Electronic Supplementary Information

ZnO as a cheap and effective filler for high breakdown strength elastomers

Liyun Yu and Anne Ladegaard Skov*

Danish Polymer Centre, Department of Chemical and Biochemical Engineering, Technical University of Denmark, Søltofts Plads Building 227, 2800 Kgs. Lyngby, Denmark

*Corresponding author: Tel.: +45 45252825. Fax: +45 45882258. E-mail: al@kt.dtu.dk

Table S1. Measured properties of prepared silicone elastomes.

Sample	ε_r		tanδ		|σ| (S/cm)		E_{BD} (V/μm)	Thickness (μm)	G' @ 0.01Hz (Pa)	G" @ 0.01Hz (Pa)	Tanδ @ 0.01Hz
	0.1 Hz	1 MHz	0.1 Hz	1 MHz	0.1 Hz	1 MHz					
EP7684 pure (**RTV**)	2.83	2.81	4.98E-03	3.54E-04	1.02E-13	9.53E-07	64	82	21333	808	3.79E-02
EP7684+0.5phrZnO (50nm)	2.96	2.91	6.67E-04	5.79E-04	1.13E-13	1.01E-6	82	74	23839	1074	4.51E-02
EP7684+1.25phrZnO (50nm)	3.13	3.08	4.83E-04	1.72E-03	1.18E-13	1.10E-06	104	67	25067	1236	4.93E-02
EP7684+1.25phrZnO +1.25phr silicone oil	3.12	3.11	6.27E-02	1.92E-03	1.18E-13	1.11E-06	60	85	17850	740	4.15E-02
EP7684+2.5phrZnO (50nm)	3.14	3.08	4.33E-03	2.67E-03	1.19E-13	1.10E-06	114	69	16148	768	4.76E-02
EP7684+2.5phrZnO +2.5phr silicone oil	3.37	3.27	1.59E-03	2.88E-03	1.32E-13	1.20E-06	79	67	18276	766	4.19E-02
EP7684+3.75phrZnO (50nm)	3.54	3.40	2.57E-03	4.29E-03	1.41E-13	1.27E-06	116	63	15447	747	4.84E-02
EP7684+3.75phrZnO +3.75phr silicone oil	3.22	3.19	5.97E-02	3.34E-03	1.24E-13	1.16E-06	63	83	14243	668	4.69E-02
EP7684+5phrZnO (50nm)	3.92	3.68	5.93E-02	3.63E-03	1.03E-13	1.42E-06	94	80	15859	856	5.40E-02
EP7684+5phrZnO+5 phr silicone oil	3.53	3.29	1.35E-02	4.93E-03	1.41E-13	1.21E-06	67	78	17187	823	4.79E-02

