Materials Advances

ARTICLE TYPE

Supporting Information

Soft, ternary, X- and gamma-ray shielding materials: paraffin-based iron-encapsulated carbon nanotube nanocomposites †

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Abstract

In the field of radiological protection, there is a growing interest in nano- and microcomposites due to their unique physicochemical properties, flexibility in the component selection (the base ingredient as well as the fillers), and lower toxicity in comparison to the lead-(Pb-based) ones. In this study, we manufactured paraffin-based composites with different concentrations of iron-encapsulated multi-walled carbon nanotubes (Fe@MWCNTs) (10 and 20 wt.%), which were prone to shape change at the average room temperature. Long Fe@MWCNT arrays were synthesized by catalytic chemical vapor deposition (c-CVD) using the saturated (at 293.15 K) toluene solution of ferrocene ($FeCp_2$) (9.6 wt.%) as a feedstock toward the highest efficiency of a complete Fe-encapsulation. The experimental data indicate that the shielding properties against gamma- and X-ray radiation are influenced by the filler concentration – the higher CNT content resulted in a greater ability to attenuate incident ionizing radiation. Finally, Fe@MWCNT-paraffin composites demonstrated corrosion resistance, as they did not react with 1 M aqueous solutions of NaCl, NaOH, and HCl.

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Optical micrographs, EDX spectra

