Supplementary Materials for

"Mechanical and Tribological Properties of FFF-Printed TPU 95A with Uniform and Step-Gradient Infill Architectures"

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This file contains Supplementary Figures and Supplementary Tables S1–S10. Raw tensile and compression stress–strain data are provided as separate CSV files: Data S1 (tensile) and Data S2 (compression).

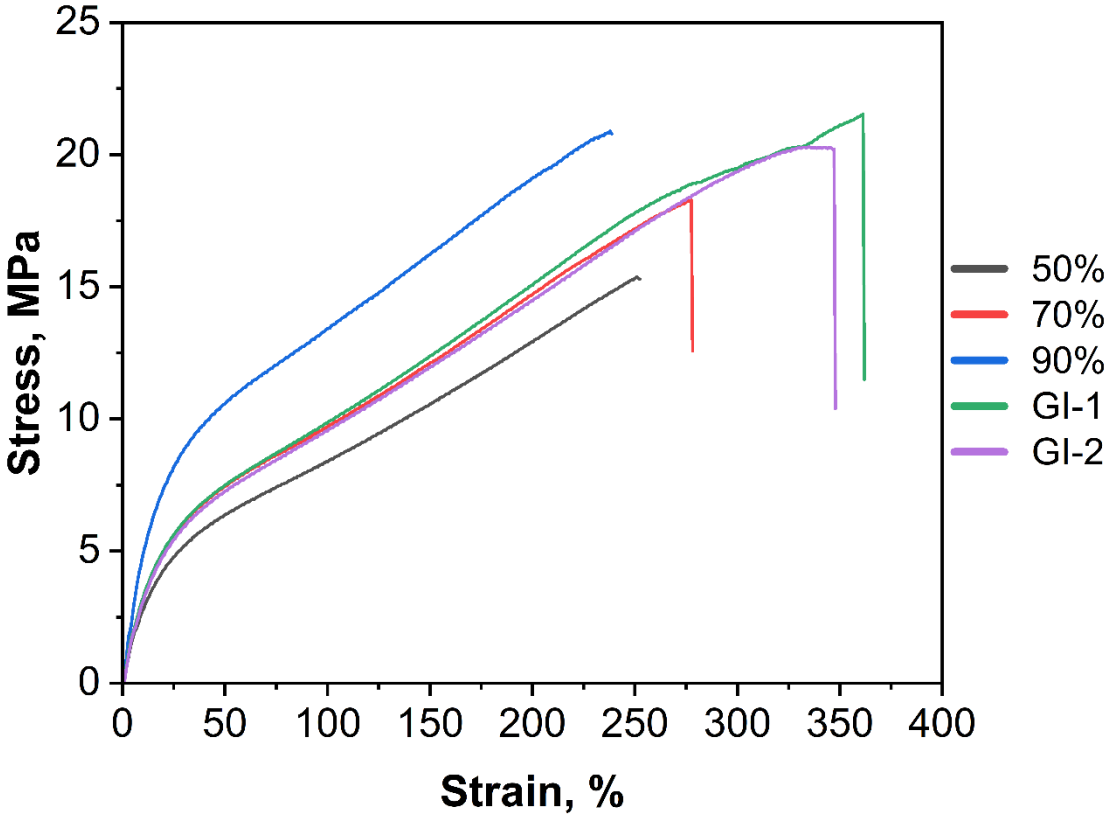

Figure S1. Representative tensile stress–strain curves for TPU 95A specimens with uniform and step-gradient infill architectures.

