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Quantifying and managing plastic waste generated from building construction in Auckland, New Zealand

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Abstract

Each year, construction and demolition (C&D) waste contributes at least 25,000 tonnes to the total amount of plastic landfilled in Auckland, New Zealand. The growing use of plastic in the packaging of building materials, use of polystyrene and products, such as building wrap, are contributing to this. Unlike countries such as the UK, most construction waste in New Zealand is not sorted on-site, and C&D waste is often co-mingled; therefore, minimal analysis on the recoverability of plastics has been attempted. This study identified and quantified the plastic waste stream produced from four construction sites, generated from various stages of construction in Auckland, New Zealand. Plastic waste was taken over three construction stages including demolition, exterior and weatherproofing and services and cladding, amounting to 112 kg (or 11.2 m^3). The main types of plastic analysed were polyethylene, contributing 77% (by mass), and polyvinyl chloride, representing 31% (by mass). The main reason for the generation of plastic waste across the four sites was highly variable and dependent on construction stage. However, it was apparent that plastic packaging of materials was not the single area of concern, and plastic building componentry and protection materials should also be investigated for their contribution. This study supports the requirement for improved understanding and awareness around the composition and fate of plastic C&D waste. Long-term benefits to the construction industry are from raising awareness of the potential to make profits from valuable waste products and to improve environmental performance and reputation, for a competitive advantage in New Zealand.

Keywords

C&D waste, waste separation, plastic, FTIR, on-site audits, recycling

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Introduction

The sustainable management of large quantities of waste materials generated by construction and demolition (C&D) activities is a growing concern worldwide, for which appropriate strategies are required. By 2012, the annual volume of C&D waste produced by 40 countries across 6 continents had reached 3 billion tonnes (Akhtar and Sarmah, 2018). Reported annual quantities of C&D waste production across developed countries include USA – 569 million tonnes (USEPA, 2019), UK – 66.2 million tonnes (USEPA, 2019), EU – 850 million tonnes (Saez and Osmani, 2019), Japan – 78.1 million tonnes (MLIT, 2019) and Australia – 20.4 million tonnes (Pickin et al., 2018). In developing countries, annual C&D waste quantities recorded include China – 1 billion tonnes (Li et al., 2020) and India – 530 million tonnes (Centre for Science and Environment, 2014). In New Zealand, the total annual volume of C&D waste is difficult to estimate, with approximately 1.7 million tonnes reaching landfills and similar amounts to cleanfill sites (for nonbiodegradable materials) every year (New Zealand Ministry for the Environment (NZ MfE), 2007). C&D waste can contribute between 10% and 50% to total municipal solid waste generated by cities around the world (Building Research Association of New Zealand, 2014; González Pericot et al., 2014; Li et al., 2016; Li and Zhang, 2013).

C&D waste can be classified as either inert or non-inert materials, where inert materials do not undergo any physical, chemical or biological transformation, will not react with other materials and are therefore unlikely to cause significant environmental harm. These include concrete, aggregate and ceramics, whereas non-inert materials can include metals, wood, plastics, plaster, packaging materials and hazardous wastes. The composition of C&D waste broken down into inert and non-inert material types for various countries is shown in Table 1.

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Table 1. Typical waste compositions for the C&D industry in selected countries.

Material	Waste composition (%)					
	New Zealand*	Japan^	USA^	Germany^	EU#	China~
Concrete, bricks, masonry	24	42.3	72.6	75.7	40–84	87
Metals	7	1.3	7.8	1.1	0.2–4	7
Wood	27	6	13.3	13.4	2–4	2
Plastics	4	1.3	1.5	0.6	0.1–2	–[1]
Bituminous mix without tar	0	34	0	0	0	0
Other	38	15	4.8	9.2	2–36	4

*NZ MfE (2007)
^Coelho and de Brito (2011)
#Ganguly (2012)
~Zheng et al. (2017).
[1] Plastics are included under 'Other'.

C&D waste sent to landfill has direct environmental (e.g. soil and groundwater leaching), social (e.g. odour and loss of amenity value) and financial implications, as well as indirect costs due to the consumption of virgin materials (in preference over recovery and reuse of existing materials). The three Rs of waste management (reduce, reuse and recycle) are fundamental to managing the amount of C&D waste diverted from landfill. Reduction of waste involves good planning and design decisions to reduce the amount of C&D waste produced. Reuse of existing products for use in a new building or construction project will not only minimise the amount of C&D waste produced but also help lower construction costs. The suitability of existing materials for reuse will depend on the type and condition of the material. Recycling of existing building materials can also be effective in minimising C&D waste production. This is dependent on the type and condition of existing materials (although to a lesser extent than reuse), and the impacts of processing required to make the material suitable for new construction should be evaluated against the benefits of waste reduction. However, both recycling and reuse options are fundamentally limited by the efficiency of waste recovery.

While the recovery of C&D waste produced is increasing, recovery rates still vary globally. In 2008 the European Commission set a 70% target for recovery rate from C&D waste by 2020 under Article 11(2) of Directive 2008/98/EC (European Commission, 2015). By 2012, at least nine member countries had achieved this target (European Commission, 2017). In comparison, Germany had a recovery rate of 88% (Crawford et al., 2017), whereas USA and Japan had recovery rates of 82% and 80%, respectively. Australia's recovery rate was 57%, whereas China had a recovery rate of just 5% (Jin et al., 2017). In New Zealand, C&D waste sent to landfills has been steadily increasing and is not subject to a substantial landfill levy, which reduces the impetus for reuse and recycling activities (Building Research Association of New Zealand, 2021).

