Supplemental Materials
IZOD impact properties of full-density FDM polymer materials with respect to raster angle and print orientation

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Abstract

This document presents the main dataset and supplemental materials for the IZOD tests described in the manuscript *Impact properties of full-density FDM polymer materials with respect to raster angle and print orientation.* In addition to the data, a image of a set of specimens, the details of the brief mass-density study, and the background review of the theoretical filament properties are given to complement the main text. The tables presented in Section 4 are the mean measured impact resistance, the mean measured impact energy, the standard deviations of both, and the coefficients of variation for each experimental case. This supplement is to accompany the main manuscript and to be used only in conjunction with it.

S1: Specimens

In this section, an image (Figure 1) of one set of the test specimens is given. These specimens have been manufactured, notched, and conditioned for testing.

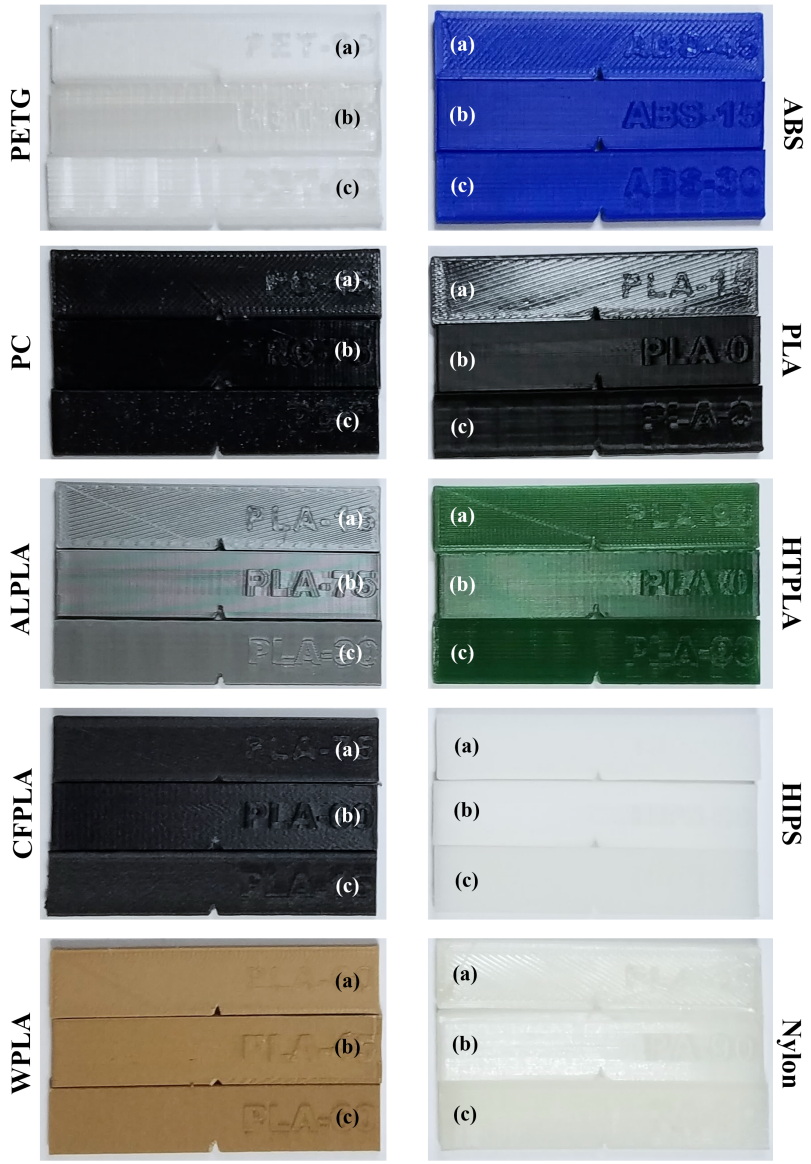

Figure 1: Example of IZOD samples after notching and conditioning. For each material, the three orientations (a) flat, (b) horizontal, and (c) vertical are shown

S2: Filament Datasheet Properties

The typical FDM mechanical properties of the materials used in this study are give in Table 1. Note that it was assumed that all the PLA-based materials have similar static mechanical properties; also note that nylon is a hyperelastic material, so it has little to no elastic modulus nor glass transition temperature. It is not known what the expected density of the composite PLA materials are, as no manufacturer datasheets were found. All of these data come from filament manufacturer datasheets, as available. The properties shown are the density ρ, the yield strength σ_y, the elastic modulus E, and the glass transition temperature GTT.

