Investigating the effect of graphene on the strength and elasticity of wood-free composite decking

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Abstract

The thickness of wood-free composite decking presents financial and environmental challenges. The production process consumes more materials, requires extensive land excavation for a strong foundation, and poses disposal issues. This research aimed to investigate the impact of graphene, an additive, on the strength and elasticity of wood-free composite decking in order to reduce its thickness. To conduct this research, polyurethane foam panels were modelled as decking, since these decking are primarily made from polyurethane resin, as well as mineral stone and Lastane coating. The impact of graphene was investigated, specifically, because of its relatively-easy accessibility, high strength, and high elasticity. The methodology involved mixing specific quantities of Part A and Part B of the polyurethane foam, and clamping it as it was left to solidify. After it was formed into the desired shape, it was placed in the Force Testing Machine and the maximum force the samples could withstand before fracture, the sample's Young's Modulus, and the sample's bending strength were measured using in-built sensors. Different percentage compositions (0%, 0.5%, and 1%) by mass of graphene were added to the samples for investigation. It was found that the decking sample with a graphene composition of 1% (the largest composition tested) had the highest maximum force, bending strength, and Young's Modulus. The mean values for this composition were 416.20 N, 2.01 MPa, and 17.15 MPa respectively, compared to the respective means of 274.95 N, 1.00 MPa, and 10.50 MPa of the samples without any graphene. This research could have significant implications on the composite decking industry, as a stronger decking would enable a potential reduction in thickness, and thereby, environmental and financial inefficiencies. The energy required to dig a smooth, strong base to place the decking could potentially reduce, and the recycling of the decking could become more energy-efficient. This research, therefore, could reduce energy costs for suppliers, lower financial burdens for consumers, and decrease waste.

Introduction

Aim

Aim: How does the addition of graphene as an additive affect the strength of wood-free composite decking?

Objectives

- Research, through online sources and interviews, different materials that can act as additives, and choose one (the chosen one was graphene)
- Research, through online sources and interviews, wood-free composite decking, its material composition, and its impact on the surrounding environment
- Understand the science behind the problem through online websites, educational videos, etc.
- Brainstorm ways to measure the maximum force, bending strength, and young's modulus of the sample
- Plan and design a realistic experiment
- Perform the experiment
- Analyse the results
- Reflect on potential improvements to the research (done in the document titled 'Reflection')

Purpose

- Reduced costs - Reduced costs would enable better access to wood-free composite decking for a greater number of people. This would be beneficial for the businesses and the consumers, as the businesses can maintain (or possibly increase) profit margins while increasing sales, and the consumers can afford luxury products that make their homes beautiful. This would especially be beneficial in the current cost of living crisis in the UK. But how would the costs reduce? If the strength of each unit of decking increases, then the panel used to make the decking can be thinner. The process of installing wood-free composite decking involves digging the ground to create a strong base first, which takes up the majority of the cost. If the panel can be thinner, then the digging can be less deep and the cost would reduce greatly.
- Sustainability - Greater sustainability in wood-free composite decking would be extremely beneficial for the environment. It is more sustainable in two ways. FIrstly, lower digging would require less energy, allowing for less fossil fuel usage and reduced greenhouse gas emissions. Secondly, since the panels may be thinner now, then less material may be used, and the product would be a lot more efficient in material usage by minimising wastage. Lastly, since it will only use one material throughout the panel, instead of using layers of different materials to increase strength, the recycling process wouldn't need to waste more non-renewable-source generated energy for separating the different layers for recycling. This may further reduce energy costs.

Hypothesis

Adding graphene would strengthen wood-free composite decking. This is because graphene is one of the strongest materials known (the main properties contributing to its strength are given in Table 1 under the subheading 'Choice of Materials'). Because of its nano-size, it can minimise the size of any pores in the decking's structure, increasing the density of the decking. This would also strengthen the bonds between the molecules of polyurethane, making the structure more difficult to deform/break. Furthermore, studies have shown that graphene is a successful additive in materials like concrete and cement, and has seen extraordinary results there.

Planning and brainstorming

Choice of Materials

3 possible additives were looked at: graphene, hexagonal boron nitride (h-Bd), and carbyne. h-Bd and graphene are very similar in structure: both are 2D hexagonal structures, but graphene has 6 carbon atoms, while h-Bd has 3 boron atoms and 3 nitrogen atoms. Below are the properties of the two, compared to graphene:

Properties	**Graphene**	**Boron Nitride**	**Carbyne**
Strength	130 GPa	100 GPa	~251 GPa
Elasticity	1.0 TPa	0.8 TPa	4.6 TPa
Fracture Resistance	4.4+-0.1 MPa (of a single layer of 80 atoms)	8.7 MPa This is higher than graphene because, due to the asymmetry in the structure with boron and nitrogen atoms, the crack bifurcates around instead of going straight down the plane, like in graphene.	Wasn't able to find an agreed value (shows the lack of research on this material till now)

Table 1

Graphene was used in the end because it seemed to be more easily accessible and has more information available compared to the other two materials. This makes it a material more likely to be used in the industry too.
Compared to h-Bd, graphene has higher strength and elasticity, which are more relevant for the purpose of this research than fracture resistance. That is because the legal limit on the maximum deflection of the decking is going to require a significantly lower amount of force to be applied than the point at which a fracture forms through the material.
Although carbyne has a higher Young's Modulus, it is not readily available, and so it won't be practical in terms of scalability in the future industrially.

As a base material to model the decking, polyurethane was chosen instead of any other material because it is the main component used for wood-free composite decking. This decking is made using polyurethane resin, with mineral stone and a unique Lastane coating surface. Resembling the decking with greater accuracy in the sample models by using polyurethane would make the research more realistic and applicable on the industrial scale.

Risk Assessment

Table 2 displays a risk assessment created to avoid risk of injury or damage to myself and the surroundings.

Risk Assessment					
Equipment	Hazard	Risk	Risk Probability	Control Measures	Disposal
Beaker	Dropping and/or breaking a beaker	Physical injury due to sharp edges of glass	Low	Wear gloves, eye goggles, and lab coat	In waste garbage bin, using dusting broom
Polyurethane	Extremely flammable	Physical injury and/or damage to the lab	Low	Wear gloves, eye goggles, and lab coat Keep substance away from other flammable equipment in the lab. Keep substance away from sources of flame/heat.	Fire extinguisher
	Limited evidence of a carcinogenic effect.	Deadly disease	Low	Wear gloves, eye goggles, and lab coat	-
	Irritating to eyes, respiratory system, and skin.	May cause sensitisation by inhalation and skin contact	Low	Wear gloves, eye goggles, and lab coat	Move to fresh air, remove contaminated clothes, rinse

					mouth/wash skin/wash eyes. Close lid cap every time the substance is used, to minimise risk of toppling it over.

