Vibration damping of granular materials: preliminary measurements

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Executive Summary

Experimental measurements were taken of the damping induced by various layers of granular materials laid on the surface of a vibrating beam. Measurements were processed using the single degree of freedom (SDOF) circle fit method. The measurement are exploratory, intended to give indications of damping levels that might be achievable in practice. Materials included SiC and crumbed rubber.

Section 1 briefly describes the experimental setup with section 2 describing the effects of the tape on the sides of the beam. Section 3 concerns SiC particles, section 4 nonlinear effects. Sections 5 to 10 describe measurement using crumb rubber, polyethylene, aluminium oxide, PLA particles, rubber and SiC mixtures, and layered materials, while section 11 discusses results. Overall, granular materials would seem to offer promising prospects as a damping treatment.

The main findings were as follows.

1. Care needs to be taken to ensure the rig itself does not introduce substantial damping.
2. Tape was added onto the sides of the beam to restrain the particles. This introduced a significant amount of damping. Cutting the sticky tape reduced this effect. Care should be taken with future experimental set ups.
3. For the first three modes of vibration, under low amplitude excitation, silicon carbide (SiC) merely mass loaded the beam. No significant changes in damping were observed for the first three modes. There were no observable changes with particle sizes ranging from 177µm to 1000µm. The finest particles at 37 µm showed weaker non-linear effects.
4. Amplitudes of vibration exceeding 1g caused a substantial increase in damping as well as strong non-linear effects. Similar results were found for a range of “hard” particles.
5. As a result of the nonlinear effects, an impact hammer is not a suitable test method as the excitation amplitude cannot be controlled. A shaker with controllable amplitude will be required for repeatable results. Additionally, the nonlinear effects makes the circle fit damping method unsuitable for precise estimates of damping, so that alternatives based on measured power might be preferred.
6. Out of all test particles, the most significant damping was observed with crumb rubber.
7. Experiments with a base layer of crumb rubber and a top layer of SiC gave promising results. The system appeared to have a mass-spring resonance close to the second mode which introduced the most significant damping observed on the second mode. This resonance is potentially tunable.
8. Damping with granular materials seems to be proportional to the mass of the added granular material.

1. Experimental Setup

Modal testing of a steel cantilever beam with a layer of granular material was undertaken. The steel beam was 314mm long, 20mm wide and 2.16mm thick. The beam was excited with an impact hammer roughly 2mm from the tip of the beam. The velocity of the beam was measured with a laser vibrometer directly underneath the forcing point (labelled as '1' in Figure 1). This setup is shown in Figure 1.

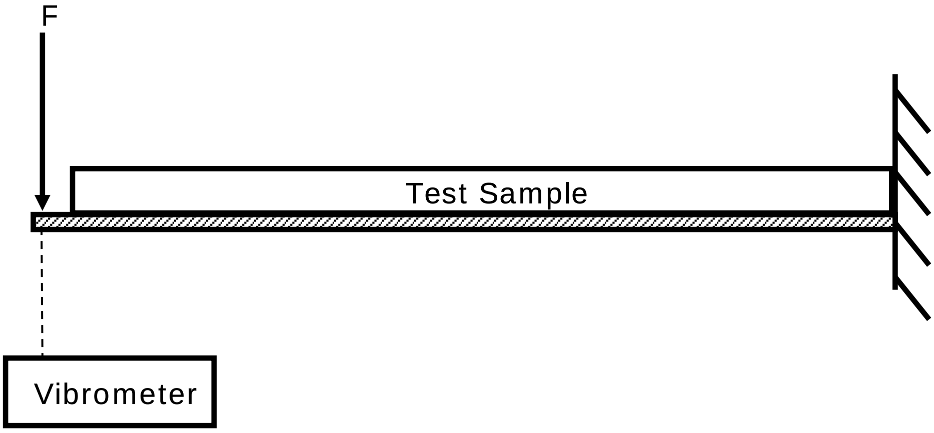

Figure 1 Experimental Setup

Sticky tape was used to contain the granular material on top of the beam as can be seen in Figure 2. The sticky tape was cut to reduce its damping effects (refer to section 2).

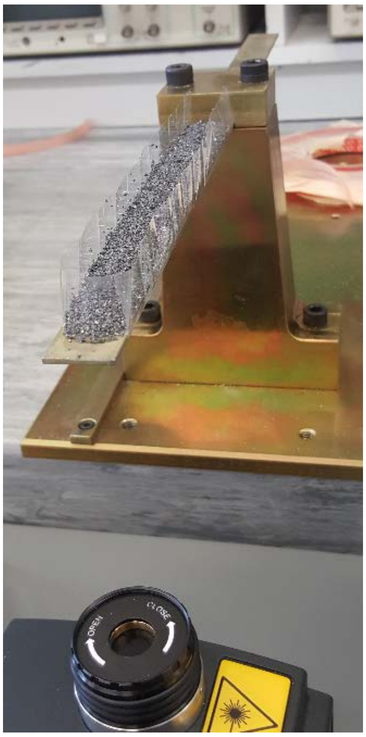

Figure 2 Photograph of experimental setup

A range of materials were tested as shown in Table 1.

Table 1 Materials Tested

Crumb Powder/SiC 10:90 Mix
Crumb Powder/SiC 20:80 Mix
Aluminium Oxide
PLA
SiC
Crumb Rubber
Polyethylene
Layer of Crumb Powder and SiC

2. Effect of Tape on the Beam

Upon adding tape to the beam a significant increase in damping on the third mode was observed (Figure 3). To reduce these effects the sticky tape was cut into strips. As seen in Figure 3 the cut sticky tape shows a reduction in damping.

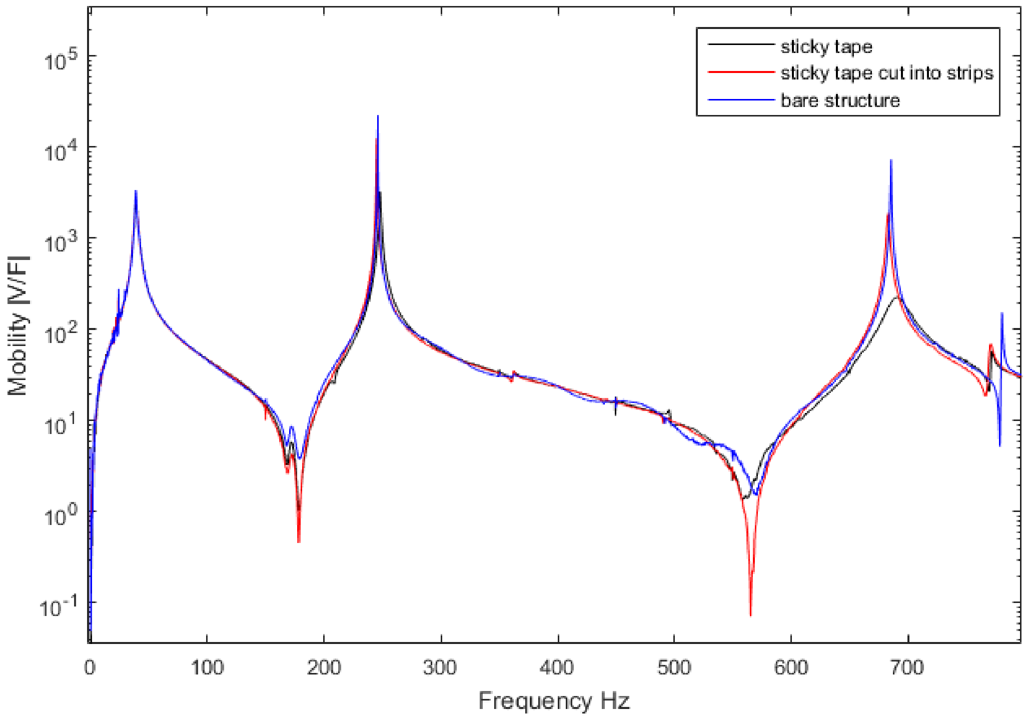

Figure 3 Effect of adding sellotape walls on the cantilever beam

3. Damping of SiC Particles

In Table 2 the damping estimates are given for the first three modes for the different sizes of SiC particles. No significant increase in damping for the first three modes is seen from the bare structure. There seems to be no quantifiable difference between particle sizes.

