SUSTAINABLE CONSTRUCTION: SINGAPORE'S JOURNEY TOWARDS ZERO LANDFILL

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ABSTRACT

With a land area of 723.2 km^2 housing a population of 5.3 million, Singapore is a resource-challenged city-state with limited land and natural resources. It is hence critical for us to focus on sustainable development. With this as the backdrop, the Sustainable Singapore Blueprint was launched in 2009 to address these challenges.

Sustainable Construction (SC) has a big part to play, given the amount of natural resources the sector consumes. As the regulatory authority, the Building & Construction Authority (BCA), plays a leading role, working with our stakeholders to champion policies and best practices. The paper outlines a number of key initiatives to drive SC adoption to meet our long term objective towards zero landfill for the building sector.

INTRODUCTION

As a resource-challenged city-state, Singapore understands the need to use resources efficiently. For this reason, the Inter-Ministerial Committee on Sustainable Development (IMCSD) launched the Sustainable Singapore Blueprint in 2009 with resource efficiency as one of its key objectives.

The building sector has a big part to play, given the amount of natural resources the sector consumes each year. As the regulatory authority for the building sector, Building & Construction Authority (BCA) has a leading role to play. Adopting a life-cycle approach, BCA has rolled out a number of SC initiatives, with a focus on Recycling / Use of recycled materials and Design.

The life-cycle approach looks at efficient use of building materials at the design stage of the development, secures a higher quality of materials salvaged at the demolition stage, promotes close-loop recycling of building materials and regulates waste flow to our landfill.

SCHEMES TO SUPPORT SC

Several schemes were put in place to support the adoption of SC initiatives. These include funding incentives such as the Sustainable Construction Capability Development Fund (SC Fund), the SC Score under BCA's Green Mark (GM) Scheme, up-cycling initiative and demolition protocol.

<u>The Sustainable Construction Capability Development Fund (SC Fund)</u>

The $15M SC Fund was set up in 2010 with the intention to build up capabilities and encourage industry stakeholders to adopt SC practices and technologies, with the eventual aim to steer the industry towards self-sustenance in the demand and supply of SC materials.

<u>BCA Green Mark (GM) Scheme</u>

BCA GM Scheme is a building rating tool launched in 2005 to drive Singapore's construction industry towards more environment-friendly buildings. It is a key supporting lever to promote the adoption of SC initiatives. Developers applying for higher-tiered awards (Gold^{Plus} and Platinum awards) are required to meet the pre-requisite points under SC section, either through using recycled materials or achieving efficient use of concrete through a well-thought-out design in their building projects, or both.

<u>Up-cycling Movement</u>

In order to conserve precious natural resources such as granite for structural building works, BCA started an up-cycling movement to channel the majority of concrete waste from lower-value applications such as road works to building works. It involves processing concrete waste into recycled concrete aggregates (RCA) to replace granite aggregates in structural concrete used for building works. At the same time, BCA is also exploring the potential use of alternative waste materials to replace concrete waste for lower-value and other civil engineering applications. In this way, it will form closed-loop recycling system where construction waste generated remains as resources for new developments.

<u>Demolition Protocol</u>

The Demolition Protocol is a set of procedures to help contractors plan their demolition process to maximise recovery of demolition waste for reuse and recycling, which helps to channel waste from the landfill. The procedures consist of three main components, namely (1) pre-demolition audit to identify potential materials to be recovered, (2)

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sequential demolition for recovery of better quality demolition waste, and lastly (3) on-site sorting where the contractors follow a waste management schedule that complies with requirement of relevant authority for sorting, processing, recovery and disposal of demolished materials.

The protocol is now being incorporated as part of a Singapore Standard, SS 557 developed by BCA in collaboration with SPRING in 2010.

PUBLIC-PRIVATE PARTNERSHIP

The ourney towards zero landfill requires concerted effort from both the public and private sector. With the SC policies and initiatives in place, BCA moved on to work with industry stakeholders to push the boundaries by adopting some of these initiatives in actual building projects such as recycling and up-cycle of concrete waste for structural building works. The success stories of these demonstration projects are an encouragement for the industry to take the initiative to adopt SC practices.

Samwoh Eco-Green Building

Samwoh Eco-Green Building is the first building in the region to use up to 100% RCA in structural concrete works. It has effectively demonstrated the feasibility of using high percentage of RCA in structural concrete and further boosts the confidence of the industry in using recycled materials for building works.

Tampines Concourse

The extensive use of recycled materials in Tampines Concourse has helped to achieve the goal towards constructing a green building. 10% washed copper slag (WCS) and 20% ground granulated blast furnace slag (GGBS) were used for primary structures including all the columns, walls and beams; while 30% WCS, 20% GGBS and 20% recycled aggregates were used for non-structural components such as apron drain and footpath used.

GAIA Residential Development

GAIA is a high-rise private residential development to adopt recycled materials in structural concrete elements, excluding the sub-structure. This project has reinforced the feasibility of using recycled materials in structural applications and further encouraged replication in other residential projects to adopt similar SC practices.

FROM RECYCLING TO FOCUS ON DESIGN

The industry has responded very positively to the recycling initiatives which focus on downstream efforts in the life-cycle approach. However, upstream efforts which emphasize on the design stage of the life-cycle approach is still rather lacking among the industry stakeholders and professionals. It is thus essential to educate the industry and raise awareness on the importance of adopting a green mindset for building developments – To design with 'Green' intent.

Concrete Usage Index (CUI)

Concrete is the most commonly used material for construction world-wide. As natural aggregates such as granite make up the bulk of a concrete mix, there is a need to look into the efficient usage of concrete.

To measure the use of concrete in building projects BCA worked with the industry and other stakeholders to formulate an index unique to only Singapore, known as the CUI. The index is defined by the volume of concrete needed to cast a square metre of constructed floor area or CFA (m^3/m^2), for superstructures including both structural and non-structural elements.

CUI allows consultants to compare the amount of concrete used for various design options. Consultants will be able to aim for greater resource efficiency through rounds of comparison and fine-tuning designs. Lesser natural materials are used for construction and in turn generate less demolition waste at the end of the building's service life.

To further recognise building owners for their green efforts, an additional bonus point will be awarded to the overall GM score for disclosing the CUI of their new development.

2 GM Platinum projects below will illustrate how sustainability is when buildings are designed with 'Green' intent.

ITE College West

The 9.54ha 'ITE College West' campus achieved a good CUI of 0.42. A combination of precast hollow-core slabs and pre-stressed flat slabs construction were adopted instead of a beam and slab structural system, resulting in a significant reduction of concrete usage.

Hundred Trees Condominium

The 396-unit private residential development 'Hundred Trees Condominium' achieves a good CUI of 0.42. This is made possible through the use of Cobiax system in the structural slabs of the development which contributed to a reduction of about $800m^3$ of concrete volume.

Cobiax system allows concrete reduction by introducing spherical hollow shells to replace concrete in the middle section of the slab that is structural redundant. The presence of the voids due to the hollow shells also leads to a reduction in the dead load component of the building.

RIDING ON BIM WAVE

BIM has established a foothold in the building sector and is identified as a key technology to improve productivity and also promote greater level of integration across various disciplines over the entire construction value chain. In November 2010, BCA formulated a BIM Roadmap and set a target to have 80% of the construction industry use BIM for planning and design by end 2015.

BIM add-on tools to automate CUI calculation

To encourage more stakeholders to consciously keep track of the concrete usage in building developments, BCA is working with potential software developers and the industry to develop add-on tools on BIM platforms to obtain CUI score automatically from the BIM models. This will replace manual CUI calculation which would otherwise take 1 week or more.

CONCLUSION

SC is playing a critical role in helping Singapore meet the challenge of being a small city-state with limited natural resources. As the regulatory authority for the building sector, BCA plays the leading role to drive the sector towards adopting SC practices with a focus on Recycling / Use of recycled materials and sustainability-focused design approach for buildings.

Our downstream recycling efforts have started to make an impact on the landfill by channelling construction waste away from it to higher-value applications such as structural concrete for building works. But more importantly, we will need to institutionalise the concept of 'design with 'Green' intent' targeting at upstream efforts so as to achieve greater resource efficiency.

With the SC policies and initiatives now in place, BCA is confident that the building sector will embark on this journey to achieve sustainability and help meet our long term objective of zero landfill in time to come.

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COMPILATION OF REGIONAL BUILDING STOCK INVENTORIES UNDER UNCERTAINTY

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ABSTRACT

Since the building sector induces large mass flows, progressive resource management approaches and models are used on regional level to manage materials' recycling. As data used in regional models do not necessarily reflect regional conditions, the regional building stock is represented inadequately leading to a considerable and often neglected uncertainty.
First, in order to identify and discuss uncertainties, we will transfer four types of uncertainty – aleatoric and epistemic uncertainty, heterogeneity and ignorance – to building stock inventory compilation. Second, to improve data on regional building stock inventories, we will propose an image-based process for the compilation of building inventories. In the proposed process, building data captured by a mobile device is transformed into an inventory classified by material groups and recycling/waste categories. Third, inherent types of uncertainty in an existing archetype process and in the proposed sample process will be analysed, opposed and discussed to reveal sources and reducible components of uncertainty.
Our work will form the basis for integrating building inventories and uncertainty estimates into regional mass flow models.

Keywords: uncertainty, building inventory, regional building stock inventories, regional resource management models

INTRODUCTION

The resource-intensive building sector induces large mass flows in new construction (C) and deconstruction (D). In 2007, C&D waste accounted for 52% of total annual waste in Germany (UBA, 2009). Although shares vary considerably between countries (Hiete et al., 2011), they nevertheless contribute considerably to annual waste generation.
Due to scarce resource and limited landfilling capacities, reuse or high quality recycling of buildings and its components are increasingly postulated statutorily (e.g. in EU-regulation No. 305/2011(55)). But regionally differing building materials and compositions as well as different decrees on material qualities and recycling-hampering substances limit C&D waste recycling options. Besides, the transportation of bulky and low-priced C&D waste and recycling materials over longer distances is not economically and ecologically sensible (Hiete et al., 2011; Marinkovíc et al., 2010; Robinson and Kapo, 2004; Thormark, 2001). To take the previously mentioned challenges into account, progressive resource management approaches are needed on regional level, e.g. such as widely used material-flow and resource management models. Essential prerequisite for efficient resource management is the accurate quantification and characterization of C&D waste supply and recycling aggregate demand on regional level.
Several building-related mass flows models exist on national (Buchert et al., 2004; Cochran et al., 2007; Gao et al., 2001; Müller, 2006; Thormark, 2001) and regional level (Blengini and Garbarino, 2010; Bohne et al., 2008; Cochran and Townsend, 2010; Görg, 1997; Hiete et al., 2011; Kofoworola and Gheewala, 2009; Robinson and Kapo, 2004; Schiller and Deilmann, 2010). These models allow forecasting of C&D waste supply and recycling material demand as well as considerations on related transportation networks, recycling and disposal facility capacities, economic and ecologic effects that are of major interest to local/regional authorities and planners of recycling and waste disposal infrastructure. Input data of mentioned regional models mainly consists of building or building stock inventories (e.g. including building types and sizes, number of buildings per type, building components and their materials per building type or size), activity rates in C&D (e.g. number of new buildings per year) or input-output data of building stock (e.g. consumed construction materials per year). Although some approaches consider scenario analyses and sensitivities of model results, uncertainties in models' input data are not reflected in literature yet.
To obtain the mentioned input data, top-down or bottom-up approaches might theoretically be viable. In the top-down perspective, aggregated national building stock inventory information and input-output-matrices could theoretically be broken down onto regional level, e.g. through regional distributions. But due to highly aggregated data it is difficult to link macroeconomic statistics with the effectively existing buildings and used materials (Kavgic et al., 2010; Kohler et al., 1999). Therefore, the following examination concentrates on the bottom-up perspective.
Bottom-up approaches collect information on building level and are divided in energy models into 'statistical' and 'engineering' modelling techniques; the latter is further separated into 'population distribution', 'archetype' and 'sample' approaches (Kavgic et al., 2010; Swan and Ugursal, 2009). Prevalent publications in building stock inventory compilation follow the archetype approaches that link simple survey information on housing stock (Statistisches Bun-

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desamt, 2012a) with few national building types with known masses and materials, before they are aggregated on regional level (Buchert et al., 1999; Schiller and Deilmann, 2010) (see *Figure 1*). As these building types do not reflect regional conditions, e.g. with regard to construction method or material compositions, the regional building stock is represented inadequately leading to a considerable and often neglected uncertainty of regional models' results.

Current sample (building-specific) quantification of building masses and materials is manual and time-consuming although several data collection tools, guidelines and checklists structure the compilation of in building inventories (LfU, 2001; Rommel et al., 1999; Schultmann, 1998). Due to often lacking building inventory information and to quantify C&D waste, practitioners rely on site inspections, on empirical indices (e.g. gross floor area, gross volume or empirical mass factors) and on estimated characteristics rather than on building inventories and thus ignoring related uncertainties. After deconstruction, buildings' masses and materials are sometimes weighted for accounting when brought to recycling or disposal facilities. However, this scattered information on building inventories and indices is neither collected in comparable processes nor gathered on regional level to improve regional building stock inventories yet. Here, new technologies like laser scanning, RFID tagging or photogrammetry could help to capture building components, characteristics, materials and dimensions to compile a detailed inventory for regional mass flow purposes.

The mentioned information gaps both in building stock inventories and regionally different conditions lead to a considerable and often neglected uncertainty in mass flow and resource management models. Often, uncertainties in used input data, parameters, assumptions or framework conditions are not reflected or its sources are not clearly defined yet. So, model users and decision makers such as local/regional authorities and planners of recycling and waste disposal infrastructure are not aware of uncertainties' influences and associated distortions of regional models' results. Therefore, uncertainties in building stock inventories need to be addressed and integrated in progressive resource management approaches on building and regional level. Consequently, appropriate methods are required which allow investigations on sources of uncertainty, quantification of uncertainties and the impact of uncertainties on the model results.

In our contribution, we transfer types of uncertainties to building stock inventory compilation processes. Thus, we propose a sample process in the second step, in order to analyze, compare and discuss two different approaches in the third step.

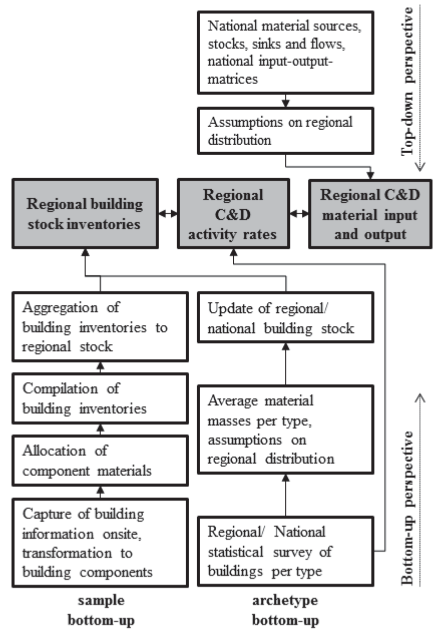

Figure 1: Bottom-up approaches to quantify and characterize regional building stock inventories

METHODOLOGY

Firstly, four types of uncertainty are presented that occur in energy and LCA models of buildings (see following paragraph) (Booth et al., 2012; Chouquet, 2007; Firth et al., 2010): aleatoric and epistemic uncertainty, heterogeneity and ignorance. These types of uncertainty allow the identification and analysis of different sources of model inherent uncertainty. This is relevant for further quantitative analysis of reliability problems e.g. in building stock inventories.

