the least squares line fitted to all of the points.

Yield stress and viscosity were estimated using a random effects regression model:

$$\Gamma_{ij} = a_i + b_i \Omega_j + \varepsilon_{ij} \qquad [21]$$

where $a_i \sim N(\alpha, \sigma_\alpha^2),\ b_i \sim N(\beta, \sigma_\beta^2),\ \varepsilon_{ij} \sim N(0, \sigma_i^2), i = 1,\ldots,5,\ j = 1,\ldots,20$.

In this model, a_i are the yield stress values for the 5 individual mixtures, and α is the consensus yield stress value for the particular geometry and % beads. Similarly, b_i are the viscosity values for the 5 individual mixtures and β is the consensus viscosity for the geometry and % beads. Unlike the simple least squares fit shown in the above figure, this model accounts for measurement uncertainty and lack of fit of each replicate using σ_i, and also for between replicate variability using σ_α and σ_β.

Fitting was done using Markov Chain Monte Carlo methods which require prior distributions on the parameters of the model. These were

$$\alpha \sim N(0,1.0E5), \beta \sim N(0,1.0E5), \sigma_\alpha^2 \sim Gamma(1.0E5,1.0E5)$$
$$\sigma_\beta^2 \sim Gamma(1.0E5,1.0E5), \sigma_i^2 \sim Gamma(1.0E5,1.0E5), i = 1,\ldots,5.$$

Figure 26 shows the fitted line with 95% uncertainty bounds based on the estimates of slope (β - plastic viscosity) and intercept (α - yield stress) with data points in green for mixture 1, 20 % bead volume fraction, using the six-blade vane.

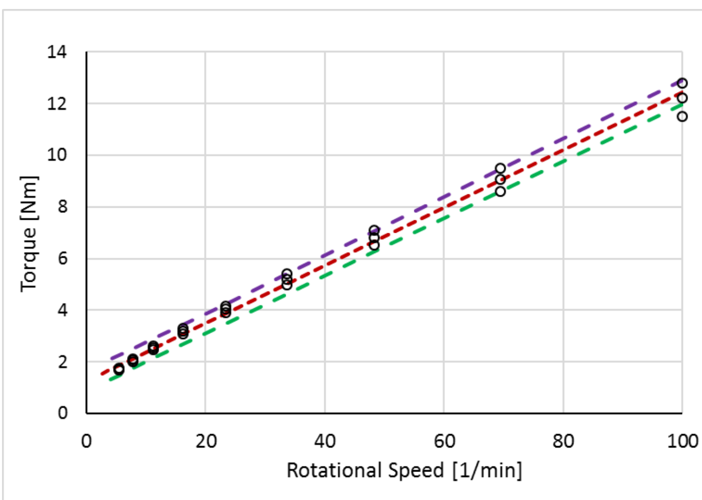


Figure 26 Example of fitted line and 95 % uncertainty bounds for 20 % beads using six-blade vane with data for mixture 1, whose median value is shown by red line.

Tables 25 to Table 27 contain the posterior means, standard deviations and 95% uncertainty bounds for α (yield stress) and Tables 28 to Table 30 contain the posterior means, standard deviations and 95 % uncertainty bounds for β (plastic viscosity).

Table 27: Double spiral spindle: Posterior means, standard deviations and 95 % uncertainty bounds for α (yield stress)

Mixture	Yield Stress [Nm]	standard uncertainty [Nm]	Expanded uncertainty [Nm]
0 %(pre 40 %)	0.002198	0.000054	0.000108
0 %(pre 20 %)	0.002247	0.000061	0.000122
0 %	0.002222	0.000037	0.000074
20 %	0.003223	0.000095	0.000190
40 %	0.007004	0.000290	0.000580

Table 28: Six-blade Vane: Posterior means, standard deviations and 95 % uncertainty bounds for α (yield stress)

Mixture	Yield Stress [Nm]	standard uncertainty [Nm]	Expanded uncertainty [Nm]
0 %(pre 40 %)	0.00090	0.00002	0.00005
0 %(pre 20 %)	0.00089	0.00002	0.00004
0 %	0.00090	0.00002	0.00004
20 %	0.00126	0.00004	0.00008
40 %	0.00223	0.00007	0.00014

Table 29: Serrated Coaxial Cylinder: Posterior means, standard deviations and 95 % uncertainty bounds for α (yield stress)

Mixture	Yield Stress [Nm]	standard uncertainty [Nm]	Expanded uncertainty [Nm]
0 %(pre 40 %)	0.000837	0.000029	0.000058
0 %(pre 20 %)	0.000876	0.000032	0.000064
0 %	0.000856	0.000020	0.000040
20 %	0.001279	0.000046	0.000092
40 %	0.002316	0.000146	0.000292

Table 30: Double spiral spindle: posterior means, standard deviations and 95 % uncertainty bounds for β (plastic viscosity)

Mixture	Viscosity [Nm·s]	Standard uncertainty [Nm·s]	Expanded uncertainty [Nm·s]
0 %(pre 40 %)	0.00239	0.00008	0.00015
0 %(pre 20 %)	0.00247	0.00011	0.00022
0 %	0.00243	0.00005	0.00010
20 %	0.00450	0.00023	0.00045
40 %	0.00954	0.00088	0.00176

Table 31: Six-Blade Vane: posterior means, standard deviations and 95 % uncertainty bounds for β (plastic viscosity)

Mixture	Viscosity [Nm·s]	Standard uncertainty [Nm·s]	Expanded uncertainty [Nm·s]
0%(pre 40%)	0.00062	0.00002	0.00004
0%(pre 20%)	0.00061	0.00002	0.00004
0%	0.00062	0.00001	0.00002
20%	0.00111	0.00003	0.00006
40%	0.00218	0.00014	0.00028

Table 32: Serrated Coaxial Cylinder: posterior means, standard deviations and 95% uncertainty bounds for β (plastic viscosity)

Mixture	Viscosity [Nm·s]	Standard uncertainty [Nm·s]	Expanded uncertainty [Nm·s]
0%(pre 40%)	0.000669	0.000029	0.000057
0%(pre 20%)	0.000702	0.000042	0.000084
0%	0.000685	0.000020	0.000040
20%	0.001172	0.000052	0.000104
40%	0.002018	0.000114	0.000228

7.3 Flow Curve Fundamental Data in Fundamental Units

7.3.1 Using the Bingham Based Method

Flow curves should be displayed in the fundamental units of viscosity [Pa·s] and shear rate [1/s]; however, the original data (raw data) obtained from the rheometer is in units of torque [Nm] and rotational speed [1/min]. This section provides the reader with the fundamental data that is directly used to compose the flow curves in this study, which were derived from calibrating the raw data into fundamental data. Table 33 to Table 35 provide the uncertainties for the fundamental data of all three spindles. These tables provide the values in fundamental units based on the Bingham method.

Table 33: Values for Double spiral spindle with uncertainties provided in fundamental units. – these are based on Bingham parameters

SPIRAL													
Shear Rate [1/s]		0% Exp. Data - Calibrated				20% Exp. Data - Calibrated				40% Exp. Data - Calibrated			
Shear Rate [1/s]	**uncertainity [1/s]**	**Shear Stress [Pa]**	**Shear Stress uncertainity [Pa]**	**Viscosity** [Pa·s]	**Viscosity uncertainity [Pa.s]**	**Shear Stress [Pa]**	**Shear Stress uncertainity [Pa]**	**Viscosity** [Pa·s]	**Viscosity uncertainity [Pa.s]**	**Shear Stress [Pa]**	**Shear Stress uncertainity [Pa]**	**Viscosity** [Pa·s]	**Viscosity uncertainity [Pa.s]**
38.95	2.014	315.7	9.8	8.1	0.4	575.2	30.0	14.8	1.0	1230.0	113.0	31.7	3.2
27.07	1.400	230.9	7.1	8.6	0.4	416.8	21.3	15.4	1.0	878.5	79.9	32.5	3.2
18.82	0.973	170.8	5.2	9.1	0.5	305.8	15.5	16.3	1.0	639.9	56.8	34.1	3.3
13.09	0.677	127.8	4.0	9.8	0.5	226.3	11.4	17.3	1.1	473.2	40.3	36.2	3.4
9.11	0.471	97.2	3.0	10.7	0.5	169.8	8.5	18.7	1.2	359.9	24.9	39.6	3.1
6.31	0.326	75.3	2.3	12.0	0.6	129.1	6.1	20.5	1.3	284.1	15.5	45.1	3.0
4.4	0.228	59.6	1.8	13.6	0.7	99.9	4.6	22.8	1.4	224.2	13.8	51.1	3.7
3.06	0.158	48.2	1.4	15.8	0.8	78.9	3.7	25.9	1.6	174.8	12.4	57.3	4.6
2.12	0.110	40.0	1.2	18.9	0.9	63.8	2.9	30.1	1.8	138.1	9.7	65.2	5.3
1.48	0.076	34.0	1.0	23.1	1.1	52.7	2.3	35.8	2.1	111.0	7.6	75.3	5.9
1.03	0.053	29.6	0.9	28.9	1.4	44.6	1.8	43.5	2.5	91.4	6.2	89.2	6.9
0.71	0.037	26.3	0.8	36.9	1.8	38.7	1.6	54.3	3.0	76.6	5.1	107.5	8.3
0.49	0.026	23.9	0.7	48.4	2.4	34.2	1.3	69.3	3.8	65.4	4.1	132.4	9.8
0.35	0.018	22.1	0.6	63.9	3.1	30.9	1.2	89.4	4.8	57.2	3.5	165.5	12.0
0.24	0.013	20.7	0.6	85.6	4.2	28.4	1.0	117.5	6.3	50.9	3.1	211.1	15.2
0.17	0.009	19.7	0.6	117.7	5.7	26.4	1.0	158.0	8.4	46.1	2.7	275.7	19.4
0.12	0.006	18.8	0.5	163.6	7.9	24.9	0.9	216.7	11.5	42.6	2.5	370.4	26.0
0.08	0.004	18.2	0.5	222.7	10.8	23.8	0.8	291.6	15.5	39.7	2.2	486.6	33.1
0.06	0.003	17.7	0.5	317.6	15.4	22.9	0.8	411.9	21.7	37.7	2.1	676.5	46.2
0.04	0.002	17.3	0.5	465.4	22.6	22.3	0.8	600.4	32.4	36.3	2.0	977.4	65.9

Table 34: Values for Six Blade Vane with uncertainties provided in fundamental units. – these are based on Bingham parameters

Vane													
Shear Rate [1/s]		0% Exp. Data - Calibrated				20% Exp. Data - Calibrated				40% Exp. Data - Calibrated			
Shear Rate [1/s]	**uncertainity [1/s]**	**Shear Stress [Pa]**	**Shear Stress uncertainity [Pa]**	**Viscosity** [Pa·s]	**Viscosity uncertainity [Pa.s]**	**Shear Stress [Pa]**	**Shear Stress uncertainity [Pa]**	**Viscosity** [Pa·s]	**Viscosity uncertainity [Pa.s]**	**Shear Stress [Pa]**	**Shear Stress uncertainity [Pa]**	**Viscosity** [Pa·s]	**Viscosity uncertainity [Pa.s]**
23.92	1.200	206.4	5.6	8.6	0.4	358.9	12.5	15.0	0.8	697.5	40.6	29.2	2.0
16.63	0.834	154.8	4.2	9.3	0.4	266.8	9.1	16.1	0.8	519.7	37.7	31.3	2.6
11.56	0.579	117.8	3.1	10.2	0.5	200.7	6.7	17.4	0.9	389.0	27.0	33.7	2.6
8.04	0.403	91.2	2.4	11.4	0.5	152.9	5.2	19.1	1.0	296.6	21.8	37.0	3.0
5.60	0.281	72.0	1.9	12.9	0.6	118.6	3.8	21.2	1.1	227.7	17.1	40.8	3.4
3.88	0.194	58.0	1.5	15.0	0.7	93.5	2.9	24.2	1.2	178.1	13.0	46.0	3.7
2.70	0.136	47.6	1.2	17.7	0.8	74.8	2.2	27.8	1.3	140.6	10.4	52.1	4.3
1.88	0.094	39.9	1.0	21.3	1.0	60.9	1.9	32.5	1.6	112.3	8.2	59.9	4.9
1.31	0.065	33.9	0.9	26.0	1.2	50.6	1.5	38.9	1.9	91.2	6.6	70.0	5.8
0.91	0.045	29.4	0.7	32.4	1.5	42.9	1.3	47.4	2.3	75.4	5.3	83.3	6.6
0.63	0.032	25.9	0.7	41.1	1.9	37.0	1.1	58.7	2.9	63.3	4.6	100.6	8.2
0.44	0.022	23.2	0.6	52.9	2.4	32.5	0.9	74.3	3.5	54.3	3.6	123.9	9.4
0.30	0.015	21.1	0.5	69.6	3.2	29.1	0.8	95.9	4.6	47.3	3.1	156.0	11.7
0.21	0.011	19.5	0.5	91.8	4.2	26.4	0.8	124.4	5.9	42.0	2.7	198.0	14.6
0.15	0.007	18.1	0.5	122.3	5.6	24.5	0.7	165.2	7.8	37.9	2.3	256.0	18.5
0.10	0.005	17.1	0.4	166.9	7.6	22.8	0.7	222.2	10.5	34.9	2.2	339.6	24.8
0.07	0.004	16.4	0.4	231.6	10.6	21.7	0.6	306.8	14.4	32.4	1.9	458.6	32.5
0.05	0.003	15.7	0.4	312.9	14.5	20.5	0.6	408.7	19.2	30.4	1.7	605.3	39.9
0.03	0.002	15.2	0.4	444.5	20.7	19.8	0.5	579.6	26.7	29.1	1.7	850.4	58.6
0.02	0.001	14.8	0.4	648.8	30.3	19.3	0.5	846.7	39.9	27.9	1.5	1224.0	80.2

Table 35: Values for serrated coaxial cylinder with uncertainties provided in fundamental units. – these are based on Bingham parameters

Coaxial													
Shear Rate [1/s]		0% Exp. Data - Calibrated				20% Exp. Data - Calibrated				40% Exp. Data - Calibrated			
Shear Rate [1/s]	**uncertainity [1/s]**	**Shear Stress [Pa]**	**Shear Stress uncertainity [Pa]**	**Viscosity** [Pa·s]	**Viscosity uncertainity [Pa.s]**	**Shear Stress [Pa]**	**Shear Stress uncertainity [Pa]**	**Viscosity** [Pa·s]	**Viscosity uncertainity [Pa.s]**	**Shear Stress [Pa]**	**Shear Stress uncertainity [Pa]**	**Viscosity** [Pa·s]	**Viscosity uncertainity [Pa.s]**
27.81	1.650	236.0	9.5	8.5	0.5	398.2	19.4	14.4	0.9	668.6	38.0	24.1	1.7
19.32	1.150	176.9	7.0	9.2	0.5	296.5	14.8	15.4	1.0	524.2	34.2	27.2	2.1
13.43	0.800	133.5	5.2	10.0	0.6	222.8	11.0	16.6	1.1	399.9	24.6	29.9	2.2
9.34	0.560	102.2	4.0	11.0	0.6	168.9	8.4	18.1	1.2	308.6	17.1	33.1	2.3
6.51	0.390	79.7	3.1	12.3	0.7	130.1	6.5	20.1	1.3	236.1	12.2	36.4	2.4
4.50	0.270	63.4	2.4	14.1	0.8	102.0	4.9	22.7	1.4	182.6	9.1	40.7	2.6
3.14	0.190	51.3	2.0	16.4	0.9	81.5	3.8	26.0	1.6	142.4	6.9	45.5	2.9
2.18	0.130	42.3	1.6	19.4	1.1	66.3	3.2	30.5	1.9	112.8	5.6	51.8	3.3
1.52	0.090	35.3	1.4	23.3	1.3	54.9	2.5	36.3	2.2	90.9	4.2	60.1	3.7
1.05	0.060	30.0	1.2	28.5	1.6	46.3	2.2	44.1	2.7	74.5	3.5	70.9	4.3
0.73	0.040	25.8	1.0	35.3	2.0	39.7	1.8	54.3	3.3	62.1	2.8	84.9	5.1
0.51	0.030	22.6	0.9	44.4	2.5	34.6	1.6	68.0	4.2	52.6	2.3	103.4	6.1
0.35	0.020	19.9	0.8	56.6	3.3	30.6	1.4	87.0	5.4	45.5	1.9	129.2	7.4
0.25	0.010	18.0	0.8	73.0	4.2	27.9	1.3	113.2	6.9	39.8	1.6	161.7	9.2
0.17	0.010	16.5	0.8	95.7	5.8	25.5	1.2	148.3	9.1	35.6	1.5	206.8	11.8
0.12	0.010	15.4	0.8	129.0	8.4	23.9	1.1	200.4	12.3	32.0	1.3	268.9	15.2
0.08	0.000	14.0	0.7	170.8	10.8	22.9	1.0	278.9	16.2	29.3	1.2	357.1	20.1
0.06	0.000	13.9	0.9	239.2	18.6	22.4	1.7	384.0	33.8	27.2	1.1	466.2	26.0
0.04	0.000	13.5	1.0	338.6	28.9	21.1	1.0	531.0	33.8	25.8	1.4	648.3	42.9
0.03	0.000	12.8	1.0	481.9	40.8	20.1	1.0	760.9	49.6	24.2	1.2	913.2	59.1

7.3.2 Using the Viscosity Fit Method

This section provides the reader with the fundamental data that is directly used to compose the flow curves in this study, which were derived from calibrating the raw data into fundamental data. Table 36 to Table 38 provide the uncertainties for the fundamental data of all three spindles and the model. These tables provide the values in fundamental units based on the viscosity fit method.

Table 36: Values for double spiral spindle with uncertainties provided in fundamental units, based on viscosity fit method

SPIRAL														
Shear Rate [1/s]		0% Exp. Data - Calibrated				20% Exp. Data - Calibrated				40% Exp. Data - Calibrated				
Shear Rate [1/s]	uncertainity [1/s]	Shear Stress [Pa]	Shear Stress uncertainity [Pa]	Viscosity [Pa·s]	Viscosity uncertainity [Pa.s]	Shear Stress [Pa]	Shear Stress uncertainity [Pa]	Viscosity [Pa·s]	Viscosity uncertainity [Pa.s]	Shear Stress [Pa]	Shear Stress uncertainity [Pa]	Viscosity [Pa·s]	Viscosity uncertainity [Pa.s]	
32.92	2.34	265.4	29.6	8.1	0.7	484.6	58.6	14.7	1.4	1041.0	147.4	31.6	3.9	
22.88	1.63	194.0	21.6	8.5	0.7	351.7	42.6	15.4	1.5	742.4	104.6	32.4	3.9	
15.90	1.13	143.6	16.0	9.0	0.8	257.6	30.9	16.2	1.5	540.1	74.8	33.9	4.0	
11.06	0.79	107.4	12.0	9.7	0.8	190.7	22.8	17.2	1.6	400.7	54.7	36.2	4.2	
7.70	0.55	81.7	9.1	10.6	0.9	143.1	17.2	18.6	1.8	304.6	39.1	39.5	4.2	
5.33	0.38	63.3	7.1	11.9	1.0	108.8	12.9	20.4	1.9	240.1	29.1	45.0	4.4	
3.72	0.26	50.1	5.6	13.5	1.2	84.3	10.0	22.7	2.1	189.4	23.5	50.9	5.2	
2.58	0.18	40.5	4.5	15.7	1.4	66.5	7.9	25.7	2.4	147.7	19.1	57.1	6.1	
1.80	0.13	33.6	3.7	18.7	1.6	53.7	6.4	29.9	2.8	116.8	15.0	65.0	6.9	
1.25	0.09	28.6	3.2	22.9	2.0	44.5	5.2	35.6	3.3	93.8	12.1	75.1	8.0	
0.87	0.06	24.9	2.8	28.7	2.5	37.6	4.4	43.3	4.0	77.1	9.8	88.8	9.3	
0.60	0.04	22.1	2.5	36.7	3.1	32.6	3.8	54.0	4.9	64.7	8.3	107.0	11.3	
0.42	0.03	20.1	2.2	48.0	4.1	28.8	3.3	68.9	6.2	55.3	7.0	132.0	13.6	
0.29	0.02	18.6	2.1	63.5	5.5	26.0	3.0	88.9	8.0	48.3	6.0	164.9	16.5	
0.20	0.02	17.4	1.9	85.0	7.3	23.9	2.7	116.8	10.4	43.1	5.3	210.6	21.2	
0.14	0.01	16.5	1.8	116.8	10.0	22.2	2.5	157.1	13.9	39.0	4.8	275.5	27.4	
0.10	0.01	15.8	1.8	162.5	13.9	21.0	2.4	215.5	19.2	36.0	4.4	369.1	36.8	
0.07	0.01	15.3	1.7	221.1	18.9	20.1	2.3	290.0	25.6	33.6	4.1	485.1	47.7	
0.05	0.00	14.9	1.7	315.3	27.0	19.3	2.2	409.5	36.2	31.8	3.9	673.8	66.5	
0.03	0.00	14.5	1.6	462.1	39.6	18.8	2.2	597.3	53.4	30.6	3.7	973.1	95.6	

Table 37: Values for six blade vane with uncertainties provided in fundamental units, based on viscosity fit method

Vane													
Shear Rate [1/s]		0% Exp. Data - Calibrated				20% Exp. Data - Calibrated				40% Exp. Data - Calibrated			
Shear Rate [1/s]	uncertainity [1/s]	Shear Stress [Pa]	Shear Stress uncertainity [Pa]	Viscosity [Pa·s]	Viscosity uncertainity [Pa.s]	Shear Stress [Pa]	Shear Stress uncertainity [Pa]	Viscosity [Pa·s]	Viscosity uncertainity [Pa.s]	Shear Stress [Pa]	Shear Stress uncertainity [Pa]	Viscosity [Pa·s]	Viscosity uncertainity [Pa.s]
23.84	4.40	188.3	36.0	7.9	0.4	328.6	63.3	13.8	0.8	640.5	127.4	26.8	1.9
16.57	3.06	141.2	27.0	8.5	0.4	244.4	47.2	14.7	0.8	477.1	97.5	28.7	2.4
11.52	2.12	107.5	20.6	9.3	0.5	183.7	35.3	15.9	0.9	356.7	72.0	30.9	2.5
8.01	1.48	83.2	15.9	10.4	0.5	140.0	26.9	17.4	1.0	272.6	55.3	33.9	2.9
5.58	1.03	65.7	12.6	11.8	0.6	108.6	20.9	19.4	1.1	209.3	42.8	37.4	3.3
3.86	0.71	52.9	10.1	13.7	0.7	85.7	16.4	22.1	1.2	163.5	33.4	42.2	3.6
2.69	0.50	43.5	8.3	16.1	0.8	68.6	13.1	25.4	1.3	129.0	26.3	47.7	4.1
1.87	0.35	36.4	7.0	19.4	1.0	55.8	10.7	29.8	1.6	103.0	21.0	54.9	4.6
1.30	0.24	30.9	5.9	23.8	1.2	46.3	8.9	35.6	1.9	83.8	17.0	64.2	5.4
0.90	0.17	26.8	5.1	29.6	1.5	39.3	7.5	43.4	2.3	69.2	14.1	76.3	6.3
0.63	0.12	23.6	4.5	37.6	1.9	33.9	6.5	53.7	2.8	58.0	11.8	92.0	7.8
0.44	0.08	21.1	4.0	48.3	2.4	29.8	5.7	68.0	3.5	49.7	10.1	113.4	9.1
0.30	0.06	19.3	3.7	63.6	3.2	26.6	5.1	87.8	4.6	43.4	8.8	143.0	11.4
0.21	0.04	17.8	3.4	83.9	4.2	24.2	4.6	113.8	6.0	38.5	7.7	181.4	13.8
0.15	0.03	16.5	3.2	111.8	5.6	22.4	4.3	151.1	7.8	34.9	7.0	234.8	17.7
0.10	0.02	15.6	3.0	152.6	7.7	20.9	4.0	203.3	10.5	32.1	6.4	312.0	23.8
0.07	0.01	14.9	2.9	211.7	10.6	19.9	3.8	280.7	14.5	29.7	5.9	420.1	31.0
0.05	0.01	14.3	2.7	285.9	14.5	18.8	3.6	374.0	19.1	27.9	5.5	554.8	38.7
0.03	0.01	13.9	2.7	406.1	20.6	18.2	3.5	530.2	26.8	26.7	5.3	778.8	56.6
0.02	0.00	13.5	2.6	592.9	30.2	17.7	3.4	774.8	40.1	25.6	5.1	1121.0	78.0

Table 38: Values for cylinder coaxial with uncertainties provided in fundamental units, based on viscosity fit method

Coaxial													
Shear Rate [1/s]		**0% Exp. Data - Calibrated**				**20% Exp. Data - Calibrated**				**40% Exp. Data - Calibrated**			
Shear Rate [1/s]	**uncertainity [1/s]**	**Shear Stress [Pa]**	**Shear Stress uncertainity [Pa]**	**Viscosity [Pa·s]**	**Viscosity uncertainity [Pa.s]**	**Shear Stress [Pa]**	**Shear Stress uncertainity [Pa]**	**Viscosity [Pa·s]**	**Viscosity uncertainity [Pa.s]**	**Shear Stress [Pa]**	**Shear Stress uncertainity [Pa]**	**Viscosity [Pa·s]**	**Viscosity uncertainity [Pa.s]**
33.89	5.86	248.4	50.1	7.3	0.8	420.8	86.0	12.4	1.3	703.9	144.4	20.7	2.3
23.55	4.07	186.2	37.6	7.9	0.8	313.4	64.0	13.3	1.4	552.1	115.0	23.4	2.7
16.37	2.83	140.5	28.3	8.6	0.9	235.6	48.0	14.4	1.5	421.1	87.3	25.7	2.9
11.39	1.97	107.6	21.7	9.4	1.0	178.5	36.4	15.6	1.6	325.3	66.5	28.5	3.1
7.93	1.37	83.9	17.0	10.6	1.1	137.6	28.0	17.3	1.8	249.0	51.0	31.4	3.4
5.49	0.95	66.7	13.5	12.1	1.2	107.8	21.9	19.6	2.1	192.1	39.2	34.9	3.7
3.83	0.66	54.1	10.9	14.1	1.4	86.1	17.5	22.4	2.3	150.0	30.5	39.1	4.1
2.66	0.46	44.5	9.0	16.7	1.7	70.1	14.2	26.3	2.7	118.9	24.3	44.6	4.7
1.85	0.32	37.2	7.5	20.1	2.0	58.0	11.8	31.3	3.2	95.8	19.5	51.7	5.4
1.29	0.22	31.6	6.4	24.5	2.5	49.0	10.0	38.0	4.0	78.6	16.0	61.1	6.4
0.89	0.15	27.1	5.5	30.3	3.1	42.0	8.5	46.9	4.8	65.3	13.2	73.0	7.5
0.62	0.11	23.8	4.8	38.2	3.9	36.5	7.4	58.6	6.1	55.3	11.2	88.9	9.2
0.43	0.07	21.0	4.3	48.7	5.0	32.4	6.6	75.0	7.8	47.9	9.7	111.2	11.4
0.30	0.05	18.9	3.8	62.7	6.4	29.5	6.0	97.6	10.2	41.9	8.5	139.1	14.1
0.21	0.04	17.3	3.5	82.3	8.6	27.0	5.5	127.9	13.3	37.5	7.6	178.0	18.1
0.15	0.03	16.2	3.3	110.9	11.8	25.2	5.1	172.7	17.9	33.8	6.8	231.6	23.6
0.10	0.02	14.8	3.0	146.8	15.5	24.2	4.9	240.5	24.5	30.9	6.2	307.4	31.2
0.07	0.01	14.7	3.1	205.6	23.7	23.6	5.0	331.1	39.8	28.6	5.8	401.3	40.7
0.05	0.01	14.1	3.0	290.4	34.9	22.3	4.5	457.8	48.2	27.1	5.6	557.6	59.8
0.03	0.01	13.4	2.9	413.8	49.7	21.3	4.4	655.8	69.1	25.5	5.2	785.0	83.7

8 Summary

A reference material that simulates mortar was developed that consists of a non-colloidal suspension comprised of corn syrup and fine limestone, and 1 mm diameter nominally spherical beads. The user needs to prepare the mixture according to the proportions defined in the certificate by following ASTM C1738 and the mixing procedure outlined in Section 4.2 of this report.

The uniqueness of this reference material is that it, like mortar, manifests Bingham rheological behavior. This reference material is the second of a series of three reference materials: 1) SRM 2492 paste with no beads; 2) SRM 2493, which is SRM 2492 paste with the addition of 1 mm beads, and 3) SRM 2497, which is SRM 2493 plus 10 mm beads (under preparation). Two different bead volume fractions, 20% and 40%, were investigated in work. A shape analysis was carried out to verify the sphercity of the glass beads. The addition of glass beads enables SRM 2493 to be used as a mortar reference material and the addition of 10 mm glass beads enables SRM 2497 to be used a concrete reference material and it is envisioned that the addition of 10 mm glass beads will enable SRM 2497 to be used a concrete reference material.

The certified values for the mortar reference material, SRM2493, were determined using an extensive experimental design, based on the paste rheological properties measured using a parallel plate calibrated rheometer, parallel computational modeling, and statistical analysis. The uniqueness of this SRM is that it based on the paste rheological properties measured using a parallel plate calibrated rheometer and a computational model. The model was necessary to obtain the fundamental values for the 20 % and 40 % bead volume fractions.

The user is provided with two methods to use SRM 2493 for calibration of rheometers for mortar:

- one method is based on experimental parameters determined from fitting the Bingham equation to the rheological data; (Table 39)
- second method is based on the computational model, by fitting the rheological data to an equation provided in this report (Equation (1) in Section 4).

In both cases, the operator will obtain calibration factors that subsequently can be used for transforming rheometer dependent untis (N.m and rad/s or rpm) into fundamental units (Pa and 1/s) for the shear stress and the shear rate.

The last step for this series of SRMs is the concrete rheology reference materials, which will be based on the same procedure as the mortar, but with the addition of 10 mm beads. This work is in progress.

Table 39: Certified values based on the Bingham parameters. A) 0% paste, B) 20% mortar and C) 40 % mortar

	Parameter	Type of geometry	Certified Value (Pa)	Standard Uncertainty (Pa)	Expanded Uncertainty (Pa)
A) 0% beads (paste)	Yield Stress	Parallel plate	24.7	0.5	1.0
		Model	23.1	1.8	3.6
	Plastic Viscosity	Type of geometry	Certified Value (Pa·s)	Standard Uncertainty (Pa·s)	Expanded Uncertainty (Pa·s)
		Parallel plate	7.9	0.2	0.5
		Model	8.1	0.8	1.6

	Parameter	Certified Value (Pa)	Standard Uncertainty (Pa)	Expanded Uncertainty (Pa)
B) 20% Beads by volume concentration	Yield Stress	31.0	3.6	5.2
	Plastic Viscosity	Certified Value (Pa·s)	Standard Uncertainty (Pa·s)	Expanded Uncertainty (Pa·s)
		14.9	2.3	3.0

	Parameter	Certified Value (Pa)	Standard Uncertainty (Pa)	Expanded Uncertainty (Pa)
C) 40% Beads by volume concentration	Yield Stress	38.8	5.2	6.2
	Plastic Viscosity	Certified Value (Pa·s)	Standard Uncertainty (Pa·s)	Expanded Uncertainty (Pa·s)
		57.9	8.7	11.8

9 References

[1] C. F. Ferraris , P. Stutzman, J. Winpigler and W. Guthrie, "Certification of SRM 2492: Bingham Paste Mixture for Rheological Measurements," SP-260-174 Rev. 2012, June 2012.

[2] A. Olivas, C. F. Ferraris, W. F. Guthrie and B. Toman , "Re-certification of SRM 2492: Bingham Paste Mixture for Rheological Measurements," National Institute of Standards and Technology. (NIST Special Publication 260-182). U.S. Department of Commerce, Gaithersburg, MD, August 2015.

[3] V. A. Hackley and C. F. Ferraris, "The Use of Nomenclature in Dispersion Science and Technology," NIST Recommended Practice Guide, SP 960-3, 2001.

[4] C. F. Ferraris and L. E. Brower, "Comparison of concrete rheometers: International tests at LCPC (Nantes, France) in October 2000 (NISTIR 6819)," National Institute of Standards and Technology, Gaithersburg, MD.

[5] C. F. Ferraris and L. E. Brower, "Comparison of concrete rheometers: International tests at MB (Cleveland OH, USA) in May 2003 (NISTIR 7154)," National Institute of Standards and Technology , Gaithersburg, MD.

[6] A. C188-09, "Standard Test Method for Density of Hydraulic Cement," ASTM vol 04.01, 2009.

[7] E. J. Garboczi, "Three-dimensional mathematical analysis of particle shape using x-ray tomography and spehical harmonics: applications to aggregates used in concrete.," Cement Concrete Research 32, 2002.

[8] M. A. Taylor, E. J. Garboczi, S. T. Erdogan and D. W. Fowler, "Some properties of irregular particles in 3-D," *Powder Technology 162,* pp. 1-15, 2006.

[9] A. Olivas, C. F. Ferraris, B. Lang, J. Richter, R.P. Ferron. "Cement Paste Reference Material (SRM 2492) Shelf-Life Extension"," NIST - TN 1934, 2016.

[10] L. Maxime, N.S. Martys, W. L. George, D. Lootens and P. Hebraud, "Scaling laws for the flow of generalized Newtonian suspensions," *Journal of Rheology* , vol. 58, 2014.

[11] H. Zhu, N.S. Martys, C.F. Ferraris, D. De Kee, "A numerical study for the flow of Bingham-like Fluids in two Dimensional Vane and Coaxial cylinders using Smoothed Particle Hydrodynamic (SPH) based Method"," *J. of Non-Newtonian Fluid Mechanics,* vol. 165, pp. 363-375, 2010.

[12] M. Allen and D. Tildesley, Computer simulations of liquids, Clarendon, Oxford, 1987.

[13] N. S. Martys, W. L. George, B.-W. Chun and D. Lootens, "A smoothed particle hydrodynamics-based fluid model with a spatially dependent viscosity: application to flow of a suspension with a non-Newtonian fluid matrix.," *Rheologica acta,* vol. 49, no. 10, pp. 1059-1069, 2010.

[14] A. Gelman, J. Carlin , H. Stern , D. Dunson, A. Vehatri and D. Rubin, Bayesian Data Analysis, Boca Raton: Chapman & Hall 3rd Edition, 2013.

[15] D. J. Lunn, D. Spiegelhalter, A. Thomas and N. Best, "The BUGS project: evolution, critique and future directions (with discussion)," *Statistics in Medicine* , pp. 3049-3082, 2009.

[16] R. C. Team, "A language and Environment for Statistical Computing," R Foundation for statistica Computing,, Vienna, Austria, http://www.R-project.org/, 2015.

[17] A. Olivas, M.A. Helsel, N.S. Martys, C.F. Ferraris, R.P. Ferron, "Rheological Measurements of Suspensions Without Slippage: experimental and Model," NIST-TN 1946, 2016.

10 Appendices

Appendix A: Original Data Measured from Rheometer

This appendix provides all the original data obtained from each test that was recorded from the rheometer. Also included are graphs needed for interpretation of the results, which portray the repeatability of the measured data.

Appendix B: Data for Calibration

This appendix provides the averaged data for each mixture which was calculated from the original data shown in Appendix A. The average data was calculated for each geometry analyzed and mortar composition (bead %). This set of data was then used in the calibration process described in Section 4.3.

Appendix A:
Original Data Measured from Rheometer

This appendix provides all the original data obtained from each test that was recorded directly from the rheometer. Also included are graphs needed for interpretation of the results, which portray the repeatability of the measured data.

Notes:

Mix#1 was discarded due to technical issues encountered during testing, thus the data tables in this appendix begin with Mix#2. The data extends from Mix#2 and continues up to Mix#11, thus a total of 10 mixes were used (See Section 4.2). Each mix was tested with three spindles used at two compositions (either 20 % or 40 % beads by volume). Therefore, six tables and corresponding figures are attached in this appendix per Mix#.

Each table will contain NIST codes showing the spindle and cup used, which are intended for NIST reference only.

<u>*Unit Notations:*</u>

N: Rotational Speed [1/min]
Γ: Measured Torque [μN·m]

The columns showing the average values contain the following unit conversions:

N: Rotational Speed → $[1/min] * 2\pi/60 = [rad/s]$

Γ: Measured Torque → $[\mu N \cdot m] * 10^{-6} = [N \cdot m]$

Table A - 1: Measured data for Mix#2 with 0 % beads using Double Spiral spindle.

Double Spiral							Bead %	
Geom.:	*RHN-83A*			*Cup:*	*Z43S*		*0%*	
Run #1		Run #2		Run #3		**Average values**		
NIST Code: SMC-113D		*NIST Code: SMC-113E*		*NIST Code: SMC-113F*				
N	Γ	N	Γ	N	Γ	**N**	**Γ**	***Γ/N*** *(Angular*
1/min	µNm	1/min	µNm	1/min	µNm	**rad/s**	**Nm**	*momentum)*
0.0943	1020	0.0945	959	0.0944	998	*0.010*	*9.92E-04*	*1.00E-01*
0.161	1500	0.161	1430	0.161	1480	*0.017*	*1.47E-03*	*8.72E-02*
0.268	1700	0.268	1640	0.268	1690	*0.028*	*1.68E-03*	*5.97E-02*
0.44	1800	0.44	1760	0.44	1810	*0.046*	*1.79E-03*	*3.88E-02*
0.72	1910	0.72	1880	0.72	1930	*0.075*	*1.91E-03*	*2.53E-02*
1.18	2080	1.18	2050	1.18	2110	*0.124*	*2.08E-03*	*1.68E-02*
1.93	2320	1.93	2300	1.93	2370	*0.202*	*2.33E-03*	*1.15E-02*
3.16	2710	3.16	2710	3.16	2780	*0.331*	*2.73E-03*	*8.26E-03*
5.18	3320	5.18	3330	5.18	3420	*0.542*	*3.36E-03*	*6.19E-03*
8.48	4260	8.48	4290	8.48	4410	*0.888*	*4.32E-03*	*4.86E-03*
13.9	5780	13.9	5860	13.9	6000	*1.456*	*5.88E-03*	*4.04E-03*
22.8	8160	22.8	8220	22.8	8470	*2.388*	*8.28E-03*	*3.47E-03*
37.3	11900	37.3	12000	37.3	12400	*3.906*	*1.21E-02*	*3.10E-03*
61.1	17700	61.1	18000	61.1	18500	*6.398*	*1.81E-02*	*2.82E-03*
100	26800	100	27200	100	28100	*10.472*	*2.74E-02*	*2.61E-03*
100	26600	100	27100	100	27900	*10.472*	*2.72E-02*	*2.60E-03*
69.5	19400	69.5	19800	69.5	20400	*7.278*	*1.99E-02*	*2.73E-03*
48.3	14400	48.3	14700	48.3	15100	*5.058*	*1.47E-02*	*2.91E-03*
33.6	10800	33.6	11000	33.6	11300	*3.519*	*1.10E-02*	*3.14E-03*
23.4	8190	23.4	8350	23.4	8590	*2.450*	*8.38E-03*	*3.42E-03*
16.2	6350	16.2	6470	16.2	6650	*1.696*	*6.49E-03*	*3.83E-03*
11.3	5020	11.3	5110	11.3	5250	*1.183*	*5.13E-03*	*4.33E-03*
7.85	4070	7.85	4140	7.85	4240	*0.822*	*4.15E-03*	*5.05E-03*
5.46	3380	5.46	3430	5.46	3510	*0.572*	*3.44E-03*	*6.02E-03*
3.79	2870	3.79	2920	3.79	2980	*0.397*	*2.92E-03*	*7.37E-03*
2.64	2500	2.64	2540	2.64	2590	*0.276*	*2.54E-03*	*9.20E-03*
1.83	2230	1.83	2260	1.83	2300	*0.192*	*2.26E-03*	*1.18E-02*
1.27	2020	1.27	2050	1.27	2090	*0.133*	*2.05E-03*	*1.54E-02*
0.886	1870	0.886	1890	0.886	1930	*0.093*	*1.90E-03*	*2.04E-02*
0.615	1750	0.616	1770	0.616	1800	*0.064*	*1.77E-03*	*2.75E-02*
0.428	1670	0.428	1680	0.427	1720	*0.045*	*1.69E-03*	*3.77E-02*
0.3	1600	0.297	1620	0.298	1650	*0.031*	*1.62E-03*	*5.20E-02*
0.206	1550	0.207	1580	0.207	1580	*0.022*	*1.57E-03*	*7.25E-02*
0.144	1500	0.144	1510	0.145	1540	*0.015*	*1.52E-03*	*1.00E-01*
0.0994	1470	0.0997	1480	0.101	1510	*0.010*	*1.49E-03*	*1.42E-01*

Table A - 2: Measured data for Mix#2 with 40 % beads using Double Spiral spindle.

Double Spiral							Bead %	
Geom.: RHN-83A				*Cup: Z43S*			*40%*	
Run #1		Run #2		Run #3		**Average values**		
NIST Code: SMC-79J		*NIST Code: SMC-79K*		*NIST Code: SMC-79L*				
N	Γ	N	Γ	N	Γ	**N**	**Γ**	*Γ/N (Angular*
1/min	µNm	1/min	µNm	1/min	µNm	**rad/s**	**Nm**	*momentum)*
0.09	2200	0.0894	2260	0.0891	2150	*0.009*	*2.20E-03*	*2.35E-01*
0.158	3110	0.162	3170	0.16	3060	*0.017*	*3.11E-03*	*1.86E-01*
0.263	3700	0.267	3610	0.269	3580	*0.028*	*3.63E-03*	*1.30E-01*
0.435	4310	0.439	4050	0.438	4020	*0.046*	*4.13E-03*	*9.01E-02*
0.719	5050	0.725	4620	0.716	4620	*0.075*	*4.76E-03*	*6.32E-02*
1.18	5950	1.19	5480	1.17	5410	*0.124*	*5.61E-03*	*4.54E-02*
1.93	7320	1.93	6660	1.93	6640	*0.202*	*6.87E-03*	*3.40E-02*
3.17	9470	3.17	8700	3.15	8560	*0.331*	*8.91E-03*	*2.69E-02*
5.18	12700	5.17	11800	5.18	11500	*0.542*	*1.20E-02*	*2.21E-02*
8.48	17900	8.48	16700	8.48	16600	*0.888*	*1.71E-02*	*1.92E-02*
13.9	25200	13.9	23600	13.9	23800	*1.456*	*2.42E-02*	*1.66E-02*
22.8	35600	22.8	33700	22.7	33900	*2.384*	*3.44E-02*	*1.44E-02*
37.3	51500	37.3	49700	37.3	50800	*3.906*	*5.07E-02*	*1.30E-02*
61.1	74500	61	73900	61	76300	*6.391*	*7.49E-02*	*1.17E-02*
100	106000	100	101000	100	108000	*10.472*	*1.05E-01*	*1.00E-02*
100	101000	100	95800	100	104000	*10.472*	*1.00E-01*	*9.57E-03*
69.6	71900	69.6	68200	69.5	75000	*7.285*	*7.17E-02*	*9.84E-03*
48.3	52700	48.3	49300	48.3	55200	*5.058*	*5.24E-02*	*1.04E-02*
33.6	39100	33.6	36300	33.6	41300	*3.519*	*3.89E-02*	*1.11E-02*
23.3	29900	23.4	27600	23.4	31700	*2.447*	*2.97E-02*	*1.22E-02*
16.2	23100	16.2	22700	16.2	24800	*1.696*	*2.35E-02*	*1.39E-02*
11.3	17600	11.3	17700	11.3	19000	*1.183*	*1.81E-02*	*1.53E-02*
7.83	13600	7.85	13800	7.86	14700	*0.822*	*1.40E-02*	*1.71E-02*
5.44	10800	5.45	10900	5.46	11600	*0.571*	*1.11E-02*	*1.94E-02*
3.79	8700	3.78	8950	3.78	9310	*0.396*	*8.99E-03*	*2.27E-02*
2.65	7120	2.64	7260	2.63	7750	*0.276*	*7.38E-03*	*2.67E-02*
1.82	5940	1.83	6100	1.82	6510	*0.191*	*6.18E-03*	*3.24E-02*
1.27	5150	1.27	5200	1.28	5540	*0.133*	*5.30E-03*	*3.97E-02*
0.889	4470	0.884	4540	0.88	4830	*0.093*	*4.61E-03*	*4.98E-02*
0.608	3980	0.617	4060	0.611	4320	*0.064*	*4.12E-03*	*6.43E-02*
0.426	3630	0.425	3680	0.428	3890	*0.045*	*3.73E-03*	*8.36E-02*
0.295	3320	0.298	3390	0.297	3590	*0.031*	*3.43E-03*	*1.11E-01*
0.203	3100	0.208	3180	0.205	3380	*0.022*	*3.22E-03*	*1.50E-01*
0.144	2980	0.147	3020	0.145	3140	*0.015*	*3.05E-03*	*2.00E-01*
0.0999	2870	0.0987	2890	0.101	3040	*0.010*	*2.93E-03*	*2.80E-01*

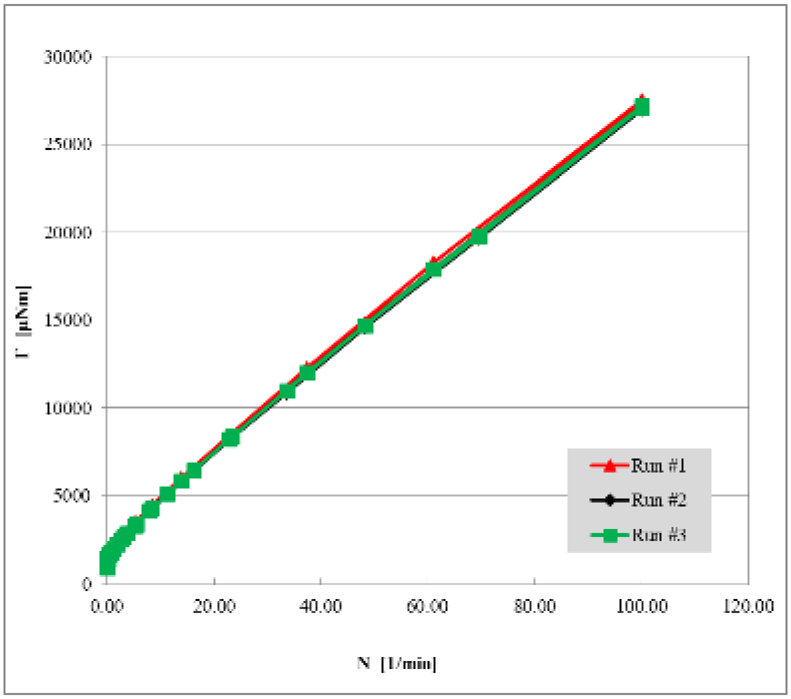


Figure A - 1: Torque vs. Angular Speed using <u>Double Spiral</u> spindle on Mix#2, with 0 % beads by volume. Portrays data from Table A-1.

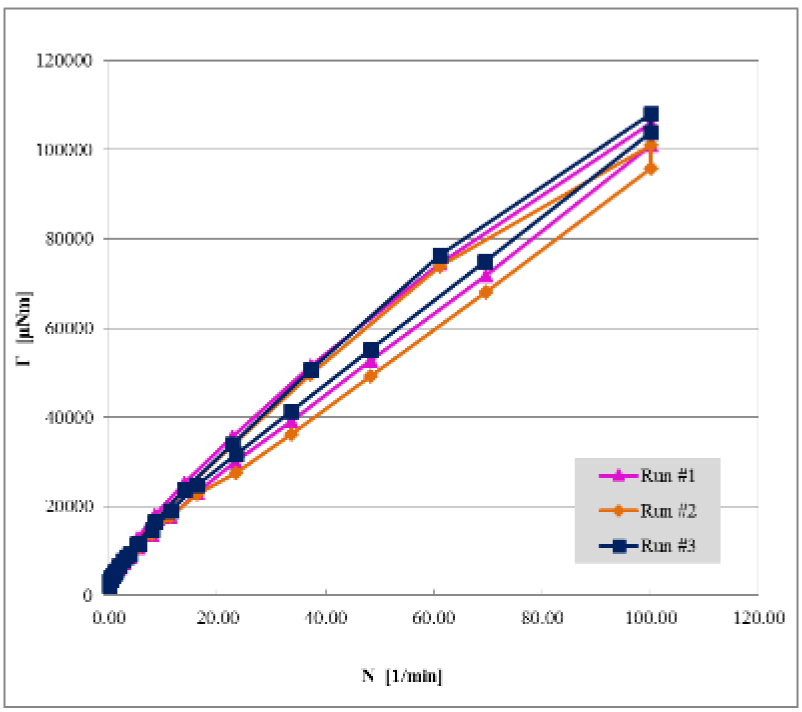


Figure A - 2: Torque vs. Angular Speed using <u>Double spiral spindle</u> on Mix#2, with 40 % beads by volume. Portrays data from Table A-2.

Table A - 3: Measured data for Mix#2 with 0 % beads using Six-blade Vane.

6 Blade Vane							Bead %	
Geom.:	*RHN-83C*			*Z43S*			*0%*	
Run #1		Run #2		Run #3		**Average values**		
NIST Code: SMC-79D		*NIST Code: SMC-79E*		*NIST Code: SMC-79F*				
N	Γ	N	Γ	N	Γ	**N**	**Γ**	***Γ/N*** *(Angular*
1/min	μNm	1/min	μNm	1/min	μNm	**rad/s**	**Nm**	*momentum)*
0.0977	434	0.1	520	0.0979	400	*0.010*	*4.51E-04*	*4.37E-02*
0.163	573	0.164	541	0.163	537	*0.017*	*5.50E-04*	*3.22E-02*
0.268	614	0.268	571	0.268	581	*0.028*	*5.89E-04*	*2.10E-02*
0.439	649	0.439	613	0.439	618	*0.046*	*6.27E-04*	*1.36E-02*
0.72	702	0.72	669	0.72	669	*0.075*	*6.80E-04*	*9.02E-03*
1.18	776	1.18	745	1.18	744	*0.124*	*7.55E-04*	*6.11E-03*
1.93	879	1.93	847	1.93	849	*0.202*	*8.58E-04*	*4.25E-03*
3.16	1030	3.16	993	3.16	1000	*0.331*	*1.01E-03*	*3.05E-03*
5.18	1240	5.18	1200	5.18	1210	*0.542*	*1.22E-03*	*2.24E-03*
8.48	1540	8.48	1490	8.48	1520	*0.888*	*1.52E-03*	*1.71E-03*
13.9	1980	13.9	1930	13.9	1970	*1.456*	*1.96E-03*	*1.35E-03*
22.8	2620	22.8	2570	22.8	2630	*2.388*	*2.61E-03*	*1.09E-03*
37.3	3620	37.3	3560	37.3	3650	*3.906*	*3.61E-03*	*9.24E-04*
61	5170	61	5080	61	5210	*6.388*	*5.15E-03*	*8.07E-04*
100	7590	100	7490	100	7620	*10.472*	*7.57E-03*	*7.23E-04*
100	7580	100	7470	100	7600	*10.472*	*7.55E-03*	*7.21E-04*
69.5	5670	69.5	5600	69.5	5680	*7.278*	*5.65E-03*	*7.76E-04*
48.3	4310	48.3	4260	48.3	4310	*5.058*	*4.29E-03*	*8.49E-04*
33.6	3330	33.6	3290	33.6	3330	*3.519*	*3.32E-03*	*9.43E-04*
23.4	2620	23.4	2590	23.4	2620	*2.450*	*2.61E-03*	*1.07E-03*
16.2	2100	16.2	2080	16.2	2100	*1.696*	*2.09E-03*	*1.23E-03*
11.3	1720	11.3	1700	11.3	1720	*1.183*	*1.71E-03*	*1.45E-03*
7.85	1440	7.85	1430	7.85	1440	*0.822*	*1.44E-03*	*1.75E-03*
5.45	1220	5.45	1210	5.45	1220	*0.571*	*1.22E-03*	*2.13E-03*
3.79	1060	3.79	1040	3.79	1050	*0.397*	*1.05E-03*	*2.65E-03*
2.64	929	2.64	917	2.64	921	*0.276*	*9.22E-04*	*3.34E-03*
1.83	830	1.83	820	1.83	822	*0.192*	*8.24E-04*	*4.30E-03*
1.27	752	1.27	741	1.27	744	*0.133*	*7.46E-04*	*5.61E-03*
0.886	691	0.886	681	0.885	690	*0.093*	*6.87E-04*	*7.41E-03*
0.616	643	0.617	648	0.616	635	*0.065*	*6.42E-04*	*9.95E-03*
0.428	604	0.428	608	0.428	596	*0.045*	*6.03E-04*	*1.34E-02*
0.298	574	0.297	569	0.297	567	*0.031*	*5.70E-04*	*1.83E-02*
0.207	548	0.21	545	0.207	541	*0.022*	*5.45E-04*	*2.50E-02*
0.144	529	0.144	520	0.144	521	*0.015*	*5.23E-04*	*3.47E-02*
0.0999	515	0.0998	505	0.101	507	*0.010*	*5.09E-04*	*4.85E-02*

Table A - 4: Measured data for Mix#2 with 40 % beads using Six-blade Vane.

6 Blade Vane						Bead %		
Geom.: RHN-83C				*Z43S*		*40%*		
Run #1		Run #2		Run #3		**Average values**		
NIST Code: SMC-79M		*NIST Code: SMC-79N*		*NIST Code: SMC-79O*				
N	Γ	N	Γ	N	Γ	**N**	**Γ**	***Γ/N*** *(Angular*
1/min	µNm	1/min	µNm	1/min	µNm	**rad/s**	**Nm**	*momentum)*
0.096	1070	0.096	1030	0.0947	1130	*0.010*	*1.08E-03*	*1.08E-01*
0.162	1310	0.161	1300	0.165	1430	*0.017*	*1.35E-03*	*7.91E-02*
0.267	1440	0.267	1390	0.271	1580	*0.028*	*1.47E-03*	*5.23E-02*
0.435	1550	0.44	1520	0.44	1630	*0.046*	*1.57E-03*	*3.41E-02*
0.717	1710	0.719	1670	0.717	1860	*0.075*	*1.75E-03*	*2.32E-02*
1.18	1960	1.18	1950	1.17	2180	*0.123*	*2.03E-03*	*1.65E-02*
1.93	2340	1.93	2330	1.92	2540	*0.202*	*2.40E-03*	*1.19E-02*
3.16	2860	3.16	2880	3.18	3130	*0.332*	*2.96E-03*	*8.92E-03*
5.17	3620	5.19	3640	5.17	4050	*0.542*	*3.77E-03*	*6.95E-03*
8.48	4690	8.49	4740	8.47	5260	*0.888*	*4.90E-03*	*5.51E-03*
13.9	6190	13.9	6430	13.9	7100	*1.456*	*6.57E-03*	*4.52E-03*
22.8	8410	22.8	8820	22.7	9640	*2.384*	*8.96E-03*	*3.76E-03*
37.3	11900	37.3	12500	37.3	13400	*3.906*	*1.26E-02*	*3.23E-03*
61.1	16700	61	17400	61	18400	*6.391*	*1.75E-02*	*2.74E-03*
100	23700	100	25600	100	26600	*10.472*	*2.53E-02*	*2.42E-03*
100	23300	100	24400	100	25600	*10.472*	*2.44E-02*	*2.33E-03*
69.5	17400	69.5	18300	69.5	19400	*7.278*	*1.84E-02*	*2.52E-03*
48.3	13300	48.3	13900	48.3	14500	*5.058*	*1.39E-02*	*2.75E-03*
33.6	10200	33.6	10700	33.6	11100	*3.519*	*1.07E-02*	*3.03E-03*
23.4	7880	23.3	8270	23.4	8530	*2.447*	*8.23E-03*	*3.36E-03*
16.2	6110	16.2	6390	16.2	6640	*1.696*	*6.38E-03*	*3.76E-03*
11.3	4860	11.3	5070	11.3	5240	*1.183*	*5.06E-03*	*4.27E-03*
7.84	3890	7.85	4040	7.85	4200	*0.822*	*4.04E-03*	*4.92E-03*
5.46	3170	5.45	3250	5.45	3390	*0.571*	*3.27E-03*	*5.73E-03*
3.8	2590	3.79	2730	3.8	2790	*0.398*	*2.70E-03*	*6.80E-03*
2.64	2190	2.64	2290	2.64	2300	*0.276*	*2.26E-03*	*8.17E-03*
1.84	1880	1.83	1940	1.83	1970	*0.192*	*1.93E-03*	*1.01E-02*
1.27	1640	1.28	1710	1.27	1720	*0.133*	*1.69E-03*	*1.27E-02*
0.889	1460	0.884	1500	0.886	1530	*0.093*	*1.50E-03*	*1.61E-02*
0.614	1320	0.62	1350	0.617	1370	*0.065*	*1.35E-03*	*2.08E-02*
0.428	1210	0.427	1240	0.428	1250	*0.045*	*1.23E-03*	*2.75E-02*
0.3	1120	0.294	1150	0.295	1170	*0.031*	*1.15E-03*	*3.70E-02*
0.206	1080	0.209	1070	0.208	1100	*0.022*	*1.08E-03*	*4.98E-02*
0.144	1010	0.145	1000	0.143	1030	*0.015*	*1.01E-03*	*6.72E-02*
0.0992	951	0.0998	989	0.1	983	*0.010*	*9.74E-04*	*9.34E-02*

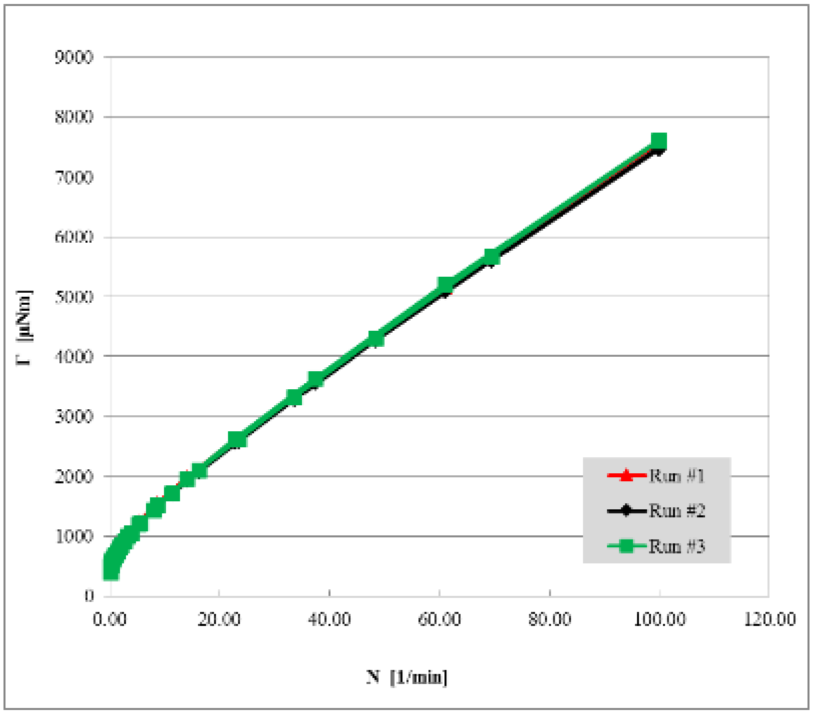


Figure A - 1: Torque vs. Angular Speed using <u>six-blade vane</u> on Mix#2, with 0 % beads by volume. Portrays data from Table A-3.

