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Fire Safe Glued Massive Timber Members Adhesive Bonding Performance under Elevated Temperature -Tests Report

by

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EXECUTIVE SUMMARY

This project was conducted to quantify the performance of adhesives bond lines under shear load subject to elevated temperature. The results add to the understanding of the performance of polyurethane adhesive bond lines under elevated temperatures to address areas of fire safety concern under the current building codes.

The project focused on studying the shear bond capacity of three wood species by using 3 types of adhesives with/without nanoclay treatment at 4 temperature levels. The three wood species are Douglas-Fir, Hemlock and SPF. The adhesives are polyurethane (PU), Phenol-Resorcinol-Formaldehyde (PRF) and Epoxy. PU and PRF specimens were also tested with nanoclay treatment and without nanoclay treatment. Epoxy specimens were tested without nanoclay treatment only. The temperature levels considered were room temperature (about 20 ℃), 60 ℃, 80 ℃ and 100 ℃. The results indicate that the influence of elevated temperature on the shear bond strength of PU and PRF adhesive was in the range of 20 to 30% regardless of nanoclay treatment. Regardless of species, PU or PRF, with or without nanoclay, the average shear strength for 100 ℃ oven temperature treatment ranged from 6.0 to 7.5 MPa. In the case of SPF PU specimens treatment with nanoclay reduced the variability of shear strength significantly from 12% at room temperature to 5% after 100 ℃ oven treatment. This is an important aspect that needs further verification for enhancement of performance. Finally the data in this study can be used to support modeling of timber component subjected to elevated temperature.

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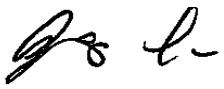

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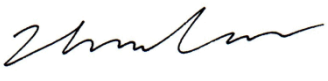

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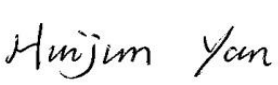

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1. INTRODUCTION

UBC has worked on the fire performance of CLT elements with full scale fire testing in cooperation with CNR-IVALSA National Research Council of Italy. The work was funded partly by FII in 2011 to 2012 with the non-destructive evaluation of the material prior to manufacturing and the construction of the test panels, IVALSA funded the fire testing.

This study is a new project in support of the wood first initiative intended to develop and extend knowledge from the past so that we can quantify the performance of polyurethane adhesives bond lines under elevated temperatures so that improved solutions can be proposed for improvements.

As a non-thermal-set adhesive, it is known that polyurethane adhesives can soften when subjected to loads under elevated temperature. Although results from limited full scale fire test indicate that structural members bonded with polyurethane adhesives does not have the same level of performance as members bonded with thermal-set adhesives, clear explanation of such behaviour is not available. Without such information, it is difficult to create rational solutions for improving the performance of polyurethane adhesive bond lines under elevated temperatures. This information is needed to address areas of fire safety concerns of heavy timber construction of structural components such as cross laminate timber under the current building codes or the potential to use polyurethane as structural adhesives in glulam.

The overall objective of the project is to quantify the behaviour of polyurethane adhesive under load subject to elevated temperature and investigate potential improved solution. The work will impact the design of structural components such as cross laminated timber and potential use of polyurethane in glulam members.

2. MATERIAL AND METHODS

2.1 Materials

Three types of wood species were tested: Spruce-Pine-Fir (SPF), Douglas fir (D-Fir), and Hemlock. The adhesives used were: epoxy (Systemthree® general purpose epoxy), phenol resorcinol formaldehyde (PRF, Cascophen® LT-75C and Cascoset® FM 282 by Momentive US), and polyurethane (PU, Purbond® CR421 by Purbond Switzerland). The montmorillonite nanoclay chosen as treatment for this test was Cloisite® 30B provided by Southern Clay Products Inc. Table 1 shows the details of test design.

Table 1 Experimental Design

Species	Temp. (℃)	PU	PU+5%Nanoclay	PRF	PRF+5%Nanoclay	Epoxy
SPF	20℃	15	15	15	15	15
	60℃	15	15	15	15	15
	80℃	15	15	15	15	15
	100℃	15	15	15	15	15
D-Fir	20℃	15	15	15	15	15
	60℃	15	15	15	15	15
	80℃	15	15	15	15	15
	100℃	15	15	15	15	15
Hemlock	20℃	15	15	15	15	15
	60℃	15	15	15	15	15
	80℃	15	15	15	15	15
	100℃	15	15	15	15	15

2.2 Preparation of the specimens

The specimen was prepared in accordance to ASTM D905-08 and ASTM D7247-07. The wood material was first cut into blocks of 63.5 by 22.2 by 2438.4 mm (2½ by 7/8 by 96 inches), and surfaced prior to bonding. The adhesive was then prepared and applied to the blocks. The nanoclay, with an amount of 5% of the adhesive weight, was mixed into the adhesive by a mechanical blender. Every two adhesive coated blocks were assembled and cold-pressed for 18 hours under the pressure recommended by the manufacturers.

Afterwards the blocks were planed into 50.8 by 19.0 by 2438.4 mm (2 by 1½ by 96 in), and then cut into the specimens shown in Figure 1 with a bonding area of 50.8 by 50.8 mm (2 by 2 in). A hole was drilled through one layer of block to reach the bond line to fit the thermocouple wire for temperature measurement. This location of the hole was at the geometry center of the bonding area. Fifteen specimens were prepared for each type of condition, representing three different joints of blocks. Figure 1 shows the details of the specimens.

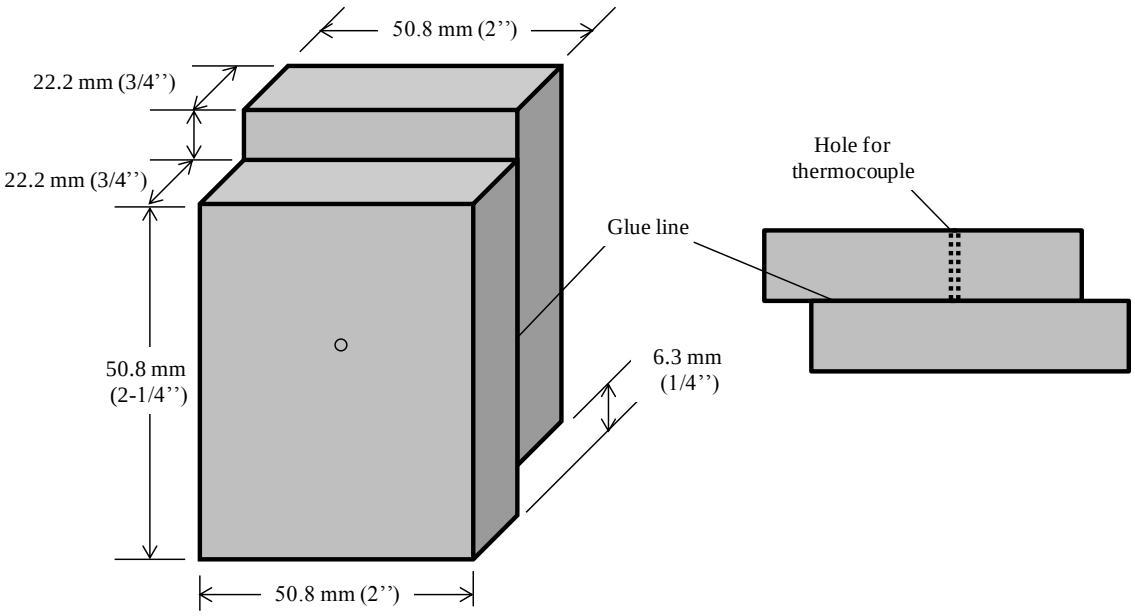


Figure 1. Form and dimension of test specimens

2.3 Test Procedure

The specimens were tested after conditioned at four temperature levels: room temperature (20 ℃), 60 ℃, 80 ℃, and 100 ℃ in accordance with ASTM D905-08 with a loading rate of 5 mm (0.2 in) /min. For the conditions of elevated temperatures, the specimens were placed in an oven preheated to the target temperature. After a period of 90 min, they were taken out to be tested immediately and the bondline temperatures measured with a thermocouple. It should be noted that the temperature measurement location is centrally located within the specimen, the temperature of the bond line closer to the perimeter of the specimen should be higher than the central location but less than the ambient oven temperature.

The specimens were tested in the MTS Flextest GT Structural Test Machine. A view of the test assembly is presented in Photo 1. The specimens were loaded until failure to obtain the peak load in the shear test. The shear strength value can be obtained from the peak load and the specimen geometry.