EP7684+5phrZnO (100nm**)**	2.85	2.81	2.66E-02	2.56E-03	1.21E-13	9.58E-07	68	77	17488	949	5.43E-02
V31 pure (with 25wt.%SiO_2)	3.10	3.07	4.81E-02	4.37E-04	1.11E-13	1.09E-06	91	93	109955	5106	4.64E-02
V31+0.5phrZnO (50nm)	3.16	3.13	5.49E-02	8.68E-04	1.14E-13	1.11E-06	98	75	93784	3789	4.04E-02
V31+1.25phrZnO (50nm)	3.23	3.17	6.33E-02	1.19E-03	1.19E-13	1.14E-06	113	78	89443	2897	3.24E-02
V31+2.5phrZnO (50nm)	3.46	3.35	8.18E-02	1.61E-03	1.24E-13	1.24E-06	117	75	82926	2696	3.25E-02
V31+3.75phrZnO (50nm)	3.59	3.47	8.52E-02	2.09E-03	1.31E-13	1.32E-06	123	70	74139	2271	3.06E-02
V31+5phrZnO (50nm)	3.85	3.60	9.13E-02	2.31E-03	1.60E-13	1.37E-06	101	97	66166	2000	3.02 E-02
RT625 pure (**RTV**)	2.70	2.71	3.72E-03	1.15E-03	9.45E-14	9.02E-07	104	67	56667	2149	3.79E-02
RT625+1.25phrZnO (50nm)	3.07	2.97	1.04E-02	1.47E-03	1.15E-13	1.04E-06	77	72	72804	2433	3.34E-02
RT625+2.5phrZnO (50nm)	3.19	3.16	9.42E-03	2.74E-03	1.22E-13	1.14E-06	104	72	78968	3341	4.23E-02
RT625+3.75phrZnO (50nm)	3.52	3.43	4.43E-02	3.69E-03	1.40E-13	1.28E-06	73	71	72142	2710	3.76E-02
RT625+5phrZnO (50nm)	3.29	3.20	7.65E-03	4.40E-03	1.27E-13	1.16E-06	110	71	63613	3076	4.84E-02
RT625+5phrZnO (100nm**)**	3.06	2.99	6.79E-03	5.32E-03	1.15E-13	1.05E-06	100	81	46523	2308	4.96E-02
MJK135 pure (**LSR**)	3.00	3.04	3.11E-02	1.10E-05	1.11E-13	1.08E-06	97	90	115261	2213	1.92E-02
MJK135+1.25phrZnO (50nm)	2.99	2.97	2.22E-02	1.06E-03	1.11E-13	1.04E-06	85	78	75642	1692	2.24E-02
MJK135+2.5phrZnO (50nm)	3.02	2.98	1.06E-02	1.63E-03	1.12E-13	1.04E-06	68	77	49475	1122	2.27E-02

MJK135+3.75phrZnO (50nm)	2.98	2.91	1.01E-02	1.78E-03	1.10E-13	1.01E-06	77	80	35228	750	2.13E-02
MJK135+5phrZnO (50nm)	2.95	2.84	1.74E-03	2.81E-03	1.08E-13	9.69E-07	87	61	53415	1138	2.13E-02

Table S2. Stress-strain results of prepared silicone elastomers.

Sample	Y (MPa) @ 5% strain	Tensile strength (MPa)	Strain at break (%)
EP7684 pure (**RTV**)	0.79±0.06	2.81±0.04	473±18
EP7684+0.5phrZnO (50nm)	0.88±0.06	3.00±0.09	493±33
EP7684+1.25phrZnO (50nm)	1.00±0.17	3.26±0.06	539±14
EP7684+1.25phrZnO+1.25phr silicone oil	0.89±0.09	2.87±0.10	470±31
EP7684+2.5phrZnO (50nm)	0.70±0.08	3.75±0.11	520±16
EP7684+2.5phrZnO+2.5phr silicone oil	0.64±0.06	2.78±0.13	405±21
EP7684+3.75phrZnO (50nm)	0.58±0.09	3.53±0.14	488±23
EP7684+3.75phrZnO+3.75phr silicone oil	0.48±0.05	1.98±0.09	390±14
EP7684+5phrZnO (50nm)	0.88±0.11	2.78±0.06	461±12
EP7684+5phrZnO+5phr silicone oil	0.61±0.05	1.82±0.08	381±15
EP7684+5phrZnO (100nm**)**	0.97±0.07	2.63±0.17	447±24
V31 pure (with 25wt.%SiO_2)	0.92±0.08	4.27±0.22	378±11
V31+0.5phrZnO (50nm)	0.88±0.10	5.02±0.10	403±13
V31+1.25phrZnO (50nm)	0.83±0.09	5.21±0.15	423±17
V31+2.5phrZnO (50nm)	0.79±0.07	4.64±0.18	405±15
V31+3.75phrZnO (50nm)	0.70±0.03	4.43±0.15	398±19
V31+5phrZnO (50nm)	1.05±0.09	3.75±0.23	336±24

