

Article

Quantifying Recycled Construction and Demolition Waste for Use in 3D-Printed Concrete

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Abstract: Despite extensive regulations, the systemic under-reporting of construction and demolition waste generation rates pervades the South African waste sector due to the extensive and active informal waste management practices that are typical of developing countries. This study merges the rapid development of high-technology 3D-printed concrete (3DPC) with the increasing pressure that the built environment is placing on both natural resource consumption and landfill space due to construction and demolition waste (CDW) by establishing an inventory of CDW that is suitable for use in 3DPC in South Africa. This is an essential step in ensuring the technical, economic, and logistical viability of using CDW as aggregate or supplementary cementitious materials in 3DPC. Of the methods considered, the lifetime material analysis and per capita multiplier methods are the most appropriate for the context and available seed data; this results in CDW estimates of 24.3 Mt and 12.2 Mt per annum in South Africa, respectively. This range is due to the different points of estimation for the two methods considered, and the per capita multiplier method provides an inevitable underestimation. In order to contextualise the estimated availability of CDW material for use in concrete in general, the demand for coarse and fine aggregate and supplementary cementitious material in South Africa is quantified as 77.9 Mt. This overall annual demand far exceeds the estimated CDW material (12.2–24.3 Mt) available as an alternative material source for concrete.

Keywords: construction and demolition waste; 3D printed concrete; lifetime material analysis; per capita multiplier method; recycled aggregate; supplementary cementitious material



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1. Introduction

This study merges the rapid development of high-technology 3D-printed concrete (3DPC) with the increasing pressure that the built environment is placing on both natural resource consumption and landfill space due to construction and demolition waste (CDW) by establishing an inventory of CDW that is suitable for use in 3DPC in the context of a developing country, South Africa. The environmental benefits of 3DPC have been demonstrated [1], and this additional circular use of solid waste materials as alternative aggregates and supplementary cementitious materials in 3DPC further improves these benefits by reducing the use of natural resources as well as the volume of solid waste diverted to landfills.

Establishing realistic CDW data is an essential step in ensuring the technical, economic, and logistical viability of using CDW in 3DPC. However, despite extensive regulations, a dualism exists in the South African waste sector, owing to substantial and active informal waste management practices, which are typical of developing countries. This creates an environment rife with the systemic under-reporting of CDW generation rates, necessitating the estimation of CDW amounts through alternative methods.

In this study, the focus is on CDW materials used as alternative materials in 3DPC. 3DPC consists of a paste fraction containing cementitious binder and water and an aggregate fraction containing fine and even coarse aggregates [2,3]. 3DPC is based on the

principle of additive manufacturing, with the layer-by-layer addition of material eliminating the need for formwork but complicating the demands on the rheology of the concrete in its fresh state, specifically its strength and stiffness, to ensure shape retention and buildability. These aspects are largely influenced by the cementitious materials and aggregates selected, and not all CDW material types are suitable for application in 3DPC.

No generally accepted mix design methods yet exist for 3DPC [4], and the limits in the selection and combination of the ingredient materials and compositions of the mix for 3D printability outlined here reflect the state-of-the-art methods and the recent developments by the authors. These limits are governed by the fresh state properties of pumpability, extrudability, shape retention, and buildability, as well as hardened mechanical strength and stiffness and durability. The fresh state properties are typically assessed by conducting rheology tests in conjunction with thixotropy [5] and buildability models [6]. The discussion of 3DPC composition in the following subsections is limited to what is relevant to the incorporation of CDW, namely the aggregate fraction and supplementary cementitious materials for the paste fraction.

1.1. CDW as Aggregate in 3DPC

In conventional concrete, aggregate comprises up to 80% of the total concrete volume. In self-compacting concretes, the sufficient smearing of aggregate particles by the paste is required for self-levelling and self-compacting, whereby the total volume of aggregate in self-compacting concrete is typically 60–70%. In 3DPC, the fresh state requirements limit aggregate content to 40–50%, recently approaching 60% [4]. Particular care should be taken with the appropriate grading of the ingredient materials to enable appropriate smearing and packing for printability. Note that the maximum particle size is limited by the pumps typically used in research laboratories, including the Stellenbosch University (SU) 3DPC facilities.

A number of notable studies have been conducted on the inclusion of CDW aggregates in 3DPC, mostly in the form of recycled sand and recycled coarse aggregate, as well as specifically recycled brick aggregate and recycled glass aggregate, both to a lesser extent. However, the effect of the aggregate fraction in 3DPC still requires extensive research, specifically the volume and particle size used, as well as aggregate origin [7].

Despite the production of recycled sand requiring significant additional processing in CDW, the use of recycled sand (see Figure 1a) as a replacement for natural fine aggregate in 3DPC is receiving significant attention [8–16]. These studies include recycled sand with a maximum particle size between 0.9 mm and 2.36 mm and natural fine aggregate replacement levels up to 100%. Generally, the inclusion of recycled sand reduces flowability and extrudability, with the reduction increasing with increased recycled sand replacement level. This reduction is mainly due to the high water absorption rate of recycled sand, but this can be addressed by increasing the superplasticiser content. Typically, the static yield stress and viscosity increase significantly, whilst decreased compressive strengths were observed, ranging from negligible (1.4% compressive strength reduction) up to a 60% reduction for a 100% replacement level [12]. Similar reduction trends were observed for flexural strength.

The inclusion of glass waste (see Figure 1b) as a fine aggregate replacement has been studied [17–21]. With a particle size below 2 mm and natural sand replacement levels up to 100%, these studies typically resulted in decreased yield stress, increased viscosity, and reduced compressive and interlayer bond strength. Reduced but still suitable pumpability was also observed.

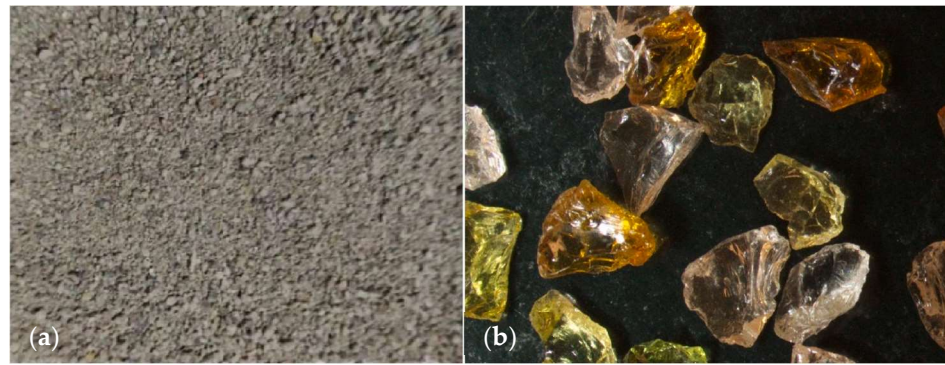


Figure 1. Recycled fine aggregates studied in 3DPC; (a) recycled sand [10] and (b) recycled glass waste [19].

