PRINTED FUTURES
Research Group

Development in new material, would it be environmentally and economically sustainable for our architectural future?

Ingrid Ruan Zhu

PRINTED FUTURES
Research Group

Development in new material, would it be environmentally and economically sustainable for our architectural future?

Ingrid Ruan Zhu

Contents

Introduction

According to The Times, an average of 50,000 buildings are demolished each year, producing nearly 126 million tonnes of construction waste, a value that amounts to almost two-thirds of the UK's total waste production (Hurst, 2021), and most of them were destined to the landfill. This has a huge environmental and economic implications not only in the UK but globally.

Additionally, from a building construction aspect, this sector generated 17% out of 13.5 million metric tons of carbon dioxide in construction sector emissions in 2019, a percentage that was 3% lower than the previous year (Tiseo, 2021). This has been slightly improved in terms of the environment, but it is not enough to reach zero carbon emissions, which is an ultimate goal of both the construction industry and government. In this amount of emission, there is a high ratio of cement production. Cement is currently indispensable construction material, yet this will continue to be used extensively in the future. However, the cement industry accounts for 7% of human-made carbon dioxide emissions worldwide, with further data of annual Ordinary Portland Cement (OPC) production of 3.5 billion tonnes, diffusing around 622 kg of CO2 per tonne (Brogan, 2021). Apart from material using, the physical condition of workers is also an inevitable social issue. Out of 81,000 labourers receiving health disease, 57% of them had musculoskeletal problem (HSE, 2020).

Despite these consequences in the construction industry, the governments and societies are already looking for solutions for each sector. For further improvement and development, this thesis investigates several alternative materials in the field of sustainable materiality, mainly focusing on biodegradable material. The analysis of how they would act under corresponding situation continues with material theories and case studies on sustainable housing. This will be followed by a brief explanation of 3D printing technology and a discussion of the possibilities of using eco-friendly alternative materials, followed by various case studies. Finally, experimentation with my own research material will be one of the solutions to improve the architectural future, testing its sustainability, durability and diversification.

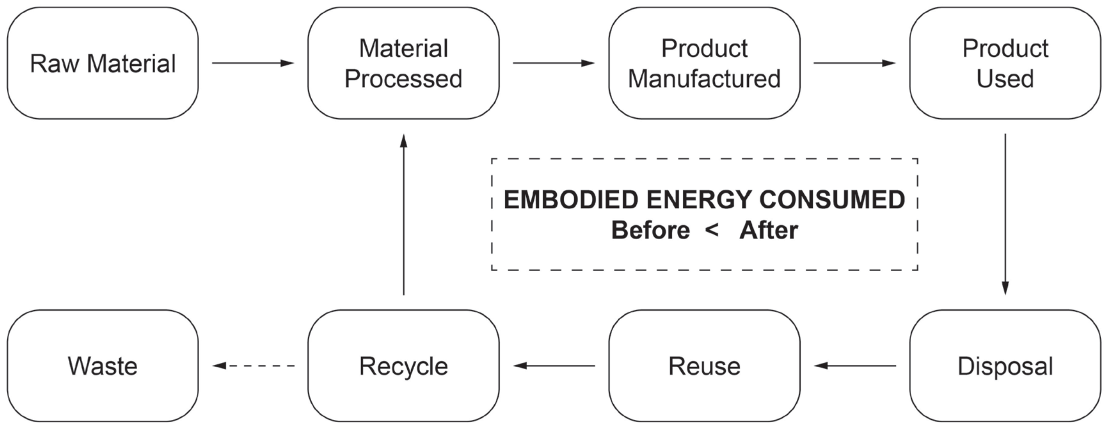

Fig.1 ***Energy Consumed in Material Production*** **(2022)**

Chapter 01: Environment, Economy and Society

From a data point of view, about 40 percent of carbon emissions in the UK are attributable to the built environment, and 60 percent of waste is generated in this context, including construction, demolition, excavation activities, etc (Penman, 2021). Buildings are considered obsolete until they are demolished, and to define the significance of obsolescence, according to the Collin English Dictionary, it means “the ability of a commodity to satisfy human wants” (Smith, 1998:72). The deeper meaning is that these buildings are no longer fulfilling the purpose for which they existed, which leads to their demolition. The social and economic factors involved here are whether the building still has an economic value, whether it will affect the daily life of the occupants due to the exhaustion of building materials, or whether there is a possibility of environmental sustainability.

> “We need buildings which fulfil their task today and will do so tomorrow, which in other words, do not age in adhering to their forms and thus become a drag upon the economy as well as the visual environment. But in order to build adaptably we must try to build as lightly, as movably, as possible and with the greatest perfection technically available.” (Beorkrem, 2017)

Leaving aside the previous setting, if we consider the building as a ‘living creature’ and put it in the perspective of the natural environment, we will be more concerned about how to make it live in harmony with the environment, and also about its life cycle, thus being aware of the mutual impact. Back to reality, if we take a fresh look at a building with the mindset portrayed above, we will look further and notice its life cycle from conceptual creation to demolition results. We would also be cognizant of the importance of the process from the extraction of materials to the final fate of the materials to the demolition (Smith, 1998:59).

Every time a building is demolished and a new one is built, excess carbon emissions are created. Emissions that would have been stored in the original building are wasted as the new building is replaced, however excess carbon emissions and energy are emitted to produce new materials and construction (Penman, 2021). Since energy will not be reduced to a lower level than before, starting from reducing emissions by recycling materials could be a method. Although a certain amount of embodied energy is still emitted during the production of construction materials, this amount will be significantly reduced once recycling is implemented (see Fig.1).

Hazard of Cement

In modern life, cement has become one of the important building materials, or rather, an indispensable presence in the construction industry. The rapid development of today's society has led to a rapid rise in demand for its production, which has also directly affected economic growth. Although its presence benefits the market in economic terms, on the other hand, the environmental aspects of cement indirectly lead to some negative results. First of all, cement is composed of limestone, chalk, shale, clay, and sand (Devi, 2017), which are processed in a series of procedure to become the construction material that we know. In the pyro-processing, which is included in the heating process, limestone emits almost one third of the carbon dioxide. During these processes, emissions like dust and odours can seriously affect the air quality. In addition, when going through pyro-processing, which is included in the heating process, nearly one third of the carbon dioxide is emitted by the limestone. As we all know, CO2 is one of the greenhouse gases that contribute to global warming and climate change. In addition to CO2, other harmful gases are also released, which have an irreversible impact on the ecosystem. Another factor to note is that the materials used to make cement are non-renewable, like fossil fuels, and once they are used up, there is no turning back.