RT625 pure (**RTV**)	1.41±0.18	11.17±0.52	628±26
RT625+1.25phrZnO (50nm)	1.43±0.17	11.39±0.59	639±17
RT625+2.5phrZnO (50nm)	1.54±0.08	12.08±0.38	689±29
RT625+3.75phrZnO (50nm)	1.61±0.07	11.17±0.43	669±16
RT625+5phrZnO (50nm)	1.31±0.11	10.90±0.29	661±19
RT625+5phrZnO (100nm**)**	1.78±0.19	9.95±0.22	610±18
MJK135 pure (**LSR**)	1.53±0.12	8.63±0.40	704±11
MJK135+1.25phrZnO (50nm)	1.20±0.14	6.19±0.28	456±17
MJK135+2.5phrZnO (50nm)	1.13±0.21	4.57±0.37	403±23
MJK135+3.75phrZnO (50nm)	1.06±0.16	4.43±0.33	383±20
MJK135+5phrZnO (50nm)	1.42±0.18	3.80±0.29	306±16

Table S3. Weibull analysis of the dielectric breakdown of the prepared silicone elastomers.

Sample	Thickness (μm)	E_{BD} (V/μm)	std	β	η	R^2
EP7684 pure (**RTV**)	82	64	0.72	96	64	0.94
EP7684+0.5phrZnO (50nm)	74	82	2.14	41	83	0.92
EP7684+1.25phrZnO (50nm)	67	104	3.73	30	105	0.90
EP7684+1.25phrZnO+1.25phr silicone oil	85	60	1.10	58	60	0.89
EP7684+2.5phrZnO (50nm)	69	114	6.78	18	117	0.96
EP7684+2.5phrZnO+2.5phr silicone oil	67	79	3.44	24	81	0.78
EP7684+3.75phrZnO (50nm)	63	116	3.18	39	117	0.92
EP7684+3.75phrZnO+3.75phr silicone oil	83	63	3.01	20	64	0.70

EP7684+5phrZnO (50nm)	80	94	1.94	54	97	0.94
EP7684+5phrZnO+5phr silicone oil	78	67	3.31	20	68	0.75
EP7684+5phrZnO (100nm**)**	77	68	1.53	49	69	0.97
V31 pure (with 25wt.%SiO_2)	93	91	2.99	29	92	0.66
V31+0.5phrZnO (50nm)	75	98	3.12	27	100	0.84
V31+1.25phrZnO (50nm)	78	113	3.78	32	115	0.88
V31+2.5phrZnO (50nm)	75	117	4.46	29	119	0.94
V31+3.75phrZnO (50nm)	70	123	2.15	62	124	0.92
V31+5phrZnO (50nm)	97	101	6.76	15	103	0.75
RT625 pure (**RTV**)	67	104	3.55	32	107	0.95
RT625+1.25phrZnO (50nm)	72	77	6.54	13	80	0.89
RT625+2.5phrZnO (50nm)	72	104	7.01	16	107	0.93
RT625+3.75phrZnO (50nm)	71	73	2.27	33	73	0.88
RT625+5phrZnO (50nm)	71	110	5.94	19	112	0.85
RT625+5phrZnO (100nm**)**	81	100	7.87	14	104	0,98
MJK135 pure (**LSR**)	90	97	3.76	28	100	0.91
MJK135+1.25phrZnO (50nm)	78	85	2.86	33	87	0.95
MJK135+2.5phrZnO (50nm)	77	68	2.41	30	69	0.91
MJK135+3.75phrZnO (50nm)	80	77	5.48	15	80	0.96
MJK135+5phrZnO (50nm)	61	87	4.34	22	89	0.95

Table S4. Figures of merit with respect to actuation and energy generation for the investigated composites. The normalised figures of merit arise from normalisation with respective pristine elastomers.