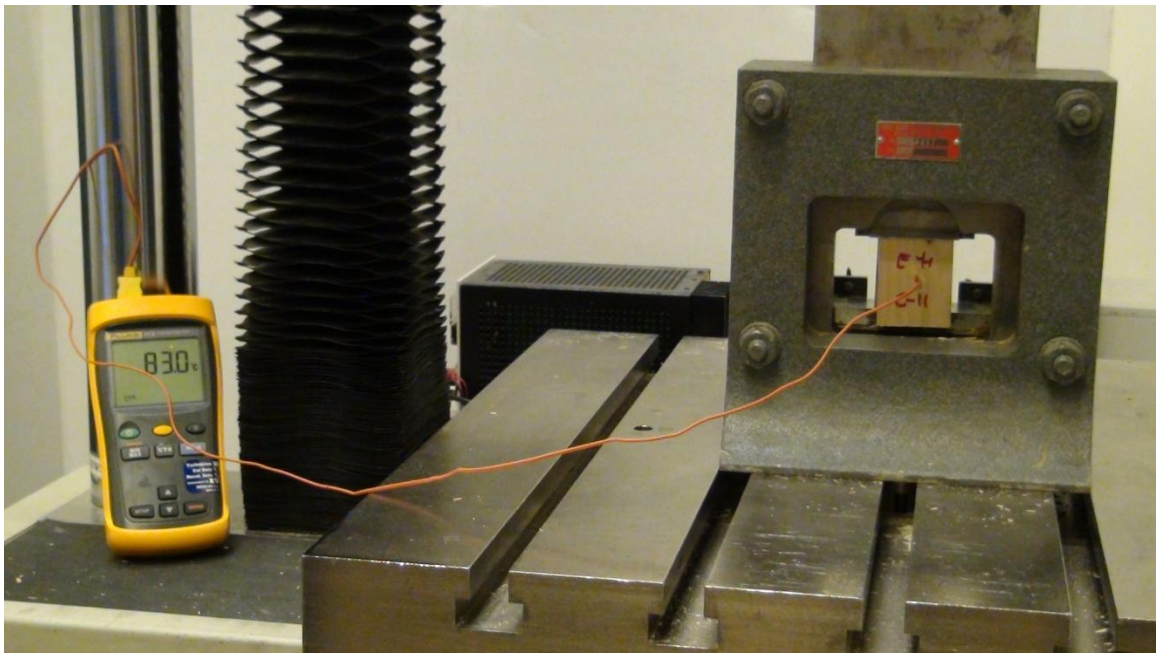


Photo 1 Shear Test in Progress

3. TEST RESULTS

Tables 2 to 4 present the summary results of the shear strength for each group tests. After the tests, the specimens were split opened at the bondline to examine the failure modes. Photo 2 shows the shear failure modes of the bonding surface. The failure modes were marked by Wood failure (WF) and Glue failure (GF) with the percentage of total wood failure and total adhesive failure such as WFxx or GFxx. Tables 5 to 7 give the statistic summary results of the adhesive bonding failure percentage. It should be noted that some times this is evaluation is difficult given the action of splitting open the specimen may have created failure plane which could be different from the original failure location.

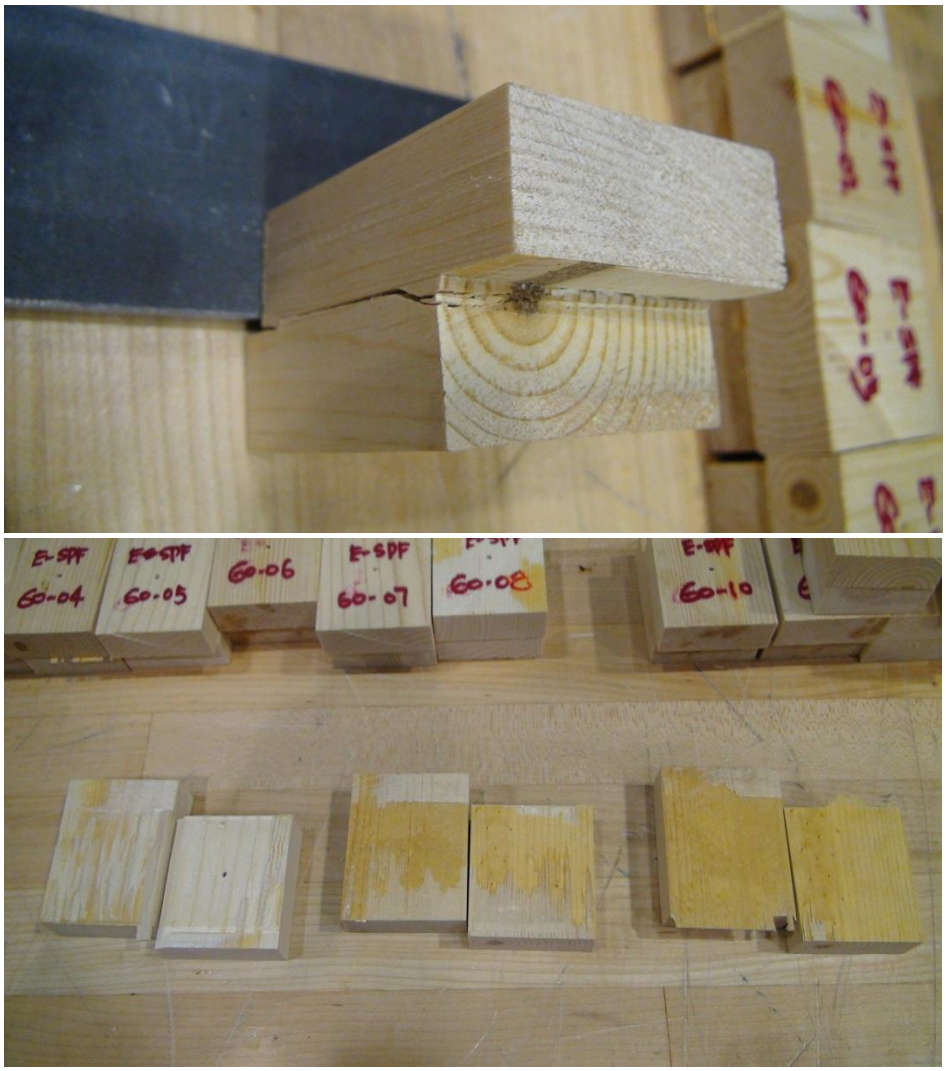


Photo 2. Failure modes

Table 2.Summary Statistics of the adhesive Bonding Tests-SPF

Oven (^{0}C)		SPF-PU				SPF-PU+Nanoclay				SPF-PRF				SPF-PRF+Nanoclay				SPF-Epoxy			
		Peak Load (N)	Bond surface temp. (^{0}C)	*MC %*	*Shear strength MPa*	Peak Load (N)	Bond surface temp. (^{0}C)	*MC %*	*Shear strength MPa*	Peak Load (N)	Bond surface temp. (^{0}C)	*MC %*	*Shear strength MPa*	Peak Load (N)	Bond surface temp. (^{0}C)	*MC %*	*Shear strength MPa*	Peak Load (N)	Bond surface temp. (^{0}C)	*MC %*	*Shear strength MPa*
	Aver.	25057	22.28	8.48	9.71	24304	22.04	8.96	9.42	20200	22.01	12.54	7.83	21775	22.03	12.73	8.44	22590	22.68	11.33	8.75
	Stdev	3212	0.11	0.18	1.24	2974	0.12	0.27	1.15	2617	0.11	0.46	1.01	2930	0.13	0.28	1.14	1801	0.26	0.41	0.70
	COV(%)	12.82	0.48	2.08	12.82	12.24	0.54	2.98	12.24	12.96	0.50	3.64	12.96	13.46	0.57	2.22	13.46	7.97	1.13	3.65	7.97
	Max.	29521	22.50	8.71	11.44	29583	22.30	9.64	11.46	24571	22.20	13.20	9.52	24765	22.20	13.36	9.60	25256	23.30	12.26	9.79
	Mini.	19048	22.00	8.09	7.38	20359	21.90	8.60	7.89	16173	21.80	11.64	6.27	13192	21.80	12.38	5.11	19484	22.30	10.61	7.55
20	**Count**	16	16	16	16	15	15	15	15	15	15	15	15	16	16	16	16	15	15	15	15
	Aver.	19799	54.18	8.25	7.67	18278	52.69	8.90	7.08	14501	51.09	12.94	5.62	12727	50.79	12.69	4.93	6959	52.53	8.91	2.70
	Stdev	2883	0.22	0.19	1.12	2024	0.52	0.17	0.78	2921	0.50	0.26	1.13	2245	0.85	0.48	0.87	1810	0.94	1.42	0.70
	COV(%)	14.56	0.40	2.25	14.56	11.07	0.99	1.89	11.07	20.14	0.98	2.00	20.14	17.64	1.67	3.80	17.64	26.01	1.79	15.97	26.01
	Max.	25570	54.60	8.55	9.91	21947	53.60	9.15	8.50	20307	52.10	13.41	7.87	16293	51.90	13.33	6.31	9299	53.50	12.02	3.60
	Mini.	15385	53.80	7.85	5.96	14349	52.00	8.55	5.56	9784	50.10	12.58	3.79	9134	49.50	11.70	3.54	3174	49.80	7.71	1.23
60	**Count**	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	18	18	18	18
	Aver.	19800	69.23	8.39	7.67	18545	67.55	8.95	7.19	14293	65.97	12.79	5.54	15762	65.37	13.01	6.11	3555	68.23	12.02	1.38
	Stdev	3460	0.78	0.18	1.34	1336	1.11	0.37	0.52	3100	0.63	0.40	1.20	2928	0.80	0.31	1.13	1555	0.86	0.42	0.60
	COV(%)	17.47	1.12	2.14	17.47	7.20	1.64	4.10	7.20	21.69	0.96	3.14	21.69	18.58	1.22	2.42	18.58	43.74	1.26	3.46	43.74
	Max.	25447	71.20	8.66	9.86	21191	69.20	9.50	8.21	18905	66.90	13.37	7.33	22205	66.80	13.62	8.60	6151	69.50	12.69	2.38
	Mini.	14361	68.20	8.14	5.57	15928	65.70	8.43	6.17	7410	65.00	11.98	2.87	10552	64.10	12.55	4.09	1241	66.50	11.24	0.48
80	**Count**	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15
	Aver.	19258	83.58	8.63	7.46	16909	82.85	9.03	6.55	15868	83.43	13.01	6.15	18618	83.16	12.61	7.21	1688	85.16	11.81	0.65
	Stdev	2902	1.25	0.11	1.12	865	1.50	0.23	0.34	2758	0.85	0.27	1.07	2071	1.39	0.51	0.80	628	2.06	0.46	0.24
	COV(%)	15.07	1.50	1.32	15.07	5.12	1.81	2.58	5.12	17.38	1.01	2.11	17.38	11.12	1.67	4.07	11.12	37.19	2.41	3.91	37.19
	Max.	25086	85.60	8.87	9.72	18348	85.80	9.66	7.11	19336	85.40	13.38	7.49	22147	85.00	13.72	8.58	2692	88.90	12.41	1.04
	Mini.	13999	81.80	8.42	5.42	15521	80.00	8.80	6.01	10440	82.30	12.47	4.05	15476	81.00	11.74	6.00	590	82.50	11.01	0.23
100	**Count**	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15