Table 2

Methodology

Independent Variable

The composition of graphene was the independent variable in this experiment. Since the aim of the project was to test how graphene affected the strength of wood-free composite decking, the percentage composition by mass of graphene of the samples was varied. Testing was done at three different percentage compositions of graphene — 0%, 0.5%, and 1% — due to time and research constraints.

Dependent Variables

The dependent variables are listed below. All of them were measured by in-built sensors — like the S-type load cell— on the Force Testing Machine used. Here is the link to the machine that was used: https://www.mecmesin.com/universal-testing-machines/universal-testing-machine?model=PC-driven.

- Maximum Force- The maximum force was measured to understand the maximum force the sample can withstand before breaking, which is an indication of its strength. The maximum force is a good indicator of strength because the physical definition of strength is how large the ultimate tensile stress (UTS) is, where UTS = Maximum Force/Area. Since area is a controlled variable, the maximum force is directly proportional to the UTS.
- Young's Modulus- The Young's Modulus was measured because the Young's Modulus essentially measures the elasticity of the sample, and knowing the elasticity will impact the usability of the material in real life. In reality, there is a legal limit for the maximum deflection allowed in a panel, and this deflection will be affected by the elasticity of the sample.
- Bending Strength- The bending strength is the ability for a material to resist deformation when any force is applied on it, which impacts how much it deflects and

how easily it breaks. However, instead of being measured (which would likely require more equipment), this will simply be calculated with the equation: $\sigma = \frac{3FL}{2bd^2}$

Controlled Variables

<u>**Controlled Variable**</u>	<u>**Need to control the variable**</u>	<u>**How to control the variable**</u>
Dimensions of sample	If the dimensions of each sample are different than those of the other samples, then the sample's volume and density would be different. Thus, the maximum force, bending strength, and young's modulus would be different. This would make the research inaccurate and its results invalid.	This will be controlled by curing the polyurethane foam in a silicon mould of the dimensions required. This will give each sample the same dimensions.
Mixing ratio	If the mixing ratio of Part A and Part B of the polyurethane foam varies with the sample, then the density of the sample would change. That is because both of these parts have different densities. Moreover, the graphene composition in the sample may change as well, as the graphene will only be mixed to Part A initially. Thus, the results recorded then will be invalid because the percentage of graphene may change and because the bending strength, maximum force, and young's modulus would differ according to the sample.	This will be controlled by measuring the mass of each part of the polyurethane foam separately, and ensuring they have the same ratio of 55:45 by mass in every sample. A high-precision weighing machine will be used to measure the mass of each of the parts (Part A and Part B), and a pipette will be used to pour each part into the beaker carefully.
Polyurethane foam mass	The mass of the foam should be kept constant. If the mass changes, then the density would change (because the dimensions of the silicon mould are constant), and	This will be controlled by measuring the weight of each sample's Part A and Part B on a high-accuracy weighing machine and using pipettes to pour the liquids

	thus, the bending strength, maximum force, and young's modulus would be affected by factors other than the percentage of graphene.	precariously. The mass of each sample will also be recorded once the curing is complete, to ensure that any damage in taking out the sample didn't affect its mass significantly (if it did, then the trial will have to be repeated until it is successful).
Set-up for the final part of the experiment, when the force is applied and the data collected	If this changes, then the point at which the force is applied changes, and thus, the maximum deflection changes. The way the force is distributed through the structure would also change, which would impact the maximum force and thus, the final results and conclusion.	This will be controlled by placing a metal ruler — whose width would coincide with the length of the sample — between the point of contact between the Force Testing Machine and the sample. This setup will remain the same for all of the samples. This would be more accurate in simulating a force as applied by a foot, since a foot applies force over a significant width. Fig. 4 shows this set up.

Table 3

Approaches to the Problem

There were three approaches brainstormed to conduct this project, as follows:

1. Simulation- This approach would have involved using Fusion 360 to create a 3D Model of a decking panel and measuring its deflection when a force is applied onto it (1216 N, which is approximately twice the average weight of a human). Then, the same would be done by changing the material properties of the decking model to take into account the addition of graphene, and this would be tested the same way with the same amount of force.
2. Theory- This methodology would have included using online research to find suitable equations that could demonstrate what was happening to the panel physically. These equations would be used to find the maximum force that can be applied to deform the decking as much as possible legally (which is the length of the decking/200). Thus, these equations would be used to determine how the maximum force legally possible changes as the properties of the material change with the addition of graphene. The

major equation used would be: $\delta_{max} = \frac{FL^3}{3EI}$. Here, dmax is the maximum deflection, F is the force applied, L is the length of the decking, E is the Young's Modulus of the decking, and I is the Area Moment of Inertia (equal to $w * t^3/12$ in this case, where w and t are the width and thickness of the decking respectively).

3. Physical experimentation- This method would have involved measuring the maximum force that the panel can sustain before breaking, noting down its bending strength, and recording its young's modulus. This would have included creating samples using polyurethane foam for the panels and comparing the performance of these samples with the ones that have different compositions of graphene (specifically, 0%, 0.5% and 1%).

In Fig. 1, you can see the advantages and disadvantages of each of the potential testing methods. If the text is unclear to read, here is the link to the mindmap: https://mm.tt/app/map/3356034400?t=FKhm77UR47