The inclusion of coarse aggregate in 3DPC is limited by the printing nozzle size, pumping capacity, and the material's fresh property requirements. The recycled coarse aggregate component typically included in 3DPC studies consists predominantly of recycled concrete (see Figure 2a), with particle sizes ranging between 4.75 mm and 12 mm [22–27]. As is the case for the recycled sand replacement of natural fine aggregate, the recycled coarse aggregate replacement of natural coarse aggregate also decreases the flowability of the 3DPC in its fresh state due to the high water absorption and rough surface texture of the recycled coarse aggregate, which can be addressed with an increase in the superplasticiser dosage. Similarly, reduced compressive and flexural strengths are observed, and the nature of the aggregate leads to an increased porosity and surface roughness.

Christen et al. [28] studied the inclusion of specifically recycled brick aggregate in 3DPC (see Figure 2b), with a particle size range of 0.3 m to 4.75 mm and a natural aggregate replacement level of 64%. Acceptable printability was achieved, but a reduction in compressive strength of 14–20% and an interlayer tensile strength reduction of 20% was observed.



Figure 2. Recycled coarse aggregates studied in 3DPC; (a) recycled concrete [29] and (b) recycled brick [28].

1.2. CDW as a Supplementary Cementitious Material in 3DPC

In a recent review [14] of six mixes from leading institutions by Zhang et al., the paste component of the 3DPC mixes ranges between 42% and 65% of the total concrete volume, necessitated by the fresh state requirements of 3DPC. A reduced paste fraction is desirable to reduce cost and emissions and increase the stiffness and dimensional stability

of the 3DPC structure in its fresh and hardened state, and this must be pursued. A further implication of a high paste content is that a lower composite elastic modulus and fracture energy of the hardened composite are likely. The elastic modulus of paste is typically significantly lower than natural aggregate or even the aggregate derived from CDW [30]. For the binder within the paste fraction, a clinker content replacement of up to 45% is typical [14] but 100% is possible in 3DP geopolymer concrete (GPC) using other industrial waste stream products such as metakaolin and ground granulated blast furnace slag.

Significant research is ongoing into the inclusion of conventional supplementary cementitious materials (fly ash, metakaolin, calcined clay, limestone powder, silica fume, and ground granulated blast furnace slag) in 3DPC (for example [31,32]), but the use of CDW-origin supplementary cementitious materials in 3DPC has received little attention to date [7]. Recycled CDW powder, typically classified as <0.10 mm post grinding, was included in 3DP mortar at cement replacement levels of 10% by Qian et al. [33], up to 20% by Zhang et al. [34], and up to 30% by Hou et al. [35]. These studies noted positive or acceptable effects on the buildability and early-age mechanical properties and reduced drying shrinkage of the 3DP mortar.

The replacement of the high cement content in 3DPC with waste materials is of environmental and economic importance [36], as well as the continued development of alternative aggregates to increase the volume fraction in 3DPC. For both potential supplementary cementitious materials and alternative aggregates, comprehensive characterisation is required. For supplementary cementitious materials, this includes X-ray fluorescence (XRF), X-ray diffraction analysis (XRD), scanning electron microscopy (SEM), particle size distribution (PSD), and specific surface area (SSA). Aggregate characterisation includes PSD, porosity, water absorption, etc.

The important properties required of CDW for it to be used in 3DPC and the application of CDW in 3DPC to date have been established. This paper further lays out the current regulation, management, and generation trends of CDW in South Africa. The limitations of the accessible CDW data are evaluated and used to select and implement the two most suitable CDW estimation methods to determine the feasibility of using CDW in 3DPC in South Africa.

Definitions of CDW vary by locality, region, and country, but for the purpose of this study, CDW is defined as the solid material generated during the pre-use, use, or end-of-life phase of constructing buildings, roads, or other infrastructure. The typical waste materials generated during these activities include concrete, mortar, masonry, bricks, blocks, ceramics, metals, timber, roofing, glass, gypsum, insulation, carpeting, plastic, cardboard, and asphalt [37]. The definition of CDW used for this study expressly excludes any hazardous waste or municipal waste that is generated during any construction or demolition activities or any excavation material.

2. CDW Regulation and Management

The management of CDW varies significantly around the globe, largely depending on the maturity and efficiency of the regulatory framework. The world's three largest economies, China, the United States (US), and the European Union (EU), are also the world's three largest generators of CDW [38], but their CDW recovery rates are below 10%, 76%, and 90%, respectively [39]. The high recovery rate of the EU is largely attributed to its Waste Framework Directive 2008/98/EC, the first iteration of which was introduced in 1975. In contrast, China's regulatory framework is less mature (the first legislation to identify CDW management methods was introduced in 2005), and it is less well enforced [40]. In quantifying the CDW generated in South Africa, it is, therefore, necessary to have insight into its waste regulatory framework and waste management practices.

2.1. South African Waste Regulatory Framework

Extensive regulation underpins the South African waste management sector, which still predominantly utilises "command and control" instruments in its policies [41]. The pro-

gression of the South African waste management sector can be defined in four stages [42] and was strongly influenced by the European waste management regulatory framework. The Environment Conservation Act (ECA) No 73 1989 provides the foundational requirements for environmental management in South Africa, including the first legal definition of waste [42], and it marks the beginning of “The Age of Landfilling”. The National Environmental Management Policy (NEMP) White Paper of 1997 and the National Environmental Management Act (NEMA) No 107 of 1998 establish principles for decision-making with respect to the environment.

The Integrated Pollution and Waste Management (IP&WM) Policy 2000 sets out the vision, principles, and objectives and serves as a departure point for the National Waste Management Strategy (NWMS), which translates the IP&WM Policy objectives into practice. The implementation of the NWMS in 2001 triggered “The Emergence of Recycling”, followed by “The Flood of Regulation”, set off by the promulgation of the National Environmental Management: Waste Act (NEM:WA) (No 59 of 2008). NEM:WA created a mechanism through which every facet of waste and the value chain of secondary sources could be regulated in South Africa, and resulted in an avalanche of regulations aimed at “controlling” the waste management sector, including the implementation of the National Environmental Management: Waste Amendment Act (No 26 of 2014). In 2012, “The Drive for Extended Producer Responsibility” began with the shift from voluntary to mandatory extended producer responsibility (EPR), with an EPR tax payable directly to the government by producers. Plausibly, the fifth stage is emergent and defined as “The Future is a Circular Economy”.