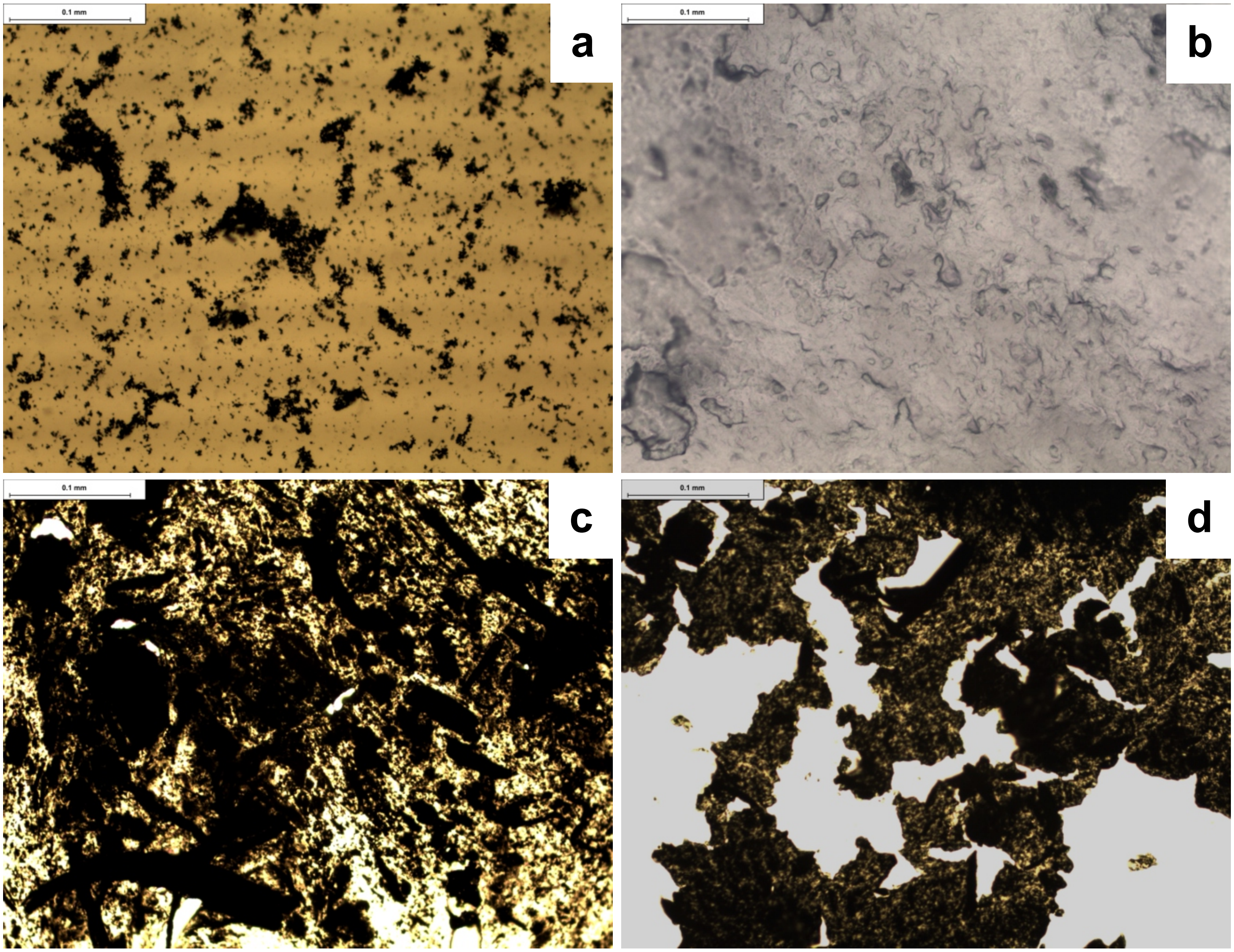

Fig. S1: Optical micrographs of: Fe@MWCNTs (a), neat paraffin (b), Paraffin + 10 wt.% Fe@MWCNT (c), and Paraffin + 20 wt.% Fe@MWCNT (d) composites

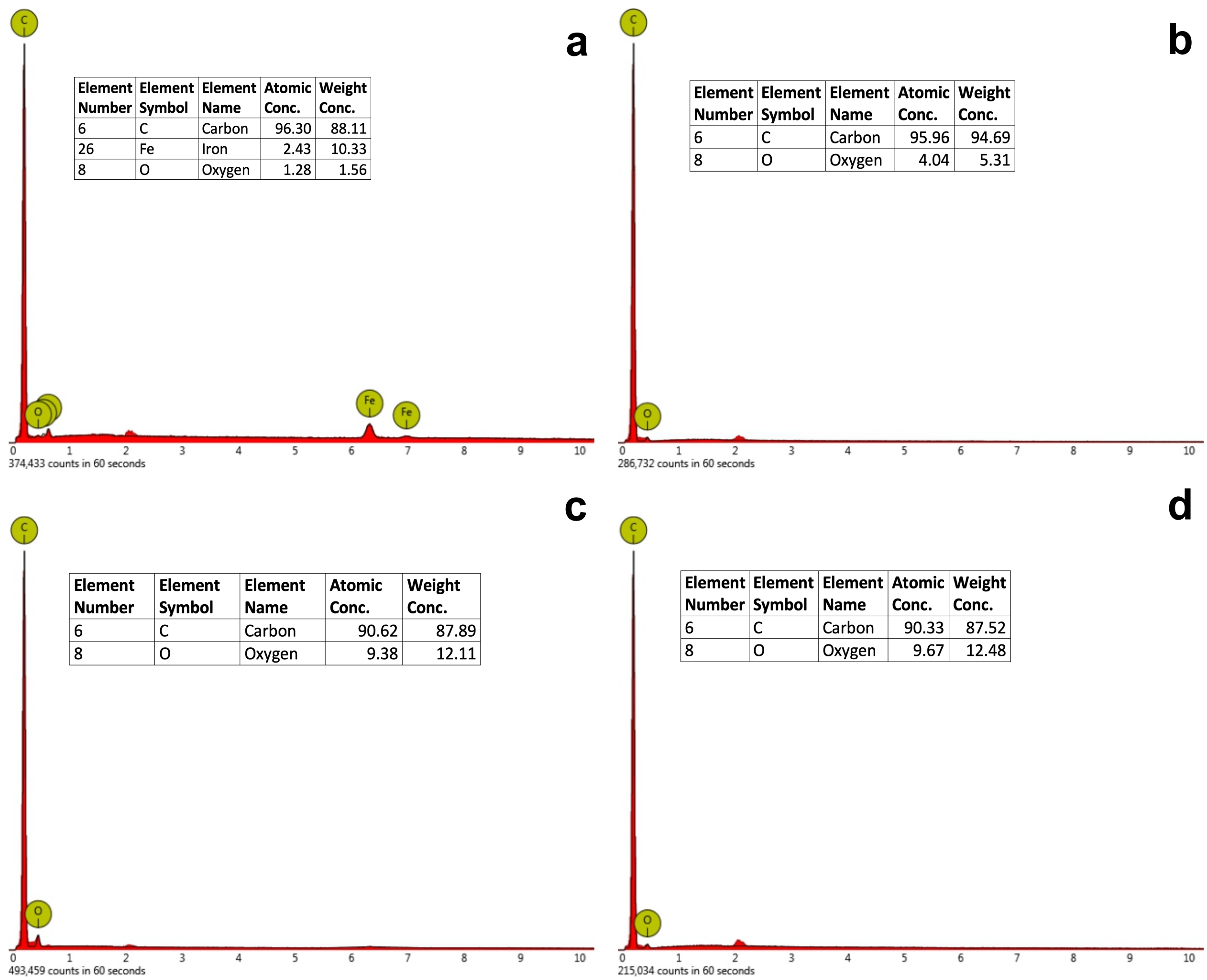

Fig. S2: EDX spectra of Fe@MWCNTs (a), neat paraffin (b), Paraffin + 10 wt.% Fe@MWCNT (c), and Paraffin + 20 wt.% Fe@MWCNT (d) composites. Field of view: 26.9 μm, Mode: 15 kV – Point, Detector: backscattered electron detector.