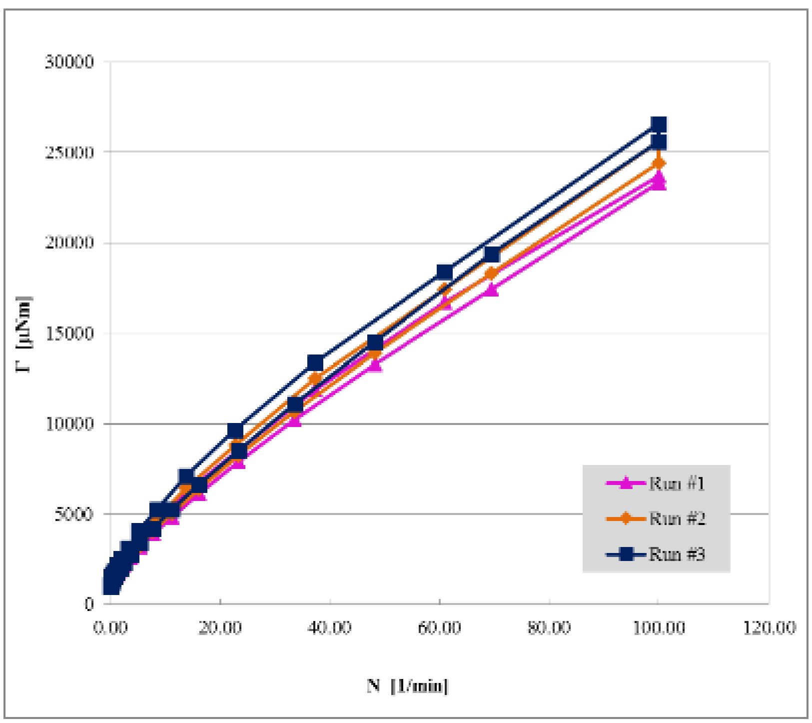


Figure A - 2: Torque vs. Angular Speed using <u>six-blade vane</u> on Mix#2, with 40 % beads by volume. Portrays data from Table A-4.

Table A - 5: Measured data for Mix#2 with 0 % beads using Serrated Coaxial Cylinder.

Serrated Coaxial Cylinder						Bead %		
Geom.:	SS18			Z43S		0%		
Run #1		Run #2		Run #3		Average values		
NIST Code: SMC-79G		NIST Code: SMC-79H		NIST Code: SMC-79I				
N	Γ	N	Γ	N	Γ	**N**	**Γ**	***Γ/N*** *(Angular*
1/min	μNm	1/min	μNm	1/min	μNm	**rad/s**	**Nm**	*momentum)*
0.0978	480	0.1	375	0.099	331	*0.010*	*3.95E-04*	*3.82E-02*
0.164	624	0.164	405	0.164	405	*0.017*	*4.78E-04*	*2.78E-02*
0.268	661	0.268	445	0.268	449	*0.028*	*5.18E-04*	*1.85E-02*
0.44	708	0.439	501	0.439	502	*0.046*	*5.70E-04*	*1.24E-02*
0.72	774	0.719	578	0.72	570	*0.075*	*6.41E-04*	*8.50E-03*
1.18	865	1.18	675	1.18	660	*0.124*	*7.33E-04*	*5.93E-03*
1.93	989	1.93	808	1.93	783	*0.202*	*8.60E-04*	*4.26E-03*
3.16	1160	3.16	986	3.16	955	*0.331*	*1.03E-03*	*3.12E-03*
5.18	1410	5.18	1230	5.18	1200	*0.542*	*1.28E-03*	*2.36E-03*
8.48	1770	8.48	1580	8.48	1540	*0.888*	*1.63E-03*	*1.84E-03*
13.9	2280	13.9	2070	13.9	2040	*1.456*	*2.13E-03*	*1.46E-03*
22.8	3030	22.8	2780	22.8	2760	*2.388*	*2.86E-03*	*1.20E-03*
37.3	4190	37.3	3880	37.3	3850	*3.906*	*3.97E-03*	*1.02E-03*
61.1	5930	61.1	5570	61.1	5540	*6.398*	*5.68E-03*	*8.88E-04*
100	8570	100	8150	100	8100	*10.472*	*8.27E-03*	*7.90E-04*
100	8450	100	8110	100	8060	*10.472*	*8.21E-03*	*7.84E-04*
69.5	6340	69.5	6090	69.5	6070	*7.278*	*6.17E-03*	*8.47E-04*
48.3	4780	48.3	4600	48.3	4570	*5.058*	*4.65E-03*	*9.19E-04*
33.6	3650	33.6	3520	33.6	3490	*3.519*	*3.55E-03*	*1.01E-03*
23.4	2840	23.4	2730	23.4	2710	*2.450*	*2.76E-03*	*1.13E-03*
16.2	2250	16.2	2170	16.2	2150	*1.696*	*2.19E-03*	*1.29E-03*
11.3	1820	11.3	1740	11.3	1730	*1.183*	*1.76E-03*	*1.49E-03*
7.85	1490	7.85	1430	7.85	1410	*0.822*	*1.44E-03*	*1.76E-03*
5.46	1240	5.46	1190	5.46	1170	*0.572*	*1.20E-03*	*2.10E-03*
3.79	1050	3.79	999	3.79	985	*0.397*	*1.01E-03*	*2.55E-03*
2.64	900	2.64	852	2.64	840	*0.276*	*8.64E-04*	*3.13E-03*
1.83	780	1.83	737	1.83	728	*0.192*	*7.48E-04*	*3.90E-03*
1.27	685	1.27	646	1.27	637	*0.133*	*6.56E-04*	*4.93E-03*
0.886	608	0.886	573	0.886	566	*0.093*	*5.82E-04*	*6.28E-03*
0.616	545	0.616	515	0.616	508	*0.065*	*5.23E-04*	*8.10E-03*
0.428	495	0.428	468	0.428	462	*0.045*	*4.75E-04*	*1.06E-02*
0.298	454	0.298	430	0.298	425	*0.031*	*4.36E-04*	*1.40E-02*
0.207	421	0.207	399	0.207	396	*0.022*	*4.05E-04*	*1.87E-02*
0.144	394	0.144	374	0.144	371	*0.015*	*3.80E-04*	*2.52E-02*
0.1	373	0.1	355	0.1	352	*0.010*	*3.60E-04*	*3.44E-02*

Table A - 6: Measured data for Mix#2 with 40 % beads using Serrated Coaxial Cylinder.

Serrated Coaxial Cylinder						Bead %		
Geom.: SS18				*Z43S*		*40%*		
Run #1		Run #2		Run #3		**Average values**		
NIST Code: SMC-79P		*NIST Code: SMC-79Q*		*NIST Code: SMC-79R*				
N	Γ	N	Γ	N	Γ	**N**	**Γ**	***Γ/N*** *(Angular*
1/min	μNm	1/min	μNm	1/min	μNm	**rad/s**	**Nm**	*momentum)*
0.0987	1050	0.0984	1040	0.0994	766	*0.010*	*9.52E-04*	*9.20E-02*
0.163	1270	0.164	1180	0.164	819	*0.017*	*1.09E-03*	*6.36E-02*
0.27	1260	0.268	1200	0.268	896	*0.028*	*1.12E-03*	*3.98E-02*
0.439	1270	0.441	1280	0.439	1010	*0.046*	*1.19E-03*	*2.58E-02*
0.719	1400	0.72	1440	0.719	1160	*0.075*	*1.33E-03*	*1.77E-02*
1.18	1620	1.18	1680	1.18	1400	*0.124*	*1.57E-03*	*1.27E-02*
1.93	1920	1.93	2030	1.93	1720	*0.202*	*1.89E-03*	*9.35E-03*
3.17	2400	3.17	2550	3.16	2200	*0.332*	*2.38E-03*	*7.19E-03*
5.18	3070	5.18	3300	5.18	2890	*0.542*	*3.09E-03*	*5.69E-03*
8.48	4080	8.48	4420	8.48	3930	*0.888*	*4.14E-03*	*4.67E-03*
13.9	5560	13.9	6020	13.9	5460	*1.456*	*5.68E-03*	*3.90E-03*
22.8	7710	22.8	8370	22.8	7780	*2.388*	*7.95E-03*	*3.33E-03*
37.3	10800	37.3	11900	37.3	11300	*3.906*	*1.13E-02*	*2.90E-03*
61.1	14800	61	16800	61.1	16600	*6.395*	*1.61E-02*	*2.51E-03*
100	19900	100	21900	100	24400	*10.472*	*2.21E-02*	*2.11E-03*
100	19900	100	21000	100	24100	*10.472*	*2.17E-02*	*2.07E-03*
69.5	15800	69.5	17100	69.5	17900	*7.278*	*1.69E-02*	*2.33E-03*
48.3	12400	48.3	12900	48.3	13400	*5.058*	*1.29E-02*	*2.55E-03*
33.6	9700	33.6	10200	33.6	10200	*3.519*	*1.00E-02*	*2.85E-03*
23.4	7450	23.4	7890	23.4	7730	*2.450*	*7.69E-03*	*3.14E-03*
16.2	5700	16.2	6070	16.2	5930	*1.696*	*5.90E-03*	*3.48E-03*
11.3	4430	11.3	4720	11.3	4640	*1.183*	*4.60E-03*	*3.88E-03*
7.85	3540	7.84	3760	7.85	3680	*0.822*	*3.66E-03*	*4.45E-03*
5.46	2860	5.45	2980	5.46	2950	*0.571*	*2.93E-03*	*5.13E-03*
3.79	2330	3.79	2460	3.79	2420	*0.397*	*2.40E-03*	*6.06E-03*
2.64	1940	2.64	2050	2.64	2000	*0.276*	*2.00E-03*	*7.22E-03*
1.84	1650	1.83	1730	1.83	1710	*0.192*	*1.70E-03*	*8.84E-03*
1.27	1430	1.27	1490	1.27	1480	*0.133*	*1.47E-03*	*1.10E-02*
0.885	1250	0.885	1310	0.886	1290	*0.093*	*1.28E-03*	*1.38E-02*
0.615	1110	0.617	1170	0.616	1140	*0.065*	*1.14E-03*	*1.77E-02*
0.427	1000	0.427	1060	0.428	1030	*0.045*	*1.03E-03*	*2.30E-02*
0.298	917	0.297	962	0.298	945	*0.031*	*9.41E-04*	*3.02E-02*
0.206	853	0.207	884	0.207	880	*0.022*	*8.72E-04*	*4.03E-02*
0.144	789	0.143	815	0.144	813	*0.015*	*8.06E-04*	*5.36E-02*
0.1	746	0.0994	776	0.1	771	*0.010*	*7.64E-04*	*7.31E-02*

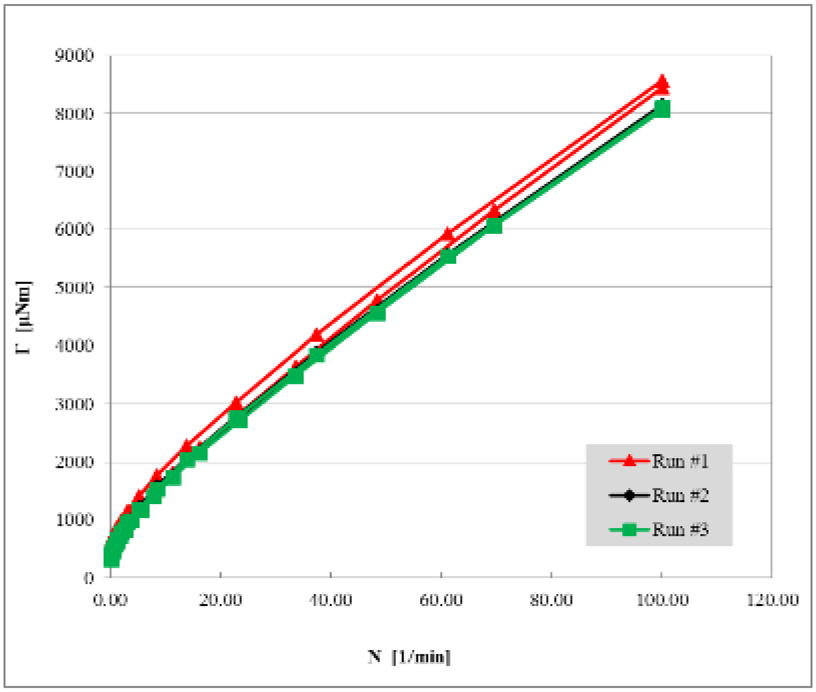


Figure A - 3: Torque vs. Angular Speed using <u>Serrated Coaxial Cylinder</u> on Mix#2, with 0 % beads by volume. Portrays data from Table A-5.

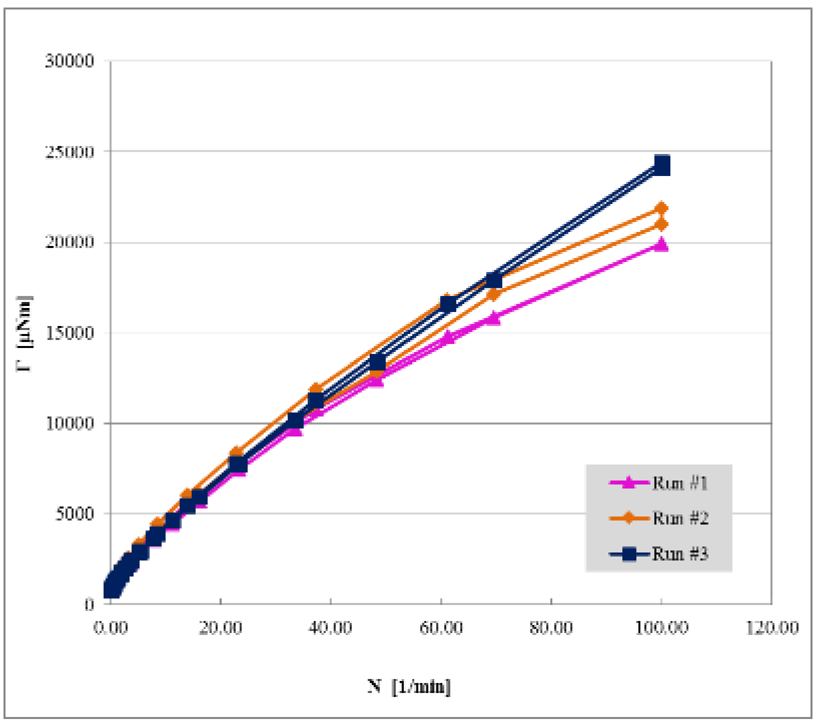


Figure A - 4: Torque vs. Angular Speed using <u>Serrated Coaxial Cylinder</u> on Mix#2, with 40 % beads by volume. Portrays data from Table A-6.

Table A - 7: Measured data for Mix#3 with 0 % beads using Double spiral spindle.

Double Spiral								
Geom.: RHN-83A				*Cup: Z43S*		*Bead % 0%*		
Run #1		Run #2		Run #3		**Average values**		
NIST Code: SMC-81D		*NIST Code: SMC-81E*		*NIST Code: SMC-81F*				
N	Γ	N	Γ	N	Γ	**N**	**Γ**	***Γ/N*** *(Angular*
1/min	μNm	1/min	μNm	1/min	μNm	**rad/s**	**Nm**	*momentum)*
0.0941	1070	0.1	1520	0.1	1520	*0.010*	*1.37E-03*	*1.33E-01*
0.161	1570	0.164	1570	0.164	1560	*0.017*	*1.57E-03*	*9.18E-02*
0.268	1760	0.269	1630	0.268	1620	*0.028*	*1.67E-03*	*5.94E-02*
0.44	1870	0.441	1720	0.44	1710	*0.046*	*1.77E-03*	*3.83E-02*
0.72	1990	0.72	1850	0.72	1840	*0.075*	*1.89E-03*	*2.51E-02*
1.18	2160	1.18	2040	1.18	2020	*0.124*	*2.07E-03*	*1.68E-02*
1.93	2420	1.93	2310	1.93	2290	*0.202*	*2.34E-03*	*1.16E-02*
3.16	2820	3.16	2740	3.16	2720	*0.331*	*2.76E-03*	*8.34E-03*
5.18	3460	5.18	3390	5.18	3370	*0.542*	*3.41E-03*	*6.28E-03*
8.48	4450	8.48	4380	8.48	4350	*0.888*	*4.39E-03*	*4.95E-03*
13.9	6010	13.9	5890	13.9	5840	*1.456*	*5.91E-03*	*4.06E-03*
22.8	8460	22.8	8360	22.8	8310	*2.388*	*8.38E-03*	*3.51E-03*
37.3	12400	37.3	12200	37.3	12100	*3.906*	*1.22E-02*	*3.13E-03*
61.1	18500	61.1	18200	61.1	18100	*6.398*	*1.83E-02*	*2.85E-03*
100	28000	100	27700	100	27500	*10.472*	*2.77E-02*	*2.65E-03*
100	27800	100	27600	100	27300	*10.472*	*2.76E-02*	*2.63E-03*
69.5	20300	69.5	20200	69.5	20000	*7.278*	*2.02E-02*	*2.77E-03*
48.3	15000	48.3	14900	48.3	14800	*5.058*	*1.49E-02*	*2.95E-03*
33.6	11200	33.6	11100	33.6	11000	*3.519*	*1.11E-02*	*3.15E-03*
23.4	8500	23.4	8440	23.4	8380	*2.450*	*8.44E-03*	*3.44E-03*
16.2	6570	16.2	6530	16.2	6480	*1.696*	*6.53E-03*	*3.85E-03*
11.3	5180	11.3	5150	11.3	5120	*1.183*	*5.15E-03*	*4.35E-03*
7.85	4190	7.85	4170	7.85	4140	*0.822*	*4.17E-03*	*5.07E-03*
5.46	3470	5.46	3450	5.46	3430	*0.572*	*3.45E-03*	*6.03E-03*
3.79	2950	3.79	2930	3.79	2910	*0.397*	*2.93E-03*	*7.38E-03*
2.64	2560	2.64	2550	2.64	2530	*0.276*	*2.55E-03*	*9.21E-03*
1.83	2280	1.83	2270	1.83	2260	*0.192*	*2.27E-03*	*1.18E-02*
1.27	2070	1.27	2060	1.27	2050	*0.133*	*2.06E-03*	*1.55E-02*
0.886	1910	0.886	1900	0.886	1890	*0.093*	*1.90E-03*	*2.05E-02*
0.616	1780	0.616	1780	0.616	1770	*0.065*	*1.78E-03*	*2.75E-02*
0.428	1700	0.427	1690	0.428	1680	*0.045*	*1.69E-03*	*3.77E-02*
0.297	1620	0.298	1620	0.298	1610	*0.031*	*1.62E-03*	*5.19E-02*
0.207	1570	0.207	1560	0.207	1550	*0.022*	*1.56E-03*	*7.20E-02*
0.144	1520	0.144	1520	0.144	1510	*0.015*	*1.52E-03*	*1.01E-01*
0.0993	1490	0.0998	1480	0.0998	1470	*0.010*	*1.48E-03*	*1.42E-01*

Table A - 8: Measured data for Mix#3 with 40 % beads using Double spiral spindle.

Double Spiral								
Geom.: RHN-83A				*Cup: Z43S*		*Bead %* *40%*		
Run #1		Run #2		Run #3		**Average values**		
NIST Code: SMC-81M		*NIST Code: SMC-81N*		*NIST Code: SMC-81O*				
N	Γ	N	Γ	N	Γ	**N**	**Γ**	***Γ/N*** *(Angular*
1/min	µNm	1/min	µNm	1/min	µNm	**rad/s**	**Nm**	*momentum)*
0.0883	2530	0.0873	2390	0.093	3160	*0.009*	*2.69E-03*	*2.87E-01*
0.158	3600	0.16	3390	0.162	3680	*0.017*	*3.56E-03*	*2.12E-01*
0.267	4240	0.264	4020	0.268	4160	*0.028*	*4.14E-03*	*1.48E-01*
0.442	4850	0.444	4580	0.445	4620	*0.046*	*4.68E-03*	*1.01E-01*
0.711	5560	0.72	5310	0.717	5440	*0.075*	*5.44E-03*	*7.25E-02*
1.17	6520	1.19	6250	1.18	6580	*0.124*	*6.45E-03*	*5.22E-02*
1.93	8090	1.92	7710	1.94	8290	*0.202*	*8.03E-03*	*3.97E-02*
3.16	10600	3.14	10100	3.16	10900	*0.330*	*1.05E-02*	*3.19E-02*
5.17	14500	5.17	13900	5.18	14600	*0.542*	*1.43E-02*	*2.65E-02*
8.47	20000	8.48	19700	8.5	20000	*0.888*	*1.99E-02*	*2.24E-02*
13.9	27500	13.9	27700	13.9	28400	*1.456*	*2.79E-02*	*1.91E-02*
22.8	38300	22.8	38500	22.7	41200	*2.384*	*3.93E-02*	*1.65E-02*
37.3	56400	37.3	57200	37.3	60600	*3.906*	*5.81E-02*	*1.49E-02*
61.1	80100	61.1	83000	61.1	88900	*6.398*	*8.40E-02*	*1.31E-02*
100	110000	100	116000	100	123000	*10.472*	*1.16E-01*	*1.11E-02*
100	105000	100	111000	100	118000	*10.472*	*1.11E-01*	*1.06E-02*
69.6	74500	69.5	78900	69.6	84000	*7.285*	*7.91E-02*	*1.09E-02*
48.3	54000	48.3	57100	48.4	61100	*5.061*	*5.74E-02*	*1.13E-02*
33.6	39700	33.6	42100	33.6	44900	*3.519*	*4.22E-02*	*1.20E-02*
23.4	29700	23.4	31600	23.4	33600	*2.450*	*3.16E-02*	*1.29E-02*
16.2	24300	16.3	25000	16.2	26300	*1.700*	*2.52E-02*	*1.48E-02*
11.3	19100	11.3	19900	11.3	20600	*1.183*	*1.99E-02*	*1.68E-02*
7.86	15100	7.85	15500	7.88	16200	*0.823*	*1.56E-02*	*1.89E-02*
5.46	11900	5.45	12200	5.46	12700	*0.571*	*1.23E-02*	*2.15E-02*
3.8	9520	3.79	9990	3.79	10200	*0.397*	*9.90E-03*	*2.49E-02*
2.64	7760	2.64	8190	2.63	8360	*0.276*	*8.10E-03*	*2.93E-02*
1.83	6510	1.83	6790	1.83	6950	*0.192*	*6.75E-03*	*3.52E-02*
1.27	5560	1.28	5780	1.28	5930	*0.134*	*5.76E-03*	*4.31E-02*
0.89	4840	0.882	5030	0.884	5190	*0.093*	*5.02E-03*	*5.41E-02*
0.618	4350	0.62	4530	0.62	4650	*0.065*	*4.51E-03*	*6.95E-02*
0.422	3890	0.422	4080	0.427	4220	*0.044*	*4.06E-03*	*9.16E-02*
0.3	3620	0.299	3770	0.297	3920	*0.031*	*3.77E-03*	*1.21E-01*
0.204	3350	0.207	3470	0.208	3610	*0.022*	*3.48E-03*	*1.61E-01*
0.143	3150	0.143	3290	0.144	3390	*0.015*	*3.28E-03*	*2.18E-01*
0.0992	3050	0.101	3170	0.0989	3250	*0.010*	*3.16E-03*	*3.02E-01*

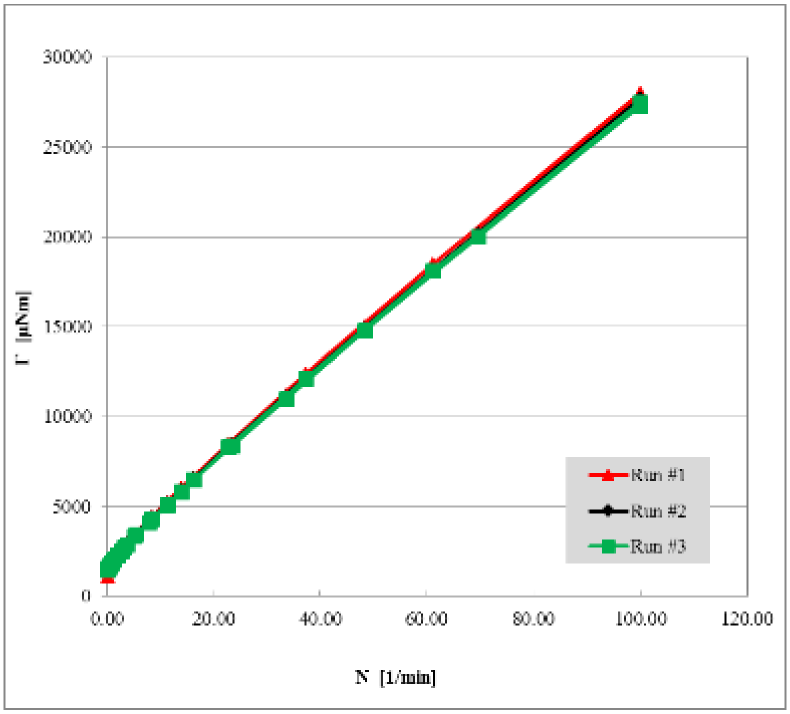


Figure A - 7: Torque vs. Angular Speed using <u>Double spiral spindle</u> on Mix#3, with 0 % beads by volume. Portrays data from Table A-7.

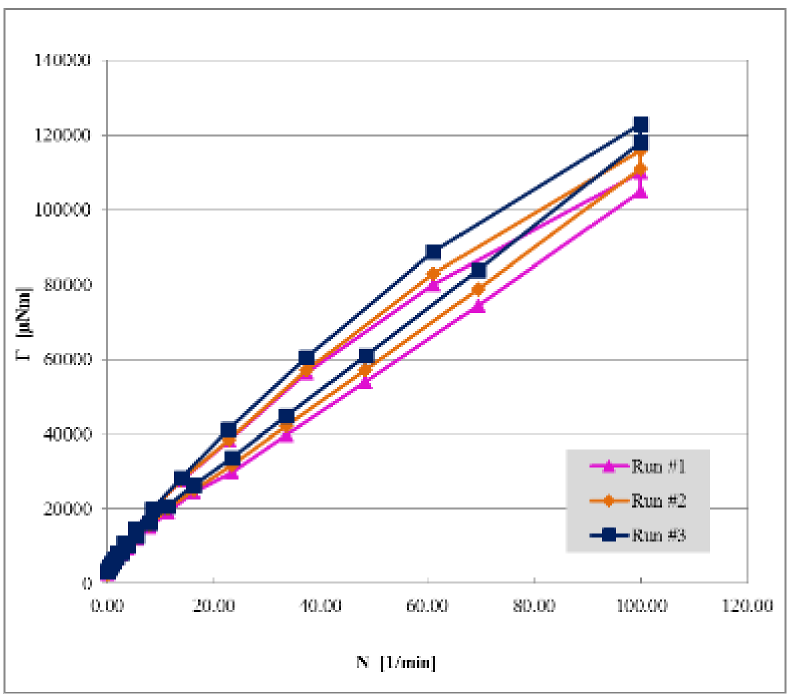


Figure A - 8: Torque vs. Angular Speed using <u>Double spiral spindle</u> on Mix#3, with 40 % beads by volume. Portrays data from Table A-8.

Table A - 9: Measured data for Mix#3 with 0 % beads using Six-blade Vane.

		6 Blade Vane					*Bead %*	
Geom.:	*RHN-83C*			*Z43S*			*0%*	
Run #1		Run #2		Run #3		**Average values**		
NIST Code: SMC-81A		*NIST Code: SMC-81B*		*NIST Code: SMC-81C*				
N	Γ	N	Γ	N	Γ	**N**	**Γ**	*Γ/N (Angular momentum)*
1/min	µNm	1/min	µNm	1/min	µNm	**rad/s**	**Nm**	
0.0978	433	0.0984	525	0.0977	430	*0.010*	*4.63E-04*	*4.51E-02*
0.163	574	0.164	538	0.163	575	*0.017*	*5.62E-04*	*3.29E-02*
0.268	618	0.268	567	0.268	615	*0.028*	*6.00E-04*	*2.14E-02*
0.439	653	0.44	612	0.439	649	*0.046*	*6.38E-04*	*1.39E-02*
0.72	704	0.72	662	0.72	700	*0.075*	*6.89E-04*	*9.13E-03*
1.18	777	1.18	736	1.18	774	*0.124*	*7.62E-04*	*6.17E-03*
1.93	877	1.93	838	1.93	876	*0.202*	*8.64E-04*	*4.27E-03*
3.16	1020	3.16	983	3.16	1020	*0.331*	*1.01E-03*	*3.05E-03*
5.18	1230	5.18	1190	5.18	1230	*0.542*	*1.22E-03*	*2.24E-03*
8.48	1520	8.48	1470	8.48	1530	*0.888*	*1.51E-03*	*1.70E-03*
13.9	1960	13.9	1900	13.9	1970	*1.456*	*1.94E-03*	*1.34E-03*
22.8	2590	22.8	2530	22.8	2610	*2.388*	*2.58E-03*	*1.08E-03*
37.3	3570	37.3	3500	37.3	3600	*3.906*	*3.56E-03*	*9.11E-04*
61	5060	61	4990	61	5110	*6.388*	*5.05E-03*	*7.91E-04*
100	7410	100	7330	100	7480	*10.472*	*7.41E-03*	*7.07E-04*
100	7390	100	7320	100	7460	*10.472*	*7.39E-03*	*7.06E-04*
69.5	5560	69.5	5500	69.5	5590	*7.278*	*5.55E-03*	*7.63E-04*
48.3	4230	48.3	4190	48.3	4250	*5.058*	*4.22E-03*	*8.35E-04*
33.6	3270	33.6	3240	33.6	3280	*3.519*	*3.26E-03*	*9.27E-04*
23.4	2570	23.4	2550	23.4	2590	*2.450*	*2.57E-03*	*1.05E-03*
16.2	2070	16.2	2050	16.2	2080	*1.696*	*2.07E-03*	*1.22E-03*
11.3	1700	11.3	1690	11.3	1700	*1.183*	*1.70E-03*	*1.43E-03*
7.85	1420	7.85	1410	7.85	1420	*0.822*	*1.42E-03*	*1.72E-03*
5.45	1210	5.45	1190	5.45	1210	*0.571*	*1.20E-03*	*2.11E-03*
3.79	1040	3.79	1030	3.79	1040	*0.397*	*1.04E-03*	*2.61E-03*
2.64	917	2.64	907	2.64	916	*0.276*	*9.13E-04*	*3.30E-03*
1.83	820	1.83	810	1.83	818	*0.192*	*8.16E-04*	*4.26E-03*
1.27	744	1.27	735	1.27	742	*0.133*	*7.40E-04*	*5.57E-03*
0.886	684	0.886	675	0.886	682	*0.093*	*6.80E-04*	*7.33E-03*
0.616	637	0.616	628	0.616	634	*0.065*	*6.33E-04*	*9.81E-03*
0.428	599	0.426	596	0.428	596	*0.045*	*5.97E-04*	*1.33E-02*
0.298	569	0.298	561	0.298	565	*0.031*	*5.65E-04*	*1.81E-02*
0.207	544	0.207	537	0.207	541	*0.022*	*5.41E-04*	*2.49E-02*
0.144	525	0.144	518	0.144	521	*0.015*	*5.21E-04*	*3.46E-02*
0.0999	510	0.0999	502	0.0996	506	*0.010*	*5.06E-04*	*4.84E-02*

Table A - 10: Measured data for Mix#3 with 40 % beads using Six-blade Vane.

6 Blade Vane						Bead %		
Geom.:	*RHN-83C*			*Z43S*		*40%*		
Run #1		Run #2		Run #3		**Average values**		
NIST Code: SMC-81J		*NIST Code: SMC-81K*		*NIST Code: SMC-81L*				
N	Γ	N	Γ	N	Γ	**N**	**Γ**	***Γ/N*** *(Angular*
1/min	µNm	1/min	µNm	1/min	µNm	**rad/s**	**Nm**	*momentum)*
0.0957	1070	0.0963	1080	0.0976	1050	*0.010*	*1.07E-03*	*1.06E-01*
0.163	1360	0.164	1340	0.161	1320	*0.017*	*1.34E-03*	*7.87E-02*
0.266	1480	0.269	1460	0.266	1430	*0.028*	*1.46E-03*	*5.21E-02*
0.441	1640	0.443	1610	0.438	1580	*0.046*	*1.61E-03*	*3.49E-02*
0.721	1800	0.717	1750	0.717	1750	*0.075*	*1.77E-03*	*2.35E-02*
1.18	2070	1.18	2020	1.19	2040	*0.124*	*2.04E-03*	*1.65E-02*
1.94	2430	1.94	2390	1.93	2440	*0.203*	*2.42E-03*	*1.19E-02*
3.17	2970	3.17	2960	3.16	3000	*0.332*	*2.98E-03*	*8.98E-03*
5.17	3730	5.18	3770	5.18	3820	*0.542*	*3.77E-03*	*6.96E-03*
8.48	4890	8.49	4890	8.48	5050	*0.888*	*4.94E-03*	*5.56E-03*
13.9	6430	13.9	6430	13.9	6770	*1.456*	*6.54E-03*	*4.50E-03*
22.8	8770	22.8	8730	22.8	9210	*2.388*	*8.90E-03*	*3.73E-03*
37.3	11900	37.3	12300	37.3	12700	*3.906*	*1.23E-02*	*3.15E-03*
61.1	16200	61.1	17200	61.1	17900	*6.398*	*1.71E-02*	*2.67E-03*
100	23800	100	24600	100	25700	*10.472*	*2.47E-02*	*2.36E-03*
100	22600	99.9	23800	99.9	25200	*10.465*	*2.39E-02*	*2.28E-03*
69.5	17100	69.5	17400	69.5	18000	*7.278*	*1.75E-02*	*2.40E-03*
48.3	12600	48.3	13000	48.3	13500	*5.058*	*1.30E-02*	*2.58E-03*
33.6	9590	33.6	10000	33.6	10400	*3.519*	*1.00E-02*	*2.84E-03*
23.4	7380	23.4	7650	23.4	7990	*2.450*	*7.67E-03*	*3.13E-03*
16.2	5800	16.2	5960	16.2	6240	*1.696*	*6.00E-03*	*3.54E-03*
11.3	4590	11.3	4730	11.3	4910	*1.183*	*4.74E-03*	*4.01E-03*
7.85	3680	7.85	3790	7.85	3950	*0.822*	*3.81E-03*	*4.63E-03*
5.46	3000	5.45	3070	5.46	3170	*0.571*	*3.08E-03*	*5.39E-03*
3.79	2490	3.79	2550	3.79	2600	*0.397*	*2.55E-03*	*6.42E-03*
2.64	2080	2.64	2130	2.64	2170	*0.276*	*2.13E-03*	*7.69E-03*
1.83	1800	1.83	1800	1.83	1870	*0.192*	*1.82E-03*	*9.51E-03*
1.27	1570	1.28	1580	1.27	1630	*0.133*	*1.59E-03*	*1.19E-02*
0.888	1380	0.884	1400	0.884	1460	*0.093*	*1.41E-03*	*1.52E-02*
0.613	1260	0.611	1260	0.62	1310	*0.064*	*1.28E-03*	*1.98E-02*
0.429	1150	0.429	1160	0.429	1200	*0.045*	*1.17E-03*	*2.60E-02*
0.297	1090	0.298	1090	0.298	1110	*0.031*	*1.10E-03*	*3.52E-02*
0.207	1020	0.206	1040	0.207	1050	*0.022*	*1.04E-03*	*4.79E-02*
0.145	974	0.143	970	0.143	995	*0.015*	*9.80E-04*	*6.51E-02*
0.101	930	0.0992	945	0.1	958	*0.010*	*9.44E-04*	*9.01E-02*

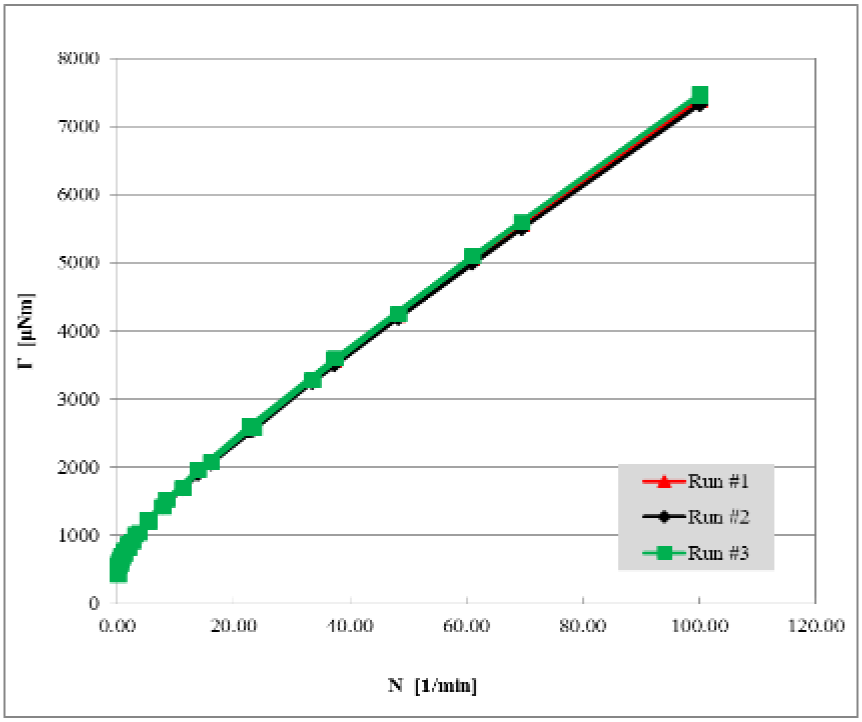


Figure A - 5: Torque vs. Angular Speed using <u>six-blade vane</u> on Mix#3, with 0 % beads by volume. Portrays data from Table A-9.

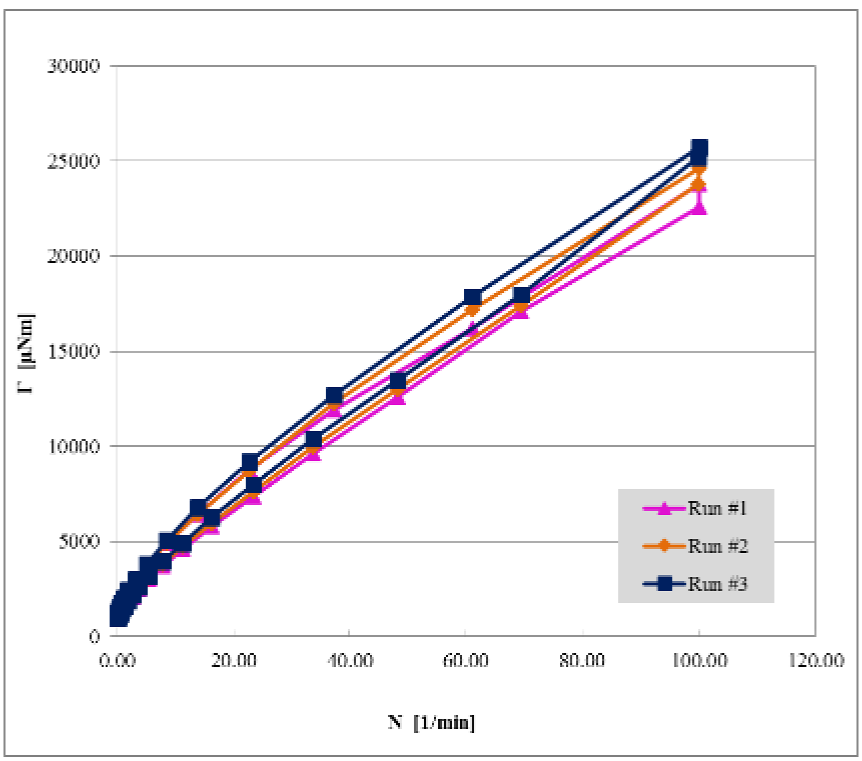


Figure A - 6: Torque vs. Angular Speed using <u>six-blade vane</u> on Mix#3, with 40 % beads by volume. Portrays data from Table A-10.

Table A - 11: Measured data for Mix#3 with 0 % beads using Serrated Coaxial Cylinder.

Serrated Coaxial Cylinder						Bead %		
Geom.:	*SS18*			*Z43S*		*0%*		
Run #1		Run #2		Run #3		**Average values**		
NIST Code: SMC-81G		*NIST Code: SMC-81H*		*NIST Code: SMC-81I*				
N	Γ	N	Γ	N	Γ	**N**	**Γ**	*Γ/N (Angular*
1/min	μNm	1/min	μNm	1/min	μNm	**rad/s**	**Nm**	*momentum)*
0.0977	442	0.1	351	0.099	322	*0.010*	*3.72E-04*	*3.59E-02*
0.164	591	0.164	379	0.164	393	*0.017*	*4.54E-04*	*2.65E-02*
0.268	623	0.268	420	0.268	438	*0.028*	*4.94E-04*	*1.76E-02*
0.44	665	0.439	475	0.439	496	*0.046*	*5.45E-04*	*1.19E-02*
0.72	725	0.72	551	0.719	573	*0.075*	*6.16E-04*	*8.18E-03*
1.18	808	1.18	650	1.18	666	*0.124*	*7.08E-04*	*5.73E-03*
1.93	925	1.93	765	1.93	783	*0.202*	*8.24E-04*	*4.08E-03*
3.16	1090	3.16	932	3.16	937	*0.331*	*9.86E-04*	*2.98E-03*
5.18	1320	5.18	1160	5.18	1160	*0.542*	*1.21E-03*	*2.24E-03*
8.48	1640	8.48	1480	8.48	1480	*0.888*	*1.53E-03*	*1.73E-03*
13.9	2110	13.9	1930	13.9	1940	*1.456*	*1.99E-03*	*1.37E-03*
22.8	2800	22.8	2590	22.8	2610	*2.388*	*2.67E-03*	*1.12E-03*
37.3	3860	37.3	3610	37.3	3650	*3.906*	*3.71E-03*	*9.49E-04*
61	5520	61	5190	61	5240	*6.388*	*5.32E-03*	*8.32E-04*
100	8030	100	7590	100	7640	*10.472*	*7.75E-03*	*7.40E-04*
100	7900	100	7520	100	7590	*10.472*	*7.67E-03*	*7.32E-04*
69.5	5910	69.5	5640	69.5	5680	*7.278*	*5.74E-03*	*7.89E-04*
48.3	4460	48.3	4260	48.3	4290	*5.058*	*4.34E-03*	*8.57E-04*
33.6	3410	33.6	3270	33.6	3280	*3.519*	*3.32E-03*	*9.44E-04*
23.4	2660	23.4	2550	23.4	2550	*2.450*	*2.59E-03*	*1.06E-03*
16.2	2110	16.2	2020	16.2	2030	*1.696*	*2.05E-03*	*1.21E-03*
11.3	1710	11.3	1640	11.3	1640	*1.183*	*1.66E-03*	*1.41E-03*
7.85	1410	7.85	1340	7.85	1340	*0.822*	*1.36E-03*	*1.66E-03*
5.45	1170	5.45	1110	5.45	1110	*0.571*	*1.13E-03*	*1.98E-03*
3.79	991	3.79	940	3.79	941	*0.397*	*9.57E-04*	*2.41E-03*
2.64	850	2.64	804	2.64	806	*0.276*	*8.20E-04*	*2.97E-03*
1.83	737	1.83	697	1.83	700	*0.192*	*7.11E-04*	*3.71E-03*
1.27	647	1.27	612	1.27	616	*0.133*	*6.25E-04*	*4.70E-03*
0.886	574	0.886	543	0.886	548	*0.093*	*5.55E-04*	*5.98E-03*
0.616	514	0.616	485	0.616	494	*0.065*	*4.98E-04*	*7.71E-03*
0.428	466	0.427	441	0.428	449	*0.045*	*4.52E-04*	*1.01E-02*
0.298	427	0.298	407	0.298	413	*0.031*	*4.16E-04*	*1.33E-02*
0.207	395	0.207	377	0.207	383	*0.022*	*3.85E-04*	*1.78E-02*
0.144	370	0.144	355	0.144	360	*0.015*	*3.62E-04*	*2.40E-02*
0.1	348	0.1	336	0.1	343	*0.010*	*3.42E-04*	*3.27E-02*

Table A - 12: Measured data for Mix#3 with 40 % beads using Serrated Coaxial Cylinder.

Serrated Coaxial Cylinder						Bead %		
Geom.:	*SS18*			*Z43S*		*40%*		
Run #1		Run #2		Run #3		**Average values**		
NIST Code: SMC-81P		*NIST Code: SMC-81Q*		*NIST Code: SMC-81R*				
N	Γ	N	Γ	N	Γ	**N**	**Γ**	***Γ/N*** *(Angular*
1/min	μNm	1/min	μNm	1/min	μNm	**rad/s**	**Nm**	*momentum)*
0.0949	1530	0.0973	1140	0.0963	1250	*0.010*	*1.31E-03*	*1.30E-01*
0.162	1920	0.164	1340	0.164	1480	*0.017*	*1.58E-03*	*9.24E-02*
0.271	2020	0.268	1360	0.271	1510	*0.028*	*1.63E-03*	*5.76E-02*
0.442	2040	0.44	1460	0.441	1590	*0.046*	*1.70E-03*	*3.67E-02*
0.717	2200	0.722	1590	0.719	1770	*0.075*	*1.85E-03*	*2.46E-02*
1.18	2320	1.18	1860	1.18	2080	*0.124*	*2.09E-03*	*1.69E-02*
1.93	2660	1.93	2290	1.93	2560	*0.202*	*2.50E-03*	*1.24E-02*
3.16	3140	3.16	2850	3.16	3200	*0.331*	*3.06E-03*	*9.26E-03*
5.18	3900	5.18	3720	5.18	4140	*0.542*	*3.92E-03*	*7.23E-03*
8.48	5050	8.48	4990	8.48	5520	*0.888*	*5.19E-03*	*5.84E-03*
13.9	6690	13.9	6890	13.9	7480	*1.456*	*7.02E-03*	*4.82E-03*
22.8	9090	22.8	9700	22.8	10400	*2.388*	*9.73E-03*	*4.08E-03*
37.3	12700	37.3	13900	37.3	14600	*3.906*	*1.37E-02*	*3.52E-03*
61	16500	61	18900	61.1	20400	*6.391*	*1.86E-02*	*2.91E-03*
99.9	23000	100	24500	100	26300	*10.468*	*2.46E-02*	*2.35E-03*
100	22300	100	26600	100	25500	*10.472*	*2.48E-02*	*2.37E-03*
69.5	18400	69.5	20200	69.5	20600	*7.278*	*1.97E-02*	*2.71E-03*
48.3	14100	48.3	15200	48.3	15600	*5.058*	*1.50E-02*	*2.96E-03*
33.6	10800	33.6	11600	33.6	11900	*3.519*	*1.14E-02*	*3.25E-03*
23.4	8270	23.4	8780	23.4	9020	*2.450*	*8.69E-03*	*3.55E-03*
16.2	6400	16.2	6750	16.2	6950	*1.696*	*6.70E-03*	*3.95E-03*
11.3	4980	11.3	5250	11.3	5400	*1.183*	*5.21E-03*	*4.40E-03*
7.85	3950	7.85	4130	7.84	4290	*0.822*	*4.12E-03*	*5.02E-03*
5.45	3170	5.46	3290	5.45	3420	*0.571*	*3.29E-03*	*5.77E-03*
3.79	2600	3.79	2690	3.79	2810	*0.397*	*2.70E-03*	*6.80E-03*
2.64	2140	2.64	2230	2.64	2320	*0.276*	*2.23E-03*	*8.07E-03*
1.83	1800	1.83	1890	1.83	1950	*0.192*	*1.88E-03*	*9.81E-03*
1.27	1560	1.27	1610	1.27	1700	*0.133*	*1.62E-03*	*1.22E-02*
0.886	1350	0.886	1410	0.884	1470	*0.093*	*1.41E-03*	*1.52E-02*
0.615	1200	0.616	1260	0.614	1310	*0.064*	*1.26E-03*	*1.95E-02*
0.427	1080	0.427	1120	0.429	1170	*0.045*	*1.12E-03*	*2.51E-02*
0.299	994	0.299	1020	0.298	1080	*0.031*	*1.03E-03*	*3.30E-02*
0.207	909	0.207	949	0.207	989	*0.022*	*9.49E-04*	*4.38E-02*
0.143	839	0.144	876	0.143	917	*0.015*	*8.77E-04*	*5.85E-02*
0.1	794	0.101	828	0.0995	863	*0.010*	*8.28E-04*	*7.90E-02*

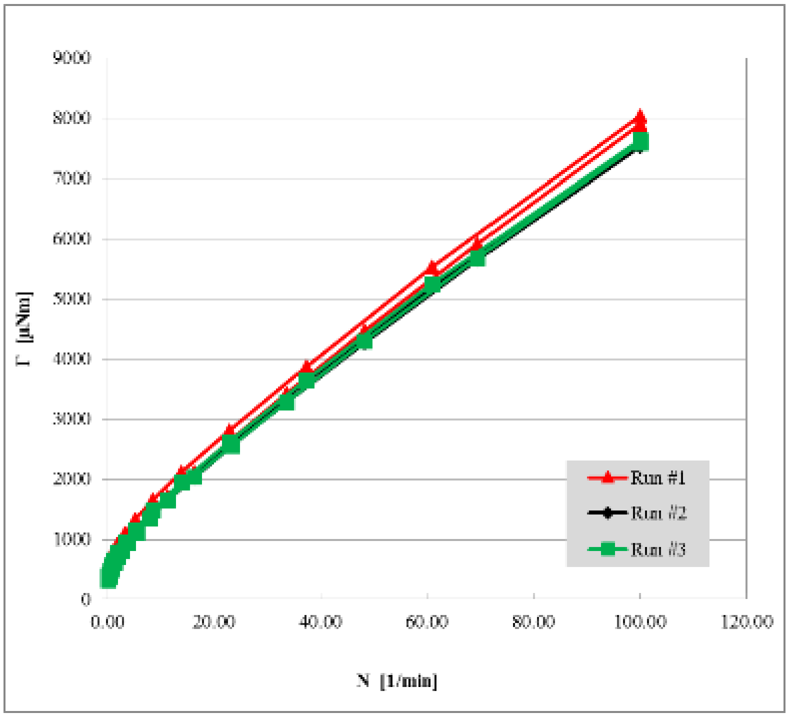


Figure A - 7: Torque vs. Angular Speed using <u>Serrated Coaxial Cylinder</u> on Mix#3, with 0 % beads by volume. Portrays data from Table A-11.

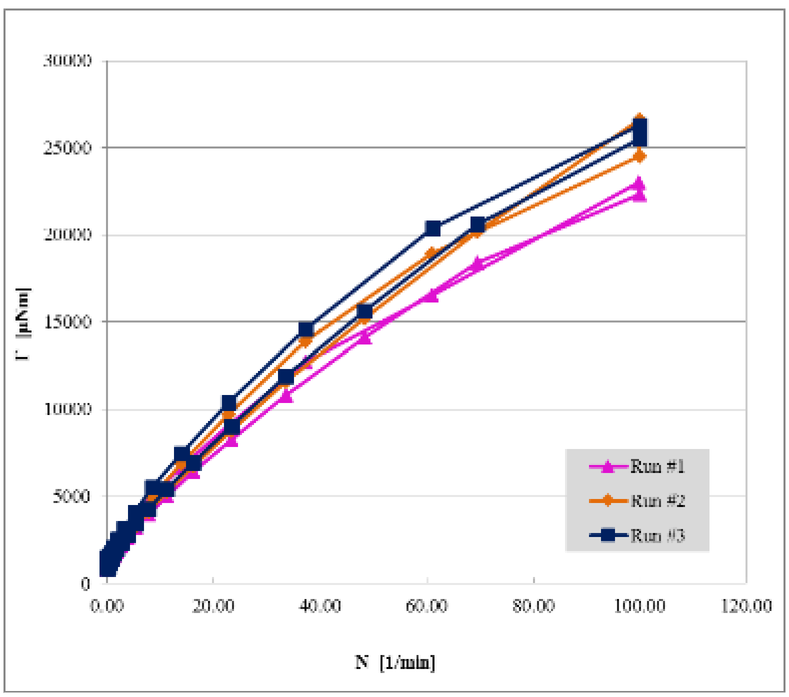


Figure A - 8: Torque vs. Angular Speed using <u>Serrated Coaxial Cylinder</u> on Mix#3, with 40 % beads by volume. Portrays data from Table A-12.

Table A - 13: Measured data for Mix#4 with 0 % beads using Double spiral spindle.

Double Spiral								Bead %
Geom.:	*RHN-83A*			*Cup:*	*Z43S*		*0%*	
Run #1		Run #2		Run #3		**Average values**		
NIST Code: SMC-85J		*NIST Code: SMC-85K*		*NIST Code: SMC-85L*				
N	Γ	N	Γ	N	Γ	**N**	**Γ**	***Γ/N*** *(Angular*
1/min	μNm	1/min	μNm	1/min	μNm	**rad/s**	**Nm**	*momentum)*
0.0942	1080	0.0948	964	0.0949	952	*0.010*	*9.99E-04*	*1.01E-01*
0.161	1570	0.162	1420	0.162	1390	*0.017*	*1.46E-03*	*8.62E-02*
0.268	1750	0.268	1610	0.268	1590	*0.028*	*1.65E-03*	*5.88E-02*
0.44	1860	0.439	1720	0.439	1700	*0.046*	*1.76E-03*	*3.83E-02*
0.72	1970	0.72	1850	0.72	1830	*0.075*	*1.88E-03*	*2.50E-02*
1.18	2140	1.18	2030	1.18	2010	*0.124*	*2.06E-03*	*1.67E-02*
1.93	2380	1.93	2280	1.93	2270	*0.202*	*2.31E-03*	*1.14E-02*
3.16	2770	3.16	2680	3.16	2670	*0.331*	*2.71E-03*	*8.18E-03*
5.18	3370	5.18	3290	5.18	3290	*0.542*	*3.32E-03*	*6.11E-03*
8.48	4310	8.48	4220	8.48	4220	*0.888*	*4.25E-03*	*4.79E-03*
13.9	5780	13.9	5710	13.9	5700	*1.456*	*5.73E-03*	*3.94E-03*
22.8	8100	22.8	8020	22.8	8020	*2.388*	*8.05E-03*	*3.37E-03*
37.3	11800	37.3	11700	37.3	11700	*3.906*	*1.17E-02*	*3.00E-03*
61.1	17500	61.1	17500	61.1	17400	*6.398*	*1.75E-02*	*2.73E-03*
100	26400	100	26500	100	26400	*10.472*	*2.64E-02*	*2.52E-03*
100	26200	100	26300	100	26300	*10.472*	*2.63E-02*	*2.51E-03*
69.5	19100	69.5	19200	69.5	19200	*7.278*	*1.92E-02*	*2.63E-03*
48.3	14100	48.3	14200	48.3	14200	*5.058*	*1.42E-02*	*2.80E-03*
33.6	10600	33.6	10600	33.6	10600	*3.519*	*1.06E-02*	*3.01E-03*
23.4	8060	23.4	8110	23.4	8110	*2.450*	*8.09E-03*	*3.30E-03*
16.2	6260	16.2	6290	16.2	6290	*1.696*	*6.28E-03*	*3.70E-03*
11.3	4960	11.3	4990	11.3	4990	*1.183*	*4.98E-03*	*4.21E-03*
7.85	4030	7.85	4050	7.85	4050	*0.822*	*4.04E-03*	*4.92E-03*
5.46	3350	5.46	3370	5.46	3360	*0.572*	*3.36E-03*	*5.88E-03*
3.79	2860	3.79	2870	3.79	2870	*0.397*	*2.87E-03*	*7.22E-03*
2.64	2500	2.64	2510	2.64	2500	*0.276*	*2.50E-03*	*9.05E-03*
1.83	2240	1.83	2240	1.83	2230	*0.192*	*2.24E-03*	*1.17E-02*
1.27	2030	1.27	2030	1.27	2030	*0.133*	*2.03E-03*	*1.53E-02*
0.886	1880	0.886	1880	0.886	1880	*0.093*	*1.88E-03*	*2.03E-02*
0.616	1770	0.616	1770	0.616	1760	*0.065*	*1.77E-03*	*2.74E-02*
0.428	1690	0.428	1680	0.428	1680	*0.045*	*1.68E-03*	*3.76E-02*
0.297	1620	0.297	1610	0.297	1610	*0.031*	*1.61E-03*	*5.19E-02*
0.207	1560	0.207	1560	0.207	1550	*0.022*	*1.56E-03*	*7.18E-02*
0.144	1520	0.144	1520	0.144	1510	*0.015*	*1.52E-03*	*1.01E-01*
0.0998	1490	0.0998	1490	0.0998	1480	*0.010*	*1.49E-03*	*1.42E-01*

Table A - 14: Measured data for Mix#4 with 40 % beads using Double spiral spindle.