The NEM:WA defines construction waste, classified under general waste (General Waste Category 30), as “waste, excluding hazardous waste, produced during the construction, alteration, repair or demolition of any structure, and includes rubble, earth, rock and wood displaced during that construction alteration, repair or demolition” [43].

This body of policy, regulation, and legislation ensures that each aspect of the waste management hierarchy in South Africa is addressed and embedded in a progressive manner [41]. Over time, environmental protection and waste generation reduction requirements, waste handling and treatment procedures, incentives for waste diversion from landfills, and the principle of “polluter pays” have been introduced. Apart from the national regulatory framework outlined above, an additional 41 National Acts have some relevance to waste management, as well as provincial and municipal legislation [42]. Contrary to the intention of this regulatory framework, the extensive legislation stifles development, growth, and competitiveness in the licensed recovery, reuse, and recycling economy. It also suppresses the transition to a formal circular economy.

2.2. South African CDW Management Practice

Despite the intentions of the regulatory framework, a dualism exists in the South African waste sector, where a local recovery, reuse, and recycling sector thrives, owing to extensive and active informal waste management practices (Godfrey and Oelofse, 2017). A basic tenet of effectively reusing and recycling materials is keeping the materials separate. However, this is beyond the capacity of many South African municipalities, which often fall short of even providing basic services [41]. This lack of separation at source generates value within the landfilled waste, leading to significant informal waste-picking activity across South Africa. The informal sector is, therefore, central to accessing the resources in the reuse and recycling economy that the private sector cannot readily gain access to [42].

Based on the Waste Management Licenses issued, there are 1,432 licensed facilities in South Africa, the majority of which are licensed for waste disposal (54%), followed by waste storage (16%), treatment (10%), and recycling and recovery (9%) [44]. Based on external annual audit reports, privately owned waste management facilities earned a relatively high compliance rate, with some achieving full compliance, while over 68% of publicly owned facilities achieved less than 50% compliance.

A lack of incentive exists to divert CDW from landfills in that many landfills charge a reduced rate, or none at all, for the disposal of CDW since, in the management of landfills, CDW is often used as cover material [45]. For example, in the City of Cape Town metropolitan area, gate fees at municipal landfill sites were ZAR 557/tonne (USD 38/tonne) for general waste in 2021, whereas builders' rubble only incurred a charge of ZAR 23/tonne (USD 1.50/tonne), or 4% of the general waste rate. Despite this low to non-existent financial barrier to the legal landfill disposal of CDW, illegal dumping is a pervasive practice in South Africa [37,42,46]. Law enforcement shortage and confusion on who bears the ultimate legal responsibility due to "The Flood of Regulation" are some of the reasons cited.

The South African government has identified EPR as a suitable vehicle to finance development and job creation in reuse and recycling for sectors where the producer is clear, such as electronic waste, lighting, paper and packaging, and tyres [42]. Indeed, waste materials, such as plastic, paper, cardboard, glass, metal, and wood, are readily reabsorbed into their corresponding industries in the main metropolitan regions of South Africa, namely Johannesburg (Gauteng), Durban (KwaZulu Natal), and Cape Town (Western Cape). However, the EPR mechanism does not serve non-packaging waste streams well, where the "producer" is less clear. Bulk waste streams, such as organic waste, mining residue, and CDW, require the identification and development of context-specific beneficiation mechanisms (such as recycled aggregates and supplementary cementitious materials in 3DPC). Asphalt recycling has achieved this to some extent in South Africa [37].

In this context, transitioning to a circular economy in a developing country will likely require adapted or different technologies and systems to those that have emerged as suitable for developed countries. Similarly, it must be acknowledged that the impact of such a transition on the generally marginalised and vulnerable who make up the informal waste sector work force will not necessarily be net positive [41].

2.3. South African CDW Data

The then National Department of Environmental Affairs (DEA) published three National Waste Information Baseline Reports in 1991, 1997, and 2012, the latest of which estimated that of the 108 million tonnes of total waste generated in South Africa in 2011, 90% was landfilled [43]. In an effort to improve reporting accuracy, the South African Waste Information System (SAWIS) was initiated in 2004 by the now Department of Environment, Forestry, and Fisheries (DEFF). SAWIS is mandated to serve as a central and single national data-capturing repository for all generation, recycling, treatment, disposal, and export of waste.

The most recent SAWIS "State of Waste Report" analyses the data captured in 2017 and reports 4,482,992 tonnes of CDW generated in South Africa, of which 58% was recycled or recovered and 42% was landfilled [44]. However, this report also acknowledges that the data are inaccurate and incomplete due to general under-reporting. Despite quarterly reporting by waste management facilities being a regulatory requirement, only 45% of the waste management facilities registered with SAWIS submitted their data in 2017. Lack of weighbridges and general capacity at municipal landfill sites are cited as common reporting obstacles.

Another significant issue in the quantification and management of CDW in South Africa is the definition of CDW. Many municipalities only regard "builders' rubble", consisting of masonry, bricks, blocks, concrete and ceramics, as CDW, thereby disregarding the other components of CDW [37]. No detailed or uniform classification of CDW exists either. Under the ECA, building rubble is excluded from the definition of waste if it is used for backfilling or site levelling.

3. CDW Estimation

In order to establish an inventory of CDW in South Africa that is suitable for use in 3DPC, the limitations of existing CDW data were analysed. CDW data collection and

estimation methods were evaluated, and suitable ones were selected and implemented based on the limitations identified.

3.1. Existing CDW Data

3.1.1. CDW Composition

Internationally and in OECD countries, CDW constitutes approximately 35% of total municipal solid waste (MSW) [47,48]. In South Africa, municipal waste characterisation studies have been limited. Nationally, the CDW component of MSW is reported as significantly lower than international levels, at 24% [43], and provincial figures reflect a similar proportion in the two (of nine) South African provinces where such data can be sourced, namely Gauteng (22%) and Western Cape (20%).

The composition of CDW varies between countries and even regions, depending on construction traditions, regulatory requirements, waste management practices, and material classification. However, a clear trend, as illustrated in Figure 3, is the dominance of concrete and masonry (approximately 70%) in CDW, with asphalt a distant second (approximately 13%).