Rheological properties

Table S1: Storage modulus and loss modulus for pure paraffin samples and composites with Fe@MWCNTs addition in a function of strain, f = 1 Hz, T = 309.75 K

Strain	Paraffin		Paraffin + 10 wt% Fe@MWCNTs		Paraffin + 20 wt% Fe@MWCNTs	
	G'	G''	G'	G''	G'	G''
[-]	[Pa]	[Pa]	[Pa]	[Pa]	[Pa]	[Pa]
0,001006	110900	42823,33	675666,67	256600	709933,33	258266,67
0,001273	111233,33	42593,33	682166,67	251666,67	721333,33	263466,67
0,001615	112466,67	42486,67	683933,33	255700	749033,33	268466,67
0,00204	113633,33	42420	690900	255133,33	764000	271833,33
0,002591	113600	42876,67	690600	255700	769966,67	270600
0,003277	114333,33	43173,33	693533,33	255366,67	772333,33	270100
0,00414	114933,33	42920	692866,67	253400	774566,67	270366,67
0,005243	114766,67	42666,67	694300	251100	775966,67	269033,33
0,006644	115000	42693,33	691433,33	251600	776700	269133,33
0,008417	115566,67	43163,33	688900	249866,67	777200	270566,67
0,01066	114100	43153,33	686833,33	250533,33	776766,67	269100
0,0135	113170	43273,33	681200	250233,33	773466,67	269266,67
0,0171	111893,33	43386,67	673200	249600	769200	269200
0,02165	109780	43566,67	662800	249100	762400	269000
0,02742	104696,67	44410	649300	248566,67	754566,67	268233,33
0,03473	95836,67	45236,67	631833,33	247566,67	743700	267900
0,04397	82200	45293,33	609000	246766,67	729666,67	267300
0,05568	65810	44153,33	578033,33	246266,67	711700	266433,33
0,07052	49496,67	40686,67	535033,33	246666,67	688400	265566,67
0,08931	38950	36643,33	475233,33	246966,67	657033,33	265666,67
0,1131	30006,67	32413,33	402500	243000	609600	267800
0,1432	22406,67	28353,33	325233,33	231266,67	531700	274900
0,1814	16080	23773,33	257333,33	210633,33	416933,33	282033,33
0,2297	11800	19840	203766,67	184266,67	305633,33	268400
0,2909	8676,67	16583,33	163333,33	157433,33	222966,67	235433,33
0,3684	6627,67	14120	131600	133233,33	171666,67	195166,67
0,4665	4852,33	11743,33	105586,67	112500	140633,33	157200
0,5907	3617	9780,33	83393,33	95506,67	116800	127700
0,7481	2483,33	7926,67	64613,33	81376,67	90120	108866,67
0,9474	1844,67	6682	49263,33	69090	67010	92830
1,2	1356,67	5746	37460	58503,33	50140	77520
1,519	1000,33	4974,67	28026,67	49316,67	37533,33	64500
1,924	739,83	4299	20760	41443,33	27846,67	53623,33
2,437	554,9	3765,33	15203,33	34753,33	20490	44533,33
3,086	412,97	3287	10979	29090	14973,33	36900
3,908	307,2	2901	7867,33	24323,33	10900	30580
4,949	229,27	2585,67	5657	20326,67	7887	25436,67
6,267	167,83	2312,33	4188,33	16976,67	5717,67	21186,67
7,936	119,1	2057	3125,33	14246,67	4258,33	17673,33
10,05	81,67	1828,33	2330	12000	3213,67	14783,33

Table S2: Storage modulus and loss modulus for pure paraffin samples and composites with Fe@MWCNTs addition in a function of temperature, $\gamma = 0.01\%$, $f = 1$ Hz