Table 1: Typical properties of FDM filaments from datasheets

	ρ (g/cc)	σ_y (MPa)	E (GPa)	GGT $(°C)$
ABS [1]	1.04	29	2.03	105
PLA [2]	1.24	36	2.30	60
HIPS [3]	1.04	19	1.55	97
Nylon [4]	1.15	45	–	–
PETG [5]	1.27	50	2.10	80
PC [6]	1.20	60	2.30	150

References

[1] Innofil3D, *ABS Technical Datasheet*, 2016. Available online: https://www.innofil3d.com/wp-content/uploads/2016/05/TDS-Innofil3D-ABS-160609.pdf.

[2] Hatchbox, *PLA Technical Datasheet*, 2017. Available online: https://www.sd3d.com/wp-content/uploads/2017/06/MaterialTDS-PLA_01.pdf.

[3] Innofil3D, *HIPS Technical Datasheet*, 2017. Available online: https://www.innofil3d.com/wp-content/uploads/2017/05/TDS-EN-Innofil3D-HiPS-170529.pdf.

[4] MaterialPro3D, *Nylon Technical Datasheet*, 2018. Available online: https://www.materialpro3d.cz/user/related_files/fillamentum_nylon_fx256_-_technical_data_sheet.pdf.

[5] Rigid.Ink, *PETG Technical Datasheet*, 2018. Available online: https://cdn.shopify.com/s/files/1/0714/6487/files/rigid.ink_PETG.pdf.

[6] Rigid.Ink, *Polycarbonate Technical Datasheet*, 2018. Available online: https://cdn.shopify.com/s/files/1/0714/6487/files/rigid.ink_Polycarbonate.pdf.

S3: Mass-Density Analysis Data and Results

The table (Figure 2) below gives the detailed inputs, calculations, and results of the mass-density study discussed in the paper. Three materials (one each from the brittle (PLA), semi-plastic (ABS), and the plastic (PC)) was selected for study. In each case, ten random samples (with no notches or markings or surface modifications) were taken for testing. The purpose and procedure of this test is discussed in-depth in the manuscript. The theoretical densities were taken from the analysis in Section 2 of this supplement.