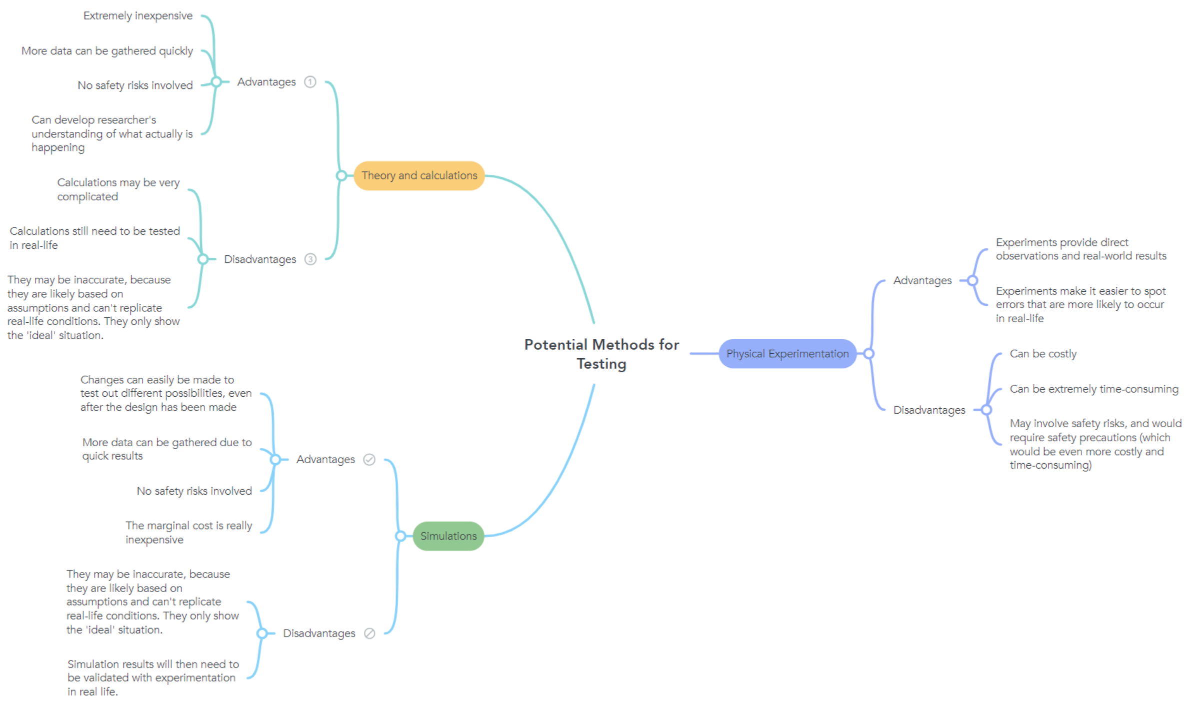

Fig. 1

Ultimately, 'physical experimentation' was used. That is because this project is, due to its practical nature, greatly influenced by real-life settings, and therefore, its experiment needed to occur in a real-life setting to account for any unexpected errors. Out of the three approaches, 'physical experimentation' achieved that the best. Along with that, though, simulations were used for some of the data points to verify, at least to an extent, the results of the physical experiment. The results of the simulation are given in the document titled 'Reflection'.

Set-up

Silicon Mould (with a polyurethane foam sample curing inside):

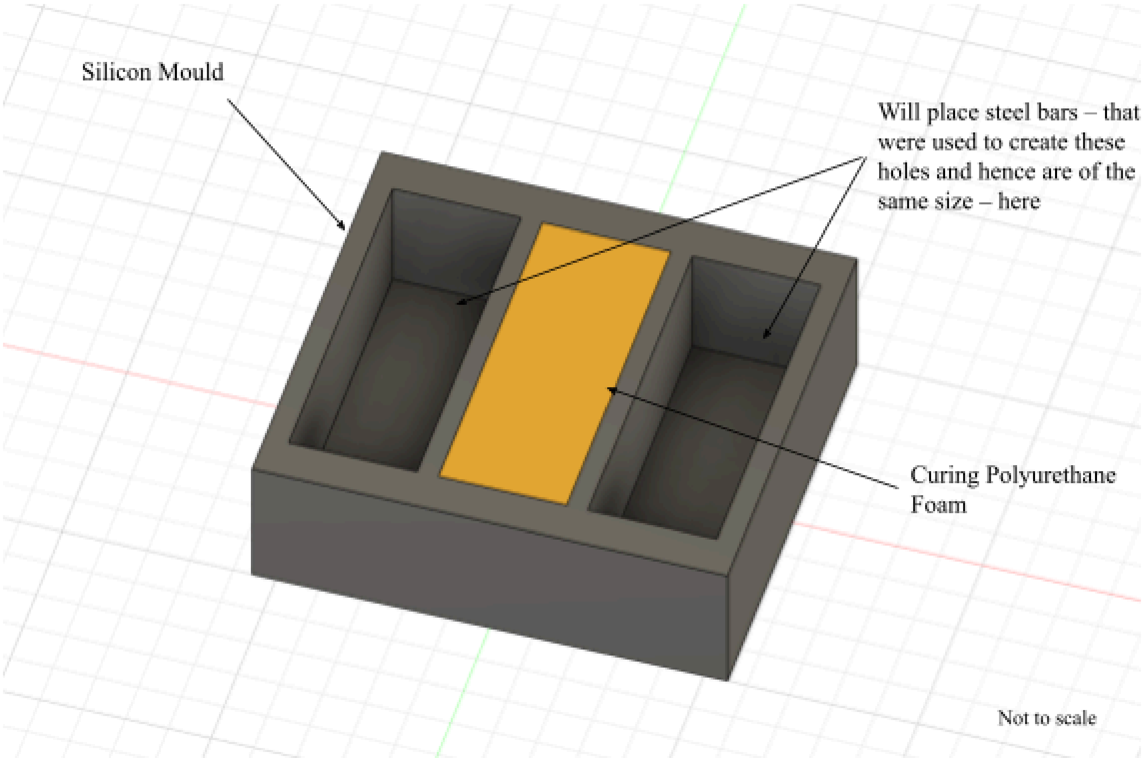

Fig. 2

To cure the polyurethane foam:

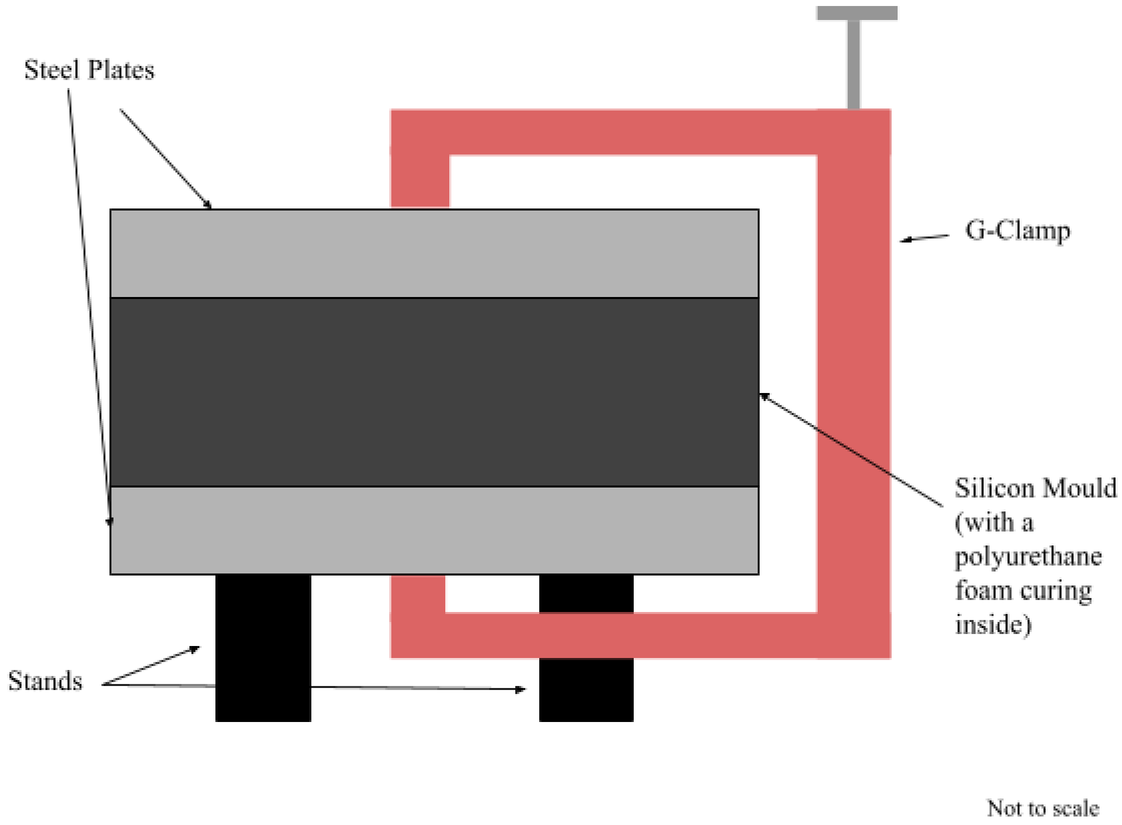

Fig. 3

Force Testing Machine:

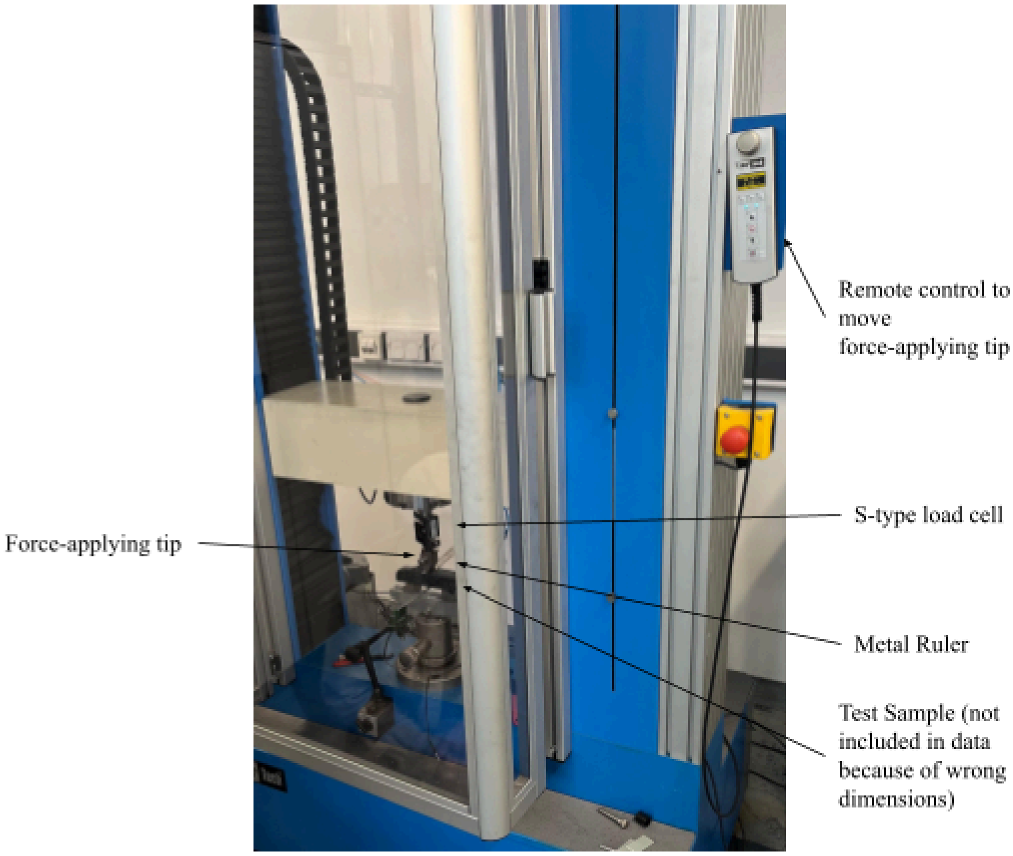

Fig. 4

Equipment

- 1 silicon mould
- 120 grams of Polycraft 5800 Polyurethane Foam Part A
- 145 grams of Polycraft 5800 Polyurethane Foam Part B
- 1.5 grams of graphene
- 1 Force Testing Machine
- 1 high-precision weighing machine
- 2 pipettes
- 1 stirring/mixing machine
- 1 metal ruler
- 2 steel plates
- 1 g-clamp
- 2 stands
- 1 stopwatch

Method

- Measure dimensions of silicon mould and calculate the volume
- Using values of mass and density given on the data sheet of the polyurethane foam, calculate the mass of it needed to fill up that volume

- Take the mass of each part (Part A and Part B) of the polyurethane, and note down the estimated density
- If using graphene, calculate the mass of graphene powder required, and add it to Part A. Stir well, or stir using a machine to ensure a smooth spread of the graphene.
    - When using graphene, the solution would require a longer time to solidify. That is because the graphene reduces the effect of the 'hardener' and slows down the 'cross-linking' of Part A and B.
    - Graphene will be mixed only to Part A for simplicity. If this isn't done, then the solution of Part A and B would start to cure while the graphene is being mixed in them, resulting in unnecessary sources of errors.
- Mix Part A and Part B together
- Pour the solution into the silicon mould evenly
- Close the mould with the steel plates, and clamp them with g-clamps.
- Wait 15 mins, and then take out the solid, porous core.
- Measure dimensions and take the reading of the mass, noting down the density and volume.
- Compare this density to the actual and estimated ones.
- Place the sample at the centre of the Force Testing Machine
- Bring down the force-applying tip of the machine as close as possible to the sample without touching.
- Place a ruler between the force-applying tip of the machine and the sample.
- Run the test until the sample breaks.
- Record the maximum force, bending strength, and Young's Modulus.
- Repeat the steps for 3 trials with the same percentage of graphene, and even more if time allows.

Alternative Brainstormed Methods

Two other methods had been brainstormed. One was to contact a wood-free composite decking maker (like Millboard) to use their machine for testing. However, due to time and resource constraints (eg. Millboard's manufacturing plant was situated too far from school) this method didn't seem plausible. The other was to conduct a simplified experiment at the school laboratory, with weight masses instead of the Force Testing Machine for example. However, this would have compromised precision, as the equipment available would not have been as precise. Therefore, I used the method detailed above, under the subheading 'Method'.

Results

The results are summarised in the spreadsheet below:

Gold CREST - PU Sample results.xlsx

As can be seen in the graphs, the maximum force, bending strength, and Young's Modulus increased tremendously when graphene was added.