T	Paraffin		Paraffin + 10 wt% Fe@MWCNTs		Paraffin + 20 wt% Fe@MWCNTs	
	G'	G''	G'	G''	G'	G''
[K]	[Pa]	[Pa]	[Pa]	[Pa]	[Pa]	[Pa]
288,15	3181666,67	1257000	11650000	3446666,67	14763300	4641333,33
289,15	2798333,33	1167733,33	10624000	3270000	13280000	4341333,33
290,15	2374666,67	1065033,33	9463333,33	3078000	11175000	3936500
291,15	1919333,33	942433,33	8141333,33	2816666,67	10207300	3883666,67
292,15	1466333,33	804200	6949333,33	2568000	8127000	3343000
293,15	1110333,33	682466,67	5972000	2348666,67	6693333,33	2949000
294,15	780633,33	537400	4719000	1939333,33	5377000	2521333,33
295,15	551400	405000	3923666,67	1630000	4226000	2072000
296,15	454833,33	341066,67	3350666,67	1411000	3574000	1803666,67
297,15	390766,67	298866,67	3040333,33	1331000	3081000	1583000
298,15	337033,33	260433,33	2631333,33	1198000	2630666,67	1378333,33
299,15	292733,33	220833,33	1956000	1011500	2238666,67	1188666,67
300,15	256233,33	194733,33	2014000	1014333,33	1956333,33	1095533,33
301,15	217066,67	168900	1967333,33	883000	1640500	932750
302,15	184566,67	149966,67	1806666,67	801766,67	1519333,33	877333,33
303,15	172033,33	118390	1316000	700100	1327000	777133,33
304,15	142700	107500	1434300	676033,33	1169000	685200
305,15	122933,33	91480	1374733,33	614900	1029266,67	626600
306,15	113076,67	74526,67	1255466,67	567766,67	1002950	531900
307,15	111200	67360	1137066,67	506933,33	878433,33	485833,33
308,15	88580	53210	1073233,33	446866,67	877266,67	388433,33
309,15	67255	42930	719700	334750	813566,67	345700
310,15	69100	41773,33	954266,67	349200	864766,67	286966,67
311,15	66656,67	37536,67	924533,33	307633,33	766900	259400
312,15	79606,67	31796,67	980066,67	268700	768900	239266,67
313,15	75136,67	27976,67	926800	255033,33	745550	213700
314,15	73215	36025	875133,33	244033,33	682666,67	189433,33
315,15	42870	21960	837866,67	226166,67	624200	167666,67
316,15	46826,67	25546,67	785133,33	216033,33	568933,33	150566,67
317,15	30150	19180	727733,33	197300	529700	117500
318,15	31490	19840	671833,33	190500	450833,33	123800
319,15	33825	17300	658050	177350	410050	98370
320,15	22210	12472	575400	156706,67	345900	95530
321,15	21066,67	12827,67	543666,67	137170	292200	80830
322,15	10280	5997	618450	155750	245966,67	70756,67
323,15	12776,67	7885,33	447200	127396,67	205866,67	55960
324,15	9542,33	4396,67	400800	105930	162200	52103,33
325,15	6490	3385,67	391250	104820	128850	37950
326,15	5485,67	2594,33	323133,33	89870	98370	32553,33
327,15	3534,67	1926	291166,67	72330	73860	26996,67
328,15	2152,33	961,33	263733,33	66833,33	61600	17476,67
329,15	1252,33	493,6	242263,33	52390	49190	16556,67
330,15	720,33	294,63	228620	48856,67	42166,67	12223,33
331,15	525,9	202,45	214873,33	44176,67	37603,33	10959,33
332,15	435,55	135,2	208670	42000	40340	9624,33
333,15	345,05	108,12	203156,67	39990	39523,33	8913,67
334,15	285,55	81,04	199360	38300	39840	8387,67
335,15	224,45	62,48	203170	34916,67	37473,33	8100,33
336,15	165,8	45,36	231185	39140	38543,33	7313,67
337,15	117,35	32,45	194210	33453,33	36643,33	6883,67
338,15	91,2	23,84	191536,67	31572	35370	6633,33

Shielding properties – gamma ray

Table S3: The summary of experimental data for the pure paraffin and manufactured composites with 10 and 20 wt.% of Fe@MWCNT addition presented in the form of the ratio of the number of counts for a given layer thickness ($N_{\text{reduced layer}}$) to the number of counts coming from the ^{60}Co source ($N_{\text{reduced source}}$) as the average of three measurement series for each composite sample

x (cm)	Paraffin	Paraffin + 10 wt% Fe@MWCNTs	Paraffin + 20 wt% Fe@MWCNTs
0	1	1	1
2	0.942	0.921	0.919
4	0.827	0.823	0.822
6	0.769	0.734	0.724
8	0.704	0.656	0.666
10	0.631	0.623	0.601
12	0.569	0.561	0.541
14	0.521	0.483	0.472
16	0.490	0.465	0.443
18	0.451	0.413	0.395
20	0.406	0.359	0.333
22	0.375	0.341	0.321
24	0.325	0.319	0.287
26	0.293	0.282	0.260