Sample		Configuration	Dimensions (mm)			Volume	Volume	Density	Ideal	Measured	Percent of
			Z	C	E	(mm^3)	(cm^3)	(g/cm^3)	Mass (g)	Mass (g)	Ideal
1	ABS	45° Horizontal	3.34	63.45	12.74	2700	2.70	1.04	2.808	2.768	98.58%
2	ABS	75° Vertical	3.32	63.57	12.70	2680	2.68	1.04	2.788	2.755	98.83%
3	ABS	15° Flat	3.34	63.43	12.67	2684	2.68	1.04	2.792	2.776	99.44%
4	ABS	60° Flat	3.39	63.38	12.67	2722	2.72	1.04	2.831	2.823	99.71%
5	ABS	45° Horizontal	3.31	63.49	12.61	2650	2.65	1.04	2.756	2.711	98.37%
6	ABS	45° Flat	3.36	63.36	12.75	2714	2.71	1.04	2.823	2.816	99.76%
7	ABS	30° Vertical	3.29	63.68	12.72	2665	2.66	1.04	2.772	2.764	99.73%
8	ABS	60° Horizontal	3.32	63.43	12.56	2645	2.64	1.04	2.751	2.714	98.66%
9	ABS	45° Vertical	3.31	63.65	12.77	2690	2.69	1.04	2.798	2.791	99.75%
10	ABS	15° Flat	3.39	63.47	12.69	2730	2.73	1.04	2.840	2.820	99.31%
							ABS mean percent of theoretical mass				**99.21%**
							ABS stdev percent of theoretical mass				**0.55%**
11	PLA	30° Flat	3.11	63.40	12.65	2494	2.49	1.24	3.093	2.884	93.25%
12	PLA	60° Vertical	3.09	63.57	12.67	2489	2.49	1.24	3.086	2.876	93.19%
13	PLA	75° Vertical	3.10	63.53	12.66	2493	2.49	1.24	3.092	2.88	93.15%
14	PLA	75° Flat	3.17	63.37	12.54	2519	2.52	1.24	3.124	2.905	93.00%
15	PLA	0° Horizontal	3.18	63.36	12.62	2543	2.54	1.24	3.153	2.963	93.97%
16	PLA	90° Horizontal	3.12	63.72	12.59	2503	2.50	1.24	3.104	2.968	95.63%
17	PLA	75° Flat	3.14	63.29	12.56	2496	2.50	1.24	3.095	2.868	92.66%
18	PLA	15° Horizontal	3.19	63.20	12.59	2538	2.54	1.24	3.147	2.937	93.31%
19	PLA	0° Horizontal	3.18	63.35	12.54	2526	2.53	1.24	3.133	3.038	96.98%
20	PLA	75° Flat	3.16	63.31	12.55	2511	2.51	1.24	3.113	2.871	92.22%
							PLA mean percent of theoretical mass				**93.74%**
							PLA stdev percent of theoretical mass				**1.46%**
21	PC	0° Flat	3.22	63.43	12.58	2569	2.57	1.20	3.083	3.055	99.08%
22	PC	30° Vertical	3.32	63.46	12.76	2688	2.69	1.20	3.226	3.206	99.38%
23	PC	15° Vertical	3.32	63.33	12.76	2683	2.68	1.20	3.219	3.196	99.27%
24	PC	75° Flat	3.26	63.45	12.72	2631	2.63	1.20	3.157	3.145	99.61%
25	PC	90° Horizontal	3.15	63.35	12.60	2514	2.51	1.20	3.017	3.000	99.43%
26	PC	75° Vertical	3.33	63.60	12.71	2692	2.69	1.20	3.230	3.213	99.47%
27	PC	75° Horizontal	3.10	63.35	12.54	2463	2.46	1.20	2.955	2.922	98.88%
28	PC	30° Horizontal	3.32	63.48	12.58	2651	2.65	1.20	3.182	3.150	99.01%
29	PC	90° Flat	3.23	63.20	12.72	2597	2.60	1.20	3.116	3.077	98.75%
30	PC	15° Vertical	3.24	63.35	12.70	2607	2.61	1.20	3.128	3.105	99.26%
							PC mean percent of theoretical mass				**99.21%**
							PC stdev percent of theoretical mass				**0.28%**