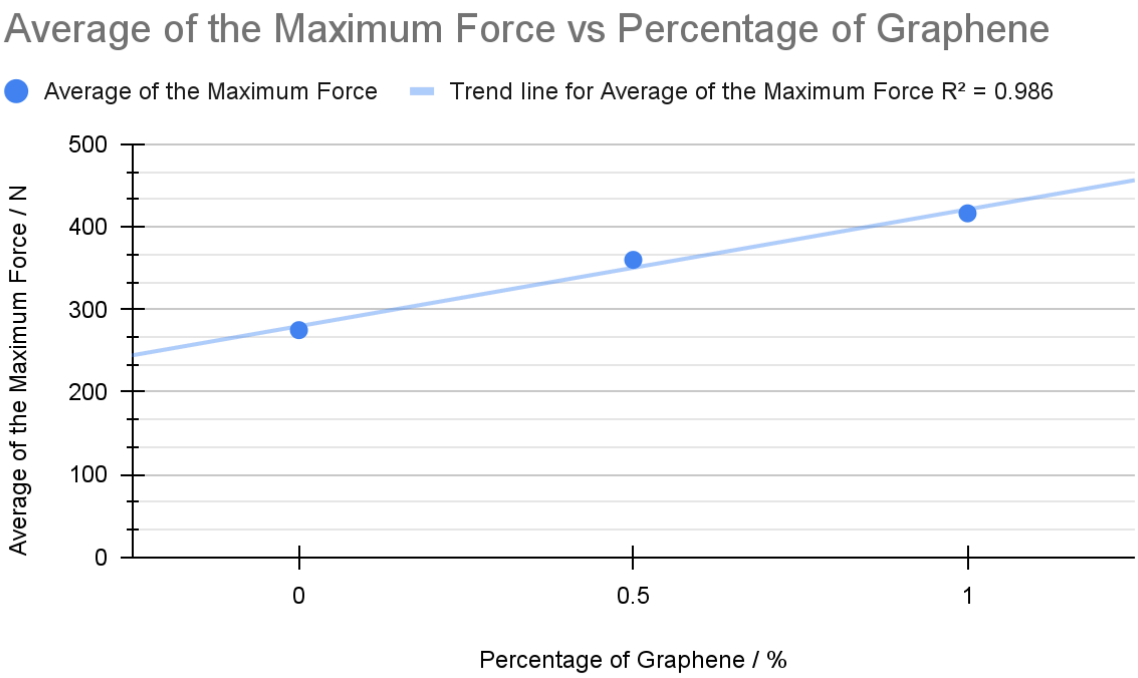
Average of the Maximum Force vs Percentage of Graphene
Average of the Maximum Force
Trend line for Average of the Maximum Force R² = 0.986
500
400
300
200
100
0
Average of the Maximum Force / N
0
0.5
1
Percentage of Graphene / %

Fig. 5

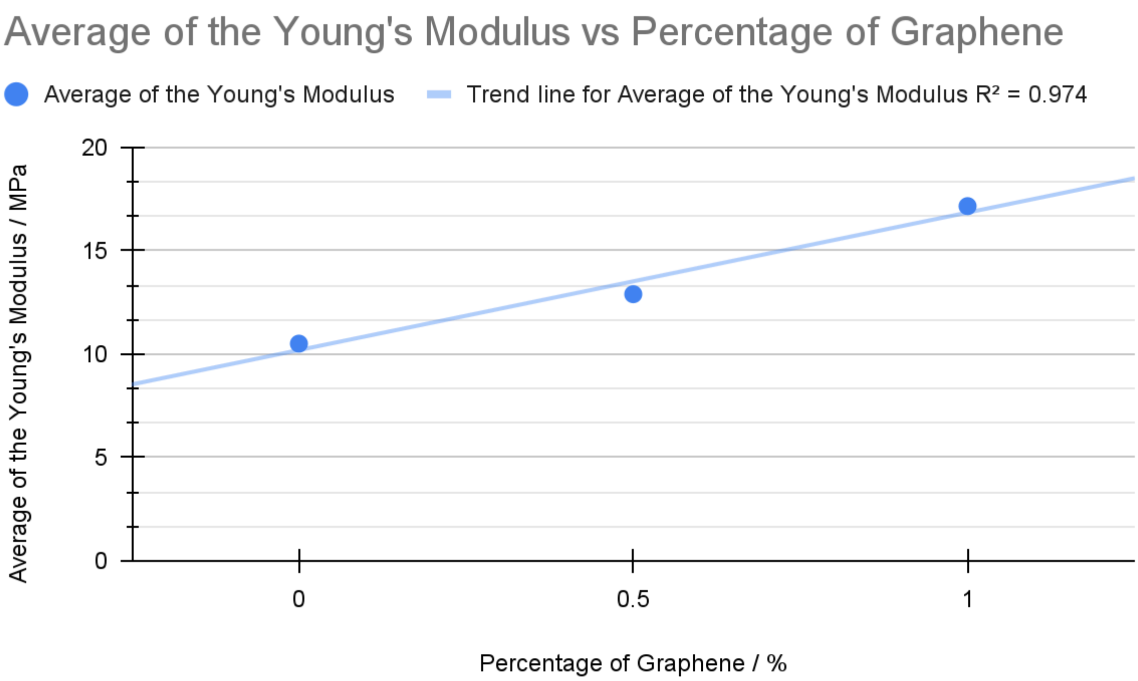
Average of the Young's Modulus vs Percentage of Graphene
Average of the Young's Modulus
Trend line for Average of the Young's Modulus R² = 0.974
20
15
10
5
0
Average of the Young's Modulus / MPa
0
0.5
1
Percentage of Graphene / %