Table 3.Summary Statistics of the adhesive Bonding Tests-DF

Oven (^{0}C)		DF-PU				DF-PU+Nanoclay				DF-PRF				DF-PRF+Nanoclay				DF-Epoxy			
		Peak Load (N)	Bond surface temp. (^{0}C)	*MC %*	*Shear strength MPa*	Peak Load (N)	Bond surface temp. (^{0}C)	*MC %*	*Shear strength MPa*	Peak Load (N)	Bond surface temp. (^{0}C)	*MC %*	*Shear strength MPa*	Peak Load (N)	Bond surface temp. (^{0}C)	*MC %*	*Shear strength MPa*	Peak Load (N)	Bond surface temp. (^{0}C)	*MC %*	*Shear strength MPa*
	Aver.	29175	22.19	8.64	11.31	24951	21.97	9.03	9.67	20983	22.15	12.50	8.13	25418	22.21	12.29	9.85	25938	22.33	11.60	10.05
	Stdev	1876	0.06	0.20	0.73	3430	0.12	0.32	1.33	2684	0.11	0.37	1.04	2556	0.10	0.32	0.99	2266	0.13	0.23	0.88
	COV(%)	6.43	0.27	2.31	6.43	13.75	0.54	3.55	13.75	12.79	0.48	3.00	12.79	10.06	0.47	2.64	10.06	8.74	0.57	1.98	8.74
	Max.	32814	22.30	8.95	12.72	29594	22.30	9.55	11.47	25697	22.30	13.01	9.96	32248	22.40	12.86	12.50	29936	22.60	12.14	11.60
	Mini.	26382	22.10	8.27	10.22	16349	21.80	8.49	6.34	16637	22.00	11.59	6.45	21933	22.00	11.73	8.50	22122	22.10	11.33	8.57
20	**Count**	15	15	15	15	16	16	16	16	15	15	15	15	15	15	15	15	15	15	15	15
	Aver.	22597	52.21	8.68	8.76	20194	53.63	9.09	7.83	14457	51.35	12.55	5.60	15442	60.17	12.26	5.98	4993	52.49	12.37	1.93
	Stdev	3072	0.65	0.23	1.19	3366	0.54	0.23	1.30	2539	0.44	0.28	0.98	2276	4.84	0.34	0.88	2021	0.42	0.40	0.78
	COV(%)	13.60	1.24	2.68	13.60	16.67	1.00	2.52	16.67	17.56	0.85	2.25	17.56	14.74	8.04	2.76	14.74	40.49	0.81	3.25	40.49
	Max.	27580	53.40	9.11	10.69	25725	54.60	9.58	9.97	18198	52.30	13.01	7.05	21974	65.50	12.79	8.51	8521	53.10	13.25	3.30
	Mini.	17936	51.30	8.32	6.95	13968	52.70	8.72	5.41	8914	50.40	12.05	3.45	13320	52.70	11.54	5.16	1818	51.60	11.70	0.70
60	**Count**	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	20	20	20	20
	Aver.	21140	66.61	8.59	8.19	20271	66.97	9.05	7.85	14808	64.21	12.66	5.74	16332	64.20	12.44	6.33	2023	67.87	12.14	0.78
	Stdev	2308	1.26	0.18	0.89	2826	0.66	0.24	1.10	2344	0.78	0.27	0.91	2245	3.08	0.44	0.87	787	0.90	0.26	0.31
	COV(%)	10.92	1.89	2.15	10.92	13.94	0.99	2.68	13.94	15.83	1.21	2.17	15.83	13.74	4.79	3.55	13.74	38.93	1.32	2.10	38.93
	Max.	25291	68.50	8.91	9.80	24504	67.90	9.46	9.50	19322	65.50	13.01	7.49	20978	67.70	12.90	8.13	3561	69.20	12.78	1.38
	Mini.	15448	64.60	8.27	5.99	13481	65.20	8.74	5.22	9090	63.00	11.98	3.52	13182	54.80	11.58	5.11	1019	66.20	11.84	0.39
80	**Count**	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15
	Aver.	19854	81.21	8.76	7.69	17674	81.84	9.02	6.85	16088	82.06	12.52	6.23	18923	81.87	12.56	7.33	1199	84.03	11.86	0.46
	Stdev	2468	1.83	0.23	0.96	2403	2.64	0.59	0.93	2313	1.34	0.39	0.90	3057	1.34	0.35	1.18	354	1.61	0.37	0.14
	COV(%)	12.43	2.25	2.59	12.43	13.60	3.22	6.54	13.60	14.38	1.63	3.11	14.38	16.16	1.64	2.76	16.16	29.53	1.92	3.12	29.53
	Max.	22859	84.50	9.16	8.86	22040	85.60	9.47	8.54	19935	84.20	12.96	7.72	24344	83.60	12.95	9.43	2003	86.90	12.56	0.78
	Mini.	15354	78.30	8.32	5.95	13780	78.10	7.01	5.34	12058	80.00	11.40	4.67	13981	80.00	11.87	5.42	771	81.00	11.33	0.30
100	**Count**	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15

Table 4.Summary Statistics of the adhesive Bonding Tests-Hemlock

Oven (^{0}C)		Hemlock-PU				Hemlock-PU+Nanoclay				Hemlock-PRF				Hemlock-PRF+Nanoclay				Hemlock-Epoxy			
		Peak Load (N)	Bond surface temp. (^{0}C)	*MC %*	*Shear strength MPa*	Peak Load (N)	Bond surface temp. (^{0}C)	*MC %*	*Shear strength MPa*	Peak Load (N)	Bond surface temp. (^{0}C)	*MC %*	*Shear strength MPa*	Peak Load (N)	Bond surface temp. (^{0}C)	*MC %*	*Shear strength MPa*	Peak Load (N)	Bond surface temp. (^{0}C)	*MC %*	*Shear strength MPa*
	Aver.	25051	22.19	8.54	9.71	26039	22.06	8.86	10.09	20664	22.17	14.18	8.01	25827	21.86	14.32	10.01	20815	21.94	13.55	8.07
	Stdev	4451	0.06	0.18	1.72	3887	0.07	0.33	1.51	3489	0.23	1.11	1.35	3092	0.13	0.53	1.20	2092	0.16	1.03	0.81
	COV(%)	17.77	0.29	2.10	17.77	14.93	0.33	3.74	14.93	16.89	1.02	7.84	16.89	11.97	0.58	3.72	11.97	10.05	0.73	7.61	10.05
	Max.	32275	22.30	8.84	12.51	32348	22.20	9.52	12.53	25618	22.50	15.53	9.93	31615	22.10	15.10	12.25	24502	22.20	15.90	9.49
	Mini.	19886	22.10	8.19	7.71	15522	22.00	8.26	6.01	13449	21.70	12.07	5.21	19320	21.60	12.86	7.49	17151	21.60	11.41	6.65
20	**Count**	15	15	15	15	16	16	16	16	18	18	18	18	16	16	16	16	15	15	15	15
	Aver.	19049	52.35	8.86	7.38	20140	52.35	9.08	7.80	16871	50.91	14.65	6.54	15433	50.39	13.91	5.98	6234	51.26	14.99	2.42
	Stdev	2837	0.87	0.21	1.10	3167	0.51	0.28	1.23	2795	0.73	1.12	1.08	3518	0.43	0.72	1.36	2184	0.66	0.68	0.85
	COV(%)	14.90	1.66	2.34	14.90	15.72	0.97	3.04	15.72	16.57	1.43	7.63	16.57	22.80	0.85	5.14	22.80	35.03	1.29	4.56	35.03
	Max.	23137	53.60	9.19	8.97	25055	53.00	9.40	9.71	24261	52.30	16.99	9.40	20686	51.20	14.98	8.02	11508	52.50	16.15	4.46
	Mini.	14247	50.80	8.30	5.52	15025	51.20	8.49	5.82	13044	50.00	11.86	5.05	8624	49.50	12.60	3.34	3256	50.10	14.04	1.26
60	**Count**	16	16	16	16	15	15	15	15	16	16	16	16	15	15	15	15	20	20	20	20
	Aver.	19264	64.77	8.85	7.46	19685	64.47	9.12	7.63	14370	63.26	14.16	5.57	17647	64.88	13.99	6.84	2772	65.41	13.95	1.07
	Stdev	2889	1.94	0.24	1.12	2688	0.90	0.28	1.04	2830	0.90	1.47	1.10	2234	0.70	1.03	0.87	804	0.84	0.61	0.31
	COV(%)	15.00	2.99	2.70	15.00	13.66	1.39	3.06	13.66	19.69	1.43	10.36	19.69	12.66	1.08	7.37	12.66	29.01	1.29	4.36	29.01
	Max.	24498	68.20	9.27	9.49	24201	66.40	9.66	9.38	19549	65.70	15.41	7.58	20497	65.90	15.07	7.94	3897	67.30	14.68	1.51
	Mini.	15268	61.40	8.57	5.92	14559	62.70	8.70	5.64	7224	62.30	10.77	2.80	12998	63.70	11.71	5.04	1367	64.30	12.61	0.53
80	**Count**	15	15	15	15	15	15	15	15	17	17	17	17	17	17	17	17	15	15	15	15
	Aver.	18477	81.86	8.85	7.16	19454	81.38	9.11	7.54	15694	81.12	14.10	6.08	18994	81.19	13.85	7.36	1561	81.05	13.64	0.60
	Stdev	2660	1.14	0.19	1.03	2782	1.65	0.26	1.08	3467	1.09	1.68	1.34	2694	1.03	1.15	1.04	637	1.29	0.56	0.25
	COV(%)	14.40	1.39	2.20	14.40	14.30	2.03	2.88	14.30	22.09	1.35	11.94	22.09	14.18	1.26	8.32%	14.18	40.81	1.59	4.11	40.81
	Max.	23080	84.20	9.14	8.94	24395	84.50	9.66	9.45	20711	83.10	15.55	8.03	22407	83.20	15.11	8.68	3016	83.70	14.67	1.17
	Mini.	14033	80.40	8.55	5.44	12999	79.50	8.66	5.04	6468	80.00	10.38	2.51	11666	80.00	11.15	4.52	608	79.60	12.48	0.24
100	**Count**	15	15	15	15	15	15	15	15	18	18	18	18	18	18	18	18	15	15	15	15