A variety of methods have been employed to quantify C&D wastes generated on construction sites. Llatas (2011) adopted an estimation model based on waste factors obtained from the European Waste List, whereas Gonzalez Pericot et al. (2011) analysed waste container delivery notes against waste densities and linked these to a construction period to generate a 'descriptive evolution' of the waste generated. Similarly, González Pericot et al. (2014) described specific training and team incentives for site workers focussed on C&D waste segregation, combined with analysis of waste contractor delivery notes to estimate quantities. In contrast, Li et al. (2016) identified several models, which can be adopted, based on survey-based percentages, generic project parameters (e.g. work breakdown structure) and macroeconomic models as alternative means of estimating waste quantities.

Plastics in the C&D industry and their embodied energy

Due to the significant amount that inert materials contribute to C&D waste (as demonstrated in Table 1), recovery of inert materials for reuse and recycling has typically received the most attention. Recovery of some woods and metals has been largely driven by the commodity values of these products. In Europe, approximately 20% of all plastics produced are used in the construction sector (Plastics Europe, 2021) including different classes of plastics, waste and nanomaterials. Along with their use for retaining building structural quality, the introduction of plastic-based construction and finishing materials for water and thermal insulation, flooring, glazing, windows, etc. supports the increasing need for energy-efficient and sustainable buildings (Liew et al. 2017; Rudel and Perovich, 2009) by providing a lower cost substitute for traditional materials such as timber (Ferdous et al., 2021). The relatively low production cost of plastics (Kerns, 2016), however, means there has been little economic incentive to develop plastics recovery from C&D waste.

Plastics are synthetic organic polymers predominantly derived from fossil hydrocarbons (Geyer et al., 2017). Plastics are typically light, versatile and cheap to purchase, and however can cause significant environmental change (Häkkinen et al., 2019). According to Geyer et al. (2017), the building and construction sector consumes 69% of the global production of polyvinyl chloride (PVC) products, and 19% of all non-fibre plastics. In

Table 2. Greenhouse gas emissions generated when various plastic types are used for construction.

Polymer	Construction uses	GHG (kg CO_2e/kg of product)
Polyethylene	Water pipes, vapour barrier, membranes, cable insulation	5.46*
Polypropylene	Sewage pipes, water pipes and membranes	1.63*
Polyvinyl chloride	Plates, tubes, profiles, façade covers, roofing, wallpapers, foils, flooring, cable insulation, windows	4.55*
Polystyrene	Cable insulation, foamed plastic, lighting fixtures	3.26*
Polyurethane	Foamed plastics, grouting compounds	2.90*
Phenol plastic	Melanin plastics, façade covers, interior walls, door handles, electric lining	4.61^
Unsaturated polyester	Bath and shower boots (rubber seal at bottom of shower), interior walls, façade covers, window frames, gutter pipes	3.79^

*Häkkinen et al. (2019).
^Hill and Norton (2020).

addition to PVC, other forms of plastics commonly used in the construction industry include polyethylene (PE), polypropylene (PP), expandable polystyrene (EPS) and polyurethane (PU).

Plastic use in the construction industry can be categorized as either direct or indirect. Construction materials containing plastics, such as building products (e.g. insulation, damp-proofing, flooring, roofing, windows and laminated surfaces), building service installations (e.g. pipes and cabling), surface treatments (e.g. paints, varnishes, sealants, glues and resins) and covers (e.g. shrink wrap) and tarpaulins are considered direct-use plastics. Plastics used for packaging of construction materials (e.g. foils and moisture barriers, covers, soft plastic wraps, EPS and PP sacks) only serve their purpose during the transport and storage of those materials and are considered indirect uses of plastic.

Embodied energy is the total amount of energy required in the production and delivery of a construction material or product to the construction site. The consumption of this energy generates CO_2, which is a component of greenhouse gas (GHG) emissions and has been shown to have direct impacts on the environment (Salcido et al., 2016). It is therefore important to consider the embodied energy of a construction material or product to enable comparisons of environmental impact. The embodied energy of plastic products is dependent not only on the material from which they are made but also on the form, shape and density of the product. For example, the embodied energy for polystyrene (PS) can range between 61 and 113 MJ/m^2/RSI and between 96 and 144 MJ/m^2/RSI for PU (Azari and Abbasabadi, 2018). Units are expressed in terms of the embodied energy of an insulation panel of 1-m^2 area with the metric *R*-value (RSI) of 1, where the *R*-value refers to the ability of insulation material to resist heat flow.

As GHG emissions occur when new materials are resourced to create building components (Salcido et al., 2016), it is important to identify those materials that make the greatest contribution. When construction materials are reused and not produced from virgin resources, there are no resulting GHG emissions. Table 2 shows the variation in GHG emissions between different types of plastic polymers used for construction materials and the corresponding levels of embodied energy. PE and PVC products produce the highest levels of GHG emissions of the given polymer types, whereas construction products containing PP produce the least.

A recent study (Kamaruddin et al., 2017) has demonstrated that some plastics generated from the construction sector can successfully be recycled into new household/commercial products, such as PVC tiles, pipe fittings, hose inner cores, carpet fibres and clear film for packaging. Plastic waste also has potential recycling applications in the construction industry, such as cement binders and aggregates, used as base and subbase for road construction, and insulation materials (Awoyera and Adesina, 2020). However, there are considerable barriers to reuse and recycling. which include health and safety considerations, material contamination and the need for education and training for on-site waste management (Low et al., 2020).