Table 2 Damping estimates of SiC

SiC Test Particle 1 (500-1000um)			
	Damping (%) on Mode		
Added Mass (g)	1	2	3
0	10.3	0.919	0.341
8.5	7.5	0.871	0.22
17.5	22.98	0.94	0.287
22.5	10.18	0.834	0.2
32	16.6	1.1	0.19
39	8.06	0.974	0.255

SiC Test Particle 2 (210-500um)			
	Damping (%) on Mode		
Added Mass (g)	1	2	3
0	11.26	0.831	0.182
8.5	8.629	0.692	0.3042
17.5	11.48	1.27	0.19
22.5	20.13	1.39	0.345
32	12.58	0.87	0.271
39	29.99	1.025	0.247

SiC Test Particle 3 (177um)			
	Damping (%) on Mode		
Added Mass (g)	1	2	3
0	3.315	0.61	0.3854
8.5	15.68	1.028	0.327
17.5	19.3	0.745	0.2723
22.5	16.51	0.7636	0.25
32	7.79	0.8487	0.271
39	3.097	1.4	0.241

SiC Test Particle 4 (37um)			
	Damping (%) on Mode		
Added Mass (g)	1	2	3
0	20.46	1.206	0.277
8.5	5.24	0.69	0.2429
17.5	11.44	0.635	0.293
22.5	57.55	1.588	0.447
32	10.95	0.844	0.326
39	3.122	0.971	0.2698

The frequency response functions (FRF) for the different particle sizes are shown in Figures 4-7. For all cases there seems to be an increased damping effect with frequency. For the larger test particles 1-3 the third and fourth resonance takes on an odd shape. Non-linear effects seem to be the most likely cause of the odd features in the FRF's. This would indicate that the circle fit method used would not be a suitable method to estimate damping in granular material at higher amplitudes. Interestingly the non-linear effects are not seen for the finest particles in Figure 7. It was observed during the experiment that the finest particles (37 µm) would pack firmer. The granular bed was more difficult to move by tapping the beam. The nonlinearity may be weaker as a result of a stiffer bed, inhibiting particle movement.

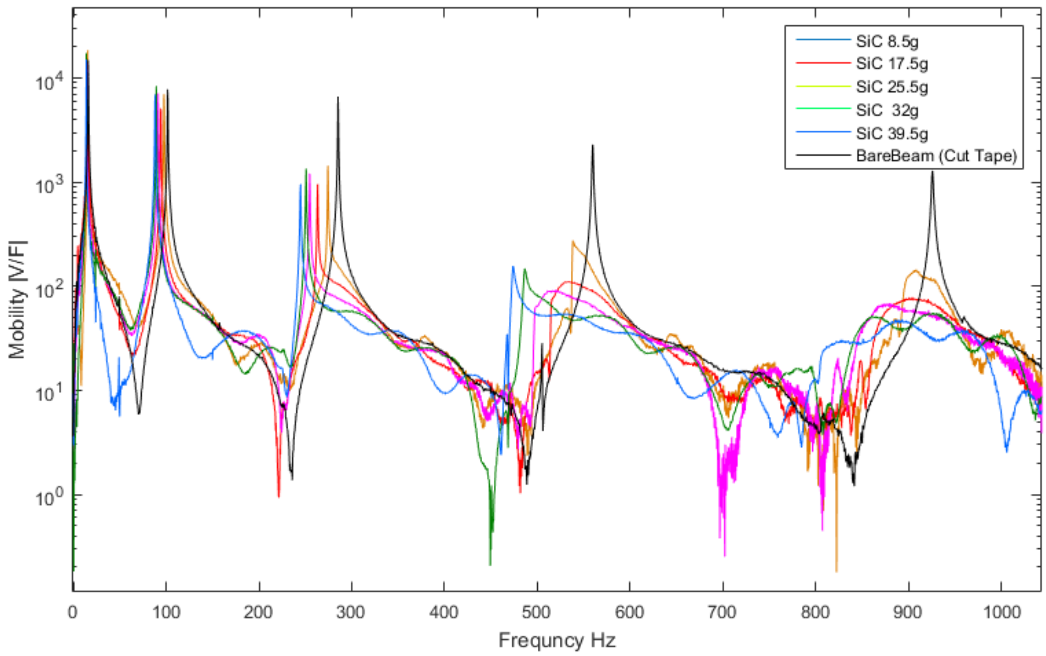

Figure 4 SiC test particle 1 (500-1000um)

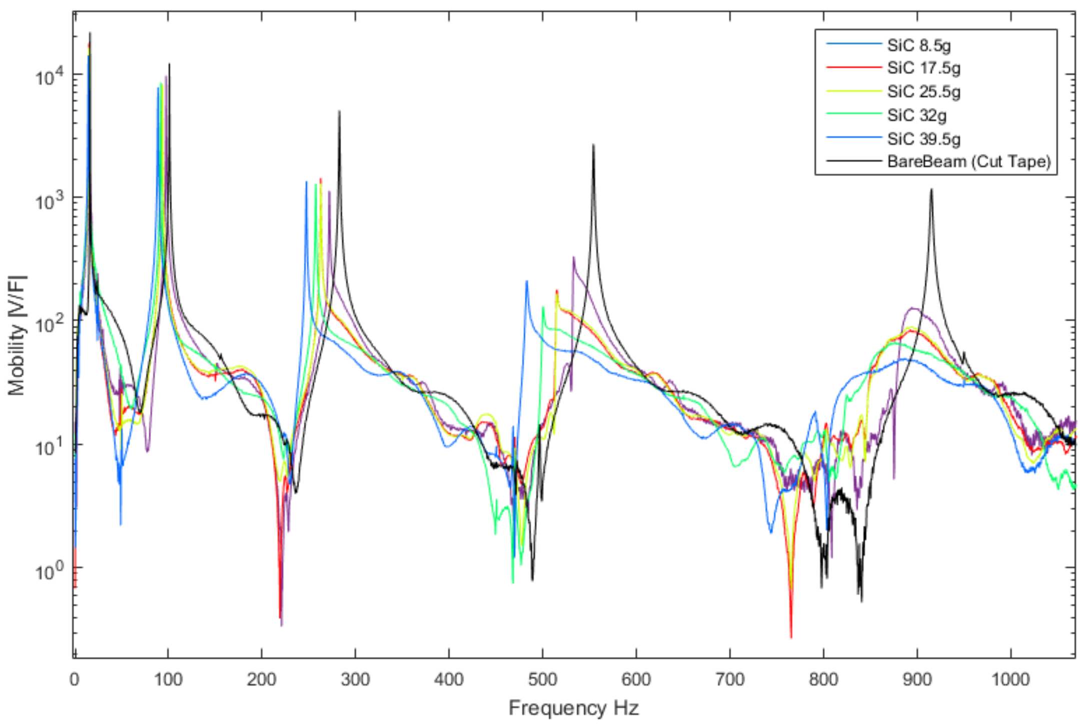

Figure 5 SiC test particle 2 (210-500um)