Supplementary Table S1. Individual tensile strength, elongation at break, and work of deformation to failure values for TPU 95A specimens with uniform and step-gradient infill architectures

Specimen ID	Tensile strength, MPa	Elongation at break, %	Work of deformation to failure, MJ/m^3
Uniform 50%-1	16.48	261.73	26.509
Uniform 50%-2	15.38	250.50	23.880
Uniform 50%-3	15.44	254.56	24.440
Uniform 50%-4	14.37	213.99	20.007
Uniform 50%-5	15.27	235.45	22.922
Uniform 70%-1	19.18	282.98	33.811
Uniform 70%-2	18.20	255.32	31.941
Uniform 70%-3	18.32	290.58	30.919
Uniform 70%-4	18.28	276.25	35.019
Uniform 70%-5	17.96	273.21	29.852
Uniform 90%-1	21.40	245.66	30.242
Uniform 90%-2	20.89	236.70	32.736
Uniform 90%-3	19.28	236.42	31.264
Uniform 90%-4	19.65	249.59	35.580
Uniform 90%-5	19.49	242.51	33.656
GI-1-1	21.37	349.06	48.574
GI-1-2	21.24	345.86	47.219
GI-1-3	21.54	360.01	45.223
GI-1-4	20.90	344.61	43.459
GI-1-5	22.22	370.17	43.303
GI-2-1	21.06	359.91	46.976
GI-2-2	20.51	359.72	46.401
GI-2-3	20.29	345.87	49.517
GI-2-4	19.99	340.00	46.366
GI-2-5	19.82	341.03	52.150

Supplementary Table S2. Descriptive and inferential statistical analysis of the tensile properties of TPU 95A specimens with uniform and step-gradient infill architectures

Part A. Descriptive statistics and 95 % confidence intervals

Outcome	Configuration	n	Mean	SD	95 % CI for the mean
Tensile strength, MPa	Uniform 50%	5	15.388	0.749	14.458 to 16.318
Tensile strength, MPa	Uniform 70%	5	18.388	0.464	17.812 to 18.964
Tensile strength, MPa	Uniform 90%	5	20.142	0.942	18.972 to 21.312
Tensile strength, MPa	GI-1	5	21.454	0.488	20.848 to 22.060
Tensile strength, MPa	GI-2	5	20.334	0.485	19.731 to 20.937
Elongation at break, %	Uniform 50%	5	243.246	18.967	219.696 to 266.797
Elongation at break, %	Uniform 70%	5	275.668	13.193	259.286 to 292.050
Elongation at break, %	Uniform 90%	5	242.176	5.708	235.088 to 249.264
Elongation at break, %	GI-1	5	353.942	10.913	340.391 to 367.493
Elongation at break, %	GI-2	5	349.306	9.846	337.080 to 361.532
Work of deformation to failure, MJ/m^3	Uniform 50%	5	23.552	2.377	20.600 to 26.503
Work of deformation to failure, MJ/m^3	Uniform 70%	5	32.308	2.104	29.696 to 34.921
Work of deformation to failure, MJ/m^3	Uniform 90%	5	32.696	2.080	30.112 to 35.279
Work of deformation to failure, MJ/m^3	GI-1	5	45.556	2.316	42.680 to 48.431
Work of deformation to failure, MJ/m^3	GI-2	5	48.282	2.520	45.153 to 51.411

Part B. One-way ANOVA results

Outcome	Source of variation	SS	df	MS	F	p-value
Tensile strength, MPa	Between configurations	112.136	4	28.034	65.529	<0.001
	Within configurations	8.556	20	0.428	-	-
	Total	120.692	24	-	-	-
Elongation at break, %	Between configurations	61215.715	4	15303.929	97.796	<0.001
	Within configurations	3129.770	20	156.489	-	-
	Total	64345.485	24	-	-	-
Work of deformation to failure, MJ/m^3	Between configurations	2102.606	4	525.651	100.621	<0.001
	Within configurations	104.481	20	5.224	-	-
	Total	2207.087	24	-	-	-

Part C. Complete Tukey HSD pairwise comparisons

Outcome	Comparison	Mean difference	Simultaneous 95 % CI	Tukey-adjusted p-value	Significant
Tensile strength, MPa	GI-1 − GI-2	1.120	−0.118 to 2.358	0.0882	No
Tensile strength, MPa	GI-1 − Uniform 50%	6.066	4.828 to 7.304	<0.001	Yes
Tensile strength, MPa	GI-1 − Uniform 70%	3.066	1.828 to 4.304	<0.001	Yes
Tensile strength, MPa	GI-1 − Uniform 90%	1.312	0.074 to 2.550	0.0345	Yes