Sample	F_{om}(DEA) ($F \cdot m^{-1} \cdot V^2 \cdot \mu m^{-2} \cdot Pa^{-1}$)	F_{om}(DEA)/ $F_{om}(DEA)_{pure}$	F_{om}(DEG) ($F \cdot m^{-1} \cdot V^2 \cdot \mu m^{-2}$)	F_{om}(DEG)/ $F_{om}(DEG)_{pure}$
EP7684 pure (**RTV**)	3.90E-13	1.00	5.13E-08	1.00
EP7684+0.5phrZnO (50nm)	6.00E-13	1.54	8.81E-08	1.72
EP7684+1.25phrZnO (50nm)	8.99E-13	2.31	1.50E-07	2.92
EP7684+1.25phrZnO +1.25phr silicone oil	3.35E-13	0.86	4.97E-08	0.97
EP7684+2.5phrZnO (50nm)	1.55E-12	3.97	1.81E-07	3.52
EP7684+2.5phrZnO+ 2.5phr silicone oil	8.73E-13	2.24	9.31E-08	1.81
EP7684+3.75phrZnO (50nm)	2.18E-12	5.60	2.11E-07	4.11
EP7684+3.75phrZnO +3.75phr silicone oil	7.07E-13	1.81	5.66E-08	1.10
EP7684+5phrZnO (50nm)	1.05E-12	2.68	1.53E-07	2.99
EP7684+5phrZnO+5 phr silicone oil	6.90E-13	1.77	7.01E-08	1.37
EP7684+5phrZnO (100nm**)**	3.61E-13	0.93	5.83E-08	1.14
V31 pure (with 25wt.%SiO_2)	7.41E-13	1.00	1.14E-07	1.00
V31+0.5phrZnO (50nm)	9.16E-13	1.24	1.34E-07	1.18
V31+1.25phrZnO (50nm)	1.32E-12	1.78	1.83E-07	1.61

V31+2.5phrZnO (50nm)	1.59E-12	2.15	2.10E-07	1.85
V31+3.75phrZnO (50nm)	2.06E-12	2.78	2.40E-07	2.12
V31+5phrZnO (50nm)	9.93E-13	1.34	1.74E-07	1.53
RT625 pure (**RTV**)	5.50E-13	1.00	1.29E-07	1.00
RT625+1.25phrZnO (50nm)	3.38E-13	0.61	8.05E-08	0.62
RT625+2.5phrZnO (50nm)	5.95E-13	1.08	1.53E-07	1.18
RT625+3.75phrZnO (50nm)	3.09E-13	0.56	8.30E-08	0.64
RT625+5phrZnO (50nm)	8.07E-13	1.47	1.76E-07	1.36
RT625+5phrZnO (100nm**)**	4.56E-13	0.83	1.35E-07	1.05
MJK135 pure (**LSR**)	4.90E-13	1.00	1.25E-07	1.00
MJK135+1.25phrZnO (50nm)	4.78E-13	0.98	9.56E-08	0.77
MJK135+2.5phrZnO (50nm)	3.28E-13	0.67	6.18E-08	0.49
MJK135+3.75phrZnO (50nm)	4.43E-13	0.90	7.82E-08	0.63
MJK135+5phrZnO (50nm)	4.17E-13	0.85	9.88E-08	0.79