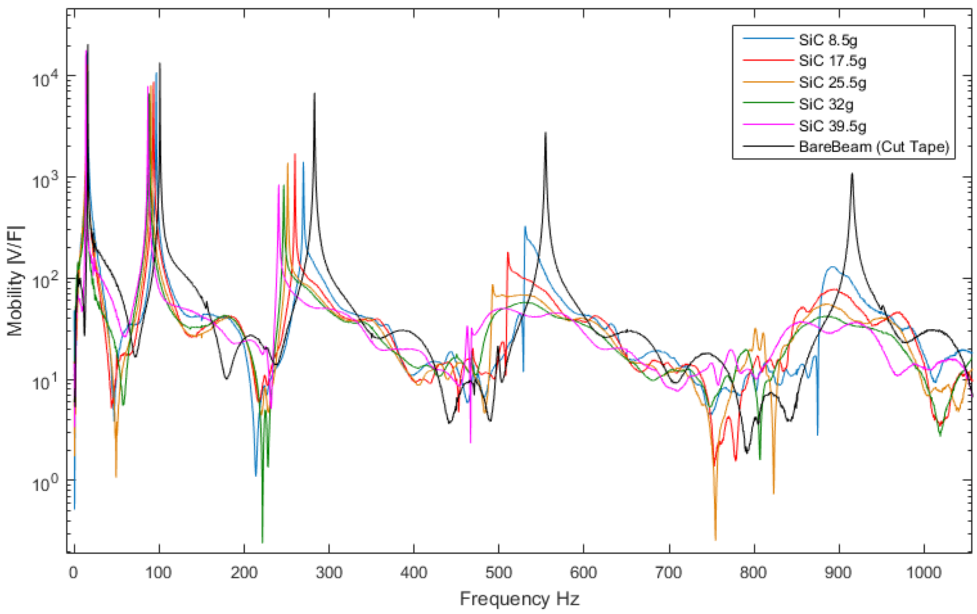

Figure 6 SiC test particle 3 (177um)

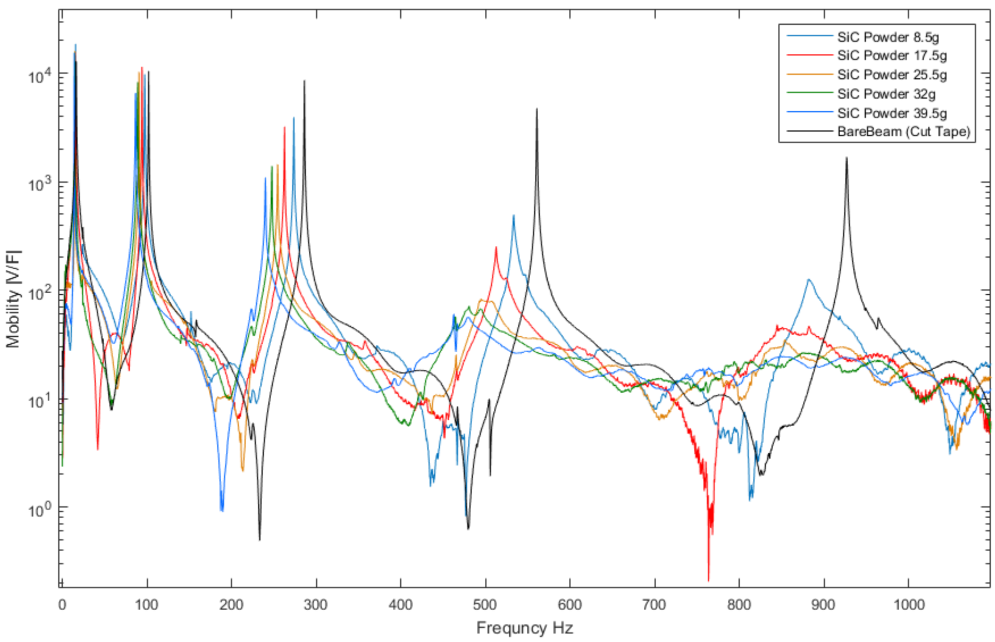

Figure 7 SiC test particle 4 (37um)

4. Amplitude Effects

The response of the system was observed to change from one impact to the next. When investigated, it was found that amplitude has a significant effect on the response of the granular material and beam system. The repeatability of an impact hammer test is limited. A user is incapable of recreating an certain acceleration or precise angle of impact. Therefore, the tests on amplitude were conducted with the intent on only identifying large scale trends. Figure 8 shows SiC test particle 1 (500-1000um) under larger excitation. Upon comparison with the soft hits in Figure 4, it is evident that there are significantly reduced amplitudes at the resonances, implying a substantial increase in damping.

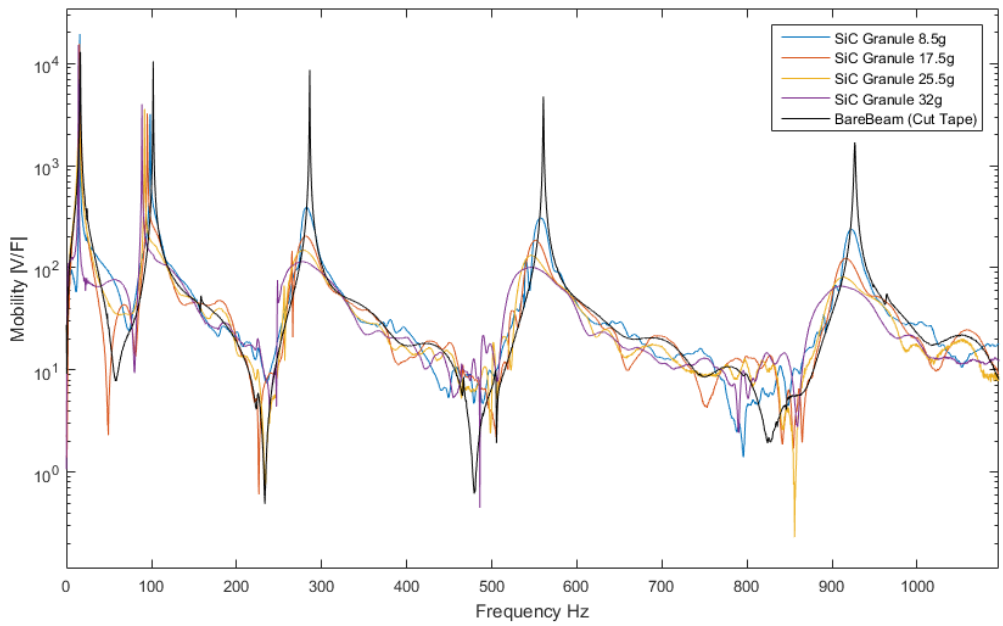

Figure 8 Test Particle 1 with Hard Hits

The damping estimates using the SDOF circle fit approach for SiC test particle 1 under high excitation levels are shown in Table 3. The damping for the second mode remains similar. However, the 3rd and 4th resonances show significant increases in damping compared to soft hits.

Table 3 Damping of SiC Test Particle 1 with hard hits

SiC test particle 1 500-1000um				
	Damping (%) on Mode			
Added Mass (g)	1	2	3	4
0	20.46	1.206	0.277	0.09451
8.5	2.825	0.8397	2.221	1.363
17.5	18.7	0.742	3.963	2.014
32	24.01	0.687	5.602	2.652
40	3.356	0.905	8.679	4.4643

To investigate the transition point of the amplitude effects the acceleration was measured at the input location. Two distinct regions of 'soft' hits, and 'hard' hits were observed, as well as some transition point somewhere in-between as seen in Figure 9.