Table 5.Summary Statistics of the adhesive bonding failure percentage-SPF

Bonding surface temp. (^{0}C)		SPF-PU		SPF-PU+Nanoclay		SPF-PRF		SPF-PRF+Nanoclay		SPF-Epoxy	
		WF	***GF***	***WF***	***GF***	***WF***	***GF***	***WF***	***GF***	***WF***	***GF***
		%	***%***	***%***	***%***	***%***	***%***	***%***	***%***	***%***	***%***
	Average	97.19	2.81	98.80	1.60	90.13	9.87	75.00	25.00	100.00	0.00
	Stdev	7.52	7.52	2.81	2.75	23.00	23.00	23.45	23.45	0.00	0.00
	COV	8%	267%	3%	172%	26%	233%	31%	94%	0%	0%
	Maximum	100	30	100	8	100	90	100	70	100	0
	Minimum	70	0	92	0	10	0	30	0	100	0
20	**Count**	16	16	15	15	15	15	16	16	15	15
	Average	99.67	0.33	97.00	3.00	83.67	16.33	68.67	32.00	7.00	93.00
	Stdev	1.29	1.29	7.02	7.02	19.77	19.77	19.77	20.07	7.40	7.40
	COV	1%	387%	7%	234%	24%	121%	29%	63%	106%	8%
	Maximum	100	5	100	25	100	60	100	70	30	100
	Minimum	95	0	75	0	40	0	30	0	0	70
60	**Count**	15	15	15	15	15	15	15	15	18	18
	Average	100.00	0.00	99.33	0.67	79.80	20.20	83.47	16.53	0.00	100.00
	Stdev	0.00	0.00	2.58	2.58	24.15	24.15	21.57	21.57	0.00	0.00
	COV	0%	0%	3%	387%	30%	120%	26%	130%	0%	0%
	Maximum	100	0	100	10	100	70	100	70	0	100
	Minimum	100	0	90	0	30	0	30	0	0	100
80	**Count**	15	15	15	15	15	15	15	15	15	15
	Average	98.67	1.33	95.00	5.00	86.67	13.33	84.47	15.53	0.00	100.00
	Stdev	2.97	2.97	7.32	7.32	16.22	16.22	28.82	28.82	0.00	0.00
	COV	3%	223%	8%	146%	19%	122%	34%	186%	0%	0%
	Maximum	100	10	100	20	100	50	100	95	0	100
	Minimum	90	0	80	0	50	0	5	0	0	100
100	**Count**	15	15	15	15	15	15	15	15	15	15

Table 6.Summary Statistics of the adhesive bonding failure percentage-DF

Bonding surface temp. (^{0}C)	Spec. No.	DF-PU		DF-PU+Nanoclay		DF-PRF		DF-PRF+Nanoclay		DF-Epoxy	
		WF	***GF***	***WF***	***GF***	***WF***	***GF***	***WF***	***GF***	***WF***	***GF***
		%	***%***	***%***	***%***	***%***	***%***	***%***	***%***	***%***	***%***
	Average	96.00	4.00	98.13	1.88	90.93	9.07	75.00	25.00	100.00	0.00
	Stdev	8.28	8.28	5.44	5.44	9.79	9.79	13.50	13.50	0.00	0.00
	COV	9%	207%	6%	290%	11%	108%	18%	54%	0%	0%
	Maximum	100	30	100	20	100	30	100	50	100	0
	Minimum	70	0	80	0	70	0	50	0	100	0
20	**Count**	15	15	16	16	15	15	15	15	15	15
	Average	98.33	1.67	95.33	4.67	93.60	6.40	57.93	42.07	1.55	98.45
	Stdev	5.23	5.23	13.56	13.56	11.06	11.06	15.94	15.94	2.31	2.31
	COV	5%	314%	14%	291%	12%	173%	28%	38%	149%	2%
	Maximum	100	20	100	50	100	40	99	60	10	100
	Minimum	80	0	50	0	60	0	40	1	0	90
60	**Count**	15	15	15	15	15	15	15	15	20	20
	Average	79.33	20.67	78.67	21.33	90.00	9.33	82.33	17.67	0.13	99.87
	Stdev	21.20	21.20	24.38	24.38	9.26	8.84	14.38	14.38	0.52	0.52
	COV	27%	103%	31%	114%	10%	95%	17%	81%	387%	1%
	Maximum	100	70	100	85	100	20	100	50	2	100
	Minimum	30	0	15	0	80	0	50	0	0	98
80	**Count**	15	15	15	15	15	15	15	15	15	15
	Average	73.93	26.07	60.33	39.67	94.07	5.93	90.67	9.33	0.13	99.87
	Stdev	26.48	26.48	31.42	31.42	6.11	6.11	13.57	13.57	0.52	0.52
	COV	36%	102%	52%	79%	6%	103%	15%	145%	387%	1%
	Maximum	100	90	100	95	100	20	100	50	2	100
	Minimum	10	0	5	0	80	0	50	0	0	98
100	**Count**	15	15	15	15	15	15	15	15	15	15

Table 7.Summary Statistics of the adhesive bonding failure percentage-Hemlock

Bonding surface temp. (^{0}C)	Spec. No.	Hemlock-PU		Hemlock-PU+Nanoclay		Hemlock-PRF		Hemlock-PRF+Nanoclay		Hemlock-Epoxy	
		WF	*GF*	*WF*	*GF*	*WF*	*GF*	*WF*	*GF*	*WF*	*GF*
		%	*%*	*%*	*%*	*%*	*%*	*%*	*%*	*%*	*%*
	Average	100.00	0.00	98.44	1.56	89.33	10.67	81.38	18.63	99.00	1.00
	Stdev	0.00	0.00	6.25	6.25	13.07	13.07	19.55	19.55	2.80	2.80
	COV	0%	0%	6%	400%	15%	123%	24%	105%	3%	280%
	Maximum	100	0	100	25	100	45	100	50	100	10
	Minimum	100	0	75	0	55	0	50	0	90	0
20	**Count**	15	15	16	16	18	18	16	16	15	15
	Average	99.06	0.94	99.33	0.67	85.94	14.06	64.13	35.87	4.85	95.15
	Stdev	3.75	3.75	2.58	2.58	27.12	27.12	26.07	26.07	5.71	5.71
	COV	4%	400%	3%	387%	32%	193%	41%	73%	118%	6%
	Maximum	100	15	100	10	100	98	100	90	25	100
	Minimum	85	0	90	0	2	0	10	0	0	75
60	**Count**	16	16	15	15	16	16	15	15	20	20
	Average	92.33	7.67	91.33	8.67	93.41	6.59	69.06	30.35	0.00	100.00
	Stdev	9.61	9.61	14.07	14.07	10.46	10.46	25.15	25.41	0.00	0.00
	COV	10%	125%	15%	162%	11%	159%	36%	84%	0%	0%
	Maximum	100	30	100	40	100	35	100	70	0	100
	Minimum	70	0	60	0	65	0	30	0	0	100
80	**Count**	15	15	15	15	17	17	17	17	15	15
	Average	99.00	1.00	96.27	3.73	85.28	14.72	62.94	37.06	0.00	100.00
	Stdev	3.87	3.87	7.97	7.97	28.93	28.93	28.57	28.57	0.00	0.00
	COV	4%	387%	8%	213%	34%	196%	45%	77%	0%	0%
	Maximum	100	15	100	30	100	100	100	80	0	100
	Minimum	85	0	70	0	0	0	20	0	0	100
100	**Count**	15	15	15	15	18	18	18	18	15	15

4. RESULTS AND DISCUSSION

Figures 2 to 10 show the relationships between the shear strength and stiffness of adhesive bonds with the temperature for bonding woods SPF, Douglas-Fir, and Hemlock, respectively. The stiffness values were estimated from the linear portion of the load deformation curve based on machine cross head movements.