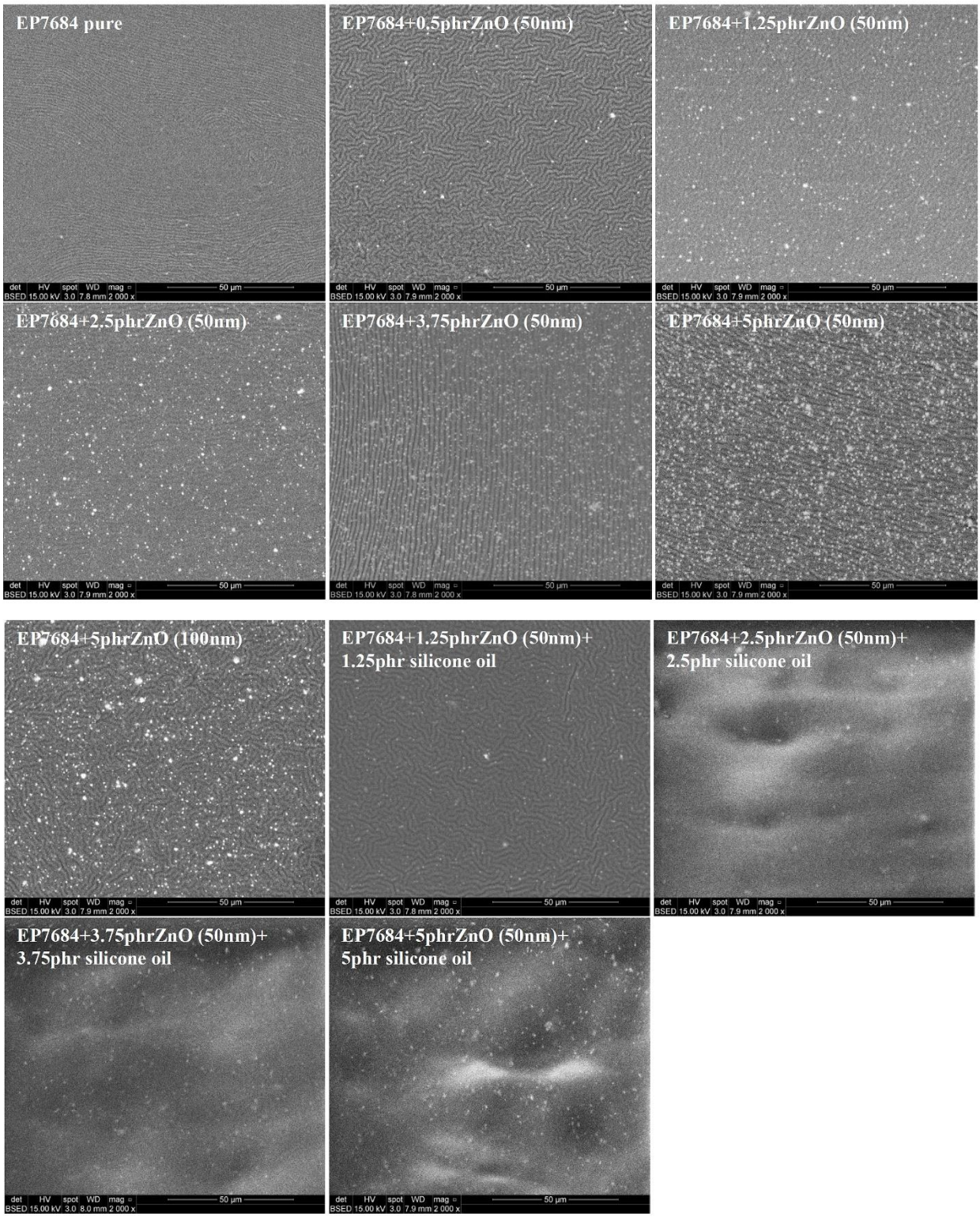

Figure S1. SEM pictures of composites from the EP7684 elastomer with varying loadings of ZnO particles and silicone oil.