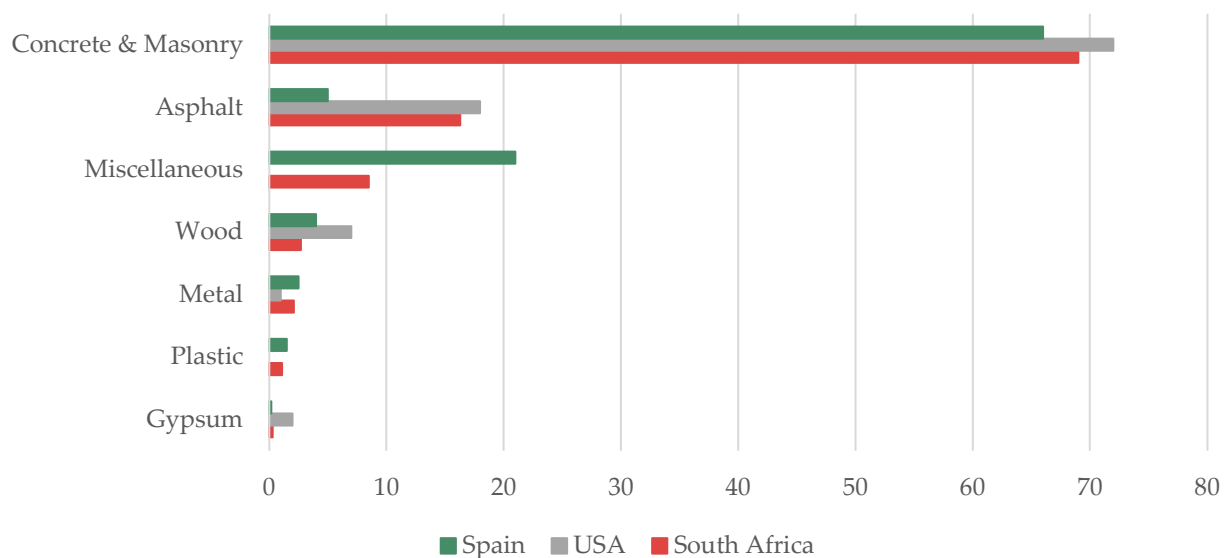


Figure 3. Composition of CDW as a percentage of total CDW generated per country in Spain [47], USA [49], and South Africa [44].

3.1.2. CDW Generation

Figure 4 indicates both the reported (REP) and estimated (EST) quantities of CDW generated in South Africa over the past two decades. Macozama [37] reports a 1.4 Mt generation (2002 REP) of CDW in South Africa in 2002, all of which ended up in landfill, but Macozama [37] also estimates the actual CDW quantities to be between 5 to 8 Mt (2002 EST), with 1 Mt of that ending up in landfill. The DEA reported a CDW generation of 4.7 Mt in 2011 [43], with the majority of that (84%) going to landfill (2011 REP). For 2017, SAWIS reported a CDW generation of 4.5 Mt [44], with 42% of that being landfilled (2017 REP); this lies in contrast to an estimated generation of between 10.8 and 20.2 Mt (2017 EST) by Berge and Von Blottnitz [50].

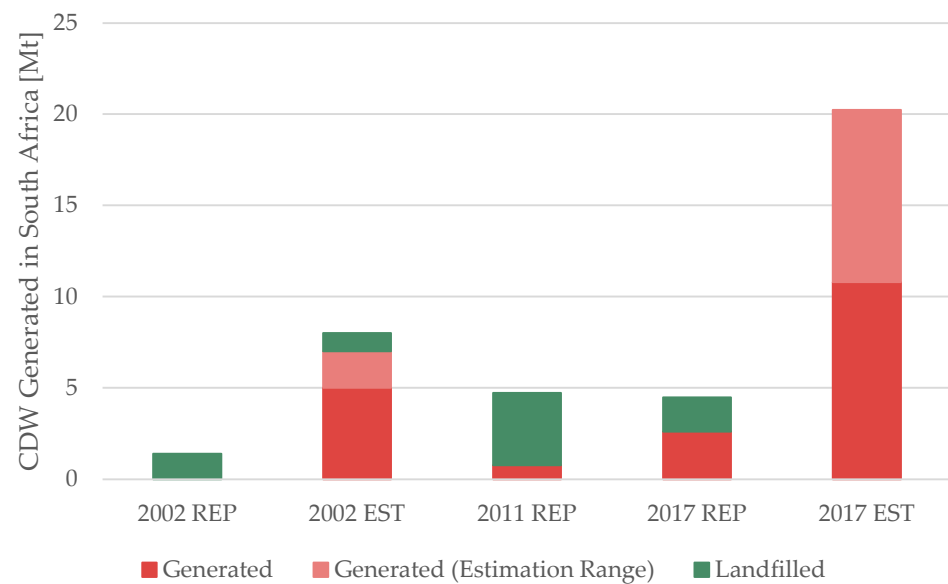


Figure 4. The reports (REPs) and estimates (ESTs) of CDW generated in South Africa and the proportions as landfill.

Overall, Figure 4 presents a contradictory and inconclusive picture; however, three important aspects are clear from this summary. Studies examining and estimating CDW in South Africa are sparse; of the CDW data that are available in South Africa, it is credible to presume significant under-reporting and notable discrepancies exist in the proportion of CDW that is reported as “Landfilled”. With exception to the 2017 EST data, in which Berge and Von Blottnitz [50] focussed solely on the generation (and not landfilling) of CDW, the proportion of CDW generated that is landfilled varies between 12.5% and 100% for the remaining four data points. The lack of clarity and the incompleteness of the data do not make it possible to differentiate between the non-landfilled CDW material that is recycled or reused and the CDW material that is illegally dumped. The informal sector is a highly probable intensive reuser of CDW, but illegal dumping is arguably as prevalent and pervasive in South Africa.

The extent of under-reporting is supported in the findings of Figure 5 in the context of municipal solid waste (MSW) reporting in South Africa, the data of which includes the CDW fraction. In the data reported by the DEA [43], the per capita MSW generation rates vary significantly per province, with the rate in Gauteng (1.13 t/pp/pa) being reported as more than 10 times that of the North West Province (0.10 t/pp/pa). While certain accommodations must be made for variations in urban/rural population distributions, income levels, etc., such a large discrepancy in per capita MSW generation is improbable. In Figure 5, the per capita MSW generation rate of each province is normalised to that of the Western Cape and is compared to the normalised per capita gross domestic product of each province and the number of waste facilities per capita. GDP is a simple but clear linear gauge of MSW generation [51], and the results indicate that MSW reporting rates for Gauteng, Western Cape, Mpumalanga, and Northern Cape may be more accurate than those of the remaining provinces. The relatively high numbers of waste facilities in KwaZulu-Natal, Eastern Cape, Limpopo, North West, and Free State also indicate that a case of MSW under-reporting is more probable than low MSW generation rates.