Secondly, due to information gaps on building stock a bottom-up process of building inventory compilation and aggregation to regional stock inventory is proposed (see following paragraph). The proposed process captures building data by a mobile device and transforms it into an inventory classified by material groups and recycling/waste categories of existing buildings, allowing further aggregation to regional stock. This semi-automated process accounts for the unique characteristics of each building and thus depicts regional stock if applied to all building of a designated region.

In a third step, we apply the different types of uncertainty to both bottom-up compilation processes of regional building stock inventory. This reveals information on reducible components of uncertainty (Kiureghian and Ditlevsen, 2009).

In a last step, the two described and analyzed processes are opposed and results are discussed to disclose structural differences and future areas of research.

Types of uncertainty

In literature, the following four types of uncertainty are differentiated (Booth et al., 2012; Chouquet, 2007; Firth et al., 2010; Kiureghian and Ditlevsen, 2009; Reuter, 2013):

I. *Aleatoric uncertainty* (chance variability) represents the variability of an outcome (e.g. building inventory) within a group of homogeneous individuals (e.g. same buildings). These uncertainties might depict e.g. measurement errors or missing model parameters. Generally, aleatoric uncertainty in models appears when modelers do not anticipate (ignore) (Kiureghian and Ditlevsen, 2009) or refrain from the possibility of reducing them. Therefore, differentiation of uncertainties of type (I) and (IV) is not always possible if it comes to lacking or inadequate model parameters.

II. *Epistemic uncertainty* arises due to lack of knowledge about the system or process in consideration (e.g. building, building cluster, building stock) and its parameters (e.g. building type, gross floor area, inherent components). Subdivisions are:
   a. *State of the world* that depicts uncertainties in parameters that could theoretically be measured. These uncertainties are prevalent e.g. during site inspections of existing buildings in the form of experts' approximations, simplifications or estimations on indices, components' masses or components' materials.
   b. *Assumptions* arise from quantitative judgements or from assumed parameter values in models e.g. of future occurences such as estimated future C&D activity rates or assumed retrofit cycles and lifetimes of components or buildings for the quantification of C&D waste resulting from building stock.

III. *Heterogeneity* evolves from variation in characteristics of individuals (e.g. buildings) that are clustered in a subgroup (e.g. buildings of the same age or size). This uncertainties might arise, e.g. if single family houses are clustered although their material characteristics vary.

IV. *Ignorance* describes the lacking knowledge of the qualitative structure of a model or a modelled process. This may concern e.g. a possibly inadequate form of the model.

While aleatoric uncertainties are not reducible by nature, a reduction of epistemic uncertainties might either be possible through an increase in data quality or quantity or through model refinements (Kiureghian and Ditlevsen, 2009).

As process steps can have both aleatoric and epistemic uncertainty components, a concluding assignment of process steps or parameters to types of uncertainty might not always be possible but will depend on the modelling approach.

Proposed sample bottom-up process

Since many existing buildings have rather insufficient documentation and to enable the compilation of building inventories, a fast and efficient image-based method to capture building physics onsite, to subsequently compile and to aggregate building inventories is required. To enlarge information on regional stock, we propose an eight-step process (see *Figure 2*):

(1) **User input of general building data*** such as building age, size, construction type etc.
(2) **Image-based capture** of the building and its dimensions onsite
(3) **Processing** of the captured data to create a surface model of the building
(4) **Recognition** of building components*
(5) **Allocation of materials** to building components*
(6) **Modeling** of building components to receive a building model*
(7) **Compilation of building inventory** providing building characteristics and mass balances of materials and components
(8) **Aggregation** of individual building inventories to obtain regional building stock inventories

(*: partly interactive step requiring user input)

While numerous recent research approaches rather focus on the steps (2) to (5) of data capture, processing, recognition and modeling (Bhatla et al., 2012; Hajian and Becerik-Gerber, 2010; Huber et al., 2011; Klein et al., 2012; Tang et al., 2010) - some of them with uncertainty or error considerations (Bhatla et al., 2012; Hajian and Becerik-Gerber, 2010; Klein et al., 2012) -, we propose to combine it with the allocation of materials (5), the compilation of single building inventories (7) and their aggregation to regional building stock inventories (8) (see *Figure 2*). The previously proposed sample process tries to structure inventory compilation and enable the following assessment of related uncertainties.

As *Figure 2* shows, the proposed process uses three inputs to create building inventories: image-based building physics, user input of general building data and a database with relevant component information. After building condition is captured and processed, recognition algorithms, user interaction as well as general and component-specific information inputs enable the modeling of building components. Depending on the capabilities of the capturing and processing steps, materials are automatically or interactively identified. As soon as building components are recognized, further component attributes such as surface coating, compositions, layers and materials including hazardous or contaminant substances will be proposed by the component database.

The user might select the building-inherent components from the database and correct erroneous modeling, attribute value suggestions or allocations interactivly. In the last step, a building inventory is compiled containing general building characteristics that are used today for C&D waste quantification, such as gross/net volume, gross/net floor area or construction method. But it also provides detailed mass balances according to building components, materials or recycling/waste categories.

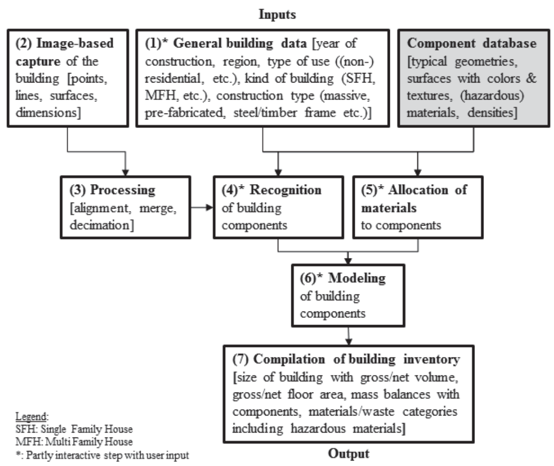

Figure 2: Proposed sample *bottom-up process steps (1) to (7)*

Single building inventories can be aggregated to regional building stock inventories, if the proposed process was previously performed on every building of the designated region.

RESULTS

The aim of the proposed process is to reduce uncertainty in regional building stocks. The more information on a system is gathered, the more uncertainty can decrease (Kiureghian and Ditlevsen, 2009). This implicates, that a comprehensive registration of regional building stock e.g. through capture of individual buildings might improve regional models' input data and reduce uncertainty. As shown in *Figure 1*, two bottom-up processes – archetype and sample – enable the compilation of regional building stock inventories. Both processes are analysed in the following to identify inherent types of uncertainty:

<u>Uncertainties in the archetype bottom-up process</u>

Input data used in regional or national models for forecasting C&D waste supply and recycling aggregate demand is often based on simple housing statistics. In Germany, the last complete counts of housing units, residential building types and building sizes were performed in 1987/1995 (west/east) and 2010 (total) (Statistisches Bundesamt, 2012a). In this survey, residential building types were differentiated between one/two family houses and multifamily houses of several building ages. Although the survey asked for parts of the technical equipment, it did not cover detailed information on building inherent components and materials that are relevant for building inventories.

During the periods between complete counts, the number of buildings per type is continually updated through C&D activity rates (Schiller and Deilmann, 2010; Statistisches Bundesamt, 2012a). C&D activity rates are generated from building permits, building completions, conversions and deconstructions that are surveyed by authorities. Uncertainties (IIa) in C&D activity rates and in the number of buildings per type might occur, due to the fact that e.g. conversions or deconstructions are only registered when reported to regional authorities. In new construction statistics, predominantly used building material is inquired since the year 2000 (Statistisches Bundesamt, 2012b), but as new construction accounts for 1-2% each year, these information are not transferable to building stock inventories yet.

As the mentioned surveys exclude detailed building inventory information, few national building types with 'typical' material characteristics are combined with the surveyed number of buildings per type to estimate regional or national building stock inventory (Buchert et al., 2004; Görg, 1997; Kohler et al., 1999; Schiller and Deilmann, 2010). Buchert et al. and Schiller/Deilmann work with 'typical' material characteristics that base on mean values of small samples of 3 to 26 buildings per type (Buchert et al., 1999, 2004; Schiller and Deilmann, 2010). Görg and Kohler et al. use reference buildings per type with material characteristics from literature (Görg, 1997; Kohler et al., 1999). Both accept aleatoric uncertainty (I) in the selection of the sample data sets.

As the considered building types and its material characteristics are quite general and do not reflect regional conditions, e.g. with regard to material compositions, regional building stock is represented inadequately. Regional differences in construction methods and material compositions are not considered (IV) and might cause significant deviations (IIa) from representatives' average values.

Currently, considered material masses include structural elements, such as walls (incl. coverings), ceilings, roofs, footings/foundations, doors and windows (Buchert et al., 2004; Görg, 1997; Schiller and Deilmann, 2010). Not represented yet are components and materials of technical equipment, interior fittings or hazardous materials that influence e.g. the quality of materials. This might be summarized in epistemic uncertainty (I).

<u>Uncertainties in the sample bottom-up process</u>

In the following, we consider the occurring types of uncertainty in the proposed process:

The collection and user input of **general building data** such as year of construction, gross floor area or construction type may cause epistemic uncertainties (IIa) if building documentation is lacking. If several attribute information is not available for a building in question, derived attribute values from similar buildings' of the same cluster might cause ignorance (IV), due to wrongly modeled derivation, or heterogeneity (III), due to the variation of individuals' characteristics in a cluster.

Techniques to **capture** buildings' physics are divided into image-based, range-based, manual and other techniques (Bhatla et al., 2012). Many research approaches focus on data capture through laser scans with post-processing into digital building models (Bosche, 2010; Huber et al., 2011; Tang et al., 2010). Other research approaches enhance building documentation and modeling of buildings through images (Barazetti et al., 2010; Bhatla et al., 2012; Golparvar-Fard et al., 2011; Klein et al., 2012) or videos (Brilakis et al., 2011). Manual and other techniques for capturing building information are based on tagging, existing documentations (e.g. floor plans) or tape measuring. Combinations of techniques are common, trying to overcome drawbacks of individual techniques (Liu et al., 2012; Valero et al., 2012). Despite many publications in this area, only few works (Barazetti et al., 2010; Bhatla et al., 2012; Hajian and Becerik-Gerber, 2010; Klein et al., 2012) examine process-inherent uncertainties. Aleatoric uncertainties (I) might arise e.g. due to erroneous recording (Klein et al., 2012) or deficient lighting conditions and might influence geometric information or dimensions' measurement (Reuter, 2013). Furthermore, epistemic uncertainties (IIa) might be caused by technical differences in data capturing methods, e.g. such as distortions in geometric information of building components. *Figure 3* shows the relative geometrical deviations (in relation to total dimension) between manual (ground truth) and image-based capture of coarse interior building components with average deviations of 1-3% that resulted mainly from openings, perimeters and obstructions (Klein et al., 2012). Also; ignorance (IV) might be caused through inadequate capturing techniques that do not provide required data quality.

The **processing** step is particularly applied to range-based and image-based captured data; other techniques demand individual processing with related epistemic uncertainties. Huge image-based and range-based data volumes require data registration, alignment and merge into one system of coordinates (Tang et al., 2010). During this process, epistemic uncertainties (IIa) might arise from interactivly detected and linked surfaces or tie points (Bhatla et al., 2012; Tang et al., 2010). To enable the following component recognition step, the data is decimated through cleaning from noise, irrelevant information and clutter (Barazetti et al., 2010; Tang et al., 2010), resulting in further epistemic uncertainties (IIa). Inadequate processing of the captured data due to ignorance (IV) might also occur.

Depending on the **recognition** process (algorithms, interaction), we have algorithm or model inherent parameter (IIa) uncertainty of theoretically identifiable building components. Besides, uncertainties due to lacking information e.g. from previous steps of data processing might occur (IIa). Most current approaches only cover coarse building components like floors, walls/facades, ceilings, windows or doors (Huber et al., 2011; Klein et al., 2012; Tang et al., 2010) and thus accept the associated uncertainty (I). Further uncertainty might arise from limitations to several, finite component attributes (I) (e.g. materials, compositions, layers, densities, colors, textures), attribute values (IIa) or from the possible inability of the recognition of the innumerable designs and customized built-in components (IV).

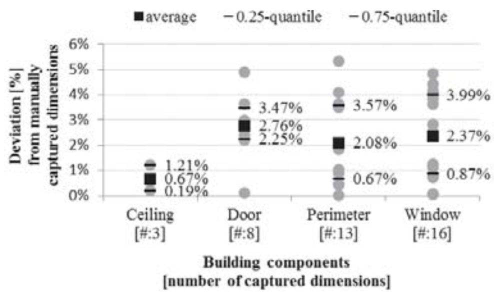

Figure 3: Exemplary deviations between manual and image-based capture of components' dimensions, based on (Klein et al., 2012)

In the proposed process, the **allocation** of materials to building components is supported by a component material database. Due to the diversity of building materials and compositions, the restriction to several, finite attribute values might cause aleatoric uncertainty (I). Recent approches on automated material detection in images (e.g. of brick, concrete, earth, wood or rebar) focus on clustering, graphical analyses as well as color and texture comparisons with training sets (Brilakis et al., 2005; Mallepudi et al., 2011; Zhu and Brilakis, 2010). Results show, that although the majority of pixels is detected correctly, manual identification provides more valid identification rates yet (Zhu and Brilakis, 2010). In automated processes, aleatoric uncertainties (I) might occur due to the influence of training sets (Mallepudi et al., 2011); other uncertainties might arise from parameter assumptions (IIa) and inadequate training sets or methods (IV). As component-related (primary) or occupancy-related (secondary) hazardous materials can be detected by laboratory testing of material samples, a users' assumption about the existance or kind of hazardous material might cause epistemic uncertainty (IIa).

Modeling of building components include the restriction to a finite number of components, attributes and attribute values and thus consequently limit the depicted level of detail (I). Due to the layered structure of many building components, further epistemic uncertainties (IIa) might arise from wholly or partly concealed components and layers (e.g. insulation, technical equipment etc.), that might be modeled in course and geometry. In the case of inadequate modeling, ignorance (IV) might occur.