Geom.: *RHN-83A*	Double Spiral			*Cup:* *Z43S*		*Bead %* *40%*		
Run #1		Run #2		Run #3		**Average values**		
NIST Code: SMC-85A		*NIST Code: SMC-85B*		*NIST Code: SMC-85C*				
N	Γ	N	Γ	N	Γ	**N**	**Γ**	***Γ/N*** *(Angular*
1/min	μNm	1/min	μNm	1/min	μNm	**rad/s**	**Nm**	*momentum)*
0.44	4720	0.0873	2370	0.0887	2490	*0.022*	*3.19E-03*	*1.49E-01*
0.44	4720	0.161	3330	0.155	3500	*0.026*	*3.85E-03*	*1.46E-01*
0.44	4720	0.263	3810	0.267	4060	*0.034*	*4.20E-03*	*1.24E-01*
0.44	4720	0.436	4360	0.441	4620	*0.046*	*4.57E-03*	*9.93E-02*
0.719	5410	0.721	4930	0.724	5190	*0.076*	*5.18E-03*	*6.85E-02*
1.17	6440	1.19	5780	1.19	6120	*0.124*	*6.11E-03*	*4.93E-02*
1.93	7750	1.93	7130	1.93	7410	*0.202*	*7.43E-03*	*3.68E-02*
3.16	9950	3.16	9060	3.17	9460	*0.331*	*9.49E-03*	*2.86E-02*
5.19	13300	5.17	12300	5.18	12800	*0.542*	*1.28E-02*	*2.36E-02*
8.48	18700	8.49	17400	8.48	18100	*0.888*	*1.81E-02*	*2.03E-02*
13.9	26300	13.9	24700	13.9	25400	*1.456*	*2.55E-02*	*1.75E-02*
22.8	37400	22.8	35000	22.8	35500	*2.388*	*3.60E-02*	*1.51E-02*
37.3	54100	37.3	51700	37.3	52100	*3.906*	*5.26E-02*	*1.35E-02*
61	78400	61.1	76300	61.1	76300	*6.395*	*7.70E-02*	*1.20E-02*
100	90500	100	89600	100	95100	*10.472*	*9.17E-02*	*8.76E-03*
100	82600	100	85000	100	90400	*10.472*	*8.60E-02*	*8.21E-03*
69.6	59200	69.5	60900	69.5	64700	*7.282*	*6.16E-02*	*8.46E-03*
48.3	43400	48.4	44700	48.4	47200	*5.065*	*4.51E-02*	*8.90E-03*
33.6	33100	33.6	33900	33.6	35500	*3.519*	*3.42E-02*	*9.71E-03*
23.4	26900	23.3	27200	23.4	27700	*2.447*	*2.73E-02*	*1.11E-02*
16.2	22000	16.2	22700	16.2	23400	*1.696*	*2.27E-02*	*1.34E-02*
11.3	17800	11.3	18600	11.3	19100	*1.183*	*1.85E-02*	*1.56E-02*
7.86	13800	7.84	14400	7.84	14800	*0.822*	*1.43E-02*	*1.74E-02*
5.45	10800	5.45	11300	5.45	11700	*0.571*	*1.13E-02*	*1.97E-02*
3.8	8790	3.8	9080	3.8	9360	*0.398*	*9.08E-03*	*2.28E-02*
2.63	7280	2.64	7470	2.63	7660	*0.276*	*7.47E-03*	*2.71E-02*
1.84	6090	1.83	6300	1.82	6470	*0.192*	*6.29E-03*	*3.28E-02*
1.27	5230	1.27	5450	1.28	5550	*0.133*	*5.41E-03*	*4.06E-02*
0.886	4640	0.887	4780	0.879	4910	*0.093*	*4.78E-03*	*5.16E-02*
0.615	4120	0.617	4260	0.615	4380	*0.064*	*4.25E-03*	*6.60E-02*
0.428	3730	0.428	3870	0.43	3990	*0.045*	*3.86E-03*	*8.61E-02*
0.3	3510	0.296	3570	0.298	3670	*0.031*	*3.58E-03*	*1.15E-01*
0.207	3280	0.207	3390	0.206	3440	*0.022*	*3.37E-03*	*1.56E-01*
0.145	3080	0.146	3190	0.142	3290	*0.015*	*3.19E-03*	*2.11E-01*
0.101	2970	0.1	3080	0.0991	3150	*0.010*	*3.07E-03*	*2.93E-01*

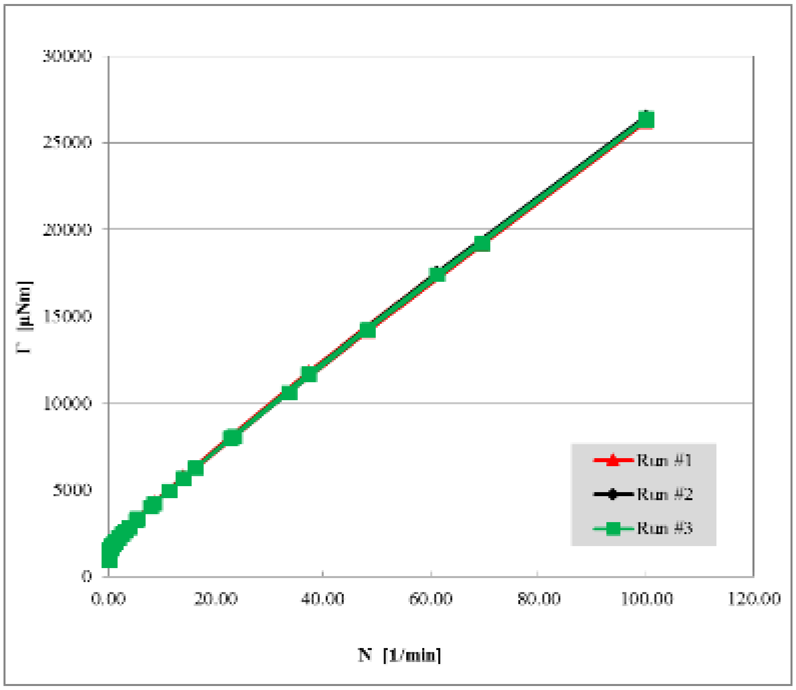


Figure A - 9: Torque vs. Angular Speed using <u>Double spiral spindle</u> on Mix#4, with 0 % beads by volume. Portrays data from Table A-13.

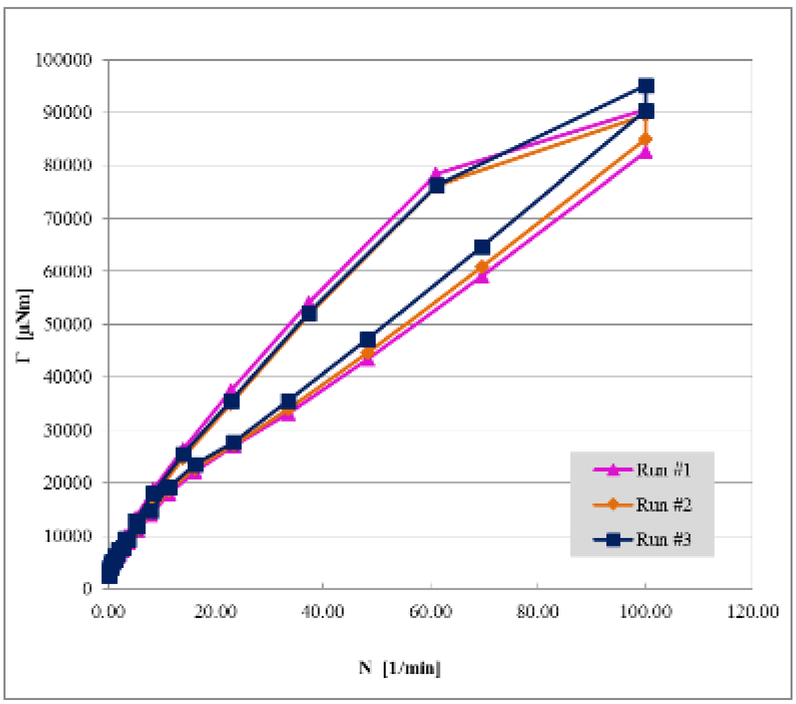


Figure A - 10: Torque vs. Angular Speed using <u>Double spiral spindle</u> on Mix#4, with 40 % beads by volume. Portrays data from Table A-14.

Table A - 15: Measured data for Mix#4 with 0 % beads using Six-blade Vane

		6 Blade Vane					Bead %	
Geom.:	*RHN-83C*			*Z43S*			*0%*	
Run #1		Run #2		Run #3		**Average values**		
NIST Code: SMC-85P		*NIST Code: SMC-85Q*		*NIST Code: SMC-85R*				
N	Γ	N	Γ	N	Γ	**N**	**Γ**	***Γ/N*** *(Angular*
1/min	µNm	1/min	µNm	1/min	µNm	**rad/s**	**Nm**	*momentum)*
0.0978	428	0.1	517	0.1	514	*0.010*	*4.86E-04*	*4.68E-02*
0.163	569	0.164	540	0.164	537	*0.017*	*5.49E-04*	*3.20E-02*
0.268	611	0.268	570	0.268	570	*0.028*	*5.84E-04*	*2.08E-02*
0.439	645	0.437	618	0.439	608	*0.046*	*6.24E-04*	*1.36E-02*
0.72	697	0.72	669	0.72	665	*0.075*	*6.77E-04*	*8.98E-03*
1.18	769	1.18	744	1.18	739	*0.124*	*7.51E-04*	*6.07E-03*
1.93	873	1.93	848	1.93	843	*0.202*	*8.55E-04*	*4.23E-03*
3.16	1020	3.16	993	3.16	989	*0.331*	*1.00E-03*	*3.02E-03*
5.18	1220	5.18	1200	5.18	1190	*0.542*	*1.20E-03*	*2.22E-03*
8.48	1530	8.48	1490	8.48	1490	*0.888*	*1.50E-03*	*1.69E-03*
13.9	1970	13.9	1930	13.9	1930	*1.456*	*1.94E-03*	*1.34E-03*
22.8	2610	22.8	2570	22.8	2570	*2.388*	*2.58E-03*	*1.08E-03*
37.3	3610	37.3	3560	37.3	3570	*3.906*	*3.58E-03*	*9.17E-04*
61	5150	61	5100	61	5100	*6.388*	*5.12E-03*	*8.01E-04*
100	7550	100	7520	100	7530	*10.472*	*7.53E-03*	*7.19E-04*
100	7540	100	7550	100	7550	*10.472*	*7.55E-03*	*7.21E-04*
69.5	5650	69.5	5660	69.5	5660	*7.278*	*5.66E-03*	*7.77E-04*
48.3	4290	48.3	4300	48.3	4300	*5.058*	*4.30E-03*	*8.49E-04*
33.6	3320	33.6	3320	33.6	3320	*3.519*	*3.32E-03*	*9.44E-04*
23.4	2610	23.4	2620	23.4	2620	*2.450*	*2.62E-03*	*1.07E-03*
16.2	2100	16.2	2100	16.2	2100	*1.696*	*2.10E-03*	*1.24E-03*
11.3	1720	11.3	1720	11.3	1720	*1.183*	*1.72E-03*	*1.45E-03*
7.85	1440	7.85	1440	7.85	1430	*0.822*	*1.44E-03*	*1.75E-03*
5.45	1220	5.45	1220	5.45	1220	*0.571*	*1.22E-03*	*2.14E-03*
3.79	1050	3.79	1050	3.79	1050	*0.397*	*1.05E-03*	*2.65E-03*
2.64	927	2.64	925	2.64	921	*0.276*	*9.24E-04*	*3.34E-03*
1.83	828	1.83	826	1.83	822	*0.192*	*8.25E-04*	*4.31E-03*
1.27	751	1.27	748	1.27	744	*0.133*	*7.48E-04*	*5.62E-03*
0.886	690	0.886	687	0.884	686	*0.093*	*6.88E-04*	*7.42E-03*
0.616	642	0.616	641	0.616	635	*0.065*	*6.39E-04*	*9.91E-03*
0.428	603	0.428	600	0.428	596	*0.045*	*6.00E-04*	*1.34E-02*
0.298	573	0.298	569	0.298	566	*0.031*	*5.69E-04*	*1.82E-02*
0.207	548	0.208	547	0.207	541	*0.022*	*5.45E-04*	*2.51E-02*
0.144	528	0.144	525	0.144	522	*0.015*	*5.25E-04*	*3.48E-02*
0.0999	512	0.0997	515	0.0999	505	*0.010*	*5.11E-04*	*4.88E-02*

Table A - 16: Measured data for Mix#4 with 40 % beads using Six-blade Vane.

6 Blade Vane						Bead %		
Geom.:	RHN-83C			Z43S		40%		
Run #1		Run #2		Run #3		Average values		
NIST Code: SMC-85G		NIST Code: SMC-85H		NIST Code: SMC-85I				
N	Γ	N	Γ	N	Γ	N	Γ	Γ/N (Angular momentum)
1/min	µNm	1/min	µNm	1/min	µNm	rad/s	Nm	
0.0941	1350	0.095	1420	0.0927	1500	0.010	1.42E-03	1.45E-01
0.161	1710	0.166	1830	0.163	1900	0.017	1.81E-03	1.06E-01
0.274	1840	0.264	1950	0.272	2090	0.028	1.96E-03	6.93E-02
0.44	2020	0.439	2130	0.44	2210	0.046	2.12E-03	4.60E-02
0.72	2240	0.72	2330	0.719	2470	0.075	2.35E-03	3.11E-02
1.18	2530	1.18	2680	1.18	2830	0.124	2.68E-03	2.17E-02
1.93	3010	1.94	3110	1.93	3390	0.202	3.17E-03	1.57E-02
3.16	3760	3.16	3840	3.15	4170	0.331	3.92E-03	1.19E-02
5.17	4710	5.17	4860	5.18	5230	0.542	4.93E-03	9.11E-03
8.48	6130	8.48	6310	8.49	6790	0.888	6.41E-03	7.22E-03
13.9	8070	13.9	8290	13.9	8870	1.456	8.41E-03	5.78E-03
22.7	10800	22.8	11100	22.8	11900	2.384	1.13E-02	4.73E-03
37.3	14500	37.3	15300	37.3	16300	3.906	1.54E-02	3.93E-03
61	20700	61.1	21300	61.1	22100	6.395	2.14E-02	3.34E-03
100	28100	100	30400	100	30500	10.472	2.97E-02	2.83E-03
100	27000	100	28300	100	28800	10.472	2.80E-02	2.68E-03
69.5	20800	69.5	21700	69.5	22200	7.278	2.16E-02	2.96E-03
48.3	15500	48.3	16000	48.3	16500	5.058	1.60E-02	3.16E-03
33.6	11800	33.6	12300	33.6	12600	3.519	1.22E-02	3.48E-03
23.4	9180	23.4	9420	23.4	9680	2.450	9.43E-03	3.85E-03
16.2	7190	16.2	7360	16.2	7570	1.696	7.37E-03	4.35E-03
11.3	5640	11.3	5900	11.3	5980	1.183	5.84E-03	4.94E-03
7.84	4510	7.83	4610	7.84	4730	0.821	4.62E-03	5.63E-03
5.45	3650	5.46	3760	5.45	3870	0.571	3.76E-03	6.58E-03
3.79	3000	3.8	3080	3.79	3200	0.397	3.09E-03	7.79E-03
2.64	2560	2.63	2630	2.63	2660	0.276	2.62E-03	9.49E-03
1.84	2180	1.84	2190	1.83	2250	0.192	2.21E-03	1.15E-02
1.28	1890	1.27	1920	1.28	1970	0.134	1.93E-03	1.44E-02
0.882	1670	0.882	1720	0.885	1720	0.092	1.70E-03	1.84E-02
0.617	1500	0.615	1540	0.613	1570	0.064	1.54E-03	2.39E-02
0.425	1400	0.43	1390	0.431	1440	0.045	1.41E-03	3.14E-02
0.3	1270	0.3	1310	0.3	1320	0.031	1.30E-03	4.14E-02
0.205	1180	0.208	1210	0.205	1230	0.022	1.21E-03	5.59E-02
0.144	1140	0.143	1160	0.144	1200	0.015	1.17E-03	7.75E-02
0.1	1090	0.101	1110	0.0993	1110	0.010	1.10E-03	1.05E-01

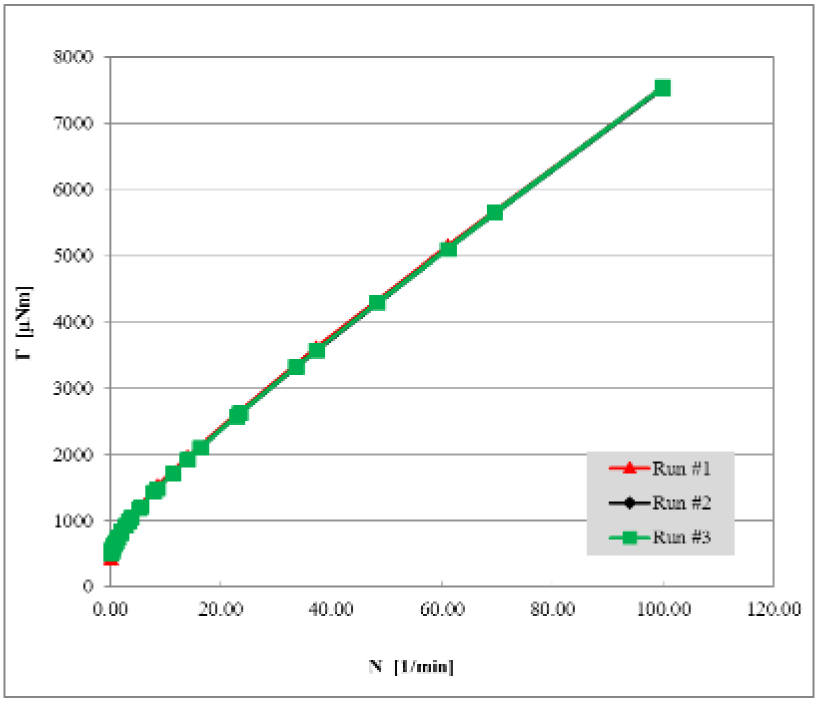


Figure A - 12: Torque vs. Angular Speed using __six-blade vane__ on Mix#4, with 0 % beads by volume. Portrays data from Table A-15.

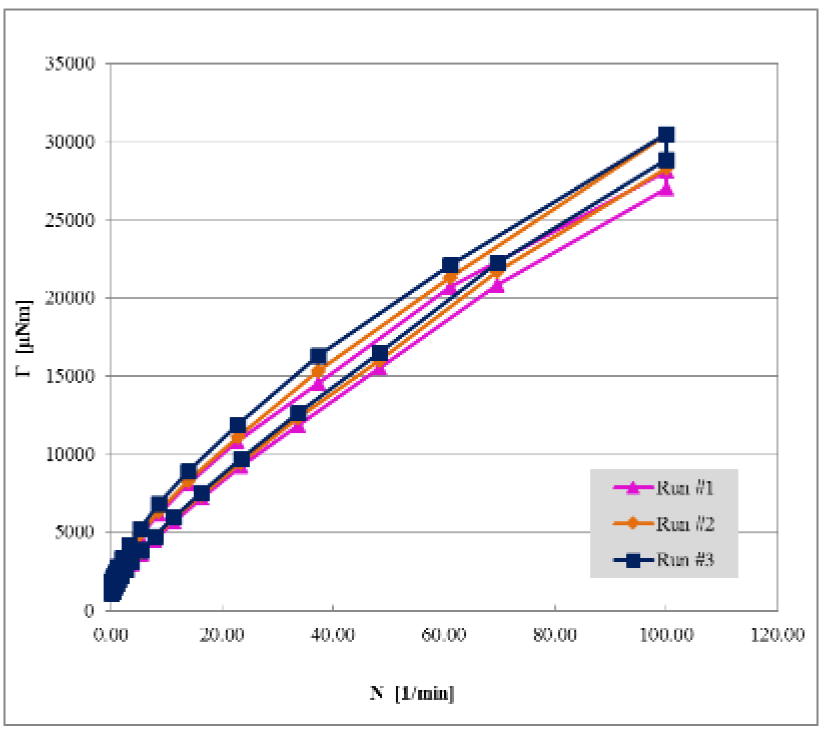


Figure A - 11: Torque vs. Angular Speed using __six-blade vane__ on Mix#4, with 40 % beads by volume. Portrays data from Table A-16.

Table A - 17: Measured data for Mix#4 with 0 % beads using Serrated Coaxial Cylinder.

Serrated Coaxial Cylinder *Geom.:* *SS18*				*Z43S*		*Bead %* *0%*		
Run #1		Run #2		Run #3		**Average values**		
NIST Code: SMC-85M		*NIST Code: SMC-85N*		*NIST Code: SMC-85O*				
N	Γ	N	Γ	N	Γ	**N**	**Γ**	***Γ/N*** *(Angular*
1/min	μNm	1/min	μNm	1/min	μNm	**rad/s**	**Nm**	*momentum)*
0.0983	449	0.099	340	0.1	348	*0.010*	*3.79E-04*	*3.65E-02*
0.164	564	0.164	413	0.164	373	*0.017*	*4.50E-04*	*2.62E-02*
0.268	598	0.268	454	0.268	409	*0.028*	*4.87E-04*	*1.74E-02*
0.44	641	0.439	503	0.439	454	*0.046*	*5.33E-04*	*1.16E-02*
0.72	700	0.72	568	0.72	516	*0.075*	*5.95E-04*	*7.89E-03*
1.18	781	1.18	656	1.18	604	*0.124*	*6.80E-04*	*5.51E-03*
1.93	891	1.93	773	1.93	718	*0.202*	*7.94E-04*	*3.93E-03*
3.16	1040	3.16	932	3.16	881	*0.331*	*9.51E-04*	*2.87E-03*
5.18	1260	5.18	1150	5.18	1100	*0.542*	*1.17E-03*	*2.16E-03*
8.48	1580	8.48	1460	8.48	1400	*0.888*	*1.48E-03*	*1.67E-03*
13.9	2030	13.9	1910	13.9	1830	*1.456*	*1.92E-03*	*1.32E-03*
22.8	2680	22.8	2560	22.8	2460	*2.388*	*2.57E-03*	*1.07E-03*
37.3	3690	37.3	3540	37.3	3430	*3.906*	*3.55E-03*	*9.10E-04*
61	5240	61	5060	61	4920	*6.388*	*5.07E-03*	*7.94E-04*
100	7710	100	7420	100	7240	*10.472*	*7.46E-03*	*7.12E-04*
100	7600	100	7380	100	7200	*10.472*	*7.39E-03*	*7.06E-04*
69.5	5690	69.5	5540	69.5	5400	*7.278*	*5.54E-03*	*7.62E-04*
48.3	4300	48.3	4180	48.3	4090	*5.058*	*4.19E-03*	*8.28E-04*
33.6	3300	33.6	3210	33.6	3140	*3.519*	*3.22E-03*	*9.14E-04*
23.4	2580	23.4	2510	23.4	2460	*2.450*	*2.52E-03*	*1.03E-03*
16.2	2050	16.2	1990	16.2	1950	*1.696*	*2.00E-03*	*1.18E-03*
11.3	1670	11.3	1620	11.3	1580	*1.183*	*1.62E-03*	*1.37E-03*
7.85	1380	7.85	1330	7.85	1300	*0.822*	*1.34E-03*	*1.63E-03*
5.46	1150	5.45	1110	5.45	1080	*0.571*	*1.11E-03*	*1.95E-03*
3.79	980	3.79	936	3.79	912	*0.397*	*9.43E-04*	*2.38E-03*
2.64	843	2.64	802	2.64	781	*0.276*	*8.09E-04*	*2.93E-03*
1.83	734	1.83	696	1.83	679	*0.192*	*7.03E-04*	*3.67E-03*
1.27	646	1.27	612	1.27	597	*0.133*	*6.18E-04*	*4.65E-03*
0.886	576	0.886	545	0.886	532	*0.093*	*5.51E-04*	*5.94E-03*
0.616	519	0.616	491	0.616	480	*0.065*	*4.97E-04*	*7.70E-03*
0.428	473	0.428	449	0.429	441	*0.045*	*4.54E-04*	*1.01E-02*
0.298	435	0.298	415	0.298	405	*0.031*	*4.18E-04*	*1.34E-02*
0.207	405	0.207	386	0.207	377	*0.022*	*3.89E-04*	*1.80E-02*
0.144	381	0.144	363	0.144	355	*0.015*	*3.66E-04*	*2.43E-02*
0.1	361	0.1	345	0.1	337	*0.010*	*3.48E-04*	*3.32E-02*

Table A - 18: Measured data for Mix#4 with 40 % beads using Serrated Coaxial Cylinder.

Serrated Coaxial Cylinder						Bead %		
Geom.:	*SS18*			*Z43S*		*40%*		
Run #1		Run #2		Run #3		**Average values**		
NIST Code: SMC-85D		*NIST Code: SMC-85E*		*NIST Code: SMC-85F*				
N	Γ	N	Γ	N	Γ	**N**	**Γ**	***Γ/N*** *(Angular*
1/min	μNm	1/min	μNm	1/min	μNm	**rad/s**	**Nm**	*momentum)*
0.0975	1400	0.0964	1340	0.0972	1290	*0.010*	*1.34E-03*	*1.32E-01*
0.163	1660	0.165	1510	0.165	1450	*0.017*	*1.54E-03*	*8.95E-02*
0.272	1740	0.268	1480	0.268	1450	*0.028*	*1.56E-03*	*5.52E-02*
0.444	1810	0.441	1580	0.44	1550	*0.046*	*1.65E-03*	*3.56E-02*
0.718	1890	0.722	1770	0.722	1720	*0.075*	*1.79E-03*	*2.38E-02*
1.18	2100	1.18	2050	1.18	2040	*0.124*	*2.06E-03*	*1.67E-02*
1.93	2370	1.93	2460	1.93	2470	*0.202*	*2.43E-03*	*1.20E-02*
3.16	2820	3.16	3050	3.17	3100	*0.331*	*2.99E-03*	*9.03E-03*
5.18	3500	5.18	3870	5.17	3990	*0.542*	*3.79E-03*	*6.99E-03*
8.48	4530	8.49	5040	8.48	5210	*0.888*	*4.93E-03*	*5.55E-03*
13.9	5990	13.9	6730	13.9	7030	*1.456*	*6.58E-03*	*4.52E-03*
22.8	8060	22.8	9150	22.8	9630	*2.388*	*8.95E-03*	*3.75E-03*
37.3	11200	37.3	12500	37.3	13400	*3.906*	*1.24E-02*	*3.17E-03*
61	15500	61.1	16500	61.1	17400	*6.395*	*1.65E-02*	*2.57E-03*
100	20100	100	21900	100	25000	*10.472*	*2.23E-02*	*2.13E-03*
100	20400	100	22100	99.9	24900	*10.468*	*2.25E-02*	*2.15E-03*
69.5	16400	69.5	17800	69.5	19300	*7.278*	*1.78E-02*	*2.45E-03*
48.3	12600	48.3	13600	48.3	14400	*5.058*	*1.35E-02*	*2.68E-03*
33.6	9640	33.6	10400	33.6	11000	*3.519*	*1.03E-02*	*2.94E-03*
23.3	7400	23.3	7910	23.4	8360	*2.443*	*7.89E-03*	*3.23E-03*
16.2	5740	16.2	6140	16.2	6470	*1.696*	*6.12E-03*	*3.61E-03*
11.3	4490	11.3	4810	11.3	5090	*1.183*	*4.80E-03*	*4.05E-03*
7.85	3570	7.84	3800	7.85	4030	*0.822*	*3.80E-03*	*4.62E-03*
5.46	2900	5.46	3090	5.46	3240	*0.572*	*3.08E-03*	*5.38E-03*
3.79	2380	3.79	2530	3.79	2660	*0.397*	*2.52E-03*	*6.36E-03*
2.64	1980	2.64	2100	2.64	2210	*0.276*	*2.10E-03*	*7.58E-03*
1.83	1690	1.83	1790	1.83	1880	*0.192*	*1.79E-03*	*9.32E-03*
1.27	1460	1.28	1550	1.28	1620	*0.134*	*1.54E-03*	*1.15E-02*
0.886	1280	0.885	1350	0.886	1420	*0.093*	*1.35E-03*	*1.46E-02*
0.617	1150	0.614	1210	0.616	1260	*0.064*	*1.21E-03*	*1.87E-02*
0.429	1030	0.429	1080	0.427	1140	*0.045*	*1.08E-03*	*2.42E-02*
0.297	945	0.298	992	0.298	1040	*0.031*	*9.92E-04*	*3.18E-02*
0.209	882	0.206	914	0.208	967	*0.022*	*9.21E-04*	*4.24E-02*
0.144	814	0.145	867	0.144	888	*0.015*	*8.56E-04*	*5.67E-02*
0.0994	763	0.0989	799	0.0998	831	*0.010*	*7.98E-04*	*7.67E-02*

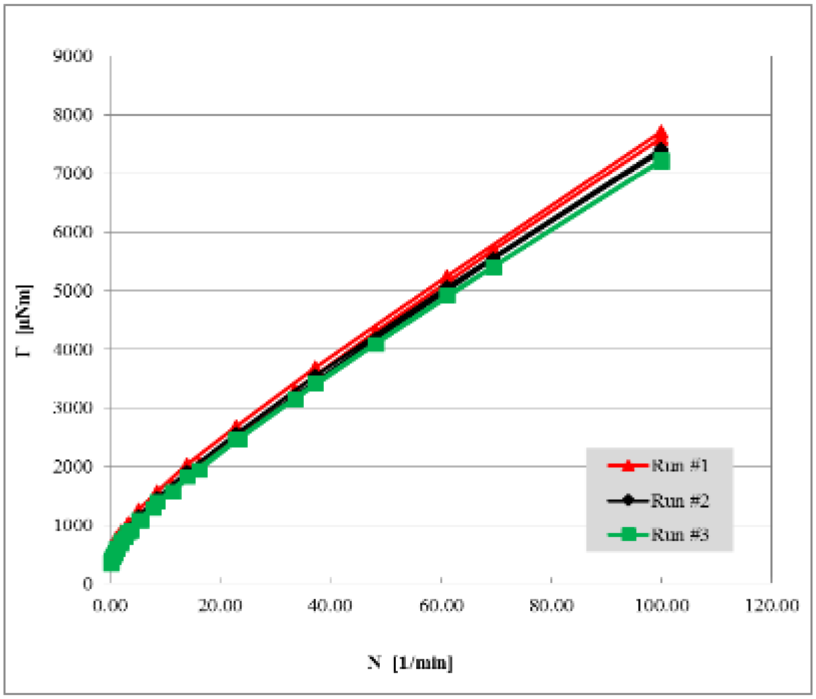


Figure A - 13: Torque vs. Angular Speed using <u>Serrated Coaxial Cylinder</u> on Mix#4, with 0 % beads by volume. Portrays data from Table A-17.

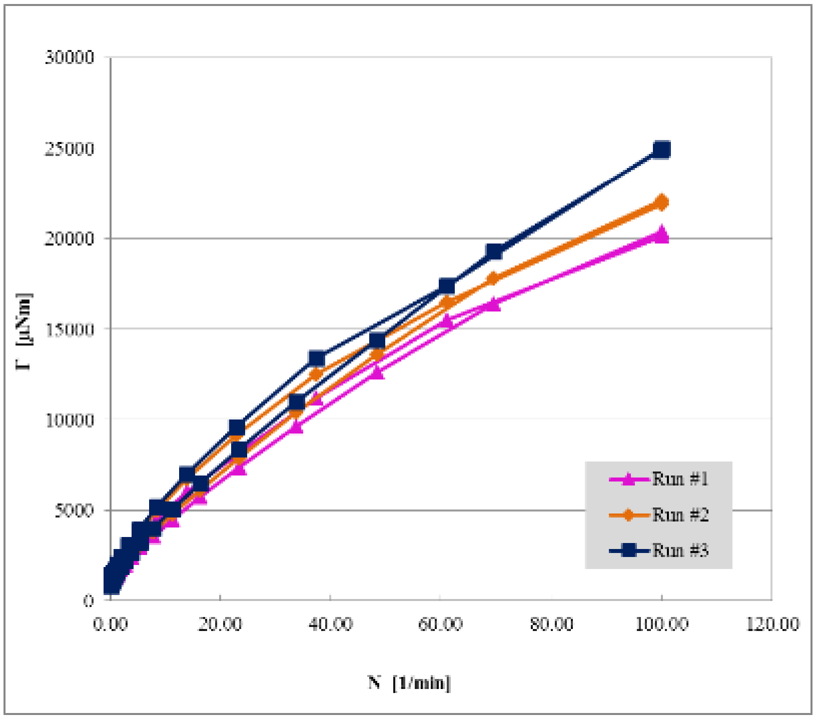


Figure A - 14: Torque vs. Angular Speed using <u>Serrated Coaxial Cylinder</u> on Mix#4, with 40 % beads by volume. Portrays data from Table A-18.

Table A - 19: Measured data for Mix#5 with 0 % beads using Double spiral spindle.

Double Spiral								Bead %
Geom.: RHN-83A				*Cup: Z43S*				*0%*
Run #1		Run #2		Run #3		**Average values**		
NIST Code: SMC-95D		*NIST Code: SMC-95E*		*NIST Code: SMC-95F*				
N	Γ	N	Γ	N	Γ	**N**	**Γ**	***Γ/N*** *(Angular*
1/min	μNm	1/min	μNm	1/min	μNm	**rad/s**	**Nm**	*momentum)*
0.0947	973	0.1	1420	0.095	902	*0.010*	*1.10E-03*	*1.09E-01*
0.162	1420	0.164	1470	0.162	1330	*0.017*	*1.41E-03*	*8.26E-02*
0.268	1590	0.268	1540	0.268	1510	*0.028*	*1.55E-03*	*5.51E-02*
0.44	1690	0.44	1620	0.44	1620	*0.046*	*1.64E-03*	*3.57E-02*
0.72	1800	0.72	1740	0.72	1740	*0.075*	*1.76E-03*	*2.33E-02*
1.18	1980	1.18	1920	1.18	1920	*0.124*	*1.94E-03*	*1.57E-02*
1.93	2220	1.93	2180	1.93	2180	*0.202*	*2.19E-03*	*1.09E-02*
3.16	2620	3.16	2570	3.16	2570	*0.331*	*2.59E-03*	*7.82E-03*
5.18	3230	5.18	3170	5.18	3160	*0.542*	*3.19E-03*	*5.87E-03*
8.48	4150	8.48	4090	8.48	4070	*0.888*	*4.10E-03*	*4.62E-03*
13.9	5580	13.9	5490	13.9	5510	*1.456*	*5.53E-03*	*3.80E-03*
22.8	7940	22.8	7760	22.8	7740	*2.388*	*7.81E-03*	*3.27E-03*
37.3	11500	37.3	11300	37.3	11300	*3.906*	*1.14E-02*	*2.91E-03*
61.1	17100	61.1	16700	61.1	16800	*6.398*	*1.69E-02*	*2.64E-03*
100	25800	100	25300	100	25300	*10.472*	*2.55E-02*	*2.43E-03*
100	25600	100	25200	100	25200	*10.472*	*2.53E-02*	*2.42E-03*
69.5	18700	69.5	18500	69.5	18500	*7.278*	*1.86E-02*	*2.55E-03*
48.3	13900	48.3	13700	48.3	13700	*5.058*	*1.38E-02*	*2.72E-03*
33.6	10400	33.6	10300	33.6	10300	*3.519*	*1.03E-02*	*2.94E-03*
23.4	7900	23.4	7830	23.4	7840	*2.450*	*7.86E-03*	*3.21E-03*
16.2	6120	16.2	6070	16.2	6080	*1.696*	*6.09E-03*	*3.59E-03*
11.3	4840	11.3	4810	11.3	4820	*1.183*	*4.82E-03*	*4.08E-03*
7.85	3920	7.85	3900	7.85	3900	*0.822*	*3.91E-03*	*4.75E-03*
5.46	3250	5.46	3230	5.46	3240	*0.572*	*3.24E-03*	*5.67E-03*
3.79	2760	3.79	2750	3.79	2760	*0.397*	*2.76E-03*	*6.95E-03*
2.64	2410	2.64	2400	2.64	2400	*0.276*	*2.40E-03*	*8.69E-03*
1.83	2140	1.83	2130	1.83	2140	*0.192*	*2.14E-03*	*1.11E-02*
1.27	1940	1.27	1940	1.27	1940	*0.133*	*1.94E-03*	*1.46E-02*
0.886	1790	0.886	1790	0.886	1790	*0.093*	*1.79E-03*	*1.93E-02*
0.616	1680	0.616	1680	0.616	1680	*0.065*	*1.68E-03*	*2.60E-02*
0.428	1590	0.428	1590	0.428	1600	*0.045*	*1.59E-03*	*3.55E-02*
0.297	1530	0.298	1520	0.297	1530	*0.031*	*1.53E-03*	*4.90E-02*
0.207	1470	0.207	1470	0.207	1470	*0.022*	*1.47E-03*	*6.78E-02*
0.144	1430	0.144	1430	0.144	1430	*0.015*	*1.43E-03*	*9.48E-02*
0.0998	1400	0.0999	1400	0.0998	1400	*0.010*	*1.40E-03*	*1.34E-01*

Table A - 20: Measured data for Mix#5 with 40 % beads using Double spiral spindle.

Double Spiral								
Geom.: RHN-83A				*Cup: Z43S*		*Bead % 40%*		
Run #1		Run #2		Run #3		**Average values**		
NIST Code: SMC-95M		*NIST Code: SMC-95N*		*NIST Code: SMC-95O*				
N	Γ	N	Γ	N	Γ	**N**	**Γ**	***Γ/N** (Angular*
1/min	µNm	1/min	µNm	1/min	µNm	**rad/s**	**Nm**	*momentum)*
0.0882	2330	0.0916	2020	0.0879	2380	*0.009*	*2.24E-03*	*2.40E-01*
0.162	3320	0.16	2810	0.157	3400	*0.017*	*3.18E-03*	*1.90E-01*
0.266	3850	0.267	3240	0.272	3890	*0.028*	*3.66E-03*	*1.30E-01*
0.435	4490	0.44	3730	0.438	4480	*0.046*	*4.23E-03*	*9.24E-02*
0.72	5170	0.721	4350	0.72	5130	*0.075*	*4.88E-03*	*6.47E-02*
1.17	6030	1.18	5150	1.18	6050	*0.123*	*5.74E-03*	*4.66E-02*
1.93	7470	1.94	6340	1.92	7380	*0.202*	*7.06E-03*	*3.49E-02*
3.18	9760	3.17	8140	3.17	9520	*0.332*	*9.14E-03*	*2.75E-02*
5.18	13500	5.18	11000	5.17	12800	*0.542*	*1.24E-02*	*2.29E-02*
8.5	18600	8.49	15500	8.51	17800	*0.890*	*1.73E-02*	*1.94E-02*
13.9	26000	13.9	22100	13.9	25200	*1.456*	*2.44E-02*	*1.68E-02*
22.8	37000	22.8	32500	22.8	35700	*2.388*	*3.51E-02*	*1.47E-02*
37.3	54000	37.2	48600	37.3	52100	*3.903*	*5.16E-02*	*1.32E-02*
61	79000	61.1	73300	61.1	76000	*6.395*	*7.61E-02*	*1.19E-02*
100	116000	100	111000	100	108000	*10.472*	*1.12E-01*	*1.07E-02*
100	114000	100	110000	100	103000	*10.472*	*1.09E-01*	*1.04E-02*
69.5	81200	69.5	80000	69.6	73900	*7.282*	*7.84E-02*	*1.08E-02*
48.4	58800	48.4	58100	48.3	54000	*5.065*	*5.70E-02*	*1.12E-02*
33.6	43300	33.6	42800	33.6	40400	*3.519*	*4.22E-02*	*1.20E-02*
23.4	32000	23.4	31800	23.4	31400	*2.450*	*3.17E-02*	*1.30E-02*
16.2	24000	16.3	23800	16.2	24100	*1.700*	*2.40E-02*	*1.41E-02*
11.3	18200	11.3	18200	11.3	18500	*1.183*	*1.83E-02*	*1.55E-02*
7.85	14100	7.84	14100	7.86	14300	*0.822*	*1.42E-02*	*1.72E-02*
5.46	11100	5.47	11100	5.46	11400	*0.572*	*1.12E-02*	*1.96E-02*
3.79	8850	3.78	8850	3.8	9140	*0.397*	*8.95E-03*	*2.25E-02*
2.65	7280	2.64	7290	2.64	7660	*0.277*	*7.41E-03*	*2.68E-02*
1.83	6080	1.83	6090	1.84	6480	*0.192*	*6.22E-03*	*3.24E-02*
1.28	5220	1.27	5220	1.27	5520	*0.133*	*5.32E-03*	*3.99E-02*
0.888	4580	0.887	4590	0.896	4820	*0.093*	*4.66E-03*	*5.00E-02*
0.615	4040	0.618	4100	0.616	4270	*0.065*	*4.14E-03*	*6.41E-02*
0.425	3680	0.431	3750	0.428	3880	*0.045*	*3.77E-03*	*8.41E-02*
0.296	3420	0.3	3450	0.297	3590	*0.031*	*3.49E-03*	*1.12E-01*
0.207	3190	0.21	3240	0.208	3330	*0.022*	*3.25E-03*	*1.49E-01*
0.142	3030	0.145	3040	0.145	3210	*0.015*	*3.09E-03*	*2.05E-01*
0.101	2940	0.101	2940	0.101	3070	*0.011*	*2.98E-03*	*2.82E-01*

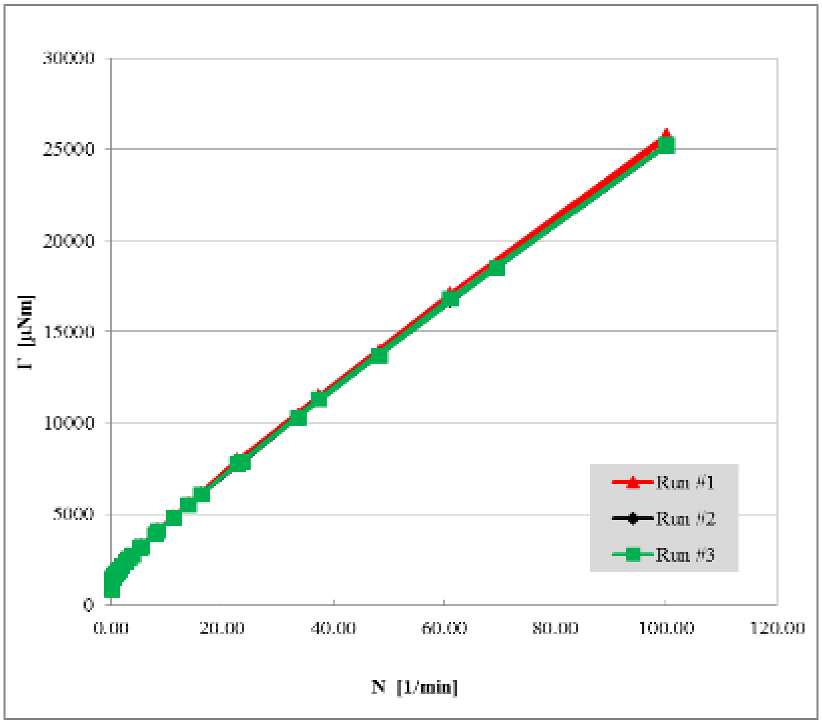


Figure A - 19: Torque vs. Angular Speed using <u>Double spiral spindle</u> on Mix#5, with 0 % beads by volume. Portrays data from Table A-19.

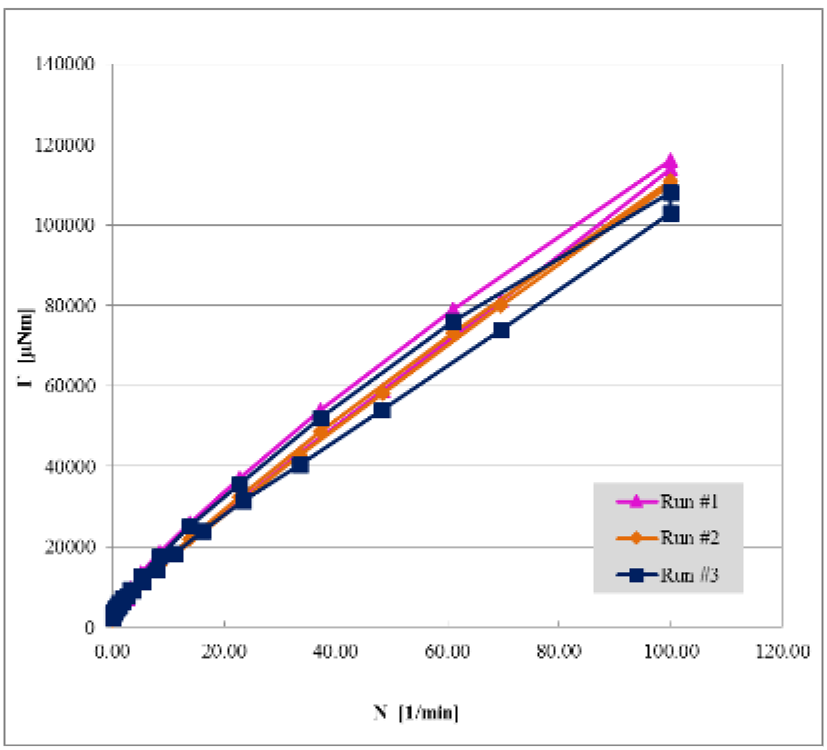


Figure A - 20: Torque vs. Angular Speed using <u>Double spiral spindle</u> on Mix#5, with 40 % beads by volume. Portrays data from Table A-20.

Table A - 21: Measured data for Mix#5 with 0 % beads using Six-blade Vane.

6 Blade Vane						Bead %		
Geom.:	RHN-83C			Z43S		0%		
Run #1		Run #2		Run #3		Average values		
NIST Code: SMC-95A		NIST Code: SMC-95B		NIST Code: SMC-95C				
N	Γ	N	Γ	N	Γ	**N**	**Γ**	*Γ/N (Angular*
1/min	μNm	1/min	μNm	1/min	μNm	**rad/s**	**Nm**	*momentum)*
0.0979	413	0.0999	502	0.098	385	*0.010*	*4.33E-04*	*4.20E-02*
0.163	547	0.164	518	0.163	513	*0.017*	*5.26E-04*	*3.08E-02*
0.268	588	0.268	553	0.268	558	*0.028*	*5.66E-04*	*2.02E-02*
0.439	624	0.439	586	0.439	591	*0.046*	*6.00E-04*	*1.31E-02*
0.72	675	0.724	647	0.72	640	*0.076*	*6.54E-04*	*8.66E-03*
1.18	745	1.18	707	1.18	710	*0.124*	*7.21E-04*	*5.83E-03*
1.93	840	1.93	821	1.93	808	*0.202*	*8.23E-04*	*4.07E-03*
3.16	976	3.16	945	3.16	946	*0.331*	*9.56E-04*	*2.89E-03*
5.18	1170	5.18	1140	5.18	1140	*0.542*	*1.15E-03*	*2.12E-03*
8.48	1450	8.48	1400	8.48	1430	*0.888*	*1.43E-03*	*1.61E-03*
13.9	1860	13.9	1800	13.9	1840	*1.456*	*1.83E-03*	*1.26E-03*
22.8	2450	22.8	2380	22.8	2450	*2.388*	*2.43E-03*	*1.02E-03*
37.3	3360	37.3	3280	37.3	3370	*3.906*	*3.34E-03*	*8.54E-04*
61	4760	61	4660	61	4760	*6.388*	*4.73E-03*	*7.40E-04*
100	6940	100	6820	100	6910	*10.472*	*6.89E-03*	*6.58E-04*
100	6900	100	6810	100	6890	*10.472*	*6.87E-03*	*6.56E-04*
69.5	5180	69.5	5120	69.5	5170	*7.278*	*5.16E-03*	*7.09E-04*
48.3	3950	48.3	3910	48.3	3940	*5.058*	*3.93E-03*	*7.78E-04*
33.6	3060	33.6	3030	33.6	3050	*3.519*	*3.05E-03*	*8.66E-04*
23.4	2420	23.4	2400	23.4	2410	*2.450*	*2.41E-03*	*9.83E-04*
16.2	1950	16.2	1930	16.2	1940	*1.696*	*1.94E-03*	*1.14E-03*
11.3	1610	11.3	1590	11.3	1600	*1.183*	*1.60E-03*	*1.35E-03*
7.85	1350	7.85	1330	7.85	1340	*0.822*	*1.34E-03*	*1.63E-03*
5.45	1150	5.45	1130	5.45	1140	*0.571*	*1.14E-03*	*2.00E-03*
3.79	993	3.79	982	3.79	985	*0.397*	*9.87E-04*	*2.49E-03*
2.64	876	2.64	865	2.64	868	*0.276*	*8.70E-04*	*3.15E-03*
1.83	784	1.83	774	1.83	777	*0.192*	*7.78E-04*	*4.06E-03*
1.27	713	1.27	703	1.27	705	*0.133*	*7.07E-04*	*5.32E-03*
0.886	657	0.886	648	0.887	655	*0.093*	*6.53E-04*	*7.04E-03*
0.616	612	0.616	604	0.616	604	*0.065*	*6.07E-04*	*9.40E-03*
0.428	577	0.428	569	0.428	568	*0.045*	*5.71E-04*	*1.27E-02*
0.298	550	0.298	540	0.298	540	*0.031*	*5.43E-04*	*1.74E-02*
0.207	525	0.207	517	0.208	518	*0.022*	*5.20E-04*	*2.40E-02*
0.144	507	0.144	498	0.144	498	*0.015*	*5.01E-04*	*3.32E-02*
0.1	493	0.0999	484	0.0999	483	*0.010*	*4.87E-04*	*4.65E-02*

Table A - 22: Measured data for Mix#5 with 40 % beads using Six-blade Vane.

6 Blade Vane						Bead %		
Geom.:	*RHN-83C*			*Z43S*		*40%*		
Run #1		Run #2		Run #3		**Average values**		
NIST Code: SMC-95J		*NIST Code: SMC-95K*		*NIST Code: SMC-95L*				
N	Γ	N	Γ	N	Γ	**N**	**Γ**	***Γ/N*** *(Angular*
1/min	μNm	1/min	μNm	1/min	μNm	**rad/s**	**Nm**	*momentum)*
0.0958	1050	0.0973	967	0.0976	1010	*0.010*	*1.01E-03*	*9.94E-02*
0.163	1330	0.163	1230	0.163	1260	*0.017*	*1.27E-03*	*7.46E-02*
0.27	1420	0.271	1340	0.272	1370	*0.028*	*1.38E-03*	*4.85E-02*
0.438	1550	0.441	1420	0.444	1510	*0.046*	*1.49E-03*	*3.23E-02*
0.72	1700	0.717	1630	0.719	1640	*0.075*	*1.66E-03*	*2.20E-02*
1.18	1960	1.18	1850	1.18	1900	*0.124*	*1.90E-03*	*1.54E-02*
1.93	2270	1.93	2200	1.93	2200	*0.202*	*2.22E-03*	*1.10E-02*
3.16	2740	3.17	2680	3.17	2720	*0.332*	*2.71E-03*	*8.18E-03*
5.18	3480	5.18	3440	5.18	3510	*0.542*	*3.48E-03*	*6.41E-03*
8.5	4450	8.48	4470	8.47	4610	*0.888*	*4.51E-03*	*5.08E-03*
13.9	5970	13.9	5960	13.9	6170	*1.456*	*6.03E-03*	*4.14E-03*
22.8	8080	22.7	8330	22.8	8510	*2.384*	*8.31E-03*	*3.48E-03*
37.3	11100	37.3	11700	37.3	12000	*3.906*	*1.16E-02*	*2.97E-03*
61.1	15400	61.1	16700	61	17100	*6.395*	*1.64E-02*	*2.56E-03*
100	21500	100	23800	100	24500	*10.472*	*2.33E-02*	*2.22E-03*
100	20900	100	22900	100	23700	*10.472*	*2.25E-02*	*2.15E-03*
69.5	15600	69.5	16600	69.5	17300	*7.278*	*1.65E-02*	*2.27E-03*
48.3	11900	48.3	12300	48.3	12800	*5.058*	*1.23E-02*	*2.44E-03*
33.6	9090	33.6	9260	33.6	9600	*3.519*	*9.32E-03*	*2.65E-03*
23.4	6960	23.3	7070	23.3	7340	*2.443*	*7.12E-03*	*2.92E-03*
16.2	5420	16.2	5510	16.2	5680	*1.696*	*5.54E-03*	*3.26E-03*
11.3	4270	11.3	4300	11.3	4470	*1.183*	*4.35E-03*	*3.67E-03*
7.84	3450	7.85	3480	7.85	3560	*0.822*	*3.50E-03*	*4.26E-03*
5.46	2800	5.46	2830	5.45	2880	*0.571*	*2.84E-03*	*4.96E-03*
3.79	2340	3.79	2320	3.79	2400	*0.397*	*2.35E-03*	*5.93E-03*
2.64	1960	2.64	1960	2.64	2000	*0.276*	*1.97E-03*	*7.14E-03*
1.83	1700	1.83	1690	1.83	1740	*0.192*	*1.71E-03*	*8.92E-03*
1.27	1490	1.27	1460	1.27	1530	*0.133*	*1.49E-03*	*1.12E-02*
0.884	1320	0.886	1320	0.887	1360	*0.093*	*1.33E-03*	*1.44E-02*
0.615	1210	0.616	1200	0.619	1230	*0.065*	*1.21E-03*	*1.88E-02*
0.43	1090	0.431	1090	0.427	1140	*0.045*	*1.11E-03*	*2.46E-02*
0.298	1020	0.295	1040	0.296	1040	*0.031*	*1.03E-03*	*3.33E-02*
0.206	962	0.208	971	0.207	990	*0.022*	*9.74E-04*	*4.49E-02*
0.143	921	0.144	932	0.144	949	*0.015*	*9.34E-04*	*6.21E-02*
0.101	889	0.0985	895	0.1	903	*0.010*	*8.96E-04*	*8.57E-02*

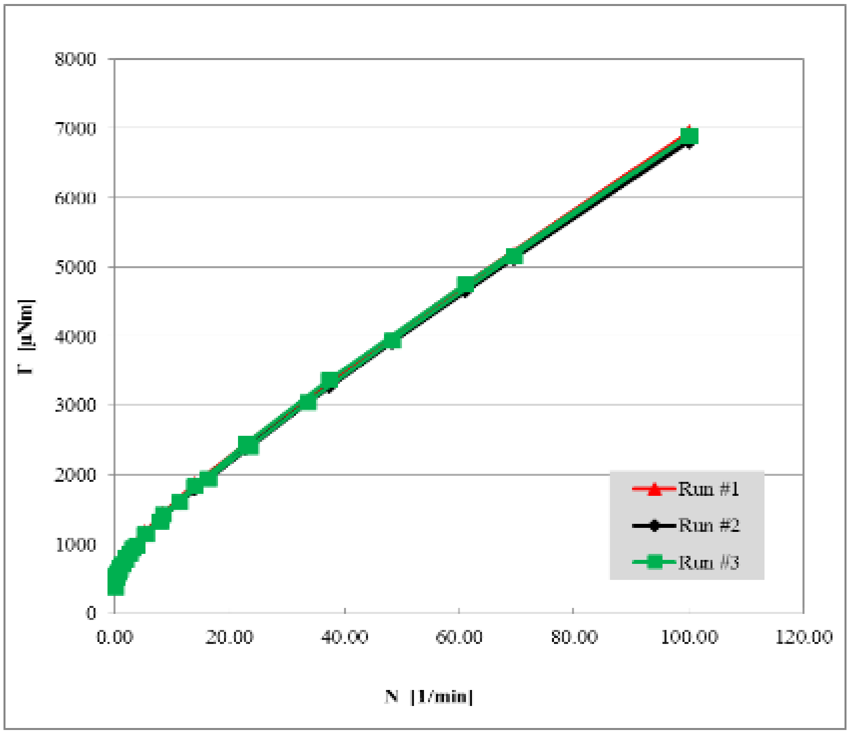


Figure A - 15: Torque vs. Angular Speed using <u>six-blade vane</u> on Mix#5, with 0 % beads by volume. Portrays data from Table A-21.

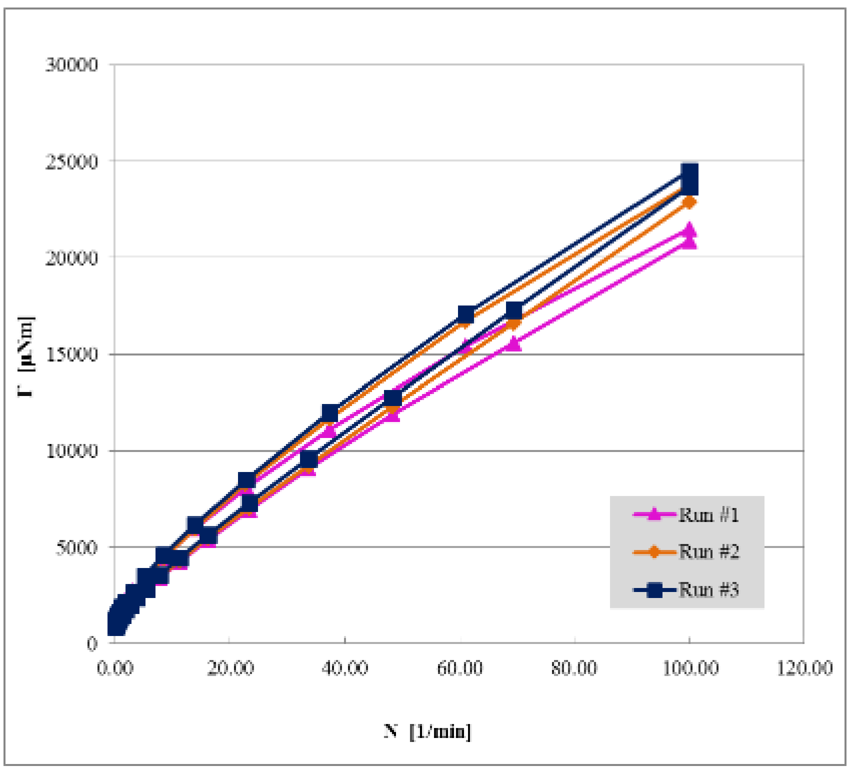


Figure A - 16: Torque vs. Angular Speed using <u>six-blade vane</u> on Mix#5, with 40 % beads by volume. Portrays data from Table A-22.

Table A - 23: Measured data for Mix#5 with 0 % beads using Serrated Coaxial Cylinder.