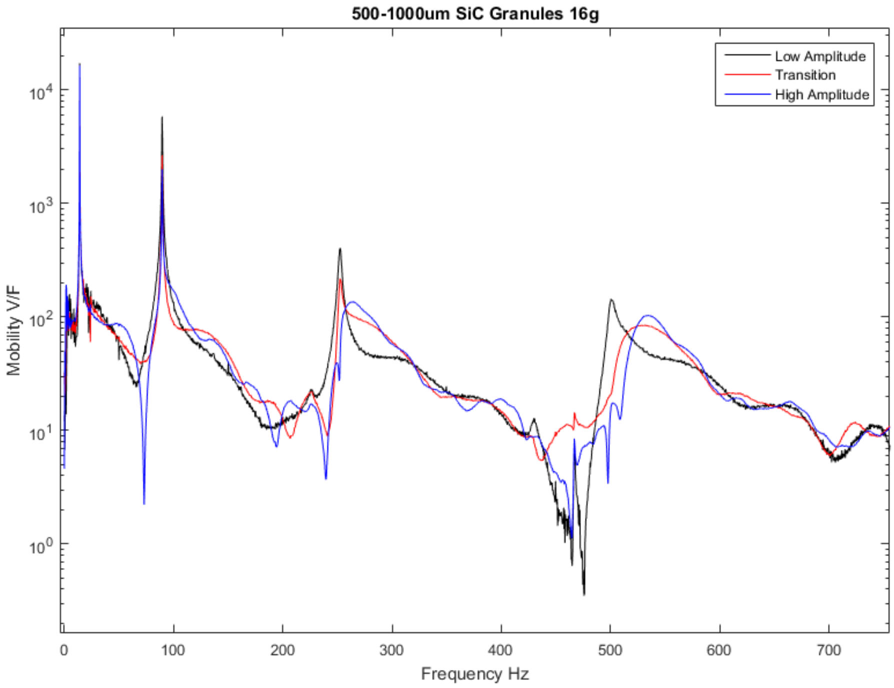

Figure 9 Test Particle 1 - Varying input amplitude

The results showed that if there was significant portion of the response above 1g the 'hard hit' response would be observed. The transition point showed accelerations above 1g for only a small time after the impact as seen in Figure 10.

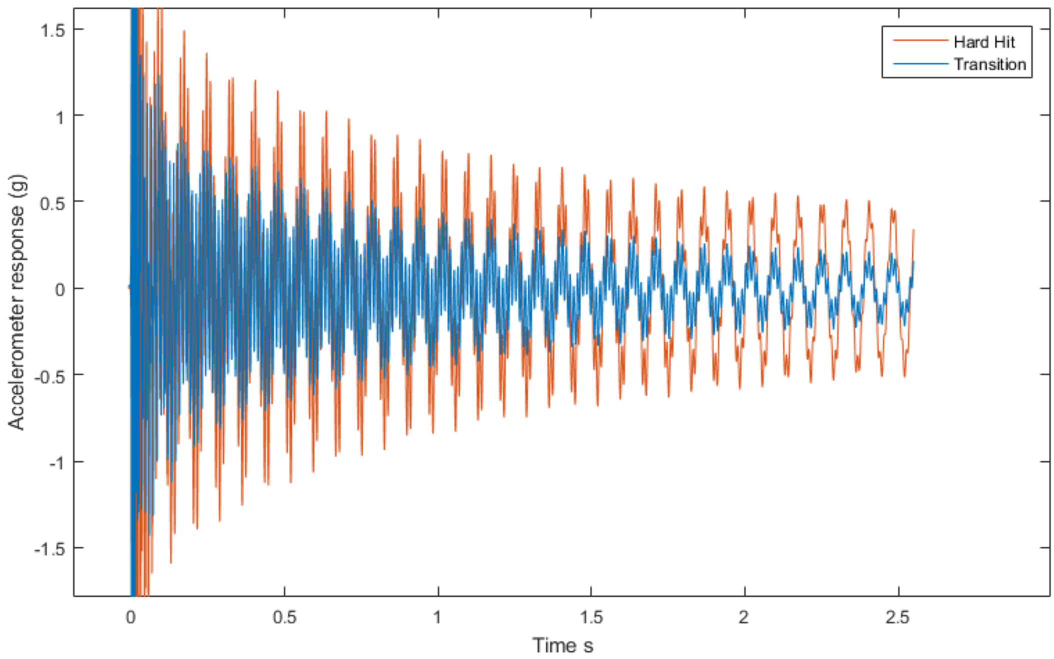

Figure 10 Acceleration response at the free end of the cantilever

Subsequently all tests were conducted under 'soft hit' conditions (to the best of the first author's ability).

It was noticed that the resonance peak shifts with changes in acceleration amplitude. Table 4 and Table 5 show how the resonance frequency corresponds to the mass loading effect of the added particles. Results were calculated analytically using an Euler Bernoulli model. For soft hits in Table 4, there is generally reasonable agreement. Deviation is expected due to the fact that the mass would not be distributed evenly on the beam.

Table 4 Resonance frequency comparison to mass loading for soft hits

Soft Hits				
Mass Added	8.5	17	25.5	34
Mode	Difference from Mass loading (g)			
1	0.16	-3.06	-4.96	-4.87
2	1.70	0.15	1.44	-0.54
3	1.21	1.16	1.24	1.26
4	2.03	2.28	2.91	4.28
5	2.02	1.23	-7.60	

Table 5 shows that the resonance peaks under hard hit conditions deviate significantly. For example the 5th mode loaded with 25.5g of SiC has a resonance peak which would correspond to 22.6g less mass that what there is on the beam (total apparent mass of only 2.9g).

Table 5 Resonance frequency comparison to mass loading for hard hits

Hard Hits				
Mass Added	8.5	17	25.5	34
Mode	Difference from Mass loading (g)			
1	0.58	-3.06	1.63	2.28
2	-0.90	-1.77	-1.77	0.62
3	-5.68	-13.95	-18.94	0.94
4	-7.29	-14.45	-19.79	-26.67
5	-7.59	-15.48	-22.59	-19.44

5. Crumb Rubber

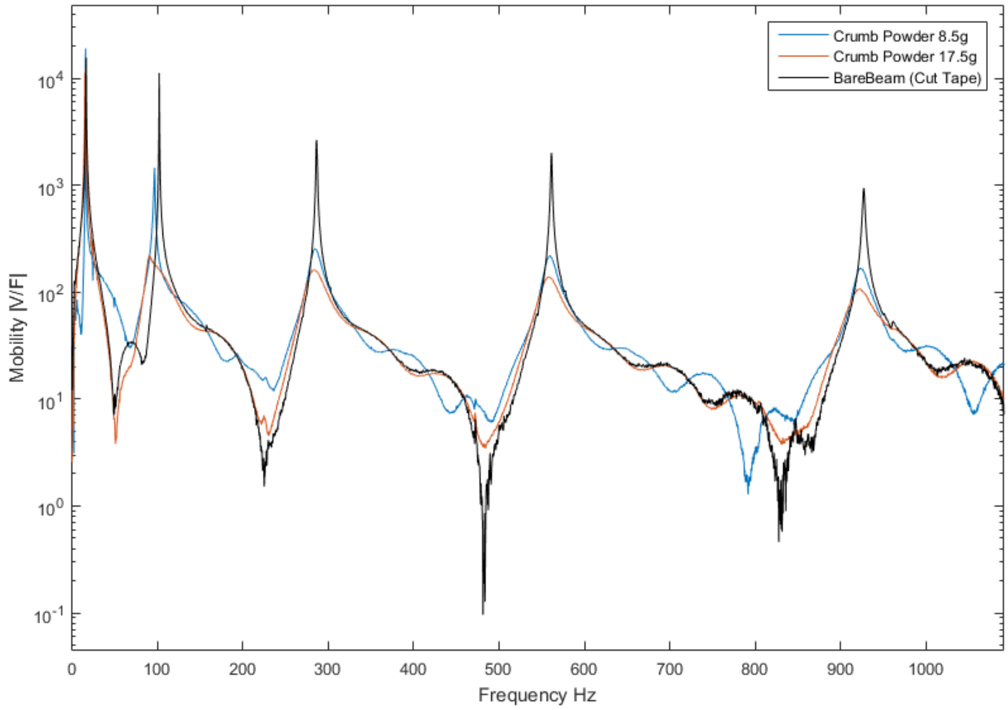

Figure 11 Crumb Rubber

Crumb rubber seemed to show less of a frequency dependence than other substances (Figure 11). Additionally, significant damping was observed especially in the second mode (Table 6). Peaks are generally symmetrical and do not show nonlinear effects as the harder test particles.