Cement also has a profound impact on human health. As mentioned above, the emission of harmful gases will not only pollute the environment, but will also harm the respiratory tract, especially the close contacts, which can cause serious diseases such as pulmonary lesions, nephron problems, etc. (Mehraj, 2013). If they accidentally inhale large amounts of gases, which can cause not only internal injuries, but also a series of traumatic skin injuries in case of mishandling.

Material Methology

According to the BBC, construction and demolition accounts a high proportion of 61% by all the total waste production, among this figure 36% is dedicated to being in the landfill (BBC, 2021). This indicates less space on junkyard and more carbon emissions, which contributes to a key problem, global warming. Thus, people are conscious of giving a second life to wasted recyclable materials by producing new substance with new purpose rather than ending up on a rubbish dump (Peters, 2011:9).

> "We are potentially on the brink of a materials revolution that could help rebalance our relationship with our planet and reshape society for the better…We then ship those products around the world, where we enjoy them all too briefly and discard them when we no longer require them." (Franklin, 2018:9)

There is a phenomenon where waste materials once are discarded, they will lose their original value and be abandoned forever. Considering that Earth resources are finite, although this seems to be a distant scenario, if the world continues wasting materials brutally, sooner or later we will destroy this planet with our own hands. Once Aldo Leopold mentioned, 'we abuse land because we regard it as a commodity belonging to us. When we see land as a community to which we belong, we may begin to use it with love and respect' (Franklin, 2018:49). Humans have taken over nature for themselves, and in this case, they will use it in a reckless manner regardless of the consequences. At a particular stage, we would expect that abundant material can be used for a long period, in fact, at a certain time it will gradually reduce until it is too late to realise. Assuming that humans are exploited indiscriminately by some other creature, as in effect we are doing with nature resources, our ultimate fate tends to be extinction. The relationship between human and natural ecology is based on a harmonious symbiosis rather than parasitism. In order to establish a friendly relationship with materials in the future, the goal of those involved in the profession, whether designers or architects, is not to create new materials, but to research and develop on the basis of existing agriculture. "Towards a future of circular agriculture, zero waste and 100% resource optimization" (Franklin, 2018:45), they are already improving the existing system economically, environmentally and socially.

Chapter 02: Sustainable Wasted Materials

Julia Lohmann cited that the word 'away' doesn't exist in a material cycle concept (Franklin, 2018:48). While 'away' disengages from the sequence, it will not disappear, instead it simply loses its own function, ending up being in the landfill without its initial usefulness (see Fig.2). Preventing any unnecessary waste, maximize the use of each material's qualities, in which it should be natural and sustainable (Peters, 2011:6). Considering the state of the environment referring to the previous chapter, sustainability is barely a must for almost every industry nowadays (Peters, 2014:6). The word 'sustainability', in accord with Cambridge Dictionary, has the meaning of 'the idea that goods and services should be produced in ways that do not use resources that cannot be replaced and that do not damage the environment' (Sustainability, s.d.). Sustainability improvement has an appealing concept while delving into it, 'makers become alchemists, designers become scientists, and artisans become social entrepreneurs' (Franklin, 2018:10). Currently, the concept of sustainability is being applied extensively in the design production to think about how we can make a positive impact to our environment. Professionals in the creative industry, as well as experts from other fields, are very keen and actively working with environmentally friendly raw materials, use them as alternatives for disposable materials. Undoubtedly, the use of petroleum-based resources is being drastically dwindled for the past few years in order to encourage the adoption of renewable resources, keeping in mind of the global environmental dilemma (Thakur, 2017: XIX).

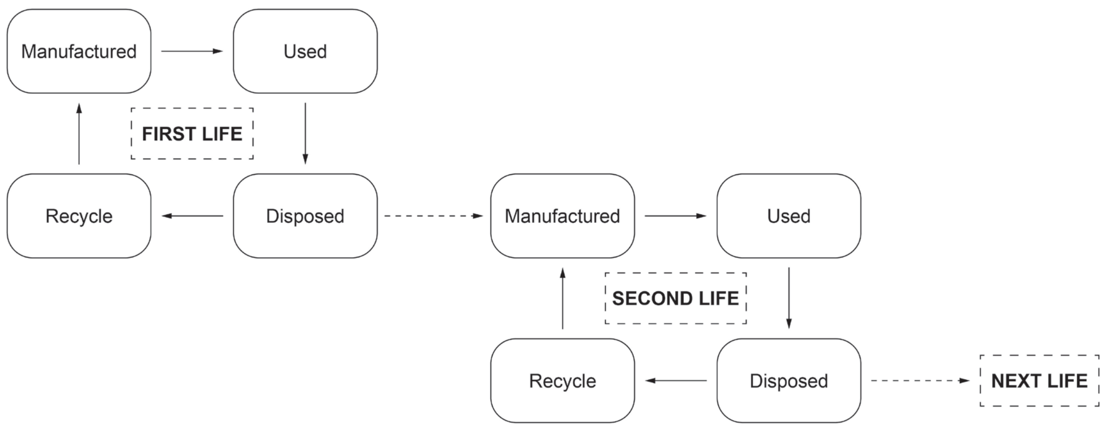

Fig.2 ***Material Cycle Concept*** **(2021)**

Biodegradable Materials

Bringing up current environmental issues with less availability in landfills and ocean pollution, there is a demand on development of recyclable and reused materials, giving them a second life with their renewable values by breaking them into specific components and convert into brand-new matters (Bastioli, 1998:193). Biodegradable materials are one of the suggestions among them. To define what is biodegradable, based on the European Union, a material that is possible to decomposed within 12 weeks somewhat its 90% in an industrial composting progress (Peters, 2011:62), avoiding environment damage and produce almost zero waste carbon commission. Essentially, these materials are easily found in our daily lives, food scraps, paper waste, etc, and their destination would be landed in the nature without harming it.