Tensile strength, MPa	GI-2 − Uniform 50%	4.946	3.708 to 6.184	<0.001	Yes
Tensile strength, MPa	GI-2 − Uniform 70%	1.946	0.708 to 3.184	0.0011	Yes
Tensile strength, MPa	GI-2 − Uniform 90%	0.192	−1.046 to 1.430	0.9897	No
Tensile strength, MPa	Uniform 70% − Uniform 50%	3.000	1.762 to 4.238	<0.001	Yes
Tensile strength, MPa	Uniform 90% − Uniform 50%	4.754	3.516 to 5.992	<0.001	Yes
Tensile strength, MPa	Uniform 90% − Uniform 70%	1.754	0.516 to 2.992	0.0033	Yes
Elongation at break, %	GI-1 − GI-2	4.636	−19.039 to 28.311	0.9756	No
Elongation at break, %	GI-1 − Uniform 50%	110.696	87.021 to 134.371	<0.001	Yes
Elongation at break, %	GI-1 − Uniform 70%	78.274	54.599 to 101.949	<0.001	Yes
Elongation at break, %	GI-1 − Uniform 90%	111.766	88.091 to 135.441	<0.001	Yes
Elongation at break, %	GI-2 − Uniform 50%	106.060	82.385 to 129.735	<0.001	Yes
Elongation at break, %	GI-2 − Uniform 70%	73.638	49.963 to 97.313	<0.001	Yes
Elongation at break, %	GI-2 − Uniform 90%	107.130	83.455 to 130.805	<0.001	Yes
Elongation at break, %	Uniform 70% − Uniform 50%	32.422	8.747 to 56.097	0.0045	Yes
Elongation at break, %	Uniform 90% − Uniform 50%	−1.070	−24.745 to 22.605	0.9999	No
Elongation at break, %	Uniform 90% − Uniform 70%	−33.492	−57.167 to −9.817	0.0033	Yes
Work of deformation to failure, MJ/m^3	GI-1 − GI-2	−2.7264	−7.0520 to 1.5992	0.3561	No
Work of deformation to failure, MJ/m^3	GI-1 − Uniform 50%	22.0040	17.6784 to 26.3296	<0.001	Yes
Work of deformation to failure, MJ/m^3	GI-1 − Uniform 70%	13.2472	8.9216 to 17.5728	<0.001	Yes
Work of deformation to failure, MJ/m^3	GI-1 − Uniform 90%	12.8600	8.5344 to 17.1856	<0.001	Yes
Work of deformation to failure, MJ/m^3	GI-2 − Uniform 50%	24.7304	20.4048 to 29.0560	<0.001	Yes
Work of deformation to failure, MJ/m^3	GI-2 − Uniform 70%	15.9736	11.6480 to 20.2992	<0.001	Yes
Work of deformation to failure, MJ/m^3	GI-2 − Uniform 90%	15.5864	11.2608 to 19.9120	<0.001	Yes
Work of deformation to failure, MJ/m^3	Uniform 70% − Uniform 50%	8.7568	4.4312 to 13.0824	0.0001	Yes
Work of deformation to failure, MJ/m^3	Uniform 90% − Uniform 50%	9.1440	4.8184 to 13.4696	<0.001	Yes

Work of deformation to failure, MJ/m^3	Uniform 90% − Uniform 70%	0.3872	−3.9384 to 4.7128	0.9988	No

Notes: Values in Part A are reported as the mean, sample standard deviation (SD), and two-sided 95 % confidence interval for the group mean (n = 5 independently printed specimens per configuration). Tensile strength, elongation at break, and work of deformation to failure were analyzed in separate one-way ANOVAs, with infill configuration as the between-specimen factor. After each significant omnibus test, all pairwise comparisons were performed using Tukey's HSD procedure. Mean differences in Part C are the mean of the first configuration minus the mean of the second. The pairwise confidence intervals are simultaneous 95 % intervals, and the p-values are Tukey-adjusted at a family-wise significance level of $\alpha = 0.05$. A difference was considered statistically significant when the simultaneous 95 % CI did not include zero. For elongation at break, mean differences are given in percentage points. Work of deformation to failure was obtained for each specimen as the area under its complete tensile stress–strain curve up to failure. For this outcome, the ANOVA residuals did not depart significantly from normality (Shapiro–Wilk $W = 0.953$, $p = 0.289$), and no significant variance heterogeneity was detected (Brown–Forsythe $F = 0.030$, $p = 0.998$). Standard deviations are sample standard deviations (denominator $n - 1$).