Table 6 Damping estimates of Crumb Rubber

Crumb Rubber				
	Damping (%) on Mode			
Added Mass (g)	1	2	3	4
0	14.2	1.03	0.18	0.89
8.5	3.49	0.564	2.01	1.32
17.5	16.7	2.75	3.84	2.01

6. Polyethylene 100um

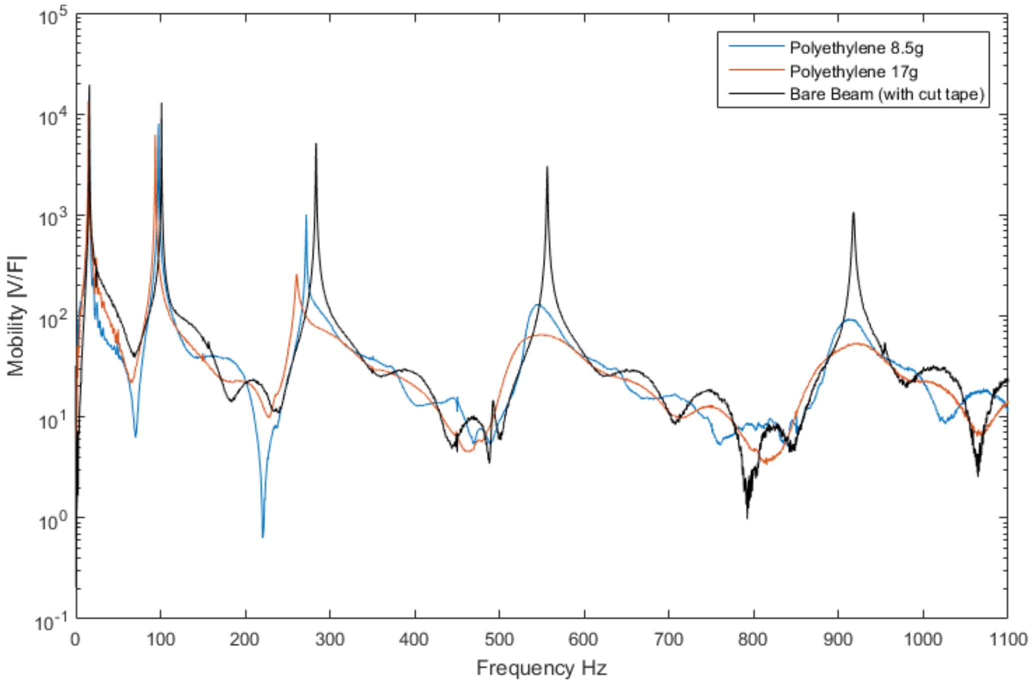

Figure 12 Polyethylene

Polyethylene shows a frequency dependence similar to what is observed in SiC (Figure 12). Table 7 shows that the damping is low for the first three modes, but significantly increases with the fourth.

Table 7 Damping estimates of polyethylene

Crumb Powder				
	Damping (%) on Mode			
Added Mass (g)	1	2	3	4
0	8.87	0.567	0.303	0.074
8.5	8.50	0.739	0.207	2.72
17.5	16.7	0.931	-	5.56

7. Aluminium oxide (>1um)

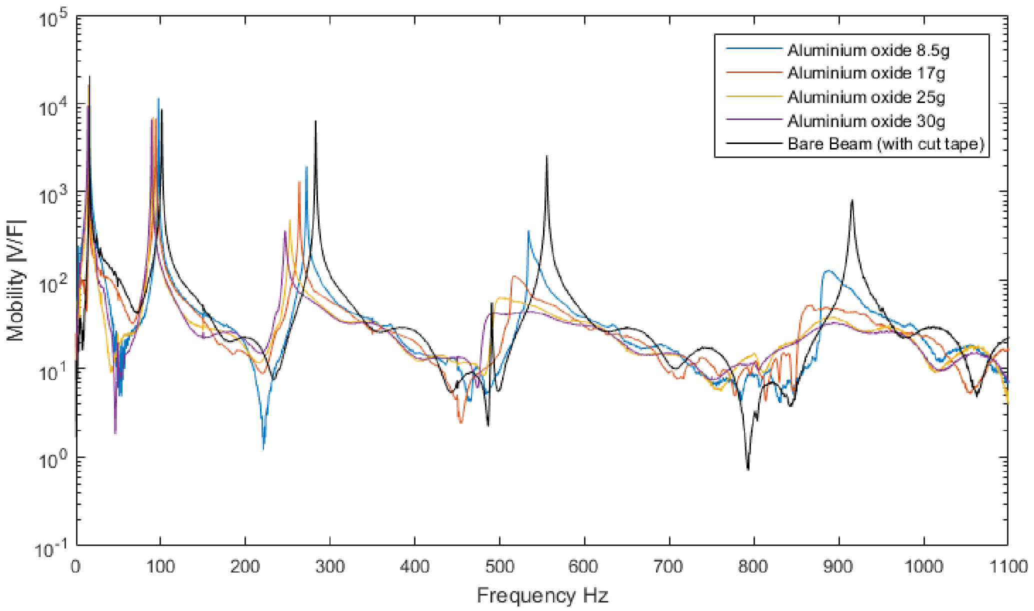

Figure 13 Aluminium oxide FRF

Aluminium oxide shows some frequency changes with damping. Little to no damping is observed in the first three modes as seen in Figure 13 and Table 8. There is a significant amount of damping in the fourth mode. The damping estimates are influenced by the nonlinear effects changing the shape of resonance peaks.

Table 8 Damping Estimates of Aluminium oxide

Aluminium Oxide				
Damping (%) on Mode				
Added Mass (g)	1	2	3	4
0	7.621	0.739	0.268	0.1338
8.5	11.3	1.669	0.33	0.267
17.5	2.887	0.8759	0.236	2.14
25.5	15.74	1.251	0.352	2.07
34	17.55	0.916	0.438	4.53

8. PLA (1x2mm)

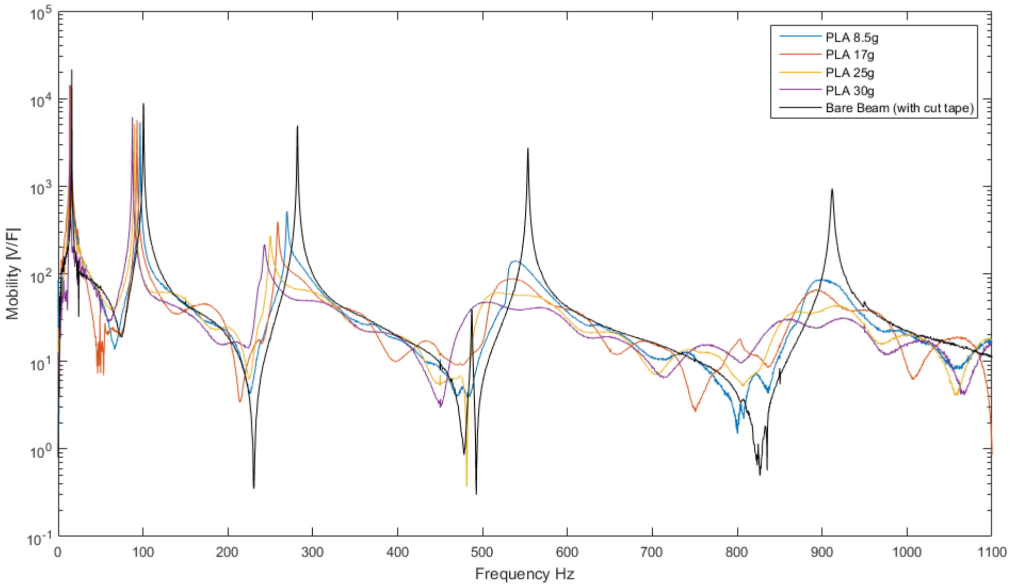

Figure 14 PLA FRF

PLA shows similar trends of a significant increase in damping after the third resonance as seen in Table 9 and Figure 14. There is a slight increase in damping on the third mode in comparison to other test particles.