Figure 2: Mass-density analysis results for random samples of ABS, PLA, and PC

S4: IZOD Tests Full Dataset

Table 2: Experimental results: Impact resistance

Material	Orientation	Mean Impact Resistance (J/m) for $n = 5$						
		Raster Angle						
		$0°$	$15°$	$30°$	$45°$	$60°$	$75°$	$90°$
ABS	Flat	127.68	124.38	132.76	160.87	133.66	111.71	109.77
	Horizontal	137.09	140.50	131.67	156.09	167.43	137.73	173.43
	Vertical	54.77	56.46	56.84	56.17	58.31	51.37	52.09
PLA	Flat	144.19	133.69	149.38	156.52	160.43	164.43	158.61
	Horizontal	108.45	92.00	113.63	122.82	119.32	127.86	108.39
	Vertical	94.19	62.30	67.35	85.07	85.80	87.63	59.57
HTPLA	Flat	140.48	145.80	133.74	129.45	138.21	142.97	147.23
	Horizontal	100.51	96.68	101.18	99.90	101.12	93.24	98.07
	Vertical	101.32	79.76	84.66	109.06	63.50	69.99	106.13
HIPS	Flat	117.44	113.77	162.90	212.07	165.17	126.14	105.27
	Horizontal	148.33	115.70	145.95	207.73	162.31	124.81	152.66
	Vertical	41.86	48.49	47.04	44.60	49.44	43.09	42.60
Nylon	Flat	262.62	422.97	343.51	171.89	514.57	254.92	303.83
	Horizontal	106.58	476.64	120.64	212.41	199.35	249.75	376.65
	Vertical	58.73	49.89	61.27	74.97	60.88	56.44	55.12
PETG	Flat	236.82	227.30	207.38	358.42	219.09	213.32	210.54
	Horizontal	253.23	165.44	130.99	204.10	164.23	127.62	201.01
	Vertical	30.50	30.50	35.43	38.46	40.39	33.31	39.56
PC	Flat	304.96	171.15	416.82	678.27	360.05	305.42	242.35
	Horizontal	602.88	377.53	450.97	477.00	553.88	499.20	642.88
	Vertical	38.66	43.67	39.55	48.23	44.57	44.55	34.95
ALPLA	Flat	99.49	92.00	89.52	93.88	93.49	90.77	92.61
	Horizontal	101.04	73.03	77.57	95.33	83.52	81.84	88.98
	Vertical	46.26	47.37	47.67	53.47	48.77	47.29	51.68
CFPLA	Flat	85.05	78.42	76.69	79.29	74.86	80.89	80.18
	Horizontal	80.95	73.43	80.80	84.39	77.98	81.75	83.86
	Vertical	40.07	39.97	46.96	42.84	41.50	40.20	36.67
WPLA	Flat	125.55	122.40	119.90	114.02	113.23	131.38	143.57
	Horizontal	98.13	92.61	95.30	98.90	93.69	106.37	114.52
	Vertical	30.41	28.56	29.23	31.19	31.41	27.88	27.53

Table 3: Experimental results: Impact resistance

Material	Orientation	Standard Deviation of Impact Resistance (J/m) for $n = 5$						
		Raster Angle						
		$0°$	$15°$	$30°$	$45°$	$60°$	$75°$	$90°$
ABS	Flat	13.56	9.97	16.28	25.48	23.36	4.72	14.05
	Horizontal	10.67	12.78	11.72	22.32	10.71	16.29	35.79
	Vertical	4.78	8.18	6.35	7.38	9.11	6.84	1.90
PLA	Flat	14.09	3.09	3.90	12.24	11.28	5.98	5.13
	Horizontal	6.19	7.28	9.23	5.84	5.92	4.95	9.87
	Vertical	26.33	7.75	4.24	15.34	20.41	12.54	5.13
HTPLA	Flat	15.62	12.48	7.63	20.76	8.83	8.32	28.46
	Horizontal	13.69	15.67	7.62	14.47	9.94	9.10	11.02
	Vertical	21.72	34.42	14.36	42.72	25.78	5.19	32.45
HIPS	Flat	7.07	34.39	34.47	26.02	25.87	13.87	9.52
	Horizontal	5.67	9.99	13.75	54.53	6.22	12.82	9.01
	Vertical	4.64	3.65	6.30	5.54	2.43	2.56	5.90
Nylon	Flat	77.72	123.79	78.32	6.36	111.48	66.47	57.12
	Horizontal	12.82	54.28	35.30	63.89	69.79	125.45	186.41
	Vertical	12.33	2.72	5.66	4.02	8.93	6.54	9.99
PETG	Flat	9.02	12.53	38.99	20.03	20.67	19.44	20.52
	Horizontal	16.73	16.04	11.65	19.60	5.98	23.94	34.77
	Vertical	3.93	3.93	7.76	7.20	3.43	2.35	5.42
PC	Flat	53.17	43.10	37.84	44.56	87.51	26.98	77.99
	Horizontal	50.16	146.03	197.80	66.62	48.90	164.64	38.14
	Vertical	3.42	6.38	4.72	13.43	7.27	3.81	2.43
ALPLA	Flat	6.79	5.28	10.31	7.60	5.29	4.10	5.67
	Horizontal	8.28	6.78	2.19	9.84	5.62	11.02	4.20
	Vertical	2.33	3.90	6.69	6.65	5.43	1.98	26.54
CFPLA	Flat	3.94	12.56	10.43	5.05	7.28	5.54	3.49
	Horizontal	4.06	12.99	12.99	7.50	4.55	18.83	6.38
	Vertical	0.87	2.99	7.75	4.79	3.84	4.20	1.21
WPLA	Flat	14.30	7.92	9.16	7.13	11.10	11.79	9.89
	Horizontal	14.23	8.22	19.40	15.67	17.01	6.94	9.19
	Vertical	0.15	1.91	3.24	3.24	1.14	2.84	1.73