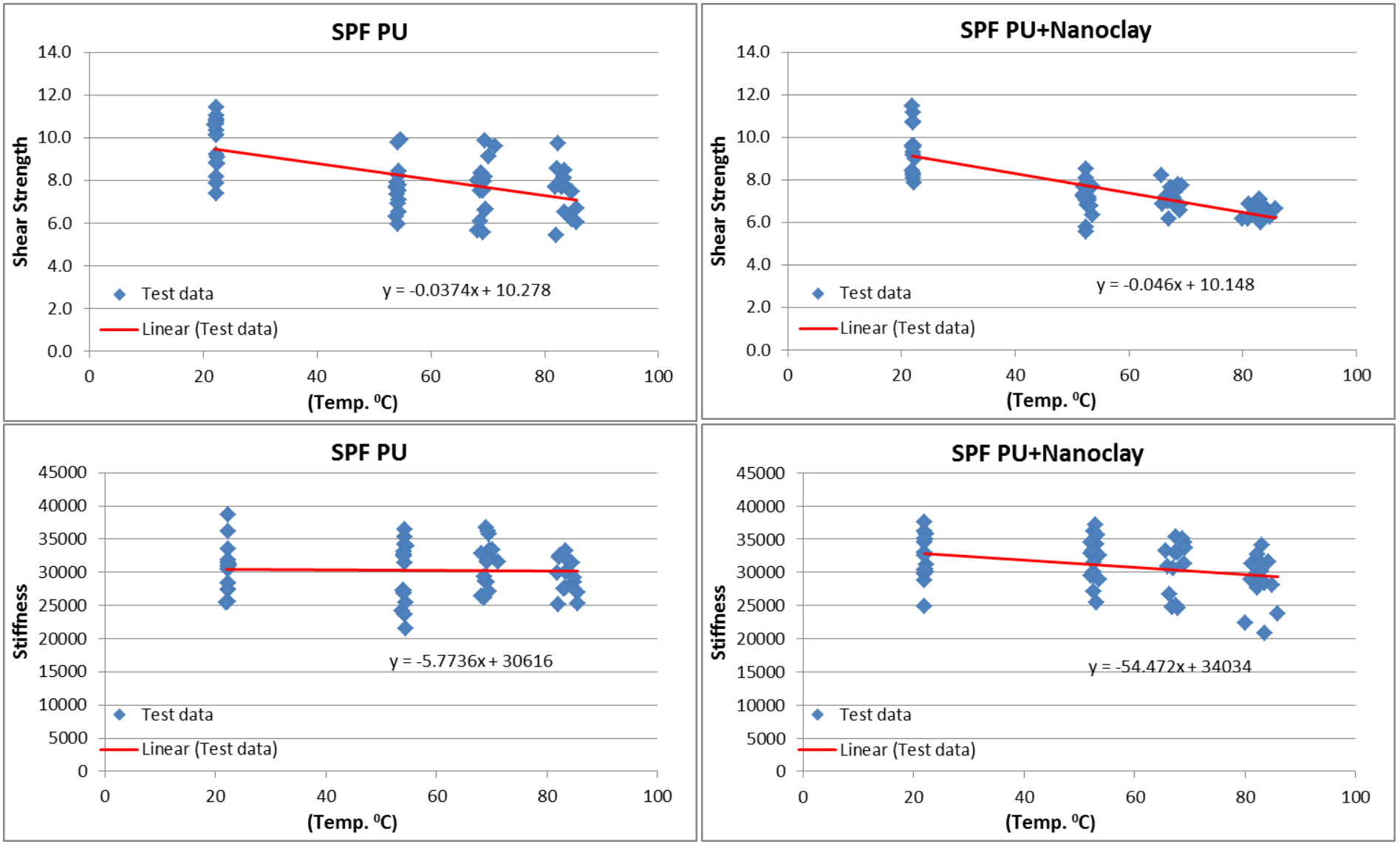


Figure 2. SPF with PU and Nanoclay

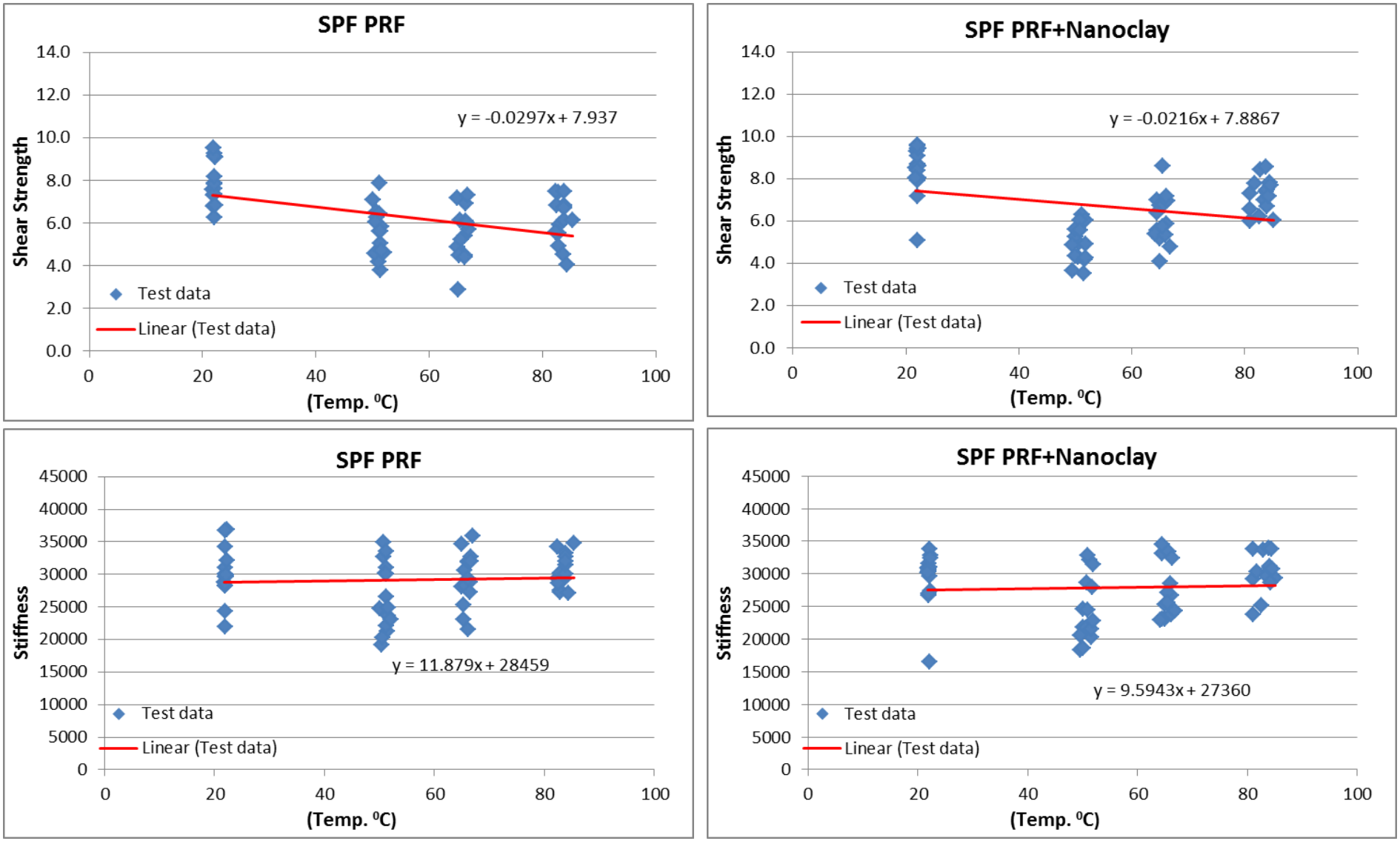
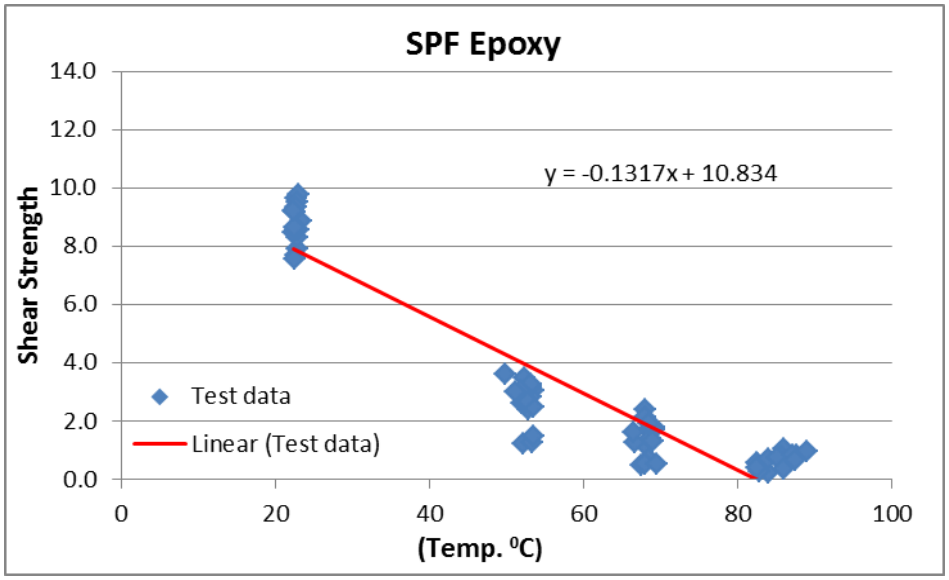