The **compilation** of building inventory depends strongly on the applied classifications of components, material groups and recycling/waste categories. In Germany, the predominant component hierarchy is standard DIN 276-1:2008-12 (Görg, 1997). Internationally, other hierarchies are used, like e.g. the Industry Foundations Classes (IFC). The building-inherent materials can either be divided into material groups (Dewulf et al., 2009; Rommel et al., 1999; Thormark, 2001), into decreed recycling/disposal categories and qualities (EU-Commission Decision No. 2000/532/EC) or into other facility-specific categories. The building inherent components and materials are aggregated depending on the chosen inventory structure, accepting heterogeneity (III) of materials in each subcategory.

The **aggregation** of building inventories to regional building stock inventories might lead to further uncertainties. Possible occurences are: calculation errors (I), dependencies between the mentioned uncertainties (I) or lacking building inventories of the designated region (IIa). In the case of the latter, the current archetype process is applied choosing a representative set of buildings of the region to estimate building stock inventory and thus accepting heterogeneity (III) within the mentioned types or clusters.

DISCUSSION

As depicted, numerous uncertainties of different types arise both in archetype and sample processes of regional building stock inventory compilation. Both processes and their associated uncertainties are opposed in the following, to identify structural similarities or differences and to reveal future areas of research:

In archetype processes, questions of representativeness arise (I) when no complete counts or survey information is available (Kohler et al., 1999) and of heterogeneity (III) issues when national values are applied on regional level. Regional distributions of building characteristics might remedy, but need further research.

As we focus in the proposed sample process on the compilation of existing buildings' inventories with only fragmentary information available, mainly epistemic uncertainties (IIa) are prevalent. The capture of inventory information is building-specific and detailed (e.g. including technical equipment or interior fitting). But although it is a semi-automated process, it faces relatively high expenses especially when applied to all buildings of a region. So far, our considerations focus on residential buildings due to the relatively well-known German residential stock that allows validation of the proposed process. But theoretically, the proposed process is transferable to non-residential (municipal, commercial etc.) buildings, building stocks or other regional infrastructure, and could help to improve their rather poor database. Besides, it might help to explore buildings and regional stock in less surveyed and documented regions.

Major differences between both processes occur in the (2) data capture, (3) processing, (4) recognition, (5) allocation and (6) modeling steps. While in the archetypal process heterogeneity (III) arises due to defined or averaged building characteristics (e.g. gross/net floor area, material shares), in the building sample approach aleatoric (I) and predominantly epistemic (IIa) uncertainties occur.

In both processes, steps might not be modeled adequately – resulting in ignorance (IV). Besides, none of the two processes allows further insight into distributions of hazardous materials, thus their detection still remains dependent on laboratory investigation.

In a consequence of the chosen approach, the specified types of uncertainties might not be complete or possibly types of uncertainties might not be assigned correctly, but our considerations provide a basis for further research. In order to deepen research on the topic, further types and differentiations of uncertainties could be taken into account and uncertainty considerations might be extended to C&D activity rates, non-residential buildings or other regional infrastructure. Besides, quantitative analyses of uncertainty in regional inventory data and incurring C&D waste should follow. Further research is necessary to gain insight into influence of uncertainty on regional mass flow and resource management models. Finally, the proposed process needs testing in practice.

CONCLUSION AND OUTLOOK

Since the building sector induces large mass flows, progressive resource management approaches and models are used on regional level to manage materials' recycling. As data used in regional models do not necessarily reflect regional conditions, the regional building stock is represented inadequately leading to a considerable and often neglected uncertainty of regional models' results.

First, in order to identify and discuss uncertainties, we transferred four types of uncertainty – aleatoric uncertainty, epistemic uncertainty, heterogeneity and ignorance – to building stock inventory compilation. Second, to improve data on regional building stock inventories, we proposed an eight-step, image-based process for the compilation of building inventories. Third, inherent types of uncertainty in the presented archetype and sample bottom-up processes are analysed, opposed and discussed to reveal sources and reducible components of uncertainty. While in the archetypal process heterogeneity (III) arises due to defined or averaged building characteristics (e.g.

gross/net floor area, material shares), in the building sample approach aleatoric (I) and predominantly epistemic (IIa) uncertainties occur.
Our contribution presents the first stage of ongoing research on integrating building inventories, uncertainty estimates and associated analyses into mentioned regional mass flow models. This will improve transparency and decision-making for local/regional authorities and stakeholders. Further development might be extended to other types or to additional differentiations of uncertainties as well as to C&D activity rates, to non-residential buildings or other regional infrastructure. Besides, a quantitative analysis of uncertainties in regional inventory data and C&D mass flows and the associated influence on regional models will require further investigation.

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ENVIRONMENTAL PRODUCT DECLARATIONS (EPD) – THE CURRENCY FOR LIFE CYCLE ASSESSMENTS IN THE CONSTRUCTION SECTOR

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ABSTRACT

This paper explains the role of Environmental Product Declarations (EPDs) in the construction industry.

EPDs are a calculation model based on international standards to assess the embedded environmental impacts of construction materials, such as their carbon footprint.

Together with the environmental footprint during the use phase EPDs add up to the information required for a full building Life Cycle Assessment.

The role of EPDs in the construction industry seems to become increasingly manifested. Nevertheless, the industry is strongly seeking for tools and synergies in the EPD creation process, while designers and specifiers are still collecting experience in the application of EPDs in building Life Cycle Assessments and Green Building Labels.

INTRODUCTION

It is common knowledge that the construction sector is significantly contributing to society's ecological footprint. Subsequently commitments are many to reduce the impact of creating, operating and reusing constructions. Further economic growth will depend on our ability to eliminate the resource consumption of our built environment.

The prerequisite for any optimization is the ability to measure efforts and their related benefits as specifically as possible. Only with the knowledge of economic and environmental profit and loss, different construction solutions can be evaluated and decision can be made.

Currently the construction sector is strongly focusing on the operational side of buildings for two reasons:

- operational impacts are by far the highest contributor to a building's life cycle.
- operational impacts are easy to calculate, basically as a function of energy and water flows at the meters.

Since the operational performance of buildings is at stake, this will be reduced to almost zero in the near future. According building techniques are available and the first regulators are requiring low-, zero- or plus-energy houses.

Because of the improved operational performance, the embedded impacts of constructions will get into the limelight soon, but far less knowledge and common agreement is available on the assessment of embedded impacts.

EPDs are tackling this lack of information by disclosing life cycle-based impact information. The challenge hereby is twofold:

- to have a robust and credible calculation model and
- to have a commonly agreed calculation method for a construction's embedded impacts

DEFINITION OF EPDS

The internationally recognized Environmental Product Declaration is a single, comprehensive disclosure of a product's environmental impacts – from its creation, distribution and use to disposal.

An Environmental Product Declarations is

- A sustainability report card for a particular product or group of products
- Based on a 360° environmental impact audit
- Developed through a product life cycle analysis
- From raw material extraction to end-of-life disposal
- Following ISO guidelines (ISO 14040 and ISO 14025)
- Verified by an independent 3rd party (Gadonniex, 2012)

EPDs provide an unbiased, within a product category comparable, information on different environmental impact categories.

The overall 24 environmental indicators are subdivided into the following four chapters.

Environmental impact indicators (7 indicators):

- Global Warming
- Ozone Depletion (stratospheric ozone layer)
- Acidification for soil and water
- Eutrophication
- Photochemical ozone creation (Summer smog)
- Abiotic resource depletion

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Resource use (10 indicators):

- Primary energy
- Secondary materials
- Secondary fuels
- Fresh water

Waste category indicators:

- Hazardous waste disposed
- Non-hazardous waste disposed
- Radioactive waste disposed

Output flow indicators:

- Components for re-use
- Materials for recycling
- Materials for energy recovery
- Exported energy

<u>Legal framework</u>

- ISO 14040 and 14044 define principles & framework and requirements & guidelines for Life Cycle Assessments.
- ISO 14025 goes more into detail on Environmental Product Declarations.

However, none of the frameworks above is specifically designed for construction products. In Europe the CEN/TC350 (Technical Committee on Sustainability of Construction Works) was given the mandate to develop a methodology for the aggregation of construction materials under the umbrella of the above ISO standards:

- The European standard EN 15804 provides core rules for the production of an EPD for construction products (Anderson, 2012). As a manual for 'How to produce a construction product EPD' EN 15804 is widely used: Also the US Carbon Leadership Forum refers to this standard in setting up guidelines for producing concrete EPDs.

PURPOSE OF EPDS

EPDs provide material background data for different types of life cycle assessments. The background data relates to a reference unit, e.g. kg or m^3 of the construction product.

Any EPD background data as a stand-alone information is of limited use. EPD data needs to be fed into a life cycle assessment, where the functional unit is a specific use, e.g. m^3 of building or m^2 of construction element. Only on the level of application the EPD date becomes 'intelligent' and provides information of the sustainable performance of a solution.

<u>Material Life Cycle Assessment</u>

Material LCAs are assessments of the environmental impacts of construction materials focusing only on the product itself without taking into account the product application.

Material LCAs can be useful to optimise a product's constituents, mix design or production process. However, a Material LCA only works on a like-for-like basis. As soon as the material properties or the construction the material is used for change, comparing different Material LCAs is pointless, since the surrounding usage parameters are not comparable anymore.

<u>Construction element Life Cycle Assessment</u>

One of the most common and easiest ways to apply EPDs is in LCAs of construction elements. The isolated analysis of a distinct part of a construction simplifies decision-making process as well as the underlying mathematical model. Typical objects of study for Construction LCAs are:

- façade types
- roofing
- heating / cooling facilities

Figure 1 shows an example of the reduced comparison of different wall types. It combines embedded information (primary energy, GWP) and operational (thickness) performance. The u-value (thermal transfer coefficient) stays identical for all samples to achieve a like-for-like assessment.

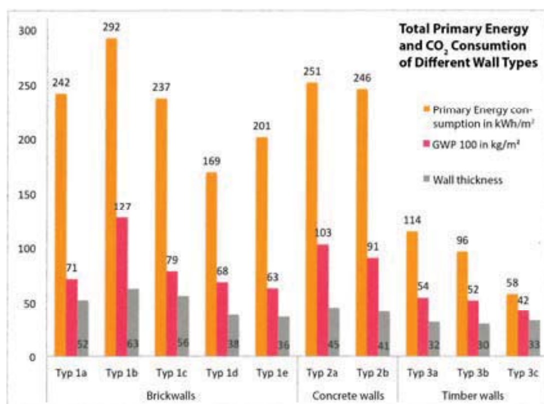

Figure 1
Life cycle assessment of wall types
(Oehler et al., 2012)

Although it would be possible to do Construction element LCAs by just calculating embodied impacts, usually both embodied and operational impacts are considered. Operational impacts can be the maintenance, repair or replacement during the element's designed lifespan; it also can take into refer to the energy consumption of an analysed system over its operating period.

For Construction element LCAs it is crucial to set the system boundaries right in order to achieve unbiased like-for-like comparisons. Again, as it is true for Material LCAs: Once the construction element's properties or surrounding settings change, comparing different Construction element LCAs becomes pointless.

Construction Life Cycle Assessment

In a full Life Cycle Assessment a construction's embodied and operational impacts on the environment get inventoried and add up to aggregated figures for one building over a defined period of time. This includes the impacts of

- material / product manufacturing
- transportation
- construction
- operation, maintenance, repair and replacement
- end of life, reuse and recycling

EPDs are one data entry amongst others in a Construction LCA. The EPD data, basically on manufacturing (cradle to gate) and end-of-life, gets combined with other data on operational energy consumption and efforts spent on operating and maintaining the construction.

In theory, Construction LCAs are supposed to assist in the design process to better understand interactions between various design parameters, e.g. the effort spent on additional thermal insulations versus the savings in energy consumption. In this LCA will help specifiers in a holistic optimisation of constructions.

In practice, full LCA calculations are sophisticated mathematical models and the interactions amongst different parts of a building are quite complex. Currently many Construction LCAs emerge as singular statements of the environmental impact of a building rather than a design and assessment tool. With some likelihood, this will change once the available software tools become more user friendly and specifiers collect more experience in operating those tools.

Whereas the physical system boundaries are usually easy to define – it are the buildings' perimeter – for Construction LCAs the reviewed period becomes crucial. Typical Construction LCA periods range from 25 to 60 years. Within the given time, occurring replacements of equipment and major construction parts can have decisive influence on the overall result. For instance for a building LCA including a façade which needs to get replaced after 30 years, the result of a 30 year LCA period differs fundamentally from the same calculation over 35 years.

Transparency

Beyond the very provision of material information, EPDs are an expression of compliant and transparent production processes. Since for setting up the EPD calculation and report as well as for conducting the independent verification 3rd parties gain deep insight into production related information and facilities. Successfully undergoing this process as a manufacturer requires supply chains and processes that comply with environmental regulations and to a given extend also with social standards.

Together with other industry standards, such as ISO 9001, ISO 14001, or Responsible Sourcing Schemes EPDs give proof of a 'nothing to hide' policy of a construction material supplier.

EPDS IN GREEN BUILDING LABELS

DGNB

The German Green Building Label was the first system, which incorporated a full building life cycle assessment. In the first step the embodied impacts could be calculated according to a generic database 'Ökobau.dat'. However, the use of product specific EPDs is continuously fostered and rewarded within the rating scheme.

BREEAM

The UK based Green Building Label used a simplified approach for a building life cycle assessment focusing on the main building parts. The data for calculation can be collected from the generic 'Green Guide' or from the product specific 'GreenBookLife', both database tailor made to the BREEAM system. Nevertheless EPDs are also accepted to provide product LCA data.

LEED

LEED in its upcoming version LEED NC v4 will ask for self-declaration (type I) EPDs or third party verified (type III) EPDs. Higher content of materials coming along with an EPD and type III EPD will improve the scoring.

PRODUCING AN EPD

Product Category Rules (PCR)

First step in producing an EPD is to select an applicable Product Category Rule (PCR). In absence of an applicable PCR, one must be developed and approved (Gadonniex, 2012).

PCRs are the guidelines for producing an EPD. They are the translating link between the overarching (=generic) ISO standards and the final EPD for a distinct product. PCRs are covering homogenous groups of product. Examples in the construction sector are concrete, steel, or zinc sheets for roofing.

Figure 2 shows that, beyond the pure inventory analysis, objective & scope (=interfaces) and the relevant impact indicators are to be defined. These three together are feed into a Life Cycle Assessment (of a product or building) as basis for decision making and communication.

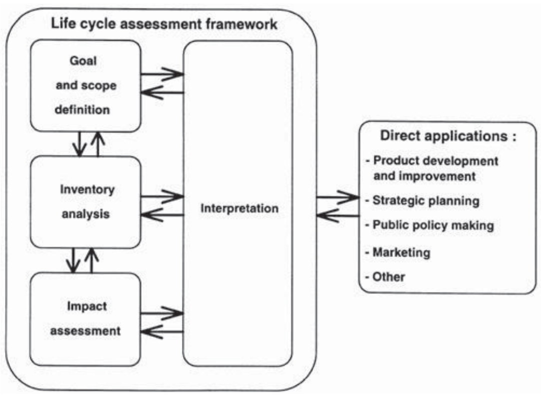

Figure 2
Life cycle assessment framework
(ISO14040, 2006)

Product Life Cycle Assessment
The product LCA is the centrepiece of an EPD. Its output is a life cycle inventory of all steps in a product's life from 'cradle to grave'. The product LCA has to follow the guidelines of selected PCA.