Serrated Coaxial Cylinder						Bead %		
Geom.:	*SS18*			*Z43S*		0%		
Run #1		Run #2		Run #3		**Average values**		
NIST Code: SMC-95G		*NIST Code: SMC-95H*		*NIST Code: SMC-95I*				
N	Γ	N	Γ	N	Γ	**N**	**Γ**	***Γ/N*** *(Angular*
1/min	μNm	1/min	μNm	1/min	μNm	**rad/s**	**Nm**	*momentum)*
0.0985	441	0.0999	353	0.0986	367	*0.010*	*3.87E-04*	*3.73E-02*
0.164	545	0.164	376	0.164	473	*0.017*	*4.65E-04*	*2.71E-02*
0.268	574	0.268	412	0.268	510	*0.028*	*4.99E-04*	*1.78E-02*
0.439	612	0.439	462	0.439	550	*0.046*	*5.41E-04*	*1.18E-02*
0.72	669	0.72	526	0.72	606	*0.075*	*6.00E-04*	*7.96E-03*
1.18	746	1.18	613	1.18	683	*0.124*	*6.81E-04*	*5.51E-03*
1.93	853	1.93	730	1.93	793	*0.202*	*7.92E-04*	*3.92E-03*
3.16	1000	3.16	888	3.16	951	*0.331*	*9.46E-04*	*2.86E-03*
5.18	1210	5.18	1100	5.18	1170	*0.542*	*1.16E-03*	*2.14E-03*
8.48	1510	8.48	1400	8.48	1490	*0.888*	*1.47E-03*	*1.65E-03*
13.9	1950	13.9	1830	13.9	1950	*1.456*	*1.91E-03*	*1.31E-03*
22.8	2580	22.8	2440	22.8	2600	*2.388*	*2.54E-03*	*1.06E-03*
37.3	3560	37.3	3380	37.3	3590	*3.906*	*3.51E-03*	*8.99E-04*
61	5050	61	4840	61	5100	*6.388*	*5.00E-03*	*7.82E-04*
100	7410	100	7120	100	7460	*10.472*	*7.33E-03*	*7.00E-04*
100	7300	100	7100	100	7350	*10.472*	*7.25E-03*	*6.92E-04*
69.5	5480	69.5	5320	69.5	5500	*7.278*	*5.43E-03*	*7.47E-04*
48.3	4140	48.3	4030	48.3	4150	*5.058*	*4.11E-03*	*8.12E-04*
33.6	3180	33.6	3090	33.6	3180	*3.519*	*3.15E-03*	*8.95E-04*
23.4	2490	23.4	2420	23.4	2480	*2.450*	*2.46E-03*	*1.01E-03*
16.2	1980	16.2	1920	16.2	1970	*1.696*	*1.96E-03*	*1.15E-03*
11.3	1610	11.3	1560	11.3	1600	*1.183*	*1.59E-03*	*1.34E-03*
7.85	1330	7.85	1280	7.85	1310	*0.822*	*1.31E-03*	*1.59E-03*
5.45	1110	5.45	1070	5.45	1090	*0.571*	*1.09E-03*	*1.91E-03*
3.79	943	3.79	902	3.79	924	*0.397*	*9.23E-04*	*2.33E-03*
2.64	810	2.64	772	2.64	793	*0.276*	*7.92E-04*	*2.86E-03*
1.83	705	1.83	670	1.83	691	*0.192*	*6.89E-04*	*3.59E-03*
1.27	622	1.27	589	1.27	609	*0.133*	*6.07E-04*	*4.56E-03*
0.886	554	0.886	525	0.886	545	*0.093*	*5.41E-04*	*5.83E-03*
0.616	499	0.616	473	0.615	490	*0.064*	*4.87E-04*	*7.56E-03*
0.428	455	0.428	431	0.428	451	*0.045*	*4.46E-04*	*9.94E-03*
0.298	418	0.298	397	0.298	416	*0.031*	*4.10E-04*	*1.31E-02*
0.207	389	0.207	371	0.207	388	*0.022*	*3.83E-04*	*1.77E-02*
0.144	365	0.144	349	0.144	366	*0.015*	*3.60E-04*	*2.39E-02*
0.1	346	0.1	331	0.1	347	*0.010*	*3.41E-04*	*3.26E-02*

Table A - 24: Measured data for Mix#5 with 40 % beads using Serrated Coaxial Cylinder.

Serrated Coaxial Cylinder						Bead %		
Geom.:	*SS18*			*Z43S*		*40%*		
Run #1		Run #2		Run #3		**Average values**		
NIST Code: SMC-95P		*NIST Code: SMC-95Q*		*NIST Code: SMC-95R*				
N	Γ	N	Γ	N	Γ	**N**	**Γ**	***Γ/N*** *(Angular*
1/min	µNm	1/min	µNm	1/min	µNm	**rad/s**	**Nm**	*momentum)*
0.0989	1270	0.0967	1080	0.0971	1090	*0.010*	*1.15E-03*	*1.12E-01*
0.161	1520	0.163	1210	0.165	1220	*0.017*	*1.32E-03*	*7.71E-02*
0.269	1580	0.27	1220	0.27	1250	*0.028*	*1.35E-03*	*4.78E-02*
0.445	1640	0.44	1300	0.438	1320	*0.046*	*1.42E-03*	*3.07E-02*
0.724	1710	0.719	1450	0.722	1510	*0.076*	*1.56E-03*	*2.06E-02*
1.18	1820	1.18	1700	1.18	1740	*0.124*	*1.75E-03*	*1.42E-02*
1.93	2100	1.93	2080	1.93	2130	*0.202*	*2.10E-03*	*1.04E-02*
3.16	2500	3.16	2580	3.16	2700	*0.331*	*2.59E-03*	*7.84E-03*
5.18	3140	5.18	3340	5.18	3470	*0.542*	*3.32E-03*	*6.11E-03*
8.49	4090	8.48	4410	8.49	4580	*0.889*	*4.36E-03*	*4.91E-03*
13.9	5470	13.9	5930	13.9	6220	*1.456*	*5.87E-03*	*4.03E-03*
22.8	7460	22.7	8170	22.8	8520	*2.384*	*8.05E-03*	*3.38E-03*
37.3	10100	37.3	11400	37.3	11900	*3.906*	*1.11E-02*	*2.85E-03*
61.1	14000	61.1	16000	61.1	16600	*6.398*	*1.55E-02*	*2.43E-03*
100	19300	100	22400	100	22700	*10.472*	*2.15E-02*	*2.05E-03*
100	19400	100	20100	99.9	20800	*10.468*	*2.01E-02*	*1.92E-03*
69.5	14900	69.5	15500	69.5	15800	*7.278*	*1.54E-02*	*2.12E-03*
48.3	11700	48.3	11800	48.3	12100	*5.058*	*1.19E-02*	*2.35E-03*
33.6	9150	33.6	9540	33.6	9660	*3.519*	*9.45E-03*	*2.69E-03*
23.4	7010	23.4	7400	23.3	7570	*2.447*	*7.33E-03*	*2.99E-03*
16.2	5430	16.2	5730	16.2	5910	*1.696*	*5.69E-03*	*3.35E-03*
11.3	4250	11.3	4470	11.3	4620	*1.183*	*4.45E-03*	*3.76E-03*
7.84	3390	7.85	3560	7.85	3640	*0.822*	*3.53E-03*	*4.30E-03*
5.46	2720	5.45	2880	5.45	2960	*0.571*	*2.85E-03*	*5.00E-03*
3.79	2260	3.79	2360	3.79	2430	*0.397*	*2.35E-03*	*5.92E-03*
2.63	1890	2.64	1970	2.63	2030	*0.276*	*1.96E-03*	*7.12E-03*
1.83	1620	1.83	1670	1.83	1710	*0.192*	*1.67E-03*	*8.70E-03*
1.27	1400	1.27	1460	1.27	1490	*0.133*	*1.45E-03*	*1.09E-02*
0.886	1230	0.887	1280	0.886	1310	*0.093*	*1.27E-03*	*1.37E-02*
0.614	1100	0.615	1140	0.616	1170	*0.064*	*1.14E-03*	*1.76E-02*
0.429	995	0.428	1030	0.428	1040	*0.045*	*1.02E-03*	*2.28E-02*
0.296	905	0.298	953	0.298	962	*0.031*	*9.40E-04*	*3.02E-02*
0.207	830	0.208	872	0.207	898	*0.022*	*8.67E-04*	*3.99E-02*
0.145	776	0.144	814	0.143	835	*0.015*	*8.08E-04*	*5.36E-02*
0.0995	725	0.101	768	0.0984	781	*0.010*	*7.58E-04*	*7.27E-02*

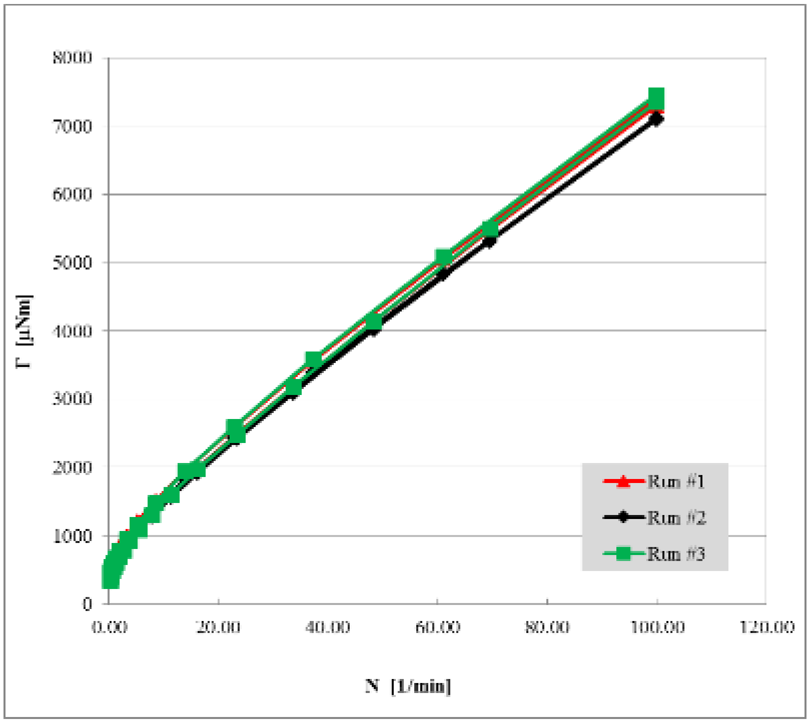


Figure A - 18: : Torque vs. Angular Speed using <u>Serrated Coaxial Cylinder</u> on Mix#5, with 0 % beads by volume. Portrays data from Table A-23.

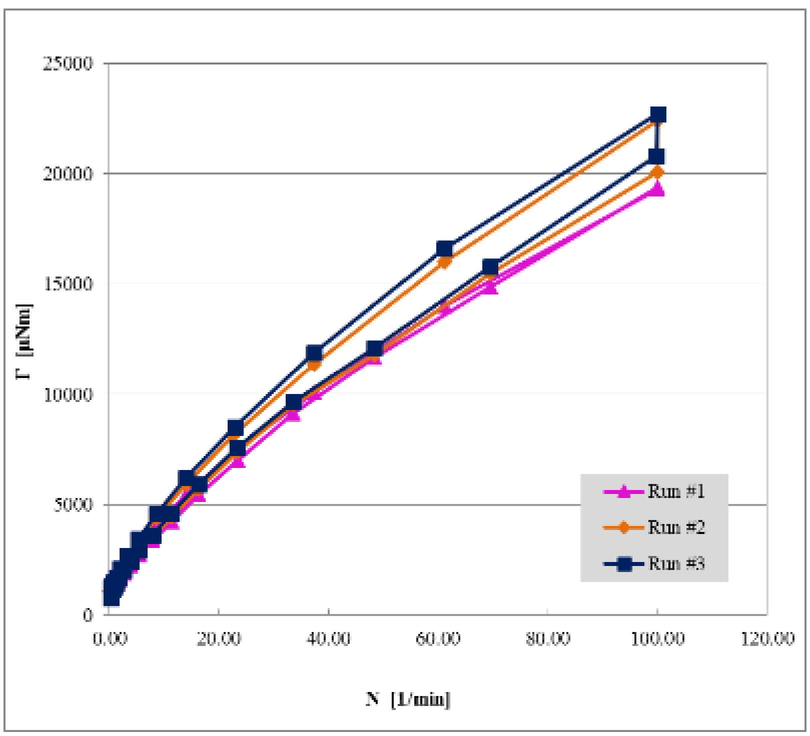


Figure A - 17: : Torque vs. Angular Speed using <u>Serrated Coaxial Cylinder</u> on Mix#5, with 40 % beads by volume. Portrays data from Table A-24.

Table A - 25: Measured data for Mix#6 with 0 % beads using Double spiral spindle.

Double Spiral								
Geom.: RHN-83A				*Cup: Z43S*		*Bead % 0%*		
Run #1		Run #2		Run #3		**Average values**		
NIST Code: SMC-97G		*NIST Code: SMC-97H*		*NIST Code: SMC-97I*				
N	Γ	N	Γ	N	Γ	**N**	**Γ**	*Γ/N (Angular*
1/min	μNm	1/min	μNm	1/min	μNm	**rad/s**	**Nm**	*momentum)*
0.0941	1080	0.0945	988	0.0945	1000	*0.010*	*1.02E-03*	*1.03E-01*
0.161	1580	0.161	1470	0.161	1480	*0.017*	*1.51E-03*	*8.96E-02*
0.268	1790	0.268	1670	0.268	1690	*0.028*	*1.72E-03*	*6.12E-02*
0.44	1900	0.439	1800	0.439	1820	*0.046*	*1.84E-03*	*4.00E-02*
0.72	2030	0.72	1940	0.72	1960	*0.075*	*1.98E-03*	*2.62E-02*
1.18	2200	1.18	2130	1.18	2150	*0.124*	*2.16E-03*	*1.75E-02*
1.93	2480	1.93	2420	1.93	2430	*0.202*	*2.44E-03*	*1.21E-02*
3.16	2900	3.16	2850	3.16	2870	*0.331*	*2.87E-03*	*8.68E-03*
5.18	3550	5.18	3510	5.18	3530	*0.542*	*3.53E-03*	*6.51E-03*
8.48	4560	8.48	4530	8.48	4540	*0.888*	*4.54E-03*	*5.12E-03*
13.9	6180	13.9	6120	13.9	6190	*1.456*	*6.16E-03*	*4.23E-03*
22.8	8710	22.8	8610	22.8	8690	*2.388*	*8.67E-03*	*3.63E-03*
37.3	12700	37.3	12500	37.3	12700	*3.906*	*1.26E-02*	*3.23E-03*
61.1	18900	61.1	18700	61.1	18900	*6.398*	*1.88E-02*	*2.94E-03*
100	28500	100	28200	100	28600	*10.472*	*2.84E-02*	*2.72E-03*
100	28300	100	28100	100	28500	*10.472*	*2.83E-02*	*2.70E-03*
69.5	20700	69.5	20600	69.5	20900	*7.278*	*2.07E-02*	*2.85E-03*
48.3	15300	48.3	15200	48.3	15400	*5.058*	*1.53E-02*	*3.02E-03*
33.6	11500	33.6	11400	33.6	11600	*3.519*	*1.15E-02*	*3.27E-03*
23.4	8720	23.4	8690	23.4	8810	*2.450*	*8.74E-03*	*3.57E-03*
16.2	6760	16.2	6740	16.2	6830	*1.696*	*6.78E-03*	*3.99E-03*
11.3	5350	11.3	5330	11.3	5410	*1.183*	*5.36E-03*	*4.53E-03*
7.85	4330	7.85	4320	7.85	4380	*0.822*	*4.34E-03*	*5.28E-03*
5.46	3590	5.46	3590	5.46	3630	*0.572*	*3.60E-03*	*6.30E-03*
3.79	3060	3.79	3060	3.79	3090	*0.397*	*3.07E-03*	*7.74E-03*
2.64	2670	2.64	2660	2.64	2690	*0.276*	*2.67E-03*	*9.67E-03*
1.83	2370	1.83	2370	1.83	2390	*0.192*	*2.38E-03*	*1.24E-02*
1.27	2160	1.27	2150	1.27	2170	*0.133*	*2.16E-03*	*1.62E-02*
0.886	1990	0.886	1990	0.886	2010	*0.093*	*2.00E-03*	*2.15E-02*
0.616	1860	0.616	1860	0.616	1870	*0.065*	*1.86E-03*	*2.89E-02*
0.428	1770	0.428	1770	0.428	1780	*0.045*	*1.77E-03*	*3.96E-02*
0.297	1700	0.298	1700	0.298	1710	*0.031*	*1.70E-03*	*5.46E-02*
0.207	1640	0.207	1640	0.208	1650	*0.022*	*1.64E-03*	*7.57E-02*
0.144	1600	0.144	1590	0.143	1600	*0.015*	*1.60E-03*	*1.06E-01*
0.0995	1560	0.0991	1560	0.0998	1560	*0.010*	*1.56E-03*	*1.50E-01*

Table A - 26: Measured data for Mix#6 with 40 % beads using Double spiral spindle.

Double Spiral								
Geom.: RHN-83A				*Cup: Z43S*		*Bead % 40%*		
Run #1		Run #2		Run #3		**Average values**		
NIST Code: SMC-97P		*NIST Code: SMC-97Q*		*NIST Code: SMC-97R*				
N	Γ	N	Γ	N	Γ	**N**	**Γ**	*Γ/N (Angular momentum)*
1/min	μNm	1/min	μNm	1/min	μNm	**rad/s**	**Nm**	
0.0815	2760	0.0861	2810	0.0862	2810	*0.009*	*2.79E-03*	*3.15E-01*
0.16	4030	0.159	4170	0.157	4010	*0.017*	*4.07E-03*	*2.45E-01*
0.261	4890	0.26	5010	0.267	4670	*0.028*	*4.86E-03*	*1.77E-01*
0.445	5810	0.438	5670	0.445	5310	*0.046*	*5.60E-03*	*1.21E-01*
0.721	6680	0.728	6490	0.728	6110	*0.076*	*6.43E-03*	*8.46E-02*
1.16	8000	1.18	7650	1.17	7020	*0.123*	*7.56E-03*	*6.17E-02*
1.94	9820	1.93	9420	1.94	8760	*0.203*	*9.33E-03*	*4.60E-02*
3.17	12800	3.16	12200	3.17	11500	*0.332*	*1.22E-02*	*3.67E-02*
5.19	17300	5.18	16600	5.19	15600	*0.543*	*1.65E-02*	*3.04E-02*
8.49	24200	8.49	23500	8.45	22100	*0.888*	*2.33E-02*	*2.62E-02*
13.9	33700	13.9	33300	13.9	31600	*1.456*	*3.29E-02*	*2.26E-02*
22.8	47000	22.8	47400	22.8	44800	*2.388*	*4.64E-02*	*1.94E-02*
37.3	68000	37.3	68900	37.3	65400	*3.906*	*6.74E-02*	*1.73E-02*
61.1	96700	61.1	100000	61.1	90800	*6.398*	*9.58E-02*	*1.50E-02*
100	133000	100	143000	100	127000	*10.472*	*1.34E-01*	*1.28E-02*
100	125000	100	135000	99.9	122000	*10.468*	*1.27E-01*	*1.22E-02*
69.6	88200	69.6	95800	69.5	86300	*7.285*	*9.01E-02*	*1.24E-02*
48.3	63700	48.4	70200	48.4	62600	*5.065*	*6.55E-02*	*1.29E-02*
33.6	46600	33.6	51900	33.6	45800	*3.519*	*4.81E-02*	*1.37E-02*
23.4	34500	23.4	38900	23.4	34300	*2.450*	*3.59E-02*	*1.47E-02*
16.2	26500	16.2	29500	16.2	26900	*1.696*	*2.76E-02*	*1.63E-02*
11.3	21600	11.3	23000	11.3	22500	*1.183*	*2.24E-02*	*1.89E-02*
7.84	17100	7.84	18000	7.85	17900	*0.821*	*1.77E-02*	*2.15E-02*
5.46	13500	5.45	14200	5.46	14400	*0.571*	*1.40E-02*	*2.46E-02*
3.79	10700	3.8	11300	3.8	11600	*0.398*	*1.12E-02*	*2.82E-02*
2.65	8860	2.64	9290	2.63	9480	*0.276*	*9.21E-03*	*3.33E-02*
1.84	7490	1.84	7760	1.83	7940	*0.192*	*7.73E-03*	*4.02E-02*
1.28	6400	1.27	6580	1.28	6700	*0.134*	*6.56E-03*	*4.91E-02*
0.886	5540	0.889	5730	0.885	5830	*0.093*	*5.70E-03*	*6.14E-02*
0.609	4920	0.612	5130	0.62	5150	*0.064*	*5.07E-03*	*7.88E-02*
0.428	4380	0.427	4640	0.422	4660	*0.045*	*4.56E-03*	*1.02E-01*
0.301	4060	0.299	4270	0.298	4270	*0.031*	*4.20E-03*	*1.34E-01*
0.204	3770	0.205	4010	0.207	3980	*0.022*	*3.92E-03*	*1.82E-01*
0.141	3580	0.14	3770	0.145	3800	*0.015*	*3.72E-03*	*2.50E-01*
0.101	3470	0.1	3610	0.101	3630	*0.011*	*3.57E-03*	*3.39E-01*

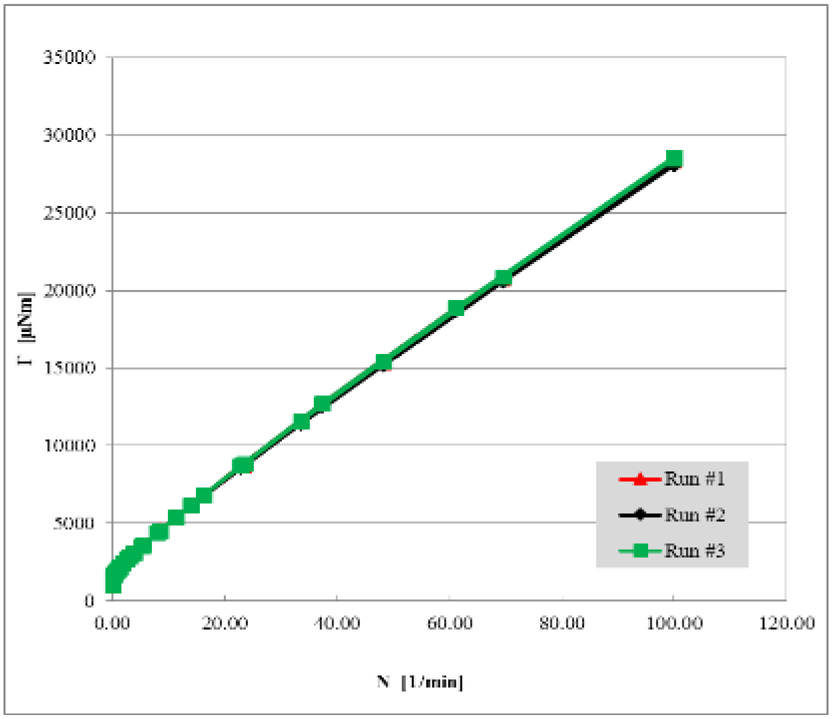


Figure A - 19: Torque vs. Angular Speed using Double spiral spindle on Mix#6, with 0 % beads by volume. Portrays data from Table A-25.

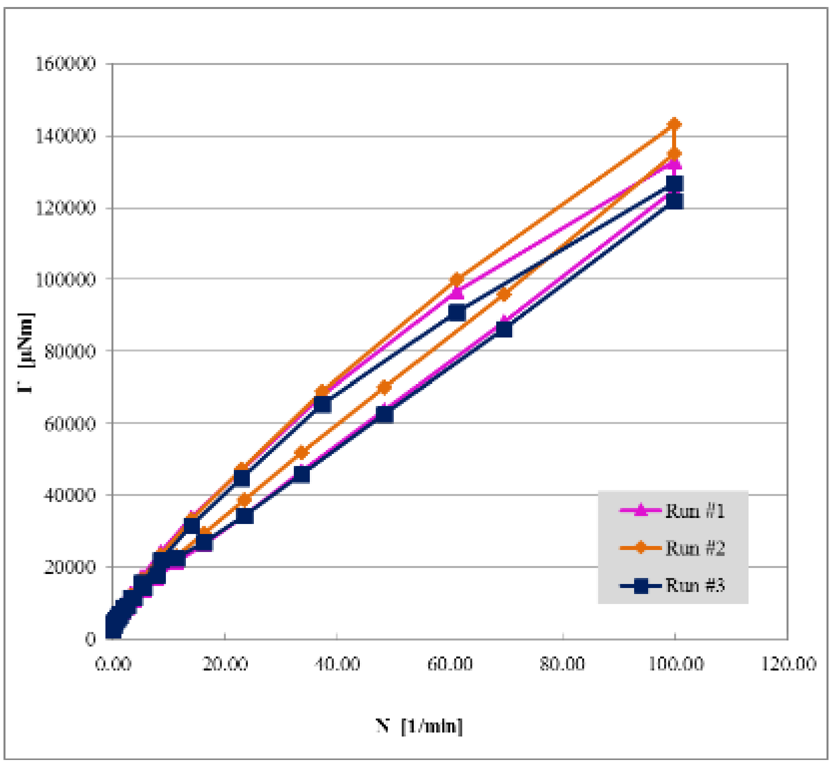


Figure A - 20: Torque vs. Angular Speed using Double spiral spindle on Mix#6, with 40 % beads by volume. Portrays data from Table A-26.

Table A - 27: Measured data for Mix#6 with 0 % beads using Six-blade Vane.

		6 Blade Vane					Bead %	
Geom.:	*RHN-83C*			*Z43S*			*0%*	
Run #1		Run #2		Run #3		**Average values**		
NIST Code: SMC-97A		*NIST Code: SMC-97B*		*NIST Code: SMC-97C*				
N	Γ	N	Γ	N	Γ	**N**	**Γ**	*Γ/N (Angular*
1/min	μNm	1/min	μNm	1/min	μNm	**rad/s**	**Nm**	*momentum)*
0.0978	452	0.0978	419	0.0981	416	*0.010*	*4.29E-04*	*4.18E-02*
0.163	591	0.163	554	0.164	553	*0.017*	*5.66E-04*	*3.31E-02*
0.268	634	0.268	593	0.267	592	*0.028*	*6.06E-04*	*2.16E-02*
0.44	670	0.44	627	0.439	625	*0.046*	*6.41E-04*	*1.39E-02*
0.72	722	0.72	679	0.72	677	*0.075*	*6.93E-04*	*9.19E-03*
1.18	793	1.18	750	1.18	756	*0.124*	*7.66E-04*	*6.20E-03*
1.93	892	1.93	855	1.93	852	*0.202*	*8.66E-04*	*4.29E-03*
3.16	1030	3.16	991	3.16	998	*0.331*	*1.01E-03*	*3.04E-03*
5.18	1230	5.18	1200	5.18	1200	*0.542*	*1.21E-03*	*2.23E-03*
8.48	1520	8.48	1490	8.48	1500	*0.888*	*1.50E-03*	*1.69E-03*
13.9	1950	13.9	1920	13.9	1930	*1.456*	*1.93E-03*	*1.33E-03*
22.8	2570	22.8	2540	22.8	2560	*2.388*	*2.56E-03*	*1.07E-03*
37.3	3520	37.3	3490	37.3	3520	*3.906*	*3.51E-03*	*8.99E-04*
61	4950	61	4940	61	4970	*6.388*	*4.95E-03*	*7.75E-04*
100	7190	100	7220	100	7230	*10.472*	*7.21E-03*	*6.89E-04*
100	7150	100	7210	100	7220	*10.472*	*7.19E-03*	*6.87E-04*
69.5	5370	69.5	5420	69.5	5420	*7.278*	*5.40E-03*	*7.42E-04*
48.3	4100	48.3	4140	48.3	4140	*5.058*	*4.13E-03*	*8.16E-04*
33.6	3190	33.6	3210	33.6	3210	*3.519*	*3.20E-03*	*9.10E-04*
23.4	2530	23.4	2540	23.4	2540	*2.450*	*2.54E-03*	*1.04E-03*
16.2	2040	16.2	2050	16.2	2050	*1.696*	*2.05E-03*	*1.21E-03*
11.3	1690	11.3	1690	11.3	1690	*1.183*	*1.69E-03*	*1.43E-03*
7.85	1410	7.85	1420	7.85	1420	*0.822*	*1.42E-03*	*1.72E-03*
5.45	1200	5.45	1210	5.45	1210	*0.571*	*1.21E-03*	*2.11E-03*
3.79	1050	3.79	1050	3.79	1050	*0.397*	*1.05E-03*	*2.65E-03*
2.64	923	2.64	926	2.64	922	*0.276*	*9.24E-04*	*3.34E-03*
1.83	828	1.83	829	1.83	826	*0.192*	*8.28E-04*	*4.32E-03*
1.27	757	1.27	755	1.27	752	*0.133*	*7.55E-04*	*5.67E-03*
0.886	694	0.886	709	0.886	692	*0.093*	*6.98E-04*	*7.53E-03*
0.615	650	0.616	649	0.616	644	*0.064*	*6.48E-04*	*1.00E-02*
0.429	621	0.429	617	0.427	613	*0.045*	*6.17E-04*	*1.38E-02*
0.296	590	0.298	579	0.299	586	*0.031*	*5.85E-04*	*1.88E-02*
0.207	564	0.205	567	0.208	569	*0.022*	*5.67E-04*	*2.62E-02*
0.143	567	0.145	544	0.145	552	*0.015*	*5.54E-04*	*3.67E-02*
0.0999	523	0.0999	548	0.101	518	*0.010*	*5.30E-04*	*5.04E-02*

Table A - 28: Measured data for Mix#6 with 40 % beads using Six-blade Vane.

6 Blade Vane						Bead %		
Geom.:	*RHN-83C*			*Z43S*		*40%*		
Run #1		Run #2		Run #3		**Average values**		
NIST Code: SMC-97J		*NIST Code: SMC-97K*		*NIST Code: SMC-97L*				
N	Γ	N	Γ	N	Γ	**N**	**Γ**	*Γ/N (Angular momentum)*
1/min	μNm	1/min	μNm	1/min	μNm	**rad/s**	**Nm**	
0.0958	1160	0.0958	1210	0.0951	1300	*0.010*	*1.22E-03*	*1.22E-01*
0.163	1420	0.167	1500	0.162	1590	*0.017*	*1.50E-03*	*8.75E-02*
0.267	1560	0.27	1660	0.265	1700	*0.028*	*1.64E-03*	*5.86E-02*
0.437	1730	0.438	1780	0.445	1800	*0.046*	*1.77E-03*	*3.84E-02*
0.723	1880	0.729	1920	0.726	2050	*0.076*	*1.95E-03*	*2.56E-02*
1.18	2140	1.19	2170	1.18	2270	*0.124*	*2.19E-03*	*1.77E-02*
1.93	2460	1.94	2580	1.94	2720	*0.203*	*2.59E-03*	*1.28E-02*
3.16	2980	3.16	3150	3.16	3300	*0.331*	*3.14E-03*	*9.50E-03*
5.19	3710	5.18	3940	5.19	4160	*0.543*	*3.94E-03*	*7.25E-03*
8.49	4790	8.48	5100	8.48	5380	*0.888*	*5.09E-03*	*5.73E-03*
13.9	6270	13.9	6790	13.9	7180	*1.456*	*6.75E-03*	*4.63E-03*
22.7	8390	22.8	9250	22.8	9790	*2.384*	*9.14E-03*	*3.84E-03*
37.3	11500	37.3	12900	37.3	13700	*3.906*	*1.27E-02*	*3.25E-03*
61.1	15900	61	18000	61.1	19200	*6.395*	*1.77E-02*	*2.77E-03*
100	23200	100	25100	100	26800	*10.472*	*2.50E-02*	*2.39E-03*
100	22000	100	23700	100	25500	*10.472*	*2.37E-02*	*2.27E-03*
69.5	16400	69.5	17400	69.5	18400	*7.278*	*1.74E-02*	*2.39E-03*
48.3	12200	48.3	13200	48.3	13700	*5.058*	*1.30E-02*	*2.58E-03*
33.6	9400	33.6	10100	33.6	10500	*3.519*	*1.00E-02*	*2.84E-03*
23.4	7150	23.4	7660	23.3	8050	*2.447*	*7.62E-03*	*3.11E-03*
16.2	5660	16.2	5970	16.2	6280	*1.696*	*5.97E-03*	*3.52E-03*
11.3	4470	11.3	4740	11.3	4930	*1.183*	*4.71E-03*	*3.98E-03*
7.85	3590	7.85	3790	7.85	3990	*0.822*	*3.79E-03*	*4.61E-03*
5.46	2920	5.45	3080	5.46	3220	*0.571*	*3.07E-03*	*5.38E-03*
3.79	2460	3.8	2540	3.79	2660	*0.397*	*2.55E-03*	*6.43E-03*
2.63	2070	2.64	2140	2.63	2190	*0.276*	*2.13E-03*	*7.74E-03*
1.83	1800	1.83	1850	1.83	1910	*0.192*	*1.85E-03*	*9.67E-03*
1.27	1560	1.27	1620	1.28	1670	*0.133*	*1.62E-03*	*1.21E-02*
0.886	1400	0.884	1440	0.887	1460	*0.093*	*1.43E-03*	*1.55E-02*
0.616	1260	0.614	1310	0.616	1320	*0.064*	*1.30E-03*	*2.01E-02*
0.425	1170	0.433	1220	0.427	1240	*0.045*	*1.21E-03*	*2.70E-02*
0.298	1100	0.293	1110	0.296	1150	*0.031*	*1.12E-03*	*3.62E-02*
0.207	1000	0.204	1060	0.207	1060	*0.022*	*1.04E-03*	*4.82E-02*
0.144	985	0.143	1020	0.143	1040	*0.015*	*1.02E-03*	*6.76E-02*
0.0996	938	0.098	978	0.0996	1030	*0.010*	*9.82E-04*	*9.47E-02*

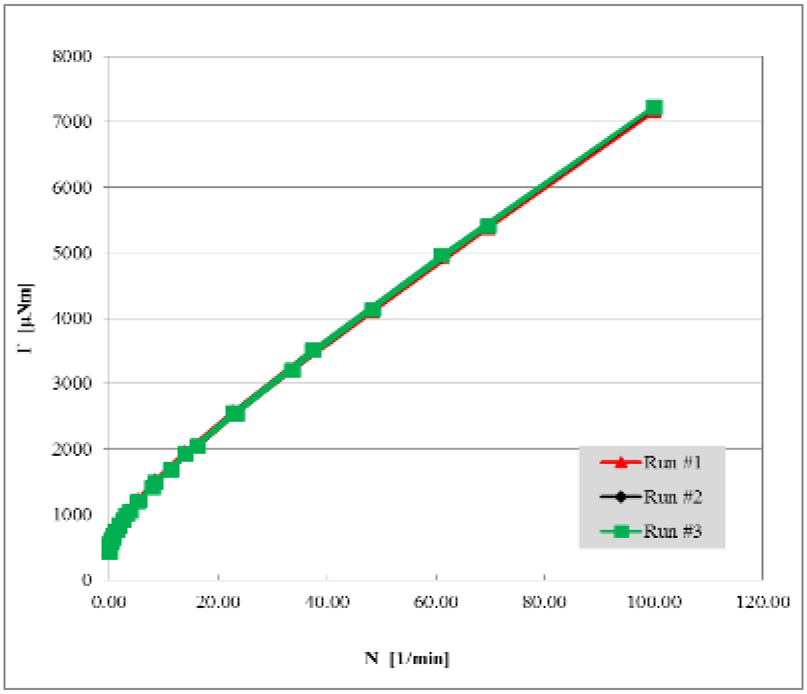


Figure A - 21: Torque vs. Angular Speed using <u>six-blade vane</u> on Mix#6, with 0 % beads by volume. Portrays data from Table A-27.

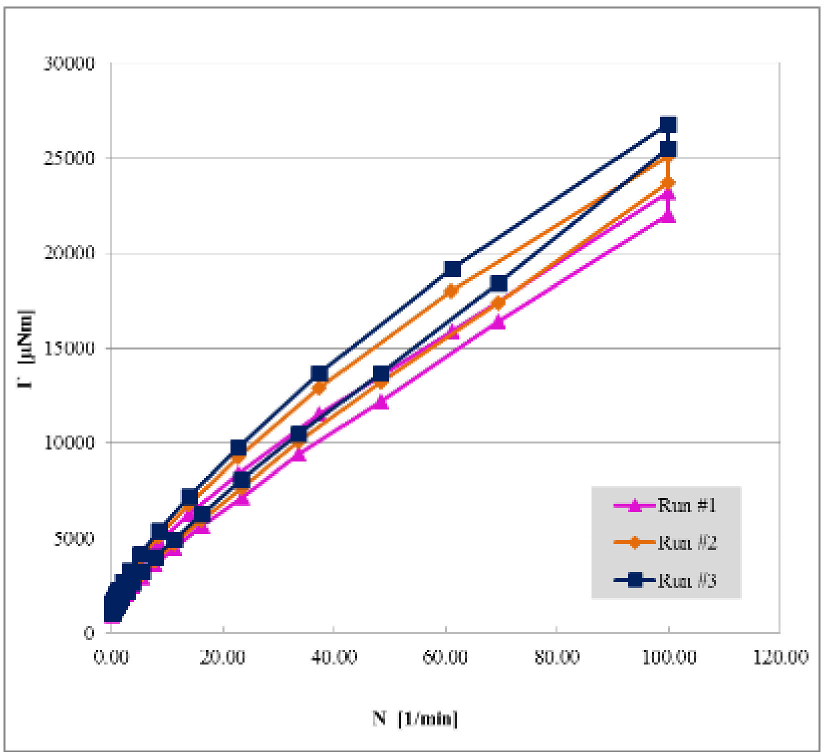


Figure A - 22: Torque vs. Angular Speed using <u>six-blade vane</u> on Mix#6, with 40 % beads by volume. Portrays data from Table A-28.

Table A - 29: Measured data for Mix#6 with 0 % beads using Serrated Coaxial Cylinder.

Serrated Coaxial Cylinder						*Bead %*		
Geom.:	*SS18*			*Z43S*		*0%*		
Run #1		Run #2		Run #3		**Average values**		
NIST Code: SMC-97D		*NIST Code: SMC-97E*		*NIST Code: SMC-97F*				
N	Γ	N	Γ	N	Γ	**N**	**Γ**	*Γ/N (Angular*
1/min	μNm	1/min	μNm	1/min	μNm	**rad/s**	**Nm**	*momentum)*
0.0981	465	0.0983	458	0.0982	438	*0.010*	*4.54E-04*	*4.41E-02*
0.164	592	0.164	576	0.164	564	*0.017*	*5.77E-04*	*3.36E-02*
0.268	626	0.268	613	0.268	606	*0.028*	*6.15E-04*	*2.19E-02*
0.439	670	0.439	660	0.439	657	*0.046*	*6.62E-04*	*1.44E-02*
0.72	732	0.72	726	0.72	724	*0.075*	*7.27E-04*	*9.65E-03*
1.18	816	1.18	815	1.18	816	*0.124*	*8.16E-04*	*6.60E-03*
1.93	931	1.93	937	1.93	939	*0.202*	*9.36E-04*	*4.63E-03*
3.16	1090	3.16	1110	3.16	1110	*0.331*	*1.10E-03*	*3.33E-03*
5.18	1320	5.18	1340	5.18	1350	*0.542*	*1.34E-03*	*2.46E-03*
8.48	1640	8.48	1680	8.48	1680	*0.888*	*1.67E-03*	*1.88E-03*
13.9	2100	13.9	2160	13.9	2170	*1.456*	*2.14E-03*	*1.47E-03*
22.8	2770	22.8	2860	22.8	2870	*2.388*	*2.83E-03*	*1.19E-03*
37.3	3800	37.3	3930	37.3	3960	*3.906*	*3.90E-03*	*9.98E-04*
61	5370	61	5560	61	5620	*6.388*	*5.52E-03*	*8.64E-04*
100	7840	100	8000	100	8130	*10.472*	*7.99E-03*	*7.63E-04*
100	7770	100	7930	100	8040	*10.472*	*7.91E-03*	*7.56E-04*
69.5	5830	69.5	5960	69.5	6030	*7.278*	*5.94E-03*	*8.16E-04*
48.3	4410	48.3	4500	48.3	4550	*5.058*	*4.49E-03*	*8.87E-04*
33.6	3390	33.6	3450	33.6	3490	*3.519*	*3.44E-03*	*9.79E-04*
23.4	2650	23.4	2700	23.4	2730	*2.450*	*2.69E-03*	*1.10E-03*
16.2	2120	16.2	2150	16.2	2170	*1.696*	*2.15E-03*	*1.27E-03*
11.3	1720	11.3	1750	11.3	1760	*1.183*	*1.74E-03*	*1.47E-03*
7.85	1420	7.85	1450	7.85	1460	*0.822*	*1.44E-03*	*1.76E-03*
5.46	1190	5.45	1210	5.45	1220	*0.571*	*1.21E-03*	*2.11E-03*
3.79	1010	3.79	1030	3.79	1040	*0.397*	*1.03E-03*	*2.59E-03*
2.64	872	2.64	891	2.64	901	*0.276*	*8.88E-04*	*3.21E-03*
1.83	760	1.83	780	1.83	786	*0.192*	*7.75E-04*	*4.05E-03*
1.27	670	1.27	689	1.28	702	*0.133*	*6.87E-04*	*5.15E-03*
0.886	599	0.886	616	0.892	713	*0.093*	*6.43E-04*	*6.91E-03*
0.615	545	0.622	588	0.616	585	*0.065*	*5.73E-04*	*8.85E-03*
0.428	500	0.419	539	0.428	527	*0.045*	*5.22E-04*	*1.17E-02*
0.298	452	0.308	508	0.295	499	*0.031*	*4.86E-04*	*1.55E-02*
0.207	423	0.207	504	0.194	507	*0.021*	*4.78E-04*	*2.25E-02*
0.144	400	0.142	428	0.137	482	*0.015*	*4.37E-04*	*2.96E-02*
0.102	390	0.101	445	0.0998	467	*0.011*	*4.34E-04*	*4.11E-02*

Table A - 30: Measured data for Mix#6 with 40% beads using Serrated Coaxial Cylinder.

Serrated Coaxial Cylinder						Bead %		
Geom.: SS18				Z43S		40%		
Run #1		Run #2		Run #3		**Average values**		
NIST Code: SMC-97M		NIST Code: SMC-97N		NIST Code: SMC-97O				
N	Γ	N	Γ	N	Γ	**N**	**Γ**	*Γ/N (Angular momentum)*
1/min	μNm	1/min	μNm	1/min	μNm	**rad/s**	**Nm**	
0.0973	1230	0.0967	1190	0.0979	1170	0.010	1.20E-03	1.17E-01
0.164	1480	0.163	1350	0.165	1330	0.017	1.39E-03	8.07E-02
0.27	1550	0.27	1380	0.268	1390	0.028	1.44E-03	5.11E-02
0.441	1570	0.441	1470	0.442	1490	0.046	1.51E-03	3.27E-02
0.721	1670	0.718	1660	0.722	1670	0.075	1.67E-03	2.21E-02
1.18	1840	1.18	1960	1.18	1980	0.124	1.93E-03	1.56E-02
1.93	2150	1.93	2350	1.93	2410	0.202	2.30E-03	1.14E-02
3.17	2640	3.16	2950	3.16	2990	0.331	2.86E-03	8.63E-03
5.18	3380	5.18	3800	5.18	3870	0.542	3.68E-03	6.79E-03
8.49	4420	8.49	4990	8.49	5090	0.889	4.83E-03	5.44E-03
13.9	5870	13.9	6700	13.9	6890	1.456	6.49E-03	4.46E-03
22.8	8090	22.8	9210	22.8	9490	2.388	8.93E-03	3.74E-03
37.3	11300	37.3	12800	37.3	13300	3.906	1.25E-02	3.19E-03
61	16000	61	16400	61.1	17300	6.391	1.66E-02	2.59E-03
100	21300	100	23700	100	24700	10.472	2.32E-02	2.22E-03
100	21000	99.9	23200	100	23800	10.468	2.27E-02	2.17E-03
69.5	16200	69.5	18100	69.5	18700	7.278	1.77E-02	2.43E-03
48.3	12600	48.3	13800	48.3	14100	5.058	1.35E-02	2.67E-03
33.6	9850	33.6	10400	33.6	10800	3.519	1.04E-02	2.94E-03
23.4	7570	23.3	7900	23.3	8160	2.443	7.88E-03	3.22E-03
16.2	5800	16.2	6100	16.2	6320	1.696	6.07E-03	3.58E-03
11.3	4530	11.3	4760	11.3	4920	1.183	4.74E-03	4.00E-03
7.85	3580	7.85	3770	7.85	3900	0.822	3.75E-03	4.56E-03
5.46	2890	5.45	3040	5.45	3150	0.571	3.03E-03	5.30E-03
3.79	2370	3.79	2490	3.79	2570	0.397	2.48E-03	6.24E-03
2.64	1980	2.64	2080	2.64	2160	0.276	2.07E-03	7.50E-03
1.83	1670	1.83	1760	1.83	1820	0.192	1.75E-03	9.13E-03
1.27	1450	1.28	1520	1.28	1590	0.134	1.52E-03	1.14E-02
0.885	1280	0.887	1330	0.885	1390	0.093	1.33E-03	1.44E-02
0.615	1140	0.614	1230	0.617	1250	0.064	1.21E-03	1.87E-02
0.428	1030	0.423	1090	0.429	1170	0.045	1.10E-03	2.45E-02
0.294	954	0.295	1000	0.294	1020	0.031	9.91E-04	3.22E-02
0.204	873	0.204	967	0.208	949	0.022	9.30E-04	4.32E-02
0.142	871	0.141	915	0.151	1070	0.015	9.52E-04	6.28E-02
0.0959	864	0.105	921	0.101	877	0.011	8.87E-04	8.42E-02

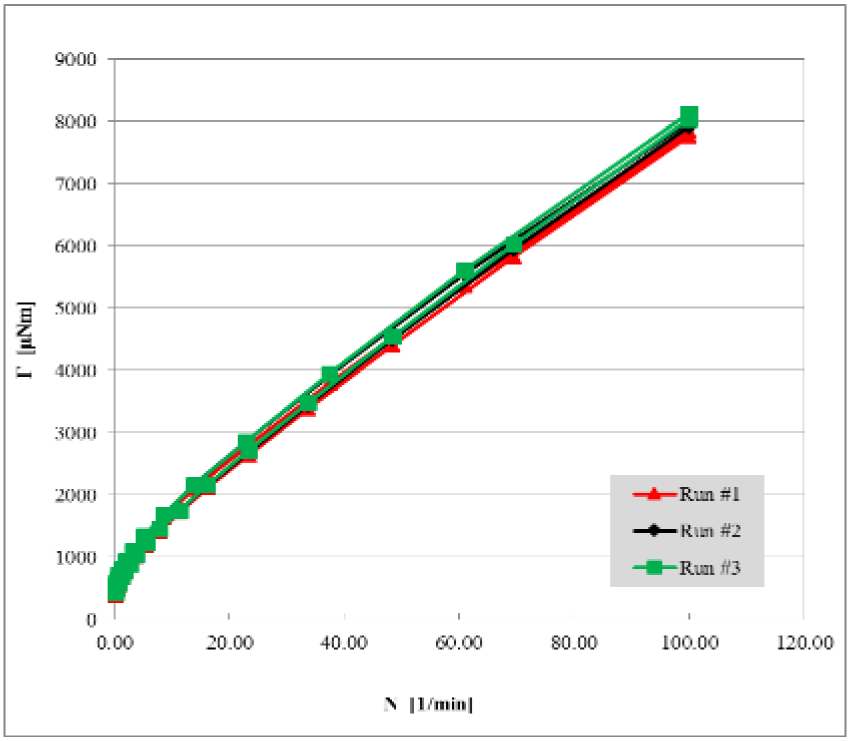


Figure A - 29: Torque vs. Angular Speed using __Serrated Coaxial Cylinder__ on Mix#6, with 0 % beads by volume. Portrays data from Table A-29.

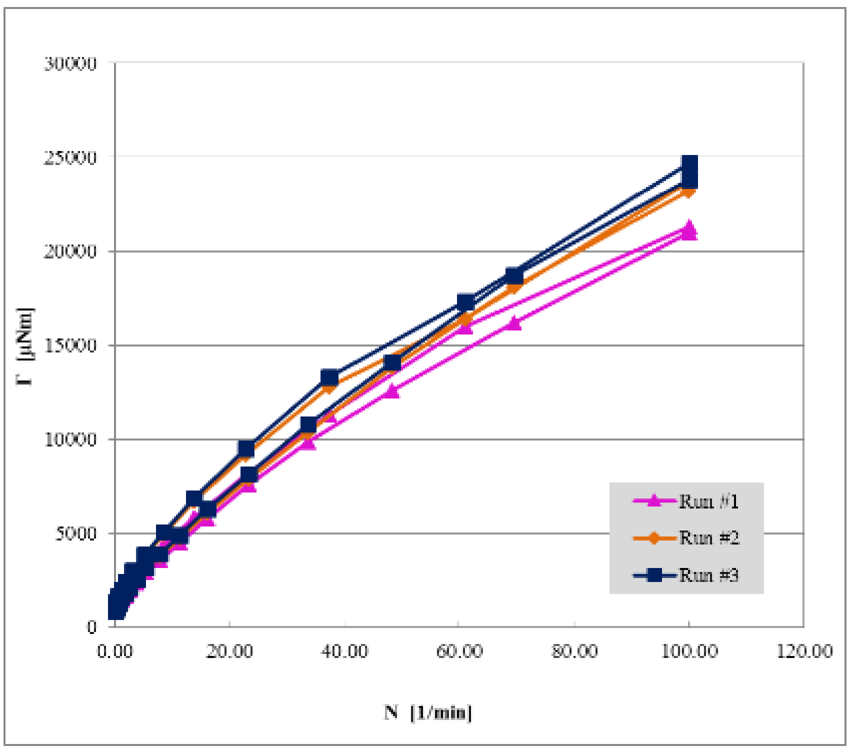


Figure A - 30: Torque vs. Angular Speed using __Serrated Coaxial Cylinder__ on Mix#6, with 40 % beads by volume. Portrays data from Table A-30.

Table A - 31: Measured data for Mix#7 with 0 % beads using Double spiral spindle.

Double Spiral						Bead %		
Geom.: RHN-83A				*Cup: Z43S*		*0%*		
Run #1		Run #2		Run #3		**Average values**		
NIST Code: SMC-101D		*NIST Code: SMC-101E*		*NIST Code: SMC-101F*				
N	Γ	N	Γ	N	Γ	**N**	**Γ**	*Γ/N (Angular momentum)*
1/min	µNm	1/min	µNm	1/min	µNm	**rad/s**	**Nm**	
0.0943	1020	0.0949	921	0.0949	918	*0.010*	*9.53E-04*	*9.61E-02*
0.161	1500	0.162	1370	0.162	1360	*0.017*	*1.41E-03*	*8.33E-02*
0.268	1690	0.268	1550	0.268	1540	*0.028*	*1.59E-03*	*5.68E-02*
0.439	1790	0.439	1660	0.439	1660	*0.046*	*1.70E-03*	*3.71E-02*
0.72	1900	0.72	1780	0.72	1780	*0.075*	*1.82E-03*	*2.41E-02*
1.18	2060	1.18	1960	1.18	1960	*0.124*	*1.99E-03*	*1.61E-02*
1.93	2290	1.93	2210	1.93	2210	*0.202*	*2.24E-03*	*1.11E-02*
3.16	2660	3.16	2590	3.16	2600	*0.331*	*2.62E-03*	*7.91E-03*
5.18	3230	5.18	3180	5.18	3190	*0.542*	*3.20E-03*	*5.90E-03*
8.48	4130	8.48	4090	8.48	4100	*0.888*	*4.11E-03*	*4.62E-03*
13.9	5550	13.9	5510	13.9	5520	*1.456*	*5.53E-03*	*3.80E-03*
22.8	7800	22.8	7730	22.8	7750	*2.388*	*7.76E-03*	*3.25E-03*
37.3	11300	37.3	11200	37.3	11300	*3.906*	*1.13E-02*	*2.88E-03*
61.1	16900	61.1	16700	61.1	16800	*6.398*	*1.68E-02*	*2.63E-03*
100	25500	100	25400	100	25500	*10.472*	*2.55E-02*	*2.43E-03*
100	25300	100	25300	100	25400	*10.472*	*2.53E-02*	*2.42E-03*
69.5	18500	69.5	18500	69.5	18600	*7.278*	*1.85E-02*	*2.55E-03*
48.3	13700	48.3	13700	48.3	13800	*5.058*	*1.37E-02*	*2.72E-03*
33.6	10300	33.6	10300	33.6	10300	*3.519*	*1.03E-02*	*2.93E-03*
23.4	7830	23.4	7830	23.4	7870	*2.450*	*7.84E-03*	*3.20E-03*
16.2	6080	16.2	6090	16.2	6110	*1.696*	*6.09E-03*	*3.59E-03*
11.3	4830	11.3	4830	11.3	4850	*1.183*	*4.84E-03*	*4.09E-03*
7.85	3920	7.85	3920	7.85	3940	*0.822*	*3.93E-03*	*4.78E-03*
5.46	3260	5.46	3270	5.46	3280	*0.572*	*3.27E-03*	*5.72E-03*
3.79	2790	3.79	2790	3.79	2790	*0.397*	*2.79E-03*	*7.03E-03*
2.64	2430	2.64	2430	2.64	2440	*0.276*	*2.43E-03*	*8.80E-03*
1.83	2170	1.83	2170	1.83	2180	*0.192*	*2.17E-03*	*1.13E-02*
1.27	1980	1.27	1980	1.27	1980	*0.133*	*1.98E-03*	*1.49E-02*
0.886	1830	0.886	1830	0.886	1830	*0.093*	*1.83E-03*	*1.97E-02*
0.616	1720	0.616	1720	0.616	1720	*0.065*	*1.72E-03*	*2.67E-02*
0.428	1640	0.428	1630	0.428	1630	*0.045*	*1.63E-03*	*3.64E-02*
0.298	1570	0.297	1560	0.297	1570	*0.031*	*1.57E-03*	*5.03E-02*
0.207	1510	0.207	1510	0.209	1530	*0.022*	*1.52E-03*	*6.97E-02*
0.144	1470	0.143	1470	0.144	1480	*0.015*	*1.47E-03*	*9.79E-02*
0.0999	1440	0.1	1440	0.0996	1440	*0.010*	*1.44E-03*	*1.38E-01*

Table A - 32: Measured data for Mix#7 with 20 % beads using Double spiral spindle.

Double Spiral								
Geom.: RHN-83A				*Cup: Z43S*		*Bead % 20%*		
Run #1		Run #2		Run #3		**Average values**		
NIST Code: SMC-101M		*NIST Code: SMC-101N*		*NIST Code: SMC-101O*				
N	Γ	N	Γ	N	Γ	**N**	**Γ**	***Γ/N*** *(Angular*
1/min	μNm	1/min	μNm	1/min	μNm	**rad/s**	**Nm**	*momentum)*
0.0935	1330	0.0972	1670	0.0933	1220	*0.010*	*1.41E-03*	*1.42E-01*
0.162	1890	0.162	1900	0.161	1760	*0.017*	*1.85E-03*	*1.09E-01*
0.269	2140	0.268	2040	0.268	1990	*0.028*	*2.06E-03*	*7.32E-02*
0.439	2290	0.44	2200	0.439	2170	*0.046*	*2.22E-03*	*4.83E-02*
0.719	2510	0.72	2400	0.72	2390	*0.075*	*2.43E-03*	*3.23E-02*
1.18	2830	1.18	2730	1.18	2710	*0.124*	*2.76E-03*	*2.23E-02*
1.93	3320	1.93	3230	1.93	3210	*0.202*	*3.25E-03*	*1.61E-02*
3.16	4100	3.16	3990	3.16	3940	*0.331*	*4.01E-03*	*1.21E-02*
5.18	5310	5.18	5130	5.18	5060	*0.542*	*5.17E-03*	*9.52E-03*
8.49	7190	8.48	6830	8.48	6750	*0.888*	*6.92E-03*	*7.79E-03*
13.9	9840	13.9	9330	13.9	9310	*1.456*	*9.49E-03*	*6.52E-03*
22.7	13800	22.8	13400	22.8	13400	*2.384*	*1.35E-02*	*5.68E-03*
37.3	20400	37.3	19900	37.3	19800	*3.906*	*2.00E-02*	*5.13E-03*
61	30900	61.1	30100	61	30000	*6.391*	*3.03E-02*	*4.75E-03*
100	46800	100	45800	100	45800	*10.472*	*4.61E-02*	*4.41E-03*
100	46200	100	45500	100	45500	*10.472*	*4.57E-02*	*4.37E-03*
69.5	33500	69.5	33000	69.5	33100	*7.278*	*3.32E-02*	*4.56E-03*
48.3	24500	48.3	24200	48.3	24300	*5.058*	*2.43E-02*	*4.81E-03*
33.6	18100	33.6	18000	33.6	18000	*3.519*	*1.80E-02*	*5.13E-03*
23.3	13600	23.4	13500	23.4	13600	*2.447*	*1.36E-02*	*5.54E-03*
16.2	10400	16.2	10300	16.2	10300	*1.696*	*1.03E-02*	*6.09E-03*
11.3	8050	11.3	7980	11.3	8020	*1.183*	*8.02E-03*	*6.77E-03*
7.84	6380	7.85	6330	7.85	6380	*0.822*	*6.36E-03*	*7.74E-03*
5.46	5140	5.46	5140	5.45	5170	*0.571*	*5.15E-03*	*9.01E-03*
3.79	4280	3.79	4270	3.8	4280	*0.397*	*4.28E-03*	*1.08E-02*
2.63	3630	2.64	3620	2.64	3630	*0.276*	*3.63E-03*	*1.31E-02*
1.83	3150	1.83	3150	1.83	3160	*0.192*	*3.15E-03*	*1.65E-02*
1.27	2780	1.27	2790	1.28	2810	*0.133*	*2.79E-03*	*2.09E-02*
0.886	2510	0.886	2520	0.886	2540	*0.093*	*2.52E-03*	*2.72E-02*
0.616	2320	0.617	2310	0.616	2340	*0.065*	*2.32E-03*	*3.60E-02*
0.429	2160	0.431	2180	0.428	2180	*0.045*	*2.17E-03*	*4.83E-02*
0.297	2050	0.294	2070	0.297	2060	*0.031*	*2.06E-03*	*6.65E-02*
0.205	1950	0.205	1980	0.208	1980	*0.022*	*1.97E-03*	*9.13E-02*
0.143	1880	0.142	1900	0.142	1900	*0.015*	*1.89E-03*	*1.27E-01*
0.101	1820	0.0997	1820	0.101	1830	*0.011*	*1.82E-03*	*1.73E-01*

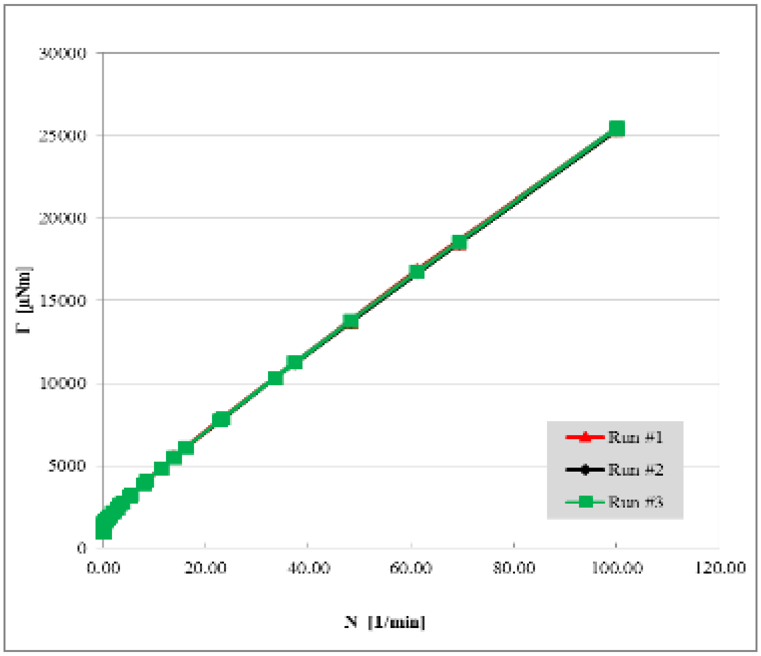


Figure A - 23: Torque vs. Angular Speed using <u>Double spiral spindle</u> on Mix#7, with 0 % beads by volume. Portrays data from Table A-31.