Fig. 6

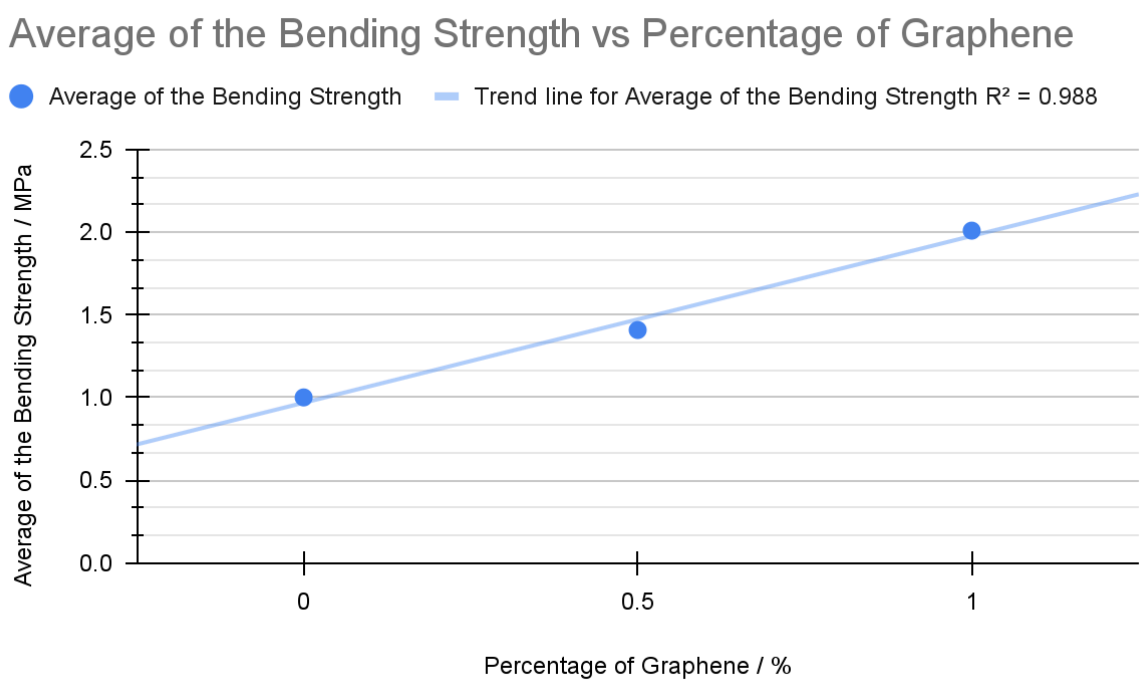

Fig. 7

Analysis of Fig. 6 shows that the average of the Young's modulus of the foam increased from about 10.5 to 17.1 MPa as the percentage of graphene increased from 0% to 1%.

The Young's modulus = Stress/Strain

Stress = Force/Area

Strain = Change in length/Original length

Thus, the increase in young's modulus can lead to one or all of two conclusions. A higher young's modulus could be caused because the foam is able to withstand a greater ultimate tensile stress, and hence a greater maximum force (which is evident in Fig. 5). A higher young's modulus could also be caused by a reduction in strain of the foam, potentially due to greater stiffness.

Since the maximum force is increasing directly with the composition of graphene, the first scenario is likely true. It is equally possible that the second case is the reason for the increase in young's modulus, as the bending strength — which essentially measures the resistance to deformation — is increasing (see Fig. 7). Thus, due to a combination of both cases, the young's modulus increases.

Therefore, the hypothesis was likely true. The hypothesis was that due to graphene's innate properties and its small size, it will be able to increase the structural integrity of the decking by strengthening the intermolecular bonds between polyurethane molecules. In the results, we see that the bending is less as the young's modulus is higher, and the strength of the sample is greater as the maximum force and bending strength are higher.

Conclusion

The aim of this research was to investigate the effectiveness of graphene as a strengthening additive for wood-free composite decking. This could have significant environmental and financial implications on the industry of composite decking, as an increase in strength could reduce the thickness of the decking, reducing the energy-intensive digging process that precedes the installation of the decking. It could reduce the costs of the decking by reducing material usage, and it could save recycling costs by diminishing the need to separate the various layers of compounds used in current decking. The latter is true because with a stronger base material, the need for more layers of different materials would reduce. To achieve this aim, an experiment was conducted using polyurethane foam panels to model the wood-free composite decking. In the experiment, each trial required making a 40 x 40 x 160 mm panel by mixing Part A and Part B of the polyurethane foam in a ratio of 55:45, while varying the composition of graphene in the foam (using the percentages 0, 0.5, and 1). A constantly-increasing force was then applied to measure the maximum force, the bending strength, and the young's modulus of the panel. The samples with 1% graphene led in all three criteria, averaging values of 416.20 N, 2.01 MPa, and 17.15 MPa respectively. The samples with no graphene performed the worst, averaging 274.95 N, 1.00 MPa, and 10.50 MPa respectively. Thus, it was concluded that adding graphene improves the strength of the decking, as had been hypothesised initially. This, if applied in the industry, could lead to higher energy efficiency and lower costs, helping the suppliers, consumers (and thereby, the whole industry), and the environment.

Reflection

How I organised my time and resources

I had to manage my time well because of a few reasons. Firstly, I knew I would be really busy during the time I have for this, because I would have just finished my end-of-year exams, would have to start working on college research and essays (especially because of the US application), would still have to continue my extra-curricular activities, and would have to participate in the essay competitions I had signed up for. Secondly, I knew I had limited time to conduct the experiment, as I only had supervised access, with Dr. Liam Britnell, to the lab for 2 days during my mid-term break. That is when I had to develop and test the project, from simulations to the testing, from scratch to finish. I would have to take rough notes then, and make the report later. Thus, I made a plan of action in the form of a Gantt Chart, also linked below.

Gold CREST Gantt Chart

To develop the product, I needed access to a lab and its resources. So, I contacted Liam Britnell, the co-founder and CTO of Vector Homes and someone who has significant experience working with graphene, for access to his company's private lab for 2 days. Thankfully, he gave me permission under his supervision. Because of this, I was also able to produce various samples and test them with the facilities at the lab accurately. Otherwise, the results wouldn't have had the precision they did with the state-of-the-art machines, as I would have had to do it at school without access to the right equipment. I also got access to Fusion 360 through the free education licence, as I didn't have enough budget to buy it for my project.

How my actions and decisions affected the project's outcome

Choosing to do physical experimentation instead of collecting data through simulation did not affect the result significantly.
I tested the first, second, and third data points from the experiment via a Static Stress simulation on Fusion 360, and compared the obtained maximum stress to the bending strength acquired through physical experimentation. I had inputted the respective values of the maximum force and the young's modulus obtained to design the material tested; the bending strength through the simulation was only slightly different. The maximum deflection of the sample in the simulation was significantly larger than the legal requirement of having to be less than or equal to the length/200, and thus, this result supports the conclusions of the physical experiment as well. That is because at that same amount of force, the material had broken in real life. The simulation used didn't have the capacity to measure if the sample breaks or not, so the results obtained were as good as anticipated. Below is a table with the comparisons of results from both the methods:

Sample Number	Bending Strength / MPa		Maximum Deflection at maximum force / mm		Legal Requirement for Maximum Deflection (Dmax <= Length/200)
	Simulation	Physical Experimentation	Simulation	Physical Experimentation	
WSD-01	0.881	0.854430503	4.733	Sample broke	Dmax <= 0.790 mm
WSD-02	0.731	0.9861549107	5.216	Sample broke	Dmax <= 0.795 mm
WSD-03	0.797	1.16395723	6.11	Sample broke	Dmax <= 0.800 mm

Table 1

For the maximum force the two tests could handle in reality, the deflection in the simulation was much higher than legally allowed. That shows that in physical experimentation and through simulation, the results may not have been extremely different. This, although rather weakly, supports the validity of the method I used for physical experimentation. The variation in the results gathered from the two methods could be better evaluated if I had more time and resources to simulate the impact of graphene on the decking in the simulation, and measure its deflection.
However, using practical experimentation was definitely the better decision, as the situation was more realistic in that case. That is because it accounted for the un-idealistic conditions in the real world more than these simulations, which is a major factor in wood-free composite decking. In fact, that is likely the most effective way to test how to reduce costs in real life, according to Dr. Britnell, me, and online sources.