EN 15804 suggests a life cycle structure, which follows closely a typical building life cycle from its construction to the final demolition. Apparently, this structure is becoming the common systematic for setting up a product LCA:

Product stage
A1 Raw material supply
A2 Transport
A3 Manufacturing

Construction Process
A4 Transport
A5 Construction-installation process

Use stage
B1 Use
B2 Maintenance
B3 Repair
B4 Replacement
B5 Refurbishment
B6 Operational energy use
B7 Operational water use

End of life
C1 Deconstruction demolition
C2 Transport
C3 Waste processing
C4 Disposal

Supplementary information beyond the building life cycle
D Reuse-
Recovery-
Recycling potential

According to EN 15804 only A1 to A3 are mandatory life cycle assessment parts for a Type III (= independently verified) EPD. This is because for many construction products, such as structural elements, the range of use cases is very wide and can hardly be generalized. However EPD owners are free to include any of the non-mandatory levels in the calculation of their EPD. For any comparison of EPDs the knowledge of product life cycle stages incorporated in the inventory is crucial.

Create an EPD
The very EPD is a comprehensive document disclosing the key properties of the assessed construction product. According to ISO 14025 is comprises amongst others:

- Identity of the parties involved (EPD owner, verifier, program operator etc.)
- Description of the product
- Declaration of the product's content
- PCR used for producing the EPD
- Life cycle assessment data
- Information on which LCA stages are not considered
- Third party verifier's check note

Third Party Approval
The entire EPD has to be verified by an independent authority. Usually the verifier gets assigned by the program operator which registers the EPD.

Register and Publish an EPD
The final stage is chose a program operator for the EPD and submit the comprehensive EPD including LCA and report to the operator.

In practice, the selection of a PCR and the EPD program operator go hand in hand. The same program operator, which approves the PCR will finally register the EPD produced on basis of this PCR. Also the third party verification will get conducted on behalf of the same EPD program operator.

EPD TOOLS
Construction product EPDs achieved a wider recognition around 2005. In these beginnings, producing an EPD was complex and costly. Most EPDs have been produced in a one-of-a-kind process. The effort standing behind an EPD has been the major obstacle for a wider success of EPDs in the construction sector.

Since then the industry undertook strong efforts to streamline the production of EPDs. Starting with the establishment of standardized PCRs the logical next steps is to set up calculation tools for the product LCA.

<u>CSI Concrete EPD tool</u>
The Cement Sustainability Initiative (CSI), a subchapter of the World Business Council for Sustainable Development (WBCSD) registered PCRs for concrete at the Environdec Platform (Hunziker, 2013).

On basis of the concrete PCRs the CSI developed an calculation tool for concrete EPDs for its members. The tool provides a standardized procedure for the EPD report.

Input data are concrete mix-design, production data (energy, water consumption, emissions and waste), transports, recycling and disposal.

Output data is the calculation of all environmental indicators according to PCR guidelines as the core of and EPD.

<u>BASF Life Cycle Analyzer</u>
The chemical admixtures supplier BASF developed a proprietary tool named 'Life cycle analyzer'. The tool produces an environmental assessment for concrete products including the product LCA. The output EPD report complies with EN 15804 so that the document can be used for registering an EPD according to ISO 14025 (Ambrosini, 2012).

The report also elaborates preliminary information on the construction product's performance according to the Green Building labels BREEAM (UK), DGNB (Germany), LEED (USA/Canada/India) and HQE (France).

<u>Zumtobel Group EPD tool</u>
The international lighting provider Zumtobel Group developed an internal tool for producing an EPD for lighting applications. The tool depicts the Zumtobel specific manufacturing process and uses the interface to already existing supply chain management tools.

The Zumtobel tool complies with ISO 14040/25 and EN 15804, it has been approved by an independent verifier assigned by the IBU (the Institute für Bauen und Umwelt [IBU] is a major EPD program operator with a strong focus on construction products). Since already the tool is third party certified, the final registration of an related EPD is basically a formal procedure significantly streamlining the entire EPD creation.

Since April 2012, the company issues EPDs for all new products, and on request for existing products as well (Gann, 2013).

AVERAGE OR PRODUCT SPECIFIC EPD

ISO 14025 does not specify the level of detail for an EPD. Subsequently three levels of detail can be observed in the construction sector:

<u>Industry EPD</u>
Industry EPDs provide average data for a product type of an entire industry, usually of a country or region. Mostly they have been created and registered by an industry overarching council or trade organization. The product type itself has to be as distinct as possible to avoid the calculation of pointless averages.

The industry EPD's inherent characteristic is that they provide industry average data without any option for product specific information. Hence industry EPDs are more common in

- the pre-consumer part of a value chain, e.g. cement EPDs which ultimately feed data into a more detailed concrete EPDs.
- fragmented industries, e.g. masonry or precast concrete, where the particular supplier rejects the effort for a more specific EPD

<u>Company EPD</u>
Company EPDs are based upon one company's average data for one of their product families. As for industry EPDs, the product family itself must be distinctly determined to avoid the insufficient averages.

Company EPDs are more accurate than industry EPDs. They offer the company the flexibility to adjust the EPD closer to their own product portfolio while being still an efficient way to create an limited number of EPDs.

<u>Product EPD</u>
The highest level of detail for an EPD is the product EPD. Here the EPD is produced out of one specific product's data. The EPD owner can group together different operations which are producing the same product (type) in a similar way.

Various reasons and motivations are differently favouring the three possible approaches, such as

- Cost and effort for an EPD
- Customer demand
- Accessibility and granularity of available data
- Competitive situation in the segment
- Confidentiality of the manufacturing process

From the very beginning, the construction industry is not decided on which of the ways described above to follow. Initiatives in both directions, industry EPD and product EPD can be observed. Currently no clear favourite can be determined.

OUTLOOK

Relevance of embedded impacts

Today in the construction sector, the energy consumption is at stake. Regulators, specifiers and users are hereby mainly focussing on the operational energy for heating, cooling, lighting and other electrical installations. Most likely solutions will soon be available, which reduce buildings energy consumption to a level. These solutions could be supplied by local renewable energy sources, at least in mature markets and metropolitan areas.

Once task of reducing operation energy is accomplished, the next step will be tackling the embedded energy of construction materials, which then will account for the biggest proportion of a building's life cycle.

The challenge in calculating buildings' embodied energy will be to rely on a standardized, commonly accepted and comparable calculation model. Here EPDs seem to offer a common denominator of what has to be included into the assessment and how the calculation model should look like, as seen in Figure 3.

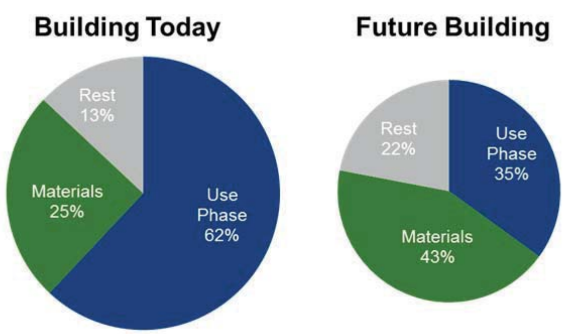

Figure 3
Building life cycle emissions today and in future
ICE (Institution of Civil engineers), 2012

Acceptance and application of building LCAs

Currently the construction industry is practicing on EPDs. Both the creation of EPDs and their use in building LCAs on the customer side are new experiences. In some cases, industries and companies proactively provide EPDs, in some (rare) cases, construction companies and specifiers ask for respective construction product information.

The knowledge on producing and applying EPDs will rapidly increase. The crucial question will remain to what extend EPDs will play a role in the decision making process for buildings, construction methods and construction elements.

A first step in EPDs extending their influence is their application in Green Building Labels, such as BREEAM, DGNB or LEED. Currently the advantage of presenting an EPD is limited within those Green Building Labels, nevertheless auditors and specifiers will not quit asking for EPDs by just following their checklists.

Only if architects, specifiers and contractors will conduct and understand building or construction element LCAs and use the findings optimization, the EPD will find a broader acceptance. If this will happen, then the step towards EPDs becoming mandatory or as-if mandatory will be a very small one.

CONCLUSION

This paper describes the purpose and content of Environmental Product Declarations, as well as the basic steps to create an EPD.

EPDs emerged from prototype like single reports of environmental product indicators to a standardized type of declaration.

Currently further tools are available and / or under development, which further streamline the EPD creation process and with this reduce the cost from 'prohibitive' to 'acceptable'.

Nevertheless the decisive question for the success of EPDs will be to what extend they will gain relevance in building Life Cycle Assessments and Green Building Labels.

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CLOSING THE RESOURCE LOOP: LIFE CYCLE BENEFITS OF HEMP LIME BUILDING CONSTRUCTION AS NEGATIVE CARBON MATERIAL FOR LOW-COST HOUSING SOLUTIONS, SIMULTANEOUSLY REMEDIATING BROWNFIELD SITES IN ASIA

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ABSTRACT

Imagine 'growing your own house', providing low-cost eco-friendly buildings, within a low Urban Heat Island masterplan of fertile soil, sanitised water and good air-quality that generates low waste.
This paper explains how this can be done with industrial hemp, growing on brownfield sites with low maintenance and no use of pesticides or herbicides. The harvested hemp hurds (woody core) when mixed with lime and water, easily casts into fire resistance, non-combustible, termite and pest resistent, breathable wall material with superior thermally performance as a wall or insulation material. This hemp-lime material can be recycled during construction and after demolition. Even other parts of the plant such as the oil seeds and bast fibre have great commercial as health food, body care products, biomass and textile. This could potentially form a model for cost effective, low carbon masterplan typology in developing parts of Asia, and closing the resource loop.

Keywords: industrial hemp, hemp-lime construction, hempcrete, embodied carbon, phytoremediation,

INTRODUCTION

All building materials have an impact on the environment. Mining extraction for raw materials can devastate habitats, pollute, create waste and consume large amounts of energy releasing global warming greenhouse gasses. Alternative natural and fast renewable materials need to be re-examined for sustainable building with minimal impact on environmental preservation and biodiversity.
Developing regions in Asia such as China, India, and Myanmar are in need of efficient infrastructure and sustainable eco-friendly buildings. Industrial hemp (Cannabis Sativa L.) is a multi-purpose economic crop which countries like Asian countries like China, India, Myanmar and Thailand have been cultivating.

Hemp seed is nutritious and contains essential fatty acids such as omega-6 and 3, B-vitamins, protein, and is a good source of dietary fiber. Ba Ma, a small village in Southern China, lauded as The Longevity Village, use hemp as a staple food and most of people there live for about 100 years. Other than health food products from hemp seeds, the hemp oil has been used as a variety of body care products. The bark of the hemp stalk contains bast fibers, which is longer, stronger, more absorbent and more insulative than cotton fiber. China is currently the largest exporter of hemp textiles. Currently, tribes and local community of the hills state in Uttarakhanda, a northern part of India, have been growing *Industrial Hemp* (*Bhang*) for building shelter, clothes, ropes, cordage, nets and other necessary tools accessories (Nisha Tripathi, et al., 2013).
Hemp has a long history of being made into paper as it produces more pulp per acre than timber and it resists decomposition, and does not yellow with age when an acid-free process is used. Hemp paper manufacturing can reduce wastewater contamination. Hemp's low lignin content reduces the need for acids used in pulping, and its creamy color lends itself to environmentally-friendly bleaching instead of harsh chlorine compounds In addition, it can be recycled more times than wood-based paper. Research has been conducted to use hemp in manufacturing biodegradable plastic products and bio-composite plastic reinforcements or biodegradable plastics. According to the US Department of Energy, hemp as a biomass fuel producer requires the least specialized growing and processing procedures of all other products. The hydrocarbons in hemp can be processed into a wide range of biomass energy sources, from fuel pellets to liquid fuels and gas (HIA, 2009).

The cellulose and hemi-cellulose in its inner woody core are called hurds. This hurd is the part of the plant which shall be used as building materials, such as walls, floor, and insulation. The hemp hurds are mixed with a binder, typically lime and mixed with water to form a 'concrete-like' building material, where in this case, the hemp hurd is the stone aggregates, and lime is the binding material. This building material, ccommercially produced and termed as "Hempcrete", has been tried, tested and explored with adding a variety of additives to the mix to further enhance its properties. More details shall be explained in the following section.

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Currently, most of the hemp grown in Asia are for manufacturing of cortege, textiles, and seeds. The use of hemp to be made into hemp-lime building materials, commonly known as Hempcrete, has not been commercially explored as ‘green’ building materials. However, such hemp-lime construction material has been used successfully around the world in various harsh climatic regions.

Industrial hemp plant, despite belonging to the similar family species as marijuana, typically has less than 10% of the tetrahydrocannabinol (THC) levels that of marijuana. According to EU regulations, farmers can only cultivate those varieties that contain less than 0.2% THC. It is heartening to know that hemp seeds and hemp stalks do not cause any psychoactive effect (HIA, 2009) as most of the THC contents are in the leaves and flowers, therefore making hemp products safe to use.

The following sections shall discuss in detail the environmental and life cycle benefits of constructing with hemp-lime building material:

- Remediating Brownfield Sites
  Growing of industrial hemp on landfill or abandoned industrial sites to improve soil conditions through phythoremediation, thus allowing future arable land.
  - Singapore as a hypothetical case study
- Ease of Sustainable Farming
  4 months to harvest with ease of organic farming, hemp thrives without the need of pesticides or herbicides thus protecting the environment through uncontaminated waterways and improved air quality.
  - China as a hypothetical case study
- Energy Efficient Wall Material
  Hemp lime construction material properties not only complies with international building material code standards, it possesses superior thermal insulating properties and maintains good indoor air quality.
  - UK Hemp buildings case studies
- Cradle to Grave Life Cycle Assessment
  Studies has documented Hempcrete as a negative embodied carbon building material. Hemp-lime material is recyclable and the rest of the plant has commercial value. It demonstrates an environmentally sustainable cradle to grave life cycle.
  - Australia business case report

REMEDIATING BROWNFIELD SITES

Industrial hemp has soil phytomediation properties as studies have shown that it was tolerant and can remove heavy metals contaminants such as cadmium (Cd) [1], often present on landfill sites. In soil conditions such as abandoned mined land, with heavy metals contaminants as well as industrial site where soil is polluted with radioactive caesium, hemp has shown qualities of phytoextraction with most of the heavy metal accumulation on the leaves (Laura, C. 2012). Hemp (*Cannabis sativa* L.) was used to examine its capability as a renewable resource to decontaminate heavy metal polluted soils. The influence of heavy metals on the fibre quality was of special interest. Determination of heavy metal content was carried out by means of atomic absorption spectroscopy (AAS). Four different parts of the plant were examined: seeds, leaves, fibres and hurds. All parts of hemp plants contain heavy metals and this is why their use as a commercially utilisable plant material is limited. The highest concentration of all examined metals was accumulated in the leaves (P. Linger, et al., 2002). In fact, with reference to the nuclear explosion in Chernobyl, Phytotech used hemp as the phytoremediation crop to remove leech toxins from the soil after Chernobyl. "Hemp is proving to be one of the best phyto-remediative plants we have been able to find," said Slavik Dushenkov, a research scientist with PHYTOTECH.