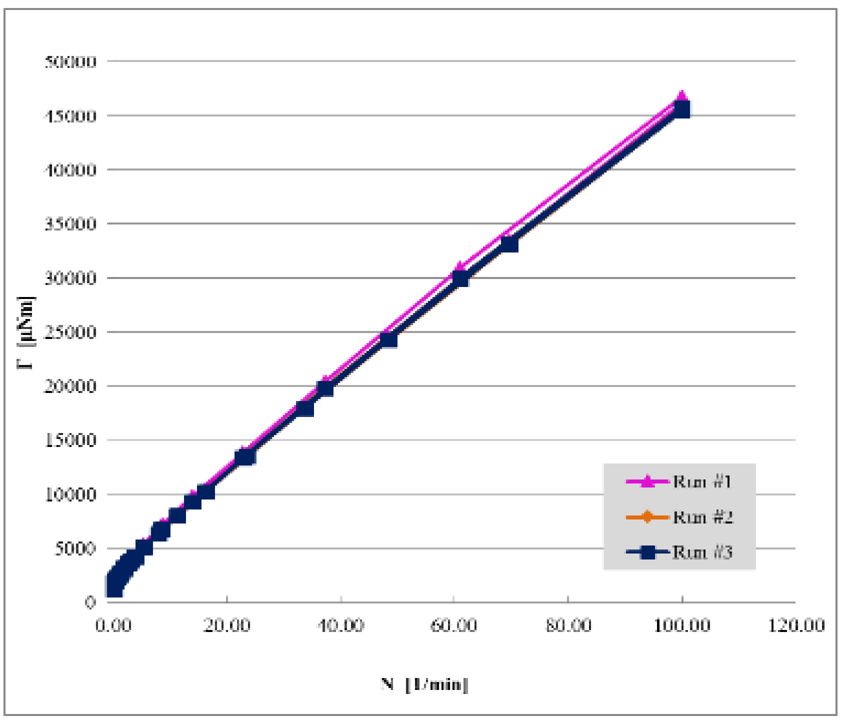


Figure A - 24: Torque vs. Angular Speed using <u>Double spiral spindle</u> on Mix#7, with 20 % beads by volume. Portrays data from Table A-32.

Table A - 33: Measured data for Mix#7 with 0 % beads using Six-blade Vane.

6 Blade Vane							Bead %	
Geom.:	*RHN-83C*			*Z43S*			*0%*	
Run #1		Run #2		Run #3		**Average values**		
NIST Code: SMC-101A		*NIST Code: SMC-101B*		*NIST Code: SMC-101C*				
N	Γ	N	Γ	N	Γ	**N**	**Γ**	***Γ/N*** *(Angular*
1/min	μNm	1/min	μNm	1/min	μNm	**rad/s**	**Nm**	*momentum)*
0.098	416	0.098	393	0.0981	387	*0.010*	*3.99E-04*	*3.88E-02*
0.163	546	0.163	520	0.163	516	*0.017*	*5.27E-04*	*3.09E-02*
0.268	587	0.268	557	0.268	561	*0.028*	*5.68E-04*	*2.03E-02*
0.439	620	0.44	594	0.441	596	*0.046*	*6.03E-04*	*1.31E-02*
0.72	668	0.719	653	0.721	633	*0.075*	*6.51E-04*	*8.64E-03*
1.18	735	1.18	714	1.18	703	*0.124*	*7.17E-04*	*5.81E-03*
1.93	827	1.93	813	1.93	794	*0.202*	*8.11E-04*	*4.01E-03*
3.16	958	3.16	946	3.16	934	*0.331*	*9.46E-04*	*2.86E-03*
5.18	1150	5.18	1130	5.18	1120	*0.542*	*1.13E-03*	*2.09E-03*
8.48	1420	8.48	1410	8.48	1400	*0.888*	*1.41E-03*	*1.59E-03*
13.9	1820	13.9	1800	13.9	1800	*1.456*	*1.81E-03*	*1.24E-03*
22.8	2390	22.8	2370	22.8	2380	*2.388*	*2.38E-03*	*9.97E-04*
37.3	3280	37.3	3260	37.3	3270	*3.906*	*3.27E-03*	*8.37E-04*
61	4640	61	4620	61	4650	*6.388*	*4.64E-03*	*7.26E-04*
100	6760	100	6750	100	6790	*10.472*	*6.77E-03*	*6.46E-04*
100	6730	100	6740	100	6780	*10.472*	*6.75E-03*	*6.45E-04*
69.5	5050	69.5	5060	69.5	5090	*7.278*	*5.07E-03*	*6.96E-04*
48.3	3860	48.3	3860	48.3	3880	*5.058*	*3.87E-03*	*7.64E-04*
33.6	3000	33.6	3000	33.6	3010	*3.519*	*3.00E-03*	*8.54E-04*
23.4	2370	23.4	2370	23.4	2390	*2.450*	*2.38E-03*	*9.70E-04*
16.2	1920	16.2	1910	16.2	1920	*1.696*	*1.92E-03*	*1.13E-03*
11.3	1580	11.3	1580	11.3	1590	*1.183*	*1.58E-03*	*1.34E-03*
7.85	1320	7.85	1320	7.85	1330	*0.822*	*1.32E-03*	*1.61E-03*
5.45	1140	5.45	1130	5.45	1130	*0.571*	*1.13E-03*	*1.99E-03*
3.79	985	3.79	980	3.79	985	*0.397*	*9.83E-04*	*2.48E-03*
2.64	880	2.64	865	2.64	869	*0.276*	*8.71E-04*	*3.15E-03*
1.83	779	1.83	776	1.83	778	*0.192*	*7.78E-04*	*4.06E-03*
1.27	713	1.27	705	1.27	716	*0.133*	*7.11E-04*	*5.35E-03*
0.885	660	0.884	657	0.886	658	*0.093*	*6.58E-04*	*7.10E-03*
0.615	614	0.616	622	0.616	613	*0.064*	*6.16E-04*	*9.56E-03*
0.428	579	0.429	580	0.429	585	*0.045*	*5.81E-04*	*1.30E-02*
0.294	573	0.299	568	0.297	570	*0.031*	*5.70E-04*	*1.84E-02*
0.207	526	0.205	553	0.208	524	*0.022*	*5.34E-04*	*2.47E-02*
0.142	532	0.144	521	0.144	527	*0.015*	*5.27E-04*	*3.51E-02*
0.0994	516	0.0982	521	0.0994	518	*0.010*	*5.18E-04*	*5.00E-02*

Table A - 34: Measured data for Mix#7 with 20 % beads using Six-blade Vane.

6 Blade Vane						Bead %		
Geom.: RHN-83C				Z43S		20%		
Run #1		Run #2		Run #3		Average values		
NIST Code: SMC-101J		NIST Code: SMC-101K		NIST Code: SMC-101L				
N	Γ	N	Γ	N	Γ	**N**	**Γ**	*Γ/N (Angular*
1/min	μNm	1/min	μNm	1/min	μNm	**rad/s**	**Nm**	*momentum)*
0.0976	576	0.0977	554	0.0976	577	*0.010*	*5.69E-04*	*5.57E-02*
0.163	728	0.163	710	0.164	726	*0.017*	*7.21E-04*	*4.22E-02*
0.268	793	0.268	777	0.268	785	*0.028*	*7.85E-04*	*2.80E-02*
0.44	847	0.44	831	0.44	847	*0.046*	*8.42E-04*	*1.83E-02*
0.719	920	0.719	907	0.72	921	*0.075*	*9.16E-04*	*1.22E-02*
1.18	1020	1.18	1020	1.18	1040	*0.124*	*1.03E-03*	*8.31E-03*
1.93	1190	1.93	1180	1.93	1200	*0.202*	*1.19E-03*	*5.89E-03*
3.16	1410	3.16	1410	3.16	1440	*0.331*	*1.42E-03*	*4.29E-03*
5.18	1730	5.18	1760	5.18	1800	*0.542*	*1.76E-03*	*3.25E-03*
8.48	2220	8.48	2250	8.48	2300	*0.888*	*2.26E-03*	*2.54E-03*
13.9	2940	13.9	3000	13.9	3080	*1.456*	*3.01E-03*	*2.07E-03*
22.8	4060	22.8	4130	22.7	4240	*2.384*	*4.14E-03*	*1.74E-03*
37.3	5680	37.3	5820	37.3	6000	*3.906*	*5.83E-03*	*1.49E-03*
61	8050	61	8410	61.1	8690	*6.391*	*8.38E-03*	*1.31E-03*
100	11600	100	12300	100	12800	*10.472*	*1.22E-02*	*1.17E-03*
100	11500	100	12200	100	12800	*10.472*	*1.22E-02*	*1.16E-03*
69.5	8600	69.5	9080	69.5	9500	*7.278*	*9.06E-03*	*1.24E-03*
48.3	6510	48.3	6820	48.3	7110	*5.058*	*6.81E-03*	*1.35E-03*
33.6	4970	33.6	5200	33.6	5400	*3.519*	*5.19E-03*	*1.48E-03*
23.4	3890	23.3	4040	23.4	4160	*2.447*	*4.03E-03*	*1.65E-03*
16.2	3080	16.2	3190	16.2	3280	*1.696*	*3.18E-03*	*1.88E-03*
11.3	2480	11.3	2550	11.3	2620	*1.183*	*2.55E-03*	*2.15E-03*
7.85	2020	7.85	2080	7.84	2120	*0.822*	*2.07E-03*	*2.52E-03*
5.45	1690	5.45	1720	5.45	1770	*0.571*	*1.73E-03*	*3.03E-03*
3.79	1430	3.79	1460	3.8	1500	*0.397*	*1.46E-03*	*3.68E-03*
2.64	1230	2.64	1260	2.64	1290	*0.276*	*1.26E-03*	*4.56E-03*
1.83	1080	1.83	1110	1.83	1130	*0.192*	*1.11E-03*	*5.77E-03*
1.28	969	1.27	990	1.28	1000	*0.134*	*9.86E-04*	*7.38E-03*
0.886	883	0.885	907	0.885	905	*0.093*	*8.98E-04*	*9.69E-03*
0.616	810	0.616	840	0.615	844	*0.064*	*8.31E-04*	*1.29E-02*
0.428	758	0.43	775	0.429	792	*0.045*	*7.75E-04*	*1.73E-02*
0.297	727	0.297	736	0.297	759	*0.031*	*7.41E-04*	*2.38E-02*
0.206	693	0.207	700	0.207	697	*0.022*	*6.97E-04*	*3.22E-02*
0.144	659	0.144	667	0.143	713	*0.015*	*6.80E-04*	*4.52E-02*
0.0995	639	0.0993	684	0.101	682	*0.010*	*6.68E-04*	*6.39E-02*

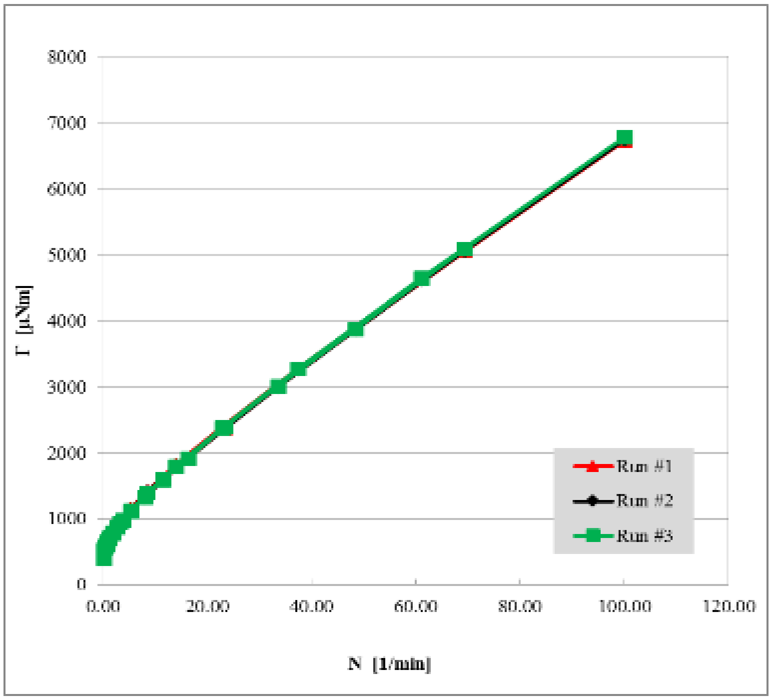


Figure A - 33: Torque vs. Angular Speed using <u>six-blade vane</u> on Mix#7, with 0 % beads by volume. Portrays data from Table A-33.

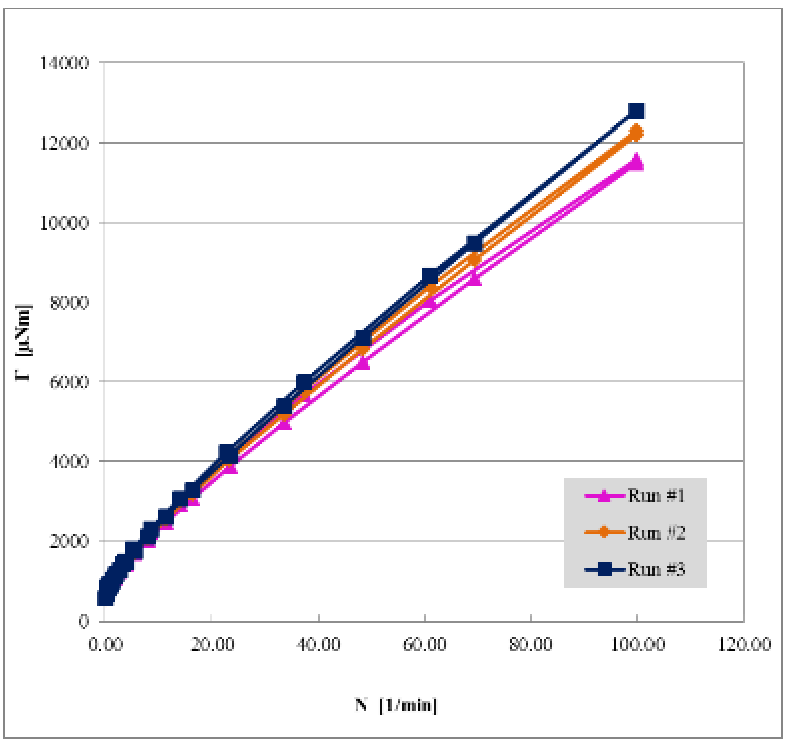


Figure A - 34: Torque vs. Angular Speed using <u>six-blade vane</u> on Mix#7, with 20 % beads by volume. Portrays data from Table A-34.

Table A - 35: Measured data for Mix#7 with 0 % beads usin[illegible]er.

Serrated Coaxial Cylinder						Bead %		
Geom.:	*SS18*			*Z43S*		*0%*		
Run #1		Run #2		Run #3		**Average values**		
NIST Code: SMC-101G		*NIST Code: SMC-101H*		*NIST Code: SMC-101I*				
N	Γ	N	Γ	N	Γ	**N**	**Γ**	*Γ/N (Angular momentum)*
1/min	μNm	1/min	μNm	1/min	μNm	**rad/s**	**Nm**	
0.0982	439	0.0986	376	0.0989	340	*0.010*	*3.85E-04*	*3.73E-02*
0.164	542	0.163	475	0.163	417	*0.017*	*4.78E-04*	*2.79E-02*
0.268	[illegible]	[illegible]	[illegible]	0.268	[illegible]	*0.028*	*5.11E-04*	*1.82E-02*
0.44	616	0.439	550	0.442	567	*0.046*	*5.78E-04*	*1.25E-02*
0.72	676	0.72	610	0.719	590	*0.075*	*6.25E-04*	*8.30E-03*
1.18	757	1.18	683	1.18	685	*0.124*	*7.08E-04*	*5.73E-03*
1.93	863	1.93	794	1.93	758	*0.202*	*8.05E-04*	*3.98E-03*
3.16	1020	3.16	950	3.16	896	*0.331*	*9.55E-04*	*2.89E-03*
5.18	1230	5.18	1170	5.18	1110	*0.542*	*1.17E-03*	*2.16E-03*
8.48	1530	8.48	1480	8.48	1420	*0.888*	*1.48E-03*	*1.66E-03*
13.9	1970	13.9	1920	13.9	1850	*1.456*	*1.91E-03*	*1.31E-03*
22.8	2610	22.8	2560	22.8	2470	*2.388*	*2.55E-03*	*1.07E-03*
37.3	3590	37.3	3530	37.3	3420	*3.906*	*3.51E-03*	*8.99E-04*
61	5090	61	5010	61	4900	*6.388*	*5.00E-03*	*7.83E-04*
100	7450	100	7330	100	7170	*10.472*	*7.32E-03*	*6.99E-04*
100	7420	100	7290	100	7120	*10.472*	*7.28E-03*	*6.95E-04*
69.5	5530	69.5	5460	69.5	5330	*7.278*	*5.44E-03*	*7.47E-04*
48.3	4170	48.3	4130	48.3	4050	*5.058*	*4.12E-03*	*8.14E-04*
33.6	3200	33.6	3160	33.6	3110	*3.519*	*3.16E-03*	*8.97E-04*
23.4	2500	23.4	2470	23.4	2430	*2.450*	*2.47E-03*	*1.01E-03*
16.2	2000	16.2	1970	16.2	1940	*1.696*	*1.97E-03*	*1.16E-03*
11.3	1630	11.3	1600	11.3	1570	*1.183*	*1.60E-03*	*1.35E-03*
7.85	1340	7.85	1310	7.85	1290	*0.822*	*1.31E-03*	*1.60E-03*
5.45	1120	5.45	1100	5.45	1080	*0.571*	*1.10E-03*	*1.93E-03*
3.79	952	3.79	929	3.79	913	*0.397*	*9.31E-04*	*2.35E-03*
2.64	819	2.64	800	2.64	782	*0.276*	*8.00E-04*	*2.89E-03*
1.83	715	1.83	696	1.83	720	*0.192*	*7.10E-04*	*3.71E-03*
1.27	632	1.27	619	1.27	610	*0.133*	*6.20E-04*	*4.66E-03*
0.886	563	0.887	564	0.887	579	*0.093*	*5.69E-04*	*6.12E-03*
0.616	507	0.615	542	0.617	537	*0.065*	*5.29E-04*	*8.20E-03*
0.428	469	0.424	491	0.426	486	*0.045*	*4.82E-04*	*1.08E-02*
0.296	434	0.289	455	0.299	454	*0.031*	*4.48E-04*	*1.45E-02*
0.203	449	0.207	415	0.209	409	*0.022*	*4.24E-04*	*1.96E-02*
0.133	443	0.147	424	0.146	456	*0.015*	*4.41E-04*	*2.97E-02*
0.0994	355	0.1	395	0.0842	440	*0.010*	*3.97E-04*	*4.01E-02*

Table A - 36: Measured data for Mix#7 with 20 % beads using Serrated Coaxial Cylinder.

Serrated Coaxial Cylinder						Bead %		
Geom.: *SS18*				*Z43S*		*20%*		
Run #1		Run #2		Run #3		**Average values**		
NIST Code: SMC-101P		*NIST Code: SMC-101Q*		*NIST Code: SMC-101R*				
N	Γ	N	Γ	N	Γ	**N**	**Γ**	***Γ/N*** *(Angular*
1/min	μNm	1/min	μNm	1/min	μNm	**rad/s**	**Nm**	*momentum)*
0.0979	638	0.0981	629	0.0978	618	*0.010*	*6.28E-04*	*6.13E-02*
0.164	761	0.164	761	0.164	776	*0.017*	*7.66E-04*	*4.46E-02*
0.268	788	0.268	813	0.269	831	*0.028*	*8.11E-04*	*2.88E-02*
0.44	832	0.44	889	0.439	909	*0.046*	*8.77E-04*	*1.90E-02*
0.719	913	0.725	991	0.719	992	*0.076*	*9.65E-04*	*1.28E-02*
1.18	1030	1.18	1110	1.18	1140	*0.124*	*1.09E-03*	*8.85E-03*
1.93	1210	1.93	1320	1.93	1330	*0.202*	*1.29E-03*	*6.37E-03*
3.16	1470	3.16	1570	3.16	1630	*0.331*	*1.56E-03*	*4.70E-03*
5.18	1830	5.18	1940	5.17	2010	*0.542*	*1.93E-03*	*3.55E-03*
8.48	2330	8.48	2480	8.48	2560	*0.888*	*2.46E-03*	*2.77E-03*
13.9	3080	13.9	3290	13.9	3390	*1.456*	*3.25E-03*	*2.24E-03*
22.8	4190	22.8	4490	22.8	4650	*2.388*	*4.44E-03*	*1.86E-03*
37.3	5890	37.3	6350	37.3	6560	*3.906*	*6.27E-03*	*1.60E-03*
61	8550	61	9140	61	9460	*6.388*	*9.05E-03*	*1.42E-03*
100	12700	100	13500	100	13900	*10.472*	*1.34E-02*	*1.28E-03*
100	12700	100	13400	100	13700	*10.472*	*1.33E-02*	*1.27E-03*
69.5	9410	69.5	9940	69.5	10200	*7.278*	*9.85E-03*	*1.35E-03*
48.3	7060	48.3	7460	48.3	7670	*5.058*	*7.40E-03*	*1.46E-03*
33.6	5360	33.6	5650	33.6	5820	*3.519*	*5.61E-03*	*1.59E-03*
23.4	4140	23.4	4350	23.4	4480	*2.450*	*4.32E-03*	*1.76E-03*
16.2	3240	16.2	3410	16.2	3510	*1.696*	*3.39E-03*	*2.00E-03*
11.3	2590	11.3	2730	11.3	2800	*1.183*	*2.71E-03*	*2.29E-03*
7.85	2110	7.85	2220	7.85	2280	*0.822*	*2.20E-03*	*2.68E-03*
5.45	1740	5.46	1840	5.46	1880	*0.571*	*1.82E-03*	*3.19E-03*
3.79	1480	3.79	1560	3.79	1590	*0.397*	*1.54E-03*	*3.89E-03*
2.64	1260	2.64	1340	2.64	1360	*0.276*	*1.32E-03*	*4.77E-03*
1.83	1090	1.83	1160	1.83	1190	*0.192*	*1.15E-03*	*5.98E-03*
1.27	968	1.27	1020	1.27	1040	*0.133*	*1.01E-03*	*7.59E-03*
0.886	862	0.886	919	0.888	944	*0.093*	*9.08E-04*	*9.78E-03*
0.616	788	0.619	875	0.612	862	*0.064*	*8.42E-04*	*1.31E-02*
0.432	757	0.428	762	0.43	782	*0.045*	*7.67E-04*	*1.70E-02*
0.304	728	0.295	750	0.299	735	*0.031*	*7.38E-04*	*2.35E-02*
0.205	678	0.207	734	0.196	768	*0.021*	*7.27E-04*	*3.42E-02*
0.146	673	0.14	664	0.141	692	*0.015*	*6.76E-04*	*4.54E-02*
0.103	580	0.0997	684	0.106	687	*0.011*	*6.50E-04*	*6.04E-02*

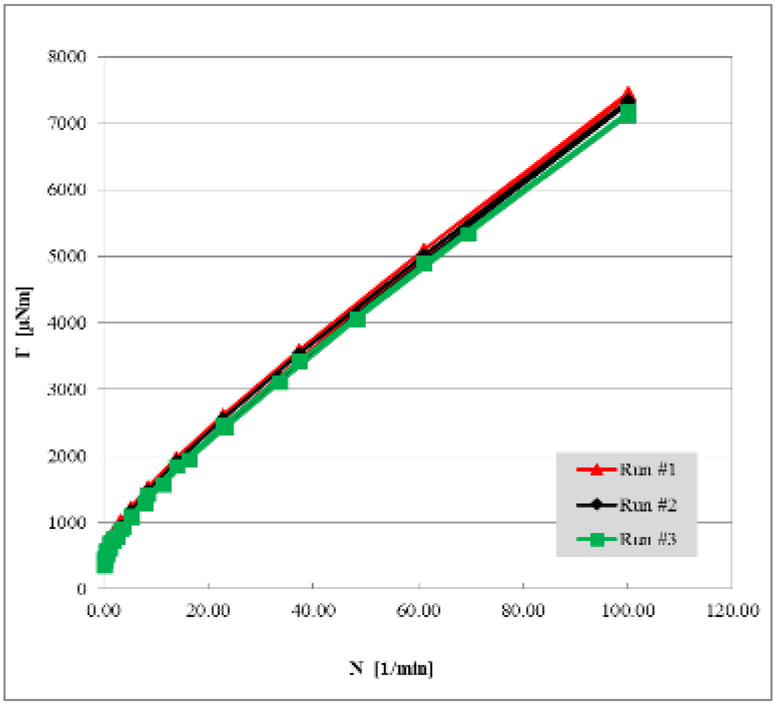


Figure A - 25: Torque vs. Angular Speed using <u>Serrated Coaxial Cylinder</u> on Mix#7, with 0 % beads by volume. Portrays data from Table A-35.

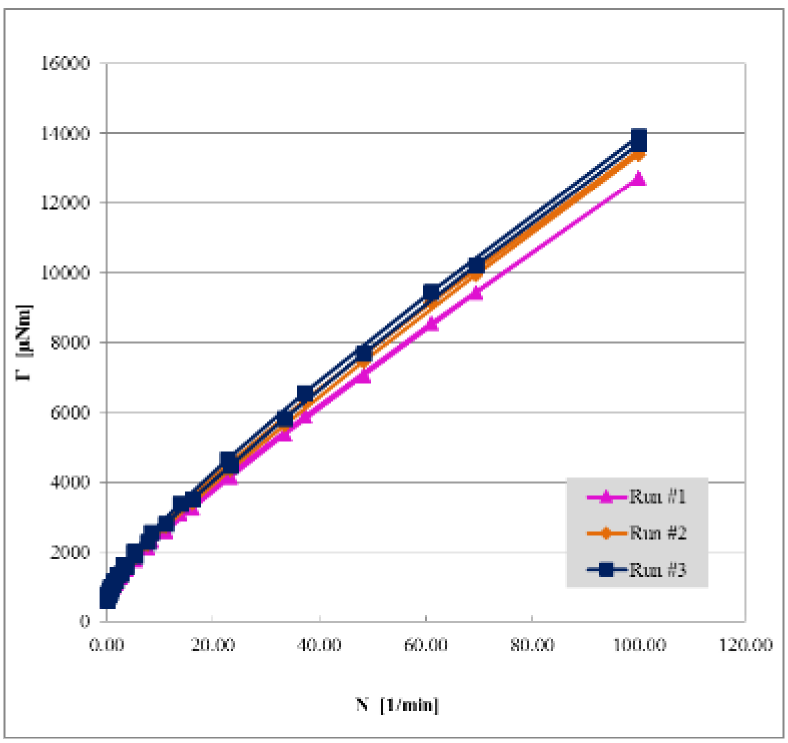


Figure A - 26: Torque vs. Angular Speed using <u>Serrated Coaxial Cylinder</u> on Mix#7, with 20 % beads by volume. Portrays data from Table A-36.

Table A - 37: Measured data for Mix#8 with 0 % beads using Double spiral spindle.

Double Spiral								
Geom.: RHN-83A				*Cup: Z43S*		*Bead %* *0%*		
Run #1		Run #2		Run #3		**Average values**		
NIST Code: SMC-103G		*NIST Code: SMC-103H*		*NIST Code: SMC-103I*				
N	Γ	N	Γ	N	Γ	**N**	**Γ**	***Γ/N*** *(Angular*
1/min	μNm	1/min	μNm	1/min	μNm	**rad/s**	**Nm**	*momentum)*
0.0942	1030	0.0945	979	0.0947	969	*0.010*	*9.93E-04*	*1.00E-01*
0.161	1520	0.161	1470	0.161	1430	*0.017*	*1.47E-03*	*8.74E-02*
0.268	1720	0.268	1680	0.267	1640	*0.028*	*1.68E-03*	*5.99E-02*
0.44	1830	0.439	1790	0.439	1750	*0.046*	*1.79E-03*	*3.89E-02*
0.72	1950	0.72	1920	0.72	1880	*0.075*	*1.92E-03*	*2.54E-02*
1.18	2120	1.18	2090	1.18	2070	*0.124*	*2.09E-03*	*1.69E-02*
1.93	2370	1.93	2350	1.93	2340	*0.202*	*2.35E-03*	*1.16E-02*
3.16	2770	3.16	2770	3.16	2760	*0.331*	*2.77E-03*	*8.36E-03*
5.18	3400	5.18	3410	5.18	3410	*0.542*	*3.41E-03*	*6.28E-03*
8.48	4360	8.48	4400	8.48	4430	*0.888*	*4.40E-03*	*4.95E-03*
13.9	5920	13.9	5990	13.9	6080	*1.456*	*6.00E-03*	*4.12E-03*
22.8	8360	22.8	8450	22.8	8510	*2.388*	*8.44E-03*	*3.53E-03*
37.3	12200	37.3	12300	37.3	12500	*3.906*	*1.23E-02*	*3.16E-03*
61.1	18200	61.1	18500	61.1	18800	*6.398*	*1.85E-02*	*2.89E-03*
100	27600	100	28000	100	28400	*10.472*	*2.80E-02*	*2.67E-03*
100	27400	100	27800	100	28300	*10.472*	*2.78E-02*	*2.66E-03*
69.5	20000	69.5	20300	69.5	20700	*7.278*	*2.03E-02*	*2.79E-03*
48.3	14700	48.3	15000	48.3	15200	*5.058*	*1.50E-02*	*2.96E-03*
33.6	11000	33.6	11200	33.6	11400	*3.519*	*1.12E-02*	*3.18E-03*
23.4	8380	23.4	8510	23.4	8650	*2.450*	*8.51E-03*	*3.47E-03*
16.2	6480	16.2	6570	16.2	6680	*1.696*	*6.58E-03*	*3.88E-03*
11.3	5110	11.3	5190	11.3	5270	*1.183*	*5.19E-03*	*4.39E-03*
7.85	4130	7.85	4190	7.85	4250	*0.822*	*4.19E-03*	*5.10E-03*
5.46	3420	5.46	3470	5.46	3520	*0.572*	*3.47E-03*	*6.07E-03*
3.79	2910	3.79	2950	3.79	2980	*0.397*	*2.95E-03*	*7.42E-03*
2.64	2530	2.64	2560	2.64	2590	*0.276*	*2.56E-03*	*9.26E-03*
1.83	2250	1.83	2280	1.83	2300	*0.192*	*2.28E-03*	*1.19E-02*
1.27	2040	1.27	2060	1.27	2090	*0.133*	*2.06E-03*	*1.55E-02*
0.887	1890	0.886	1900	0.887	1930	*0.093*	*1.91E-03*	*2.05E-02*
0.616	1760	0.615	1790	0.616	1810	*0.064*	*1.79E-03*	*2.77E-02*
0.43	1680	0.428	1690	0.43	1750	*0.045*	*1.71E-03*	*3.80E-02*
0.296	1610	0.296	1620	0.298	1660	*0.031*	*1.63E-03*	*5.25E-02*
0.206	1540	0.207	1580	0.208	1600	*0.022*	*1.57E-03*	*7.26E-02*
0.144	1500	0.143	1520	0.143	1560	*0.015*	*1.53E-03*	*1.02E-01*
0.0991	1470	0.0996	1480	0.1	1510	*0.010*	*1.49E-03*	*1.43E-01*

Table A - 38: Measured data for Mix#8 with 20 % beads using Double spiral spindle.

Double Spiral								
Geom.: RHN-83A				*Cup: Z43S*		*Bead % 20%*		
Run #1		Run #2		Run #3		**Average values**		
NIST Code: SMC-103P		*NIST Code: SMC-103Q*		*NIST Code: SMC-103R*				
N	Γ	N	Γ	N	Γ	**N**	**Γ**	***Γ/N*** *(Angular*
1/min	μNm	1/min	μNm	1/min	μNm	**rad/s**	**Nm**	*momentum)*
0.0931	1340	0.0924	1350	0.0927	1390	*0.010*	*1.36E-03*	*1.40E-01*
0.161	1930	0.161	1960	0.161	2000	*0.017*	*1.96E-03*	*1.16E-01*
0.268	2190	0.269	2220	0.269	2290	*0.028*	*2.23E-03*	*7.94E-02*
0.439	2360	0.439	2400	0.439	2460	*0.046*	*2.41E-03*	*5.24E-02*
0.72	2590	0.721	2650	0.719	2710	*0.075*	*2.65E-03*	*3.51E-02*
1.18	2920	1.18	2970	1.18	3060	*0.124*	*2.98E-03*	*2.41E-02*
1.93	3460	1.93	3490	1.93	3600	*0.202*	*3.52E-03*	*1.74E-02*
3.16	4320	3.16	4280	3.16	4420	*0.331*	*4.34E-03*	*1.31E-02*
5.18	5650	5.18	5560	5.18	5720	*0.542*	*5.64E-03*	*1.04E-02*
8.48	7710	8.48	7540	8.49	7800	*0.888*	*7.68E-03*	*8.65E-03*
13.9	10700	13.9	10600	13.9	10900	*1.456*	*1.07E-02*	*7.37E-03*
22.8	14900	22.7	15100	22.8	15600	*2.384*	*1.52E-02*	*6.38E-03*
37.3	22200	37.3	22500	37.3	23400	*3.906*	*2.27E-02*	*5.81E-03*
61	33600	61.1	34100	61.1	35400	*6.395*	*3.44E-02*	*5.37E-03*
100	50800	100	51900	100	53900	*10.472*	*5.22E-02*	*4.98E-03*
100	50200	100	51500	100	53500	*10.472*	*5.17E-02*	*4.94E-03*
69.5	36400	69.5	37300	69.5	38800	*7.278*	*3.75E-02*	*5.15E-03*
48.3	26600	48.3	27400	48.3	28400	*5.058*	*2.75E-02*	*5.43E-03*
33.6	19700	33.6	20300	33.6	21100	*3.519*	*2.04E-02*	*5.79E-03*
23.4	14800	23.3	15200	23.4	15800	*2.447*	*1.53E-02*	*6.24E-03*
16.2	11200	16.2	11600	16.2	12000	*1.696*	*1.16E-02*	*6.84E-03*
11.3	8670	11.3	8900	11.3	9240	*1.183*	*8.94E-03*	*7.55E-03*
7.85	6820	7.85	7060	7.85	7290	*0.822*	*7.06E-03*	*8.58E-03*
5.46	5500	5.46	5700	5.46	5870	*0.572*	*5.69E-03*	*9.95E-03*
3.79	4560	3.79	4690	3.79	4840	*0.397*	*4.70E-03*	*1.18E-02*
2.63	3830	2.64	3950	2.64	4080	*0.276*	*3.95E-03*	*1.43E-02*
1.83	3320	1.83	3420	1.83	3510	*0.192*	*3.42E-03*	*1.78E-02*
1.27	2940	1.28	3020	1.28	3110	*0.134*	*3.02E-03*	*2.26E-02*
0.887	2640	0.886	2730	0.885	2790	*0.093*	*2.72E-03*	*2.93E-02*
0.617	2420	0.614	2500	0.615	2560	*0.064*	*2.49E-03*	*3.87E-02*
0.428	2250	0.429	2320	0.427	2370	*0.045*	*2.31E-03*	*5.16E-02*
0.298	2120	0.296	2190	0.297	2240	*0.031*	*2.18E-03*	*7.02E-02*
0.207	2030	0.205	2080	0.207	2130	*0.022*	*2.08E-03*	*9.63E-02*
0.145	1950	0.142	2030	0.144	2050	*0.015*	*2.01E-03*	*1.34E-01*
0.0998	1900	0.102	2000	0.101	1990	*0.011*	*1.96E-03*	*1.86E-01*

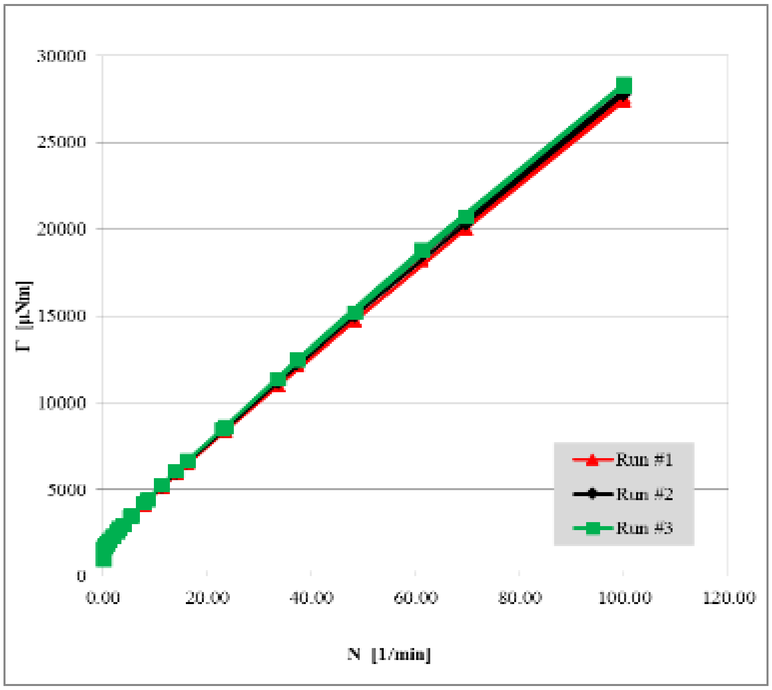


Figure A - 37: Torque vs. Angular Speed using <u>Double spiral spindle</u> on Mix#8, with 0 % beads by volume. Portrays data from Table A-37.

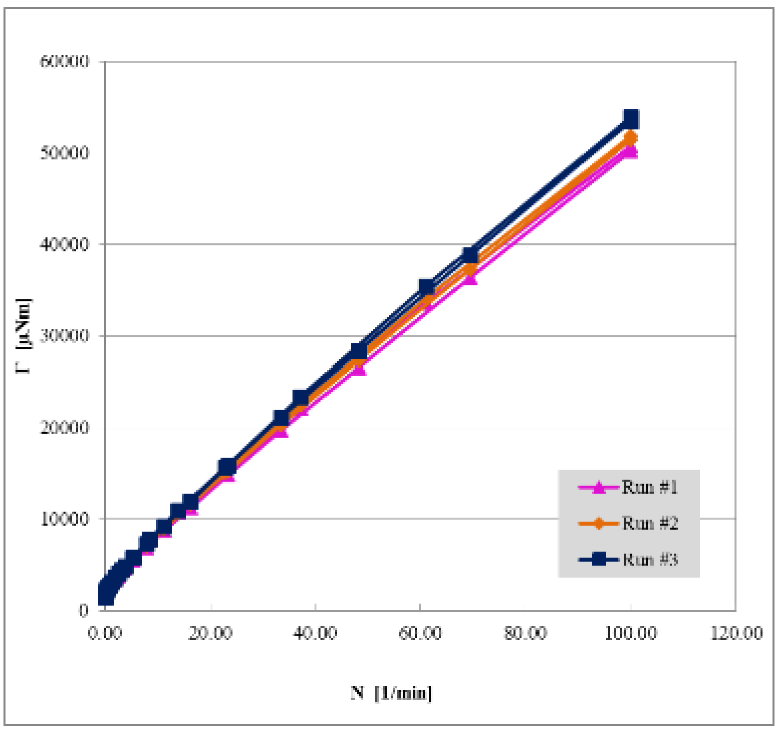


Figure A - 38: Torque vs. Angular Speed using <u>Double spiral spindle</u> on Mix#8, with 20 % beads by volume. Portrays data from Table A-38.

Table A - 39: Measured data for Mix#8 with 0 % beads using Six-blade Vane.

		6 Blade Vane					Bead %	
Geom.:	*RHN-83C*			*Z43S*			*0%*	
Run #1		Run #2		Run #3		**Average values**		
NIST Code: SMC-103D		*NIST Code: SMC-103E*		*NIST Code: SMC-103F*				
N	Γ	N	Γ	N	Γ	**N**	**Γ**	*(Angular*
1/min	μNm	1/min	μNm	1/min	μNm	**rad/s**	**Nm**	*momentum*
0.0979	425	0.0979	401	0.0977	421	*0.010*	*4.16E-04*	*4.06E-02*
0.163	557	0.163	537	0.163	570	*0.017*	*5.55E-04*	*3.25E-02*
0.268	595	0.268	580	0.268	611	*0.028*	*5.95E-04*	*2.12E-02*
0.439	629	0.439	614	0.439	645	*0.046*	*6.29E-04*	*1.37E-02*
0.72	679	0.72	664	0.72	695	*0.075*	*6.79E-04*	*9.01E-03*
1.18	749	1.18	735	1.18	767	*0.124*	*7.50E-04*	*6.07E-03*
1.93	849	1.93	834	1.93	867	*0.202*	*8.50E-04*	*4.21E-03*
3.16	984	3.16	975	3.16	1010	*0.331*	*9.90E-04*	*2.99E-03*
5.18	1180	5.18	1180	5.18	1210	*0.542*	*1.19E-03*	*2.19E-03*
8.48	1470	8.48	1470	8.48	1510	*0.888*	*1.48E-03*	*1.67E-03*
13.9	1890	13.9	1900	13.9	1940	*1.456*	*1.91E-03*	*1.31E-03*
22.8	2500	22.8	2530	22.8	2570	*2.388*	*2.53E-03*	*1.06E-03*
37.3	3450	37.3	3480	37.3	3550	*3.906*	*3.49E-03*	*8.94E-04*
61	4880	61	4960	61	5040	*6.388*	*4.96E-03*	*7.76E-04*
100	7130	100	7270	100	7390	*10.472*	*7.26E-03*	*6.94E-04*
100	7100	100	7250	100	7360	*10.472*	*7.24E-03*	*6.91E-04*
69.5	5330	69.5	5420	69.5	5500	*7.278*	*5.42E-03*	*7.44E-04*
48.3	4050	48.3	4120	48.3	4170	*5.058*	*4.11E-03*	*8.13E-04*
33.6	3140	33.6	3190	33.6	3220	*3.519*	*3.18E-03*	*9.05E-04*
23.4	2480	23.4	2510	23.4	2540	*2.450*	*2.51E-03*	*1.02E-03*
16.2	1990	16.2	2020	16.2	2040	*1.696*	*2.02E-03*	*1.19E-03*
11.3	1640	11.3	1660	11.3	1670	*1.183*	*1.66E-03*	*1.40E-03*
7.85	1370	7.85	1390	7.85	1390	*0.822*	*1.38E-03*	*1.68E-03*
5.45	1160	5.46	1180	5.45	1180	*0.571*	*1.17E-03*	*2.05E-03*
3.79	1010	3.79	1020	3.79	1030	*0.397*	*1.02E-03*	*2.57E-03*
2.64	886	2.63	900	2.64	904	*0.276*	*8.97E-04*	*3.25E-03*
1.83	797	1.83	811	1.83	811	*0.192*	*8.06E-04*	*4.21E-03*
1.27	723	1.27	735	1.28	739	*0.133*	*7.32E-04*	*5.49E-03*
0.887	669	0.887	675	0.885	681	*0.093*	*6.75E-04*	*7.27E-03*
0.616	633	0.618	637	0.618	640	*0.065*	*6.37E-04*	*9.85E-03*
0.43	601	0.426	602	0.428	595	*0.045*	*5.99E-04*	*1.34E-02*
0.298	566	0.295	586	0.296	568	*0.031*	*5.73E-04*	*1.85E-02*
0.205	562	0.208	550	0.206	569	*0.022*	*5.60E-04*	*2.59E-02*
0.143	522	0.143	525	0.144	555	*0.015*	*5.34E-04*	*3.56E-02*
0.0986	518	0.102	523	0.1	538	*0.010*	*5.26E-04*	*5.02E-02*

Table A - 40: Measured data for Mix#8 with 20 % beads using Six-blade Vane.

6 Blade Vane						Bead %		
Geom.: RHN-83C				Z43S		20%		
Run #1		Run #2		Run #3		**Average values**		
NIST Code: SMC-103M		NIST Code: SMC-103N		NIST Code: SMC-103O				
N	Γ	N	Γ	N	Γ	**N**	**Γ**	*(Angular*
1/min	μNm	1/min	μNm	1/min	μNm	**rad/s**	**Nm**	*momentum)*
0.0974	581	0.0973	582	0.0972	604	*0.010*	*5.89E-04*	*5.78E-02*
0.163	737	0.163	749	0.164	782	*0.017*	*7.56E-04*	*4.42E-02*
0.268	799	0.269	817	0.268	849	*0.028*	*8.22E-04*	*2.92E-02*
0.439	871	0.439	879	0.44	924	*0.046*	*8.91E-04*	*1.94E-02*
0.72	945	0.719	958	0.718	1000	*0.075*	*9.68E-04*	*1.29E-02*
1.18	1080	1.18	1080	1.18	1130	*0.124*	*1.10E-03*	*8.87E-03*
1.93	1240	1.93	1260	1.93	1320	*0.202*	*1.27E-03*	*6.30E-03*
3.16	1500	3.16	1520	3.16	1580	*0.331*	*1.53E-03*	*4.63E-03*
5.18	1860	5.18	1900	5.18	1980	*0.542*	*1.91E-03*	*3.53E-03*
8.48	2400	8.48	2450	8.48	2530	*0.888*	*2.46E-03*	*2.77E-03*
13.9	3230	13.9	3270	13.9	3370	*1.456*	*3.29E-03*	*2.26E-03*
22.8	4440	22.8	4510	22.8	4670	*2.388*	*4.54E-03*	*1.90E-03*
37.3	6220	37.3	6370	37.3	6630	*3.906*	*6.41E-03*	*1.64E-03*
61.1	8820	61.1	9180	61	9590	*6.395*	*9.20E-03*	*1.44E-03*
100	12900	100	13500	100	14200	*10.472*	*1.35E-02*	*1.29E-03*
100	12800	100	13400	100	14000	*10.472*	*1.34E-02*	*1.28E-03*
69.5	9530	69.5	9950	69.5	10300	*7.278*	*9.93E-03*	*1.36E-03*
48.3	7160	48.3	7470	48.3	7720	*5.058*	*7.45E-03*	*1.47E-03*
33.6	5460	33.6	5670	33.6	5890	*3.519*	*5.67E-03*	*1.61E-03*
23.3	4210	23.4	4360	23.3	4500	*2.443*	*4.36E-03*	*1.78E-03*
16.2	3320	16.2	3410	16.2	3520	*1.696*	*3.42E-03*	*2.01E-03*
11.3	2650	11.3	2720	11.3	2800	*1.183*	*2.72E-03*	*2.30E-03*
7.85	2160	7.85	2220	7.85	2270	*0.822*	*2.22E-03*	*2.70E-03*
5.46	1780	5.45	1840	5.45	1870	*0.571*	*1.83E-03*	*3.20E-03*
3.79	1510	3.79	1550	3.79	1590	*0.397*	*1.55E-03*	*3.91E-03*
2.64	1300	2.64	1330	2.64	1360	*0.276*	*1.33E-03*	*4.81E-03*
1.83	1140	1.83	1170	1.83	1200	*0.192*	*1.17E-03*	*6.11E-03*
1.27	1020	1.27	1040	1.27	1070	*0.133*	*1.04E-03*	*7.84E-03*
0.887	922	0.882	941	0.889	953	*0.093*	*9.39E-04*	*1.01E-02*
0.616	844	0.615	867	0.617	880	*0.065*	*8.64E-04*	*1.34E-02*
0.428	793	0.427	812	0.426	837	*0.045*	*8.14E-04*	*1.82E-02*
0.297	745	0.302	783	0.299	776	*0.031*	*7.68E-04*	*2.45E-02*
0.207	709	0.206	719	0.208	735	*0.022*	*7.21E-04*	*3.33E-02*
0.144	683	0.141	708	0.145	709	*0.015*	*7.00E-04*	*4.66E-02*
0.0996	657	0.102	691	0.0974	703	*0.010*	*6.84E-04*	*6.55E-02*

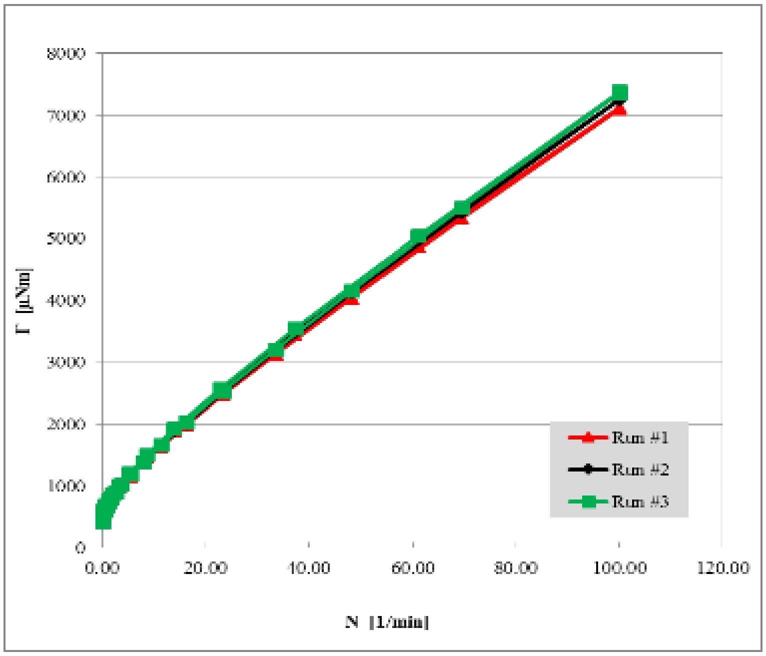


Figure A - 27: Torque vs. Angular Speed using <u>six-blade vane</u> on Mix#8, with 0 % beads by volume. Portrays data from Table A-39.

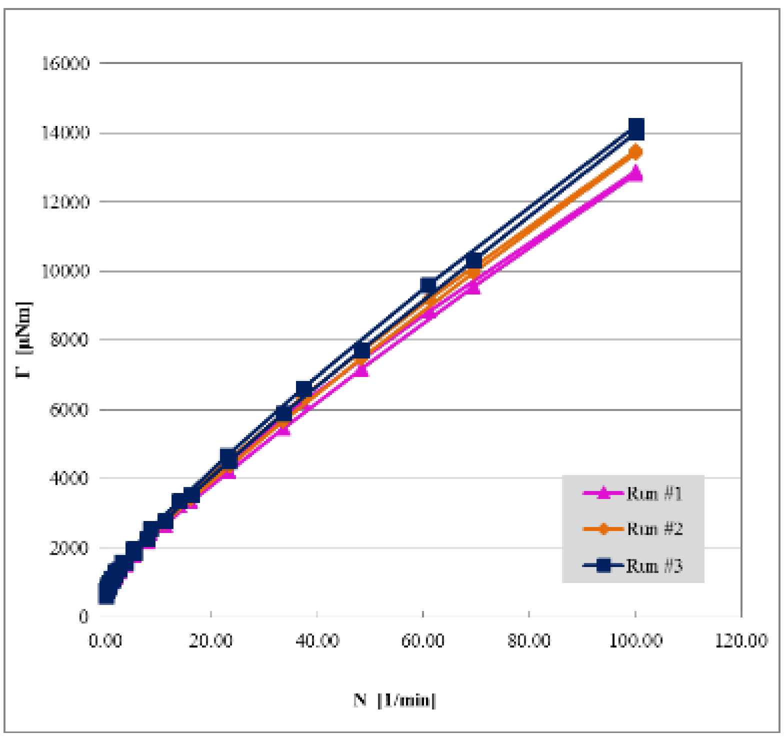


Figure A - 28: Torque vs. Angular Speed using <u>six-blade vane</u> on Mix#8, with 20 % beads by volume. Portrays data from Table A-40.

Table A - 41: Measured data for Mix#8 with 0 % beads using Serrated Coaxial Cylinder.

Serrated Coaxial Cylinder						Bead %		
Geom.:	*SS18*			*Z43S*		*0%*		
Run #1		Run #2		Run #3		**Average values**		
NIST Code: SMC-103A		*NIST Code: SMC-103B*		*NIST Code: SMC-103C*				
N	Γ	N	Γ	N	Γ	**N**	**Γ**	***Γ/N*** *(Angular*
1/min	μNm	1/min	μNm	1/min	μNm	**rad/s**	**Nm**	*momentum)*
0.0983	460	0.0984	411	0.0979	413	*0.010*	*4.28E-04*	*4.16E-02*
0.164	563	0.164	521	0.164	551	*0.017*	*5.45E-04*	*3.17E-02*
0.268	591	0.268	561	0.269	596	*0.028*	*5.83E-04*	*2.07E-02*
0.439	630	0.44	610	0.439	636	*0.046*	*6.25E-04*	*1.36E-02*
0.72	687	0.72	674	0.719	700	*0.075*	*6.87E-04*	*9.12E-03*
1.18	766	1.18	758	1.18	778	*0.124*	*7.67E-04*	*6.21E-03*
1.93	873	1.93	871	1.93	893	*0.202*	*8.79E-04*	*4.35E-03*
3.16	1020	3.16	1030	3.16	1060	*0.331*	*1.04E-03*	*3.13E-03*
5.18	1240	5.18	1240	5.18	1270	*0.542*	*1.25E-03*	*2.30E-03*
8.48	1540	8.48	1550	8.48	1590	*0.888*	*1.56E-03*	*1.76E-03*
13.9	1980	13.9	2000	13.9	2050	*1.456*	*2.01E-03*	*1.38E-03*
22.8	2600	22.8	2650	22.8	2700	*2.388*	*2.65E-03*	*1.11E-03*
37.3	3560	37.3	3640	37.3	3710	*3.906*	*3.64E-03*	*9.31E-04*
61	5040	61	5180	61	5280	*6.388*	*5.17E-03*	*8.09E-04*
100	7440	100	7550	100	7650	*10.472*	*7.55E-03*	*7.21E-04*
100	7290	100	7460	100	7570	*10.472*	*7.44E-03*	*7.10E-04*
69.5	5450	69.5	5570	69.5	5660	*7.278*	*5.56E-03*	*7.64E-04*
48.3	4130	48.3	4210	48.3	4270	*5.058*	*4.20E-03*	*8.31E-04*
33.6	3170	33.6	3220	33.6	3270	*3.519*	*3.22E-03*	*9.15E-04*
23.4	2480	23.4	2520	23.4	2560	*2.450*	*2.52E-03*	*1.03E-03*
16.2	1980	16.2	2010	16.2	2040	*1.696*	*2.01E-03*	*1.18E-03*
11.3	1620	11.3	1640	11.3	1660	*1.183*	*1.64E-03*	*1.39E-03*
7.85	1330	7.85	1350	7.85	1370	*0.822*	*1.35E-03*	*1.64E-03*
5.45	1120	5.45	1130	5.46	1150	*0.571*	*1.13E-03*	*1.98E-03*
3.79	952	3.79	963	3.79	982	*0.397*	*9.66E-04*	*2.43E-03*
2.64	820	2.64	832	2.64	851	*0.276*	*8.34E-04*	*3.02E-03*
1.83	717	1.83	730	1.83	751	*0.192*	*7.33E-04*	*3.82E-03*
1.27	645	1.27	643	1.27	670	*0.133*	*6.53E-04*	*4.91E-03*
0.886	571	0.884	616	0.887	605	*0.093*	*5.97E-04*	*6.44E-03*
0.612	538	0.623	561	0.617	566	*0.065*	*5.55E-04*	*8.59E-03*
0.421	497	0.438	625	0.422	579	*0.045*	*5.67E-04*	*1.27E-02*
0.301	445	0.301	512	0.303	486	*0.032*	*4.81E-04*	*1.52E-02*
0.207	458	0.211	499	0.216	592	*0.022*	*5.16E-04*	*2.33E-02*
0.148	469	0.152	497	0.148	464	*0.016*	*4.77E-04*	*3.05E-02*
0.103	431	0.11	528	0.0895	522	*0.011*	*4.94E-04*	*4.68E-02*

Table A - 42: Measured data for Mix#8 with 20 % beads using Serrated Coaxial Cylinder.