Figure 3. SPF with PRF and Nanoclay



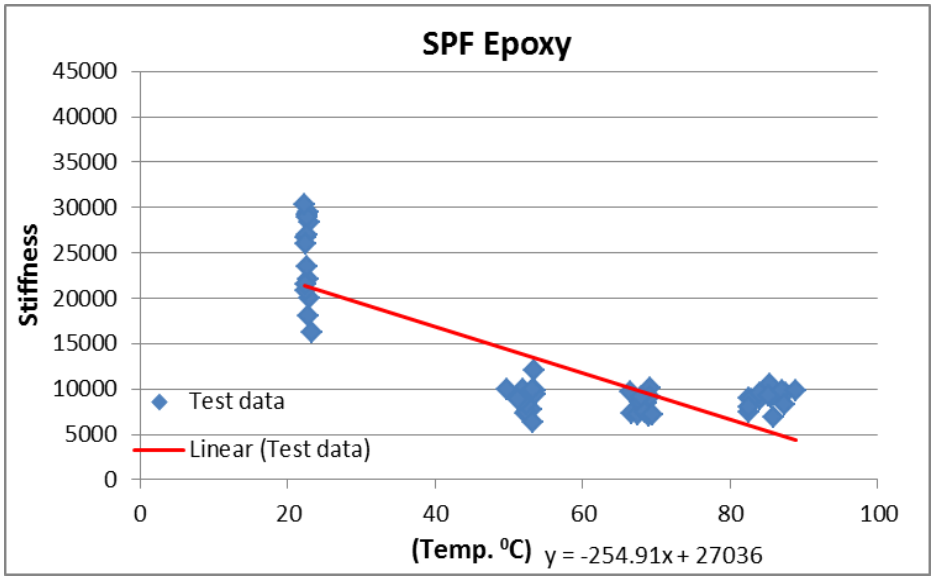
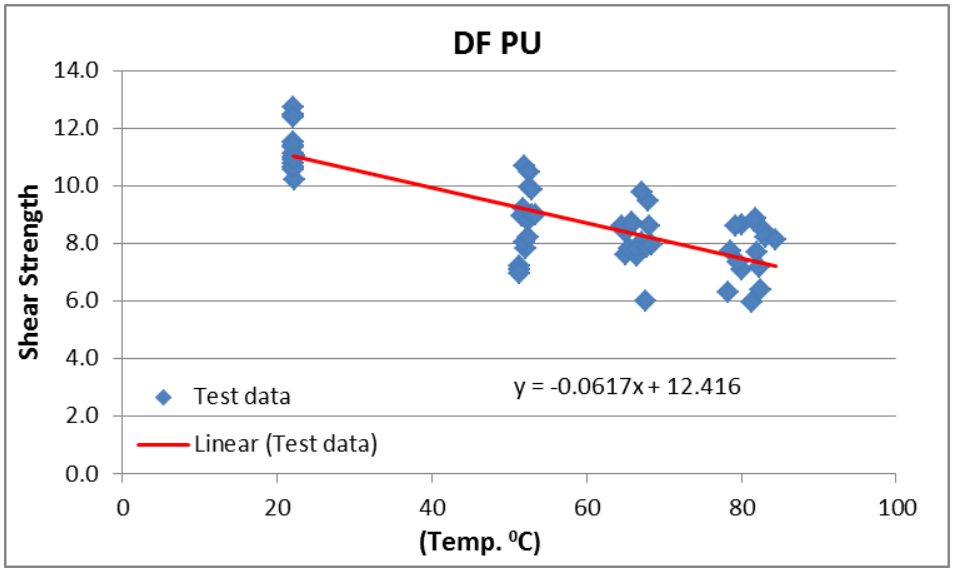
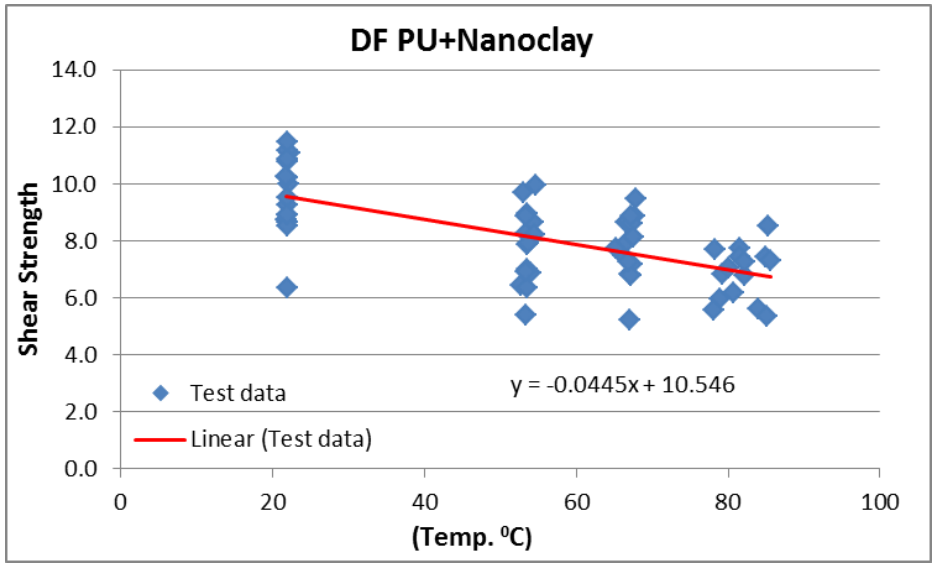
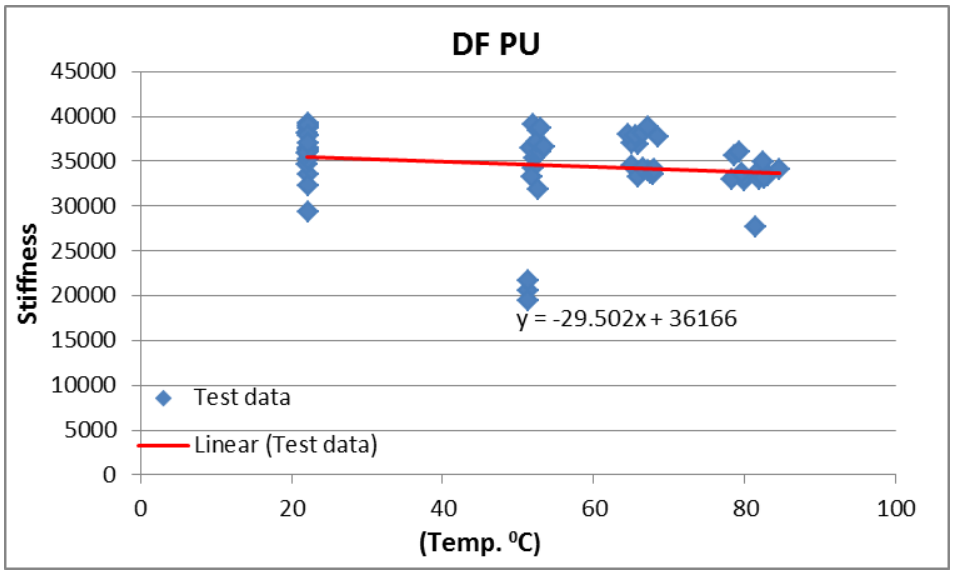