Table 9 Damping Estimates of PLA

PLA				
Damping (%) on Mode				
Added Mass (g)	1	2	3	4
0	15.96	0.788	0.3485	1.643
8.5	15.91	0.932	0.4078	5.755
17.5	13.36	1.002	0.578	4.986
25.5	13.75	0.995	1.15	7.078
30	21.91	1.426	1.273	-

9. Crumb Rubber and SiC Mixtures

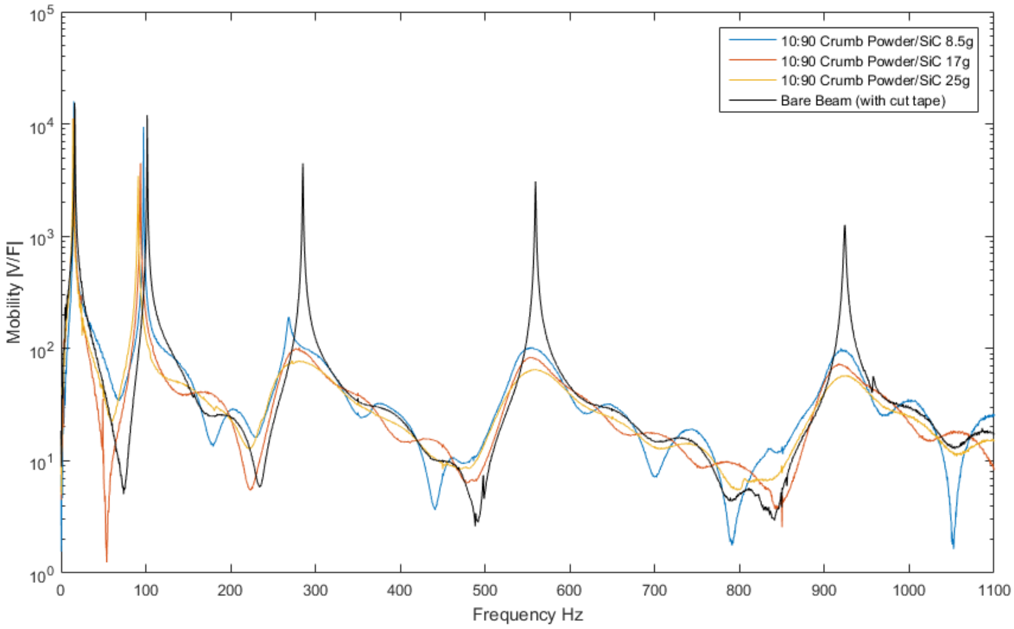

Figure 15 10% crumb rubber 90% SiC by Mass FRF

The crumb rubber and SiC mixture in Figure 15 shows slightly more resemblance to crumb rubber rather than the majority (SiC) of the mix by mass. The peaks are generally smooth. Similar damping estimates are seen in crumb powder alone and the mixture with the exception of the second mode, where crumb powder alone performs better (Table 10 and Table 6).

Table 10 Damping Estimates of 10:90 crumb rubber and SiC

10:90 Mix of Crumb Rubber and SiC			
Damping (%) on Mode			
Added Mass (g)	1	2	3
0	13.3	0.605	0.194
8.5	21.48	1.05	1.224
17.5	17.8	0.905	4.183
25.5	23.63	0.732	10.28

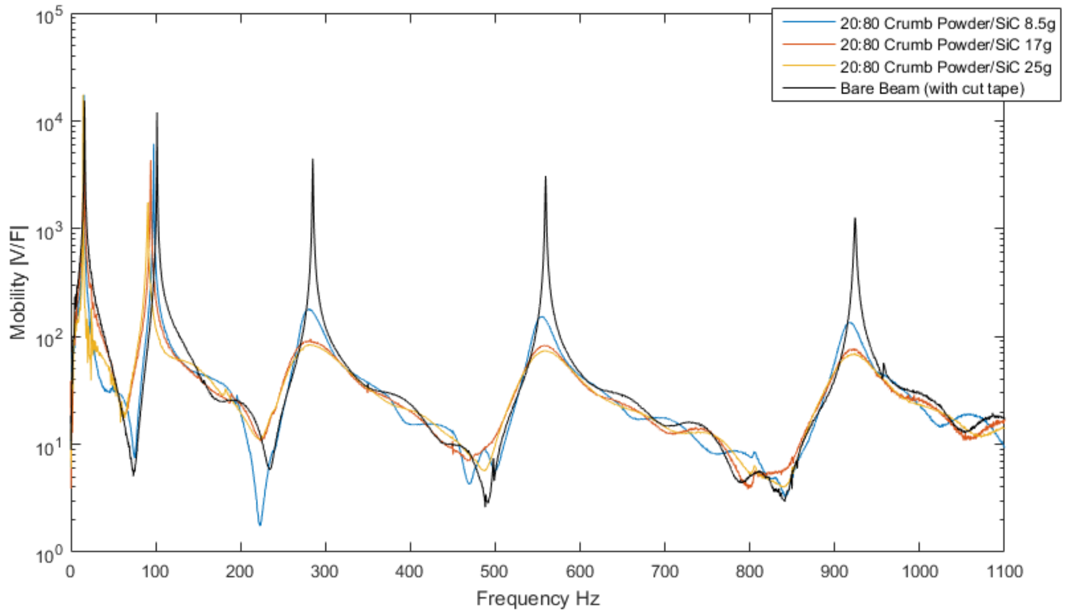

Figure 16 20% Crumb Rubber with 80% SiC by Mass FRF

The 20:80 mixture of crumb rubber and SiC showed an increase in damping in the third mode compared to both SiC and crumb powder alone (Table 11 and Table 6). However, the second mode of the purely crumb powder mixture at 17g performs significantly better than both mixtures.

Table 11 Damping Estimates of 20:80 Mix of Crumb rubber and SiC

20:80 Mix of Crumb Rubber and SiC			
Damping (%) on Mode			
Added Mass (g)	1	2	3
0	13.3	0.605	0.194
8.5	7.545	0.886	4.25
17.5	18.05	0.995	8.119
25.5	2.932	-	9.381

10. Layered Tests

Experiments were performed with a base layer of 8.5g crumb rubber with various amounts of SiC added on top. The layers were separated with cling wrap. The addition of the cling wrap seemed to have a minimal effect by itself as seen in Figure 20. The layered system performed similarly to the crumb powder and crumb powder and SiC mixtures as seen in Figure 17 and Table 12.

However there was a drastic improvement in damping on the second mode. With the exception of crumb powder, no other test particle showed any significant damping on the second mode. The layered system showed the best performance in the second mode. Interestingly, Figure 18 shows the second mode appears to be splitting into two separate modes with an increase in SiC mass added, the phase is shown in Figure 19.