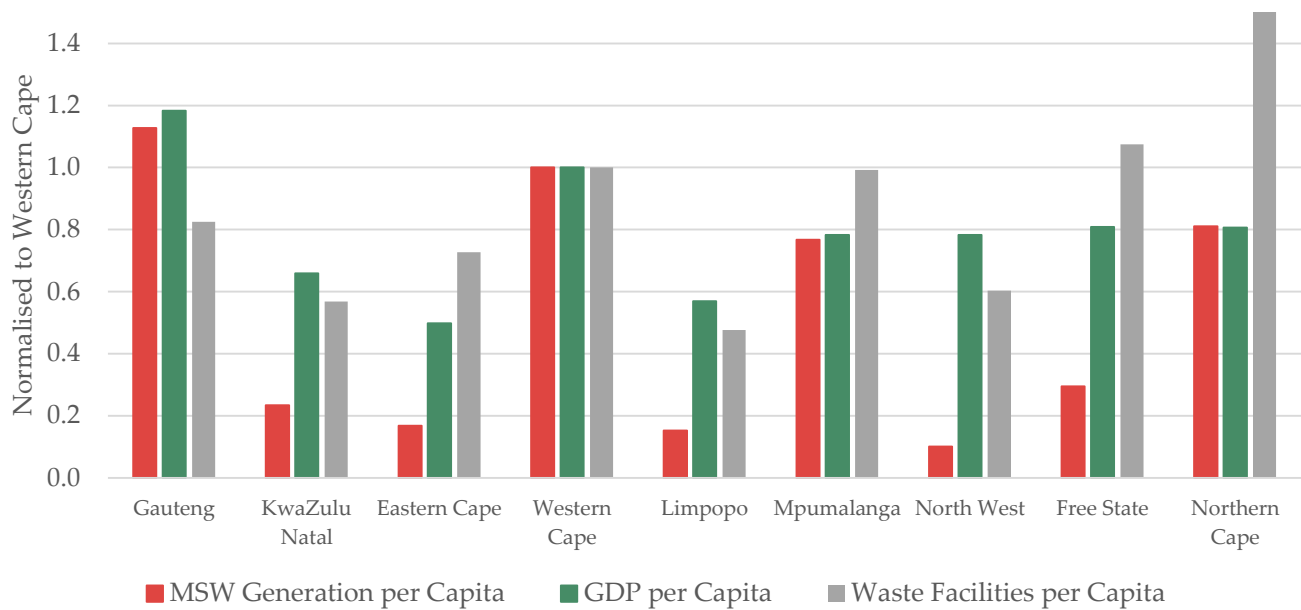


Figure 5. Provincial per capita municipal solid waste generation rates [43], gross domestic product [52], and no. of waste facilities [44] normalised to the Western Cape.

3.2. CDW Estimation Methods

Several established methods for CDW data collection exist: site visits (direct or indirect measurement), the generation rate calculation method (per capita multiplier, financial value extrapolation, area-based calculation), the lifetime analysis method, the classification system accumulation method, and variables modelling method; selecting the most appropriate one for a given context depends on a number of factors.

Wu et al. [29] conducted an extensive review of these data collection methods and developed a methodology selection relevance tree. Based on this approach, certain methods are easily excluded. Conducting site visits to the extent necessary for realistic and representative data is constrained by time, labour, and access. Building and construction/demolition information is not contained in a central repository in South Africa, nor is it readily accessible, which rules out the area-based and financial value extrapolation generation rate calculation methods, as well as the building lifetime analysis method. Given the accessible and reliable population data in South Africa, together with limited CDW data, the methods best suited to the context are the material lifetime analysis and per capita multiplier methods.

3.2.1. Material Lifetime Analysis Method

Lifetime analysis methods are most typically used for quantifying demolition waste, specifically, using the principle of material mass balance, assuming that waste will inevitably result from the demolition of built structures [29]. As a result, the mass of demolition waste generated is equivalent to the mass of the built structure. This mass of demolition waste can be projected through rational assumptions about the lifespans of the structure (building lifetime analysis) or the material (material lifetime analysis). The significant advantage of both these lifetime analysis methods is that they can be used in regions that lack demolition area data [29].

The material lifetime analysis method is based on the material flow analysis of current production amounts and the typical stock lives of essential construction materials [50]. The current consumption of construction materials, together with average material-specific construction waste factors, provide an estimation of present-day construction waste generation. Present-day demolition waste is estimated by factoring the current construction amount to the amount of construction that would have occurred a material's lifetime ago, less the original construction waste [53].

In this study, the material lifetime analysis is used to estimate the concrete and masonry CDW generated in South Africa, specifically for the year 2017, the most recent year for which sufficient supporting data are available. The method is conducted in four steps:

Step 1 is to estimate the amount of new construction material based on material production data: $C_{M,2017}$. Of the total cement production of 14.6 Mt [54], 50% is used in the residential building market [55], assumed to be predominantly masonry application, with the remaining 50% used in cast concrete. For the cast concrete, a typical mix ratio of cement:sand:coarse aggregate of 1:2:4 is assumed. For the concrete used in masonry, 25% is assumed to be used in blocks (with a cement:sand ratio of 1:8) and 75% in mortar and plaster (with a cement:sand ratio of 1:3). The total clay brick and tile manufacturing is taken as 7.4 Mt [56].

Step 2 is to estimate the amount of new construction material that immediately becomes construction waste using construction waste factors: $C_{W,2017}$. The construction waste factors for concrete and masonry are taken as 3% and 4%, respectively [57].

Step 3 is to estimate the amount of demolition waste generated in the present based on the amount of construction that took place a lifetime ago (t years), less the construction waste originally generated:

$$D_{W,2017} = C_{M,2017-t} - C_{W,2017-t} = (C_{M,2017} - C_{W,2017})/e^{rt}$$

The design life of common structures, and by extension, of their materials, is taken as 50 years (SANS 10160-1, 2011). The growth rate is taken as the average construction GDP growth rate for South Africa over the past 60 years, which is 2.86% [58].