What I learnt, what I demonstrated, and what I could improve on

I have summed this up in a mindmap, whose image is added below. Because the text is not visible, I have also shared a link to the mindmap.

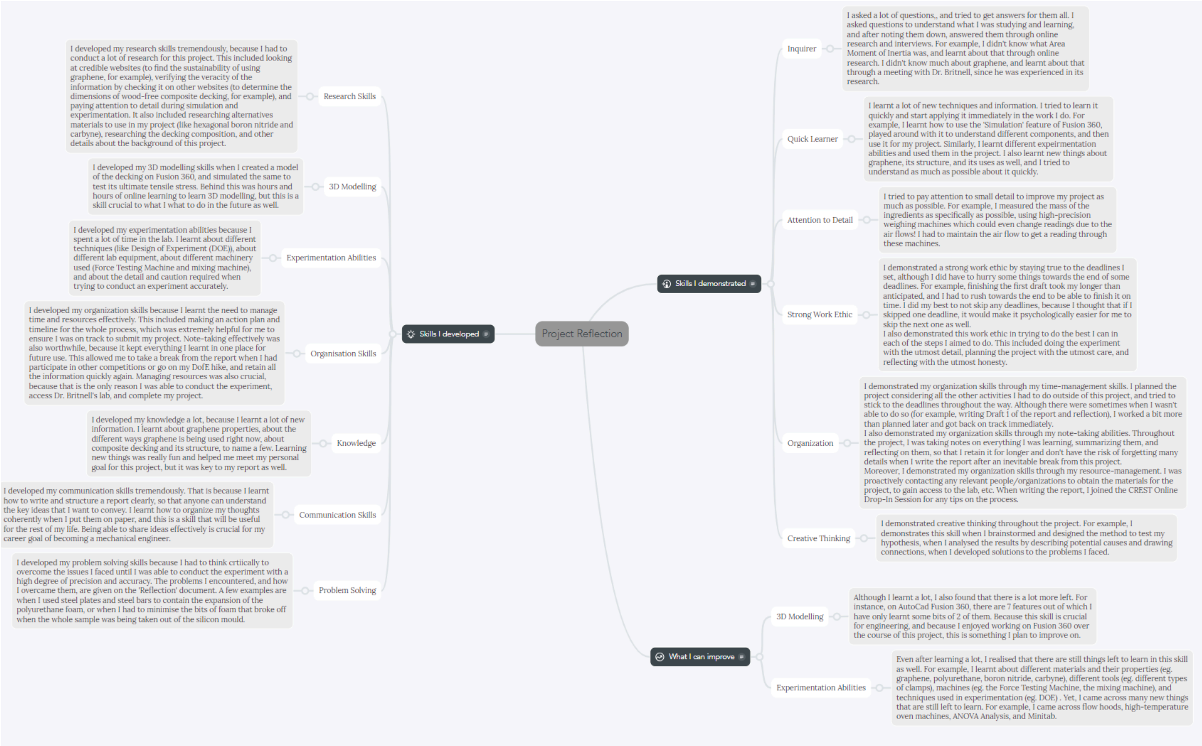

Fig. 1

Link to mindmap: https://mm.tt/app/map/3356742245?t=Z2u5itywTx

What science concepts I learnt and applied as a result of this project

Learnt about Area Moment of Inertia - When researching why the decking bends in the way that it does, I came across the area moment of inertia. It took me a good amount of time to understand what this actually signifies in real life, but I understood it after watching a few online videos that helped me visualise it. It quantifies the bending of a decking based on the cross-sectional area of the decking.

Learnt why the graphene slows the effect of the hardener - Since I haven't done much chemistry in the past year, researching this took longer than expected. Here is what I learnt. The polyurethane foaming process involves two chemical reactions. One is a gas reaction, which leads to the expansion of the foam: isocyanate + water = CO_2. The other is a gel reaction that leads to the crosslinking, or solidification, of the two parts of the foam: isocyanate + polyol = (poly)urethane. Graphene interferes with the crosslinking process, elongating this cure time.

Learnt why the graphene strengthens the decking - Graphene acts as fillers that increase the ability of the material to withstand cracking and wear. It has previously been used in concrete before, with promising results. This is because graphene can interlock with the molecules of decking due to its substantial surface area and nano dimensions.

Used knowledge of young's modulus, stress, strain, and ultimate tensile strength - I used this knowledge I had gained in the classroom to design the experiment and analyse the data I obtained. It was useful in drawing conclusions to the investigation I did, and it highlighted my ability to apply knowledge from school into real-life scenarios.

Interdisciplinary Connections

This project required me to bring together various interdisciplinary topics. For example, it involved concepts ranging from material science to mechanical engineering, and I had to bring knowledge together from these two fields to develop this project. I used material science knowledge when understanding how graphene could impact the strength of the wood-free composite decking through its physical properties, and I used knowledge from mechanical engineering when analysing forces and their impact on the decking. This interdisciplinary connection was inherent in the aim of the project itself, and thereby was key for the completion of the project. Throughout the project, I also had to bring knowledge from different aspects of my physics class. I had to use the practical skills I had learnt alongside the knowledge I had gained about topics like Young's Modulus and Ultimate Tensile Stress to conduct the experiment and analyse the results. This was crucial in arriving at a conclusion to this project. I even had to combine all the technical knowledge with the writing skills I had developed in school and in other projects I had done outside of school to be able to communicate the ideas simply and understandably.

What problems I faced, and how I overcame them

Here are the problems I faced throughout the experiment and the project, how I overcame these issues, and how my decisions impacted the project as a whole.