Case Study Singapore: This case study shows great potential of cultivating industrial hemp on landfills in Singapore’s Pulau Semakau. Pulau Semakau (or Semakau Island) is an off-shore island about 10 km south of Singapore Island. Pulau Semakua and its neighbouring island Pulau Sekang, were developed in 1995 to be Singapore’s landfill. Its total landfilling capacity is 63 million m^3. Semakau Landfill is filled mainly with ash produced by Singapore's four incineration plants. These plants incinerate the country's waste and ship ashes to Semakau landfill in a covered barge (to prevent the ash from getting blown into the air) every night. The landfill only accepts non-organic waste such as incinerated ash and non-incinerable materials transformed into little ground subsidence with zero landfill gas production (e.g. methane). In 2005, the Semakau landfill was officially opened for recreational activities for interest groups to appreciate the biodiversity through intertidal walks. However, after 2045, when Semakau landfill can no longer accommodate further waste disposal, a new solution will need to be found. (NEA, 2011). The Singapore National Environmental Agency (NEA) has set targets to strive ‘Towards Zero Landfill’ and ‘Close the Waste Loop’ (The Singapore Green Plan, 2012). Research has been conducted to use incinerated waste as road paving, thereby reducing bottom ash sent to Pulau Semakau. Apart from reducing and recycling waste to meet the Singapore Green Plan 2012, cultivation of phytoremediating industrial hemp as part of the leachtate treatment and removal of remnant heavy metal pollutants can help turn waste landfill into useful land for economic crop cultivation and potentially increase Singapore’s landmass for future industrial building sectors. As part of the Population White Paper, 2013, Singapore has projected a population growth to 6.5 to 6.9 million by 2030 from the current 5.3 million, where they will need to create, optimise and recycle land to support the future generations of Singapore (MND, 2013).

Advantages:

i. With an area of 350ha and still growing, cultivating industrial hemp on Pulau Semakau can provide additional land for industrial areas as zoned by the latest Land Use Plan (MND, 2013).
ii. Hemp building products can be manufactured using the harvested plant to provide for the increased need of building materials.
iii. Bio-energy can be produced from hemp seeds and other parts of the plant where biomass energy can be generated from the neighbouring Jurong Island Sembcorp's Biomass Power Station.

EASE OF SUSTAINABLE FARMING

Hemp can be grown organically, which is critical in protecting surrounding biodiversity since research has shown that fish numbers are adversely affected by fertilisers and pesticides. Only eight, out of about one hundred known pests, are harmful to hemp, and hemp is most often grown without herbicides, fungicides or pesticides. Hemp is also a natural weed suppressor due to fast growth of the canopy (HIA, 2009). Hemp when grown as part of an organic farm rotation to produce textile quality fibre was found to have a low environmental footprint of with 1 hectare requiring 6,596MJ/ton of fibre less energy than conventionally grown hemp, and with no loss in yields (Cherrett, 2005).

Hemp lends itself to an organic farming rotation and its requirements for fertilization can be achieved without the use of artificial fertilisers (Robson 2001, Wright 1995, Vogl, 2004). Almost 70% of its nutrients are returned to the soil if it is field retted. Its leaves are shed rapidly throughout growth providing a leaf litter mulch for the soil that protects it from wind and rain erosion, and provides nutrients and holds in moisture. Hemp removes heavy metals and other toxins from the soil (Angelova, 2004). Its large deep tap roots (2-3m) enrich the soil by bringing essential nutrients up from the sub-soil and its roots rot quickly breaking up the soil improving its condition. As a land clearing crop, hemp frees fields of most weeds and also several soil pests for the crop (Robson, 2001).

However, should it be a brownfield site where suitability of hemp cultivation needs to be assessed, hemp grows well on deep, free-draining and sandy or silty loam soil with high organic matter that is well-aerated with pH 6.2-7. It grows well with soil containing nitrogen (140-180kg/ha), phosphorus (50-80kg/ha), potassium (60-80kg/ha), calcium and magnesium. Approximately 3-5 ML/ha of water (300-500mm rain/irrigation) is required over the 3-4 month crop growing period, varying according to soil type and depth, initial soil moisture content, soil water holding capacity, irrigation systems, temperatures reached and evapo-transpiration rates. Hemp does not require any herbicides for weed control and is pest-tolerant and pests rarely cause economic damage, particularly in fibre crops (Phil Warner, 2010). However, it is not well suited on compacted soils or waterlogged areas so this might limit certain ground sites to remediate.

Case Study China: China's increasingly restive population of 1.3 billion people faces the following environmental catastrophes on a daily basis.

From air pollution, in January 2013 alone, there were 19 days when the index in Beijing surpassed the 300 threshold set by Environmental Protection Agency's air quality scale. Any pollution rating above 300 means the air is unsafe to breath, and readings above 500 are no longer unusual. On Jan. 12, the reading reached an eye-bleeding 886, comparable to living inside a smoking lounge (Marc Lallanilla, 2013).

More than half of China's surface water is so polluted that cannot be treated to make it drinkable (The Economist, 2013), and one-quarter of it is so dangerous it can't even be used for industrial purposes. Groundwater isn't any safer: about 40 percent of China's farmland relies on underground water for irrigation, and an estimated 90 percent is polluted (Reuters, 2013).

In terms of desertification resulting from rural urban to migration, the destruction of vegetative land cover that resulted in a landscape made of bare soil and rock. According to IPS News Agency about 1 million square miles (2.6 million sq km) of China is now under desertification — that's about one-quarter of the country's total land surface, spread across 18 provinces. The resulting loss of arable land has created a generation of "eco-migrants," the Guardian reports, who are forced to leave their homelands, because their traditional agricultural lifestyle is no longer an option (Marc Lallanilla, 2013).

Advantages: In this case where hemp can be used as an organic farming rotation crop for use as part of their agricultural farming industry, China could potentially reduce their dependence on polluting fertilisers and use non-arable land for food cultivation so as to preserve their forest biodiversity.

ENERGY EFFICIENT WALL MATERIAL

In the case for rural parts of China, India, Myanmar and other ASEAN regions, hemp-lime construction can provide low-cost, basic construction methods, for 'green' buildings.

Hemp-lime wall construction material is comprised of hemp hurd (or shiv), the woody core of the industrial hemp plant, and lime-based binders to form a bio-composite material, similar to lightweight concrete, with the hurd as the aggregate and lime as the binder.

One hectare of hemp is sufficient to build a standard house. It grows up to 4 meters high in 14 weeks. Sixty percent of the plant can be used in buildings (Hempcrete, 2013).

Hemp lime construction is less dense than masonry with typical densities of 300-450 kg/m3 for hand tamped wall infill and even lower densities when the mix is spray applied (Bevan & Woolley, 2008). Typical densities of hemp lime masonry depends on whether blocks are used for structural or thermal applications. Thermal blocks densities range between 300 and 500 kg/m3 (Chanvribloc, 2010; Lime Technology, 2009a) while structural blocks between 600 and 1200 kg/m3 (Lime Technology, 2009b; Bütschi et al., 2003; Bütschi et al., 2004), as such hemp lime construction would generally not be of equivalent density as concrete (Daly, et al., 2009).

Benefits of hemp-lime construction

Good Thermal Properties: Hemp-lime construction is growing in popularity in the European region due to its superior thermal performance. Generally, a 200mm normal mix of Hempcrete would provide a U-value of 0.45 W/m^2K, which would be 7 times more than that of concrete walls. In more detail, the thermal conductivity values across a range of studies on hemp lime wall infill vary between 0.06 and 0.13 W/mK depending on the density and composition of the mix. Work by Cerezo reports values of 0.06 to 1.0 W/mK for low density mixes of 200 kg/m^3 and 0.1 to 0.13 W/mK for medium density mixes of 450 kg/m^3, (Cerezo, 2005). Thermal conductivity values for hemp lime masonry are generally influenced by whether blocks have thermal or structural function, and their overall mix and compaction methods. For example results from studies on hemp lime cement block samples, that were machine vibrated and compacted, recorded a value of 0.34 W/mK (Bütschi et al., 2004) while hemp lime block samples from a different study that were spray applied reported values ranging from 0.179 to 0.543 W/mK (Elfordy et al., 2007).

Good Indoor Air Quality: Hemp-lime material has a hygroscopic nature which does not allow water droplets to penetrate inside the building, but allows interior moisture to escape, therefore avoiding indoor moisture built-up. This means that the humidity and air quality inside the building are controlled. With reference to ASTM standards, hemp lime walls of either masonry or infill are generally finished with a lime based external render and the literature review of hemp lime constructions has indicated no evidence of moisture penetration failures (Daly, et al., 2009). Hemp lime impact on indoor air quality is considered positive in part due to its vapour permeability, with reports of good humidity balancing and limitations on condensation which restrict mould growth (Bevan & Woolley, 2008). The lime portion of the mix acts as a biocide making hempcrete buildings naturally pest, mould and mildew resistant (Hempcrete, 2013).

Fire Resistance: Hemp lime mix is fire resistance and non-combustible when tested using BS EN standards. A 200mm thick hemp-lime wall construction, a fire resistance of 1.5hrs can be reached based on BS EN 1351, and is non combustible tested with the EN ISO test report (Daly, et al., 2009).

Non-toxic: The toxicity of hemp and lime processing and use in construction is limited to the production of dusts. Dusts can irritate lungs and form part of photochemical oxidants (Berge, 2000). Hemp lime bio-composite is a natural material with no or very little toxicity or off gassing, therefore its toxicity during demolition process is very low (Daly, et al., 2009).

Flexibility in Usage:

Hemp-lime wall cast in-situ method

The hemp-lime mix can either be cast within shuttering or sprayed onto the wall using a compressed air concrete sprayer. The casting method involves constructing a wooden framework against the wall to which temporary shuttering can be applied. The hemp-lime is poured into the framework, in layers approximately 200mm to 300mm thick and is tamped into place. It is important not to over or under tamp as the material will become too dense or too porous (respectively). Dense materials have lower thermal performance and loose materials lack sufficient structural stability. (Bevan & Woolley, 2008; Rhydwen, pers. comm.). The initial set is sufficient to allow the shuttering to be removed shortly after tamping, so it can be re-used in a subsequent section of the framework (Daly, et al., 2009). The spraying process is theoretically quicker and should result in a less dense and more even coating. However is more energy intensive.

The drying out and curing time for hemp-lime is dependant on the mix, the climate and the weather and may take weeks (Bevan & Woolley, 2009) to months (Rhydwen, pers. comm.).

Application of hemp-lime as insulation to internal walls can also be done as retrofitting works to improve existing external wall insulation. Hydrated or hydraulic lime can be used to make hemp-lime, dependent on the intended function. For walls, a mixture of 2:1 hydrated lime / hydraulic lime is recommended (Rhydwen, pers. comm.). Variations to the proportion mix can also be used for roof insulation.

Hemp-lime prefabricated module method

Prefabricated panels, bricks and blocks are a possible application most likely in framed constructions where they are used in conjunction with a structural frame and as such require no direct load bearing function. Typical solutions are floor-to-floor panels with either insulation applied, e.g. a secondary insulated stud wall to the internal side of the pre-cast panels, or integral as a pre-cast sandwich panel with an insulation core (Daly, et al., 2009). Many suppliers worldwide including UK's Limetechnology, Spain's Cannabric, and France's Chanvibloc, are examples of suppliers who have developed prefabricated hemp panels, blocks and bricks for commercial buildings. Hemp lime products have been used in commercial projects, amongst them, is a seven storey office building built for the Regional Government Office of Housing and Environment in Clermont Ferrand, France (Bevan &Woolley, 2008), where hemp lime blocks have been used as insulating wall infill in association with a wood and concrete structure.

One example of commercial prefabricated panels is the wine society warehouse in Hertfordshire, UK. Hemp lime has been employed for the production of pre-fabricated 3.6 by 2.4 m panels of 400mm thick-sprayed products within timber cassettes. Panels are supported by a structural steel frame and were employed for the construction of a 50,000 m3 warehouse housing more than 3.5 million bottles of wine (Lime Technology, 2010).

Case Study Hemp Buildings: Whilst hemp building were predominently used for residential homes dating back 300 years ago in Japan, more notable advancement for commercial scalability has been used in UK and France with a number of significant demonstration projects and emerging commercial activities. Hemp lime has been used in France since the early 1990s. It was initially discovered and successfully used as material for the restoration of historic timber buildings. It was later employed in new construction as wall infill in combination with structural timber frame, as well as insulation for floor and roof. In the UK, Lime Technology, the major processing company of industrial hemp in the UK, has been manufacturing and distributing hemp hurds and lime binder under the Tradical® Hemcrete® trademark for about ten years (Lime Technology, 2007). One of its key demonstration and dissemination projects was a social housing development for the Suffolk Housing Society in 2001, with important performance assessment data carried out by the BRE and being widely disseminated via the Internet. conducted field test measurements of the thermal conductivity of a 200mm thick hemp lime wall with a density of 463kg/m3,using a thermal probe, (test method unknown). His study showed that the thermal conductivity of the wall was in the range of 0.072 W/mK to 0.099 W/mK (Pilkington, 2006). Hemp Lime thermal conductivity values are generally superior to concrete and subject to detailing can have additional benefits in terms of reduced thermal transmission at junctions, which reduces overall heat loss during winter. Using a hemp lime block in place of the concrete block will give a 5.7% reduction in heat loss through the junction. (Daly, et al., 2009).

Advantages: Hemp-lime is an energy efficient building façade material, that provides good indoor air quality, while it is resistant to termite resistant and fire. It is a low operating cost material for passive building designs. As a holistic masterplan of hemp cultivation through to hemp building construction, a low carbon community with low urban heat island and green economy can potentially sprout around developing regions in many parts of Asia.

CRADLE TO GRAVE LIFE CYCLE ASSESSMENT

A hemp lime mix can be recycled at the end of its life by crushing it, mixing it with water and some additional lime binder and casting it anew. This applies to any form of hemp lime application, be it monolithic walls, bricks or blocks. The material also has potential for recycling in other applications such as composting, backfill or crushed up and spread on flower beds or fields in order to increase the ph of the soil and use as a mulch. Being made of a biomass (hemp shiv) and carbonated lime, the hemp lime mix would have minimal environmental impact if sent to landfill. It may also be possible to break it up and disperse it onto land or agricultural fields, where the hemp shiv would biodegrade and lime (calcium carbonate) would blend with the soil. (Lime Technology, 2007).