Serrated Coaxial Cylinder						Bead %		
Geom.:	*SS18*			*Z43S*		20%		
Run #1		Run #2		Run #3		**Average values**		
NIST Code: SMC-103J		*NIST Code: SMC-103K*		*NIST Code: SMC-103L*				
N	Γ	N	Γ	N	Γ	**N**	**Γ**	*Γ/N (Angular*
1/min	µNm	1/min	µNm	1/min	µNm	**rad/s**	**Nm**	*momentum)*
0.0972	632	0.0982	584	0.098	590	*1.02E-02*	*6.02E-04*	*5.88E-02*
0.164	784	0.164	714	0.164	729	*1.72E-02*	*7.42E-04*	*4.32E-02*
0.269	801	0.269	762	0.268	784	*2.81E-02*	*7.82E-04*	*2.78E-02*
0.439	818	0.44	814	0.44	838	*4.60E-02*	*8.23E-04*	*1.79E-02*
0.719	900	0.719	897	0.719	931	*7.53E-02*	*9.09E-04*	*1.21E-02*
1.18	1010	1.18	1030	1.18	1050	*1.24E-01*	*1.03E-03*	*8.34E-03*
1.93	1180	1.93	1200	1.93	1240	*2.02E-01*	*1.21E-03*	*5.97E-03*
3.16	1430	3.16	1450	3.16	1500	*3.31E-01*	*1.46E-03*	*4.41E-03*
5.18	1760	5.18	1800	5.18	1870	*5.42E-01*	*1.81E-03*	*3.34E-03*
8.48	2250	8.48	2310	8.48	2380	*8.88E-01*	*2.31E-03*	*2.61E-03*
13.9	2950	13.9	3060	13.9	3140	*1.46E+00*	*3.05E-03*	*2.10E-03*
22.8	3990	22.8	4150	22.8	4290	*2.39E+00*	*4.14E-03*	*1.74E-03*
37.3	5580	37.3	5850	37.3	6030	*3.91E+00*	*5.82E-03*	*1.49E-03*
61	8040	61	8410	61.1	8650	*6.39E+00*	*8.37E-03*	*1.31E-03*
100	11900	100	12400	100	12600	*1.05E+01*	*1.23E-02*	*1.17E-03*
100	11800	100	12200	100	12500	*1.05E+01*	*1.22E-02*	*1.16E-03*
69.5	8810	69.5	9110	69.5	9280	*7.28E+00*	*9.07E-03*	*1.25E-03*
48.3	6610	48.3	6820	48.3	6940	*5.06E+00*	*6.79E-03*	*1.34E-03*
33.6	5020	33.6	5170	33.6	5270	*3.52E+00*	*5.15E-03*	*1.46E-03*
23.4	3870	23.4	3980	23.4	4060	*2.45E+00*	*3.97E-03*	*1.62E-03*
16.2	3040	16.2	3130	16.2	3180	*1.70E+00*	*3.12E-03*	*1.84E-03*
11.3	2440	11.3	2510	11.3	2540	*1.18E+00*	*2.50E-03*	*2.11E-03*
7.85	1990	7.85	2040	7.85	2070	*8.22E-01*	*2.03E-03*	*2.47E-03*
5.45	1650	5.45	1700	5.45	1720	*5.71E-01*	*1.69E-03*	*2.96E-03*
3.79	1390	3.79	1430	3.79	1450	*3.97E-01*	*1.42E-03*	*3.59E-03*
2.64	1200	2.64	1230	2.64	1250	*2.76E-01*	*1.23E-03*	*4.44E-03*
1.83	1040	1.83	1070	1.83	1080	*1.92E-01*	*1.06E-03*	*5.55E-03*
1.27	918	1.27	947	1.28	964	*1.33E-01*	*9.43E-04*	*7.07E-03*
0.886	855	0.886	847	0.887	880	*9.28E-02*	*8.61E-04*	*9.27E-03*
0.615	757	0.617	771	0.61	822	*6.43E-02*	*7.83E-04*	*1.22E-02*
0.418	752	0.427	777	0.422	753	*4.42E-02*	*7.61E-04*	*1.72E-02*
0.29	675	0.297	777	0.294	734	*3.08E-02*	*7.29E-04*	*2.37E-02*
0.214	616	0.205	633	0.211	710	*2.20E-02*	*6.53E-04*	*2.97E-02*
0.149	667	0.133	669	0.143	620	*1.48E-02*	*6.52E-04*	*4.39E-02*
0.104	592	0.107	607	0.104	627	*1.10E-02*	*6.09E-04*	*5.54E-02*

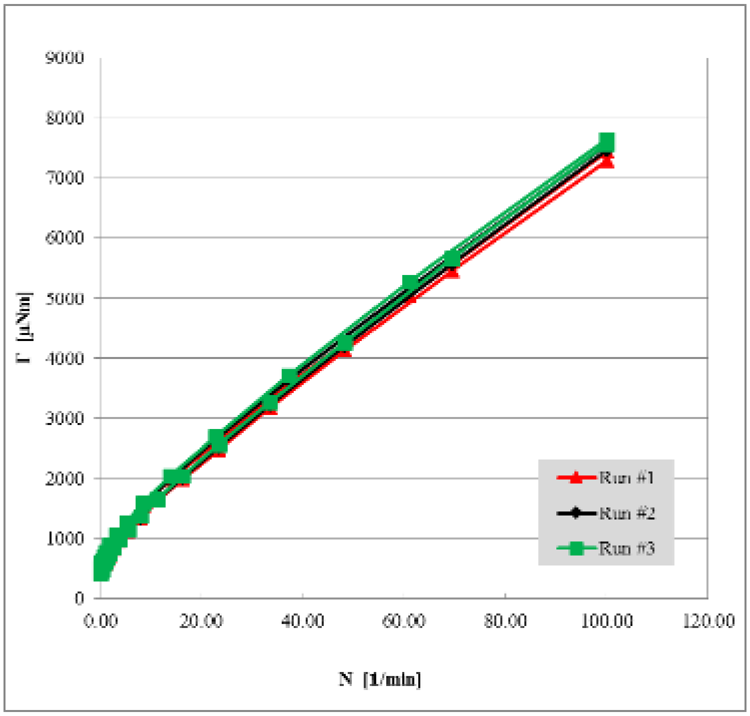


Figure A - 29: Torque vs. Angular Speed using <u>Serrated Coaxial Cylinder</u> on Mix#8, with 0 % beads by volume. Portrays data from Table A-41.

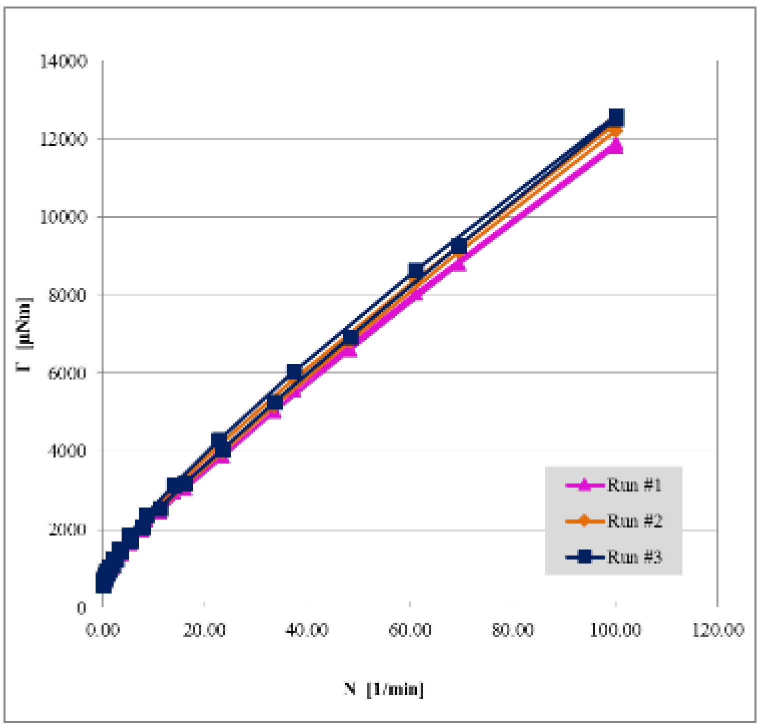


Figure A - 30: Torque vs. Angular Speed using <u>Serrated Coaxial Cylinder</u> on Mix#8, with 20 % beads by volume. Portrays data from Table A-42.

Table A - 43: Measured data for Mix#9 with 0 % beads using Double spiral spindle.

Double Spiral								
Geom.:	*RHN-83A*			*Cup:*	*Z43S*	*Bead %* *0%*		
Run #1		Run #2		Run #3		**Average values**		
NIST Code: SMC-109D		*NIST Code: SMC-109E*		*NIST Code: SMC-109F*				
N	Γ	N	Γ	N	Γ	**N**	**Γ**	***Γ/N*** *(Angular*
1/min	µNm	1/min	µNm	1/min	µNm	**rad/s**	**Nm**	*momentum)*
0.0941	1060	0.0946	983	0.0944	998	*0.010*	*1.01E-03*	*1.03E-01*
0.161	1560	0.161	1460	0.161	1480	*0.017*	*1.50E-03*	*8.90E-02*
0.268	1770	0.268	1660	0.268	1690	*0.028*	*1.71E-03*	*6.08E-02*
0.439	1880	0.44	1790	0.439	1810	*0.046*	*1.83E-03*	*3.97E-02*
0.72	2000	0.72	1920	0.72	1950	*0.075*	*1.96E-03*	*2.60E-02*
1.18	2170	1.18	2110	1.18	2140	*0.124*	*2.14E-03*	*1.73E-02*
1.93	2430	1.93	2380	1.93	2420	*0.202*	*2.41E-03*	*1.19E-02*
3.16	2840	3.16	2810	3.16	2850	*0.331*	*2.83E-03*	*8.56E-03*
5.18	3470	5.18	3460	5.18	3510	*0.542*	*3.48E-03*	*6.42E-03*
8.48	4460	8.48	4470	8.48	4540	*0.888*	*4.49E-03*	*5.06E-03*
13.9	6050	13.9	6090	13.9	6210	*1.456*	*6.12E-03*	*4.20E-03*
22.8	8540	22.8	8580	22.8	8730	*2.388*	*8.62E-03*	*3.61E-03*
37.3	12500	37.3	12500	37.3	12800	*3.906*	*1.26E-02*	*3.23E-03*
61.1	18600	61.1	18700	61.1	19100	*6.398*	*1.88E-02*	*2.94E-03*
100	28100	100	28400	100	28900	*10.472*	*2.85E-02*	*2.72E-03*
100	27800	100	28200	100	28800	*10.472*	*2.83E-02*	*2.70E-03*
69.5	20300	69.5	20600	69.5	21100	*7.278*	*2.07E-02*	*2.84E-03*
48.3	15100	48.3	15300	48.3	15600	*5.058*	*1.53E-02*	*3.03E-03*
33.6	11300	33.6	11400	33.6	11700	*3.519*	*1.15E-02*	*3.26E-03*
23.4	8570	23.4	8690	23.4	8860	*2.450*	*8.71E-03*	*3.55E-03*
16.2	6640	16.2	6730	16.2	6860	*1.696*	*6.74E-03*	*3.97E-03*
11.3	5250	11.3	5320	11.3	5410	*1.183*	*5.33E-03*	*4.50E-03*
7.85	4240	7.85	4300	7.85	4380	*0.822*	*4.31E-03*	*5.24E-03*
5.46	3520	5.46	3560	5.46	3620	*0.572*	*3.57E-03*	*6.24E-03*
3.79	2990	3.79	3030	3.79	3070	*0.397*	*3.03E-03*	*7.63E-03*
2.64	2600	2.64	2630	2.64	2670	*0.276*	*2.63E-03*	*9.53E-03*
1.83	2320	1.83	2340	1.83	2370	*0.192*	*2.34E-03*	*1.22E-02*
1.27	2100	1.27	2130	1.27	2150	*0.133*	*2.13E-03*	*1.60E-02*
0.886	1940	0.886	1960	0.886	1980	*0.093*	*1.96E-03*	*2.11E-02*
0.616	1820	0.616	1830	0.616	1860	*0.065*	*1.84E-03*	*2.85E-02*
0.428	1720	0.427	1740	0.429	1780	*0.045*	*1.75E-03*	*3.90E-02*
0.298	1660	0.297	1670	0.297	1690	*0.031*	*1.67E-03*	*5.37E-02*
0.207	1600	0.21	1620	0.206	1630	*0.022*	*1.62E-03*	*7.43E-02*
0.144	1560	0.146	1580	0.145	1590	*0.015*	*1.58E-03*	*1.04E-01*
0.0993	1520	0.1	1540	0.099	1570	*0.010*	*1.54E-03*	*1.48E-01*

Table A - 44: Measured data for Mix#9 with 20 % beads using Double spiral spindle.

Double Spiral								Bead %
Geom.: RHN-83A				*Cup: Z43S*				*20%*
Run #1		Run #2		Run #3		**Average values**		
NIST Code: SMC-109M		*NIST Code: SMC-109N*		*NIST Code: SMC-109O*				
N	Γ	N	Γ	N	Γ	**N**	**Γ**	***Γ/N*** *(Angular*
1/min	μNm	1/min	μNm	1/min	μNm	**rad/s**	**Nm**	*momentum)*
0.0925	1420	0.0937	1300	0.0935	1320	*0.010*	*1.35E-03*	*1.38E-01*
0.161	2010	0.162	1860	0.162	1870	*0.017*	*1.91E-03*	*1.13E-01*
0.269	2260	0.269	2100	0.268	2120	*0.028*	*2.16E-03*	*7.68E-02*
0.438	2440	0.44	2280	0.438	2300	*0.046*	*2.34E-03*	*5.09E-02*
0.72	2670	0.718	2520	0.721	2560	*0.075*	*2.58E-03*	*3.43E-02*
1.18	2990	1.18	2880	1.18	2910	*0.124*	*2.93E-03*	*2.37E-02*
1.93	3530	1.93	3400	1.93	3430	*0.202*	*3.45E-03*	*1.71E-02*
3.16	4360	3.16	4200	3.16	4220	*0.331*	*4.26E-03*	*1.29E-02*
5.18	5660	5.19	5410	5.18	5430	*0.543*	*5.50E-03*	*1.01E-02*
8.49	7650	8.49	7250	8.49	7270	*0.889*	*7.39E-03*	*8.31E-03*
13.9	10500	13.9	10100	13.9	10200	*1.456*	*1.03E-02*	*7.05E-03*
22.7	14700	22.8	14400	22.8	14500	*2.384*	*1.45E-02*	*6.10E-03*
37.3	21900	37.3	21400	37.3	21600	*3.906*	*2.16E-02*	*5.54E-03*
61.1	33000	61.1	32400	61	32700	*6.395*	*3.27E-02*	*5.11E-03*
100	49900	100	49300	100	49800	*10.472*	*4.97E-02*	*4.74E-03*
100	49200	100	49000	100	49500	*10.472*	*4.92E-02*	*4.70E-03*
69.5	35600	69.5	35500	69.5	36000	*7.278*	*3.57E-02*	*4.91E-03*
48.3	26000	48.3	26100	48.3	26400	*5.058*	*2.62E-02*	*5.17E-03*
33.6	19300	33.6	19300	33.6	19600	*3.519*	*1.94E-02*	*5.51E-03*
23.4	14500	23.4	14500	23.4	14700	*2.450*	*1.46E-02*	*5.94E-03*
16.2	11000	16.2	11000	16.2	11200	*1.696*	*1.11E-02*	*6.52E-03*
11.3	8520	11.3	8550	11.3	8680	*1.183*	*8.58E-03*	*7.25E-03*
7.84	6730	7.85	6750	7.85	6870	*0.822*	*6.78E-03*	*8.26E-03*
5.45	5440	5.46	5470	5.46	5560	*0.571*	*5.49E-03*	*9.61E-03*
3.79	4500	3.79	4540	3.79	4600	*0.397*	*4.55E-03*	*1.15E-02*
2.63	3810	2.63	3840	2.63	3920	*0.275*	*3.86E-03*	*1.40E-02*
1.83	3310	1.83	3340	1.83	3390	*0.192*	*3.35E-03*	*1.75E-02*
1.27	2930	1.27	2960	1.27	3010	*0.133*	*2.97E-03*	*2.23E-02*
0.887	2640	0.885	2670	0.882	2740	*0.093*	*2.68E-03*	*2.90E-02*
0.617	2440	0.614	2480	0.617	2490	*0.065*	*2.47E-03*	*3.83E-02*
0.429	2280	0.429	2300	0.429	2320	*0.045*	*2.30E-03*	*5.12E-02*
0.298	2150	0.298	2170	0.294	2220	*0.031*	*2.18E-03*	*7.02E-02*
0.207	2040	0.208	2060	0.204	2150	*0.022*	*2.08E-03*	*9.64E-02*
0.144	1970	0.144	2010	0.144	2020	*0.015*	*2.00E-03*	*1.33E-01*
0.0997	1920	0.1	1950	0.0966	1980	*0.010*	*1.95E-03*	*1.89E-01*

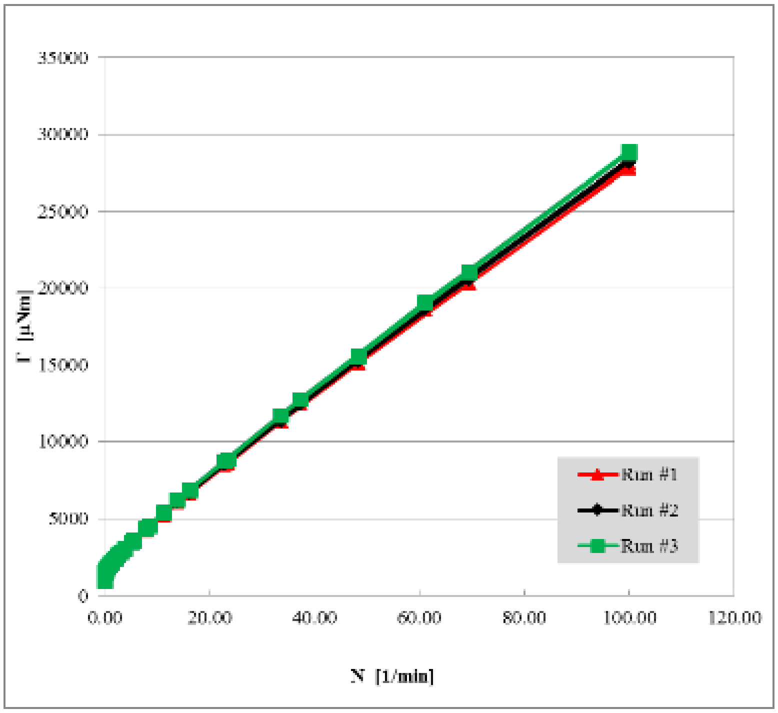


Figure A - 31: Torque vs. Angular Speed using Double spiral spindle on Mix#9, with 0 % beads by volume. Portrays data from Table A-43.

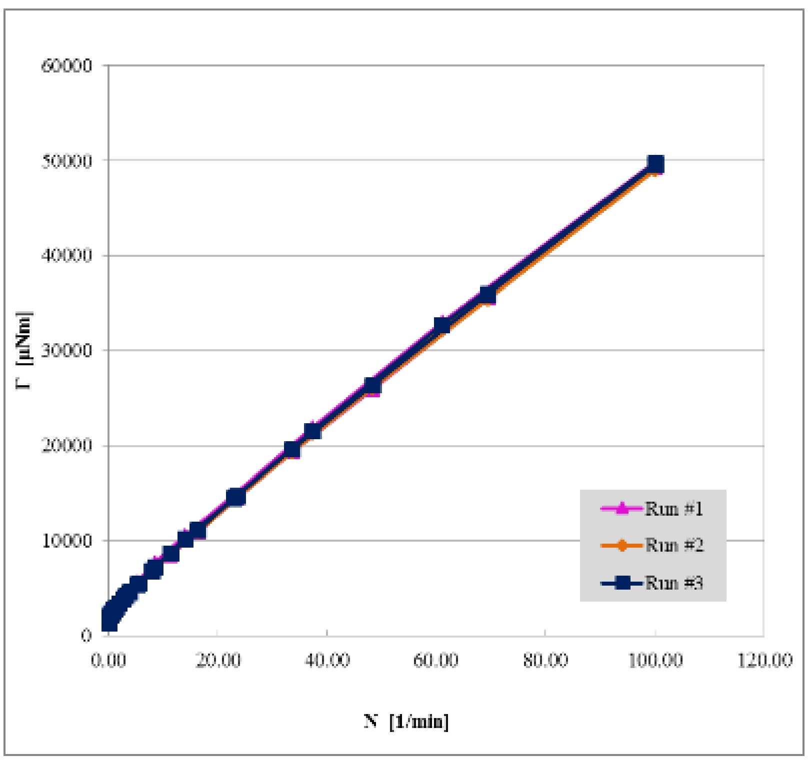


Figure A - 32: Torque vs. Angular Speed using Double spiral spindle on Mix#9, with 20 % beads by volume. Portrays data from Table A-44.

Table A - 45: Measured data for Mix#9 with 0 % beads using Six-blade Vane.

6 Blade Vane						Bead %		
Geom.: *RHN-83C*				*Z43S*		*0%*		
Run #1		Run #2		Run #3		**Average values**		
NIST Code: SMC-109A		*NIST Code: SMC-109B*		*NIST Code: SMC-109C*				
N	Γ	N	Γ	N	Γ	**N**	**Γ**	***Γ/N*** *(Angular*
1/min	µNm	1/min	µNm	1/min	µNm	**rad/s**	**Nm**	*momentum)*
0.0978	440	0.0976	409	0.0977	419	*0.010*	*4.23E-04*	*4.13E-02*
0.163	584	0.163	563	0.163	575	*0.017*	*5.74E-04*	*3.36E-02*
0.268	629	0.268	609	0.268	620	*0.028*	*6.19E-04*	*2.21E-02*
0.439	665	0.439	643	0.439	655	*0.046*	*6.54E-04*	*1.42E-02*
0.72	717	0.72	695	0.72	707	*0.075*	*7.06E-04*	*9.37E-03*
1.18	791	1.18	767	1.18	781	*0.124*	*7.80E-04*	*6.31E-03*
1.93	891	1.93	868	1.93	886	*0.202*	*8.82E-04*	*4.36E-03*
3.16	1030	3.16	1020	3.16	1030	*0.331*	*1.03E-03*	*3.10E-03*
5.18	1240	5.18	1220	5.18	1240	*0.542*	*1.23E-03*	*2.27E-03*
8.48	1540	8.48	1510	8.48	1540	*0.888*	*1.53E-03*	*1.72E-03*
13.9	1980	13.9	1950	13.9	1980	*1.456*	*1.97E-03*	*1.35E-03*
22.8	2610	22.8	2580	22.8	2620	*2.388*	*2.60E-03*	*1.09E-03*
37.3	3580	37.3	3560	37.3	3610	*3.906*	*3.58E-03*	*9.17E-04*
61	5060	61	5070	61	5140	*6.388*	*5.09E-03*	*7.97E-04*
100	7370	100	7410	100	7520	*10.472*	*7.43E-03*	*7.10E-04*
100	7320	100	7390	100	7510	*10.472*	*7.41E-03*	*7.07E-04*
69.5	5490	69.5	5540	69.5	5620	*7.278*	*5.55E-03*	*7.63E-04*
48.3	4180	48.3	4220	48.3	4270	*5.058*	*4.22E-03*	*8.35E-04*
33.6	3240	33.6	3260	33.6	3300	*3.519*	*3.27E-03*	*9.28E-04*
23.4	2560	23.4	2570	23.4	2600	*2.450*	*2.58E-03*	*1.05E-03*
16.2	2060	16.2	2070	16.2	2090	*1.696*	*2.07E-03*	*1.22E-03*
11.3	1690	11.3	1700	11.3	1710	*1.183*	*1.70E-03*	*1.44E-03*
7.85	1410	7.85	1420	7.85	1440	*0.822*	*1.42E-03*	*1.73E-03*
5.46	1200	5.45	1210	5.45	1220	*0.571*	*1.21E-03*	*2.12E-03*
3.79	1040	3.79	1050	3.79	1060	*0.397*	*1.05E-03*	*2.65E-03*
2.64	920	2.64	924	2.64	930	*0.276*	*9.25E-04*	*3.34E-03*
1.83	824	1.83	832	1.83	833	*0.192*	*8.30E-04*	*4.33E-03*
1.27	767	1.27	752	1.27	760	*0.133*	*7.60E-04*	*5.71E-03*
0.887	706	0.886	700	0.886	709	*0.093*	*7.05E-04*	*7.60E-03*
0.615	645	0.616	650	0.614	667	*0.064*	*6.54E-04*	*1.02E-02*
0.429	626	0.428	616	0.429	615	*0.045*	*6.19E-04*	*1.38E-02*
0.297	578	0.296	596	0.299	597	*0.031*	*5.90E-04*	*1.90E-02*
0.208	563	0.203	587	0.205	582	*0.022*	*5.77E-04*	*2.68E-02*
0.144	551	0.145	551	0.145	545	*0.015*	*5.49E-04*	*3.62E-02*
0.0991	537	0.0985	550	0.101	559	*0.010*	*5.49E-04*	*5.26E-02*

Table A - 46: Measured data for Mix#9 with 20 % beads using Six-blade Vane.

6 Blade Vane						Bead %		
Geom.: *RHN-83C*				*Z43S*		*20%*		
Run #1		Run #2		Run #3		**Average values**		
NIST Code: SMC-109J		*NIST Code: SMC-109K*		*NIST Code: SMC-109L*				
N	Γ	N	Γ	N	Γ	**N**	**Γ**	*Γ/N (Angular*
1/min	μNm	1/min	μNm	1/min	μNm	**rad/s**	**Nm**	*momentum)*
0.0973	615	0.0973	614	0.0973	596	*0.010*	*6.08E-04*	*5.97E-02*
0.163	776	0.163	793	0.163	758	*0.017*	*7.76E-04*	*4.54E-02*
0.268	825	0.268	842	0.269	818	*0.028*	*8.28E-04*	*2.95E-02*
0.44	897	0.439	914	0.44	886	*0.046*	*8.99E-04*	*1.95E-02*
0.72	966	0.721	987	0.72	968	*0.075*	*9.74E-04*	*1.29E-02*
1.18	1080	1.18	1110	1.18	1090	*0.124*	*1.09E-03*	*8.85E-03*
1.93	1240	1.93	1280	1.93	1260	*0.202*	*1.26E-03*	*6.23E-03*
3.16	1470	3.16	1540	3.16	1530	*0.331*	*1.51E-03*	*4.57E-03*
5.18	1820	5.18	1910	5.18	1890	*0.542*	*1.87E-03*	*3.45E-03*
8.48	2300	8.49	2430	8.48	2440	*0.888*	*2.39E-03*	*2.69E-03*
13.9	3070	13.9	3240	13.9	3250	*1.456*	*3.19E-03*	*2.19E-03*
22.8	4230	22.8	4430	22.8	4490	*2.388*	*4.38E-03*	*1.84E-03*
37.3	5910	37.3	6200	37.3	6360	*3.906*	*6.16E-03*	*1.58E-03*
61	8350	61	8900	61.1	9210	*6.391*	*8.82E-03*	*1.38E-03*
100	11900	100	12900	100	13500	*10.472*	*1.28E-02*	*1.22E-03*
100	11600	100	12800	100	13400	*10.472*	*1.26E-02*	*1.20E-03*
69.5	8700	69.5	9490	69.5	9890	*7.278*	*9.36E-03*	*1.29E-03*
48.3	6600	48.3	7110	48.3	7420	*5.058*	*7.04E-03*	*1.39E-03*
33.6	5100	33.6	5430	33.6	5650	*3.519*	*5.39E-03*	*1.53E-03*
23.4	4020	23.4	4220	23.4	4360	*2.450*	*4.20E-03*	*1.71E-03*
16.2	3170	16.2	3340	16.2	3450	*1.696*	*3.32E-03*	*1.96E-03*
11.3	2540	11.3	2660	11.3	2750	*1.183*	*2.65E-03*	*2.24E-03*
7.85	2080	7.84	2180	7.85	2230	*0.822*	*2.16E-03*	*2.63E-03*
5.45	1730	5.46	1810	5.46	1850	*0.571*	*1.80E-03*	*3.14E-03*
3.79	1480	3.79	1540	3.79	1560	*0.397*	*1.53E-03*	*3.85E-03*
2.64	1280	2.64	1330	2.64	1350	*0.276*	*1.32E-03*	*4.77E-03*
1.83	1120	1.83	1170	1.83	1180	*0.192*	*1.16E-03*	*6.04E-03*
1.28	1010	1.27	1040	1.27	1070	*0.133*	*1.04E-03*	*7.80E-03*
0.886	912	0.887	943	0.888	960	*0.093*	*9.38E-04*	*1.01E-02*
0.614	867	0.615	870	0.615	901	*0.064*	*8.79E-04*	*1.37E-02*
0.428	784	0.43	817	0.43	838	*0.045*	*8.13E-04*	*1.81E-02*
0.296	755	0.296	782	0.296	792	*0.031*	*7.76E-04*	*2.50E-02*
0.208	738	0.209	747	0.205	735	*0.022*	*7.40E-04*	*3.41E-02*
0.143	689	0.144	710	0.142	721	*0.015*	*7.07E-04*	*4.72E-02*
0.099	682	0.103	701	0.101	695	*0.011*	*6.93E-04*	*6.55E-02*

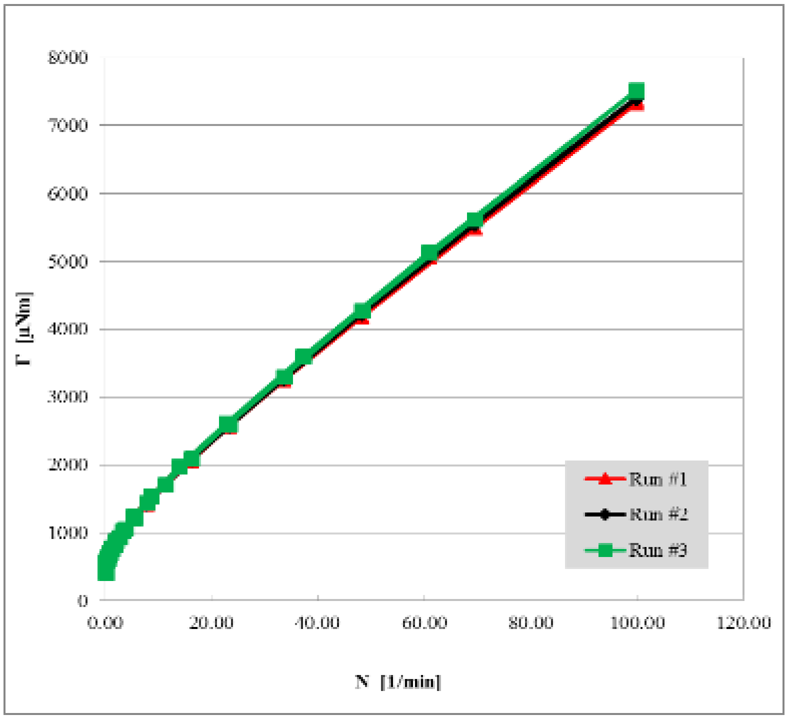


Figure A - 45: Torque vs. Angular Speed using <u>six-blade vane</u> on Mix#9, with 0 % beads by volume. Portrays data from Table A-45.

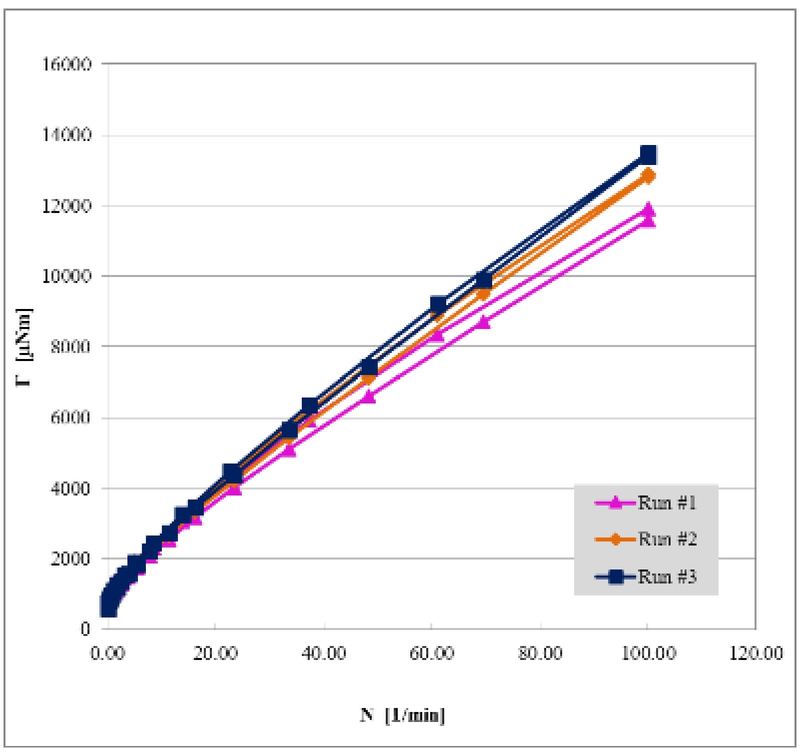


Figure A - 46: Torque vs. Angular Speed using <u>six-blade vane</u> on Mix#9, with 20 % beads by volume. Portrays data from Table A-46.

Table A - 47: Measured data for Mix#9 with 0 % beads using Serrated Coaxial Cylinder.

Serrated Coaxial Cylinder						Bead %		
Geom.:	*SS18*			*Z43S*		*0%*		
Run #1		Run #2		Run #3		**Average values**		
NIST Code: SMC-109G		*NIST Code: SMC-109H*		*NIST Code: SMC-109I*				
N	Γ	N	Γ	N	Γ	**N**	**Γ**	***Γ/N*** *(Angular*
1/min	µNm	1/min	µNm	1/min	µNm	**rad/s**	**Nm**	*momentum)*
0.0979	480	0.0977	436	0.098	461	*0.010*	*4.59E-04*	*4.48E-02*
0.164	629	0.164	591	0.164	612	*0.017*	*6.11E-04*	*3.56E-02*
0.268	671	0.268	634	0.268	657	*0.028*	*6.54E-04*	*2.33E-02*
0.44	723	0.44	685	0.44	713	*0.046*	*7.07E-04*	*1.53E-02*
0.72	789	0.72	759	0.72	792	*0.075*	*7.80E-04*	*1.03E-02*
1.18	885	1.18	856	1.17	925	*0.123*	*8.89E-04*	*7.21E-03*
1.93	1010	1.93	1040	1.93	1030	*0.202*	*1.03E-03*	*5.08E-03*
3.16	1190	3.16	1170	3.16	1210	*0.331*	*1.19E-03*	*3.60E-03*
5.18	1430	5.18	1420	5.18	1470	*0.542*	*1.44E-03*	*2.65E-03*
8.48	1790	8.48	1790	8.48	1850	*0.888*	*1.81E-03*	*2.04E-03*
13.9	2300	13.9	2300	13.9	2390	*1.456*	*2.33E-03*	*1.60E-03*
22.8	3050	22.8	3080	22.8	3190	*2.388*	*3.11E-03*	*1.30E-03*
37.3	4200	37.3	4260	37.3	4410	*3.906*	*4.29E-03*	*1.10E-03*
61	5950	61	6060	61	6270	*6.388*	*6.09E-03*	*9.54E-04*
100	8750	100	8800	100	9030	*10.472*	*8.86E-03*	*8.46E-04*
100	8580	100	8700	100	8910	*10.472*	*8.73E-03*	*8.34E-04*
69.5	6420	69.5	6520	69.5	6670	*7.278*	*6.54E-03*	*8.98E-04*
48.3	4840	48.3	4910	48.3	5020	*5.058*	*4.92E-03*	*9.73E-04*
33.6	3700	33.6	3750	33.6	3830	*3.519*	*3.76E-03*	*1.07E-03*
23.4	2880	23.4	2910	23.4	2980	*2.450*	*2.92E-03*	*1.19E-03*
16.2	2290	16.2	2310	16.2	2360	*1.696*	*2.32E-03*	*1.37E-03*
11.3	1850	11.3	1870	11.3	1910	*1.183*	*1.88E-03*	*1.59E-03*
7.85	1520	7.85	1540	7.85	1570	*0.822*	*1.54E-03*	*1.88E-03*
5.45	1270	5.45	1290	5.45	1320	*0.571*	*1.29E-03*	*2.27E-03*
3.79	1080	3.79	1100	3.79	1130	*0.397*	*1.10E-03*	*2.78E-03*
2.64	924	2.64	968	2.64	977	*0.276*	*9.56E-04*	*3.46E-03*
1.83	804	1.83	872	1.83	874	*0.192*	*8.50E-04*	*4.44E-03*
1.28	719	1.27	755	1.27	750	*0.133*	*7.41E-04*	*5.56E-03*
0.885	634	0.889	659	0.885	690	*0.093*	*6.61E-04*	*7.12E-03*
0.616	590	0.614	611	0.619	641	*0.065*	*6.14E-04*	*9.51E-03*
0.422	579	0.422	575	0.422	604	*0.044*	*5.86E-04*	*1.33E-02*
0.299	497	0.298	548	0.304	569	*0.031*	*5.38E-04*	*1.71E-02*
0.211	525	0.209	545	0.207	629	*0.022*	*5.66E-04*	*2.59E-02*
0.149	523	0.143	574	0.142	605	*0.015*	*5.67E-04*	*3.74E-02*
0.0952	493	0.11	537	0.0896	654	*0.010*	*0.000561*	*0.054548899*

Table A - 48: Measured data for Mix#9 with 20 % beads using Serrated Coaxial Cylinder.

Serrated Coaxial Cylinder						Bead %		
Geom.:	*SS18*			*Z43S*		*20%*		
Run #1		Run #2		Run #3		**Average values**		
NIST Code: SMC-109P		*NIST Code: SMC-109Q*		*NIST Code: SMC-109R*				
N	Γ	N	Γ	N	Γ	**N**	**Γ**	***Γ/N*** *(Angular*
1/min	μNm	1/min	μNm	1/min	μNm	**rad/s**	**Nm**	*momentum)*
0.0975	719	0.0978	625	0.0972	681	*0.010*	*6.75E-04*	*6.61E-02*
0.164	880	0.164	790	0.167	846	*0.017*	*8.39E-04*	*4.85E-02*
0.269	885	0.268	851	0.266	930	*0.028*	*8.89E-04*	*3.17E-02*
0.439	930	0.441	929	0.441	1000	*0.046*	*9.53E-04*	*2.07E-02*
0.719	1020	0.721	1050	0.723	1090	*0.076*	*1.05E-03*	*1.40E-02*
1.18	1150	1.18	1180	1.18	1260	*0.124*	*1.20E-03*	*9.68E-03*
1.93	1340	1.93	1370	1.93	1480	*0.202*	*1.40E-03*	*6.91E-03*
3.16	1610	3.16	1650	3.16	1760	*0.331*	*1.67E-03*	*5.06E-03*
5.18	2000	5.18	2060	5.18	2200	*0.542*	*2.09E-03*	*3.85E-03*
8.48	2540	8.48	2630	8.48	2830	*0.888*	*2.67E-03*	*3.00E-03*
13.9	3340	13.9	3500	13.9	3750	*1.456*	*3.53E-03*	*2.43E-03*
22.8	4540	22.8	4790	22.8	5150	*2.388*	*4.83E-03*	*2.02E-03*
37.3	6370	37.3	6790	37.3	7270	*3.906*	*6.81E-03*	*1.74E-03*
61	9140	61	9710	61.1	10500	*6.391*	*9.78E-03*	*1.53E-03*
100	13500	100	14300	100	15300	*10.472*	*1.44E-02*	*1.37E-03*
100	13500	100	14100	100	15200	*10.472*	*1.43E-02*	*1.36E-03*
69.5	10100	69.5	10500	69.5	11300	*7.278*	*1.06E-02*	*1.46E-03*
48.3	7580	48.3	7910	48.3	8460	*5.058*	*7.98E-03*	*1.58E-03*
33.6	5750	33.6	6000	33.6	6420	*3.519*	*6.06E-03*	*1.72E-03*
23.4	4430	23.4	4610	23.4	4930	*2.450*	*4.66E-03*	*1.90E-03*
16.2	3480	16.2	3620	16.2	3860	*1.696*	*3.65E-03*	*2.15E-03*
11.3	2780	11.3	2890	11.3	3070	*1.183*	*2.91E-03*	*2.46E-03*
7.85	2260	7.85	2350	7.85	2500	*0.822*	*2.37E-03*	*2.88E-03*
5.45	1870	5.46	1950	5.46	2060	*0.571*	*1.96E-03*	*3.43E-03*
3.79	1580	3.79	1650	3.79	1730	*0.397*	*1.65E-03*	*4.17E-03*
2.64	1350	2.63	1410	2.63	1480	*0.276*	*1.41E-03*	*5.13E-03*
1.83	1180	1.83	1240	1.83	1280	*0.192*	*1.23E-03*	*6.44E-03*
1.27	1070	1.27	1080	1.27	1140	*0.133*	*1.10E-03*	*8.25E-03*
0.887	979	0.886	979	0.885	1040	*0.093*	*9.99E-04*	*1.08E-02*
0.611	864	0.617	888	0.607	980	*0.064*	*9.11E-04*	*1.42E-02*
0.429	841	0.422	897	0.432	864	*0.045*	*8.67E-04*	*1.94E-02*
0.298	794	0.301	769	0.299	875	*0.031*	*8.13E-04*	*2.59E-02*
0.207	679	0.198	806	0.201	886	*0.021*	*7.90E-04*	*3.74E-02*
0.149	737	0.138	720	0.148	822	*0.015*	*7.60E-04*	*5.00E-02*
0.101	668	0.087	780	0.101	701	*0.010*	*7.16E-04*	*7.10E-02*

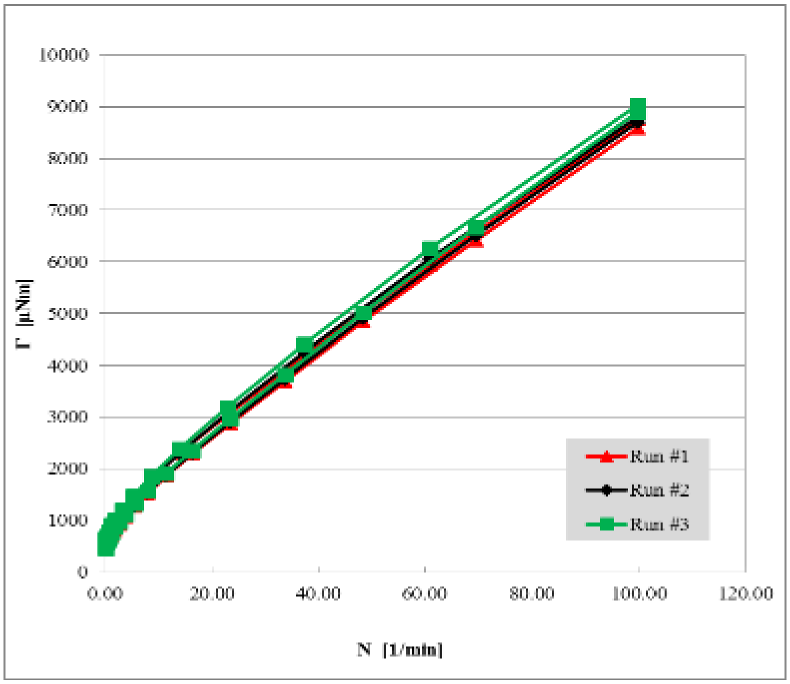


Figure A - 33: Torque vs. Angular Speed using Serrated Coaxial Cylinder on Mix#9, with 0 % beads by volume. Portrays data from Table A-47.

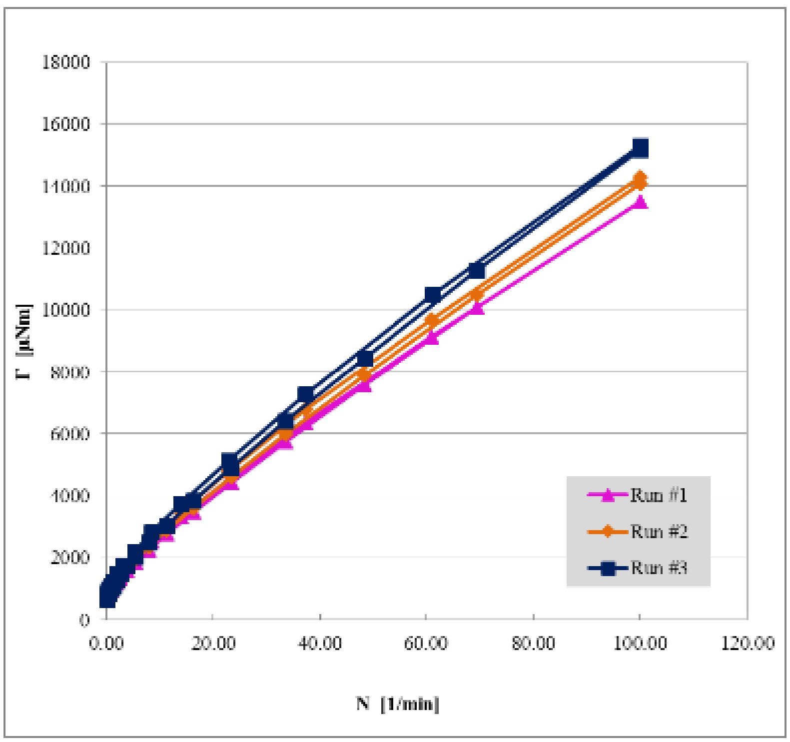


Figure A - 34: Torque vs. Angular Speed using Serrated Coaxial Cylinder on Mix#9, with 20 % beads by volume. Portrays data from Table A-48.

Table A - 49: Measured data for Mix#10 with 0 % beads using Double spiral spindle.

Double Spiral								Bead %
Geom.: RHN-83A				*Cup: Z43S*				*0%*
Run #1		Run #2		Run #3		**Average values**		
NIST Code: SMC-111G		*NIST Code: SMC-111H*		*NIST Code: SMC-111I*				
N	Γ	N	Γ	N	Γ	**N**	**Γ**	*Γ/N (Angular momentum)*
1/min	µNm	1/min	µNm	1/min	µNm	**rad/s**	**Nm**	
0.094	1050	0.0941	1020	0.0939	1020	*0.010*	*1.03E-03*	*1.05E-01*
0.161	1580	0.161	1540	0.161	1550	*0.017*	*1.56E-03*	*9.23E-02*
0.268	1790	0.268	1780	0.268	1790	*0.028*	*1.79E-03*	*6.37E-02*
0.439	1910	0.439	1900	0.44	1910	*0.046*	*1.91E-03*	*4.14E-02*
0.72	2050	0.72	2040	0.72	2060	*0.075*	*2.05E-03*	*2.72E-02*
1.18	2240	1.18	2230	1.18	2250	*0.124*	*2.24E-03*	*1.81E-02*
1.93	2520	1.93	2520	1.93	2560	*0.202*	*2.53E-03*	*1.25E-02*
3.16	2970	3.16	2970	3.16	3020	*0.331*	*2.99E-03*	*9.03E-03*
5.18	3660	5.18	3670	5.18	3730	*0.542*	*3.69E-03*	*6.80E-03*
8.48	4740	8.48	4750	8.48	4830	*0.888*	*4.77E-03*	*5.38E-03*
13.9	6420	13.9	6470	13.9	6630	*1.456*	*6.51E-03*	*4.47E-03*
22.8	9040	22.8	9130	22.8	9340	*2.388*	*9.17E-03*	*3.84E-03*
37.3	13200	37.3	13300	37.3	13700	*3.906*	*1.34E-02*	*3.43E-03*
61.1	19700	61.1	20000	61.1	20500	*6.398*	*2.01E-02*	*3.14E-03*
100	29700	100	30300	100	31100	*10.472*	*3.04E-02*	*2.90E-03*
100	29500	100	30100	100	31000	*10.472*	*3.02E-02*	*2.88E-03*
69.5	21600	69.5	22000	69.5	22700	*7.278*	*2.21E-02*	*3.04E-03*
48.3	16000	48.3	16300	48.3	16700	*5.058*	*1.63E-02*	*3.23E-03*
33.6	12000	33.6	12200	33.6	12500	*3.519*	*1.22E-02*	*3.48E-03*
23.4	9100	23.4	9260	23.4	9510	*2.450*	*9.29E-03*	*3.79E-03*
16.2	7040	16.2	7160	16.2	7340	*1.696*	*7.18E-03*	*4.23E-03*
11.3	5560	11.3	5650	11.3	5790	*1.183*	*5.67E-03*	*4.79E-03*
7.85	4490	7.85	4560	7.85	4660	*0.822*	*4.57E-03*	*5.56E-03*
5.46	3710	5.46	3770	5.46	3850	*0.572*	*3.78E-03*	*6.61E-03*
3.79	3150	3.79	3190	3.79	3260	*0.397*	*3.20E-03*	*8.06E-03*
2.64	2740	2.64	2770	2.64	2830	*0.276*	*2.78E-03*	*1.01E-02*
1.83	2430	1.83	2460	1.83	2500	*0.192*	*2.46E-03*	*1.29E-02*
1.27	2200	1.27	2230	1.27	2270	*0.133*	*2.23E-03*	*1.68E-02*
0.885	2040	0.886	2060	0.883	2100	*0.093*	*2.07E-03*	*2.23E-02*
0.615	1900	0.617	1920	0.617	1950	*0.065*	*1.92E-03*	*2.98E-02*
0.428	1800	0.428	1810	0.428	1840	*0.045*	*1.82E-03*	*4.05E-02*
0.295	1720	0.296	1750	0.296	1770	*0.031*	*1.75E-03*	*5.64E-02*
0.207	1670	0.207	1680	0.206	1700	*0.022*	*1.68E-03*	*7.78E-02*
0.143	1640	0.143	1630	0.142	1660	*0.015*	*1.64E-03*	*1.10E-01*
0.1	1590	0.1	1590	0.1	1630	*0.010*	*1.60E-03*	*1.53E-01*

Table A - 50: Measured data for Mix#10 with 20 % beads using Double spiral spindle.

Double Spiral								Bead %
Geom.: RHN-83A				*Cup: Z43S*				*20%*
Run #1		Run #2		Run #3		**Average values**		
NIST Code: SMC-111P		*NIST Code: SMC-111Q*		*NIST Code: SMC-111R*				
N	Γ	N	Γ	N	Γ	**N**	**Γ**	***Γ/N*** *(Angular*
1/min	μNm	1/min	μNm	1/min	μNm	**rad/s**	**Nm**	*momentum)*
0.0925	1450	0.0925	1350	0.0924	1410	*0.010*	*1.40E-03*	*1.45E-01*
0.161	2070	0.162	1960	0.161	2060	*0.017*	*2.03E-03*	*1.20E-01*
0.268	2340	0.268	2220	0.268	2340	*0.028*	*2.30E-03*	*8.20E-02*
0.44	2540	0.439	2420	0.439	2530	*0.046*	*2.50E-03*	*5.43E-02*
0.719	2790	0.721	2700	0.72	2800	*0.075*	*2.76E-03*	*3.66E-02*
1.18	3180	1.18	3100	1.18	3150	*0.124*	*3.14E-03*	*2.54E-02*
1.94	3750	1.93	3660	1.93	3700	*0.202*	*3.70E-03*	*1.83E-02*
3.16	4660	3.16	4540	3.16	4540	*0.331*	*4.58E-03*	*1.38E-02*
5.18	6150	5.18	5880	5.18	5870	*0.542*	*5.97E-03*	*1.10E-02*
8.48	8420	8.48	7930	8.49	7970	*0.888*	*8.11E-03*	*9.13E-03*
13.9	11700	13.9	11100	13.9	11200	*1.456*	*1.13E-02*	*7.79E-03*
22.8	16400	22.8	15900	22.8	16100	*2.388*	*1.61E-02*	*6.76E-03*
37.3	24500	37.3	23700	37.3	24100	*3.906*	*2.41E-02*	*6.17E-03*
61.1	36900	61.1	35900	61	36600	*6.395*	*3.65E-02*	*5.70E-03*
100	55700	100	54600	100	55900	*10.472*	*5.54E-02*	*5.29E-03*
100	55000	100	54100	100	55500	*10.472*	*5.49E-02*	*5.24E-03*
69.5	39600	69.5	39200	69.5	40300	*7.278*	*3.97E-02*	*5.45E-03*
48.3	28900	48.3	28700	48.3	29600	*5.058*	*2.91E-02*	*5.75E-03*
33.6	21300	33.6	21300	33.6	21800	*3.519*	*2.15E-02*	*6.10E-03*
23.4	16000	23.4	15900	23.4	16400	*2.450*	*1.61E-02*	*6.57E-03*
16.2	12100	16.2	12100	16.2	12400	*1.696*	*1.22E-02*	*7.19E-03*
11.3	9360	11.3	9370	11.3	9620	*1.183*	*9.45E-03*	*7.99E-03*
7.85	7360	7.85	7360	7.85	7550	*0.822*	*7.42E-03*	*9.03E-03*
5.45	5910	5.45	5930	5.46	6090	*0.571*	*5.98E-03*	*1.05E-02*
3.79	4880	3.79	4880	3.79	5010	*0.397*	*4.92E-03*	*1.24E-02*
2.64	4100	2.64	4130	2.63	4230	*0.276*	*4.15E-03*	*1.50E-02*
1.83	3560	1.83	3560	1.83	3650	*0.192*	*3.59E-03*	*1.87E-02*
1.27	3140	1.27	3140	1.28	3220	*0.133*	*3.17E-03*	*2.37E-02*
0.884	2820	0.886	2840	0.885	2900	*0.093*	*2.85E-03*	*3.08E-02*
0.616	2570	0.616	2600	0.616	2660	*0.065*	*2.61E-03*	*4.05E-02*
0.426	2390	0.426	2410	0.428	2470	*0.045*	*2.42E-03*	*5.42E-02*
0.297	2280	0.298	2270	0.297	2320	*0.031*	*2.29E-03*	*7.35E-02*
0.207	2160	0.204	2180	0.21	2220	*0.022*	*2.19E-03*	*1.01E-01*
0.143	2080	0.142	2090	0.144	2140	*0.015*	*2.10E-03*	*1.40E-01*
0.0991	2020	0.1	2030	0.0989	2070	*0.010*	*2.04E-03*	*1.96E-01*

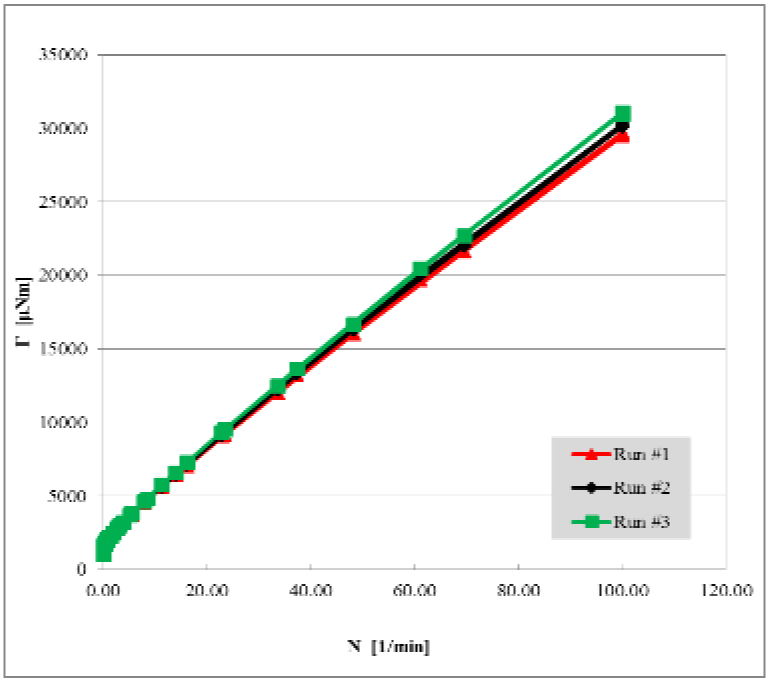


Figure A - 35: Torque vs. Angular Speed using <u>Double spiral spindle</u> on Mix#10, with 0 % beads by volume. Portrays data from Table A-49.

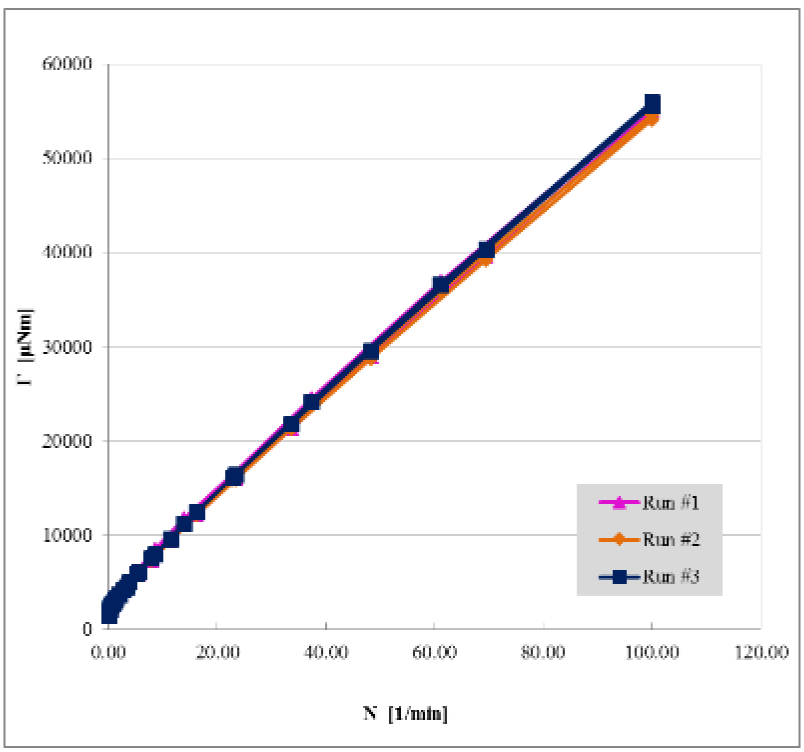


Figure A - 36: Torque vs. Angular Speed using <u>Double spiral spindle</u> on Mix#10, with 20 % beads by volume. Portrays data from Table A-50.

Table A - 51: Measured data for Mix#10 with 0 % beads using Six-blade Vane.