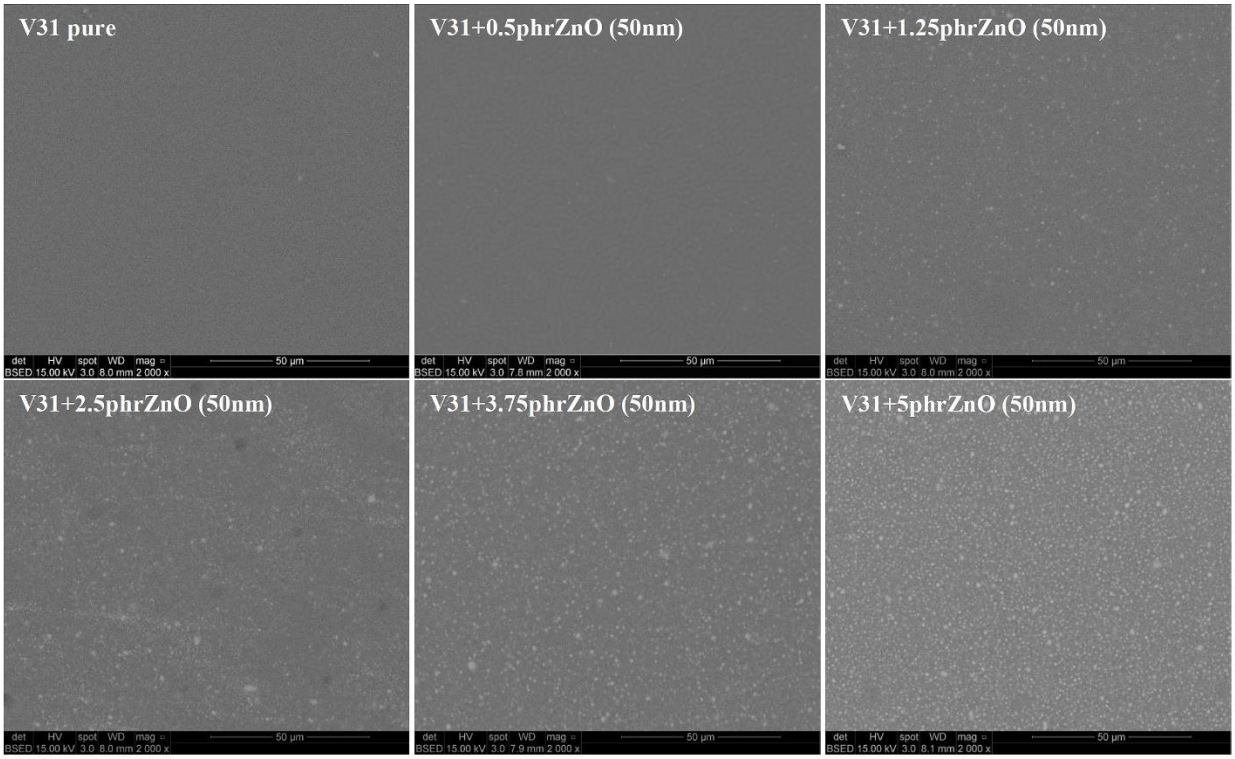

Figure S2. SEM pictures of composites from the V31 elastomer with varying loadings of 50 nm ZnO particles.