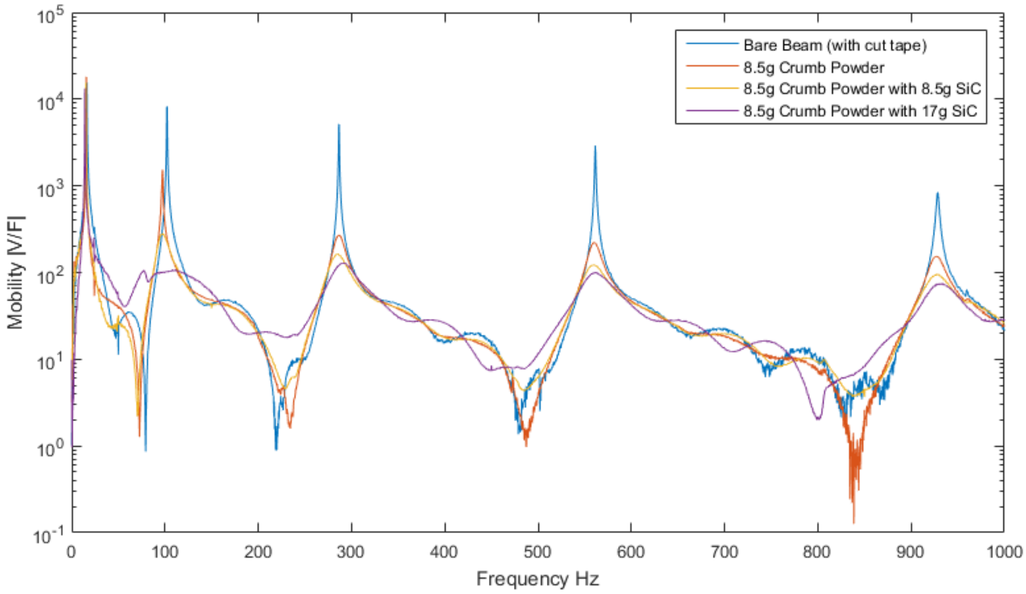

Figure 17 Base layer of 8.5g crumb rubber with a separate layer of SiC on top

A very peculiar observation is that the resonance frequency seemed to be independent of the mass added to the beam. Generally, one would expect the resonance frequencies to decrease with added mass. The 60g of Sic test added a mass ratio of 60% and still no change is observed (Figure 18).

Table 12 Damping estimates of layed crumb rubber and SiC system

8.5g Crumb Rubber with SiC Added			
Damping (%) on Mode			
SiC Mass (g)	1	2	3
0	21.48	1.05	1.224
8.5	7.1979	6.756	3.451
17.5	25.6	15.4	4.173
25.5	7.572	-	4.937
32	10.17	4.859	4.662
40	12.85	4.625	5.085
60	18.93	-	6.4629

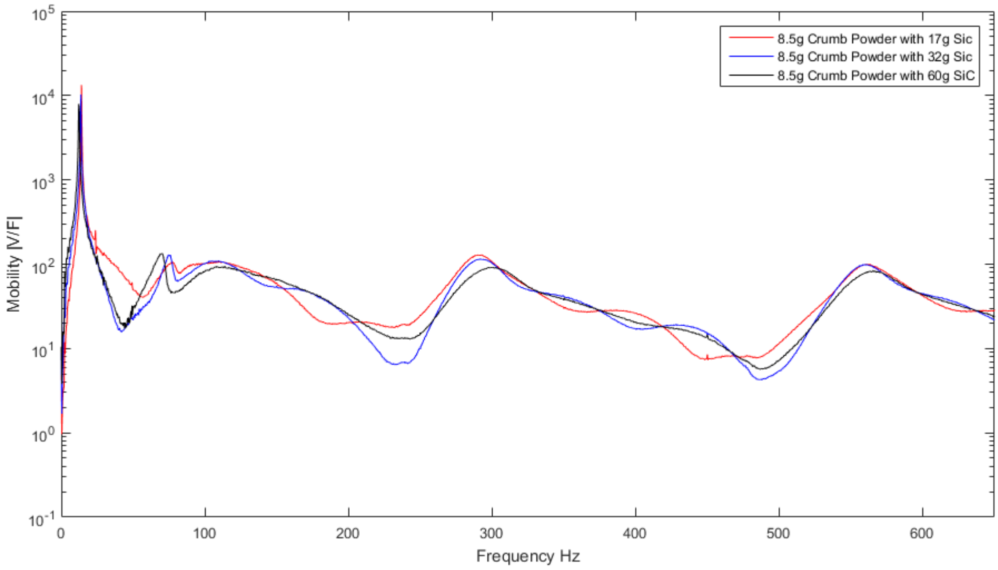

Figure 18 Second mode splits into two modes as large amounts of SiC is added

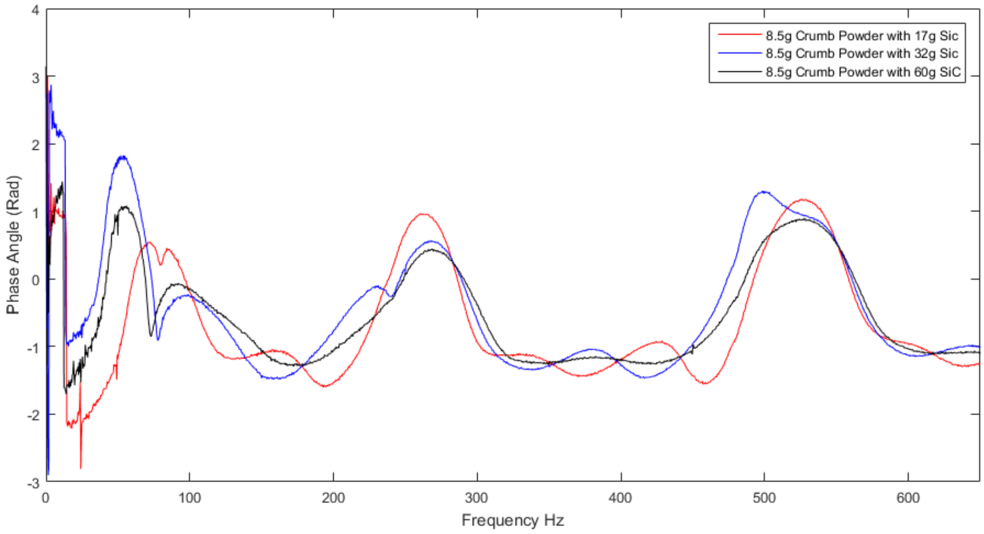

Figure 19 Phase plot showing the second mode splitting

The crumb rubber and SiC particles seems to be acting like a spring mass system on top of the beam. It seems the resonance frequency of the crumb rubber and Sic system lies roughly around the second natural frequency. The increase in mass would make the mass spring behaviour more prominent, and lower the resonant frequency. This seems to coincide with the mode splitting observed. The higher masses show a phase reversal at lower frequencies. Additionally, a peak appears with increasing mass as the mass-spring system resonance shifts to lower frequencies.