Figure 4. SPF with Epoxy







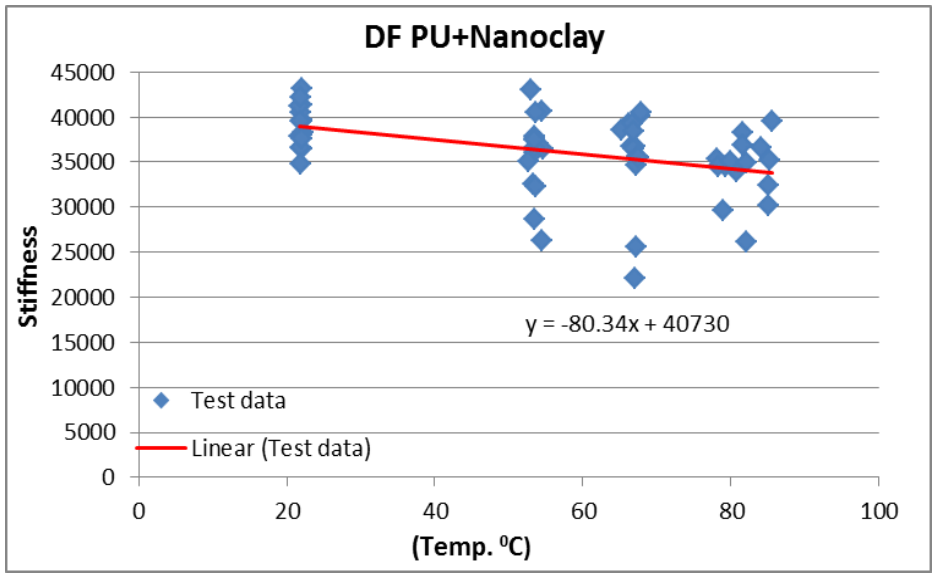


Figure 5. DF with PU and Nanoclay

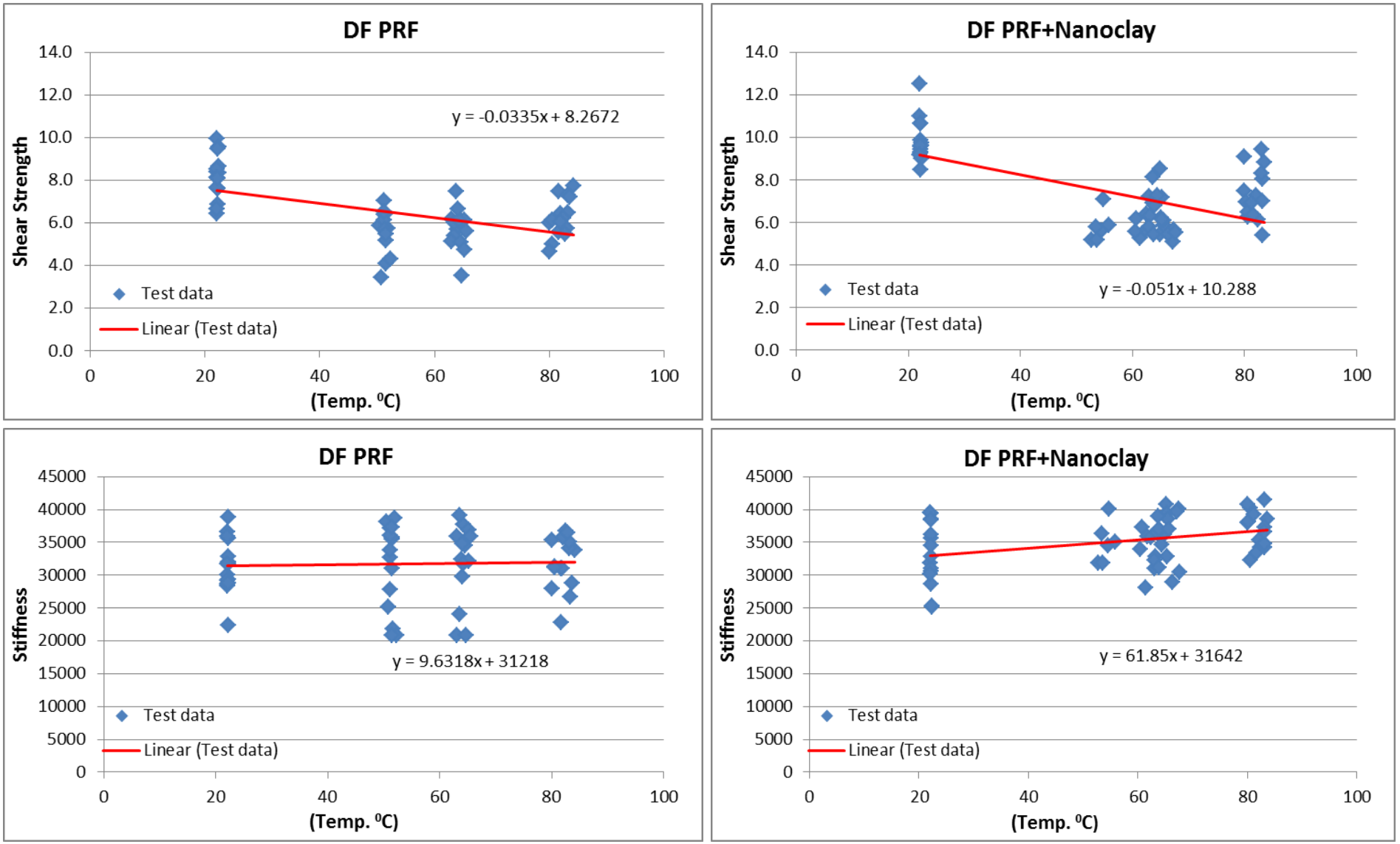
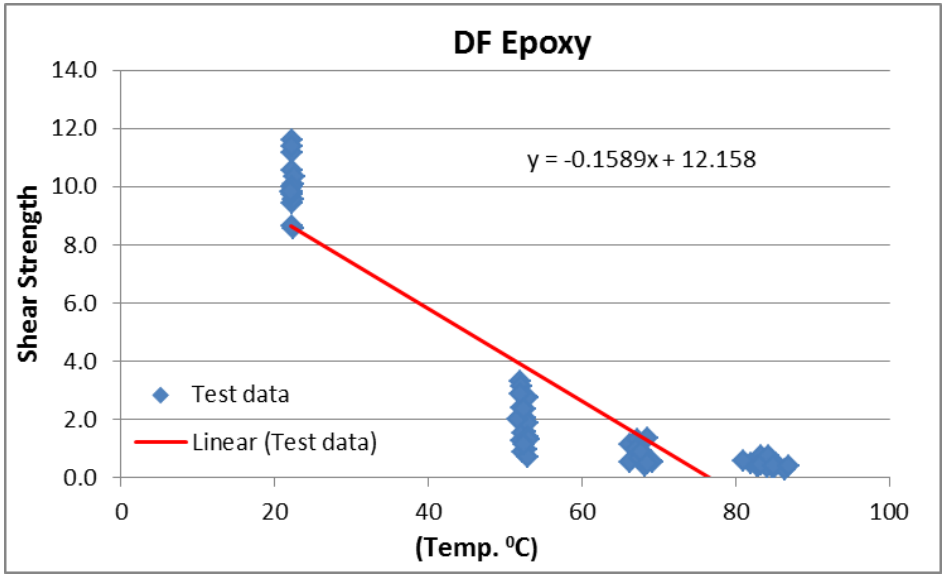