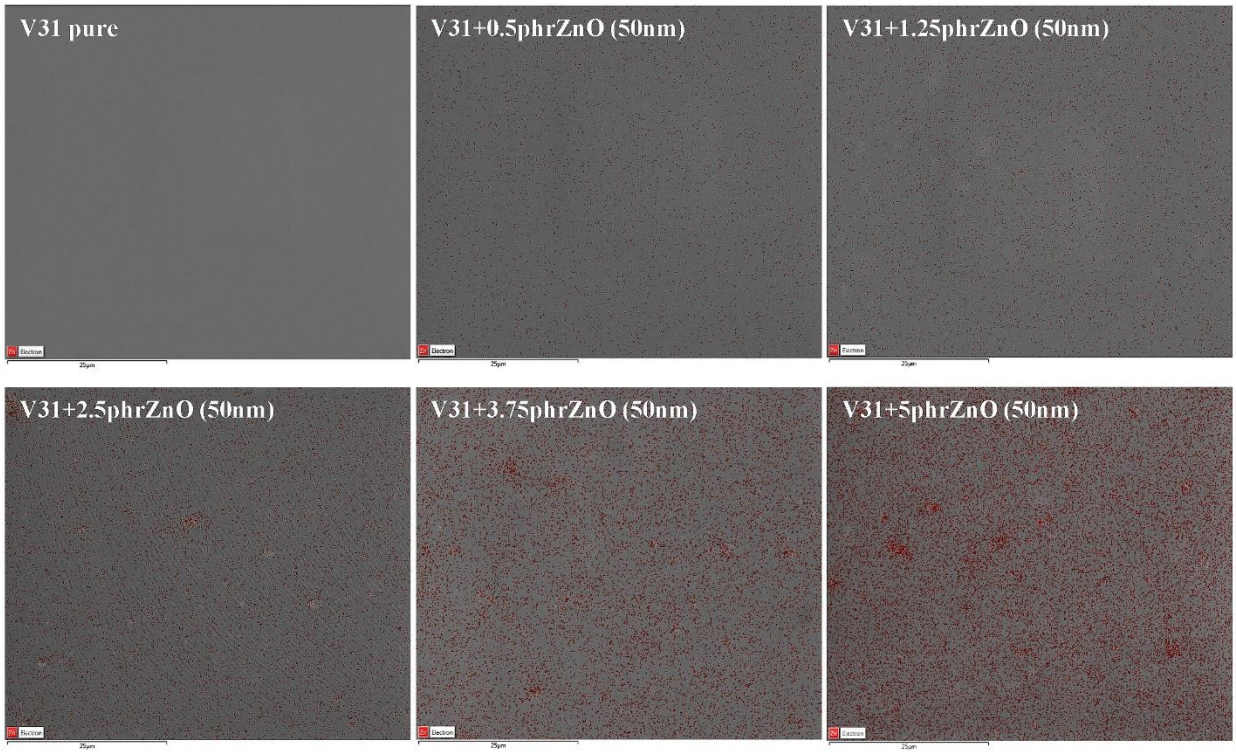

Figure S3. EDX pictures of composites from the V31 elastomer with varying loadings of 50 nm ZnO particles. EDX color legend: Red: Zinc.