Step 4 is to determine the total construction and demolition waste by summing the results of Steps 2 and 3.

This material lifetime analysis is largely based on the study by Berge and Von Blottnitz [50], with some notable differences. This analysis is limited to concrete and masonry CDW only; the construction waste generated a lifetime ago is subtracted from the amount of demolition waste generated in the present, as carried out by Cochran and Townsend [53]; and the material lifetime is taken as 50 years instead of 75 years, as per SANS 10160-1 [59].

3.2.2. Per Capita Multiplier Method

The generation rate calculation method is the most widely used method for estimating CDW amounts and entails obtaining reasonable data in a concentrated area and scaling them up using one of a number of mechanisms, such as the per capita multiplier, financial value extrapolation, and area-based calculation (Wu et al., 2014 [29]). The per capita multiplier method is the earliest and most frequently used method to forecast the impact of construction. According to McBean and Fortin [60], regional CDW generation data is gathered over time, and an average annual per-person CDW generation rate is established for that region. The total CDW generated over a wider application area is extrapolated based on the total population size. A criticism of this method is that, in periods of stable population growth, it fails to reflect any fluctuations in construction and demolition activity [29].

The per capita multiplier method is employed to provide a comparative estimate for the lifetime material method for the year 2017. This method is, again, based on the study by Berge and Von Blottnitz [50], with some alternate input parameters used and extrapolates a region-specific good-quality set of CDW generation data to a broader scope whilst accounting for possible differences in regional variations in population density and productivity. The choice of dataset, therefore, is critical to the accuracy of the method.

The municipal metropolitan area of the City of Cape Town, located in Western Cape, reports the CDW (builders' rubble) entering its landfill sites on a monthly basis on an open access online data portal [61]. As far as can be reasonably established, it is the only municipality of significant size in South Africa to do so. Radzilani [62] assessed the IWMPs for eight of South Africa's major metropolitan municipalities on the basis of waste management practices, monitoring, and reporting and found the City of Cape Town to have

the best quality IWMP of the eight metropolises analysed. The City of Cape Town’s monthly reported data was, therefore, chosen as the baseline for the per capita multiplier method. The degree to which this dataset is representative of the rest of the country is a critical aspect. As discussed, few waste analysis or characterisation studies have been conducted in South Africa; however, two independent waste characterisation studies conducted in the City of Cape Town and the province of Gauteng—South Africa’s most populous province—provide comparative data in this regard [43]. Figure 6 indicates that there is no statistically significant difference in the municipal waste composition between the two study areas, and it is, therefore, assumed that the monthly CDW dataset reported by the City of Cape Town is sufficiently representative of the remainder of the country.

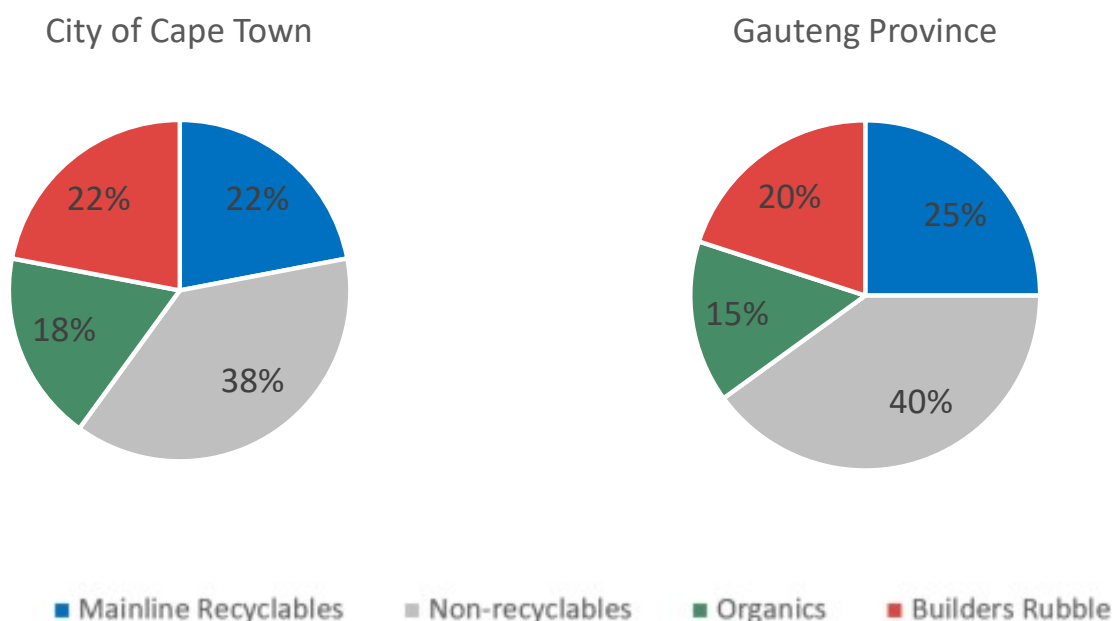


Figure 6. Municipal waste composition by mass for the City of Cape Town and Gauteng Province [43].

The population of the City of Cape Town is 100% urban. The per capita CDW generation rate determined for the City of Cape Town is, therefore, an urban generation rate, and since population density and urban/rural fractions vary significantly across the country, a rural generation rate must be determined. Berge and Von Blottnitz [50] assumed the rural CDW generation intensity to be 20% of the urban generation rate, but a substantiation for this choice could not be established. The provincial per capita GDP [44,63], together with the rural population fraction of each of the nine South African provinces [52], were used to determine an indicator of the productivity of the rural proportion; see Figure 7. An entirely rural population generates a GDP of 40% of that of an entirely urban population. This rural productivity indicator is taken as a gauge of the rural CDW generation intensity, i.e., 40% of the urban per capita CDW generation rate.

In this analysis, the population distribution and urban/rural proportion data are considered to be reasonably accurate. Apart from the initial City of Cape Town CDW generation data, the only other parameter is the rural CDW generation intensity, which was taken as 40%. If this intensity is assumed to be 20%, as assumed by Berge and Von Blottnitz [50], a concrete and masonry CDW estimate of 11.1 Mt results, or a 9% decrease in estimation.