Comp-a-tent, found by London based artist Amanda Campbell, is a compostable tent using eco-friendly materials. The idea to make a decomposing tent came to her while attending a number of music festivals around the UK. Typically, at music festivals people usually pitch their tents and spend the night on site. However, on the next day, Campbell realised most of the disposable tents were abandoned on the ground, waiting to be collected and sent to the landfill. Instead of wasting single-use tents, she has designed a tent made of biodegradable materials which can decompose within 120 days, poles made of paper, cover sheet associated with bioplastics and using milk or casein as binder (Peters, 2019:37), developing into a tipi form, using the properties of each material (see Fig.3). This has helped the ecosystem as well as from a societal perspective. She developed a deposit-return service model so that once the festival is over, customers are encouraged to return their tents for a deposit. This result has reduced human resources and time consumed in the cleaning process (Molkenthin, 2017).

Fig.3 ***Comp-a-Tent*** **(s.d.)**

Considering a larger scale, within the context of architecture, biodegradable materials support on the way of construction and demolition (Karimjee, 2014). Thinking about architecture, it comes to mind as a permanent existent, but over time, it could be vacated and not being used as it should be, which comes to the end of its life cycle. Buildings made from disposable materials, such as concrete, are those that are abandoned due to difficulty of recycling. The way of using single-use materials should be appropriate adopted as the industry is developing alternatives to building materials. Among them, including bamboo, bioplastic and more, cork is currently one of the well-researched and practiced in the construction industry. Cork, made from bark of cork oak tree, is not only environmentally friendly, but used as a building material, it does have the corresponding architectural qualities: waterproof, fire and acoustic insulation (Thorns, 2018). The following case study would explain furthermore on the benefits of using cork on housing.

The Cork Studio is a building prototype produced by Studio Bark using wholly cork for the entire structure and it is 100% recyclable and compostable. The purpose of this project, said the architect, is “to show that there is an alternative” to “unhealthy single-use materials” (Crook, 2018). Although it is already well known for interior flooring, they found cork is long-lasting and strong enough to sustain a bigger structure, it is, as well as, resistant to water, fire and rot (Studio Bark, 2018). Walls are made of higher density cork slabs binding with recyclable screws, preventing any side pressure; low density cork were used on the roof structure hold by timber joists (see Fig.5), characterised by its waterproof property; door was simply a piece plywood covered with cork, decorating with a corkscrew as the handle. Manufacturing every single component without the support of any other material, cork can be considered a veritable primary source for housing construction. When this prototype comes to its end life, every part could be easily reused after demolition. This is what Studio Bark would like to convey: “one eco-friendly material can be used to form an entire building envelope” (Crook, 2018).

Fig.4 ***The Cork Studio*** **(2018)**

Fig.5 ***Opened Roof Made of Cork and Timber Joists*** **(2018)**

Alternatives: Adhesives and Granules

Nowadays, both designers and manufacturers are looking for alternatives from natural matters, to gradually substitute petroleum-based materials in various industries (Peters, 2014:64). Some are being explored and some are yet to be discovered. For example, human knowledge of the ocean is currently very limited, and there must be some organisms that have not yet been detected or having insufficient information of them. Algae is one of marine plants that can be exploited and put to good use, although in its early years it was considered infectious in the Western world (Peters, 2019:92). Many designers are working on them in the present as they can be found wherever there is water and have an extremely high growth capacity. Product designers Jonas Edvard and Nikolaj Steenfatt have used the abundant local algae in Denmark, to make furniture pieces. It has a binding effect while mixing with boiled water in the ground state, giving a stable result when hardened. Once the furniture ends its life, it can be biodegraded into fertilizer, creating a closed system (Franklin, 2018:61). No doubt, algae as an alternative can be used in smaller scale structure, however, would it have the potential to be useful in building construction?

Fig.6 ***Algae: dry kelp*** **(2022)**

Another underwater resource that is sustainable in terms of material substitution is shells, especially mussel shells. The main element of a mussel shell is lime, same ingredient for cement (Peters, 2014:76). Due to its hardness and sustainability, it is widely applied in jewelry and architecture industry. Previously it was commonly mixed in the aggregate for interior and exterior coating mortars, within a certain ratio, it does not cause much energy consumption (Martínez-García, 2021). Nevertheless, the controversy is in the similar situation as above - does it have the capability to replace cement in a large-scale construction? The answer is not clear, but when it comes to manufacturing the material in a bigger proportion, its CO2 emissions can be compared to those of cement (Crook, 2020).

Fig.7 ***Mussel shells*** **(2022)**

Eggshells

In our daily life, eggs are one of the most ordinary food we would have in a meal. There are in total of 12.9 billion eggs consumed per year in the UK based on industry estimation (UK Egg Industry Data, 2020). Nonetheless, we don't even notice how many eggshells are wasted, so much so that without notion eggshells can turn into a brand-new healthy material. "Traditionally, designers work with materials and processes that are handed to them, with limited knowledge about their environmental impacts", said the German designer Basse Stittgen (Treggiden, 2020:167). Eggshell as a substance is composed of the following chemical elements: calcium, carbon and oxygen, of which limestone has similar composition (Böttcher, 2012). Moreover, eggshell membrane contains glycoproteins and is highly viscous (Peters, 2014:48). Taking advantage of its traits, designer Ulrike Böttcher has developed a castable material which acts like plaster and can be applied on interior walls.

Akin precedent happened in Japan. Eggshells are already commonly used as a coating for walls, providing moisture and mold resistance. Later, Kouji Shimo, president of Green Techno 21, discovered the value of using eggshells after noticing the drawbacks of their incineration, the company then created a new material called Shell Walls which is a mixture of water, gypsum and mostly eggshell with a ratio of over 70% (Thomas, 2005). This remarkable material, being lightweight and owning fireproof property, has been widely used in different fields around the industry. In addition, with the headline of low cost and biodegradable material, zero carbon emission can be implemented as soon as possible.

In terms of quantity, an eggshell weigh about 6.4g (Travel, 2011). Taking the data from above, there would be 82.560 tonnes of eggshells collected annually in the UK. Would it be possible to replace or gradually add into any disposable construction material preventing further environment problems?

Fig.8 ***Eggshells*** **(2021)**

Chapter 03: 3D printing in Architecture

In traditional cement buildings, whether fabricated off-site in advance or poured on-site (Rael, 2018:118), a series of painstaking pre-arrangements are required, which is the process of formwork. A great deal of time, tooling, labour, and financial resources are consumed in this process, even as the materials used to frame the finished construction range from lumber and plywood used to attach small proportion structure to the use of heavy machinery on a large scale, all of which end up in vain and indirectly cause emissions pollution. What's more, there are also unavoidable factors during the process, such as the possibility of accidental employee injuries and frequent machine errors, which can lead to additional time and financial demands. However, with the development of technology in recent years, many alternative construction methods have emerged, including 3D printing.