Research has shown that manufacturing and use of hemp-lime construction as an eco-friendly building material has negative embodied energy. From a complete life-cycle assessment conducted on a typical house in UK, a likely case of -.7kg/CO/m^2 of atmospheric carbon dioxide can be sequestered from growing, manufacturing, transporting, and building a house with hemp-lime construction. (Miskin, 2010)

The breakdown of the carbon sequestration excluding transportation, which depends on the house location, is as follows:

In one cubic metre mix of hempcrete, emitted CO_2 is:
- 110kg of hemp hurd = - 202 kg (CO_2 absorbed)
- 220 kg of lime binder = +94 kg (CO_2 released)
- Total sequestration = -108 kg/m^3 of wall built (Hempcrete, 2013).

Case Study Australia: Industrial Hemp Association of Queensland Inc. prepared a recommendation study on a business case of industrial hemp production where they suggested that, because of its unique properties for carbon bio-sequestration, as an export food crop in times of uncertainty to world food security, and as a contributor to eco-friendly building materials science and bio energy, it is clear that fast growing industrial hemp is a major asset in the fight against climate change as well as to claim carbon credits (IHAQ, 2011).

They acknowledged that hemp is capable of enhancing carbon removal because of its properties such as the ability to provide temporary cover between planting seasons and cover bare paddocks with vegetation .This protects soil from the sun and allows the soil to hold more water and be more attractive to carbon-capturing microbes, and restore degraded land, which slows carbon release while returning the land to agriculture or other use (IHAQ, 2011).

They see this as a perfectly suited large scale agribusiness providing income to farmers. A conservative estimate of the total retail value of hemp products sold in the United States in 2007 is $350 Million (Hansen, 2012).

CONCLUSION

With the growing popularity of hemp building, there have been several social housing schemes that have been built with hemp lime in France. Around 4,000 tons of hemp hurds are used annually by the building industry, with an overall value of € 35 million (Woolley, 2006). This is well demonstrated by the fairly large number of companies identified that are involved in the production, distribution and application of hemp lime materials in France. And in the UK, a 42 hemp home development in Swindon called the Triangle has recently been completed as passively design homes to address the British concern of energy efficiency (Moore, 2011).

Unfortunately, the propagation of hemp cultivation and hemp building faces the controversy of it belonging to the family of cannabis species and does produce the cannaboid tetrahydrocannabinol (THC, the narcotic in hemp) in minute quantities. The minute THC level, generally at 0.3%, is mainly on the leaves and flowers instead of the hemp hurd. Recreational cannabis can produce up to 20% THC and European legislation insists on THC levels being below 0.2% (ADAS 2005). There are now some cultivars that produce no THC at all (Weightman 2005) and such future development on a commercial scale could potentially address many green building and environmental protection issues.

Another area for further research would be to improve the compressive strength of hemp-lime mix with bio additives. For hemp lime infill, compressive strength values reported by Cerezo range between 0.25 and 1.15 MPa (Cerezo 2005), compared with values from a test method for cellular plastics - BS ISO 844: 1998, of between 0.46 and 0.84 N/mm2, (BRE 2002). And for prefabricated blocks, should cement be used as an additive, which is not encouraged due to its high embodied energy, tests carried out by Bütschi et al on hemp lime cement block samples show compressive strengths ranging 1.3 and 3.4 MPa, (Bütschi et al., 2003 and 2004), with results from Chew & MacDougall reaching compressive strengths values up to 13.58 N/mm2 based on significant cement addition, (Chew & MacDougall 2007). A number of studies report the high deformation capacity of hemp lime, which is effected by compaction and also presence of fibres. Results from flextural tests on hemp lime mixtures range from 0.38 (infill mix) to 1.21 N/mm2 (block mix), (BBA, 2010), (Elfordy et al., 2007). Higher values ranging between 6.8 and 9.5 N/mm2 are reported for a mix of hemp fibre reinforced cement, (Sedan et al., 2007).

Tensile strength values for a hemp lime sand mix ranged between 0.08 and 0.25 N/mm2 and average at 0.16 N/mm2, (O'Dowd & Quinn, 2005). An extreme value of 11.9 N/mm2 has been reported for a mix containing hemp shives and cement. (Bydžovský & Khestl,2007).

Further research is underway to improve hemp-lime structural strength in prefabricated panels as hemp lime material predominanatly is not a load bearing wall. Bio-additives can be added to improve its compressive strength and speed of curing, where research on pozzolan, metakaolin, magnesium oxide and other potential polymers are being studies.

Despite its limitations on structural strength, the versatility of colour of hemp-lime mixes through colour pigments provide a myriad of aesthetical preference of colour and a variety of pattern formwork to the designers' creativity. This makes for varied interesting wall designs using one simple material.

Whilst economic development activities such as mining or infrastructure and building construction are unavoidable for a sustainable development, regulated rehabilitation of abandoned mines, landfill mining, and a renewable source of eco-friendly building material can address these environmental problems.

Asia's needs of efficient infrastructure and buildings to feed their growing population is growing, especially in India where arable land is depredated by their large mining sector and unregulated open dumping landfill grounds. Irresponsible mining operations have damaged the health, water, environment, and livelihoods of neighbouring communities (Human Rights Watch,, 2012), and open landfill dumpsites are breeding grounds for diseases posing threat to human health.

Whilst economic development activities such as mining or infrastructure and building construction are unavoidable for a sustainable development, a holistic 'green' masterplan through this economic crop cultivation, industrial hemp, can provide for an environmentally sustainable, low cost building infrastructure, within a low carbon life cycle cradle to grave framework.

Singapore's 1st Hemp Building: Finally, the Singapore's 1st hemp building has just been completed in Singapore Botanic Garden and is due to open in November 2013. This is a gallery project by developer City Development Limited (CDL) in collaboration with National Parks Board of Singapore. This building, CDL Green Gallery @

SBG Heritage Museum is also designed to be a zero energy air-conditioned gallery space to showcase the botanical artwork of the Botanical Garden.

This air-conditioned 250sqm building uses a fully unitised prefabricated building construction method, where Unitised Building, UB® System, provides for the main structural carcass. All the components will be prefabricated and assembled in the factory before being transported to the site to minimise any environmental disruption at SBG. Like building blocks, these structures are modular and will be pieced together onsite to form the building. The benefits of the UB technology is its flexibility, easy-to-build modular system which results in faster construction time, superior quality, lower environmental impact; and the structure can also be recycled at the end of its life. This could possibly be one of the fastest "buildings" to be constructed in Singapore.

However, being made of steel as the structure and building envelop, the solar heat gain on the façade of the air-conditioned gallery would be high as metal has high thermal conductivity. Therefore, a mix of Hempcrete and vertical green walls are used to clad this metal building envelop, creating a visual mix palette of bio-façade material that has low embodied energy.

Hempcrete as the external wall material is imported from Australia and contains no THC levels. In this project, a 200mm wall thickness was used to provide a u-value of $0.45W/m^2K$. It also complies with a 1.5hours fire resistance and has been tested to be non combustible. The hemp-lime construction method in this project was a mix of prefabricated panels and cast-in-situ Hempcrete done in the factory before being transported to Botanic Garden site. In this project, a varity of colour pigments, and recycled aggregates of which the natural Hempcrete texture was left exposed to demonstrate the natural beauty of the hemp building material texture. However, a coat of lime render had to be applied as a finishing coat to ensure the durability of this material in Singapore's harsh rainy, hot and humid climatic conditions.

Field studies shall be conducted on the performance of these hemp external walls in relation to application in tropical climates such as Singapore. Other areas of interest also include formulation of load-bearing prefabricated panels that have low embodied energy for future applications around Asia, as well as the appropriate additives in hemp-lime construction material for ideal hydrothermal balance for tropical countries.

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DESIGN OF DURABLE CONCRETE MIX FOR SUSTAINABILITY

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ABSTRACT

In order to achieve the sustainability of social development, low carbon emission has played more and more important role. In this complex world scenario, infrastructure regeneration and rehabilitation; cement and concrete materials have an undeniable part to play in enhancing the quality of human life. If we are to avoid unredeemable environmental degradation globally, sustainable development of the cement and concrete industry has to be the foundation for all construction activity in the next millennium. The durability of cement and concrete materials is closely related to low carbon emission and energy saving. High performance and high durable concrete materials can contribute to the saving of raw materials, reducing of cement usage as well as low maintenance for long life. In order to achieve the objective of low carbon emission for ready mix concrete products, the design of concrete mix should be reconsidered. In this paper, the principles of ready mix concrete design has been discussed based on the durability requirements according to the new concrete Standard SS EN206-1. In every step of the design, the requirements of low carbon emission and green materials has been considered. Examples of design procedures are also illustrated in this paper for easy reference.

INTRODUCTION

Concrete material is one of the important construction materials with the highest volume in the construction industry today. To achieve low carbon emission for concrete industry, ready mix concrete should play very important role. To build low carbon emission building, low carbon and energy saving concrete must be available (R.N. Swamy, 2000).

Most of Singapore Standards (SS) for civil engineering are based on British Standards (BS) and BS has been integrated into European Standards. Since 2006, Spring Singapore and Building and Construction Authority (BCA) have organized experts in concrete industry to review and draft the new Singapore Concrete Standards SS EN 206-1(Spring Singapore, 2009) and complementary Standards SS 544-1 and SS 544-2 (Spring Singapore, 2009). These new standards were officially published in 2009.

In SS 544-1: Method of specifying and guidance for the specifier, the basic and additional requirements for different concrete mix are listed. In this paper, different kinds of concrete will be introduced according to SS 544-1. The design procedure and methods for different concretes will be discussed. The consideration of low carbon and green requirements has been incorporated into the mix design method. An example is used to illustrate the every step of the concrete design.

CONCRETE SPECIFICATION BY SS 544-1

SS 544-1 offers five approaches to the specification of concrete (Spring Singapore, 2009):

a. Designated concretes: For many common applications, the simplest approach is to specify a designated concrete. Designated concretes were developed to make the specification of designed concretes simpler, complete and more reliable.
b. Designed concretes: Designed concretes are suitable for almost all applications. They may be used as an alternative to designated concrete and should be used where the requirements are outside of those covered by designated concretes.
c. Prescribed concretes: This approach allows the specifier to prescribe the exact composition and constituents of the concrete. It is not permitted to include requirements on concrete strength, and so this option has only limited applicability.
d. Standardised prescribed concretes: Standardised prescribed concretes are applicable for housing and similar construction where concrete is site-batched on a small site or obtained from a ready-mixed concrete producer who does not have accredited third-party certification.
e. Proprietary concretes: This approach is appropriate where it is required that the concrete achieves a specific performance, using defined test methods.

Generally, in Singapore, most concrete supplied in the market is designed concrete. For designed concrete, the specification requirements according to SS 544-1 are listed as below (SS 544-1, 2009):

Basic requirements:
a. a requirement to conform to SS 544-2;
b. the compressive strength class (Table 1);

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c. the limiting values of composition, e.g. maximum *w/c* ratio, minimum cement content or the DC-class where appropriate (Table 2);
d. where the DC-class has not been specified, the permitted cements and combinations (Table 3);
e. the maximum aggregate size where a value other than 20 mm is required;
f. the chloride class where a class other than Cl *0.4* is required;
g. for lightweight concrete, the density class or target density;
h. for heavyweight concrete, the target density;
i) the class of consistence or, in special cases, a target value for consistence (Table 4).

Additional requirements:

a. special types or classes of aggregate, e.g. for wear resistance or freeze-thaw resistance;
b. where the use of coarse RA is deemed acceptable, a statement that coarse RA is permitted and a requirement for the RA to conform to SS 544-2 : 2009, 4.3;
c. restrictions on the use of certain aggregates;
d. generic type and dosage of fibres;
e. characteristics required to resist freeze-thaw attack, e.g. air content ;
f. requirements for the temperature of the fresh concrete, where different from the lower limit in SS EN 206-1 : 2009, 5.2.8 or the upper limit in SS 544-2 : 2009, 5.4;
g. strength development;
h. heat development during hydration;
i. retarded stiffening;
j. resistance to water penetration;
k. resistance to abrasion;
l. tensile splitting strength;
m. other technical requirements, e.g. requirements related to the achievement of a particular finish or special method of placing;
n. any "concerning" effects together with the tests to be applied and the acceptability criteria.

LOW CARBON EMISSION CONSIDERATION FOR SPECIFICATION

As we know, carbon emission of concrete mainly comes from cement production. One ton of carbon dioxide will be released for production of one ton of cement. There are 3 main sources of carbon emission from cement production as shown in Fig 1.

a. Energy supplied to clinker kiln: 50% (300-450kg CO_2 per ton of cement);
b. Decomposition of limestone: 50% (450kg CO_2 per ton of cement);
c. Electricity and transportation: very low percentage.

Table 1 Compressive strength classes for normal-weight and heavy-weight concrete

Compressive strength class	Minimum characteristic cylinder strength N/mm^2	Minimum characteristic cube strength N/mm^2
C8/10	8	10
C12/15	12	15
C16/20	16	20
C20/25	20	25
C25/30	25	30
C30/37	30	37
C35/45	35	45
C40/50	40	50
C45/55	45	55
C50/60	50	60
C55/67	55	67
C60/75	60	75
C70/85	70	85
C80/95	80	95
C90/105	90	105
C100/115	100	115

Table 2 Limiting values of composition and properties for concrete where a DC-class is specified

DC-Class	Max, w/c ratio	Min. Cement content for 20mm aggregate	Cement and combination types
DC-[1A)]	-	-	All
DC-2	0.55	320	IIB-V+SR, IIIA+SR, IIIB+SR, IVB-V
	0.50	340	CEM I, SRPC, IIA-D, IIA-Q, IIA-S, IIA-V, IIB-S, IIB-V, IIIA, IIIB
	0.45	360	IIA-L or LL≥42.5
	0.40	380	IIA-L or LL 32.5
DC2z	0.55	320	All
DC-3	0.50	340	IIIB+SR
	0.45	360	IVB-V
	0.40	380	IIB-V+SR, IIIA+SR, SRPC
DC-3z	0.50	340	All
DC-4	0.45	360	IIIB+SR
	0.40	380	IVB-V
	0.35	380	IIB-V+SR, IIIA+SR,SRPC
DC-4z	0.45	360	All
DC-4m	0.45	360	IIIB+SR

[A)] If the concrete is reinforced or contains embedded metal, the min concrete quality for 20mm maximum aggregate size is C25/30, 0.65, 260

Table 3 Maximum chloride content of concrete

Concrete use	Chloride content class[a]	Maximum CI content by mass of cement[b]
Not containing steel reinforcement or other embedded metal with the exception of corrosion-resisting lifting devices	Cl 1.0	1.0 %
Containing steel reinforcement or other embedded metal	Cl 0.20	0.20%
	Cl 0.40	*0.40 %*
Containing prestressing steel reinforcement	Cl 0.10	*0.10 %*
	Cl 0.20	0.20%

[a] For a specific concrete use, the class to be applied depends upon the provisions valid in the place of use of the concrete.
[b] Where type II additions are used and are taken into account for the cement content, the chloride content is expressed as the percentage chloride ion by mass of cement plus total mass of additions that are taken into account.