Supplementary Table S3. Individual compressive stress values at relative strains of 5 %, 10 %, and 20 % for TPU 95A specimens with uniform and step-gradient infill architectures

Specimen ID	Compressive stress at 5 % strain, MPa	Compressive stress at 10 % strain, MPa	Compressive stress at 20 % strain, MPa
Uniform 50%-1	1.29717	2.51291	4.49303
Uniform 50%-2	1.34561	2.58917	4.62642
Uniform 50%-3	1.32988	2.58493	4.61623
Uniform 50%-4	1.35257	2.59807	4.59551
Uniform 50%-5	1.35617	2.60035	4.59185
Uniform 70%-1	1.60668	3.13091	5.84873
Uniform 70%-2	1.62705	3.1608	5.90404
Uniform 70%-3	1.46861	3.00881	5.74487
Uniform 70%-4	1.60003	3.11381	5.81506
Uniform 70%-5	1.61188	3.1351	5.86829
Uniform 90%-1	1.80635	3.5609	6.70865
Uniform 90%-2	1.80495	3.59465	6.77682
Uniform 90%-3	1.76538	3.5176	6.64783
Uniform 90%-4	1.77641	3.52274	6.66253
Uniform 90%-5	1.79034	3.57153	6.76679
GI-1-1	1.54676	3.014	4.69558
GI-1-2	1.57024	3.00795	4.74041
GI-1-3	1.54397	2.99199	4.6709
GI-1-4	1.53886	2.98604	4.62055
GI-1-5	1.56432	3.00127	4.55387
GI-2-1	1.45152	2.78882	4.53791
GI-2-2	1.4461	2.78579	4.52288
GI-2-3	1.45138	2.79779	4.51161
GI-2-4	1.43359	2.75244	4.44483
GI-2-5	1.43124	2.78183	4.54709

Supplementary Table S4. Descriptive and inferential statistical analysis of compressive stress at 5 %, 10 %, and 20 % strain for TPU 95A specimens with uniform and step-gradient infill architectures

Part A. Descriptive statistics and 95 % confidence intervals

Relative strain	Configuration	n	Mean compressive stress, MPa	SD, MPa	95 % CI for the mean, MPa
5%	Uniform 50%	5	1.3363	0.0241	1.3064 to 1.3662
5%	Uniform 70%	5	1.5829	0.0646	1.5026 to 1.6631
5%	Uniform 90%	5	1.7887	0.0178	1.7665 to 1.8108
5%	GI-1	5	1.5528	0.0137	1.5359 to 1.5698
5%	GI-2	5	1.4428	0.0097	1.4307 to 1.4549
10%	Uniform 50%	5	2.5771	0.0364	2.5319 to 2.6223
10%	Uniform 70%	5	3.1099	0.0590	3.0367 to 3.1831
10%	Uniform 90%	5	3.5535	0.0328	3.5127 to 3.5942
10%	GI-1	5	3.0003	0.0114	2.9861 to 3.0144
10%	GI-2	5	2.7813	0.0172	2.7600 to 2.8027
20%	Uniform 50%	5	4.5846	0.0532	4.5186 to 4.6506
20%	Uniform 70%	5	5.8362	0.0604	5.7612 to 5.9112
20%	Uniform 90%	5	6.7125	0.0587	6.6396 to 6.7854
20%	GI-1	5	4.6563	0.0718	4.5672 to 4.7454
20%	GI-2	5	4.5129	0.0404	4.4627 to 4.5630