Figure 6. DF with PRF and Nanoclay



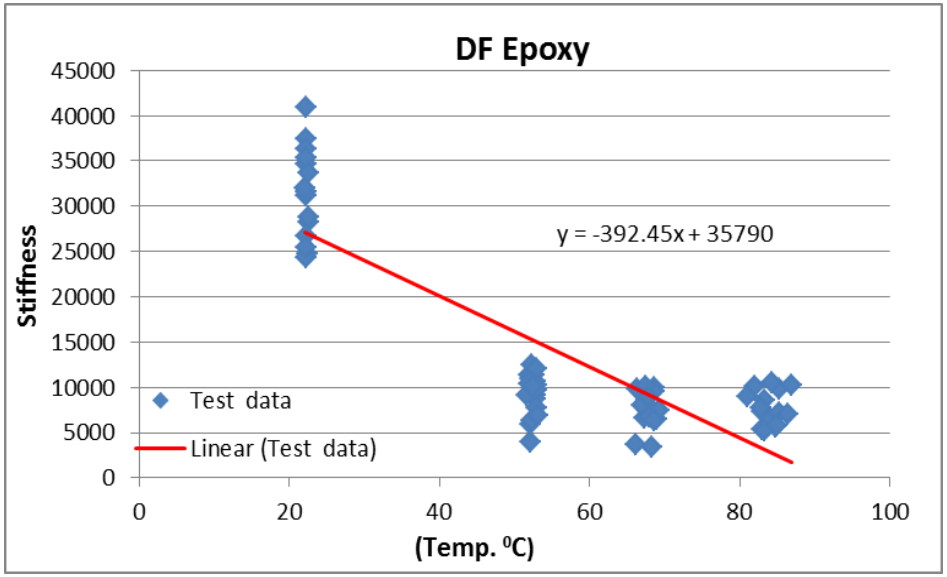


Figure 7. DF with Epoxy

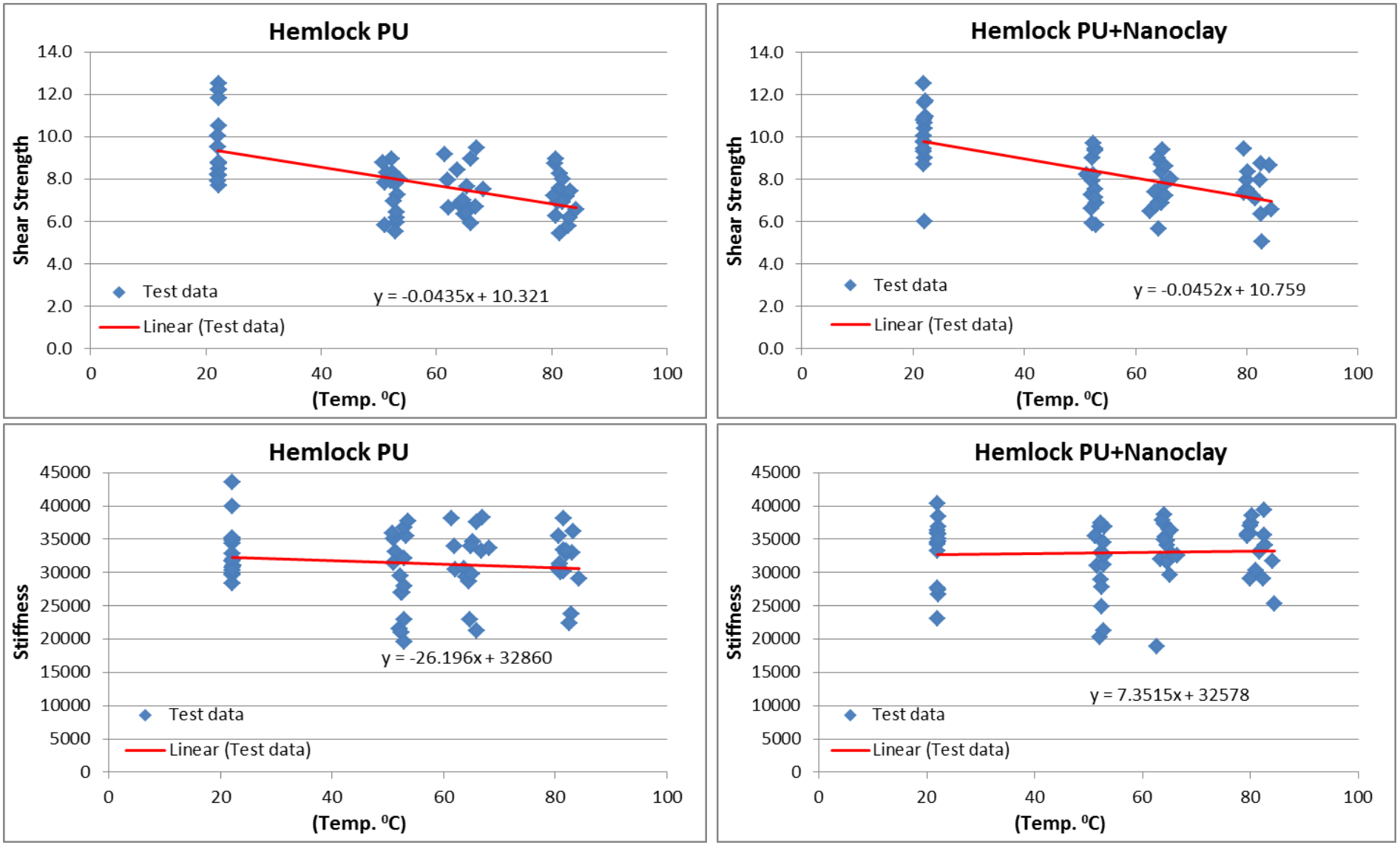


Figure 8. Hemlock with PU and Nanoclay

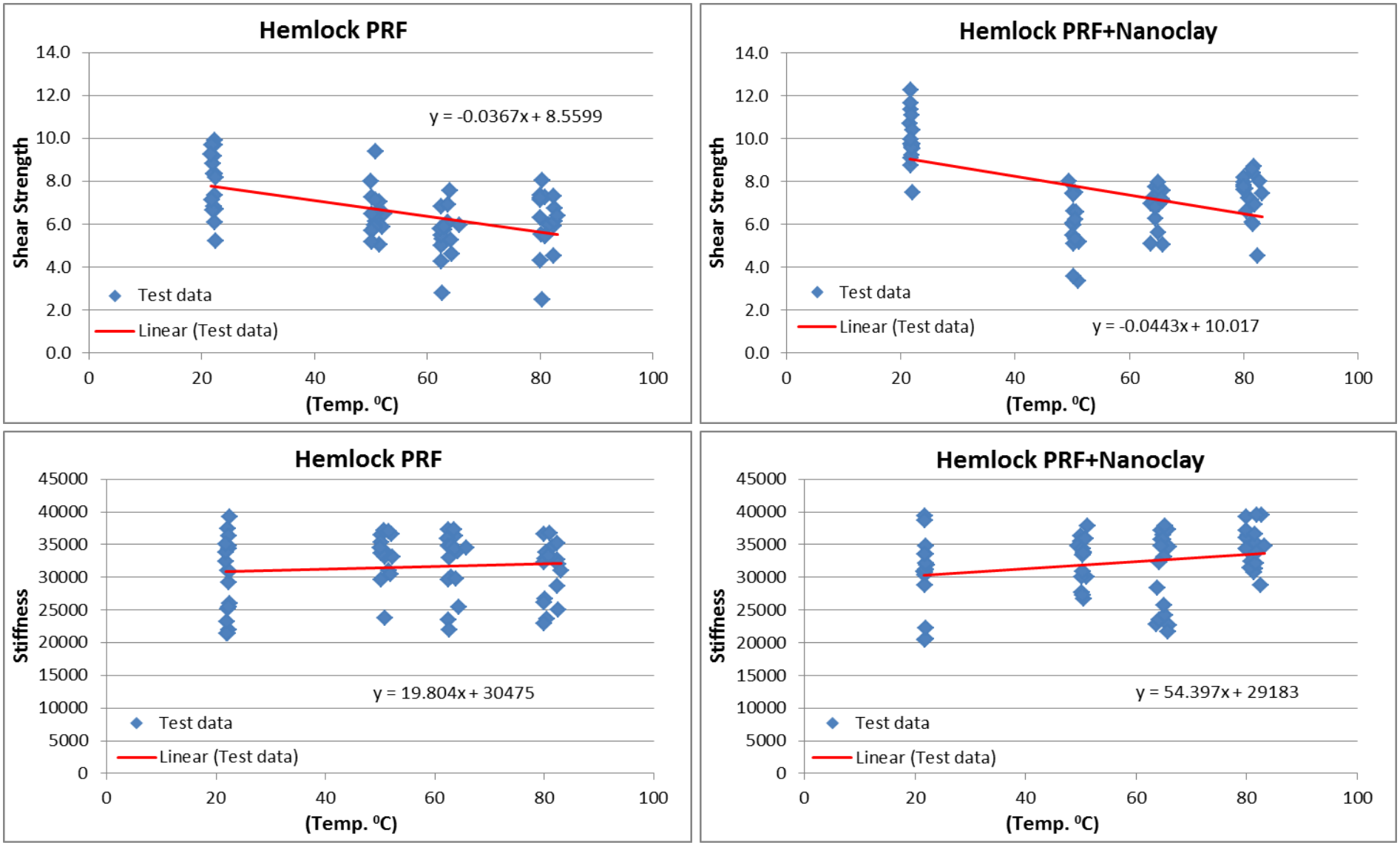
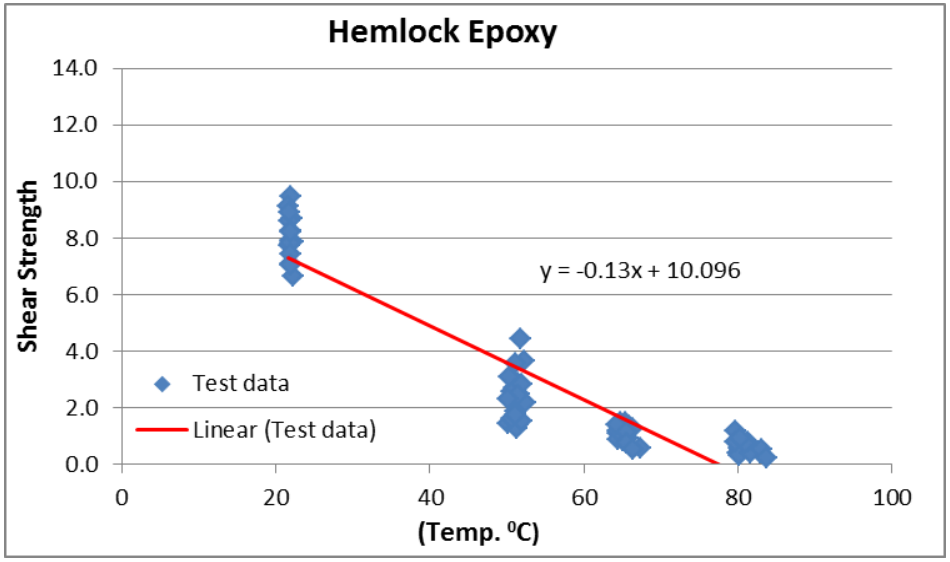


Figure 9. Hemlock with PRF and Nanoclay



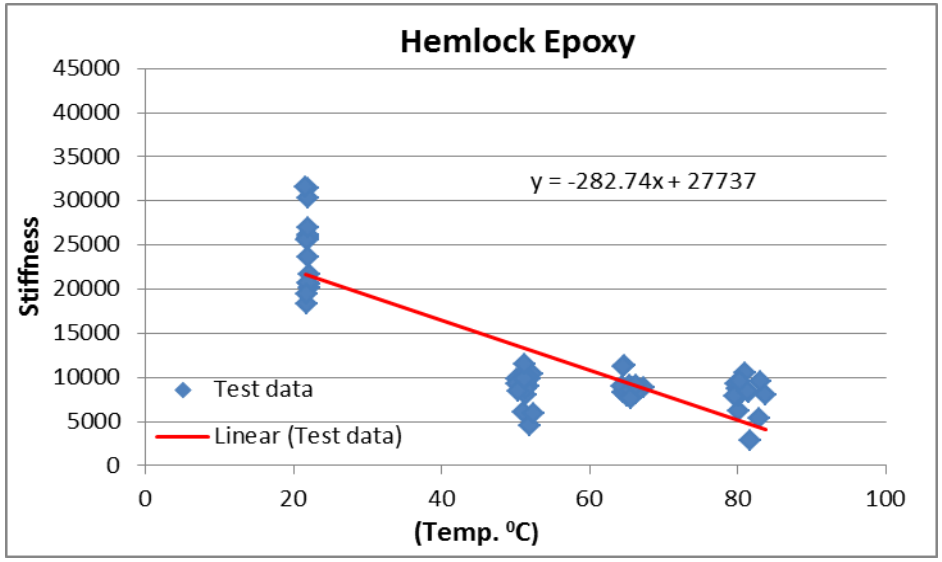


Figure 10. Hemlock with Epoxy

From Tables 5 to 7, the failure modes of three wood species by using PU and PRF with/without nanoclay treatment at 4 temperature levels (20 ℃, 60 ℃, 80 ℃ and 100 ℃) are governed by wood failure. Again these results should be considered with care as the original failure plane may different from the final open plane. The percentages of wood failure are over 60%. For the Epoxy case, all the bonding failure modes are glue failures when the temperature is above 20 ℃. That is the reason why the shear bonding capacity performed are sharply reduced in the Epoxy case when the temperature is above 20 ℃.

Refer to the Figures 2 to 10, the following conclusions have been drawn:

Shear Strength

- For PU adhesive with/without nanoclay treatment: the shear strength of the bonding blocks from three wood species was reduced with elevated temperatures. From the slope of the linear regression line in the various cases, it seems the contribution of nanoclay was minimal to enhance the shear strength performance at elevated temperature for the PU adhesive. It seems however the variability of the SPF PU specimens treated with nanoclay was reduced significantly. This is an important aspect that needs further verification for enhancement of performance.
- For PRF adhesive with/without nanoclay treatment: the shear strength of the bonding blocks from three wood species was reduced with elevated temperatures. From the slope of the linear regression line in the various cases, it seems the contribution of nanoclay was minimal to enhance the shear strength performance at elevated temperature for the PRF adhesive.
- The Epoxy adhesive: the shear strength and stiffness of the bonding blocks from three wood species are reduced sharply with the elevated temperatures. From room temperature to oven temperature of 100 ℃ the reduction in strength was close to 95%.

Shear Stiffness

- The influence of elevated temperature on the stiffness of the bond connection seemed minimal as such the nanoclay treatment was also non-effective.

5. REFERENCES

ASTM D 143 – 09. (2012) Test Methods for Small Clear Specimens of Timber. Annual Book of ASTM Standard, Vol. 04.10. ASTM International West Conshohocken, PA, USA.

ASTM D 905 – 08. (2008) Standard Test Methods for Strength Properties of Adhesive Bonds in Shear by Compression Loading. Annual Book of ASTM Standard, ASTM International West Conshohocken, PA, USA.

End