Approximately 25,000 tonnes of plastic waste is contributed by the C&D sector in Auckland annually. This figure is calculated using an estimated 1.6 million tonnes of waste to landfill in the Auckland region (Auckland Council, 2017); of which 4% of all landfilled waste is plastic (NZ MfE, 2007), and 40% of all waste to landfill is contributed from C&D waste (Rohani et al., 2019). There is a need for improved understanding of the composition and origins of plastic C&D waste, to identify opportunities for better waste management including advancing the development of reuse and recycling solutions.

Previous studies, such as Hoang et al. (2020) and Poon et al. (2001), have performed in-depth surveys and analysis of wastes generated for all major material types across typical construction sites. These studies concluded that while generation rates and composition of C&D waste often varied significantly from project to project, the most common elements were typically concrete, brick and soil, with recycling and reuse limited to around 10% of total waste generated. Separation and sorting of C&D waste by component was highlighted as necessary to promote future reuse and recycling.

However, it is believed that this study is the first to consider the spectrum of plastic types used in construction and their descriptive evolution from source to end use. This research aimed to identify and quantity the plastic waste stream produced from four construction sites, generated from various stages of construction

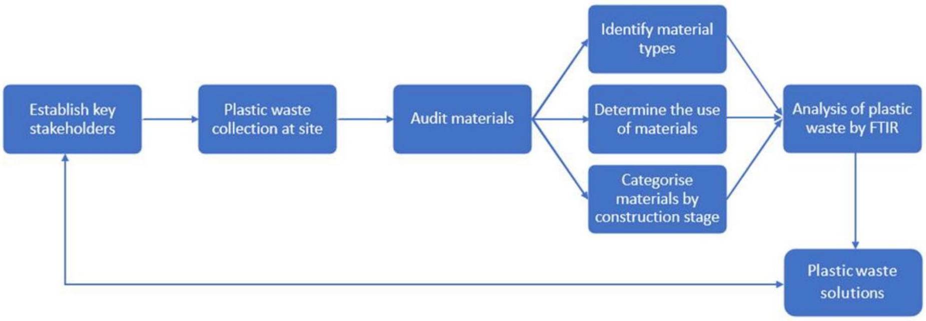


Figure 1. Plastic waste auditing process.

Table 3. Summary of construction sites audited.

Sites	1	2	3	4
Number of levels	22	4	3	1
Works	Conversion of heritage building into apartments.	Conversion of building to hotel.	Rebuild over existing shopping centre.	New 6000 m^2 shopping centre.
Description	Exterior fit-out including weatherproofing	Demolition (strip to concrete)	Structural strengthening, building fit-out; Steel framing, exterior wall cladding.	Tilt slab exterior with timber and steel stud interior walls. GIB linings
Collection phase	Exterior and weatherproofing	Demolition	Services and cladding	Services and cladding
Total duration (year(s))	2.58	<1	2.58	1.25

GIB: Gibraltar Board.

in Auckland, New Zealand. The origins of plastic wastes were determined for each stage of construction to encourage plastic reduction at supplier level as best practice for their minimisation. Further options for reuse and recycling were examined as well as the significant barriers to effective waste management on active construction sites, which may impact future reductions in plastic waste generation.

Methodology

Plastic waste audits were conducted on C&D waste collected from four different sites across Auckland, New Zealand during 2020. The purpose of this study was to identify the different types and sources of plastic waste generated during construction and to track their final destination. The waste audit was carried out with the assistance and cooperation of three different partner companies: a construction company, a supplier company and a waste collection company. An overview of the waste auditing process has been provided as shown in Figure 1. The partner construction company is the largest privately owned construction company in New Zealand, specialising in vertical construction including industrial, retail, education, commercial and residential buildings. In 2019, the company had an annual turnover equivalent to 1.5% of the national industry total.

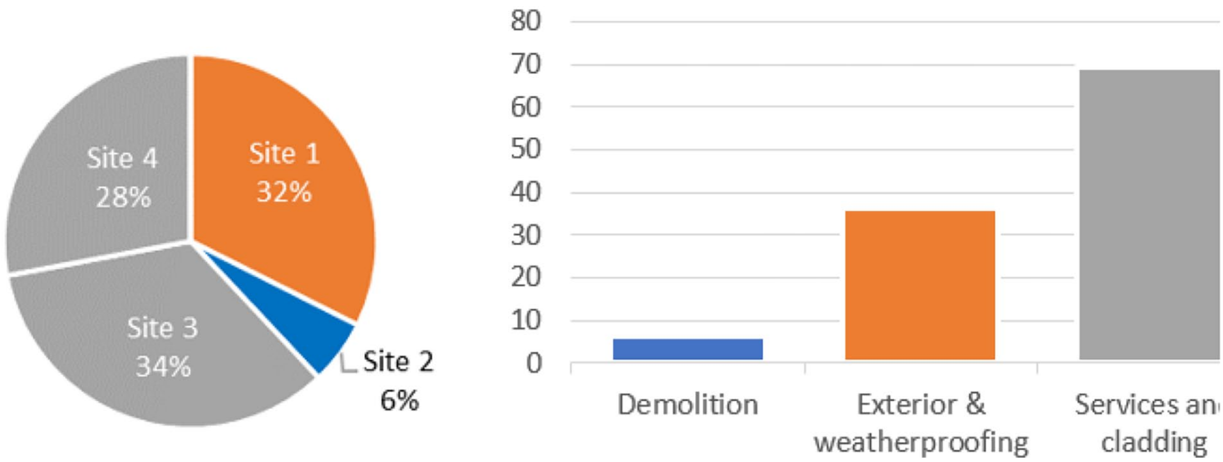
The construction sites audited during this study were commercial buildings, with projects being a mix of demolition/partial rebuild or completely new construction. Most of the sites were low rise (three or four storey) hotels or shopping complexes, with the exception of one 22 storey office building which was being converted into apartments.