Part B. Separate one-way ANOVA results

Outcome	Source of variation	SS	df	MS	F	p-value
Compressive stress at 5% strain	Between configurations	0.573997	4	0.143499	133.945	<0.001
	Within configurations	0.021427	20	0.001071	—	—
	Total	0.595424	24	—	—	—
Compressive stress at 10% strain	Between configurations	2.724967	4	0.681242	540.263	<0.001
	Within configurations	0.025219	20	0.001261	—	—
	Total	2.750186	24	—	—	—
Compressive stress at 20% strain	Between configurations	19.103475	4	4.775869	1430.085	<0.001
	Within configurations	0.066791	20	0.003340	—	—
	Total	19.170266	24	—	—	—

Part C. Complete Tukey HSD pairwise comparisons

Compressive stress at 5 % strain

Comparison	Mean difference, MPa	Simultaneous 95 % CI, MPa	Tukey-adjusted p-value	Significant
GI-1 − GI-2	0.110064	0.048119 to 0.172009	<0.001	Yes
GI-1 − Uniform 50%	0.216550	0.154605 to 0.278495	<0.001	Yes
GI-1 − Uniform 70%	−0.030020	−0.091965 to 0.031925	0.6043	No
GI-1 − Uniform 90%	−0.235856	−0.297801 to −0.173911	<0.001	Yes
GI-2 − Uniform 50%	0.106486	0.044541 to 0.168431	<0.001	Yes
GI-2 − Uniform 70%	−0.140084	−0.202029 to −0.078139	<0.001	Yes
GI-2 − Uniform 90%	−0.345920	−0.407865 to −0.283975	<0.001	Yes
Uniform 70% − Uniform 50%	0.246570	0.184625 to 0.308515	<0.001	Yes
Uniform 90% − Uniform 50%	0.452406	0.390461 to 0.514351	<0.001	Yes
Uniform 90% − Uniform 70%	0.205836	0.143891 to 0.267781	<0.001	Yes

Compressive stress at 10 % strain

Comparison	Mean difference, MPa	Simultaneous 95 % CI, MPa	Tukey-adjusted p-value	Significant
GI-1 − GI-2	0.218916	0.151712 to 0.286120	<0.001	Yes
GI-1 − Uniform 50%	0.423164	0.355960 to 0.490368	<0.001	Yes
GI-1 − Uniform 70%	−0.109636	−0.176840 to −0.042432	<0.001	Yes
GI-1 − Uniform 90%	−0.553234	−0.620438 to −0.486030	<0.001	Yes
GI-2 − Uniform 50%	0.204248	0.137044 to 0.271452	<0.001	Yes
GI-2 − Uniform 70%	−0.328552	−0.395756 to −0.261348	<0.001	Yes
GI-2 − Uniform 90%	−0.772150	−0.839354 to −0.704946	<0.001	Yes
Uniform 70% − Uniform 50%	0.532800	0.465596 to 0.600004	<0.001	Yes
Uniform 90% − Uniform 50%	0.976398	0.909194 to 1.043602	<0.001	Yes
Uniform 90% − Uniform 70%	0.443598	0.376394 to 0.510802	<0.001	Yes

Compressive stress at 20 % strain

Comparison	Mean difference, MPa	Simultaneous 95 % CI, MPa	Tukey-adjusted p-value	Significant
GI-1 − GI-2	0.143398	0.034030 to 0.252766	0.0067	Yes
GI-1 − Uniform 50%	0.071654	−0.037714 to 0.181022	0.3199	No
GI-1 − Uniform 70%	−1.179936	−1.289304 to −1.070568	<0.001	Yes
GI-1 − Uniform 90%	−2.056262	−2.165630 to −1.946894	<0.001	Yes
GI-2 − Uniform 50%	−0.071744	−0.181112 to 0.037624	0.3187	No
GI-2 − Uniform 70%	−1.323334	−1.432702 to −1.213966	<0.001	Yes
GI-2 − Uniform 90%	−2.199660	−2.309028 to −2.090292	<0.001	Yes
Uniform 70% − Uniform 50%	1.251590	1.142222 to 1.360958	<0.001	Yes
Uniform 90% − Uniform 50%	2.127916	2.018548 to 2.237284	<0.001	Yes
Uniform 90% − Uniform 70%	0.876326	0.766958 to 0.985694	<0.001	Yes