For an introduction, 3D printing is an "additive manufacturing technology through which 3 dimensional models can be created by layering successive layers of material" (Mathur, 2016). Among all the 3D printing methods in the world, fused deposition modeling FDM, which was invented by S. Scott Crump in 1988 (Hager, 2016), is one of the most popular and has been used widely in the current day. The machine basically consists of three parts: a platform that moves vertically, a highly ductile filament, and a nozzle where the filament is extruded. The ingenuity of this technology lies in its ability to regulate the temperature of the nozzle according to the nature and properties of the filament, controlling it in a way that allows the material to be extruded in appropriate melting point and to harden in time for the next layer. Another feature of this technology is the flexibility of the materials used, mainly the two types of thermoplastics: ABS (Acrylonitrile Butadiene Styrene) and PLA (Polylactic acid), but according to the research and development in the past few years, many materials have been applied to make the filament rolls such as wood fibers, milled chalk, and more (Hager, 2016). This technology is slowly emerging in construction, from which it is also found to be very cost effective. It is substantially more efficient than traditional construction, thus reducing production time and, along with it, reducing the carbon footprint and unnecessary capital requirements. Consequently, research for better technology is for superior living. The first Dutch couple in Europe to live in a 3d printed building, Elize Lutz and Harrie Dekkers once said when they lived in, "it is beautiful," and added, "It has the feel of a bunker – it feels safe." (Boffey, 2021)

Fig.9 ***Contour Crafting of a 3D Printed Castle*** **(2016)**

Fig.10 ***Waste from Rice Production Fills the Structure for Insulation*** **(2018)**

Contour crafting is one of the most anticipated 3d printing technologies in the construction industry, which is founded by Behrokh Khoshnevis in 1996 at the University of Southern California (Rael, 2018:118). This technique is very similar to the printing method described above, except that the printing process is done entirely on site, from bottom to top, layer by layer, after the foundation is laid. It is also mentioned above that the extruded material can be replaced as needed. For instance, Andrey Rudenko, a contractor, he has used 3d printing technology to build a castle with cement and sand as the base material for his children in his back garden as shown in Figure 9. Since there are precedents of applying various materials, is it possible to achieve a 3d printed building based on biodegradable materials?

Gaia House

WASP, an Italian 3d printing studio, have used relevant technology to build an unprecedented residential prototype using biodegradable materials barely in 10 days in a town called Massa Lombarda, in the area of Emilia-Romagna (Jordahn, 2019). The house covers an area of 30 square meters and its exterior walls are printed with mixture of local materials and natural waste, whereas the interior walls are mainly structured by wooden beams to support the timber roof. The material mixture, which is "composed of 25 percent soil, 40 percent chopped rice straw, 25 percent rice husk, and 10 percent hydraulic lime" (Marani, 2019), was extruded layer by layer forming vertical triangle cavities between the inner and outer wall. The interesting factor about this project is that the gaps in the middle are filled with rice husks, thus providing insulation as shown in Figure 10. Because of the perfect use of the cavities and recognition of material qualities, there is no need to install other heating or cooling systems, whether in winter or summer.

For the design team, the purpose of doing this project was to construct a template for a mass-produced biodegradable structure. This principle also makes it clear that this is a house with almost zero environmental impact and that it will biodegrade itself over time. The waste materials have a high chance of being reused, thus becoming a cycle and creating a certain sustainability.

Chapter 04: Material experiments

“Inspired by a resurging environmental consciousness in society, both designers and materials manufacturers are looking for alternative materials designed from natural substances.” (Peters, 2014) Nowadays, there are many professional companies developing more sustainable building materials, and as a student on my way to becoming a designer, I have this sense of mission to try to develop more alternative possibilities. In this part of the thesis, I choose eggshell as my main experimenting ingredient to test its feasibility. During the pre-operation of collecting eggshells, I found that every 20 units can produce an average of 120g of powder along with the data above on egg consumed annually in the UK, there would be about 77.4 thousand tons of eggshell powder produced every year, which looks like a decent number. Reducing the proportion of cement used and increasing the ratio of biodegradable materials is the aim of doing the following experiments. I will conduct 4 types of investigations and comparisons, which are testing the ratio of eggshell to cement, the size scale of eggshell plus cement, the possibility of eggshell plus cement and other biodegradable aggregates, and 3D printing with mixture of eggshell and cement. I will analyse the respective hardness, strength, toughness and adaptability with the help of external forces.

Experiment 1 Eggshell Proportion

The first series of experiment were made in a container of 3 cm x 3 cm x 3 cm. Make such a small scale to barely test the strength of different proportions of eggshells mixed with cement and its upper scale limit. Because this was a simple test, I estimated a ratio of 1.5 powder to 1 water to distribute the ingredients. Although it was not an accurate proportion and I found excess water on the surface of the samples, it did not affect my experiment much. Next, I used a ratio and the volume of the container to distribute the weight of eggshells and cement in grams. Firstly, made a 100% cement mix in order to compare with the other ones containing eggshells. After I have increased the percentage of eggshells in order from 20% to 80% at 20-unit intervals.

I tested the resistance of each sample with the following external forces, from light to heavy: scraping, poking, dropping and smashing. When I scraped the first sample which does not contain eggshell, only very light marks were left on the surface and not much powder was scratched off. In the next stage, I poked as hard as I could with a pushpin but could not get it in at all, the only part that I could barely get down were the edges, punched with the same force. Tried to drop it from a height of 30 cm, except that only bit of the edges came off, the rest was intact. When it came to the last stage of smashing to the ground, there was no significant change, still only the corners broke off. However, because this is a 100% cement mixture, it should be as resistant and hard as it should be.

Moving onto the second sample with 20% of eggshell, compare to the first one, some powder was scratched off and a deeper groove is clearly present. This one was poked with the same intensity as above, although the pin did not go in completely it was fixed in the hole. When dropping it from the same height as above, I was surprised that it did not break. I have repeated the same action and it showed a similar result. At the final stage of the smashing, it did not hold up and the corners were broken into small pieces, but the original shape could still be seen. The above results can also be carried over to the third sample, which I did not expect. It is basically as strong as the last one, even in the surface of the scraping traces were shallower than the second one.