All plastic waste generated at these sites was separated and deposited in dedicated on-site storage bins during the collection period (February–May 2020). Construction stage and material sources were recorded to investigate the evolution of plastic wastes generated. As a result of the different timing of construction projects, these collection phases coincided with different stages of construction. A summary of the different construction sites audited is provided in Table 3.

Each storage bin had its contents audited, whereby the type and volume and/or mass of each piece of plastic waste material was recorded. While volume is an important and commonly reported statistic for C&D waste (due to implications on waste disposal costs), mass is also an important measure as it quantifies waste independent of compactness (Llatas, 2011). Relative waste compositions as shown have been calculated in terms of mass, unless described otherwise.

Lab analysis

Samples of each type of plastic material were retained for laboratory analysis to identify polymer types. Samples were characterised via Fourier transform infrared (FTIR) spectroscopy, Bruker Vertex 70 FTIR spectrophotometer in the attenuated total reflectance (ATR) mode equipped with a diamond ATR crystal. The spectra of the samples were recorded as an average of 16 scans. From these spectra, the plastic type(s) was/were determined.



(a) (b)

Figure 2. (a) Plastic waste mass (%) by site and (b) plastic waste mass (kg) by construction stage.

Construction stages and plastic-use classification

Due to the timing of the four construction sites, each plastic collection phase fell under a different stage of construction. Therefore, the following *construction stages* have been identified for this study:

- *Demolition*
- *Exterior and weatherproofing*
- *Services and cladding*

In order to categorise the plastic waste materials, the following plastic-use classifications have been determined for this study.

- Building protection (e.g. shrinkwrap, damp proof membranes and carpet protectors)
- Product packaging (e.g. cling film wrap, bubble wrap and plastic bags)
- Construction components (e.g. PVC pipe offcuts, tape, power points and light fittings)

Results and discussion

Plastic waste quantity and energy savings

A total of 104 samples of plastic waste were collected from the four sites, weighing 112 kg, with a total volume of 11.2 m^3. Approximately 94% of the total mass of plastic waste was generated from just three of the construction sites, sites 1, 3 and 4, as shown in Figure 2(a).

In terms of *construction stage*, the majority of plastic waste analysed was obtained during the *services and cladding* stage, as shown in Figure 2(b); 69 kg by mass (62% of samples), with 36 kg (32% of samples) from *exterior and weatherproofing* stage, and 6 kg (6% of samples) from *demolition* stage. The greater masses obtained during *services and cladding* may be in part due to the larger project sizes (sites 3 and 4) examined at this stage relative to smaller projects examined at other stages. For comparison, a C&D waste study conducted for all waste material types (not just plastic) across three multi-level housing projects in Madrid, Spain (González Pericot et al., 2014) identified that 33% of plastic C&D waste was generated during the *services and cladding stage* ('partitions', 'building services' and 'roof and siding panels') and 33% was generated during the *exterior and weatherproofing* stage ('thermal and moisture protection' and 'finishes').

The on-site plastic collection was carried out over a 4-month period, with each *construction stage* lasting on average 1 month. This 4-month collection period was split into two smaller 2-month periods due to the Government requirements during COVID-19 lockdowns. The sites examined represented approximately 40% of the partner construction company's Auckland-based construction, which in turn represented approximately 36% of their national total. Extrapolation of the study results indicates the partner construction company's nationwide annual production of waste plastic is approximately 9300 kg/year. Comparing the partner construction company's annual turnover to the annual value of the New Zealand construction industry (MBIE, 2019), and assuming the plastic waste the partner construction company produces is typical of the New Zealand construction industry, an estimate of at least of 534,000 kg of plastic is generated each year in the C&D industry. The calculation from the results of this audit are considerably lower than the estimated value of 25,000 tonnes, and there are a number of reasons for this difference including:

1. The sites considered in this study were commercial and not residential (the authors do not have data for residential sites); however, it is feasible that particularly smaller residential sites produce more waste, especially as it is harder for smaller contractors to reuse materials or order in bulk.
2. There was a steep learning curve on-site for construction workers to separate and collect plastic waste effectively, and

Table 4. Plastic waste by primary polymer detected.

Site number and construction stage	Plastic type (kg) and quantity (% of project)						Total (kg)
	PE	PVC	PP	ET	PA	Others	
1. Exterior and weatherproofing	35.753 (99%)	0.025 (0.1%)	0.367 (1%)	–	–	0.1 (0.3%)	36.245
2. Demolition	6.267 (100%)	–	–	–	–	–	6.267
3. Services and cladding	33.456 (88%)	1.980 (5%)	1.585 (4%)	0.738 (2%)	0.004 (0.01%)	0.302 (0.95%)	38.108
4. Services and cladding	10.973 (35%)	19.111 (61%)	0.523 (2%)	–	0.664 (2%)	–	31.271
Total (kg)	86.449	21.116	2.475	0.738	0.668	0.445	111.891

PE: polyethylene; PVC: polyvinylchloride; PP: polypropylene, ET: ethylene and PA: polyamide.

it was acknowledged during audits that not every plastic item was collected, as occasional items were disposed of as general waste.