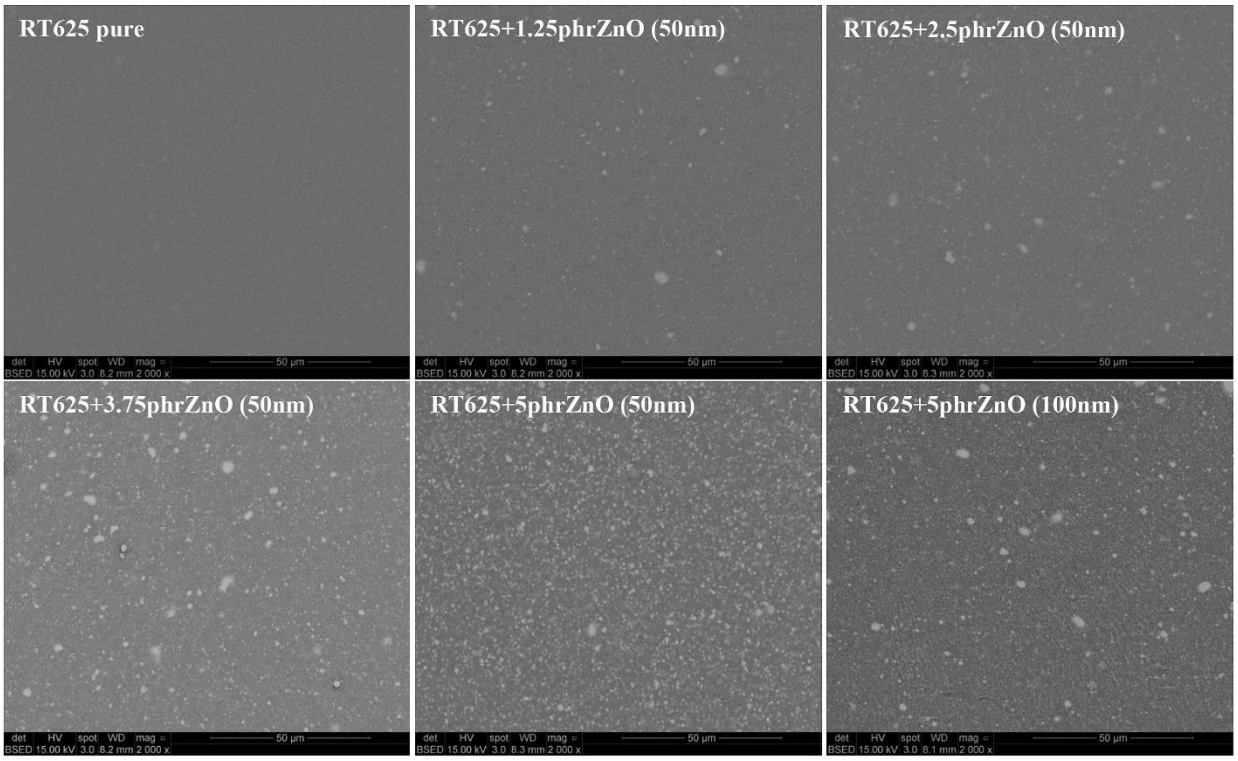

Figure S4. SEM pictures of composites from the RT625 elastomer with varying loadings of ZnO particles.

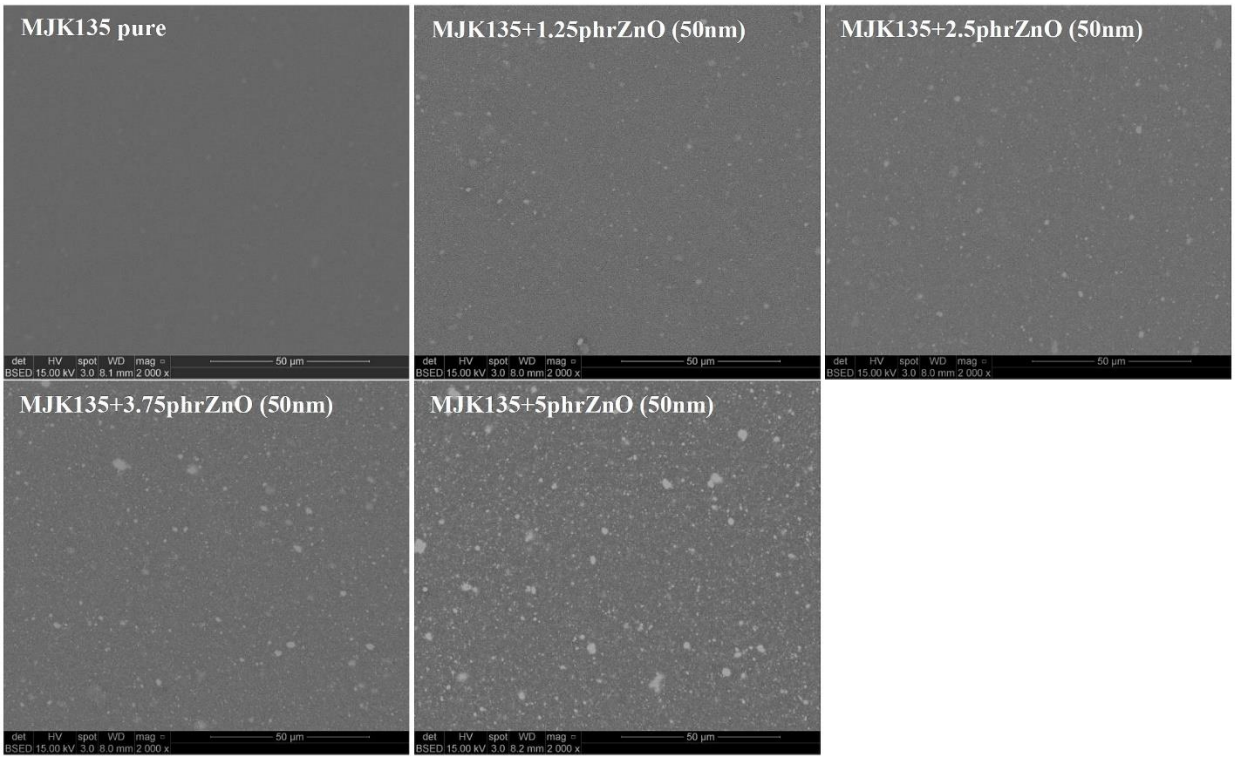

Figure S5. SEM pictures of composites from the MJK elastomer with varying loadings of 50 nm ZnO particles.