From the fourth sample onwards, some obvious results were popped up. There was a noticeable feeling of its softness when I scraped it, powder was still being scraped out. Onto the second phase, I could not push it in fully to the bottom but it was easy to poke in, and the same goes for the edges. This time dropping from a height of 20 cm, the outcome showed that the corners were flattened and a few pieces of crumbs fell off. By the last part, gently smashed down several pieces were scattered out. The last sample containing 80% eggshells was a clear contrast. When scraping it would hang a large crater directly on the surface and even rub off the rim. With simple poke it cracked straight away. It became shattered when falling from a height of merely 10 cm. This sample can be easily crumbled into powder, so much so that I accidently pinched the first version into scraps.

As a conclusion, the third sample was the best outcome of this experiment. It was the one that contains the most eggshells among the samples that were not entirely destroyed, and it can carry different kinds of external force. Although this was a simple test, it has proved that the cement mixture with a certain amount of eggshells is still durable and hard in structure.

	RATIO DATA (Powder : Water / 1.5 : 1)					PROPORTION DATA [ml or g]				
EGGSHELL PROPORTION	Eggshell	:	Cement	:	Water	Eggshell	:	Cement	:	Water
[1] 0% Eggshell	/	:	1.5	:	1	/	:	16.2	:	10.8
[2] 20% Eggshell	0.3	:	1.2	:	1	3.24	:	12.96	:	10.8
[3] 40% Eggshell	0.6	:	0.9	:	1	6.48	:	9.72	:	10.8
[4] 60% Eggshell	0.9	:	0.6	:	1	9.72	:	6.48	:	10.8
[5] 80% Eggshell	1.2	:	0.3	:	1	12.96	:	3.24	:	10.8

Fig.11 *Eggshell proportion Experiment Chart* (2022)

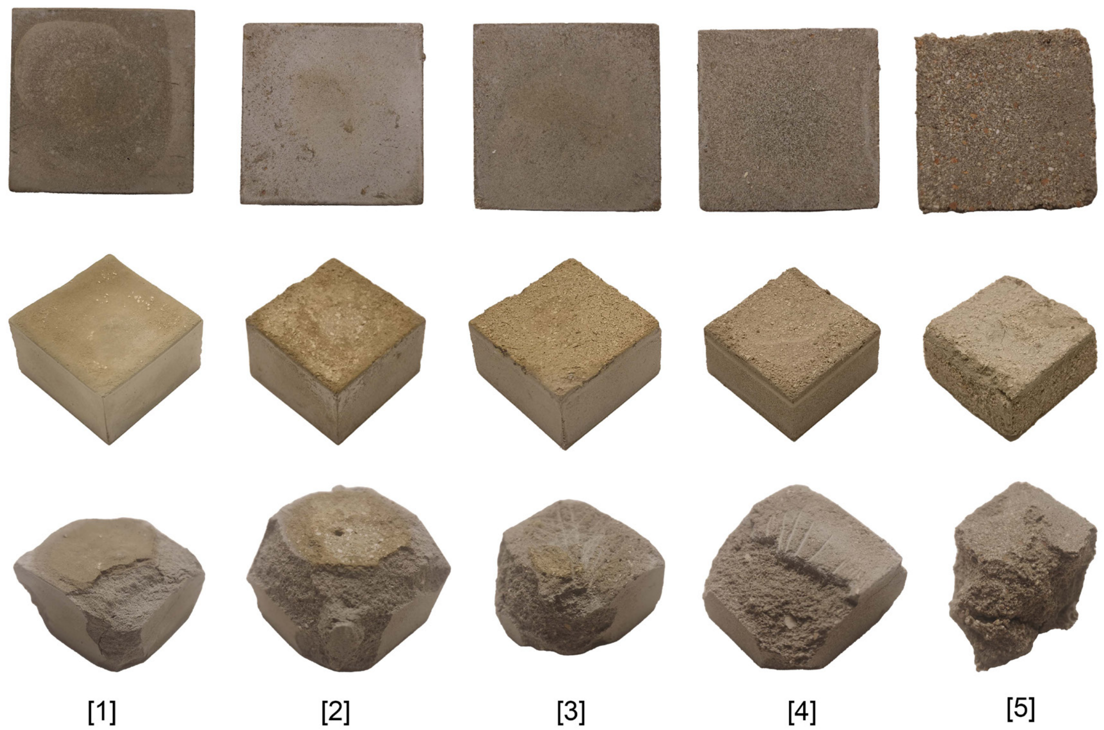

Fig.12 ***Eggshell proportion Experiments*** **(2022)**

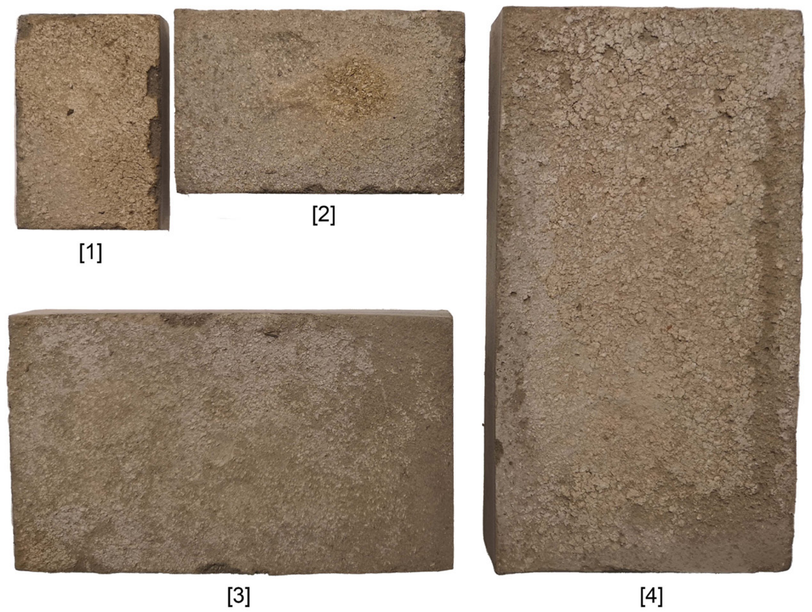

Fig.13 ***Eggshell Scale Size Experiments*** **(2022)**

Fig.14 ***Eggshell Scale Size Experiments Destroyed*** **(2022)**

Experiment 2 Eggshell Scale Size

In this experiment, instead of focusing on the proportional distribution of materials, I tested its feasibility in different size variations, in keeping the ratio of 50 eggshells and 50 cement. Using a standard brick as a reference, which is 21.5 cm long x 10.25 cm wide x 6.5 cm high (Hanson, s.d.), I have made four sizes of moulds from small to large respectively: 2 × 4 × 6 cm, 3 × 5 × 8 cm, 4 × 7 × 12 cm and 5 × 8 × 15 cm. According to the same ratios as in the previous experiment (1.5 powder to 1 water), the three ingredients were assigned a corresponding number of grams based on each volume.