6 Blade Vane								Bead %
Geom.: RHN-83C				Z43S				0%
Run #1		Run #2		Run #3		Average values		
NIST Code: SMC-111A		NIST Code: SMC-111B		NIST Code: SMC-111C				
N	Γ	N	Γ	N	Γ	**N**	**Γ**	*Γ/N (Angular*
1/min	µNm	1/min	µNm	1/min	µNm	**rad/s**	**Nm**	*momentum)*
0.0977	454	0.0976	444	0.0975	437	*0.0102*	*4.45E-04*	*4.35E-02*
0.163	602	0.163	595	0.163	597	*0.0171*	*5.98E-04*	*3.50E-02*
0.268	644	0.268	636	0.268	640	*0.0281*	*6.40E-04*	*2.28E-02*
0.439	681	0.439	672	0.439	675	*0.0460*	*6.76E-04*	*1.47E-02*
0.72	734	0.72	724	0.72	728	*0.0754*	*7.29E-04*	*9.66E-03*
1.18	808	1.18	799	1.18	803	*0.1236*	*8.03E-04*	*6.50E-03*
1.93	910	1.93	901	1.93	906	*0.2021*	*9.06E-04*	*4.48E-03*
3.16	1060	3.16	1050	3.16	1050	*0.3309*	*1.05E-03*	*3.18E-03*
5.18	1260	5.18	1260	5.18	1270	*0.5424*	*1.26E-03*	*2.33E-03*
8.48	1570	8.48	1560	8.48	1570	*0.8880*	*1.57E-03*	*1.76E-03*
13.9	2010	13.9	2000	13.9	2020	*1.4556*	*2.01E-03*	*1.38E-03*
22.8	2650	22.8	2650	22.8	2670	*2.3876*	*2.66E-03*	*1.11E-03*
37.3	3630	37.3	3650	37.3	3680	*3.9060*	*3.65E-03*	*9.35E-04*
61	5130	61	5170	61	5220	*6.3879*	*5.17E-03*	*8.10E-04*
100	7460	100	7530	100	7640	*10.4720*	*7.54E-03*	*7.20E-04*
100	7430	100	7500	100	7620	*10.4720*	*7.52E-03*	*7.18E-04*
69.5	5580	69.5	5630	69.5	5710	*7.2780*	*5.64E-03*	*7.75E-04*
48.3	4250	48.3	4280	48.3	4350	*5.0580*	*4.29E-03*	*8.49E-04*
33.6	3290	33.6	3320	33.6	3360	*3.5186*	*3.32E-03*	*9.45E-04*
23.4	2600	23.4	2620	23.4	2650	*2.4504*	*2.62E-03*	*1.07E-03*
16.2	2100	16.2	2110	16.2	2140	*1.6965*	*2.12E-03*	*1.25E-03*
11.3	1720	11.3	1730	11.3	1750	*1.1833*	*1.73E-03*	*1.46E-03*
7.85	1450	7.85	1460	7.85	1470	*0.8221*	*1.46E-03*	*1.78E-03*
5.45	1230	5.46	1240	5.46	1250	*0.5714*	*1.24E-03*	*2.17E-03*
3.79	1070	3.79	1080	3.79	1080	*0.3969*	*1.08E-03*	*2.71E-03*
2.64	943	2.63	950	2.64	954	*0.2761*	*9.49E-04*	*3.44E-03*
1.83	841	1.83	847	1.83	854	*0.1916*	*8.47E-04*	*4.42E-03*
1.28	773	1.27	780	1.27	797	*0.1333*	*7.83E-04*	*5.87E-03*
0.884	707	0.889	721	0.889	723	*0.0929*	*7.17E-04*	*7.72E-03*
0.616	661	0.615	666	0.616	669	*0.0645*	*6.65E-04*	*1.03E-02*
0.427	629	0.426	641	0.428	638	*0.0447*	*6.36E-04*	*1.42E-02*
0.296	601	0.298	612	0.298	616	*0.0311*	*6.10E-04*	*1.96E-02*
0.208	569	0.206	578	0.208	589	*0.0217*	*5.79E-04*	*2.67E-02*
0.142	564	0.145	561	0.145	557	*0.0151*	*5.61E-04*	*3.72E-02*
0.0988	552	0.103	566	0.1	532	*0.0105*	*5.50E-04*	*5.22E-02*

Table A - 52: Measured data for Mix#10 with 20 % beads using Six-blade Vane.

6 Blade Vane						Bead %		
Geom.:	*RHN-83C*			*Z43S*		*20%*		
Run #1		Run #2		Run #3		**Average values**		
NIST Code: SMC-111J		*NIST Code: SMC-111K*		*NIST Code: SMC-111L*				
N	Γ	N	Γ	N	Γ	**N**	**Γ**	***Γ/N** (Angular*
1/min	μNm	1/min	μNm	1/min	μNm	**rad/s**	**Nm**	*momentum)*
0.0974	618	0.0974	602	0.0972	597	*0.010*	*6.06E-04*	*5.94E-02*
0.163	779	0.163	775	0.163	755	*0.017*	*7.70E-04*	*4.51E-02*
0.268	849	0.268	835	0.269	826	*0.028*	*8.37E-04*	*2.98E-02*
0.439	907	0.439	893	0.439	892	*0.046*	*8.97E-04*	*1.95E-02*
0.721	978	0.719	965	0.721	977	*0.075*	*9.73E-04*	*1.29E-02*
1.18	1080	1.18	1090	1.18	1100	*0.124*	*1.09E-03*	*8.82E-03*
1.93	1250	1.93	1260	1.93	1280	*0.202*	*1.26E-03*	*6.25E-03*
3.16	1490	3.16	1510	3.16	1540	*0.331*	*1.51E-03*	*4.57E-03*
5.18	1830	5.18	1870	5.18	1920	*0.542*	*1.87E-03*	*3.45E-03*
8.48	2330	8.48	2390	8.48	2450	*0.888*	*2.39E-03*	*2.69E-03*
13.9	3110	13.9	3180	13.9	3270	*1.456*	*3.19E-03*	*2.19E-03*
22.8	4280	22.8	4380	22.8	4500	*2.388*	*4.39E-03*	*1.84E-03*
37.3	5980	37.3	6140	37.3	6370	*3.906*	*6.16E-03*	*1.58E-03*
61.1	8440	61	8880	61.1	9210	*6.395*	*8.84E-03*	*1.38E-03*
100	12200	100	12900	100	13500	*10.472*	*1.29E-02*	*1.23E-03*
100	12000	100	12800	100	13400	*10.472*	*1.27E-02*	*1.22E-03*
69.5	8990	69.5	9510	69.5	9930	*7.278*	*9.48E-03*	*1.30E-03*
48.3	6780	48.3	7160	48.3	7450	*5.058*	*7.13E-03*	*1.41E-03*
33.6	5200	33.6	5450	33.6	5650	*3.519*	*5.43E-03*	*1.54E-03*
23.3	4080	23.4	4220	23.4	4370	*2.447*	*4.22E-03*	*1.73E-03*
16.2	3220	16.2	3340	16.2	3440	*1.696*	*3.33E-03*	*1.96E-03*
11.3	2600	11.3	2680	11.3	2740	*1.183*	*2.67E-03*	*2.26E-03*
7.85	2120	7.84	2190	7.84	2230	*0.821*	*2.18E-03*	*2.65E-03*
5.46	1760	5.45	1820	5.45	1840	*0.571*	*1.81E-03*	*3.16E-03*
3.79	1500	3.79	1540	3.79	1560	*0.397*	*1.53E-03*	*3.86E-03*
2.64	1300	2.64	1330	2.63	1350	*0.276*	*1.33E-03*	*4.80E-03*
1.83	1140	1.83	1170	1.84	1180	*0.192*	*1.16E-03*	*6.06E-03*
1.27	1020	1.27	1050	1.27	1060	*0.133*	*1.04E-03*	*7.84E-03*
0.889	944	0.887	984	0.884	948	*0.093*	*9.59E-04*	*1.03E-02*
0.615	872	0.61	899	0.615	880	*0.064*	*8.84E-04*	*1.38E-02*
0.43	812	0.427	805	0.43	844	*0.045*	*8.20E-04*	*1.83E-02*
0.297	794	0.297	765	0.301	778	*0.031*	*7.79E-04*	*2.49E-02*
0.206	726	0.207	732	0.208	739	*0.022*	*7.32E-04*	*3.38E-02*
0.142	709	0.143	694	0.143	723	*0.015*	*7.09E-04*	*4.74E-02*
0.0988	683	0.101	682	0.0997	710	*0.010*	*6.92E-04*	*6.62E-02*

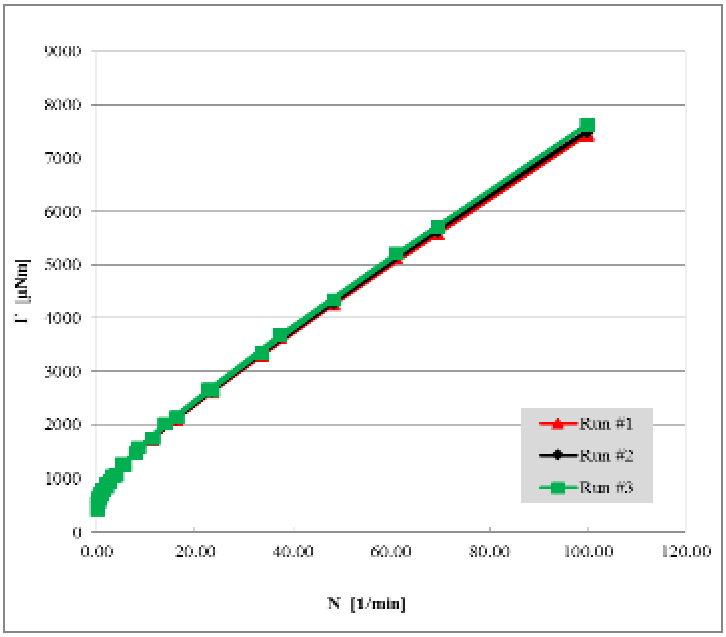


Figure A - 37: Torque vs. Angular Speed using <u>six-blade vane</u> on Mix#10, with 0 % beads by volume. Portrays data from Table A-51.

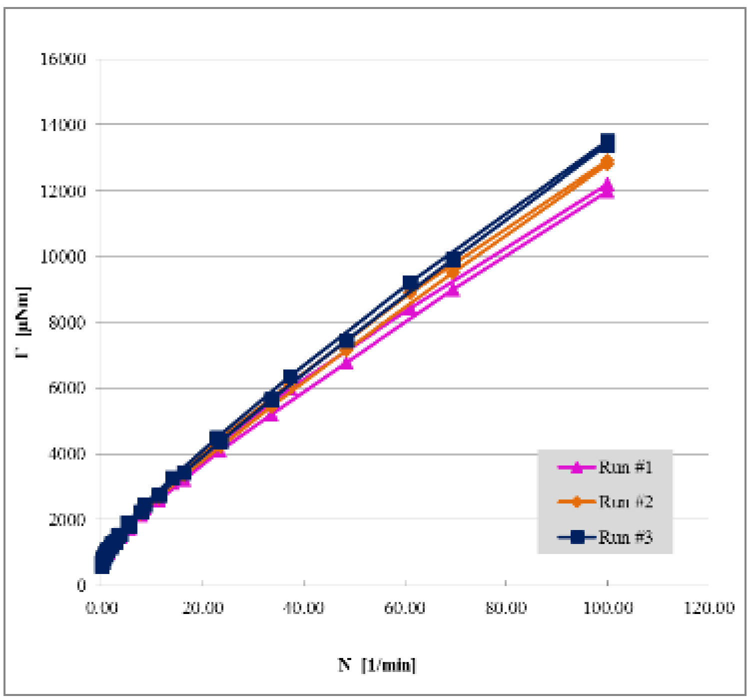


Figure A - 38: Torque vs. Angular Speed using <u>six-blade vane</u> on Mix#10, with 20 % beads by volume. Portrays data from Table A-52.

Table A - 53: Measured data for Mix#10 with 0 % beads using Serrated Coaxial Cylinder.

Serrated Coaxial Cylinder						Bead %		
Geom.: *SS18*				*Z43S*		*0%*		
Run #1		Run #2		Run #3		**Average values**		
NIST Code: SMC-111D		*NIST Code: SMC-111E*		*NIST Code: SMC-111F*				
N	Γ	N	Γ	N	Γ	**N**	**Γ**	***Γ/N*** *(Angular*
1/min	µNm	1/min	µNm	1/min	µNm	**rad/s**	**Nm**	*momentum)*
0.0981	469	0.0981	447	0.0984	409	*0.010*	*4.42E-04*	*4.29E-02*
0.164	600	0.164	586	0.164	522	*0.017*	*5.69E-04*	*3.32E-02*
0.268	638	0.268	634	0.268	579	*0.028*	*6.17E-04*	*2.20E-02*
0.44	685	0.439	688	0.439	649	*0.046*	*6.74E-04*	*1.46E-02*
0.72	751	0.72	760	0.72	734	*0.075*	*7.48E-04*	*9.93E-03*
1.18	841	1.18	885	1.18	847	*0.124*	*8.58E-04*	*6.94E-03*
1.93	965	1.93	991	1.93	974	*0.202*	*9.77E-04*	*4.83E-03*
3.16	1140	3.16	1170	3.16	1190	*0.331*	*1.17E-03*	*3.53E-03*
5.18	1390	5.18	1420	5.18	1430	*0.542*	*1.41E-03*	*2.61E-03*
8.48	1730	8.48	1780	8.48	1790	*0.888*	*1.77E-03*	*1.99E-03*
13.9	2220	13.9	2290	13.9	2310	*1.456*	*2.27E-03*	*1.56E-03*
22.8	2950	22.8	3050	22.8	3090	*2.388*	*3.03E-03*	*1.27E-03*
37.3	4060	37.3	4210	37.3	4260	*3.906*	*4.18E-03*	*1.07E-03*
61	5750	61	5970	61	6050	*6.388*	*5.92E-03*	*9.27E-04*
100	8440	100	8660	100	8690	*10.472*	*8.60E-03*	*8.21E-04*
100	8360	100	8550	100	8580	*10.472*	*8.50E-03*	*8.11E-04*
69.5	6250	69.5	6400	69.5	6440	*7.278*	*6.36E-03*	*8.74E-04*
48.3	4720	48.3	4830	48.3	4850	*5.058*	*4.80E-03*	*9.49E-04*
33.6	3610	33.6	3700	33.6	3710	*3.519*	*3.67E-03*	*1.04E-03*
23.4	2810	23.4	2880	23.4	2890	*2.450*	*2.86E-03*	*1.17E-03*
16.2	2240	16.2	2290	16.2	2290	*1.696*	*2.27E-03*	*1.34E-03*
11.3	1810	11.3	1850	11.3	1850	*1.183*	*1.84E-03*	*1.55E-03*
7.85	1490	7.85	1530	7.85	1530	*0.822*	*1.52E-03*	*1.84E-03*
5.45	1250	5.45	1280	5.45	1270	*0.571*	*1.27E-03*	*2.22E-03*
3.79	1060	3.79	1080	3.79	1080	*0.397*	*1.07E-03*	*2.70E-03*
2.64	906	2.64	928	2.63	932	*0.276*	*9.22E-04*	*3.34E-03*
1.83	788	1.83	810	1.83	830	*0.192*	*8.09E-04*	*4.22E-03*
1.27	694	1.27	741	1.27	724	*0.133*	*7.20E-04*	*5.41E-03*
0.886	619	0.883	659	0.885	683	*0.093*	*6.54E-04*	*7.06E-03*
0.611	597	0.615	659	0.628	633	*0.065*	*6.30E-04*	*9.73E-03*
0.429	512	0.433	594	0.428	639	*0.045*	*5.82E-04*	*1.29E-02*
0.298	468	0.299	514	0.293	531	*0.031*	*5.04E-04*	*1.62E-02*
0.204	479	0.202	555	0.202	552	*0.021*	*5.29E-04*	*2.49E-02*
0.146	550	0.128	492	0.14	571	*0.014*	*5.38E-04*	*3.72E-02*
0.101	405	0.107	538	0.104	515	*0.011*	*4.86E-04*	*4.46E-02*

Table A - 54: Measured data for Mix#10 with 20 % beads using Serrated Coaxial Cylinder.

Serrated Coaxial Cylinder						Bead %		
Geom.:	*SS18*			*Z43S*		*20%*		
Run #1		Run #2		Run #3		**Average values**		
NIST Code: SMC-111M		*NIST Code: SMC-111N*		*NIST Code: SMC-111O*				
N	Γ	N	Γ	N	Γ	**N**	**Γ**	***Γ/N*** *(Angular*
1/min	μNm	1/min	μNm	1/min	μNm	**rad/s**	**Nm**	*momentum)*
0.0978	611	0.0976	599	0.0977	607	*0.010*	*6.06E-04*	*5.92E-02*
0.164	736	0.164	758	0.164	775	*0.017*	*7.56E-04*	*4.40E-02*
0.268	771	0.268	810	0.268	831	*0.028*	*8.04E-04*	*2.86E-02*
0.439	824	0.44	876	0.439	895	*0.046*	*8.65E-04*	*1.88E-02*
0.72	905	0.72	964	0.719	992	*0.075*	*9.54E-04*	*1.27E-02*
1.18	1030	1.18	1100	1.18	1120	*0.124*	*1.08E-03*	*8.77E-03*
1.93	1190	1.93	1280	1.93	1310	*0.202*	*1.26E-03*	*6.23E-03*
3.16	1430	3.16	1540	3.16	1590	*0.331*	*1.52E-03*	*4.59E-03*
5.18	1780	5.18	1910	5.18	1970	*0.542*	*1.89E-03*	*3.48E-03*
8.48	2270	8.48	2440	8.48	2530	*0.888*	*2.41E-03*	*2.72E-03*
13.9	3000	13.9	3240	13.9	3350	*1.456*	*3.20E-03*	*2.20E-03*
22.8	4090	22.8	4440	22.8	4600	*2.388*	*4.38E-03*	*1.83E-03*
37.3	5780	37.3	6300	37.3	6540	*3.906*	*6.21E-03*	*1.59E-03*
61	8330	61	9090	61	9430	*6.388*	*8.95E-03*	*1.40E-03*
100	12400	100	13300	100	13800	*10.472*	*1.32E-02*	*1.26E-03*
100	12300	100	13200	100	13600	*10.472*	*1.30E-02*	*1.24E-03*
69.5	9180	69.5	9830	69.5	10100	*7.278*	*9.70E-03*	*1.33E-03*
48.3	6910	48.3	7380	48.3	7610	*5.058*	*7.30E-03*	*1.44E-03*
33.6	5270	33.6	5610	33.6	5780	*3.519*	*5.55E-03*	*1.58E-03*
23.4	4080	23.4	4320	23.4	4450	*2.450*	*4.28E-03*	*1.75E-03*
16.2	3210	16.2	3390	16.2	3490	*1.696*	*3.36E-03*	*1.98E-03*
11.3	2580	11.3	2710	11.3	2790	*1.183*	*2.69E-03*	*2.28E-03*
7.85	2100	7.85	2210	7.85	2270	*0.822*	*2.19E-03*	*2.67E-03*
5.46	1750	5.45	1840	5.46	1880	*0.571*	*1.82E-03*	*3.19E-03*
3.79	1470	3.79	1560	3.79	1590	*0.397*	*1.54E-03*	*3.88E-03*
2.64	1260	2.64	1330	2.64	1360	*0.276*	*1.32E-03*	*4.76E-03*
1.83	1120	1.83	1160	1.83	1190	*0.192*	*1.16E-03*	*6.04E-03*
1.27	975	1.27	1030	1.27	1050	*0.133*	*1.02E-03*	*7.66E-03*
0.881	940	0.888	930	0.887	939	*0.093*	*9.36E-04*	*1.01E-02*
0.617	793	0.611	898	0.617	862	*0.064*	*8.51E-04*	*1.32E-02*
0.438	770	0.43	783	0.424	808	*0.045*	*7.87E-04*	*1.75E-02*
0.283	738	0.297	777	0.3	809	*0.031*	*7.75E-04*	*2.52E-02*
0.205	677	0.207	690	0.212	725	*0.022*	*6.97E-04*	*3.20E-02*
0.147	627	0.145	753	0.148	825	*0.015*	*7.35E-04*	*4.79E-02*
0.101	686	0.0814	698	0.0916	715	*0.010*	*7.00E-04*	*7.32E-02*

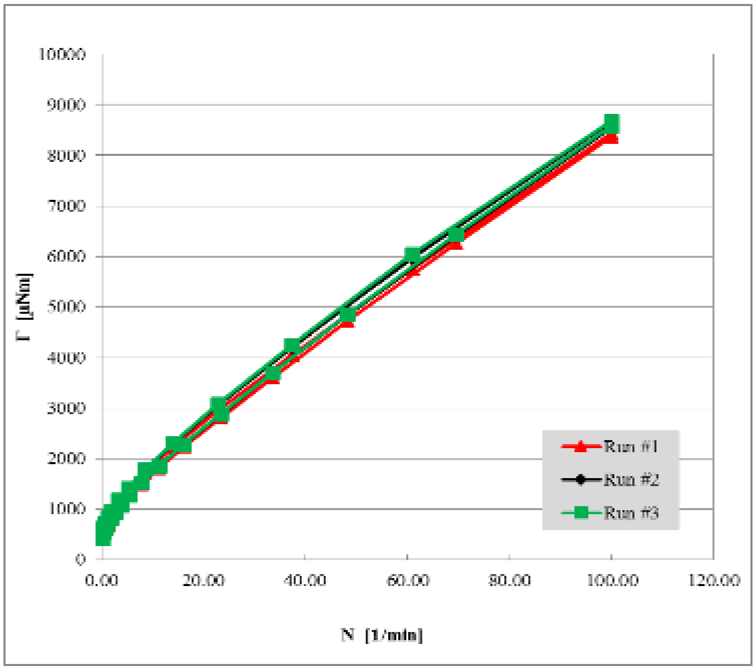


Figure A - 39: Torque vs. Angular Speed using <u>Serrated Coaxial Cylinder</u> on Mix#10, with 0 % beads by volume. Portrays data from Table A-53.

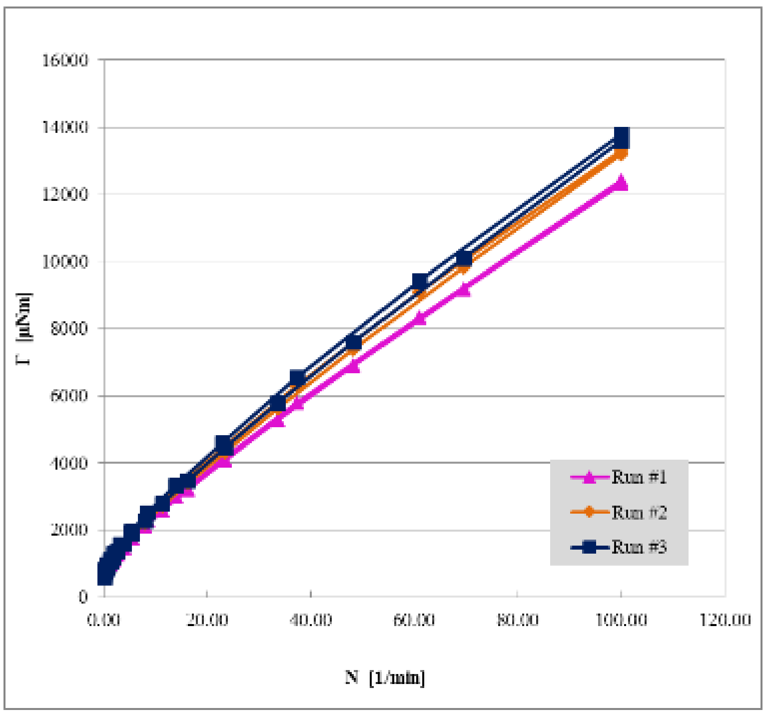


Figure A - 40: Torque vs. Angular Speed using <u>Serrated Coaxial Cylinder</u> on Mix#10, with 20 % beads by volume. Portrays data from Table A-54.

Table A - 55: Measured data for Mix#11 with 0 % beads using Double spiral spindle.

Double Spiral							Bead %	
Geom.: RHN-83A				*Cup: Z43S*			*0%*	
Run #1		Run #2		Run #3		**Average values**		
NIST Code: SMC-113D		*NIST Code: SMC-113E*		*NIST Code: SMC-113F*				
N	Γ	N	Γ	N	Γ	**N**	**Γ**	***Γ/N** (Angular*
1/min	μNm	1/min	μNm	1/min	μNm	**rad/s**	**Nm**	*momentum)*
0.0943	1020	0.0945	959	0.0944	998	*0.010*	*9.92E-04*	*1.00E-01*
0.161	1500	0.161	1430	0.161	1480	*0.017*	*1.47E-03*	*8.72E-02*
0.268	1700	0.268	1640	0.268	1690	*0.028*	*1.68E-03*	*5.97E-02*
0.44	1800	0.44	1760	0.44	1810	*0.046*	*1.79E-03*	*3.88E-02*
0.72	1910	0.72	1880	0.72	1930	*0.075*	*1.91E-03*	*2.53E-02*
1.18	2080	1.18	2050	1.18	2110	*0.124*	*2.08E-03*	*1.68E-02*
1.93	2320	1.93	2300	1.93	2370	*0.202*	*2.33E-03*	*1.15E-02*
3.16	2710	3.16	2710	3.16	2780	*0.331*	*2.73E-03*	*8.26E-03*
5.18	3320	5.18	3330	5.18	3420	*0.542*	*3.36E-03*	*6.19E-03*
8.48	4260	8.48	4290	8.48	4410	*0.888*	*4.32E-03*	*4.86E-03*
13.9	5780	13.9	5860	13.9	6000	*1.456*	*5.88E-03*	*4.04E-03*
22.8	8160	22.8	8220	22.8	8470	*2.388*	*8.28E-03*	*3.47E-03*
37.3	11900	37.3	12000	37.3	12400	*3.906*	*1.21E-02*	*3.10E-03*
61.1	17700	61.1	18000	61.1	18500	*6.398*	*1.81E-02*	*2.82E-03*
100	26800	100	27200	100	28100	*10.472*	*2.74E-02*	*2.61E-03*
100	26600	100	27100	100	27900	*10.472*	*2.72E-02*	*2.60E-03*
69.5	19400	69.5	19800	69.5	20400	*7.278*	*1.99E-02*	*2.73E-03*
48.3	14400	48.3	14700	48.3	15100	*5.058*	*1.47E-02*	*2.91E-03*
33.6	10800	33.6	11000	33.6	11300	*3.519*	*1.10E-02*	*3.14E-03*
23.4	8190	23.4	8350	23.4	8590	*2.450*	*8.38E-03*	*3.42E-03*
16.2	6350	16.2	6470	16.2	6650	*1.696*	*6.49E-03*	*3.83E-03*
11.3	5020	11.3	5110	11.3	5250	*1.183*	*5.13E-03*	*4.33E-03*
7.85	4070	7.85	4140	7.85	4240	*0.822*	*4.15E-03*	*5.05E-03*
5.46	3380	5.46	3430	5.46	3510	*0.572*	*3.44E-03*	*6.02E-03*
3.79	2870	3.79	2920	3.79	2980	*0.397*	*2.92E-03*	*7.37E-03*
2.64	2500	2.64	2540	2.64	2590	*0.276*	*2.54E-03*	*9.20E-03*
1.83	2230	1.83	2260	1.83	2300	*0.192*	*2.26E-03*	*1.18E-02*
1.27	2020	1.27	2050	1.27	2090	*0.133*	*2.05E-03*	*1.54E-02*
0.886	1870	0.886	1890	0.886	1930	*0.093*	*1.90E-03*	*2.04E-02*
0.615	1750	0.616	1770	0.616	1800	*0.064*	*1.77E-03*	*2.75E-02*
0.428	1670	0.428	1680	0.427	1720	*0.045*	*1.69E-03*	*3.77E-02*
0.3	1600	0.297	1620	0.298	1650	*0.031*	*1.62E-03*	*5.20E-02*
0.206	1550	0.207	1580	0.207	1580	*0.022*	*1.57E-03*	*7.25E-02*
0.144	1500	0.144	1510	0.145	1540	*0.015*	*1.52E-03*	*1.00E-01*
0.0994	1470	0.0997	1480	0.101	1510	*0.010*	*1.49E-03*	*1.42E-01*

Table A - 56: Measured data for Mix#11 with 20 % beads using Double spiral spindle.

Double Spiral						Bead %		
Geom.: RHN-83A				*Cup: Z43S*		*20%*		
Run #1		Run #2		Run #3		**Average values**		
NIST Code: SMC-113M		*NIST Code: SMC-113N*		*NIST Code: SMC-113O*				
N	Γ	N	Γ	N	Γ	**N**	**Γ**	***Γ/N*** *(Angular*
1/min	μNm	1/min	μNm	1/min	μNm	**rad/s**	**Nm**	*momentum)*
0.0929	1350	0.0938	1290	0.0925	1330	*0.010*	*1.32E-03*	*1.36E-01*
0.161	1900	0.16	1850	0.161	1900	*0.017*	*1.88E-03*	*1.12E-01*
0.268	2120	0.268	2110	0.267	2160	*0.028*	*2.13E-03*	*7.60E-02*
0.44	2300	0.439	2270	0.439	2340	*0.046*	*2.30E-03*	*5.01E-02*
0.72	2500	0.72	2500	0.72	2570	*0.075*	*2.52E-03*	*3.35E-02*
1.18	2840	1.18	2800	1.18	2880	*0.124*	*2.84E-03*	*2.30E-02*
1.93	3320	1.93	3270	1.93	3370	*0.202*	*3.32E-03*	*1.64E-02*
3.17	4090	3.16	4000	3.16	4110	*0.331*	*4.07E-03*	*1.23E-02*
5.18	5320	5.18	5130	5.18	5290	*0.542*	*5.25E-03*	*9.67E-03*
8.49	7210	8.48	6930	8.49	7130	*0.889*	*7.09E-03*	*7.98E-03*
13.9	10000	13.9	9720	13.9	10000	*1.456*	*9.91E-03*	*6.81E-03*
22.8	14000	22.8	13900	22.8	14300	*2.388*	*1.41E-02*	*5.89E-03*
37.3	20800	37.3	20700	37.3	21300	*3.906*	*2.09E-02*	*5.36E-03*
61	31300	61.1	31300	61	32300	*6.391*	*3.16E-02*	*4.95E-03*
100	47300	100	47500	100	49200	*10.472*	*4.80E-02*	*4.58E-03*
100	46800	100	47200	100	48900	*10.472*	*4.76E-02*	*4.55E-03*
69.5	33900	69.5	34300	69.5	35600	*7.278*	*3.46E-02*	*4.75E-03*
48.3	24800	48.3	25200	48.3	26100	*5.058*	*2.54E-02*	*5.02E-03*
33.6	18400	33.6	18700	33.6	19400	*3.519*	*1.88E-02*	*5.35E-03*
23.4	13800	23.4	14000	23.4	14500	*2.450*	*1.41E-02*	*5.75E-03*
16.2	10500	16.2	10700	16.2	11100	*1.696*	*1.08E-02*	*6.35E-03*
11.3	8120	11.3	8290	11.3	8570	*1.183*	*8.33E-03*	*7.04E-03*
7.84	6430	7.85	6540	7.85	6760	*0.822*	*6.58E-03*	*8.00E-03*
5.46	5210	5.45	5320	5.46	5470	*0.571*	*5.33E-03*	*9.33E-03*
3.79	4300	3.8	4400	3.79	4530	*0.397*	*4.41E-03*	*1.11E-02*
2.64	3650	2.64	3730	2.64	3840	*0.276*	*3.74E-03*	*1.35E-02*
1.83	3180	1.83	3240	1.83	3330	*0.192*	*3.25E-03*	*1.70E-02*
1.27	2810	1.27	2860	1.27	2950	*0.133*	*2.87E-03*	*2.16E-02*
0.887	2540	0.885	2590	0.887	2650	*0.093*	*2.59E-03*	*2.79E-02*
0.618	2330	0.615	2380	0.615	2440	*0.065*	*2.38E-03*	*3.69E-02*
0.428	2160	0.43	2220	0.428	2280	*0.045*	*2.22E-03*	*4.95E-02*
0.298	2040	0.297	2090	0.297	2150	*0.031*	*2.09E-03*	*6.72E-02*
0.206	1970	0.208	2000	0.207	2040	*0.022*	*2.00E-03*	*9.24E-02*
0.144	1900	0.144	1930	0.143	1960	*0.015*	*1.93E-03*	*1.28E-01*
0.102	1840	0.0996	1880	0.1	1920	*0.011*	*1.88E-03*	*1.79E-01*

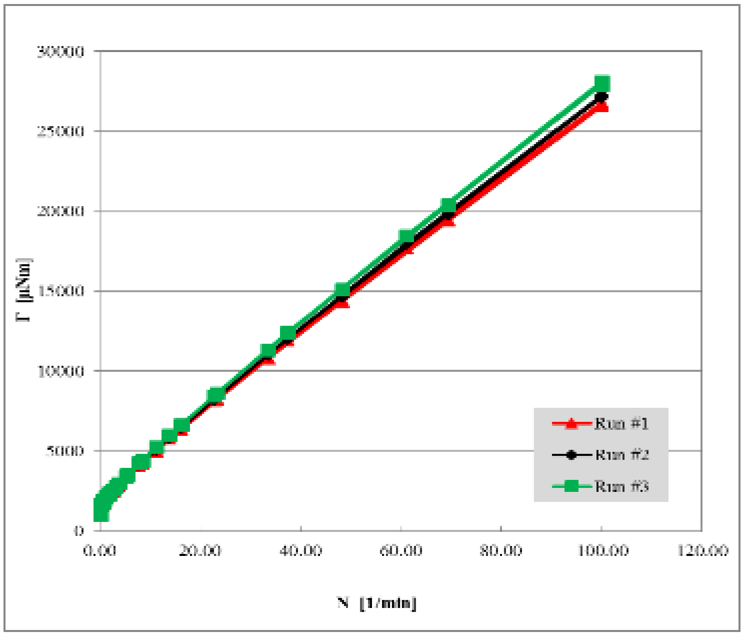


Figure A - 41: Torque vs. Angular Speed using <u>Double spiral spindle</u> on Mix#11, with 0 % beads by volume. Portrays data from Table A-55.

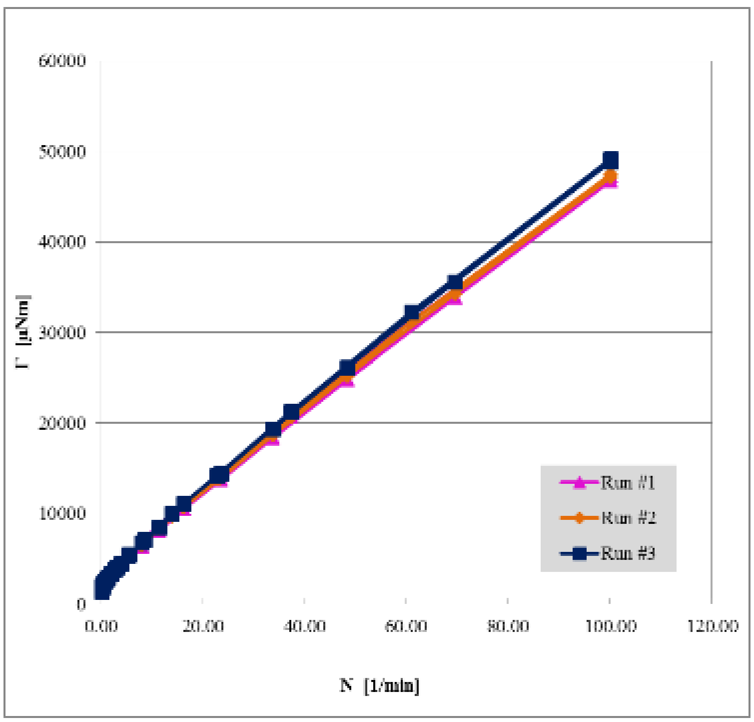


Figure A - 42: Torque vs. Angular Speed using <u>Double spiral spindle</u> on Mix#11, with 20 % beads by volume. Portrays data from Table A-56.

Table A - 57: Measured data for Mix#11 with 0 % beads using Six-blade Vane.

6 Blade Vane						Bead %		
Geom.: *RHN-83C*				*Z43S*		*0%*		
Run #1		Run #2		Run #3		**Average values**		
NIST Code: SMC-113A		*NIST Code: SMC-113B*		*NIST Code: SMC-113C*				
N	Γ	N	Γ	N	Γ	**N**	**Γ**	***Γ/N*** *(Angular*
1/min	µNm	1/min	µNm	1/min	µNm	**rad/s**	**Nm**	*momentum)*
0.0987	441	0.0977	415	0.0978	412	*0.010*	*4.23E-04*	*4.12E-02*
0.164	512	0.163	563	0.163	559	*0.017*	*5.45E-04*	*3.18E-02*
0.268	545	0.268	602	0.268	602	*0.028*	*5.83E-04*	*2.08E-02*
0.439	583	0.439	633	0.439	634	*0.046*	*6.17E-04*	*1.34E-02*
0.72	650	0.72	682	0.72	683	*0.075*	*6.72E-04*	*8.91E-03*
1.18	713	1.18	751	1.18	753	*0.124*	*7.39E-04*	*5.98E-03*
1.93	805	1.93	847	1.93	849	*0.202*	*8.34E-04*	*4.12E-03*
3.16	933	3.16	982	3.16	990	*0.331*	*9.68E-04*	*2.93E-03*
5.18	1120	5.18	1180	5.18	1180	*0.542*	*1.16E-03*	*2.14E-03*
8.48	1390	8.48	1460	8.48	1470	*0.888*	*1.44E-03*	*1.62E-03*
13.9	1790	13.9	1870	13.9	1890	*1.456*	*1.85E-03*	*1.27E-03*
22.8	2380	22.8	2470	22.8	2510	*2.388*	*2.45E-03*	*1.03E-03*
37.3	3290	37.3	3400	37.3	3450	*3.906*	*3.38E-03*	*8.65E-04*
61	4670	61	4820	61	4900	*6.388*	*4.80E-03*	*7.51E-04*
100	6850	100	7050	100	7160	*10.472*	*7.02E-03*	*6.70E-04*
100	6860	100	7030	100	7170	*10.472*	*7.02E-03*	*6.70E-04*
69.5	5150	69.5	5270	69.5	5370	*7.278*	*5.26E-03*	*7.23E-04*
48.3	3930	48.3	4010	48.3	4090	*5.058*	*4.01E-03*	*7.93E-04*
33.6	3050	33.6	3110	33.6	3160	*3.519*	*3.11E-03*	*8.83E-04*
23.4	2410	23.4	2450	23.4	2490	*2.450*	*2.45E-03*	*1.00E-03*
16.2	1950	16.2	1980	16.2	2010	*1.696*	*1.98E-03*	*1.17E-03*
11.3	1600	11.3	1630	11.3	1650	*1.183*	*1.63E-03*	*1.37E-03*
7.85	1340	7.85	1360	7.85	1380	*0.822*	*1.36E-03*	*1.65E-03*
5.45	1140	5.46	1160	5.46	1170	*0.571*	*1.16E-03*	*2.02E-03*
3.79	989	3.79	1010	3.79	1020	*0.397*	*1.01E-03*	*2.54E-03*
2.64	872	2.64	885	2.64	894	*0.276*	*8.84E-04*	*3.20E-03*
1.83	788	1.83	793	1.83	809	*0.192*	*7.97E-04*	*4.16E-03*
1.28	717	1.27	730	1.27	733	*0.133*	*7.27E-04*	*5.45E-03*
0.887	669	0.887	669	0.882	680	*0.093*	*6.73E-04*	*7.26E-03*
0.618	621	0.616	626	0.618	630	*0.065*	*6.26E-04*	*9.68E-03*
0.424	582	0.428	590	0.426	604	*0.045*	*5.92E-04*	*1.33E-02*
0.298	567	0.3	564	0.298	585	*0.031*	*5.72E-04*	*1.83E-02*
0.207	535	0.207	544	0.205	553	*0.022*	*5.44E-04*	*2.52E-02*
0.142	543	0.141	534	0.138	548	*0.015*	*5.42E-04*	*3.69E-02*
0.0994	496	0.101	503	0.101	530	*0.011*	*5.10E-04*	*4.84E-02*

Table A - 58: Measured data for Mix#11 with 20 % beads using Six-blade Vane.

6 Blade Vane						Bead %		
Geom.: RHN-83C				*Z43S*		*20%*		
Run #1		Run #2		Run #3		**Average values**		
NIST Code: SMC-113J		*NIST Code: SMC-113K*		*NIST Code: SMC-113L*				
N	Γ	N	Γ	N	Γ	**N**	**Γ**	***Γ/N*** *(Angular*
1/min	μNm	1/min	μNm	1/min	μNm	**rad/s**	**Nm**	*momentum)*
0.0976	585	0.0975	570	0.0973	590	*0.010*	*5.82E-04*	*5.70E-02*
0.163	732	0.163	719	0.163	752	*0.017*	*7.34E-04*	*4.30E-02*
0.268	791	0.268	775	0.268	807	*0.028*	*7.91E-04*	*2.82E-02*
0.44	844	0.44	839	0.44	868	*0.046*	*8.50E-04*	*1.85E-02*
0.72	927	0.719	921	0.719	955	*0.075*	*9.34E-04*	*1.24E-02*
1.18	1040	1.18	1040	1.18	1070	*0.124*	*1.05E-03*	*8.50E-03*
1.93	1190	1.93	1210	1.93	1250	*0.202*	*1.22E-03*	*6.02E-03*
3.16	1410	3.16	1440	3.16	1480	*0.331*	*1.44E-03*	*4.36E-03*
5.18	1730	5.18	1800	5.18	1850	*0.542*	*1.79E-03*	*3.31E-03*
8.48	2210	8.48	2300	8.48	2360	*0.888*	*2.29E-03*	*2.58E-03*
13.9	2940	13.9	3060	13.9	3150	*1.456*	*3.05E-03*	*2.10E-03*
22.8	4050	22.8	4220	22.8	4310	*2.388*	*4.19E-03*	*1.76E-03*
37.3	5660	37.3	5950	37.3	6030	*3.906*	*5.88E-03*	*1.51E-03*
61.1	8060	61	8550	61	8650	*6.391*	*8.42E-03*	*1.32E-03*
100	11600	100	12400	100	12700	*10.472*	*1.22E-02*	*1.17E-03*
100	11500	100	12300	100	12600	*10.472*	*1.21E-02*	*1.16E-03*
69.5	8590	69.5	9180	69.5	9370	*7.278*	*9.05E-03*	*1.24E-03*
48.3	6490	48.3	6880	48.3	7020	*5.058*	*6.80E-03*	*1.34E-03*
33.6	4980	33.6	5240	33.6	5330	*3.519*	*5.18E-03*	*1.47E-03*
23.4	3900	23.4	4040	23.3	4130	*2.447*	*4.02E-03*	*1.64E-03*
16.2	3090	16.2	3200	16.2	3240	*1.696*	*3.18E-03*	*1.87E-03*
11.3	2480	11.3	2580	11.3	2600	*1.183*	*2.55E-03*	*2.16E-03*
7.85	2030	7.85	2080	7.85	2110	*0.822*	*2.07E-03*	*2.52E-03*
5.46	1690	5.45	1740	5.46	1750	*0.571*	*1.73E-03*	*3.02E-03*
3.79	1430	3.79	1470	3.79	1480	*0.397*	*1.46E-03*	*3.68E-03*
2.64	1240	2.64	1260	2.64	1270	*0.276*	*1.26E-03*	*4.55E-03*
1.83	1090	1.83	1120	1.83	1130	*0.192*	*1.11E-03*	*5.81E-03*
1.27	986	1.28	1010	1.27	996	*0.133*	*9.97E-04*	*7.48E-03*
0.885	889	0.887	898	0.886	908	*0.093*	*8.98E-04*	*9.68E-03*
0.615	837	0.613	840	0.612	847	*0.064*	*8.41E-04*	*1.31E-02*
0.425	768	0.431	788	0.43	789	*0.045*	*7.82E-04*	*1.74E-02*
0.297	747	0.296	741	0.297	747	*0.031*	*7.45E-04*	*2.40E-02*
0.205	705	0.209	709	0.206	724	*0.022*	*7.13E-04*	*3.29E-02*
0.143	676	0.145	689	0.144	694	*0.015*	*6.86E-04*	*4.55E-02*
0.0996	639	0.0993	656	0.0999	668	*0.010*	*6.54E-04*	*6.27E-02*

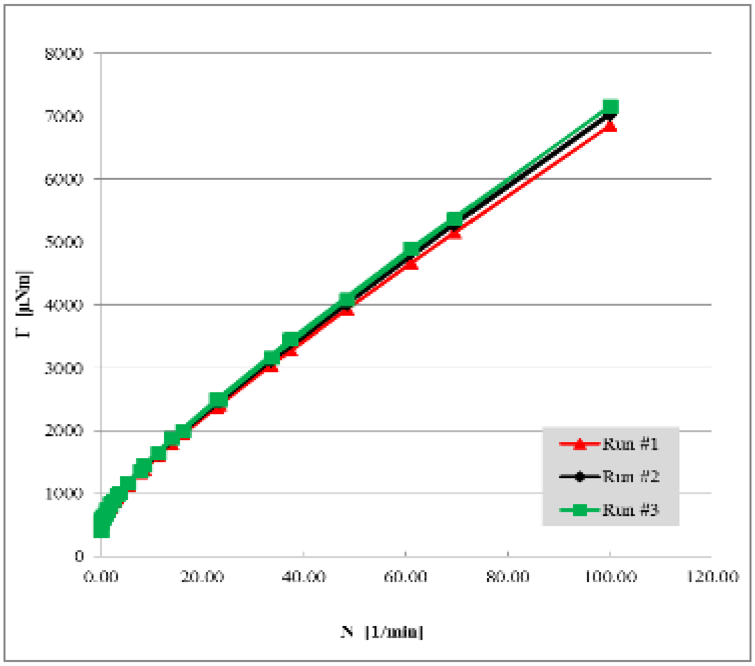


Figure A - 57: Torque vs. Angular Speed using <u>six-blade vane</u> on Mix#11, with 0 % beads by volume. Portrays data from Table A-57.

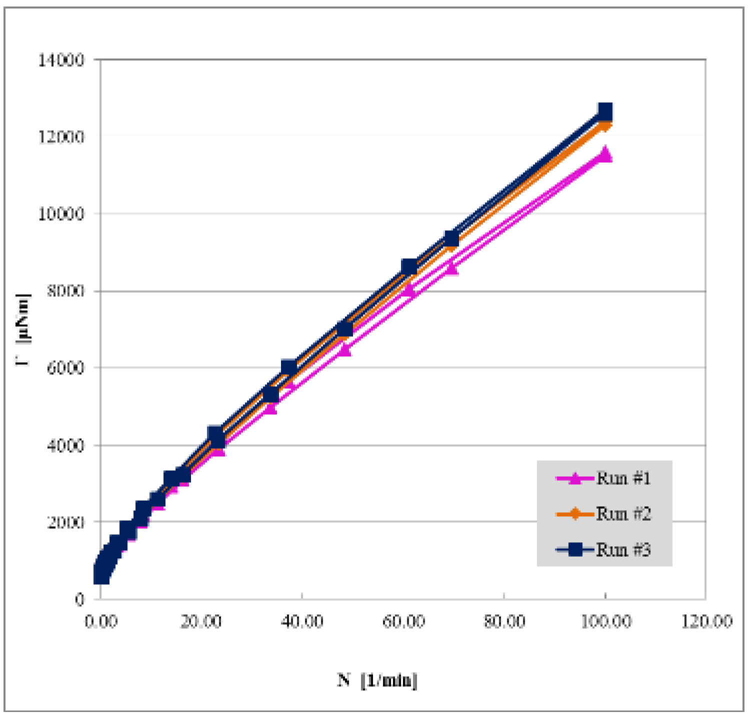


Figure A - 58: Torque vs. Angular Speed using <u>six-blade vane</u> on Mix#11, with 20 % beads by volume. Portrays data from Table A-58.

Table A - 59: Measured data for Mix#11 with 0 % beads using Serrated Coaxial Cylinder.

Serrated Coaxial Cylinder						Bead %		
Geom.:	*SS18*			*Z43S*		*0%*		
Run #1		Run #2		Run #3		**Average values**		
NIST Code: SMC-113G		*NIST Code: SMC-113H*		*NIST Code: SMC-113I*				
N	Γ	N	Γ	N	Γ	**N**	**Γ**	***Γ/N** (Angular*
1/min	μNm	1/min	μNm	1/min	μNm	**rad/s**	**Nm**	*momentum)*
0.0978	444	0.0984	436	0.0983	426	*0.010*	*4.35E-04*	*4.23E-02*
0.164	598	0.164	561	0.164	549	*0.017*	*5.69E-04*	*3.32E-02*
0.268	638	0.269	615	0.268	618	*0.028*	*6.24E-04*	*2.22E-02*
0.439	682	0.44	669	0.439	676	*0.046*	*6.76E-04*	*1.47E-02*
0.72	746	0.721	749	0.72	745	*0.075*	*7.47E-04*	*9.90E-03*
1.18	839	1.18	857	1.18	853	*0.124*	*8.50E-04*	*6.88E-03*
1.93	959	1.93	983	1.93	985	*0.202*	*9.76E-04*	*4.83E-03*
3.16	1140	3.16	1160	3.16	1170	*0.331*	*1.16E-03*	*3.50E-03*
5.18	1370	5.18	1420	5.18	1430	*0.542*	*1.41E-03*	*2.59E-03*
8.48	1710	8.48	1770	8.48	1800	*0.888*	*1.76E-03*	*1.98E-03*
13.9	2200	13.9	2270	13.9	2320	*1.456*	*2.26E-03*	*1.55E-03*
22.8	2910	22.8	3020	22.8	3100	*2.388*	*3.01E-03*	*1.26E-03*
37.3	4020	37.3	4160	37.3	4280	*3.906*	*4.15E-03*	*1.06E-03*
61	5700	61	5930	61	6070	*6.388*	*5.90E-03*	*9.24E-04*
100	8290	100	8580	100	8740	*10.472*	*8.54E-03*	*8.15E-04*
100	8180	100	8460	100	8620	*10.472*	*8.42E-03*	*8.04E-04*
69.5	6120	69.5	6340	69.5	6460	*7.278*	*6.31E-03*	*8.67E-04*
48.3	4620	48.3	4770	48.3	4860	*5.058*	*4.75E-03*	*9.39E-04*
33.6	3530	33.6	3640	33.6	3710	*3.519*	*3.63E-03*	*1.03E-03*
23.4	2750	23.4	2830	23.4	2880	*2.450*	*2.82E-03*	*1.15E-03*
16.2	2180	16.2	2250	16.2	2280	*1.696*	*2.24E-03*	*1.32E-03*
11.3	1760	11.3	1820	11.3	1840	*1.183*	*1.81E-03*	*1.53E-03*
7.85	1460	7.85	1500	7.85	1520	*0.822*	*1.49E-03*	*1.82E-03*
5.45	1210	5.46	1260	5.45	1280	*0.571*	*1.25E-03*	*2.19E-03*
3.79	1030	3.79	1090	3.79	1090	*0.397*	*1.07E-03*	*2.70E-03*
2.64	882	2.63	930	2.64	943	*0.276*	*9.18E-04*	*3.33E-03*
1.82	792	1.83	810	1.83	831	*0.191*	*8.11E-04*	*4.24E-03*
1.27	716	1.27	727	1.28	741	*0.133*	*7.28E-04*	*5.46E-03*
0.887	609	0.885	670	0.887	663	*0.093*	*6.47E-04*	*6.97E-03*
0.614	567	0.623	619	0.616	605	*0.065*	*5.97E-04*	*9.23E-03*
0.425	595	0.428	537	0.432	571	*0.045*	*5.68E-04*	*1.27E-02*
0.297	511	0.297	514	0.306	598	*0.031*	*5.41E-04*	*1.72E-02*
0.217	547	0.208	587	0.193	587	*0.022*	*5.74E-04*	*2.66E-02*
0.143	576	0.141	497	0.113	594	*0.014*	*5.56E-04*	*4.01E-02*
0.1	522	0.0819	517	0.102	452	*0.010*	*4.97E-04*	*5.02E-02*

Table A - 60: Measured data for Mix#11 with 20 % beads using Serrated Coaxial Cylinder.

Serrated Coaxial Cylinder						Bead %		
Geom.:	*SS18*			*Z43S*		*20%*		
Run #1		Run #2		Run #3		**Average values**		
NIST Code: SMC-113P		*NIST Code: SMC-113Q*		*NIST Code: SMC-113R*				
N	Γ	N	Γ	N	Γ	**N**	**Γ**	***Γ/N*** *(Angular*
1/min	μNm	1/min	μNm	1/min	μNm	**rad/s**	**Nm**	*momentum)*
0.0975	667	0.0982	609	0.0982	617	*0.010*	*6.31E-04*	*6.15E-02*
0.164	814	0.164	716	0.164	748	*0.017*	*7.59E-04*	*4.42E-02*
0.269	818	0.268	781	0.268	818	*0.028*	*8.06E-04*	*2.87E-02*
0.44	862	0.439	855	0.439	904	*0.046*	*8.74E-04*	*1.90E-02*
0.72	948	0.719	968	0.72	1010	*0.075*	*9.75E-04*	*1.29E-02*
1.18	1070	1.18	1110	1.18	1160	*0.124*	*1.11E-03*	*9.01E-03*
1.93	1260	1.93	1320	1.93	1370	*0.202*	*1.32E-03*	*6.51E-03*
3.16	1520	3.16	1600	3.16	1660	*0.331*	*1.59E-03*	*4.81E-03*
5.18	1890	5.18	2010	5.18	2080	*0.542*	*1.99E-03*	*3.67E-03*
8.48	2420	8.48	2590	8.48	2690	*0.888*	*2.57E-03*	*2.89E-03*
13.9	3200	13.9	3430	13.9	3580	*1.456*	*3.40E-03*	*2.34E-03*
22.8	4370	22.8	4710	22.8	4910	*2.388*	*4.66E-03*	*1.95E-03*
37.3	6170	37.3	6620	37.3	6950	*3.906*	*6.58E-03*	*1.68E-03*
61	8860	61	9470	61	9930	*6.388*	*9.42E-03*	*1.47E-03*
100	13100	100	13900	100	14600	*10.472*	*1.39E-02*	*1.32E-03*
100	13000	100	13800	100	14500	*10.472*	*1.38E-02*	*1.31E-03*
69.5	9770	69.5	10300	69.5	10800	*7.278*	*1.03E-02*	*1.41E-03*
48.3	7350	48.3	7720	48.3	8080	*5.058*	*7.72E-03*	*1.53E-03*
33.6	5580	33.6	5860	33.6	6130	*3.519*	*5.86E-03*	*1.66E-03*
23.4	4300	23.4	4500	23.4	4720	*2.450*	*4.51E-03*	*1.84E-03*
16.2	3360	16.2	3520	16.2	3680	*1.696*	*3.52E-03*	*2.07E-03*
11.3	2680	11.3	2810	11.3	2930	*1.183*	*2.81E-03*	*2.37E-03*
7.85	2180	7.85	2280	7.85	2370	*0.822*	*2.28E-03*	*2.77E-03*
5.46	1790	5.45	1880	5.46	1960	*0.571*	*1.88E-03*	*3.28E-03*
3.79	1510	3.79	1590	3.79	1650	*0.397*	*1.58E-03*	*3.99E-03*
2.64	1300	2.64	1370	2.64	1410	*0.276*	*1.36E-03*	*4.92E-03*
1.84	1140	1.83	1170	1.83	1220	*0.192*	*1.18E-03*	*6.13E-03*
1.27	986	1.27	1030	1.28	1140	*0.133*	*1.05E-03*	*7.89E-03*
0.885	931	0.888	951	0.878	980	*0.093*	*9.54E-04*	*1.03E-02*
0.624	817	0.613	869	0.613	943	*0.065*	*8.76E-04*	*1.36E-02*
0.43	756	0.431	800	0.419	857	*0.045*	*8.04E-04*	*1.80E-02*
0.296	717	0.281	813	0.291	783	*0.030*	*7.71E-04*	*2.54E-02*
0.212	793	0.187	928	0.198	908	*0.021*	*8.76E-04*	*4.21E-02*
0.138	685	0.146	705	0.148	708	*0.015*	*6.99E-04*	*4.64E-02*
0.106	704	0.111	699	0.092	668	*0.011*	*6.90E-04*	*6.40E-02*

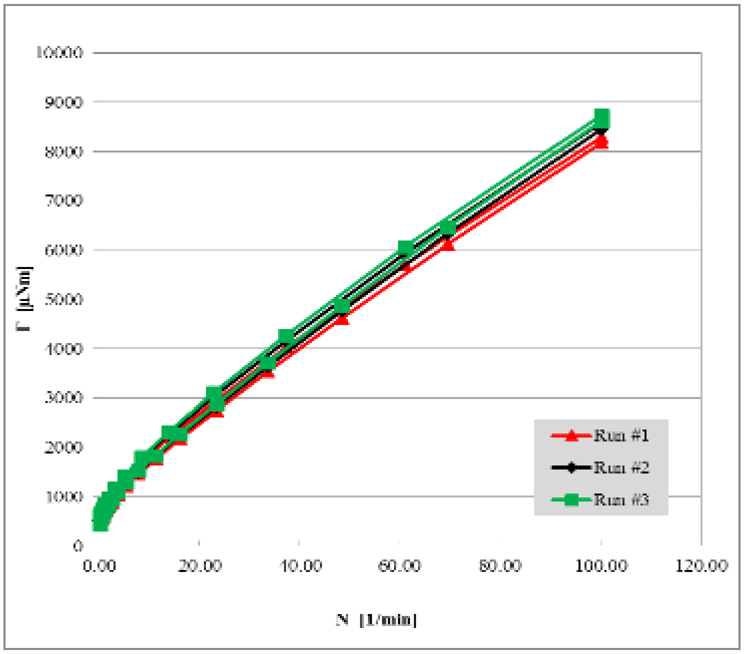


Figure A - 43: Torque vs. Angular Speed using Serrated Coaxial Cylinder on Mix#11, with 0 % beads by volume. Portrays data from Table A-59.

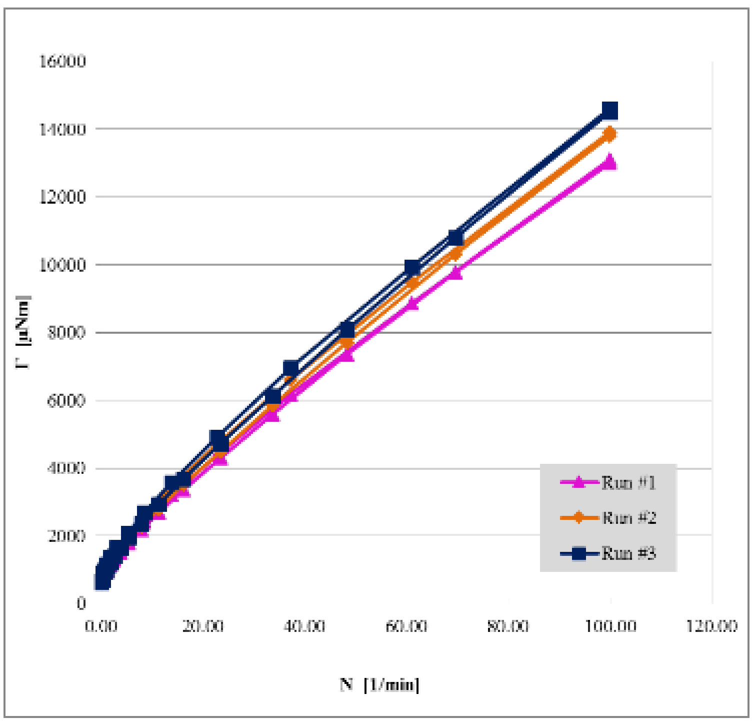


Figure A - 44: Torque vs. Angular Speed using Serrated Coaxial Cylinder on Mix#11, with 20 % beads by volume. Portrays data from Table A-60.

Appendix B: Data for Calibration

This appendix summarizes the average values calculated from the original data shown in Appendix A. These average data sets were combined into a set of average values (green colored columns) for each spindle and mortar composition (bead %). The combined average data sets shown in this appendix were used during the calibration process described in Section 4.3 to convert the original raw data into fundamental units.