Shielding properties – X-ray

Table S4: The data summary of X-ray shielding ability for the composites with 10 and 20 wt.% addition of Fe@MWCNTs and for the pure paraffin presented in the form of the ratio of the signal intensity of given material layer thickness ($I_{\text{layer sample}}$) to the signal intensity for aired field (I_{air}) at 70 kV voltage

x (cm)	Paraffin	Paraffin + 10 wt% Fe@MWCNTs	Paraffin + 20 wt% Fe@MWCNTs
0	1	1	1
2	0.685	0.678	0.670
4	0.489	0.453	0.425
6	0.346	0.298	0.266
8	0.240	0.197	0.168

Table S5: The data summary of X-ray shielding ability for the composites with 10 and 20 wt.% addition of Fe@MWCNTs and for the pure paraffin presented in the form of the ratio of the signal intensity of given material layer thickness ($I_{\text{layer sample}}$) to the signal intensity for aired field (I_{air}) at 80 kV voltage

x (cm)	Paraffin	Paraffin + 10 wt% Fe@MWCNTs	Paraffin + 20 wt% Fe@MWCNTs
0	1	1	1
2	0.892	0.855	0.854
4	0.654	0.594	0.565
6	0.468	0.398	0.363
8	0.333	0.269	0.235

Table S6: The data summary of X-ray shielding ability for the composites with 10 and 20 wt.% addition of Fe@MWCNTs and for the pure paraffin presented in the form of the ratio of the signal intensity of given material layer thickness ($I_{\text{layer sample}}$) to the signal intensity for aired field (I_{air}) at 90 kV voltage

x (cm)	Paraffin	Paraffin + 10 wt% Fe@MWCNTs	Paraffin + 20 wt% Fe@MWCNTs
0	1	1	1
2	0.999	0.999	0.999
4	0.936	0.867	0.832
6	0.687	0.596	0.549
8	0.495	0.411	0.363

Table S7: The data summary of X-ray shielding ability for the composites with 10 and 20 wt.% addition of Fe@MWCNTs and for the pure paraffin presented in the form of the ratio of the signal intensity of given material layer thickness ($I_{\text{layer sample}}$) to the signal intensity for aired field (I_{air}) at 100 kV voltage

x (cm)	Paraffin	Paraffin + 10 wt% Fe@MWCNTs	Paraffin + 20 wt% Fe@MWCNTs
0	1	1	1
2	0.999	0.999	0.999
4	0.999	0.999	0.999
6	0.915	0.808	0.751
8	0.673	0.567	0.505

Table S8: The data summary of X-ray shielding ability for the composites with 10 and 20 wt.% addition of Fe@MWCNTs and for the pure paraffin presented in the form of the ratio of the signal intensity of given material layer thickness ($I_{\text{layer sample}}$) to the signal intensity for aired field (I_{air}) at 110 kV voltage

x (cm)	Paraffin	Paraffin + 10 wt% Fe@MWCNTs	Paraffin + 20 wt% Fe@MWCNTs
0	1	1	1
2	0.999	0.999	0.999
4	0.999	0.999	0.999
6	0.999	0.999	0.973
8	0.865	0.741	0.666

Table S9: The data summary of X-ray shielding ability for the composites with 10 and 20 wt.% addition of Fe@MWCNTs and for the pure paraffin presented in the form of the ratio of the signal intensity of given material layer thickness ($I_{\text{layer sample}}$) to the signal intensity for aired field (I_{air}) at 120 kV voltage

x (cm)	Paraffin	Paraffin + 10 wt% Fe@MWCNTs	Paraffin + 20 wt% Fe@MWCNTs
0	1	1	1
2	0.999	0.999	0.999
4	0.999	0.999	0.999
6	0.999	0.999	0.999
8	0.999	0.922	0.836