Table 4: Experimental results: Impact energy

Material	Orientation	Mean Impact Energy (J/m^2) for $n = 5$						
		Raster Angle						
		$0°$	$15°$	$30°$	$45°$	$60°$	$75°$	$90°$
ABS	Flat	12,558	12,238	13,070	15,819	13,151	10,991	10,797
	Horizontal	13,488	13,815	12,955	15,354	16,470	13,546	17,064
	Vertical	5,389	5,557	5,593	5,527	5,739	5,054	5,129
PLA	Flat	14,184	13,150	14,688	15,402	15,787	16,224	15,617
	Horizontal	10,656	9,049	11,182	12,079	11,741	12,592	10,661
	Vertical	9,264	6,130	6,627	8,378	8,449	8,623	5,865
HTPLA	Flat	13,827	14,342	13,153	12,723	13,606	14,064	14,500
	Horizontal	9,890	9,513	9,955	9,824	9,953	9,175	9,653
	Vertical	9,973	7,857	8,336	10,731	6,245	6,885	10,446
HIPS	Flat	11,564	11,195	16,036	20,890	16,262	12,419	10,373
	Horizontal	14,600	11,390	14,348	20,441	15,985	12,281	15,002
	Vertical	4,119	4,769	4,634	4,388	4,862	4,241	4,190
Nylon	Flat	25,861	41,648	33,800	16,922	50,611	25,087	29,889
	Horizontal	10,507	46,968	11,866	20,891	19,604	24,539	37,014
	Vertical	5,778	4,909	6,025	7,372	5,987	5,555	5,423
PETG	Flat	23,304	22,364	20,397	35,277	21,580	20,999	20,751
	Horizontal	24,904	16,292	12,895	20,097	16,174	12,559	19,797
	Vertical	2,997	2,997	3,494	3,786	3,974	3,276	3,894
PC	Flat	30,017	16,855	41,028	66,707	35,437	30,061	23,852
	Horizontal	59,302	37,162	44,396	46,971	54,496	49,168	63,329
	Vertical	3,811	4,301	3,894	4,751	4,383	4,386	3,437
ALPLA	Flat	9,793	9.055	8.819	9,233	9,207	8,929	9,119
	Horizontal	9,937	7,177	7,638	9,379	8,218	8,052	8,754
	Vertical	4,550	4,661	4,693	5,258	4,799	4,656	5,085
CFPLA	Flat	8,366	7,731	7,546	7,809	7,373	7,957	7,888
	Horizontal	7,969	7,225	7,953	8,301	7,669	8,039	8,260
	Vertical	3,945	3,930	4,619	4,216	4,086	3,955	3,609
WPLA	Flat	12,361	12,064	11,792	11,225	11,138	12,915	14,143
	Horizontal	9,642	9,120	9,383	9,727	9,217	10,472	11,281
	Vertical	2,994	2,813	2,880	3,068	3,094	2,747	2,708