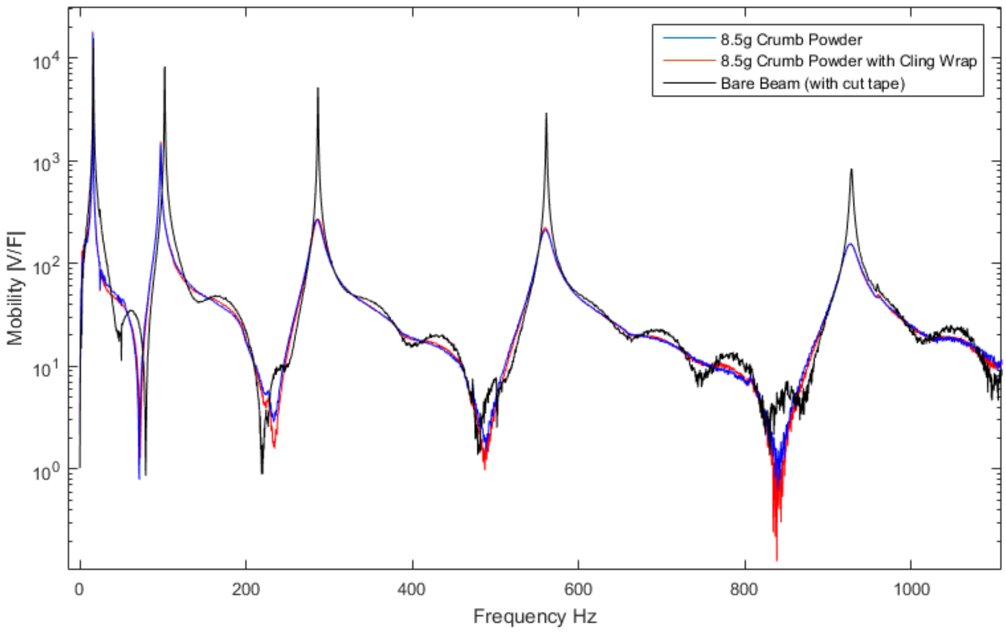

Figure 20 Effect of cling wrap on the base layer of rubber

11. Comparison

Figure 21 and Figure 22 show all the results for layers of particles of mass of 8.5g and 17g respectively. The damping estimates for the first mode displayed significant variation, and this raises issues about the accuracy of the damping estimates for the first mode using the set-up of these experiments (particularly the frequency range and sample length). From the results of experiments with granular material having mass of 8.5g, it was observed that the damping of the second mode varies little for all particles tested. Generally, there seems to be an increase of damping with frequency. For both 8.5g and 17g cases the resonance peaks show significant variation in both their shape and peak frequency with different test particles.

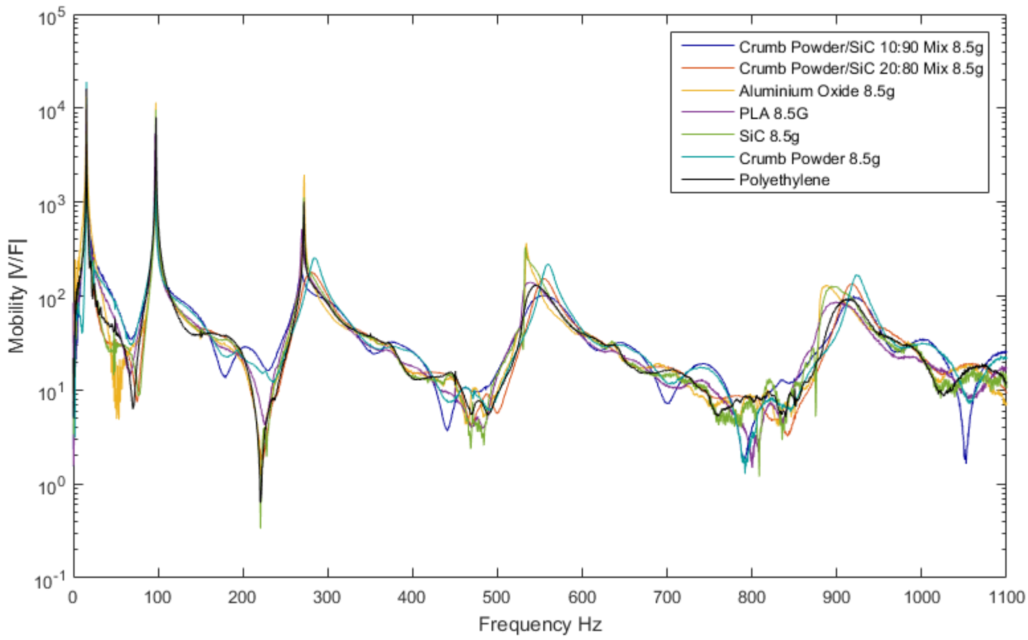

Figure 21 All test particles with mass of 8.5g

Table 13 shows the summary of the damping estimates for all test particles with a weight of 8.5g added to the beam. The most promising materials appear to be the 20:80 mix of crumb powder and Sic, as well as the crumb rubber alone on the third mode. There seems to be relatively little effect on the first and second modes. For many particles estimates at the 4^{th} mode were difficult to acquire.

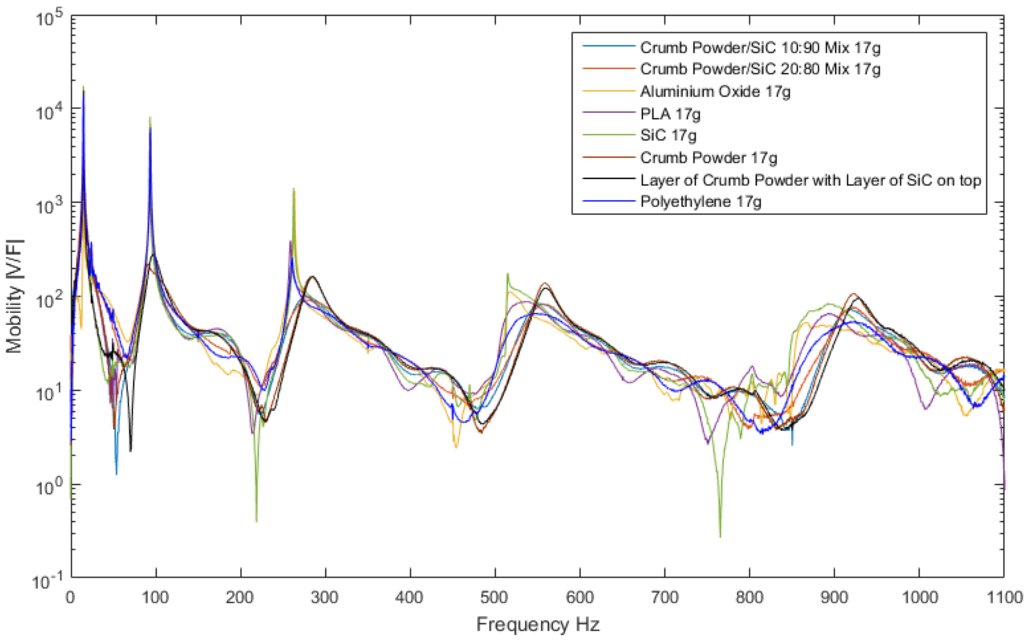

Figure 22 All test particles with mass 17g

Table 13 Damping estimate of test particles with mass of 8.5g

Damping (%) on Mode				
	1	2	3	4
Crumb Powder/SiC 10:90 Mix	21.48	1.05	1.224	
Crumb Powder/SiC 20:80 Mix	7.545	0.886	4.25	
Aluminium Oxide	11.3	1.669	0.33	0.267
PLA	15.91	0.932	0.4078	5.755
SiC	7.5	0.871	0.22	
Crumb Rubber	3.489	1.315	2.01	
Polyethylene	8.497	0.7389	0.207	2.717

Figure 22 shows that the only test particles that affected the second mode substantially was the crumb powder and the layered system. Table 14 shows the summary of the damping estimates for all test particles with a weight of 17g added to the beam. Similar to the 8.5g case the highest levels of induced damping were for those layers that included the crumb powder. The damping of these granular materials seem to be proportional to the amount of mass added.

Table 14 Damping estiamtes of test particles with mass of 17g

Damping (%) on Mode				
	1	2	3	4
Crumb Powder/SiC 10:90 Mix	17.8	0.905	4.183	
Crumb Powder/SiC 20:80 Mix	18.05	0.995	8.119	
Aluminium Oxide	2.887	0.8759	0.236	2.14
PLA	13.36	1.002	0.578	4.986
SiC	22.98	0.94	0.287	
Crumb Rubber	16.69	2.75	3.835	2.01
Polyethylene	16.68	0.931	-	5.557
Layer of Crumb Powder and SiC	7.1979	6.756	3.451	