3. The authors experienced some thefts of plastics stored in prepaid collection bags on some sites.
4. Some plastics that the authors know are used in the C&D sector were not detected, for example EPS.
5. The proportion of plastic in waste to landfill of 4% may require updating (NZ MfE, 2007).

In terms of CO_2 emissions, the generation of approximately 2,915,000 kg of CO_2 could be avoided by reusing and recycling construction plastic (under the assumption the PE accounts for the majority of plastic waste generated, with a GHG of 5.46 kg of CO_2e/kg of product (Table 2)).

Plastic waste determination

Plastic waste samples were analysed to identify the primary polymer contained within each sample. The density of waste material products ranged from 0.86 to 1.37 g/cm^3, with a mean value of 1.0 g/cm^3. PE was the dominant form of waste identified during the study, accounting for 77% by mass (82% by volume), whereas PVC was the second most common form, comprising 19% by mass (14% by volume) of plastic waste analysed. PVC is the main plastic used in NZ construction, forming 65% (26,000 tonnes) of the national consumption of PVC in 2005 (Marston and Jones, 2007). Minor contributions to the plastic waste samples analysed comprised PP (2% by mass and volume), ethylene (ET) and polyamide (PA) (1% each).

'Other' polymers identified during the study included polyethylene terephthalate, polymethyl methacrylate, polycarbonate and polydimethylsiloxane. However, these amounted to less than 1% in total. PS, styrene and acrylonitrile were detected in samples taken from other construction sites during a pre-trial but did not appear in this construction waste audit.

The relationship between primary polymer and *construction stage* is presented in Table 4. Plastics used in the *demolition* stage (site 2) were derived entirely from plastics used for product packaging. Plastics used during the *exterior and weatherproofing* stage (site 1) comprised of plastics used for building protection (84%) and product packaging (15%), with construction components comprising just 1%. The *services and cladding* stage (sites 3 and 4) used plastics derived primarily from construction components (53%), with plastics from building protection and product packaging making up 23% and 24%, respectively. During the *demolition* stage, 100% of the plastics generated were PE. PE also formed the bulk of plastics generated during the *exterior and weatherproofing* stage (99%), with the other 1% comprising PP. The *services and cladding* stage comprised a greater variety of polymer types: 64% PE, 31% PVC, 3% PP, 1% PA and 1% ET.

Plastic waste use

Waste distribution by site and use. The three main identified categories of plastic use were represented fairly equally between the audits where on average 33% of the waste analysed was construction components, 34% used for building protection and 24% for product packaging. However, despite the audit mean showing an even distribution, the main use of plastic waste across the four sites was highly variable depending on *construction stage*. Gonzalez Pericot et al. (2011) recognises packaging waste as one of the primary contributors to C&D waste, whereas González Pericot et al. (2014) and Llatas (2011) have shown plastics to contribute around 10%–20% of packaging waste. The growing use of prefabricated building materials has been identified as a primary reason for an overall increase in packaging volumes in recent years (Gonzalez Pericot et al., 2011).

The plastics generated from sites 2 and 4 were almost exclusively from two categories of use, product packaging (100%) and construction components (99%), respectively. The majority of the waste from site 1 was derived from building protection with only 15% from product packaging and 1% construction components. Finally, waste collected from site 3 comprised plastics used for product packaging (44%), building protection (40%) and construction components (16%). It was not possible to identify a pattern or trend in this data to indicate the main use of plastics on construction sites; however, auditing an active site across all stages of construction would provide more information.

Waste distribution by stage and use. The greatest contribution of plastic waste derived from construction components was during the *services and cladding stage* (99%). By comparison, a study of C&D waste (all materials) across 20 residential dwellings constructed in Andalusia, Spain (Llatas, 2011) also found

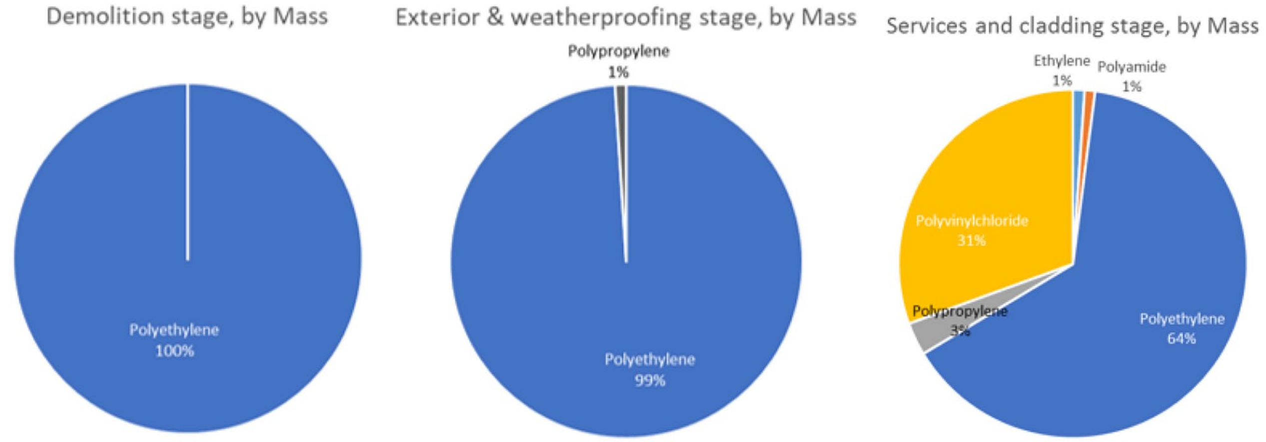


Figure 3. Plastic waste composition by primary polymer, for each construction stage.

that the s*ervices and cladding* stage ('masonry', 'roofing' and 'services') contributed the majority (48%) of plastic waste derived from construction components ('remains').