As mentioned in the previous experiment, because of some miscalculations, when all the materials were mixed together evenly, the mixture would accumulate on the bottom of the mould so that some excess net water would remain on top. After the samples were dry, a layer of powder remained on the surface and could be easily wiped off, which led to a reduction of nearly one-third of the thickness of all samples. Despite this consequence, the results of the test still had a good response. I did both poking and breaking to test each of their toughness. The small and medium samples turned out as I expected, being extremely thin that they were cracked when the pins were poked in. When breaking by hands, they were easily split into half. On the other hand, the contrasting results were shown on the last two pieces. When trying to poke the pin in, the result was similar to the previous experiment with Sample 3, which could poke through the surface but not to the end. And in the breaking action there is a clear sensation that they were harder to break than the first two. This shows that the larger the size, the more resistance to external forces.

		DIMENSION [cm * cm * cm = cm^3]							PROPORTION DATA [ml or g]				
50% EGGSHELL SCALE SIZE		Height	*	Width	*	Length	=	Volume	Eggshell	:	Cement	:	Water
[1]	Small	2	*	4	*	6	=	48	14.4	:	14.4	:	19.2
[2]	Medium	3	*	5	*	8	=	120	36	:	36	:	48
[3]	Big	4	*	7	*	12	=	336	100.8	:	100.8	:	134.4
[4]	Large	5	*	8	*	15	=	600	180	:	180	:	240

Fig.15 ***Eggshell Scale Size Experiment Chart*** **(2022)**

Experiment 3 Eggshell, Cement, other Biodegradable Ingredients

In this phase of the experiment, I have made 7 samples using the materials analysed in the previous chapter: algae, mussel shell and, potato starch as an extra, to test the suitability of these materials to eggshells and cement along with the compatibility with each other. The sample size for this small-scale test was a uniform 3 x 5 × 8 cm container. Based on the above practical experience, I adjusted the ratio of aggregates to water to 1 to 0.25. With this ratio, there is no concern about excess water, and I could always add as much as needed if there was a shortage of water during the mixing process. And it turns out that this is true, although the amount of water on the diagram (see Fig.16) is uniform, according to the initial situation of each sample extra water would be added. From this I analysed the water absorption characteristics of the three biodegradable ingredients: algae are the most absorbent ingredient, in this case I used dried kelp, this raw material originally came from the ocean, which caused the water poured in was being absorbed by the kelp first and not being able to stir the mixture evenly. The second place comes to potato starch, because of its high density, the water will only take up the surface when poured, thus requiring more water while stirring and mixing. Compared to the first two, mussel shell powder has the opposite reaction, it is not a water-absorbing substance like eggshells.

To do the endurance test, I still used the same external action from Experiment 1: scraping, poking, dropping, and rubbing. From the test results, I found that those samples containing kelp would have a sticky consistency before drying, but once dried it would reflect a grainy tactile sensation, like Sample 1, when I tried to rub it, the particles on the surface have fallen off, which also indicated that it was as untight as easy to poke a corner down with a pin. Sample 4 and Sample 5, which also contain kelp, are looser than the others, although the structure is reinforced by the addition of other materials. They still shattered into pieces after dropping them from a height of 10 cm. Another finding was that when the potato starch is mixed with water there is a binding effect, but once the water was diluted by the cement or evaporated, it returned to its original powdered form, so those samples that included starch, such as the second and sixth, no matter what action I caused to them, they would react immediately like kinetic sand. Last but not least, the strongest structure among all is the third sample which contains only mussel shell along with the two base materials, followed by the one with all the ingredients. As stated above, mussel shell is composed of lime, which is equivalent to cement. Since they have the same property, the effect presented will be similar. In addition, the last sample is also highly resistant, basically withstanding all the external slamming, and only the corners of the edges have come down during the fall.

EGGSHELL + CEMENT + BIODEGRADABLE	RATIO DATA (Powder : Water / 1 : 0.25)						PROPORTION DATA [ml or g]					
	Egg-shell	Cement	Algae	Potato starch	Mussel shell	Water	Egg-shell	Cement	Algae	Potato starch	Mussel shell	Water
[1] Algae	0.33	0.33	0.33	/	/	0.25	32	32	32	/	/	24
[2] Potato Starch	0.33	0.33	/	0.33	/	0.25	32	32	/	32	/	24
[3] Mussel shell	0.33	0.33	/	/	0.33	0.25	32	32	/	/	32	24
[4] [1] + [2]	0.25	0.25	0.25	0.25	/	0.25	24	24	24	24	/	24
[5] [1] + [3]	0.25	0.25	0.25	/	0.25	0.25	24	24	24	/	24	24
[6] [2] + [3]	0.25	0.25	/	0.25	0.25	0.25	24	24	/	24	24	24
[7] [1] + [2] + [3]	0.2	0.2	0.2	0.2	0.2	0.25	19.2	19.2	19.2	19.2	19.2	24

Fig.16 ***Eggshell , Cement, Biodegradable Materials Experiment Chart*** **(2022)**