Table 4 Slump Class

Class	Slump in mm
S1	10 to 40
S2	50 to 90
S3	100 to 150
S4	160 to 210
S5	≥ 220

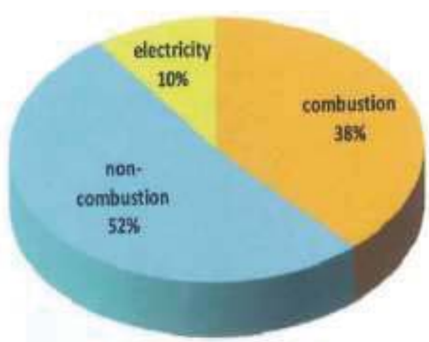

Fig 1 Carbon emissions in cement production

Therefore, for the design of low carbon concrete the first choice is to use the minimum cement content to produce durable and high performance concrete mix to meet the requirements of structure design. Choice of suitable raw materials, including concrete admixture, is the second consideration. It is followed by usage of industry and construction waste materials. Design of durable and high performance is essential for green concrete.

Design of high performance concrete to replace normal concrete

Compared to normal concrete, the use of high strength concrete can reduce the structure size, so that not only the volume of concrete materials, energy consumption and manpower can be reduced; but also the usable area of the building can be increased. It is illustrated in Table 5 where, for the same loading capacity, the columns with high performance concrete can save up to 55% of concrete volume or 18% cement usage. Although the cement content per m^3 concrete is increased, the following effectiveness can be achieved:

a. Increasing of compressive strength of concrete can reduce concrete volume;
b. The weight of structure is reduced, so that the size of foundations can be reduced.
c. The design for earthquakes can be reduced.

Table 5 Comparison between high performance concrete and normal concrete

Type of Concrete	Normal (28 MPa)	High Performance (62 MPa)
Total binding materials(kg/m^3)	330	510
Mineral Addition (kg/m^3)	65 fly ash	24 silica fume
OPC(kg/m^3)	260	490
Column size(mm)	900 X 900	600 X 600
Concrete volume(m^3)	3.8	1.7
Volume reduction(%)	-	55
Cement reduction (kg)	1000	820
Cement reduction(%)	-	18

Use supplementary cementing materials

There are 27 types of cement in the new cement standards SS EN 197. With the exceptions of of CEM I and SRPC, all other cements contain supplementary cementing materials. In SS 544-2, cements are grouped into 7 categories, as shown in Table 6.

Table 7 shows the comparison of energy consumption of ordinary cement with supplementary cementing materials. To produce 1 ton of cement with 65% slag powder only needs 0.5 ton raw materials, and 1,500-1,600MJ of energy. Every ton of cement can save at least 6,000 MJ energy.

To produce one ton cement, 1.0-1.2 ton of CO_2 will be released. Table 8 provides a comparison of concrete with supplementary cementing materials. It can be seen that cement with 30% fly ash can reduce carbon emission by 20%, while cement with 50% GGBS can reduce Carbon emission by 43-50%.

Table 6 Categories of Cements

CEM I	Portland cement
SRPC	Sulfate-resisting Portland cement
IIA	PC with 6 to 20% other material
IIB-V	PC with 21 to 35% fly ash
IIIA	PC with 36 to 65% ggbs
IIIB	PC with 66 to 80% ggbs
IVB-V	PC with 36 to 55% fly ash

Table 7 Comparison of energy consumption

Energy Consumption		
Cement	7,500	MJ/ton
Fly Ash	150-400	MJ/ton
Slag	700-1,000	MJ/ton
CO_2 emission		
Cement	1.0-1.2	Ton/ton clinker

In conclusion, for the design of low carbon concrete, the principles for choosing cement should be as below:

a. Avoid to only use Ordinary Portland Cement;
b. For normal construction, to use II B-V or III A cement (Table 2 and 7);
c. For underground or marine construction, to use IV B-V or III B cement.

<u>Use recycled aggregate to replace natural aggregate</u>

Worldwide concrete industry faces the problem of shortage of aggregate resources. Looking for new sources of aggregate for concrete production started decades ago.

There are various studies on usage of sea sand, recycled concrete aggregate, mining tail and manufactured aggregate, etc. How to effectively use all available aggregate for concrete production is very important, especially for Singapore, which is a small country without any natural resource of aggregate. Compared to the old Singapore Standard on aggregate SS 31, the new Singapore Standard SS EN 12620 covers a wider range of aggregates, including natural aggregates, recycled aaggregate as well as industry by-products. Complementary Singapore Standards for concrete SS 544-2 provides the definition and requirements for recycled aggregate.

Table 8 Comparison of carbon emission

Carbon emission (kgCO2/m3)			**Comparison to Normal concrete**	
Normal concrete	30% fly ash concrete	50% slag concrete	30% fly ash concrete	50% slag concrete
208	161	104	78%	50%
217	174	109	80%	50%
291	233	155	80%	53%
310	252	170	81%	55%
342	281	196	82%	57%

The definition of recycled aggregate in SS EN 206-1, Clause 3.0:

- Manufactured aggregate: aggregate of mineral origin resulting from an industrial process involving thermal or other modification.
- Recycled aggregate: aggregate resulting from the processing of inorganic material previously used in construction

The definition in SS 544-1, Clause 3.1:

- Recycled aggregate (RA): Aggregate resulting from the reprocessing of inorganic material previously used in construction.
- Recycled concrete aggregate (RCA): Recycled aggregate principally comprising crushed concrete.

The definition of recovered aggregate in SS EN 206-1, Clause 5.2.3.3:

- Recovered aggregate: Aggregate recovered from wash water or fresh concrete may be used as aggregate for concrete.

SS 544-2 specified the quality requirements of recycled aggregate as shown in Table 9.

SS 544-2 limits the usage of recycled coarse aggregate only for the concrete as listed in Table 10.

Clause 6.2.2 of SS 544-2 limits the usage of recycled aggregate: Where coarse RA or RCA is to be used in designated concretes *RC20/25* to RC40/50, its proportion shall be not more than a mass fraction of 20 % of coarse aggregate except where the specification permits higher proportions to be used.
RA or RCA shall not be used in any of the FND or PAV designated concretes nor in designated concrete RC50XF.

Table 9 Requirements for coarse RCA and coarse RA

Type	Requirement [A]					
	Max masonry content	**Max fines**	**Max light-weight material [B]**	**Max asphalt**	**Max other foreign material e.g. glass, plastics, metals**	**Max acid-soluble sulfate (SO_3)**
RCA [A)C)]	5	5	0.5	5.0	1.0	1.0
RA	100	3	1.0	10.0	1.0	- [D]

[A] Where the material to be used is obtained by crushing hardened concrete of known composition that has not been in use, e.g. surplus precast units or returned fresh concrete, and not contaminated during storage and processing, the only requirements are those for grading and maximum fines.
[B] Material with a density less than 1000 kg/m^3.
[C] The provisions for coarse RCA may be applied to mixtures of natural coarse aggregates blended with the listed constituents.
[D] The appropriate limit and test method needs to be determined on a case-by-case basis.

Table 10 Limit of recycled coarse aggregate for concrete

Type of Aggregate	Limitations on use	
	Maximum strength class[A]	Exposure classes [B]
RCA	C40/50	XO, XC1, XC2, XC3, XC4, XF1, DC-1

[A] Material obtained by crushing hardened concrete of known composition that has not been in use and not contaminated during storage and processing may be used in any strength class.。
[B] These aggregates may be used in other exposure classes provided it has been demonstrated that the resulting concrete is suitable for the intended environment, e.g. freeze-thaw resisting, sulfate-resisting.

Table 11 Use of Concrete admixture to reduce cement content

Water reducing Rate (l/m^3)	**Water reducing Rate** (%)	**Cement reducing (kg/m^3) (@0.55 w/c)**	**Cement reducing (kg/m^3) (@ 0.40 w/c)**
10	5.6	18	25
15	8.3	27	37
20	11.1	36	50
25	13.9	45	62
30	16.7	54	75

In SS EN206-1, undivided recovered aggregate shall not be added in quantities greater than 5 % of the total aggregate. Where the quantities of the recovered aggregates is greater than 5 % of the total aggregate, they shall be of the same type as the primary aggregate and shall be divided into separate coarse and fine fractions and conform to SS EN 12620.

Use of concrete admixture

Concrete properties can be modified by concrete admixtures. By using a concrete admixture, high performance durable concrete can be designed with low cement content, good workability, so that saving of raw materials, carbon emission, manpower and energy can be achieved. Table 10 shows the saving of cement content by using of concrete admixture.

In Summary, for design of low carbon emission concrete the following points shall be considered:

- Use supplementary cementing materials to replace OPC, for normal construction, CEM II B-V or III A cement should be used, while for underground and marine construction, CEM IV B-V or III B cement should be used;
- Use of concrete admixture;

- Use of recycled aggregate to replace natural aggregate;
- Avoid overdesign.

DESIGN PROCEDURE OF LOW CARBON CONCRETE

Design procedure according to SS 544-1

The design procedure for specifying concrete mix recommended by SS 544-1 is explained (T A Harrison and O Brooker, 2005) as below:

Step 1: Using Table A.1 in SS 544-1 to identify relevant exposure classes (Figure 3). If an aggressive chemical class is included, then go to Step 2. If not, then go to Step 10.

Step 2: Using Table A.2 to classify ground conditions.

Step 3: Using Table A.3 to select structural performance level.

Step 4: Using Table A.4 to select DC-Class and number of APMs.

Step 5: Are APMs recommended? If yes, go to Step 6, if no, go to step 10.

Step 6: Are starred or double-Starred classes available? If yes, go to Step 4. If no, go to step 7.

Step 7: Using table A.5 to select APMs

Step 8: is APM 1 included? If yes, go to Step 9, if no, go to step 10.

Step 9: Increase DC-Class by 1 class for each application of APM1.

Step 10: From Scheme design, note intended working life, compressive strength class, cover and margin (Δc).

Step 11: Consider and note other factors to be considered.

Step 12: Using Table A.10 to A.16 for each of the relevant exposure classes, note the nominal cover, limiting values and properties.

Step 13: Select the limiting values to be used in the specification.

Step 14: Is the resulting strength class or nominal cover different from that noted in Step 10? Are APMs other than APM1 required. If yes, go to step 15. If no, go to step 16.

Step 15: Take account of the changes in the design.

Step 16: Specify the basic requirement using clause 4.3.2 in SS 544-2 as a checklist.

Step 17: Specify any additional requirements and provisions using clause 4.3.3 as a checklist.

Step 18: Add, where relevant, information from the specifier using clause 5.1 as a checklist.

Step 19: Where required, list information required from the producer using clause 5.2 as a checklist.

Example of the design procedure

This example follows the steps illustrated on the above.

Suspended reinforced concrete internal office slab that will be carpeted:
The concrete will be pumped, compacted with a beam vibrator and finished with a bull-float. The columns of this building require C32/40 concrete.

As the slab is carpeted, there are no abrasion considerations. From Figure 3, the only relevant exposure class is XC1. For the determination of exposure class, Figure.3 can be referred to.

As there are no aggressive chemical classes, go to Step 10.

As this is a normal building structure, EN 1990: Basis of design, recommends an intended working life of (at least) 50 years.

The scheme design was done to EN 1990 and this assumed a C25/30 concrete with 25 mm nominal cover. There is also a need to select the margin and express the nominal cover as a minimum cover plus the margin (Δc).

EN 1992–1: Eurocode 2: Design of concrete structures – Part 1: general rules and rules for buildings gives guidance on the selection of the margin Δc. It indicates that the value should be a function of the level of control on site. However the consequence of low cover should also be a factor in its selection and as this is an internal environment with no real durability concerns, a value of 5 mm for Δc with normal levels of workmanship is appropriate. A value of 5 mm for Δc is selected. The nominal cover from the scheme design is therefore (20 + 5) mm.

Go to Step 11.

The specifier should select the maximum aggregate size and the consistence class (or target value). The specifier selects a maximum aggregate size of 20 mm. The concrete is reinforced and the specifier decides to follow the guidance in clause 4.2A in SS 544-1 for the chloride class, namely Cl 0.4.

The specifier selects slump class S3 as being suitable for the pumped concrete. As the concrete will be ready-mixed, the specifier decides that accredited third party certification is required.

Refer to Table A.4 in SS 544-1, the limiting values and properties of concrete and the nominal cover to reinforcement for the XC1 exposure is:

Nominal cover for durability is (15 + 5) mm and concrete C20/25, 0.70, 240 (from Table 12 for maximum aggregate size of 20 mm) and all cements/combinations in Table A.6.

There are no other exposure classes to consider. Go to Step 13.

For a nominal cover of (15 + 5) mm, the limiting values and properties of the concrete are C20/25, 0.70, 240, 20 mm maximum aggregate size and any cement/combination.

Cement or combination types IIIB and IVB are normally specified for situations requiring high resistance to chlorides, sulphates or other aggressive chemicals. They also tend to have low rates of strength development in thin sections. Because the exposure classes do not include XD, XS or aggressive chemicals, cement/combination types IIIB and IVB were discarded at this stage of the process. As SRPC is also a special cement used for producing sulphate-resisting concrete, it is also discarded. Go to Step 14.

Yes, there are differences between the durability design and the preliminary scheme design. Go to Step 15.

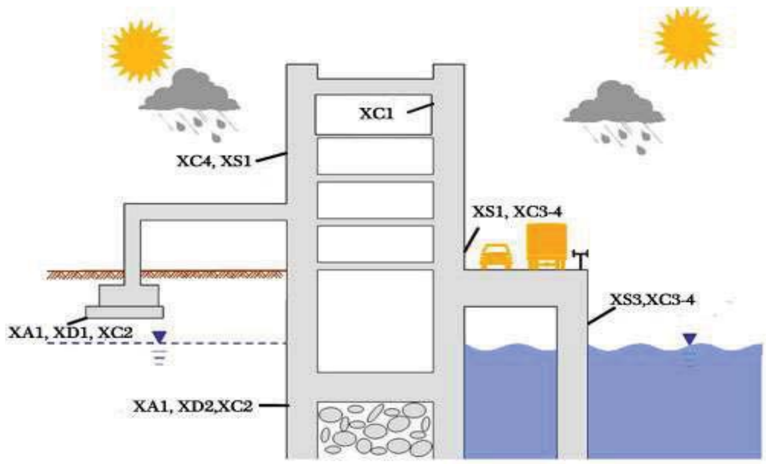

Figure 3, Exposure Class

Table 12 Durability recommendations for reinforced or prestressed elements with an intended working life of at least 50 years (extracted from Table A.4, SS-544-1)

Nominal **cover B)** mm	Compressive strength class where recommended, maximum water-cement ratio and minimum cement or combination content for normal-weight concrete C) with 20 mm maximum aggregate size)								Cement/ combination types
	15 +Δc	20 + Δc	25 +Δc	30 +Δc	35 +Δc	40 +Δc	45 +Δc	50 +Δc	
Corrosion induced by carbonation (XC exposure classes)									
XC1	*C20/25* 0.70 240	*C20/25* 0.70 240	*C20/25* 0.70 240	*C20/25* 0.70 240	*C20/25* 0.70 240	*C20/25* 0.70 240	*C20/25* 0.70 240	*C20/25* 0.70 240	All in Table A.6
XC2	-	-	*C25/30* 0.65 260	*C25/30* 0.65 260	*C25/30* 0.65 260	*C25/30* 0.65 260	*C25/30* 0.65 260	*C25/30* 0.65 260	All in Table A.6
XC3/4	- -	*C40/50* 0.45 340 -	*C30/37* 0.55 300 *C40/50* 0.45 340	*C28/35* 0.60 280 *C30/37* 0.55 300	*C25/30* 0.65 260 *C28/35* 0.60 280	*C25/30* 0.65 260 *C25/30* 0.65 260	*C25/30* 0.65 260 *C25/30* 0.65 260	*C25/30* 0.65 260 *C25/30* 0.65 260	All in Table A.6 except IVB-V IVB-V

The requirements are less onerous than those given in the scheme design, i.e. the strength class is down from C25/30 to C20/25 and the nominal cover is down from 25 mm to 20 mm. The designer then has the choice of leaving the scheme design unchanged or seeing if a more efficient design is possible.