Product packaging plastics across the four sites were generated mainly during the *demolition* and *services and cladding* stages. From this study, the mean generation rate of product packaging plastics, based on project floor area, was calculated to be 0.0019 kg/m^2 (from a range of 0.0001–0.004 kg/m^2 across all four sites). González Pericot et al. (2014) found that the majority of packaging plastics were generated during the *exterior and weatherproofing* stage and *services and cladding* stage, with a significantly higher generation rate of 0.53 kg/m^2. The current study only analysed plastic wastes across specific phases of each site, not the entire project, which may explain this difference. Other potential factors may include inaccuracies in reporting due to lack of training and staff behaviour; the difference in building types (commercial vs residential) involving different amounts of packaging; different construction methods and packaging standards between New Zealand and Spain.

As previously mentioned, PE was found to be the dominant waste polymer for each of the *construction stages*, contributing 100% at *demolition* stage, 99% at *exterior and weatherproofing* stage and 64% at *services and cladding* stage (Figure 3). PE was mainly used for building protection (100% of plastic waste type derived from this use) and product packaging (91%, with just 7% PP and 2% ET). At *exterior and weatherproofing* stage, a further 1% was contributed by PP. At the *services and cladding* stage, PVC was a significant component to the waste stream, representing 31%, with another 3% of waste generated from PP and 1% each from ET and PA. PVC was the dominant polymer in plastic waste originating from construction components (57%), followed by PE (39%). Minor contributions to plastic waste from construction components came from PP and PA (2% each).

Encouraging a circular economy

Despite being a major provider of employment opportunities and contributing to gross domestic product, the construction industry creates serious environmental problems, mainly due to the generation of C&D waste and the manufacture of new building materials (Ruiz et al., 2020). C&D waste is the largest waste stream representing 30–40% of total solid waste (Jin et al., 2018), and yet only 20%–30% of C&D waste is recovered globally (WEF, 2016). It is clear that the current 'linear economy model', which considers buildings materials as merely 'waste in transit', is not a sustainable approach, and new strategies for C&D waste problems are required (Jaillon and Poon, 2014).

A circular economy approach involves optimising the use of materials and their value throughout their whole lifecycle with an aim to minimise waste (Brown et al., 2019). One definition of this term is: '*A circular economy is an economic and industrial system where material loops are closed and slowed and value creation is aimed for at every chain in the system*' (EMF, 2013). This approach would seek to reduce environmental impacts (by reducing energy requirements during production of new materials and reducing waste production) while contributing to economic growth (Lieder and Rashid, 2016).

Within the building sector, the concept of circular economy is still relatively new (Leising et al., 2018), but in practice this can include strategies such as considering buildings to be 'material banks' and the use of resource passports to keep track of materials (Leising et al., 2018). An essential activity to move towards a circular building sector is the long-term collaboration between all partners involved which includes suppliers, designers, demolishers and waste companies (Leising et al., 2018).

Success also requires establishing the multiple barriers (behavioural, technical and legal), which hinder the development of this type of waste management, such as ownership issues (in waste management), poor site-staff incentivisation and limited land space for waste segregation (Low et al., 2020; Mahpour, 2018). In this study, despite the engagement between academia, industry and government regulators, gains in waste diversion were hindered by difficulties such as high staff turnover (which impacted on-site training initiatives) and the theft of dedicated plastic waste disposal bins on a number of occasions. Successes were achieved due to a number of practical solutions devised by the team such as the design and trial of permanent plastic collection bins (with appropriate drainage).

Working towards a circular economy strategy, the greatest gain came from the inclusion of an option to enable purchasers to select for the use of packaging for all materials ordered on an online customer portal. Over a 12-month period, only 3% of materials were supplied with packaging as 97% of the purchasers opted out of requesting it. Additionally, the main suppliers of PVC pipes agreed to accept all (clean) offcuts from construction sites for this contractor, which was another positive outcome.

Conclusions

Waste taken from four different construction sites over three construction stages including *demolition, exterior and weatherproofing* and *services and cladding* comprised 112 kg of plastic (11.2 m^3). Approximately, 62% (by mass) of the plastic waste originated from the *services and cladding* stage; however, this may be in part due to the larger project size of the two sites at this particular stage relative to the smaller sites at other stages. Examination of a single construction site through all stages would provide a more accurate indication of the relevance of *construction stage* on plastic waste type and quantity.

The main type of plastic analysed from construction was PE, contributing 77% (by mass), which was mainly derived from use as building protection and product packaging. PVC was also a significant component to the waste stream, representing 19% (by mass) with minor contributions from PP, ET and PA. PVC was the dominant polymer in plastic waste originating from construction components (57%).