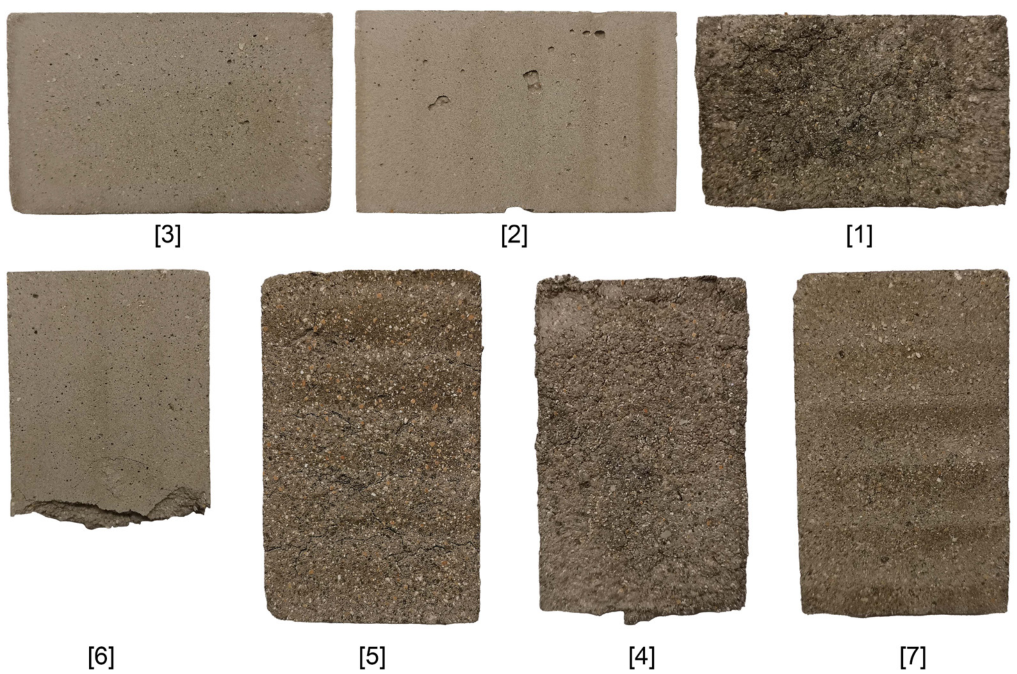

Fig.17 ***Eggshell , Cement, Biodegradable Materials Experiments*** **(2022)**

Fig.18 ***Eggshell , Cement and Mussel Shell Experiments Destroyed*** **(2022)**

Fig.20 ***Eggshell, Cement and all of the Biodegradable Materials Experiments Destroyed*** **(2022)**

Fig.19 ***Eggshell, Cement, Potato Starch and Mussel Shell Experiments Destroyed*** **(2022)**

Fig.21 ***All of the Samples Experiments Destroyed*** **(2022)**

Experiment 4 Eggshell 3D Printing Proportion

For this final experiment, I wanted to test to see if I could successfully print an extruded material containing eggshells and have the structure hold up. I used a laminating bag as a syringe to extrude the material for small scale 3d printing around a 3 by 3 area. Originally, I wanted to use the data from the first experiment to mix the aggregates, but that result did not look very applicable to this experiment, so I used the 1 aggregate to 0.25 water ratio for the combination. In the first attempt, I extruded a few layers with a mixture of 100 percent cement, but because of the rapid hardening of the cement, I was not able to squeeze out much halfway through. Then I tried to print the mixture with 20% eggshells, and the result was similar to the previous one, but given that the eggshells are heavier than the cement, the nozzle was blocked by the eggshells, so I tried to cut the opening bigger so that the mixture could be extruded easily. When I was about to do a 40% eggshell printing, a similar situation happened, where the nozzle was hindered by the eggshell that only water was being squeezed out. When I cut a larger opening, instead of the mixture coming down, more water drained out.

Since increasing the proportion of eggshells did not work for this experiment, I reduced the ratio percentage of eggshells, but the result turned out identical for 30% eggshells. However, the 10% eggshell is stronger than the 20% as expected, with its size ratio can support 1 kg of weight. Although it did not crack, the top surface was flattened. Nonetheless, if the test is conducted in a large-scale way, maybe the result will be better.

	RATIO DATA (Powder : Water / 1 : 0.25)					PROPORTION DATA [ml or g]				
3D PRINTING PROPORTION	Eggshell	:	Cement	:	Water	Eggshell	:	Cement	:	Water
[1] 0% Eggshell	/	:	1	:	0.25	/	:	40	:	10
[2] 10% Eggshell	0.1	:	0.9	:	0.25	4	:	36	:	10
[3] 20% Eggshell	0.2	:	0.8	:	0.25	8	:	32	:	10
[4] 30% Eggshell	0.3	:	0.7	:	0.25	12	:	28	:	10
[5] 40% Eggshell	0.4	:	0.6	:	0.25	16	:	24	:	10

Fig.22 ***Eggshell 3D Printing Proportion Experiment Chart*** **(2022)**

Fig.23 ***Eggshell 3D Printing Proportion Experiments*** **(2022)**

Conclusion

After thorough research and analysis, I realised that there is a presence in our lives that is inconspicuous but is gradually harming our environment and affecting human society. Cement, for example, is a well-known building material, but not everyone has access to this field, there is a possibility that they are not aware of the dangers it poses, and some may even feel that it is not their concern. In addition, its raw material is extracted from petroleum, and now there is a tendency that is slowly depleting, it is after all a limited material. Although there is no immediate crisis, many community groups, whether large corporations or individual studio, are calling for recycling or alternatives to prevent that day from coming.

In addition, modern technology has developed to ensure environmental sustainability. Traditional construction methods consume a lot of disposable materials, energy and time, while 3d printing has improved in all aspects, for instance, the machine can print endlessly, day or night, it does not require human labour, which increases efficiency. Another example, the mixture can be changed according to the demand, so now there are many buildings are made of more eco-friendly materials to implement environmental protection.

As a student designer, I do not have the proper ability to change the existing situation, but I can start experimenting with the materials that are usually found in our life. This is where biodegradable materials come into play. I did not know that these types of materials could be used as building elements. In recent years, many artists have produced innovative designs using this group of materials. The main purpose of this thesis was to prove whether biodegradable materials could replace harmful substances. So, I have also tried to use one of the most common biodegradable waste, eggshells, to make similar products. Later, I also mixed in other materials with the same property. After a series of experiments, the first part of the result is that eggshells can replace 50% of the cement ratio, but still maintain the corresponding hardness. The other part is that the sample containing eggshell, mussel shell powder and cement has the strongest resistance. This is perhaps one of the passages to a sustainable future.

List of Illustrations

Bibliography

Bastioli, C. (1998) 'Biodegradable materials - Present situation and future perspectives' In: *Macromolecular symposia* 135 (1) pp.193–204.

BBC News (2021) 'Where does recycling and rubbish from the UK go?' In: BBC 25/10/2021 At: https://www.bbc.co.uk/news/science-environment-49827945 (Accessed 09/11/2021).

Beorkrem, C. (2017) *Material strategies in digital fabrication.* (Second edition.) New York: Routledge, Taylor & Francis Group.

Boffey, D. (2021) 'Dutch couple become Europe's first inhabitants of a 3D-printed house' In: The Guardian 30/04/2021 At: http://www.theguardian.com/technology/2021/apr/30/dutch-couple-move-into-europe-first-fully-3d-printed-house-eindhoven (Accessed 18/01/2022).