Table 5: Experimental results: Impact energy

Material	Orientation	Standard Deviation of Impact Energy (J/m^2) for $n = 5$						
		Raster Angle						
		$0°$	$15°$	$30°$	$45°$	$60°$	$75°$	$90°$
ABS	Flat	1,335	981	1,607	2,508	2,302	462	1,374
	Horizontal	1,048	1,256	1,157	2,194	1,054	1,608	3,503
	Vertical	472	807	618	731	895	672	183
PLA	Flat	1,385	301	378	1,197	1,113	581	512
	Horizontal	607	729	913	579	577	481	976
	Vertical	2,582	760	414	1,518	2,006	1,220	498
HTPLA	Flat	1,533	1,226	756	2,040	863	818	2,807
	Horizontal	1,340	1,532	760	1,425	987	899	1,089
	Vertical	2,129	3,390	1,403	4,194	2,539	518	3,199
HIPS	Flat	704	3,397	3,393	2,563	2,535	1,254	933
	Horizontal	554	993	1,343	5,358	621	1,251	880
	Vertical	455	354	625	549	239	255	580
Nylon	Flat	7,647	12,157	7,718	633	10,938	6,582	5,629
	Horizontal	1,269	5,342	3,479	6,272	6,837	12,345	18,332
	Vertical	1,208	262	561	396	871	652	982
PETG	Flat	871	1,238	3,842	1,966	2,019	1,900	2,024
	Horizontal	1,620	1,571	1,146	1,929	589	2,361	3,403
	Vertical	386	386	769	704	339	231	537
PC	Flat	5,211	4,255	3,746	4,380	8,637	2,656	7,667
	Horizontal	4,906	14,400	19,486	6,518	4,841	16,228	3,820
	Vertical	339	627	468	1,322	711	371	243
ALPLA	Flat	678	521	1,015	749	529	400	549
	Horizontal	804	664	218	967	547	1,082	4.15
	Vertical	229	384	658	651	537	196	2,613
CFPLA	Flat	388	1,241	1,024	500	718	543	355
	Horizontal	398	1,275	1,280	730	446	1,855	631
	Vertical	81	296	758	472	375	417	124
WPLA	Flat	1,413	784	899	698	1,090	1,154	951
	Horizontal	1,394	816	1,929	1,544	1,682	683	891
	Vertical	13	189	320	318	111	282	171

Table 6: Experimental results: Coefficient of Variation

Material	Orientation	Coefficient of Variation Raster Angle						
		0°	15°	30°	45°	60°	75°	90°
ABS	Flat	0.106	0.080	0.123	0.158	0.175	0.042	0.128
	Horizontal	0.078	0.091	0.089	0.143	0.064	0.118	0.206
	Vertical	0.087	0.145	0.112	0.131	0.156	0.133	0.036
PLA	Flat	0.098	0.023	0.026	0.078	0.070	0.036	0.032
	Horizontal	0.057	0.079	0.081	0.048	0.050	0.039	0.091
	Vertical	0.280	0.124	0.063	0.180	0.238	0.142	0.086
HTPLA	Flat	0.111	0.086	0.057	0.160	0.064	0.058	0.193
	Horizontal	0.136	0.162	0.075	0.145	0.098	0.098	0.112
	Vertical	0.214	0.432	0.170	0.392	0.406	0.074	0.306
HIPS	Flat	0.060	0.302	0.212	0.123	0.157	0.110	0.090
	Horizontal	0.038	0.086	0.094	0.263	0.038	0.103	0.059
	Vertical	0.111	0.075	0.134	0.124	0.049	0.059	0.139
Nylon	Flat	0.296	0.293	0.228	0.037	0.217	0.261	0.188
	Horizontal	0.120	0.114	0.293	0.301	0.350	0.502	0.495
	Vertical	0.210	0.055	0.092	0.054	0.147	0.116	0.181
PETG	Flat	0.038	0.055	0.188	0.056	0.094	0.091	0.097
	Horizontal	0.066	0.097	0.089	0.096	0.036	0.188	0.173
	Vertical	0.129	0.129	0.219	0.187	0.085	0.071	0.137
PC	Flat	0.174	0.252	0.091	0.066	0.243	0.088	0.322
	Horizontal	0.038	0.387	0.439	0.140	0.088	0.330	0.059
	Vertical	0.088	0.146	0.119	0.278	0.163	0.085	0.070
ALPLA	Flat	0.068	0.057	0.115	0.081	0.057	0.045	0.061
	Horizontal	0.082	0.093	0.028	0.103	0.067	0.135	0.047
	Vertical	0.050	0.082	0.140	0.124	0.111	0.042	0.514
CFPLA	Flat	0.046	0.160	0.136	0.064	0.097	0.068	0.045
	Horizontal	0.050	0.177	0.161	0.089	0.058	0.230	0.076
	Vertical	0.022	0.075	0.165	0.112	0.092	0.105	0.033
WPLA	Flat	0.114	0.065	0.076	0.063	0.098	0.090	0.069
	Horizontal	0.145	0.089	0.204	0.158	0.182	0.065	0.080
	Vertical	0.005	0.067	0.111	0.104	0.036	0.102	0.063