Notes: Values in Part A are reported as the mean, sample standard deviation (SD), and two-sided 95 % confidence interval for the group mean (n = 5 independently printed specimens per configuration). Compressive stress at 5 %, 10 %, and 20 % strain was analyzed in separate one-way ANOVAs, followed by Tukey's HSD pairwise comparisons. Mean differences in Part C are the mean of the first configuration minus the mean of the second. The pairwise confidence intervals are simultaneous 95 % intervals, and the p-values are Tukey-adjusted at $\alpha = 0.05$. A difference was considered statistically significant when the simultaneous 95 % CI did not include zero. The three strain-specific values from the same specimen were treated as separate prespecified responses and were not pooled as independent observations.

Supplementary Table S5. Individual Shore D hardness values for TPU 95A specimens with uniform and step-gradient infill architectures

Specimen ID	Shore D hardness, units
Uniform 50%-1	30
Uniform 50%-2	32
Uniform 50%-3	32
Uniform 50%-4	30
Uniform 50%-5	34
Uniform 70%-1	38
Uniform 70%-2	39
Uniform 70%-3	38
Uniform 70%-4	37
Uniform 70%-5	38
Uniform 90%-1	52
Uniform 90%-2	48
Uniform 90%-3	45
Uniform 90%-4	49
Uniform 90%-5	48
GI-1-1	48
GI-1-2	50
GI-1-3	51
GI-1-4	50
GI-1-5	47
GI-2-1	30
GI-2-2	33
GI-2-3	35
GI-2-4	35
GI-2-5	34

Supplementary Table S6. Descriptive and inferential statistical analysis of Shore D hardness for TPU 95A specimens with uniform and step-gradient infill architectures

Part A. Descriptive statistics and 95 % confidence intervals

Configuration	*n*	Mean Shore D hardness	SD	95 % CI for the mean
Uniform 50%	5	31.600	1.673	29.522 to 33.678
Uniform 70%	5	38.000	0.707	37.122 to 38.878
Uniform 90%	5	48.400	2.510	45.283 to 51.517
GI-1	5	49.200	1.643	47.160 to 51.240
GI-2	5	33.400	2.074	30.825 to 35.975

Part B. One-way ANOVA results

Source of variation	SS	*df*	MS	*F*	*p*-value
Between configurations	1366.240	4	341.560	102.880	<0.001
Within configurations	66.400	20	3.320	—	—
Total	1432.640	24	—	—	—

Part C. Complete Tukey HSD pairwise comparisons

Comparison	Mean difference, Shore D units	Simultaneous 95 % CI	Tukey-adjusted *p*-value	Significant
GI-1 − GI-2	15.800	12.352 to 19.248	<0.001	Yes
GI-1 − Uniform 50%	17.600	14.152 to 21.048	<0.001	Yes
GI-1 − Uniform 70%	11.200	7.752 to 14.648	<0.001	Yes
GI-1 − Uniform 90%	0.800	−2.648 to 4.248	0.9554	No
GI-2 − Uniform 50%	1.800	−1.648 to 5.248	0.5369	No
GI-2 − Uniform 70%	−4.600	−8.048 to −1.152	0.0057	Yes
GI-2 − Uniform 90%	−15.000	−18.448 to −11.552	<0.001	Yes
Uniform 70% − Uniform 50%	6.400	2.952 to 9.848	<0.001	Yes
Uniform 90% − Uniform 50%	16.800	13.352 to 20.248	<0.001	Yes
Uniform 90% − Uniform 70%	10.400	6.952 to 13.848	<0.001	Yes

Notes: Values in Part A are reported as the mean, sample standard deviation (SD), and two-sided 95 % confidence interval for the group mean (n = 5 independently printed specimens per configuration). Shore D hardness was analyzed by one-way ANOVA with infill configuration as the between-specimen factor. The residuals did not depart significantly from normality (Shapiro–Wilk p = 0.794), and no significant variance heterogeneity was detected (Brown–Forsythe p = 0.673). Pairwise comparisons used Tukey's HSD procedure. Mean differences in Part C are the mean of the first configuration minus the mean of the second. The pairwise confidence intervals are simultaneous 95 % intervals, and the p-values are Tukey-adjusted at $\alpha = 0.05$. A difference was considered statistically significant when the simultaneous 95 % CI did not include zero.