Table S10: The data summary of X-ray shielding ability for the composites with 10 and 20 wt.% addition of Fe@MWCNTs and for the pure paraffin presented in the form of the ratio of the signal intensity of given material layer thickness ($I_{\text{layer sample}}$) to the signal intensity for aired field (I_{air}) at 130 kV voltage

x (cm)	Paraffin	Paraffin + 10 wt% Fe@MWCNTs	Paraffin + 20 wt% Fe@MWCNTs
0	1	1	1
2	0.999	0.999	0.999
4	0.999	0.999	0.999
6	0.999	0.999	0.999
8	0.999	0.999	0.986

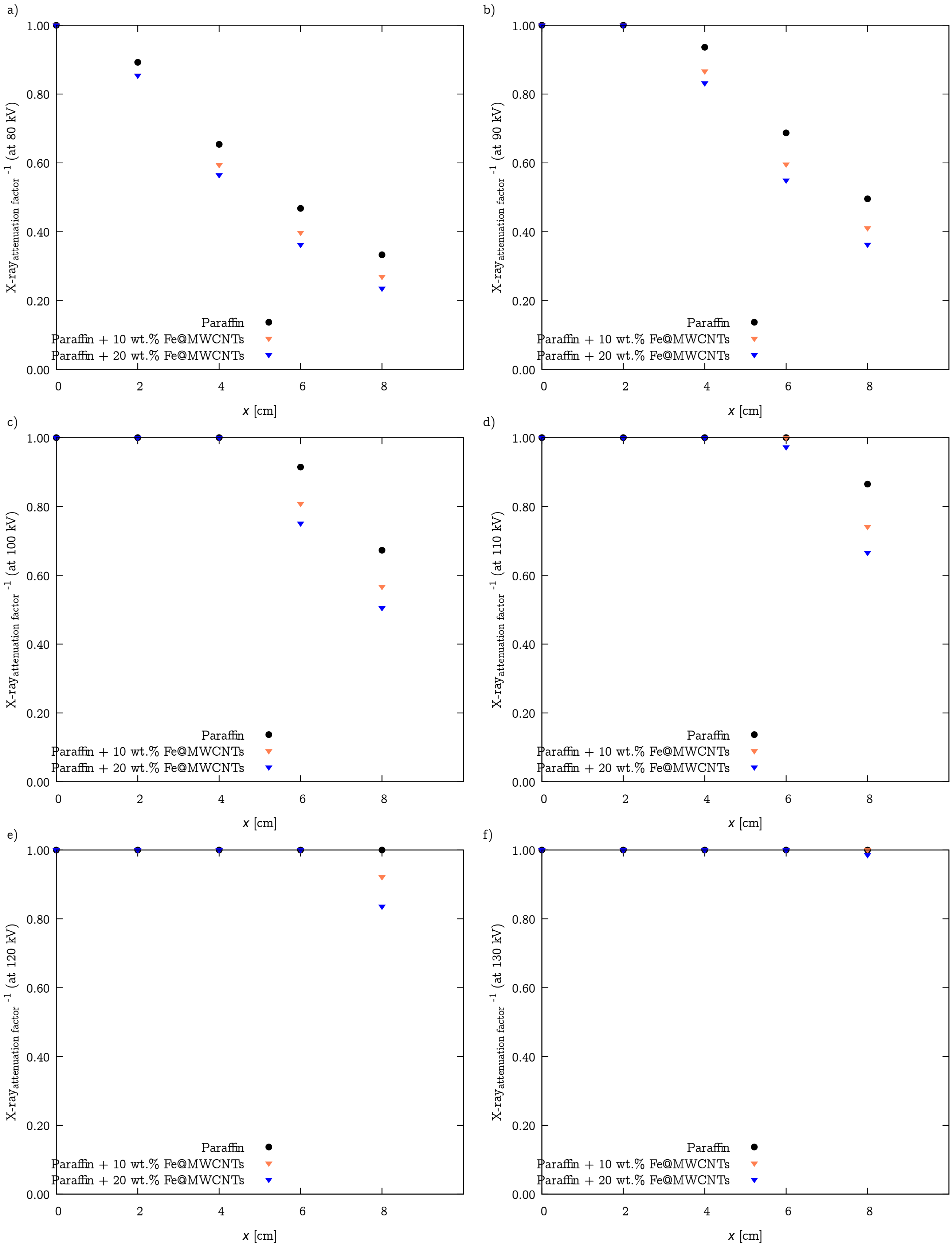

Fig. S3: The dependence of X-ray$_{\text{attenuation factor}}$ $^{-1}$ for the manufactured composites with 10 wt.% and 20 wt.% of Fe@MWCNTs addition and for the pure paraffin at 80, 90, 100, 110, 120 and 130 kV voltage.