Although the three main identified categories of plastic use were represented fairly equally between the audits, that is, 33% of the waste from construction components, 34% from building protection and 24% from product packaging, the main use of plastic waste across the four sites was highly variable and dependent on *construction stage*. It was not possible to identify the main contributor(s) to plastic waste generation on construction sites (by mass); however, auditing an active site across all stages of construction would provide more complete information. While the focus in New Zealand has been on minimising packaging waste generated by certain producers (e.g. domestic), it was apparent that plastic packaging of materials is not a single area of concern, and plastic building componentry and protection materials should also be investigated for their contribution to C&D plastic waste.

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References

Akhtar A and Sarmah AK (2018) Construction and demolition waste generation and properties of recycled aggregate concrete: A global perspective. *Journal of Cleaner Production* 186: 262–281.

Auckland Council (2017) *Auckland's Waste Assessment 2017: Technical Report*. Available at: https://www.aucklandcouncil.govt.nz/plans-projects-policies-reports-bylaws/our-plans-strategies/topic-based-plans-strategies/environmental-plans-strategies/docswastemanagementplan/waste-assessment-2017.pdf (accessed 12 August 2021).

Awoyera PO and Adesina A (2020) Plastic wastes to construction products: Status, limitations and future perspective. *Case Studies in Construction Materials* 12: e00330.

Azari R and Abbasabadi N (2018) Embodied energy of buildings: A review of data, methods, challenges, and research trends. *Energy and Buildings* 168: 225–235.

Brown P, Bocken N and Balkenende R (2019) Why do companies pursue collaborative circular oriented innovation? *Sustainability* 11: 635.

Building Research Association of New Zealand (BRANZ) (2014) Easy guide to waste reduction – construction. Available at: https://d39d3mj7qio96p.cloudfront.net/media/documents/REBRI_Easy_Guide_to_Waste_Reduction_-_Construction.pdf (accessed 13 August 2021).

Building Research Association of New Zealand (BRANZ) (2021) Material use: Minimising waste – specifying efficient use of materials and considering their impact from manufacture to disposal. Available at: http://www.level.org.nz/material-use/minimising-waste/ (accessed 13 August 2021).

Centre for Science and Environment (CSE), India (2014) Construction and demolition waste. Available at: https://www.cseindia.org/cse-welcomes-moefcc-notification-on-use-of-construction-and-demolition-waste-would-like-to-see-a-clear-mechanism-for-stringent-implementation-of-rules-6339 (accessed 13 August 2021).

Coelho A and de Brito J (2011) Distribution of materials in construction and demolition waste in Portugal. *Waste Management and Research* 29: 843–853.

Crawford RH, Mathur D and Gerritsen R (2017) Barriers to improving the environmental performance of construction waste management in remote communities. *Procedia Engineering* 196: 830–837.

Ellen McArthur Foundation (EMF) (2013) Towards the circular economy Vol. 2: opportunities for the consumer goods sector. Available at: https://ellenmacarthurfoundation.org/towards-the-circular-economy-vol-2-opportunities-for-the-consumer-goods (accessed 10 December 2021).

European Commission (2017) Resource efficient use of mixed wastes: Improving management of construction and demolition waste. Final Report. Available at: https://op.europa.eu/en/publication-detail/-/publication/78e42e6c-d8a6-11e7-a506-01aa75ed71a1/language-en (accessed 12 August 2021).

European Commission (2015) Proposal for a Directive of the European Parliament and of the Council: Amending Directive 2008/98/EC on Waste. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52015PC0595 (accessed 12 August 2021).

Ferdous W, Manalo A, Siddique R, et al. (2021). Recycling of landfill wastes (tyres, plastics and glass) in construction – A review on global waste generation, performance, application and future opportunities. *Resources, Conservation & Recycling* 173: 105745.

Ganguly P (2012) Construction and demolition waste handling in the EU. *Littera Scripta* 2: 205–217.

Geyer R, Jambeck JR and Law KL (2017) Production, use, and fate of all plastics ever made. *Science Advances* 3: e1700782.

Gonzalez Pericot N and Del Rio Merino M (2011) Management of waste from packaging of construction materials in building construction works. *The Open Construction and Building Technology Journal* 5: 149–155.

González Pericot N, Villoria Sáez P, Del Río Merino M, et al. (2014) Production patterns of packaging waste categories generated at typical Mediterranean residential building worksites. *Waste Management* 34: 1932–1938.

Häkkinen T, Kuittinen M and Vares S (2019) Plastics in buildings: A Study of Finnish Blocks of Flats and Daycare Centres. Available at: https://www.ym.fi/download/noname/%7B76B1ED3C-6D8D-4108-80D1-487F69957E45%7D/152008 (accessed 5 August 2021).

Hill C and Norton A (2020) European Commission: LCA database of environmental impacts to inform material selection process. Available at: https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5c240650f&appId=PPGMS (accessed 16 August 2021).

Hoang NH, Ishigaki T, Kubota R, et al. (2020) Waste generation, composition, and handling in building-related construction and demolition in Hanoi, Vietnam. *Waste Management* 117: 32–41.

Jaillon L and Poon CS (2014) Life cycle design and prefabrication in buildings: A review and case studies in Hong Kong. *Automation in Construction* 39: 195–202.

Jin R, Li B, Zhou T, et al. (2017) An empirical study of perceptions towards construction and demolition waste recycling and reuse in China. *Resources, Conservation and Recycling* 126: 86–98.

Jin R, Yuan H and Chen Q (2018) Science mapping approach to assisting the review of construction and demolition waste management research published between 2009 and 2018. *Resources, Conservation and Recycling* 140: 175–188.