Supplementary Table S7. Individual experimental density values and descriptive statistics for TPU 95A specimens with uniform and step-gradient infill architectures

Configuration	Specimen 1	Specimen 2	Specimen 3	Specimen 4	Specimen 5	Mean, g/cm^3	SD, g/cm^3	CV, %
Uniform 50% infill	0.84	0.86	0.87	0.85	0.88	0.860	0.016	1.86
Uniform 70% infill	0.97	1.00	0.98	1.01	0.99	0.990	0.016	1.62
Uniform 90% infill	1.06	1.10	1.08	1.12	1.09	1.090	0.022	2.02
GI-1	1.00	1.05	1.02	1.04	1.03	1.028	0.019	1.85
GI-2	0.95	1.02	1.00	0.98	0.99	0.988	0.026	2.63

Values are individual measurements and the mean ± sample standard deviation (n = 5 per configuration). CV, coefficient of variation.

Supplementary Table S8. One-way ANOVA results for the experimental density of TPU 95A specimens

Source of variation	SS	df	MS	F	p-value
Between configurations	0.141704	4	0.035426	86.83	<0.001
Within configurations	0.008160	20	0.000408	-	-
Total	0.149864	24	-	-	-

The analysis was performed using individual experimental density measurements, with n = 5 specimens per configuration.

Supplementary Table S9. Tukey's HSD pairwise comparisons of experimental density among the investigated infill configurations

Comparison	Mean difference, g/cm^3	Simultaneous 95 % CI, g/cm^3	Tukey-adjusted *p*-value	Significant
GI-2 − GI-1	−0.040	−0.0782 to −0.0018	0.0375	Yes
Uniform 50% − GI-1	−0.168	−0.2062 to −0.1298	<0.001	Yes
Uniform 70% − GI-1	−0.038	−0.0762 to 0.0002	0.0519	No
Uniform 90% − GI-1	0.062	0.0238 to 0.1002	<0.001	Yes
Uniform 50% − GI-2	−0.128	−0.1662 to −0.0898	<0.001	Yes
Uniform 70% − GI-2	0.002	−0.0362 to 0.0402	0.9999	No
Uniform 90% − GI-2	0.102	0.0638 to 0.1402	<0.001	Yes
Uniform 70% − Uniform 50%	0.130	0.0918 to 0.1682	<0.001	Yes
Uniform 90% − Uniform 50%	0.230	0.1918 to 0.2682	<0.001	Yes
Uniform 90% − Uniform 70%	0.100	0.0618 to 0.1382	<0.001	Yes

Mean differences were calculated as the mean of the first configuration minus the mean of the second configuration shown in each comparison. The confidence intervals and p-values were adjusted using Tukey's HSD procedure with a family-wise significance level of $\alpha = 0.05$. A pairwise difference was considered statistically significant when the simultaneous 95 % confidence interval did not include zero.

Supplementary Table S10. Individual specimen-level mean COF values calculated over the 250–300 m sliding-distance interval.

Configuration	Specimen 1	Specimen 2	Specimen 3	Mean ± SD
Uniform 50%	0.81	0.83	0.80	0.81 ± 0.02
Uniform 70%	0.63	0.61	0.62	0.62 ± 0.01
Uniform 90%	0.59	0.57	0.60	0.59 ± 0.02
GI-1	0.50	0.49	0.50	0.50 ± 0.01
GI-2	0.62	0.59	0.61	0.61 ± 0.02

The COF value for each specimen is the arithmetic mean of all readings recorded over the 250–300 m sliding interval. Group means and standard deviations were then calculated from these specimen-level means (n = 3 independently printed specimens per configuration). Individual time points within a friction curve were not treated as independent observations.