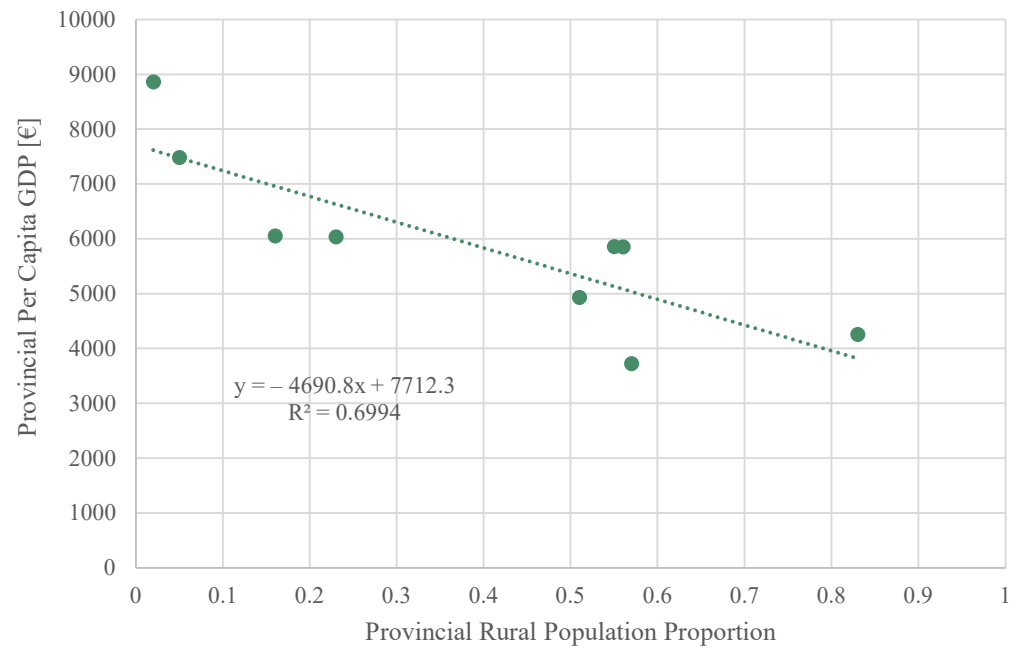


Figure 7. Provincial rural proportion productivity.

4. CDW Data Results

Two methods were employed to estimate the CDW generated in South Africa, namely the material lifetime analysis and the per capita multiplier. It is important to note that the CDW estimation levels reported in this section are limited to materials originating as concrete and masonry. This was considered for three reasons. Concrete and masonry CDW is most suitable for inclusion in 3DPC in large volumes as both the aggregate and supplementary cementitious material; it constitutes the bulk of CDW materials, as illustrated in Figure 3; and the limited CDW data reported in South Africa is typically reported as “builders’ rubble”, which is understood to consist predominantly of concrete and masonry.

4.1. Material Lifetime Analysis Results

The material lifetime analysis is summarised in Table 1 and results in a concrete and masonry CDW estimate of 24.3 Mt.

Table 1. Estimated CDW [Mt] for concrete and masonry based on material lifetime analysis for 2017.

	Identifier	Concrete	Masonry	Total
New Construction Material [Mt]	$C_{M,2017}$	51.2	40.3	91.5
Construction Waste Factor [%]	-	3.0	4.0	-
Material Service Life [Years]	-	50	50	-
Construction Waste Estimate [Mt]	$C_{W,2017}$	1.5	1.6	3.1
Demolition Waste Estimate [Mt]	$D_{W,2017}$	11.9	9.3	21.1
Construction and Demolition Waste Estimate [Mt]	$(C_W + D_W)_{2017}$	13.4	10.9	24.3

In the analysis, a number of assumptions or approximations are required due to the lack of more specific data, but most of these factors have a relatively small influence on the outcome. However, the assumed material lifetime is decisive since it is applied to an exponential function. Varying the material lifetime between 25 and 100 years results in a concrete and masonry CDW estimate variation between 46.3 Mt for a 25-year material lifetime and 8.2 Mt for a 100-year material lifetime, highlighting the importance of durable structures and building reuse and refurbishment.

4.2. Per Capita Multiplier Analysis Results

The per capita multiplier analysis is summarised in Table 2 and results in a concrete and masonry CDW estimate of 12.2 Mt.

Table 2. Estimated CDW [Mt] for concrete and masonry based on the per capita multiplier method for 2017.

		Reference
CoCT CDW [Mt]	1.138	CoCT Open Data Portal [61]
CoCT Population [$\times 10^6$]	4.010	StatsSA, 2016 [52]
CoCT per Capita CDW Generation Rate [t/pp/pa]	0.284	-
SA Urban Population [$\times 10^6$]	35.151	StatsSA, 2016 [52]
SA Rural Population [$\times 10^6$]	20.245	StatsSA, 2016 [52]
SA Urban:Rural Population Fraction	0.63:0.37	-
Rural CDW Generation Intensity	0.40	Figure 7
SA Urban per Capita CDW Generation Rate [t/pp/pa]	0.284	-
SA Rural per Capita CDW Generation Rate [t/pp/pa]	0.112	-
SA Urban CDW Generation [Mt]	9.97	-
SA Rural CDW Generation [Mt]	2.25	-
SA Total CDW Generation [Mt]	12.2	-

The per capita multiplier analysis results of 12.2 Mt represent an aggregation on a national level; however, the results are presented on a provincial level in Figure 8. Inherent to the analysis method used and the natural concentration of construction activity in areas of dense population, the availability of CDW is highest in the most populous metropolitan areas of Gauteng (3.7 Mt), KwaZulu Natal (2.2 Mt), and Western Cape (1.7 Mt). This distribution of CDW is an intrinsic strength of the circular economy of construction materials.