Kamaruddin MA, Abdullah MMA, Zawawi MH, et al. (2017). Potential use of plastic waste as construction materials: Recent progress and future prospect. *IOP Conference Series: Materials Science and Engineering* 267: 012011.

Kerns J (2016) Machine design – replacing metal with plastic. Available at: https://www.machinedesign.com/materials/article/21834845/replacing-metal-with-plastic (accessed 10 December 2021).

Leising E, Quist J and Bocken N (2018) Circular economy in the building sector: Three cases and a collaboration tool. *Journal of Cleaner Production* 176: 976–989.

Li J, Yao Y, Zuo J, et al. (2020) Key policies to the development of construction and demolition waste recycling industry in China. *Waste Management* 108: 137–143.

Li Y and Zhang X (2013) Web-based construction waste estimation system for building construction projects. *Automation in Construction* 35: 142–156.

Li Y, Zhang X, Ding G, et al. (2016) Developing a quantitative construction waste estimation model for building construction projects. *Resources, Conservation and Recycling* 106: 9–20.

Lieder M and Rashid A (2016) Towards circular economy implementation: a comprehensive review in context of manufacturing industry. *Journal of Cleaner Production* 115: 36–51.

Liew KM, Sojobi AO and Zhang LW (2017) Green concrete: Prospects and challenges. *Construction and Building Materials* 156: 1063–1095.

Llatas C (2011) A model for quantifying construction waste in projects according to the European waste list. *Waste Management* 31: 1261–1276.

Low JK, Wallis SL, Hernandez G, et al. (2020) Encouraging circular waste economies for the New Zealand construction industry: Opportunities and barriers. *Frontiers in Sustainable Cities* 2: 1–7.

Mahpour A (2018) Prioritizing barriers to adopt circular economy in construction and demolition management. *Resources, Conservation & Recycling*, 134: 216–227.

Marston N and Jones M (2007) BRANZ: Weathering of polymeric materials in New Zealand. Available at: https://d39d3mj7qio96p.cloudfront.net/media/documents/SR182_Weathering_of_polymeric_materials_in_New_Zealand.pdf (accessed 20 August 2021).

Ministry of Land, Infrastructure, Transport and Tourism (MLIT) (2019) White paper on land, infrastructure, transport and tourism in Japan, 2019. Available at: https://www.mlit.go.jp/common/001325161.pdf (accessed 20 August 2021).

New Zealand Ministry of Business, Innovation and Employment (MBIE) (2019) National Construction Pipeline Report 2019: A forecast of building and construction activity, 7th ed. Available at: https://www.mbie.govt.nz/assets/national-construction-pipeline-report-2019.pdf (accessed 15 August 2021).

New Zealand Ministry for the Environment (NZ MfE) (2007) Targets in the New Zealand waste strategy: 2006 review of progress. Available at: https://environment.govt.nz/publications/targets-in-the-new-zealand-waste-strategy-2006-review-of-progress/ (accessed 22 August 2021).

Pickin J, Randell P, Trinh J, et al. (2018) National Waste Report 2018. Available at: https://www.environment.gov.au/system/files/resources/7381c1de-31d0-429b-912c-91a6dbc83af7/files/national-waste-report-2018.pdf (accessed 2 August 2021).

Plastics Europe (2021) Building & construction. Available at: https://plasticseurope.org/plastics-explained/plastics-in-use/building-and-construction/ (accessed 12 December 2021).

Poon CS, Yu AT and Ng LH (2001) On-site sorting of construction and demolition waste in Hong Kong. *Resources, Conservation and Recycling* 32: 157–172.

Rohani M, Huang T, Hoffman L, et al. (2019). Costs benefit analysis of construction and demolition waste diversion from landfill: A case study based on HLC Ltd development in Auckland. Available at: https://knowledgeauckland.org.nz/media/1071/tr2019-009-cba-on-waste-diversion-from-landfill-homes-land-community-auckland.pdf (accessed 12 August 2021).

Rudel RA and Perovich LJ (2009) Endocrine disrupting chemicals in indoor and outdoor air. *Atmospheric Environment* 43: 170–181.

Ruiz LAL, Ramon XR and Domingo SG (2020) The circular economy in the construction and demolition waste sector – A review and an integrative model approach. *Journal of Cleaner Production* 248: 119238.

Saez PV and Osmani M (2019) A diagnosis of construction and demolition waste generation and recovery practice in the European Union. *Journal of Cleaner Production* 241: 118400.

Salcido JC, Raheem AA and Ravi S (2016) Comparison of embodied energy and environmental impact of alternative materials used in reticulated dome construction. *Building and Environment* 96: 22–34.

United States Environmental Protection Agency (USEPA) (2019) Advancing Sustainable Materials Management: 2017 Fact Sheet – Assessing Trends in Material Generation, Recycling, Composting, Combustion with Energy Recovery and Landfilling in the United States. Available at: https://www.epa.gov/sites/production/files/2019-11/documents/2017_facts_and_figures_fact_sheet_final.pdf (accessed 20 August 2021).

World Economic Forum (WEF) (2016) Shaping the future of construction – A breakthrough in mindset and technology. Available at: http://www3.weforum.org/docs/WEF_Shaping_the_Future_of_Construction_full_report__.pdf (accessed 12 December 2021).

Zheng L, Wu H, Zhang H, et al. (2017) Characterizing the generation and flows of construction and demolition waste in China. *Construction and Building Materials* 136: 405–413.