Böttcher, U. (2012) CaCO3. At: https://eierschalee.wordpress.com/2012/05/14/caco3/ (Accessed 14/11/2021).

Brogan, C. (2021) *Best ways to cut carbon emissions from the cement industry explored.* At: https://www.imperial.ac.uk/news/221654/best-ways-carbon-emissions-from-cement/ (Accessed 07/11/2021).

Crook, L. (2018) *Studio Bark builds 'fully biodegradable and recyclable' cork building.* At: https://www.dezeen.com/2018/12/20/studio-bark-cork-studio-recyclable-building-sustainable-architecture/ (Accessed 14/11/2021).

Crook, L. (2020) *Sea Stone is a concrete-like material made from shells.* At: https://www.dezeen.com/2020/08/28/sea-stone-newtab-22-design-shells-materials/ (Accessed 17/11/2021).

Devi, K. S. et al. (2017) 'Impacts of cement industry on environment-an overview' In: *Asia Pac. J. Res* At: https://www.researchgate.net/profile/Kuruva-Devi/publication/323029097_Impacts_of_Cement_Industry_on_Environment_-_An_Overview/links/5a7d72cd458515dea40f98f5/Impacts-of-Cement-Industry-on-Environment-An-Overview.pdf

Franklin, K. and Till, C. (2018) *Radical matter: rethinking materials for a sustainable future.* London: Thames & Hudson.

Hager, I. et al. (2016) '3D Printing of Buildings and Building Components as the Future of Sustainable Construction?' In: *Procedia Engineering* 151 pp.292–299.

Hanson, J. (s.d.) [No title]. At: https://www.wienerberger.co.uk/tips-and-advice/brickwork/does-brick-size-matter.html (Accessed 24/01/2022).

Hurst, W. (2021) 'Demolishing 50,000 buildings a year is a national disgrace' In: *The Times* 28/06/2021 At: https://www.thetimes.co.uk/article/demolishing-50-000-buildings-a-year-is-a-national-disgrace-wbrf09952 (Accessed 06/11/2021).

HSE (2020) 'Construction statistic in Great Britain, 2020' At: https://www.hse.gov.uk/statistics/industry/construction.pdf

Jordahn, S. (2019) *3D-printed Gaia house is made from biodegradable materials.* At: https://www.dezeen.com/2019/02/27/gaia-wasp-3d-printed-house-biodegradable-video/ (Accessed 19/01/2022).

Karimjee, M. (2014) *Biodegradable Architecture: Finite Construction for Endless Futures.* Carleton University. At: https://curve.carleton.ca/df91b36d-bbf3-4e19-bcdd-6364f8444eef

Marani, M. (2019) *The Gaia House is a 3D-printed prototype made of biodegradable materials.* At: https://www.archpaper.com/2019/04/gaia-house-facadesplus/ (Accessed 19/01/2022).

Martínez-García, C. et al. (2021) 'Assessment of mussel shells building solutions: A real-scale application' In: *Journal of Building Engineering* 44 p.102635.

Mathur, R. (2016) '3D printing in architecture' In: *International journal of innovative science, engineering* At: http://ijiset.com/vol3/v3s7/IJISET_V3_I7_70.pdf

Mehraj, S. S. et al. (2013) 'Cement factories and human health' In: *International journal of current research and review* 5 pp.47–54.

Molkenthin, J. (2017) Comp-A-Tent. At: https://www.jamesdysonaward.org/en-GB/2017/project/comp-a-tent/ (Accessed 13/11/2021).

Penman, B. (2021) *The choice between demolition or reuse: developer insights - UKGBC - UK Green Building Council.* At: https://www.ukgbc.org/news/the-choice-between-demolition-or-refurbishment-developer-insights/ (Accessed 06/11/2021).

Peters, S. (2011) *Material Revolution: Sustainable and Multi-Purpose Materials for Design and Architecture.* Basel/Berlin/Boston, SWITZERLAND: Walter de Gruyter GmbH.

Peters, S. (2014) *Material Revolution 2: New Sustainable and Multi-Purpose Materials* *for Design and Architecture.* Basel/Berlin/Boston, SWITZERLAND: Walter de Gruyter GmbH.

Peters, S. and Drewes, D. (2019) *Materials in Progress: Innovations for Designers and Architects.* Basel/Berlin/Boston, GERMANY: Walter de Gruyter GmbH.

Rael, R. and San Fratello, V. (2018) *Printing Architecture : Innovative Recipes for 3D Printing.* New York, NY, UNITED STATES: Princeton Architectural Press.

Smith, M. and Whitelegg, J. (1998) *Greening the built environment.* (s.l.): Earthscan.
Sustainability (s.d.) At: https://dictionary.cambridge.org/dictionary/english/sustainability (Accessed 09/11/2021).

Studio Bark (2018) *Buildings can be made of solid cork: we built this to prove it. - Studio Bark.* At: https://studiobark.co.uk/buildings-can-be-made-of-solid-cork-we-built-this-to-prove-it/ (Accessed 14/11/2021).

Thakur, V. K. et al. (2017) *Handbook of Composites from Renewable Materials, Biodegradable Materials.* Somerset, UNITED STATES: John Wiley & Sons, Incorporated.

Thomas, J. (2005) *Using Eggshells To Build Walls In Japan.* At: https://metaefficient.com/news/using-eggshells-to-build-walls-in-japan.html (Accessed 15/11/2021).

Thorns, E. (2018) 8 *Biodegradable Materials the Construction Industry Needs to Know About.* At: https://www.archdaily.com/893552/8-biodegradable-materials-the-construction-industry-needs-to-know-about (Accessed 14/11/2021).

Tiseo, I. (2021) *UK: construction industry CO2 emissions 1990-2019.* At: https://www.statista.com/statistics/486106/co2-emission-from-the-construction-industry-uk/ (Accessed 07/11/2021).

Travel, A. et al. (2011) '13 - Effect of hen age, moult, laying environment and egg storage on egg quality' In: Nys, Y. et al. (eds.) *Improving the Safety and Quality of Eggs and Egg Products.* (s.l.): Woodhead Publishing. pp.300–329.

Treggiden, K. (2020) *Wasted: When Trash Becomes Treasure.* (s.l.): Thames & Hudson.

UK Egg Industry Data (2020) At: https://www.egginfo.co.uk/egg-facts-and-figures/industry-information/data (Accessed 14/11/2021).