Problem encountered	**How I overcame it**	**How my decision impacted the results**
To shape the polyurethane foam into the desired shape, I had poured the solution into a silicon mould to cure. While curing, however, it leaked out of the mould.	To overcome this leakage, I put a steel tray on top of the mould, and another one on the bottom. Then, using a G-Clamp, I clamped the whole structure together. This applied pressure on the foam to stay in the desired shape.	This made the results more accurate by ensuring that the dimensions of the sample were similar to the others. This would ensure the controlled variables (which include the dimensions) remain the same.
When I used steel trays to apply pressure on the curing foam, it put pressure on the sides of the 3-rectangular shaped silicon mould and deformed.	To prevent this from happening, I put the steel cuboids that had initially been used to create the rectangular holes in the silicon mould in the holes	This ensured the dimensions of the samples were similar, and that the results weren't affected by this controlled variable significantly. Thus, the results obtained were

	next to the one being used. Fig. 2 on the document titled 'Report' helps visualise this. This applied pressure on the curing polyurethane foam from all directions, forcing it to obtain and maintain the desired shape.	more accurate.
The solution wasn't rising in thickness as much as desired in a few of my trials. This led to the dimensions of the foam, a controlled variable, to vary.	To find out the cause of this, I went back to the data sheet of the polyurethane foam. Noticing that I was mixing Part A and Part B well into the cream time of the solution, I decided to time myself when I was mixing the two together and stop as soon as the timer stopped. This allowed the foam to expand to the desired thickness.	This ensured that the volume of the samples didn't vary significantly as the thickness of the samples was kept constant. Thus, the density wasn't majorly affected due to the change in dimensions, and the results were obtained with greater accuracy.
When taken out of the mould, bits of the cured polyurethane foam broke. This deformed the shape of the foam, and posed some possibilities of errors in the experiment. This also reduced its mass and changed its dimensions.	I left the foam in the mould for a bit longer (approximately 5 more mins) than usual in the next trials, and used the back end of a spatula to scrape out and detach any bits of foam sticking to the silicon mould before taking the whole sample out of the mould. This reduced the number of broken pieces significantly, increasing the accuracy of my results.	This maintained the structural integrity, dimensions and shape of the sample, ensuring that the distribution of load that occurs when a force is applied is similar throughout the trials. Hence, the method's accuracy increased.
I was having trouble applying a centre load on the simulation, and was only able to apply a uniform load.	I created an edge on the top plane of the decking model, and applied a uniform force across that edge. This simulated the dimensions of a foot better than a 0-dimensional point, and therefore gave more realistic results. I thought of adding another, smaller cuboid on top of the panel and applying the force	This made the simulation more realistic as well, verifying, to some extent at least, the results I obtained through physical experimentation. Although the force was applied over a 1-dimensional line instead of an ideal 2-dimensional plane of contact, the width of a foot compared to a decking panel is relatively

	uniformly across that. This would be even more realistic as it would demonstrate the 2-dimensional surface of the foot that would be in contact with the decking in reality, but the thickness of the cuboid, its material, and other differences in its physical properties when compared to a foot dissuaded me from doing so.	small. Thus, the error would likely not have been a major one.
I needed help understanding how to simulate the decking's reaction to various forces acting on it. This was because I had minimal experience with Fusion 360 before this project.	I tried to find online resources like the Help pages on the Autodesk website. I soon turned to resources on Youtube, being a visual learner. This taught me the steps needed to test my model according to my project requirements.	Through this, I was able to develop my Fusion 360 skills tremendously and become really efficient at it, due to the new short-cuts and tricks I learnt online. Additionally, I was able to verify the results of my physical experimentation with the simulation as well.

Table 2

Potential improvements/additions to the project

If the project were repeated, here are the things I would modify/add to increase the accuracy of the research and its applicability:

Category	**Action**	**Description of Action**	**Reason for Action**	**Requirements**
Improvement on current method	Increase the number of trials	This means conducting 5-7 trials for each percentage of graphene added. For example, conducting 5 trials with panels	This will reduce the margin of error in the data collected, and ensure that the data is accurate without anomalies.	More time will be needed for this, but more quantity of each of the materials used during the physical experimentation will also be necessary.

		consisting of 1% graphene by mass.		
Improvement on current method	Increase the range of data collected	This means collecting data with more percentages of graphene. For example, instead of just having 0%, 0.5%, and 1%, this means having 1.5%, 2%, and increments of 0.5 percentage points up to 5%.	This will allow for a greater volume of data to be analysed, to make sure that the final graphene percentage chosen is truly the optimal value. It will also make it simpler to spot trends to the maximum force required as more graphene is added, without the need to extrapolate data.	More time will be needed for this, but more quantity of resources will also be necessary.
Improvement on current method	Use a sturdier mould	This means using a mould made of a sturdier material like metal or wood, for example. It means using any material that isn't as easy to bend as silicon.	This would remove the need for clamping the creaming polyurethane from all sides using steel bars/plates, and hence make the data more precise by removing further sources of errors.	More resources will be required; this includes the heat, energy, and equipment needed to be able to mould materials like metal into the required shape. If not this, then carpentry equipment would be required to join slabs of wood and create the required shape.
Improvement on current method	Larger dimensions	This means using dimensions for samples similar to the actual dimensions of the decking (126 x 32 x 3600 mm).	This would make the research more usable on the industrial scale, which is the purpose of this project.	Significantly larger equipment will be required to be able to conduct the tests on a real-life scale; more time will also be required.
Further potential	Look at more	This means looking at	Looking at more variables will further	More equipment will be required to

research	aspects that can affect the strength of wood-free composite decking (by conducting DOE analysis)	mass, volume, density, yield strength, and other physical properties of the material that can have a significant impact on the strength of the decking. In this project, I had just looked at the maximum force, young's modulus, and bending strength.	maximise the strength of the wood-free composite decking, as it will optimise more properties affecting the decking's strengths. Furthermore, this may shed light on the importance of different physical properties on affecting the strength of a material.	measure different properties of the material, and more time would be required to conduct a DOE analysis to determine the optimal conditions for enhancing the decking's strength.
Further potential research	Compare with simulation and theory thoroughly	This means testing everything done through physical experimentation through simulations and through calculations as well. This includes data from all different percentage compositions of graphene and all trials.	This would highlight any flaws in the physical experimentation method, and make the results more precise. This may also shed light on the benefits and drawbacks of using different research methods.	More time will be required to analyse the results obtained from the three different methods.
Further potential research	Use different additives	This means using boron nitride and carbyne, and comparing their impact on the polyurethane foam to the impact of graphene.	This would increase the scope of the research by investigating the impact on the strength of polyurethane by the use of different additives. This may result in conclusions about the effectiveness of these additives (although this is outside	More time and resources will be required, as the method will be more elaborate. More trials will need to be conducted, requiring more materials and equipment. It will

			of the purpose of my specific project), but it may also improve the strength of the wood-free composite decking, if so possible with the other additives.	also require a greater variety of additives, and the testing process, therefore, will take longer as well.

Table 3

On the whole, this was an amazing experience. I learnt a huge amount of information, understood it, and applied it into my project (either in the experiment, in the report writing, or in the research process). I was able to do something to help the world in some way, and that is a really fulfilling thought. Although there is a lot more I can do with this project in the future, I am satisfied with what I achieved so far with the resources I had.

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