Table B - 1: Average values for SRM paste with 0 % beads (by volume) performed prior to the 20 % mortar tests using a double spiral spindle geometry. *[NIST Codes]*

Double Spiral [RHN-83A]									
0 % Beads *(Pre-20 %)*									
Mix #7 [SMC-101]		**Mix #8** [SMC-103]		**Mix #9** [SMC-109]		**Mix #10** [SMC-111]		**Mix #11** [SMC-113]	
N [1/min]	Γ [μNm]	N [1/min]	Γ [μNm]	N [1/min]	Γ [μNm]	N [1/min]	Γ [μNm]	N [1/min]	Γ [μNm]
0.09	953	0.09	993	0.09	1014	0.09	1030	0.09	992
0.16	1410	0.16	1473	0.16	1500	0.16	1557	0.16	1470
0.27	1593	0.27	1680	0.27	1707	0.27	1787	0.27	1677
0.44	1703	0.44	1790	0.44	1827	0.44	1907	0.44	1790
0.72	1820	0.72	1917	0.72	1957	0.72	2050	0.72	1907
1.18	1993	1.18	2093	1.18	2140	1.18	2240	1.18	2080
1.93	2237	1.93	2353	1.93	2410	1.93	2533	1.93	2330
3.16	2617	3.16	2767	3.16	2833	3.16	2987	3.16	2733
5.18	3200	5.18	3407	5.18	3480	5.18	3687	5.18	3357
8.48	4107	8.48	4397	8.48	4490	8.48	4773	8.48	4320
13.90	5527	13.90	5997	13.90	6117	13.90	6507	13.90	5880
22.80	7760	22.80	8440	22.80	8617	22.80	9170	22.80	8283
37.30	11267	37.30	12333	37.30	12600	37.30	13400	37.30	12100
61.10	16800	61.10	18500	61.10	18800	61.10	20067	61.10	18067
100.00	25467	100.00	28000	100.00	28467	100.00	30367	100.00	27367
100.00	25333	100.00	27833	100.00	28267	100.00	30200	100.00	27200
69.50	18533	69.50	20333	69.50	20667	69.50	22100	69.50	19867
48.30	13733	48.30	14967	48.30	15333	48.30	16333	48.30	14733
33.60	10300	33.60	11200	33.60	11467	33.60	12233	33.60	11033
23.40	7843	23.40	8513	23.40	8707	23.40	9290	23.40	8377
16.20	6093	16.20	6577	16.20	6743	16.20	7180	16.20	6490
11.30	4837	11.30	5190	11.30	5327	11.30	5667	11.30	5127
7.85	3927	7.85	4190	7.85	4307	7.85	4570	7.85	4150
5.46	3270	5.46	3470	5.46	3567	5.46	3777	5.46	3440
3.79	2790	3.79	2947	3.79	3030	3.79	3200	3.79	2923
2.64	2433	2.64	2560	2.64	2633	2.64	2780	2.64	2543
1.83	2173	1.83	2277	1.83	2343	1.83	2463	1.83	2263
1.27	1980	1.27	2063	1.27	2127	1.27	2233	1.27	2053
0.89	1830	0.89	1907	0.89	1960	0.88	2067	0.89	1897
0.62	1720	0.62	1787	0.62	1837	0.62	1923	0.62	1773
0.43	1633	0.43	1707	0.43	1747	0.43	1817	0.43	1690
0.30	1567	0.30	1630	0.30	1673	0.30	1747	0.30	1623
0.21	1517	0.21	1573	0.21	1617	0.21	1683	0.21	1570
0.14	1473	0.14	1527	0.15	1577	0.14	1643	0.14	1517
0.10	1440	0.10	1487	0.10	1543	0.10	1603	0.10	1487

Table B - 2: Average values for SRM paste with 0 % beads (by volume) performed prior to the 40 % mortar tests using a double spiral spindle geometry. *[NIST Codes]*

Double Spiral [RHN-83A]									
0 % Beads *(Pre-40 %)*									
Mix #2 [SMC-79]		**Mix #3** [SMC-81]		**Mix #4** [SMC-85]		**Mix #5** [SMC-95]		**Mix #6** [SMC-97]	
N [1/min]	Γ [μNm]	N [1/min]	Γ [μNm]	N [1/min]	Γ [μNm]	N [1/min]	Γ [μNm]	N [1/min]	Γ [μNm]
0.10	1181	0.10	1370	0.09	999	0.10	1098	0.09	1023
0.16	1507	0.16	1567	0.16	1460	0.16	1407	0.16	1510
0.27	1660	0.27	1670	0.27	1650	0.27	1547	0.27	1717
0.44	1770	0.44	1767	0.44	1760	0.44	1643	0.44	1840
0.72	1893	0.72	1893	0.72	1883	0.72	1760	0.72	1977
1.18	2083	1.18	2073	1.18	2060	1.18	1940	1.18	2160
1.93	2347	1.93	2340	1.93	2310	1.93	2193	1.93	2443
3.16	2760	3.16	2760	3.16	2707	3.16	2587	3.16	2873
5.18	3393	5.18	3407	5.18	3317	5.18	3187	5.18	3530
8.48	4373	8.48	4393	8.48	4250	8.48	4103	8.48	4543
13.90	5900	13.90	5913	13.90	5730	13.90	5527	13.90	6163
22.80	8307	22.80	8377	22.80	8047	22.80	7813	22.80	8670
37.30	12100	37.30	12233	37.30	11733	37.30	11367	37.30	12633
61.00	18033	61.10	18267	61.10	17467	61.10	16867	61.10	18833
100.00	27233	100.00	27733	100.00	26433	100.00	25467	100.00	28433
100.00	27133	100.00	27567	100.00	26267	100.00	25333	100.00	28300
69.50	19833	69.50	20167	69.50	19167	69.50	18567	69.50	20733
48.30	14700	48.30	14900	48.30	14167	48.30	13767	48.30	15300
33.60	10967	33.60	11100	33.60	10600	33.60	10333	33.60	11500
23.40	8363	23.40	8440	23.40	8093	23.40	7857	23.40	8740
16.20	6477	16.20	6527	16.20	6280	16.20	6090	16.20	6777
11.30	5120	11.30	5150	11.30	4980	11.30	4823	11.30	5363
7.85	4143	7.85	4167	7.85	4043	7.85	3907	7.85	4343
5.45	3437	5.46	3450	5.46	3360	5.46	3240	5.46	3603
3.79	2920	3.79	2930	3.79	2867	3.79	2757	3.79	3070
2.64	2540	2.64	2547	2.64	2503	2.64	2403	2.64	2673
1.83	2263	1.83	2270	1.83	2237	1.83	2137	1.83	2377
1.27	2053	1.27	2060	1.27	2030	1.27	1940	1.27	2160
0.89	1893	0.89	1900	0.89	1880	0.89	1790	0.89	1997
0.62	1773	0.62	1777	0.62	1767	0.62	1680	0.62	1863
0.43	1693	0.43	1690	0.43	1683	0.43	1593	0.43	1773
0.30	1613	0.30	1617	0.30	1613	0.30	1527	0.30	1703
0.21	1563	0.21	1560	0.21	1557	0.21	1470	0.21	1643
0.14	1520	0.14	1517	0.14	1517	0.14	1430	0.14	1597
0.10	1483	0.10	1480	0.10	1487	0.10	1400	0.10	1560

Table B - 3: Average data set for the combined measured values of SRM paste (0 % beads) using Double spiral spindle geometry.

Double Spiral			
0% Average Values			
N [1/min]	*SD*	**Γ** [μNm]	*SD*
0.10	*1.3E-03*	**1065**	*119*
0.16	*7.1E-04*	**1486**	*51*
0.27	*1.8E-04*	**1669**	*62*
0.44	*4.0E-04*	**1780**	*69*
0.72	*3.0E-04*	**1906**	*76*
1.18	*0.0E+00*	**2086**	*79*
1.93	*2.2E-16*	**2350**	*92*
3.16	*0.0E+00*	**2762**	*111*
5.18	*0.0E+00*	**3396**	*141*
8.48	*1.8E-15*	**4375**	*191*
13.90	*1.8E-15*	**5926**	*282*
22.80	*3.6E-15*	**8348**	*399*
37.30	*7.1E-15*	**12177**	*600*
61.09	*3.0E-02*	**18170**	*930*
100.00	*0.0E+00*	**27497**	*1408*
100.00	*0.0E+00*	**27343**	*1397*
69.50	*0.0E+00*	**19997**	*1024*
48.30	*7.1E-15*	**14793**	*745*
33.60	*7.1E-15*	**11073**	*555*
23.40	*3.6E-15*	**8422**	*414*
16.20	*3.6E-15*	**6523**	*313*
11.30	*1.8E-15*	**5158**	*241*
7.85	*0.0E+00*	**4175**	*188*
5.46	*3.0E-03*	**3461**	*151*
3.79	*4.4E-16*	**2943**	*124*
2.64	*0.0E+00*	**2562**	*105*
1.83	*4.4E-16*	**2280**	*90*
1.27	*2.2E-16*	**2070**	*81*
0.89	*5.0E-04*	**1912**	*75*
0.62	*2.6E-04*	**1790**	*66*
0.43	*4.5E-04*	**1703**	*61*
0.30	*6.7E-04*	**1631**	*60*
0.21	*3.6E-04*	**1575**	*58*
0.14	*5.8E-04*	**1532**	*58*
0.10	*2.1E-04*	**1497**	*56*

Table B - 4: Average values for 20 % mortar mixes (by volume) using a Double spiral spindle geometry. *[NIST Codes]*

Double Spiral [RHN-83A]													
20% Beads										**Double Spiral**			
Mix #7 [SMC-101]		**Mix #8** [SMC-103]		**Mix #9** [SMC-109]		**Mix #10** [SMC-111]		**Mix #11** [SMC-113]		**20% Average Values**			
N [1/min]	Γ [μNm]	N [1/min]	Γ [μNm]	N [1/min]	Γ [μNm]	N [1/min]	Γ [μNm]	N [1/min]	Γ [μNm]	**N** [1/min]	*SD*	**Γ** [μNm]	*SD*
0.09	1407	0.09	1360	0.09	1347	0.09	1403	0.09	1323	**0.09**	*7.6E-04*	**1368**	*32*
0.16	1850	0.16	1963	0.16	1913	0.16	2030	0.16	1883	**0.16**	*3.9E-04*	**1928**	*63*
0.27	2057	0.27	2233	0.27	2160	0.27	2300	0.27	2130	**0.27**	*3.9E-04*	**2176**	*84*
0.44	2220	0.44	2407	0.44	2340	0.44	2497	0.44	2303	**0.44**	*2.7E-04*	**2353**	*94*
0.72	2433	0.72	2650	0.72	2583	0.72	2763	0.72	2523	**0.72**	*1.6E-04*	**2591**	*112*
1.18	2757	1.18	2983	1.18	2927	1.18	3143	1.18	2840	**1.18**	*0.0E+00*	**2930**	*132*
1.93	3253	1.93	3517	1.93	3453	1.93	3703	1.93	3320	**1.93**	*1.3E-03*	**3449**	*158*
3.16	4010	3.16	4340	3.16	4260	3.16	4580	3.16	4067	**3.16**	*1.3E-03*	**4251**	*204*
5.18	5167	5.18	5643	5.18	5500	5.18	5967	5.18	5247	**5.18**	*1.3E-03*	**5505**	*288*
8.48	6923	8.48	7683	8.49	7390	8.48	8107	8.49	7090	**8.49**	*2.7E-03*	**7439**	*423*
13.90	9493	13.90	10733	13.90	10267	13.90	11333	13.90	9907	**13.90**	*0.0E+00*	**10347**	*640*
22.77	13533	22.77	15200	22.77	14533	22.80	16133	22.80	14067	**22.78**	*1.6E-02*	**14693**	*905*
37.30	20033	37.30	22700	37.30	21633	37.30	24100	37.30	20933	**37.30**	*0.0E+00*	**21880**	*1412*
61.03	30333	61.07	34367	61.07	32700	61.07	36467	61.03	31633	**61.05**	*1.6E-02*	**33100**	*2140*
100.00	46133	100.00	52200	100.00	49667	100.00	55400	100.00	48000	**100.00**	*0.0E+00*	**50280**	*3246*
100.00	45733	100.00	51733	100.00	49233	100.00	54867	100.00	47633	**100.00**	*0.0E+00*	**49840**	*3192*
69.50	33200	69.50	37500	69.50	35700	69.50	39700	69.50	34600	**69.50**	*0.0E+00*	**36140**	*2269*
48.30	24333	48.30	27467	48.30	26167	48.30	29067	48.30	25367	**48.30**	*0.0E+00*	**26480**	*1650*
33.60	18033	33.60	20367	33.60	19400	33.60	21467	33.60	18833	**33.60**	*0.0E+00*	**19620**	*1196*
23.37	13567	23.37	15267	23.40	14567	23.40	16100	23.40	14100	**23.39**	*1.6E-02*	**14720**	*888*
16.20	10333	16.20	11600	16.20	11067	16.20	12200	16.20	10767	**16.20**	*0.0E+00*	**11193**	*651*
11.30	8017	11.30	8937	11.30	8583	11.30	9450	11.30	8327	**11.30**	*0.0E+00*	**8663**	*496*
7.85	6363	7.85	7057	7.85	6783	7.85	7423	7.85	6577	**7.85**	*1.6E-03*	**6841**	*371*
5.46	5150	5.46	5690	5.46	5490	5.45	5977	5.46	5333	**5.46**	*2.1E-03*	**5528**	*286*
3.79	4277	3.79	4697	3.79	4547	3.79	4923	3.79	4410	**3.79**	*1.6E-03*	**4571**	*225*
2.64	3627	2.64	3953	2.63	3857	2.64	4153	2.64	3740	**2.64**	*3.3E-03*	**3866**	*181*
1.83	3153	1.83	3417	1.83	3347	1.83	3590	1.83	3250	**1.83**	*0.0E+00*	**3351**	*149*
1.27	2793	1.28	3023	1.27	2967	1.27	3167	1.27	2873	**1.27**	*2.5E-03*	**2965**	*128*
0.89	2523	0.89	2720	0.88	2683	0.89	2853	0.89	2593	**0.89**	*6.5E-04*	**2675**	*113*
0.62	2323	0.62	2493	0.62	2470	0.62	2610	0.62	2383	**0.62**	*3.3E-04*	**2456**	*98*
0.43	2173	0.43	2313	0.43	2300	0.43	2423	0.43	2220	**0.43**	*9.4E-04*	**2286**	*86*
0.30	2060	0.30	2183	0.30	2180	0.30	2290	0.30	2093	**0.30**	*5.0E-04*	**2161**	*80*
0.21	1970	0.21	2080	0.21	2083	0.21	2187	0.21	2003	**0.21**	*4.0E-04*	**2065**	*75*
0.14	1893	0.14	2010	0.14	2000	0.14	2103	0.14	1930	**0.14**	*6.0E-04*	**1987**	*72*
0.10	1823	0.10	1963	0.10	1950	0.10	2040	0.10	1880	**0.10**	*8.3E-04*	**1931**	*74*

Table B - 5: Average values for 40 % mortar mixes (by volume) using a Double spiral spindle geometry. *[NIST Codes]*

Double Spiral [RHN-83A]													
40% Beads										**Double Spiral**			
Mix #2 [SMC-79]		**Mix #3** [SMC-81]		**Mix #4** [SMC-85]		**Mix #5** [SMC-95]		**Mix #6** [SMC-97]		**40% Average Values**			
N [1/min]	Γ [μNm]	N [1/min]	Γ [μNm]	N [1/min]	Γ [μNm]	N [1/min]	Γ [μNm]	N [1/min]	Γ [μNm]	**N** [1/min]	*SD*	**Γ** [μNm]	*SD*
0.09	2203	0.09	2693	0.21	3193	0.09	2243	0.08	2793	**0.11**	*0.047*	**2625**	*369*
0.16	3113	0.16	3557	0.25	3850	0.16	3177	0.16	4070	**0.18**	*0.037*	**3553**	*372*
0.27	3630	0.27	4140	0.32	4197	0.27	3660	0.26	4857	**0.28**	*0.023*	**4097**	*447*
0.44	4127	0.44	4683	0.44	4567	0.44	4233	0.44	5597	**0.44**	*0.003*	**4641**	*520*
0.72	4763	0.72	5437	0.72	5177	0.72	4883	0.73	6427	**0.72**	*0.003*	**5337**	*593*
1.18	5613	1.18	6450	1.18	6113	1.18	5743	1.17	7557	**1.18**	*0.005*	**6295**	*695*
1.93	6873	1.93	8030	1.93	7430	1.93	7063	1.94	9333	**1.93**	*0.003*	**7746**	*886*
3.16	8910	3.15	10533	3.16	9490	3.17	9140	3.17	12167	**3.16**	*0.006*	**10048**	*1196*
5.18	12000	5.17	14333	5.18	12800	5.18	12433	5.19	16500	**5.18**	*0.005*	**13613**	*1644*
8.48	17067	8.48	19900	8.48	18067	8.50	17300	8.48	23267	**8.48**	*0.008*	**19120**	*2300*
13.90	24200	13.90	27867	13.90	25467	13.90	24433	13.90	32867	**13.90**	*0.000*	**26967**	*3223*
22.77	34400	22.77	39333	22.80	35967	22.80	35067	22.80	46400	**22.79**	*0.016*	**38233**	*4422*
37.30	50667	37.30	58067	37.30	52633	37.27	51567	37.30	67433	**37.29**	*0.013*	**56073**	*6235*
61.03	74900	61.10	84000	61.07	77000	61.07	76100	61.10	95833	**61.07**	*0.025*	**81567**	*7806*
100.00	105000	100.00	116333	100.00	91733	100.00	111667	100.00	134333	**100.00**	*0.000*	**111813**	*13980*
100.00	100267	100.00	111333	100.00	86000	100.00	109000	99.97	127333	**99.99**	*0.013*	**106787**	*13582*
69.57	71700	69.57	79133	69.53	61600	69.53	78367	69.57	90100	**69.55**	*0.016*	**76180**	*9380*
48.30	52400	48.33	57400	48.37	45100	48.37	56967	48.37	65500	**48.35**	*0.027*	**55473**	*6686*
33.60	38900	33.60	42233	33.60	34167	33.60	42167	33.60	48100	**33.60**	*0.000*	**41113**	*4568*
23.37	29733	23.40	31633	23.37	27267	23.40	31733	23.40	35900	**23.39**	*0.016*	**31253**	*2834*
16.20	23533	16.23	25200	16.20	22700	16.23	23967	16.20	27633	**16.21**	*0.016*	**24607**	*1715*
11.30	18100	11.30	19867	11.30	18500	11.30	18300	11.30	22367	**11.30**	*0.000*	**19427**	*1595*
7.85	14033	7.86	15600	7.85	14333	7.85	14167	7.84	17667	**7.85**	*0.007*	**15160**	*1372*
5.45	11100	5.46	12267	5.45	11267	5.46	11200	5.46	14033	**5.46**	*0.005*	**11973**	*1113*
3.78	8987	3.79	9903	3.80	9077	3.79	8947	3.80	11200	**3.79**	*0.006*	**9623**	*863*
2.64	7377	2.64	8103	2.63	7470	2.64	7410	2.64	9210	**2.64**	*0.003*	**7914**	*701*
1.82	6183	1.83	6750	1.83	6287	1.83	6217	1.84	7730	**1.83**	*0.004*	**6633**	*585*
1.27	5297	1.28	5757	1.27	5410	1.27	5320	1.28	6560	**1.27**	*0.002*	**5669**	*475*
0.88	4613	0.89	5020	0.88	4777	0.89	4663	0.89	5700	**0.89**	*0.002*	**4955**	*398*
0.61	4120	0.62	4510	0.62	4253	0.62	4137	0.61	5067	**0.62**	*0.002*	**4417**	*353*
0.43	3733	0.42	4063	0.43	3863	0.43	3770	0.43	4560	**0.43**	*0.002*	**3998**	*303*
0.30	3433	0.30	3770	0.30	3583	0.30	3487	0.30	4200	**0.30**	*0.001*	**3695**	*277*
0.21	3220	0.21	3477	0.21	3370	0.21	3253	0.21	3920	**0.21**	*0.001*	**3448**	*253*
0.15	3047	0.14	3277	0.14	3187	0.14	3093	0.14	3717	**0.14**	*0.001*	**3264**	*240*
0.10	2933	0.10	3157	0.10	3067	0.10	2983	0.10	3570	**0.10**	*0.000*	**3142**	*227*

Table B - 6: Average values for SRM paste with 0 % beads (by volume) performed prior to the 20 % mortar tests using six-blade vane geometry. *[NIST Codes]*

6 Blade Vane [RHN-83C]									
0 % Beads *(Pre-20 %)*									
Mix #7 [SMC-101]		**Mix #8** [SMC-103]		**Mix #9** [SMC-109]		**Mix #10** [SMC-111]		**Mix #11** [SMC-113]	
N [1/min]	M [μNm]	N [1/min]	M [μNm]	N [1/min]	M [μNm]	N [1/min]	M [μNm]	N [1/min]	M [μNm]
0.10	399	0.10	416	0.10	423	0.10	445	0.10	423
0.16	527	0.16	555	0.16	574	0.16	598	0.16	545
0.27	568	0.27	595	0.27	619	0.27	640	0.27	583
0.44	603	0.44	629	0.44	654	0.44	676	0.44	617
0.72	651	0.72	679	0.72	706	0.72	729	0.72	672
1.18	717	1.18	750	1.18	780	1.18	803	1.18	739
1.93	811	1.93	850	1.93	882	1.93	906	1.93	834
3.16	946	3.16	990	3.16	1027	3.16	1053	3.16	968
5.18	1133	5.18	1190	5.18	1233	5.18	1263	5.18	1160
8.48	1410	8.48	1483	8.48	1530	8.48	1567	8.48	1440
13.90	1807	13.90	1910	13.90	1970	13.90	2010	13.90	1850
22.80	2380	22.80	2533	22.80	2603	22.80	2657	22.80	2453
37.30	3270	37.30	3493	37.30	3583	37.30	3653	37.30	3380
61.00	4637	61.00	4960	61.00	5090	61.00	5173	61.00	4797
100.00	6767	100.00	7263	100.00	7433	100.00	7543	100.00	7020
100.00	6750	100.00	7237	100.00	7407	100.00	7517	100.00	7020
69.50	5067	69.50	5417	69.50	5550	69.50	5640	69.50	5263
48.30	3867	48.30	4113	48.30	4223	48.30	4293	48.30	4010
33.60	3003	33.60	3183	33.60	3267	33.60	3323	33.60	3107
23.40	2377	23.40	2510	23.40	2577	23.40	2623	23.40	2450
16.20	1917	16.20	2017	16.20	2073	16.20	2117	16.20	1980
11.30	1583	11.30	1657	11.30	1700	11.30	1733	11.30	1627
7.85	1323	7.85	1383	7.85	1423	7.85	1460	7.85	1360
5.45	1133	5.45	1173	5.45	1210	5.46	1240	5.46	1157
3.79	983	3.79	1020	3.79	1050	3.79	1077	3.79	1006
2.64	871	2.64	897	2.64	925	2.64	949	2.64	884
1.83	778	1.83	806	1.83	830	1.83	847	1.83	797
1.27	711	1.27	732	1.27	760	1.27	783	1.27	727
0.89	658	0.89	675	0.89	705	0.89	717	0.89	673
0.62	616	0.62	637	0.62	654	0.62	665	0.62	626
0.43	581	0.43	599	0.43	619	0.43	636	0.43	592
0.30	570	0.30	573	0.30	590	0.30	610	0.30	572
0.21	534	0.21	560	0.21	577	0.21	579	0.21	544
0.14	527	0.14	534	0.14	549	0.14	561	0.14	542
0.10	518	0.10	526	0.10	549	0.10	550	0.10	510

Table B - 7: Average values for SRM paste with 0 % beads (by volume) performed prior to the 40 % mortar tests using six-blade vane geometry. *[NIST Codes]*

6 Blade Vane [RHN-83C]									
0 % Beads *(Pre-40 %)*									
Mix #2 [SMC-79]		**Mix #3** [SMC-81]		**Mix #4** [SMC-85]		**Mix #5** [SMC-95]		**Mix #6** [SMC-97]	
N [1/min]	M [μNm]	N [1/min]	M [μNm]	N [1/min]	M [μNm]	N [1/min]	M [μNm]	N [1/min]	M [μNm]
0.10	451	0.10	463	0.10	486	0.10	433	0.10	429
0.16	550	0.16	562	0.16	549	0.16	526	0.16	566
0.27	589	0.27	600	0.27	584	0.27	566	0.27	606
0.44	627	0.44	638	0.44	624	0.44	600	0.44	641
0.72	680	0.72	689	0.72	677	0.72	654	0.72	693
1.18	755	1.18	762	1.18	751	1.18	721	1.18	766
1.93	858	1.93	864	1.93	855	1.93	823	1.93	866
3.16	1008	3.16	1008	3.16	1001	3.16	956	3.16	1006
5.18	1217	5.18	1217	5.18	1203	5.18	1150	5.18	1210
8.48	1517	8.48	1507	8.48	1503	8.48	1427	8.48	1503
13.90	1960	13.90	1943	13.90	1943	13.90	1833	13.90	1933
22.80	2607	22.80	2577	22.80	2583	22.80	2427	22.80	2557
37.30	3610	37.30	3557	37.30	3580	37.30	3337	37.30	3510
61.00	5153	61.00	5053	61.00	5117	61.00	4727	61.00	4953
100.00	7567	100.00	7407	100.00	7533	100.00	6890	100.00	7213
100.00	7550	100.00	7390	100.00	7547	100.00	6867	100.00	7193
69.50	5650	69.50	5550	69.50	5657	69.50	5157	69.50	5403
48.30	4293	48.30	4223	48.30	4297	48.30	3933	48.30	4127
33.60	3317	33.60	3263	33.60	3320	33.60	3047	33.60	3203
23.40	2610	23.40	2570	23.40	2617	23.40	2410	23.40	2537
16.20	2093	16.20	2067	16.20	2100	16.20	1940	16.20	2047
11.30	1713	11.30	1697	11.30	1720	11.30	1600	11.30	1690
7.85	1437	7.85	1417	7.85	1437	7.85	1340	7.85	1417
5.45	1217	5.45	1203	5.45	1220	5.45	1140	5.45	1207
3.79	1050	3.79	1037	3.79	1050	3.79	987	3.79	1050
2.64	922	2.64	913	2.64	924	2.64	870	2.64	924
1.83	824	1.83	816	1.83	825	1.83	778	1.83	828
1.27	746	1.27	740	1.27	748	1.27	707	1.27	755
0.89	687	0.89	680	0.89	688	0.89	653	0.89	698
0.62	642	0.62	633	0.62	639	0.62	607	0.62	648
0.43	603	0.43	597	0.43	600	0.43	571	0.43	617
0.30	570	0.30	565	0.30	569	0.30	543	0.30	585
0.21	545	0.21	541	0.21	545	0.21	520	0.21	567
0.14	523	0.14	521	0.14	525	0.14	501	0.14	554
0.10	509	0.10	506	0.10	511	0.10	487	0.10	530

Table B - 8: Average data set for the combined measured values of SRM paste (0 % beads) using six blade vane geometry.

6 Blade Vane			
0% Average Values			
N [1/min]	*SD*	**M** [µNm]	*SD*
0.10	*4.8E-04*	**437**	*24*
0.16	*2.1E-04*	**555**	*20*
0.27	*1.0E-04*	**595**	*21*
0.44	*4.3E-04*	**631**	*22*
0.72	*4.0E-04*	**683**	*22*
1.18	*0.0E+00*	**754**	*25*
1.93	*2.2E-16*	**855**	*26*
3.16	*0.0E+00*	**996**	*31*
5.18	*0.0E+00*	**1198**	*38*
8.48	*1.8E-15*	**1489**	*47*
13.90	*1.8E-15*	**1916**	*62*
22.80	*3.6E-15*	**2538**	*85*
37.30	*7.1E-15*	**3497**	*121*
61.00	*0.0E+00*	**4966**	*178*
100.00	*0.0E+00*	**7264**	*272*
100.00	*0.0E+00*	**7248**	*273*
69.50	*0.0E+00*	**5435**	*202*
48.30	*7.1E-15*	**4138**	*149*
33.60	*7.1E-15*	**3203**	*111*
23.40	*3.6E-15*	**2528**	*84*
16.20	*3.6E-15*	**2035**	*66*
11.30	*1.8E-15*	**1672**	*50*
7.85	*0.0E+00*	**1400**	*43*
5.45	*2.7E-03*	**1190**	*35*
3.79	*4.4E-16*	**1031**	*29*
2.64	*1.3E-03*	**908**	*25*
1.83	*4.4E-16*	**813**	*22*
1.27	*1.5E-03*	**741**	*22*
0.89	*6.4E-04*	**684**	*19*
0.62	*7.0E-04*	**637**	*17*
0.43	*7.8E-04*	**602**	*18*
0.30	*6.5E-04*	**575**	*17*
0.21	*7.0E-04*	**551**	*18*
0.14	*1.2E-03*	**534**	*17*
0.10	*4.5E-04*	**520**	*19*

Table B - 9: Average values for 20 % mortar mixes (by volume) using six-blade vane geometry. *[NIST Codes]*

6 Blade Vane [RHN-83C]													
20 % Beads										**6 Blade Vane [RHN-83C]**			
Mix #7 [SMC-101]		**Mix #8** [SMC-103]		**Mix #9** [SMC-109]		**Mix #10** [SMC-111]		**Mix #11** [SMC-113]		**20% Average Values**			
N [1/min]	M [μNm]	N [1/min]	M [μNm]	N [1/min]	M [μNm]	N [1/min]	M [μNm]	N [1/min]	M [μNm]	**N [1/min]**	*SD*	**M [μNm]**	*SD*
0.10	569	0.10	589	0.10	608	0.10	606	0.10	582	**0.10**	*0.000*	**591**	*591*
0.16	721	0.16	756	0.16	776	0.16	770	0.16	734	**0.16**	*0.000*	**751**	*751*
0.27	785	0.27	822	0.27	828	0.27	837	0.27	791	**0.27**	*0.000*	**813**	*813*
0.44	842	0.44	891	0.44	899	0.44	897	0.44	850	**0.44**	*0.000*	**876**	*876*
0.72	916	0.72	968	0.72	974	0.72	973	0.72	934	**0.72**	*0.001*	**953**	*953*
1.18	1027	1.18	1097	1.18	1093	1.18	1090	1.18	1050	**1.18**	*0.000*	**1071**	*1071*
1.93	1190	1.93	1273	1.93	1260	1.93	1263	1.93	1217	**1.93**	*0.000*	**1241**	*1241*
3.16	1420	3.16	1533	3.16	1513	3.16	1513	3.16	1443	**3.16**	*0.000*	**1485**	*1485*
5.18	1763	5.18	1913	5.18	1873	5.18	1873	5.18	1793	**5.18**	*0.000*	**1843**	*1843*
8.48	2257	8.48	2460	8.48	2390	8.48	2390	8.48	2290	**8.48**	*0.001*	**2357**	*2357*
13.90	3007	13.90	3290	13.90	3187	13.90	3187	13.90	3050	**13.90**	*0.000*	**3144**	*3144*
22.77	4143	22.80	4540	22.80	4383	22.80	4387	22.80	4193	**22.79**	*0.013*	**4329**	*4329*
37.30	5833	37.30	6407	37.30	6157	37.30	6163	37.30	5880	**37.30**	*0.000*	**6088**	*6088*
61.03	8383	61.07	9197	61.03	8820	61.07	8843	61.03	8420	**61.05**	*0.016*	**8733**	*8733*
100.00	12233	100.00	13533	100.00	12767	100.00	12867	100.00	12233	**100.00**	*0.000*	**12727**	*12727*
100.00	12167	100.00	13400	100.00	12600	100.00	12733	100.00	12133	**100.00**	*0.000*	**12607**	*12607*
69.50	9060	69.50	9927	69.50	9360	69.50	9477	69.50	9047	**69.50**	*0.000*	**9374**	*9374*
48.30	6813	48.30	7450	48.30	7043	48.30	7130	48.30	6797	**48.30**	*0.000*	**7047**	*7047*
33.60	5190	33.60	5673	33.60	5393	33.60	5433	33.60	5183	**33.60**	*0.000*	**5375**	*5375*
23.37	4030	23.33	4357	23.40	4200	23.37	4223	23.37	4023	**23.37**	*0.021*	**4167**	*4167*
16.20	3183	16.20	3417	16.20	3320	16.20	3333	16.20	3177	**16.20**	*0.000*	**3286**	*3286*
11.30	2550	11.30	2723	11.30	2650	11.30	2673	11.30	2553	**11.30**	*0.000*	**2630**	*2630*
7.85	2073	7.85	2217	7.85	2163	7.84	2180	7.85	2073	**7.85**	*0.002*	**2141**	*2141*
5.45	1727	5.45	1830	5.46	1797	5.45	1807	5.46	1727	**5.45**	*0.002*	**1777**	*1777*
3.79	1463	3.79	1550	3.79	1527	3.79	1533	3.79	1460	**3.79**	*0.001*	**1507**	*1507*
2.64	1260	2.64	1330	2.64	1320	2.64	1327	2.64	1257	**2.64**	*0.001*	**1299**	*1299*
1.83	1107	1.83	1170	1.83	1157	1.83	1163	1.83	1113	**1.83**	*0.001*	**1142**	*1142*
1.28	986	1.27	1043	1.27	1040	1.27	1043	1.27	997	**1.27**	*0.002*	**1022**	*1022*
0.89	898	0.89	939	0.89	938	0.89	959	0.89	898	**0.89**	*0.001*	**926**	*926*
0.62	831	0.62	864	0.61	879	0.61	884	0.61	841	**0.61**	*0.001*	**860**	*860*
0.43	775	0.43	814	0.43	813	0.43	820	0.43	782	**0.43**	*0.001*	**801**	*801*
0.30	741	0.30	768	0.30	776	0.30	779	0.30	745	**0.30**	*0.001*	**762**	*762*
0.21	697	0.21	721	0.21	740	0.21	732	0.21	713	**0.21**	*0.000*	**721**	*721*
0.14	680	0.14	700	0.14	707	0.14	709	0.14	686	**0.14**	*0.000*	**696**	*696*
0.10	668	0.10	684	0.10	693	0.10	692	0.10	654	**0.10**	*0.001*	**678**	*678*

Table B - 10: Average values for 40 % mortar mixes (by volume) using six-blade vane geometry. *[NIST Codes]*

6 Blade Vane [RHN-83C]													
40 % Beads										**6 Blade Vane [RHN-83C]**			
Mix #2 [SMC-79]		**Mix #3** [SMC-81]		**Mix #4** [SMC-85]		**Mix #5** [SMC-95]		**Mix #6** [SMC-97]		**40% Average Values**			
N [1/min]	M [μNm]	N [1/min]	M [μNm]	N [1/min]	M [μNm]	N [1/min]	M [μNm]	N [1/min]	M [μNm]	**N [1/min]**	*SD*	**M [μNm]**	*SD*
0.10	1077	0.10	1067	0.09	1423	0.10	1009	0.10	1223	**0.10**	*0.001*	**1160**	*150*
0.16	1347	0.16	1340	0.16	1813	0.16	1273	0.16	1503	**0.16**	*0.000*	**1455**	*194*
0.27	1470	0.27	1457	0.27	1960	0.27	1377	0.27	1640	**0.27**	*0.002*	**1581**	*208*
0.44	1567	0.44	1610	0.44	2120	0.44	1493	0.44	1770	**0.44**	*0.001*	**1712**	*223*
0.72	1747	0.72	1767	0.72	2347	0.72	1657	0.73	1950	**0.72**	*0.003*	**1893**	*246*
1.18	2030	1.18	2043	1.18	2680	1.18	1903	1.18	2193	**1.18**	*0.002*	**2170**	*271*
1.93	2403	1.94	2420	1.93	3170	1.93	2223	1.94	2587	**1.93**	*0.004*	**2561**	*326*
3.17	2957	3.17	2977	3.16	3923	3.17	2713	3.16	3143	**3.16**	*0.004*	**3143**	*414*
5.18	3770	5.18	3773	5.17	4933	5.18	3477	5.19	3937	**5.18**	*0.005*	**3978**	*500*
8.48	4897	8.48	4943	8.48	6410	8.48	4510	8.48	5090	**8.48**	*0.001*	**5170**	*649*
13.90	6573	13.90	6543	13.90	8410	13.90	6033	13.90	6747	**13.90**	*0.000*	**6861**	*810*
22.77	8957	22.80	8903	22.77	11267	22.77	8307	22.77	9143	**22.77**	*0.013*	**9315**	*1015*
37.30	12600	37.30	12300	37.30	15367	37.30	11600	37.30	12700	**37.30**	*0.000*	**12913**	*1286*
61.03	17500	61.10	17100	61.07	21367	61.07	16400	61.07	17700	**61.07**	*0.021*	**18013**	*1735*
100.00	25300	100.00	24700	100.00	29667	100.00	23267	100.00	25033	**100.00**	*0.000*	**25593**	*2154*
100.00	24433	99.93	23867	100.00	28033	100.00	22500	100.00	23733	**99.99**	*0.027*	**24513**	*1870*
69.50	18367	69.50	17500	69.50	21567	69.50	16500	69.50	17400	**69.50**	*0.000*	**18267**	*1753*
48.30	13900	48.30	13033	48.30	16000	48.30	12333	48.30	13033	**48.30**	*0.000*	**13660**	*1271*
33.60	10667	33.60	9997	33.60	12233	33.60	9317	33.60	10000	**33.60**	*0.000*	**10443**	*992*
23.37	8227	23.40	7673	23.40	9427	23.33	7123	23.37	7620	**23.37**	*0.025*	**8014**	*788*
16.20	6380	16.20	6000	16.20	7373	16.20	5537	16.20	5970	**16.20**	*0.000*	**6252**	*621*
11.30	5057	11.30	4743	11.30	5840	11.30	4347	11.30	4713	**11.30**	*0.000*	**4940**	*503*
7.85	4043	7.85	3807	7.84	4617	7.85	3497	7.85	3790	**7.85**	*0.005*	**3951**	*375*
5.45	3270	5.46	3080	5.45	3760	5.46	2837	5.46	3073	**5.46**	*0.002*	**3204**	*310*
3.80	2703	3.79	2547	3.79	3093	3.79	2353	3.79	2553	**3.79**	*0.002*	**2650**	*248*
2.64	2260	2.64	2127	2.63	2617	2.64	1973	2.63	2133	**2.64**	*0.003*	**2222**	*217*
1.83	1930	1.83	1823	1.84	2207	1.83	1710	1.83	1853	**1.83**	*0.003*	**1905**	*167*
1.27	1690	1.27	1593	1.28	1927	1.27	1493	1.27	1617	**1.27**	*0.002*	**1664**	*146*
0.89	1497	0.89	1413	0.88	1703	0.89	1333	0.89	1433	**0.89**	*0.001*	**1476**	*125*
0.62	1347	0.61	1277	0.62	1537	0.62	1213	0.62	1297	**0.62**	*0.001*	**1334**	*110*
0.43	1233	0.43	1170	0.43	1410	0.43	1107	0.43	1210	**0.43**	*0.001*	**1226**	*102*
0.30	1147	0.30	1097	0.30	1300	0.30	1033	0.30	1120	**0.30**	*0.002*	**1139**	*89*
0.21	1083	0.21	1037	0.21	1207	0.21	974	0.21	1040	**0.21**	*0.001*	**1068**	*77*
0.14	1013	0.14	980	0.14	1167	0.14	934	0.14	1015	**0.14**	*0.000*	**1022**	*78*
0.10	974	0.10	944	0.10	1103	0.10	896	0.10	982	**0.10**	*0.000*	**980**	*69*

Table B - 11: Average values for SRM paste with 0 % beads (by volume) performed prior to the 20 % mortar tests using serrated coaxial cylinder geometry. *[NIST Codes]*

Serrated Coaxial Cylinder [SS18]									
0 % Beads *(Pre-20 %)*									
Mix #7 [SMC-101]		**Mix #8** [SMC-103]		**Mix #9** [SMC-109]		**Mix #10** [SMC-111]		**Mix #11** [SMC-113]	
N [1/min]	M [µNm]	N [1/min]	M [µNm]	N [1/min]	M [µNm]	N [1/min]	M [µNm]	N [1/min]	M [µNm]
0.10	385	0.10	428	0.10	459	0.10	442	0.10	435
0.16	478	0.16	545	0.16	611	0.16	569	0.16	569
0.27	511	0.27	583	0.27	654	0.27	617	0.27	624
0.44	578	0.44	625	0.44	707	0.44	674	0.44	676
0.72	625	0.72	687	0.72	780	0.72	748	0.72	747
1.18	708	1.18	767	1.18	889	1.18	858	1.18	850
1.93	805	1.93	879	1.93	1027	1.93	977	1.93	976
3.16	955	3.16	1037	3.16	1190	3.16	1167	3.16	1157
5.18	1170	5.18	1250	5.18	1440	5.18	1413	5.18	1407
8.48	1477	8.48	1560	8.48	1810	8.48	1767	8.48	1760
13.90	1913	13.90	2010	13.90	2330	13.90	2273	13.90	2263
22.80	2547	22.80	2650	22.80	3107	22.80	3030	22.80	3010
37.30	3513	37.30	3637	37.30	4290	37.30	4177	37.30	4153
61.00	5000	61.00	5167	61.00	6093	61.00	5923	61.00	5900
100.00	7317	100.00	7547	100.00	8860	100.00	8597	100.00	8537
100.00	7277	100.00	7440	100.00	8730	100.00	8497	100.00	8420
69.50	5440	69.50	5560	69.50	6537	69.50	6363	69.50	6307
48.30	4117	48.30	4203	48.30	4923	48.30	4800	48.30	4750
33.60	3157	33.60	3220	33.60	3760	33.60	3673	33.60	3627
23.40	2467	23.40	2520	23.40	2923	23.40	2860	23.40	2820
16.20	1970	16.20	2010	16.20	2320	16.20	2273	16.20	2237
11.30	1600	11.30	1640	11.30	1877	11.30	1837	11.30	1807
7.85	1313	7.85	1350	7.85	1543	7.85	1517	7.85	1493
5.45	1100	5.45	1133	5.45	1293	5.45	1267	5.45	1250
3.79	931	3.79	966	3.79	1103	3.79	1073	3.79	1070
2.64	800	2.64	834	2.64	956	2.64	922	2.64	918
1.83	710	1.83	733	1.83	850	1.83	809	1.83	811
1.27	620	1.27	653	1.27	741	1.27	720	1.27	728
0.89	569	0.89	597	0.89	661	0.88	654	0.89	647
0.62	529	0.62	555	0.62	614	0.62	630	0.62	597
0.43	482	0.43	567	0.42	586	0.43	582	0.43	568
0.29	448	0.30	481	0.30	538	0.30	504	0.30	541
0.21	424	0.21	516	0.21	566	0.20	529	0.21	574
0.14	441	0.15	477	0.14	567	0.14	538	0.13	556
0.09	397	0.10	494	0.10	561	0.10	486	0.09	497

Table B - 12: Average values for SRM paste with 0 % beads (by volume) performed prior to the 40 % mortar tests using serrated coaxial cylinder geometry. *[NIST Codes]*

Serrated Coaxial Cylinder [SS18]									
0 % Beads *(Pre-40 %)*									
Mix #2 [SMC-79]		**Mix #3** [SMC-81]		**Mix #4** [SMC-85]		**Mix #5** [SMC-95]		**Mix #6** [SMC-97]	
N [1/min]	M [μNm]	N [1/min]	M [μNm]	N [1/min]	M [μNm]	N [1/min]	M [μNm]	N [1/min]	M [μNm]
0.10	395	0.10	372	0.10	379	0.10	387	0.10	454
0.16	478	0.16	454	0.16	450	0.16	465	0.16	577
0.27	518	0.27	494	0.27	487	0.27	499	0.27	615
0.44	570	0.44	545	0.44	533	0.44	541	0.44	662
0.72	641	0.72	616	0.72	595	0.72	600	0.72	727
1.18	733	1.18	708	1.18	680	1.18	681	1.18	816
1.93	860	1.93	824	1.93	794	1.93	792	1.93	936
3.16	1034	3.16	986	3.16	951	3.16	946	3.16	1103
5.18	1280	5.18	1213	5.18	1170	5.18	1160	5.18	1337
8.48	1630	8.48	1533	8.48	1480	8.48	1467	8.48	1667
13.90	2130	13.90	1993	13.90	1923	13.90	1910	13.90	2143
22.80	2857	22.80	2667	22.80	2567	22.80	2540	22.80	2833
37.30	3973	37.30	3707	37.30	3553	37.30	3510	37.30	3897
61.10	5680	61.00	5317	61.00	5073	61.00	4997	61.00	5517
100.00	8273	100.00	7753	100.00	7457	100.00	7330	100.00	7990
100.00	8207	100.00	7670	100.00	7393	100.00	7250	100.00	7913
69.50	6167	69.50	5743	69.50	5543	69.50	5433	69.50	5940
48.30	4650	48.30	4337	48.30	4190	48.30	4107	48.30	4487
33.60	3553	33.60	3320	33.60	3217	33.60	3150	33.60	3443
23.40	2760	23.40	2587	23.40	2517	23.40	2463	23.40	2693
16.20	2190	16.20	2053	16.20	1997	16.20	1957	16.20	2147
11.30	1763	11.30	1663	11.30	1623	11.30	1590	11.30	1743
7.85	1443	7.85	1363	7.85	1337	7.85	1307	7.85	1443
5.46	1200	5.45	1130	5.45	1113	5.45	1090	5.45	1207
3.79	1011	3.79	957	3.79	943	3.79	923	3.79	1027
2.64	864	2.64	820	2.64	809	2.64	792	2.64	888
1.83	748	1.83	711	1.83	703	1.83	689	1.83	775
1.27	656	1.27	625	1.27	618	1.27	607	1.27	687
0.89	582	0.89	555	0.89	551	0.89	541	0.89	643
0.62	523	0.62	498	0.62	497	0.62	487	0.62	573
0.43	475	0.43	452	0.43	454	0.43	446	0.43	522
0.30	436	0.30	416	0.30	418	0.30	410	0.30	486
0.21	405	0.21	385	0.21	389	0.21	383	0.20	478
0.14	380	0.14	362	0.14	366	0.14	360	0.14	437
0.10	360	0.10	342	0.10	348	0.10	341	0.10	434

Table B - 13: Average data set for the combined measured values of SRM paste (0 % beads) using serrated coaxial cylinder geometry.

Coaxial Cylinder			
0% Average Values			
N [1/min]	*SD*	**M** [μNm]	*SD*
0.10	*4.2E-04*	**414**	*32*
0.16	*2.0E-04*	**520**	*57*
0.27	*1.3E-04*	**560**	*61*
0.44	*4.0E-04*	**611**	*62*
0.72	*2.1E-04*	**677**	*66*
1.18	*1.0E-03*	**769**	*74*
1.93	*2.2E-16*	**887**	*82*
3.16	*0.0E+00*	**1053**	*90*
5.18	*0.0E+00*	**1284**	*103*
8.48	*1.8E-15*	**1615**	*124*
13.90	*1.8E-15*	**2089**	*153*
22.80	*3.6E-15*	**2781**	*204*
37.30	*7.1E-15*	**3841**	*281*
61.01	*3.0E-02*	**5467**	*393*
100.00	*0.0E+00*	**7966**	*541*
100.00	*0.0E+00*	**7880**	*523*
69.50	*0.0E+00*	**5903**	*394*
48.30	*7.1E-15*	**4456**	*291*
33.60	*7.1E-15*	**3412**	*218*
23.40	*3.6E-15*	**2661**	*164*
16.20	*3.6E-15*	**2115**	*128*
11.30	*1.8E-15*	**1714**	*99*
7.85	*0.0E+00*	**1411**	*83*
5.45	*3.0E-03*	**1178**	*71*
3.79	*4.4E-16*	**1000**	*62*
2.64	*1.3E-03*	**860**	*55*
1.83	*1.0E-03*	**754**	*52*
1.27	*1.5E-03*	**666**	*48*
0.89	*7.9E-04*	**600**	*45*
0.62	*8.4E-04*	**550**	*49*
0.43	*2.1E-03*	**513**	*55*
0.30	*1.9E-03*	**468**	*47*
0.21	*2.5E-03*	**465**	*73*
0.14	*4.3E-03*	**448**	*78*
0.10	*2.7E-03*	**426**	*76*

Table B - 14: Average values for 20 % mortar mixes (by volume) using serrated coaxial cylinder geometry. *[NIST Codes]*

Serrated Coaxial Cylinder [SS18]													
20 % Beads										Serrated Coaxial Cylinder [SS18]			
Mix #7 [SMC-101]		Mix #8 [SMC-103]		Mix #9 [SMC-109]		Mix #10 [SMC-111]		Mix #11 [SMC-113]		20 % Average Values			
N [1/min]	M [µNm]	N [1/min]	M [µNm]	N [1/min]	M [µNm]	N [1/min]	M [µNm]	N [1/min]	M [µNm]	**N [1/min]**	*SD*	**M [µNm]**	*SD*
0.10	628	0.10	602	0.10	675	0.10	606	0.10	631	0.1	*0.000*	0.1	*26*
0.16	766	0.16	742	0.17	839	0.16	756	0.16	759	0.2	*0.000*	0.2	*34*
0.27	811	0.27	782	0.27	889	0.27	804	0.27	806	0.3	*0.000*	0.3	*37*
0.44	877	0.44	823	0.44	953	0.44	865	0.44	874	0.4	*0.000*	0.4	*42*
0.72	965	0.72	909	0.72	1053	0.72	954	0.72	975	0.7	*0.001*	0.7	*47*
1.18	1093	1.18	1030	1.18	1197	1.18	1083	1.18	1113	1.2	*0.000*	1.2	*54*
1.93	1287	1.93	1207	1.93	1397	1.93	1260	1.93	1317	1.9	*0.000*	1.9	*63*
3.16	1557	3.16	1460	3.16	1673	3.16	1520	3.16	1593	3.2	*0.000*	3.2	*72*
5.18	1927	5.18	1810	5.18	2087	5.18	1887	5.18	1993	5.2	*0.001*	5.2	*94*
8.48	2457	8.48	2313	8.48	2667	8.48	2413	8.48	2567	8.5	*0.000*	8.5	*123*
13.90	3253	13.90	3050	13.90	3530	13.90	3197	13.90	3403	13.9	*0.000*	13.9	*166*
22.80	4443	22.80	4143	22.80	4827	22.80	4377	22.80	4663	22.8	*0.000*	22.8	*236*
37.30	6267	37.30	5820	37.30	6810	37.30	6207	37.30	6580	37.3	*0.000*	37.3	*338*
61.00	9050	61.03	8367	61.03	9783	61.00	8950	61.00	9420	61.0	*0.016*	61.0	*476*
100.00	13367	100.00	12300	100.00	14367	100.00	13167	100.00	13867	100.0	*0.000*	100.0	*695*
100.00	13267	100.00	12167	100.00	14267	100.00	13033	100.00	13767	100.0	*0.000*	100.0	*708*
69.50	9850	69.50	9067	69.50	10633	69.50	9703	69.50	10290	69.5	*0.000*	69.5	*534*
48.30	7397	48.30	6790	48.30	7983	48.30	7300	48.30	7717	48.3	*0.000*	48.3	*404*
33.60	5610	33.60	5153	33.60	6057	33.60	5553	33.60	5857	33.6	*0.000*	33.6	*305*
23.40	4323	23.40	3970	23.40	4657	23.40	4283	23.40	4507	23.4	*0.000*	23.4	*232*
16.20	3387	16.20	3117	16.20	3653	16.20	3363	16.20	3520	16.2	*0.000*	16.2	*179*
11.30	2707	11.30	2497	11.30	2913	11.30	2693	11.30	2807	11.3	*0.000*	11.3	*138*
7.85	2203	7.85	2033	7.85	2370	7.85	2193	7.85	2277	7.9	*0.000*	7.9	*111*
5.46	1820	5.45	1690	5.46	1960	5.46	1823	5.46	1877	5.5	*0.003*	5.5	*88*
3.79	1543	3.79	1423	3.79	1653	3.79	1540	3.79	1583	3.8	*0.000*	3.8	*75*
2.64	1320	2.64	1227	2.63	1413	2.64	1317	2.64	1360	2.6	*0.003*	2.6	*61*
1.83	1147	1.83	1063	1.83	1233	1.83	1157	1.83	1177	1.8	*0.001*	1.8	*55*
1.27	1009	1.27	943	1.27	1097	1.27	1018	1.27	1052	1.3	*0.002*	1.3	*51*
0.89	908	0.89	861	0.89	999	0.89	936	0.88	954	0.9	*0.001*	0.9	*46*
0.62	842	0.61	783	0.61	911	0.62	851	0.62	876	0.6	*0.002*	0.6	*42*
0.43	767	0.42	761	0.43	867	0.43	787	0.43	804	0.4	*0.003*	0.4	*38*
0.30	738	0.29	729	0.30	813	0.29	775	0.29	771	0.3	*0.004*	0.3	*30*
0.20	727	0.21	653	0.20	790	0.21	697	0.20	876	0.2	*0.004*	0.2	*78*
0.14	676	0.14	652	0.15	760	0.15	735	0.14	699	0.1	*0.002*	0.1	*39*
0.10	650	0.11	609	0.10	716	0.09	700	0.10	690	0.1	*0.005*	0.1	*39*

Table B - 15: Average values for 40 % mortar mixes (by volume) using serrated coaxial cylinder geometry. *[NIST Codes]*

Serrated Coaxial Cylinder [SS18]													
40 % Beads										**Serrated Coaxial Cylinder [SS18]**			
Mix #2 [SMC-79]		**Mix #3** [SMC-81]		**Mix #4** [SMC-85]		**Mix #5** [SMC-95]		**Mix #6** [SMC-97]		**40 % Average Values**			
N [1/min]	M [μNm]	N [1/min]	M [μNm]	N [1/min]	M [μNm]	N [1/min]	M [μNm]	N [1/min]	M [μNm]	**N [1/min]**	*SD*	**M [μNm]**	*SD*
0.10	952	0.10	1307	0.10	1343	0.10	1147	0.10	1197	**0.10**	*0.001*	**1189**	*138*
0.16	1090	0.16	1580	0.16	1540	0.16	1317	0.16	1387	**0.16**	*0.000*	**1383**	*175*
0.27	1119	0.27	1630	0.27	1557	0.27	1350	0.27	1440	**0.27**	*0.000*	**1419**	*178*
0.44	1187	0.44	1697	0.44	1647	0.44	1420	0.44	1510	**0.44**	*0.001*	**1492**	*181*
0.72	1333	0.72	1853	0.72	1793	0.72	1557	0.72	1667	**0.72**	*0.001*	**1641**	*185*
1.18	1567	1.18	2087	1.18	2063	1.18	1753	1.18	1927	**1.18**	*0.000*	**1879**	*196*
1.93	1890	1.93	2503	1.93	2433	1.93	2103	1.93	2303	**1.93**	*0.000*	**2247**	*224*
3.17	2383	3.16	3063	3.16	2990	3.16	2593	3.16	2860	**3.16**	*0.002*	**2778**	*254*
5.18	3087	5.18	3920	5.18	3787	5.18	3317	5.18	3683	**5.18**	*0.001*	**3559**	*310*
8.48	4143	8.48	5187	8.48	4927	8.49	4360	8.49	4833	**8.48**	*0.004*	**4690**	*382*
13.90	5680	13.90	7020	13.90	6583	13.90	5873	13.90	6487	**13.90**	*0.000*	**6329**	*489*
22.80	7953	22.80	9730	22.80	8947	22.77	8050	22.80	8930	**22.79**	*0.013*	**8722**	*656*
37.30	11333	37.30	13733	37.30	12367	37.30	11133	37.30	12467	**37.30**	*0.000*	**12207**	*932*
61.07	16067	61.03	18600	61.07	16467	61.10	15533	61.03	16567	**61.06**	*0.025*	**16647**	*1042*
100.00	22067	99.97	24600	100.00	22333	100.00	21467	100.00	23233	**99.99**	*0.013*	**22740**	*1090*
100.00	21667	100.00	24800	99.97	22467	99.97	20100	99.97	22667	**99.98**	*0.016*	**22340**	*1526*
69.50	16933	69.50	19733	69.50	17833	69.50	15400	69.50	17667	**69.50**	*0.000*	**17513**	*1404*
48.30	12900	48.30	14967	48.30	13533	48.30	11867	48.30	13500	**48.30**	*0.000*	**13353**	*1007*
33.60	10033	33.60	11433	33.60	10347	33.60	9450	33.60	10350	**33.60**	*0.000*	**10323**	*645*
23.40	7690	23.40	8690	23.33	7890	23.37	7327	23.33	7877	**23.37**	*0.030*	**7895**	*447*
16.20	5900	16.20	6700	16.20	6117	16.20	5690	16.20	6073	**16.20**	*0.000*	**6096**	*337*
11.30	4597	11.30	5210	11.30	4797	11.30	4447	11.30	4737	**11.30**	*0.000*	**4757**	*257*
7.85	3660	7.85	4123	7.85	3800	7.85	3530	7.85	3750	**7.85**	*0.001*	**3773**	*198*
5.46	2930	5.45	3293	5.46	3077	5.45	2853	5.45	3027	**5.46**	*0.003*	**3036**	*150*
3.79	2403	3.79	2700	3.79	2523	3.79	2350	3.79	2477	**3.79**	*0.000*	**2491**	*120*
2.64	1997	2.64	2230	2.64	2097	2.63	1963	2.64	2073	**2.64**	*0.003*	**2072**	*93*
1.83	1697	1.83	1880	1.83	1787	1.83	1667	1.83	1750	**1.83**	*0.001*	**1756**	*75*
1.27	1467	1.27	1623	1.28	1543	1.27	1450	1.28	1520	**1.27**	*0.003*	**1521**	*62*
0.89	1283	0.89	1410	0.89	1350	0.89	1273	0.89	1333	**0.89**	*0.000*	**1330**	*49*
0.62	1140	0.62	1257	0.62	1207	0.62	1137	0.62	1207	**0.62**	*0.000*	**1189**	*45*
0.43	1030	0.43	1123	0.43	1083	0.43	1022	0.43	1097	**0.43**	*0.001*	**1071**	*39*
0.30	941	0.30	1031	0.30	992	0.30	940	0.29	991	**0.30**	*0.001*	**979**	*35*
0.21	872	0.21	949	0.21	921	0.21	867	0.21	930	**0.21**	*0.001*	**908**	*33*
0.14	806	0.14	877	0.14	856	0.14	808	0.14	952	**0.14**	*0.000*	**860**	*54*
0.10	764	0.10	828	0.10	798	0.10	758	0.10	887	**0.10**	*0.000*	**807**	*47*