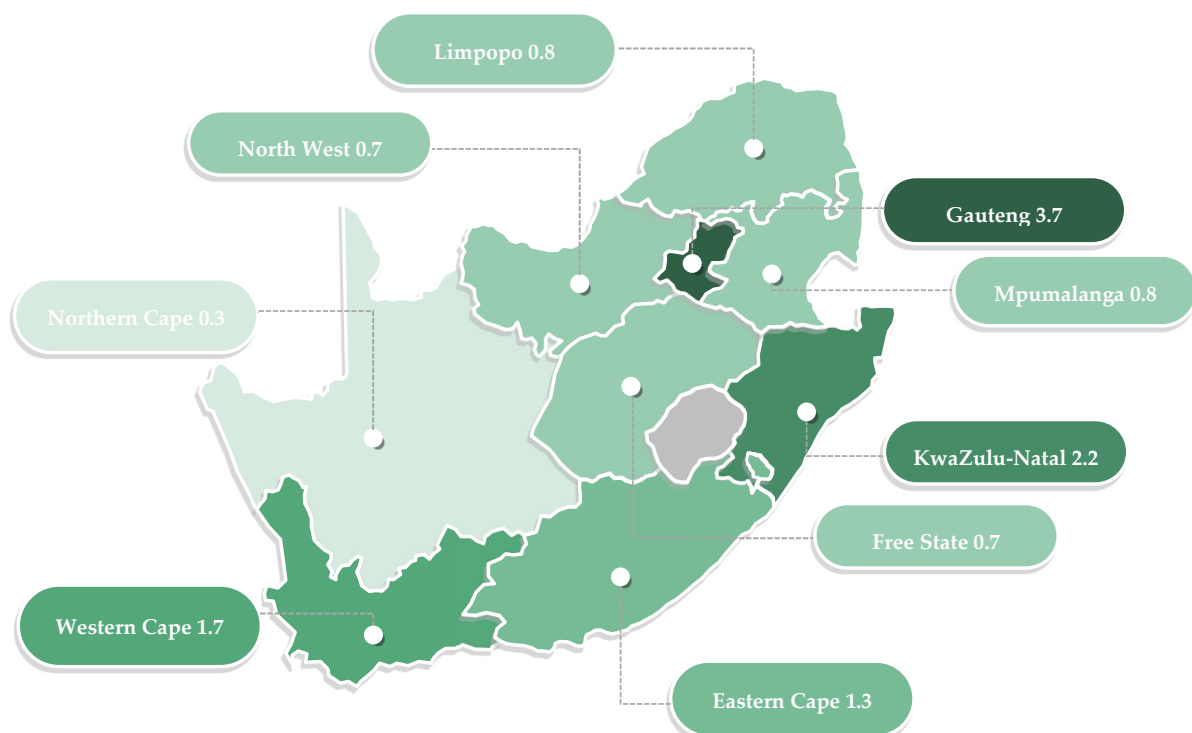


Figure 8. Provincial concrete and masonry CDW generation [Mt] based on the per capita multiplier method for 2017.

4.3. Discussion

For the two methods used to estimate the concrete and masonry CDW generated in South Africa in a typical year, the lifetime material analysis method and per capita multiplier method yielded 24.3 Mt and 12.2 Mt, respectively, a difference of a factor of almost two. There are a number of reasons for this range. The point of estimation for the lifetime material analysis method is in the pre-use phase of material manufacturing. The CDW estimate resulting from this method, therefore, includes all the material in all the possible downstream activities of formal and informal reuse and recycling, as well as illegal dumping and is an inevitable overestimation. This method is also sensitive to so-called ghost stock, which are buildings that have exceeded the design life or anticipated material lifetime but have not been demolished. The point of estimation for the per capita multiplier method is in the end-of-life phase as the CDW enters the landfill gates. The CDW estimate resulting from this method, therefore, excludes all informal and some formal reuse and recycling, as well as all illegal dumping. This method is an inevitable underestimation.

Notably, if a material lifetime of 75 years is assumed, as assumed by Berge and Von Blottnitz [50], as opposed to the 50 years originally assumed in this study, the concrete and masonry CDW estimate result for the lifetime material analysis method is 13.4 Mt, a close comparison to the 12.2 Mt of the per capita multiplier method. This highlights the significant influence of the material lifetime factor, as discussed in Section 4.1.

In order to contextualise the estimated availability of CDW material for use in concrete, the annual demand in South Africa for concrete input materials is quantified as 29.2 Mt of coarse aggregate, 45.7 Mt fine aggregate, and 2.9 Mt supplementary cementitious material, resulting in a total demand of 77.9 Mt. These quantities are determined using the assumptions and parameters detailed in Section 3.2.1, as well as an assumed 20% replacement level of supplementary cementitious material in the form of powdered CDW.

Globally, the 3DPC market share of total construction was 0.01% in 2022 and is projected to be 0.05% by 2030 [64,65]. The same projections do not necessarily hold true for South Africa, and given that 3DPC is only at technology readiness level (TRL) 6–7 [66], projections of material usage in 3DPC are difficult to quantify. However, the overall annual demand for coarse and fine aggregates and supplementary cementitious material (77.9 Mt) in South Africa far exceeds the estimated CDW material (12.2–24.3 Mt) available as an alternative constituent material source for concrete.

5. Conclusions

The incorporation of CDW in the rapidly developing technology of 3DPC improves the circularity of materials in the construction industry, reduces the extraction of natural resources, and aids in addressing the United Nations Sustainable Development Goals of industry, innovation and infrastructure, sustainable cities and communities, and responsible consumption and production.

An essential step in establishing the feasibility of this material circularity is quantifying the availability of CDW in the absence of reliable and accurate data, which this study set out to achieve. Despite pervasive under-reporting of CDW data, owing to extensive and active informal waste management practices, a lack of capacity at the municipal level, and inconsistencies in CDW definitions, it has been demonstrated that estimating an inventory of CDW that is suitable for use in 3DPC in the context of a developing country, such as South Africa, is possible.

Of the CDW estimation methods considered, the lifetime material analysis and per capita multiplier methods are the most appropriate for the context and available seed data and result in CDW estimates of 24.3 Mt and 12.2 Mt per annum in South Africa, respectively. This range is due to the different points of estimation for the two methods considered. Sensitivity to the material lifetime chosen is also significant.

The focus of CDW material estimation has been limited to what is relevant to the incorporation of CDW in 3DPC, namely for the aggregate fraction and supplementary cementitious materials for the paste fraction. The only CDW materials that meet these ap-

plication criteria and that are generated in sufficiently significant amounts are concrete and masonry CDW. However, the total demand for aggregate and supplementary cementitious materials (77.9 Mt) far exceeds the estimated available CDW material as an alternative resource (12.2–24.3 Mt).

Several barriers to the widespread adoption of CDW in 3DPC exist and remain to be addressed through research. The recovery rate of CDW in a country or region is dependent on a number of factors, but a mature and efficient waste management regulatory framework is essential. While South Africa's waste management regulations and policies are extensive, the "Flood of Regulations" triggered in the early 2000s have stifled development and suppressed the transition to a formal circular economy.

The performance of 3DPC containing CDW is currently being investigated at various institutions, including Stellenbosch University, and factors that are typical when incorporating CDW in cast concrete, such as contamination and the variability of source material, are as important, if not more so, in 3DPC and require extensive research. Furthermore, a comprehensive lifecycle analysis of 3DPC containing CDW relative to 3DPC containing conventional materials is necessary to evaluate the energy, environmental, economic, and social benefits or detriments of CDW-3DPC.

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