In this case, a check on the structural design showed that both the cover and concrete strength class could be reduced without material change to member sizes or reinforcement quantities. Hence the reduced cover and concrete strength are adopted. Go to Step 16.

Basic specification requirements:

a) The concrete shall conform to SS 544–2 and SS EN 206–1;
b) Compressive strength class: C20/25;
c) Maximum w/c ratio: 0.70; minimum cement/combination content: 240 kg/m3;
d) Cement or combination types I, II, IIIA from SS 544–2: 2002, Table 1;
e) Maximum aggregate size: 20 mm;
f) Chloride class: Cl 0.40;
g) do not apply;
h) do not apply;
i) Consistence class: S3.

Go to Step 17.

Additional requirements (see Step 11):

The producer shall operate an accredited quality system meeting the requirements of SS ISO 9001.

When tested in accordance with BS EN 1367–4, the aggregate drying shrinkage shall be not more than 0.075%. The SS EN 12620 Los Angeles category of the coarse aggregate shall not be greater than LA40. Go to Step 18.

Information from the specifier to producer: The concrete will be pumped, compacted with a beam vibrator and finished with a bull-float. Go to Step 19.

Information required from the concrete producer: The specifier identifies that items f) and g) are relevant and therefore requests this information as follows:

Please supply the following information prior to delivery:

a) If RCA or RA is to be used, the type of material and the proportion to be used.

b) Where RCA or RA is not classed as highly reactive with respect to alkali-silica reaction, the proof on which the lower classification was based.

CONCLUSION

- Design of concrete specification must follow the new Singapore Standards SS EN 206-1, SS544-1 and SS 544-2;
- To design and produce high performance and durable concrete is meaningful for low carbon emission and sustainability of concrete industry;
- The design of concrete specification for low carbon and durable concrete can follow the principles as below:
  - Use supplementary cementing materials to replace OPC, for normal construction, CEM II B-V or III A cement should be used, while for underground and marine construction, CEM IV B-V or III B cement should be used;
  - Use of concrete admixture;
  - Use of recycled aggregate to replace natural aggregate;
  - Avoid overdesign.

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REUSE OF FURNACE LADLE STEEL SLAG AS PRE-CAST CONCRETE AGGREGATES

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ABSTRACT

Furnace ladle steel slag (FSS) is a by-product of the iron and steel making process. In Singapore, one of the largest producers of FSS is Natsteel, that produces approximately 1 million tons of FSS per year. Only 30% of FSS is currently recycled into aggregate materials for road construction and foundation works, while the remaining 70% is being landfill at Pulau Semakau. The present practice of landfilling FSS is not environmentally sustainable and is costly for the company. To further increase the recycling rate of FSS, the use of FSS as a replacement for natural aggregates in non-structural precast concrete was investigated. Working with Natsteel Holdings Pte Ltd, the physical, chemical, and mineral compositions of FSS were determined in accordance to SS EN12620; 2008 (Singapore Standard specification for aggregates for concrete). Various percentages of FSS were used in concrete mixtures and the mixture properties were evaluated. It was noted that the FSS aggregates exhibited a strong tendency for alkali-silica reactions (ASR) when incorporated into concrete. This would make them unfavourable for use in concrete as it could result in cracking and deterioration of the mechanical properties of the concrete. To overcome the ASR issue, a pre- treatment of FSS was carried out before its incorporation into concrete. Different approaches were evaluated to determine the best treatment method. Results showed that the treated coarse FSS can be used to replace natural coarse aggregates in Grade 30 concrete. This will increase the recycling potential of furnace ladle steel slag and hence provide a means for sustainable use of the natural stone in building and construction industry.

INTRODUCTION

Ladle steel slag is a by-product of the steel making process, which currently ends up in the landfill. In the past 10 years, many efforts have been explored to increase the recycling possibility of steel slag in various fields [1-3]. Among them are re-use of steel slag as aggregates for road construction, armour stones for hydraulic structures and natural aggregates replacement for concrete material. However, in Singapore, the re-use of ladle steel slag as aggregates in concrete material is still limited. Singapore is a small island without a huge amount of natural resources. In recent times, the demand for natural aggregates has increased and the resources are becoming less accessible. In this paper steel slag is explored as an alternative aggregate material for the Singapore construction industry.

MATERIALS AND EXPERIMENTS

Ladle steel slag (FSS)

The FSS (Figure 1) used in this study was obtained from a Natsteel facility known as the Tanjong Kling plant. The chemical analysis results showed that FSS is a complex mixture of many substances with the main components being calcium, aluminium, silicate and magnesium silicon (Table 1).

Figure 1
Furnace ladle steel slag (FSS) from Natsteel Holding Pte Ltd

Table 1
Chemical composition of FSS from Natsteel Holding Pte Ltd

Chemical elements	Ladle furnace Steel Slag
O	50.10%
Ca	26.81%
Si	12.96%
Mg	3.80%
Al	3.31%
Other : P,S,K Ti, Cr, Zn	3.00%

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Characterization of furnace ladle steel slag (FSS)

The FSS properties such as particle size distribution, apparent particle density, water absorption, drying shrinkage, water soluble chlorine content, acid soluble sulphate and sulphur content were characterized in accordance to Singapore Building and Construction Authority (BCA) Standard [4].

Concrete mixtures

In this study, two groups of concrete admixtures were investigated. Both groups of mixtures had the same amount of cement, water, hardener and plasticizer, and different amount of sand and stone. The first group of mixtures used un-segregated FSS to produce Grade 40 precast concrete, while the second group of mixtures used segregated FSS. FSS was segregated into fine and coarse aggregate by crushing and sieving. The fine and coarse FSS were used to replace the natural sand and stone in Grade 30 precast concrete mixture. Figure 2 (a-c) shows the FSS used in the mixtures.

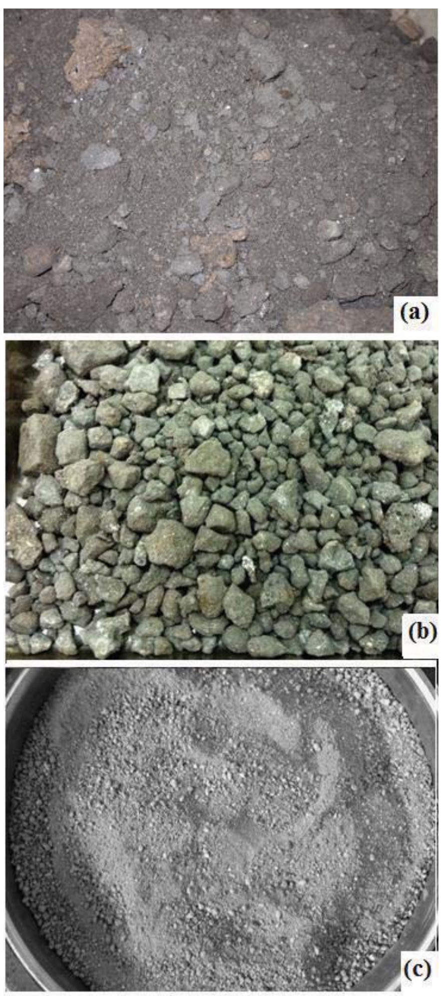

Figure 2
(a) un-segregated (b) coarse and (c) fine FSS used in this studies

RESULTS AND DISCUSSION

Particle size distribution of FSS

The particle size distribution of FSS is shown in Figure 3. As can be seen, the particle size of FSS exceeds the EN 12620 recommended size range for concrete aggregates. In particular, the amount of allowable particles size less than 10 mm, less than 4 mm, and less than 2 mm exceeded the values by approximate 10%, 45% and 42%, respectively. Hence, the direct use of FSS in precast concrete is not suitable. Instead, a pre-handling step was required to segregate the outlier particles.

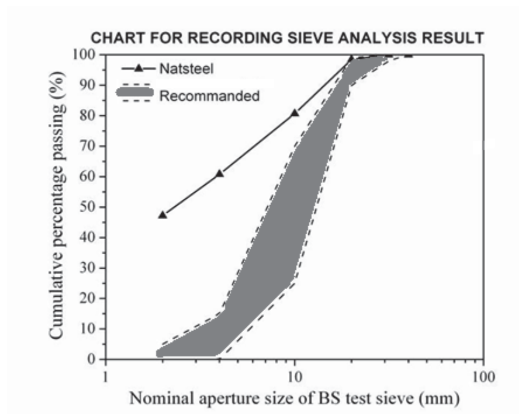

Figure 3
Particle size distribution of ladle steel slag

Physical and Chemical properties

The physical and chemical properties of FSS are summarized in Table 2. As can been seen, the drying shrinkage, water-soluble chloride, total sulphur and acid-soluble sulphate content of FSS met the requirements of SS EN12620; 2008 aggregates for concrete. It has been reported that the presence of chloride and sulphate above this amounts in cement can lead to potential failure of concrete, e.g increase the corrosion rate of embedded metal as well as expansion of concrete [5-6]. The particle density and water content of FSS were also investigated; although there is no specific requirement in SS EN12620 on relative density and water absorption for aggregates. However, it is known that the apparent particle density and moisture content play an important role in the water/cementitious ratio in the mixture design [5]. Therefore, as a good practise, it is recommended to measure the physical and chemical properties of recycled aggregate at the frequency of once per year for concrete application.

Table 2
Basic properties of Natsteel Ladle Furnace Steel Slag (FSS)

Property	Ladle Steel Slag	EN 12620 requirement
Apparent particle Density	2.78 -3.05 g/cm^3	No
Water Absorption (%)	2.2 - 2.3 %	No
Drying Shrinkage	0.068%	≤ 0.075 %
Water soluble chloride content	<0.01 %	<0.01 %
Acid Soluble Sulfate	0.8%	≤ 0.8 %
Sulfur Containing Compounds	0.59%	≤ 1 %

<ins>Potential Expansion of concrete (Alkali-Silica Reactivity- ASR)</ins>

Alkali-silica reaction can cause serious expansion and cracking in concrete, resulting in major structural problems and sometimes lead to necessitating demolition of the building [3, 8-9]. According to SS EN12620 specification, the expansion of concrete caused by ASR shall not exceed 0.20% after 16 days submerge in alkaline environment. In this study, the potential alkali reactivity test of aggregates was investigated according to ASTM C1260-07 Standard (Mortar bar method)[10]. The results are summarized in table 3. It was noticed that the unsegregated FSS expanded by 1.4% and broke at 10 days. Meanwhile the ASR of mortar bar with fine FSS expanded by 0.22% at 16 days without any breakage while coarse FSS expanded by 0.25% at 5 days and broke off on the sixth day. This observation indicated that the direct use of un-segregated FSS and coarse and fine FSS into precast concrete is not advisable. Figure 4 shows the broken mortar bar with unsegregated FSS, coarse FSS and fine FSS.

Table 3
Mortar bar test result of unsegregated, coarse and fine FSS

Mortar Bar	ASR	Breakage	ASTM 1260
Unseggregated FSS	1.4% at 10 days	10 days	
Coarse FSS	0.25% at 5 days	6 days	<0.2% at 16 days and without any sample breakage
Fine FSS	0.22% at 16 days	No	

Figure 4
Mortar bar of unsegregated FSS

It is known that the expansion of steel slag is mainly caused by the formation of a highly expandable gel that is initiated by free lime such as Calcium Oxide (CaO) and Magnesium Oxide (MgO) [8, 9, 11]. Therefore, to overcome the expansion problem, a pre-treatment (steaming) step was incorporated with the aim of accelerating the ASR of FSS before it is used in concrete. In this study, two different methods, i.e., autoclave and pressure cooker were explored. The results are illustrated in Table 4. As can be seen, the ASR of coarse FSS was significantly reduced to 0.06% and 0.16% by using autoclave and pressure cooker steaming at 24 hours, respectively. On the contrary, the steaming of fine FSS seems to be ineffective and didn't reduce the expansion of the fine aggregates. The fine FSS continued to expand more than 0.20% after 24 hours of steaming using both methods. This concludes that fine FSS is not recommended to replace fine aggregates in concrete products.

Table 4
Mortar bar test result of steamed FSS

Steaming	Mortar Bar	ASR	Breakage
Autoclave	Coarse FSS	0.06% at 16 days	No
	Fine FSS	1.39% at 16 days	No
Pressure cookeer	Coarse FSS	0.16% at 16 days	No
	Fine FSS	1.98% at 16 days	16 days

To further understand the ASR-steaming correlation, the free lime content of coarse FSS was measured (EN17441). The result showed that the free lime content of coarse FSS decreased by almost 67%, whereby the free lime was reduced from 0.51% m/m to 0.17% m/m after steaming at 24 hours. This finding confirmed that the steaming process had accelerated the ASR reaction of FSS. Many studies have reported the influence factor of ASR in cement [8, 9, 11]. The expansion of cement decrease with larger aggregates and increased with increase of aggregates content. In the mortar bar test, since the amount of aggregates is fixed, we can conclude that the ASR is mainly contributed by the size of aggregates. Another possible reason is the reactive sites for ASR increase as the specific surface area of the aggregate increases. With smaller particles, more sites for ASR reaction are provided which lead to a more expandable gel. However, this theory has not been thoroughly verified and more work is required.

Concrete mixtures

The concrete mix designs used in this research are summarized in table 5. Two sets of mix designs were investigated. The first set was made by direct incorporation of FSS into grade 40 concrete mixture. As discussed earlier, the particle size distribution of un-segregated FSS from Natsteel plant is not suitable to be incorporated directly into the concrete mix. Therefore, the second set of mix design was made by using segregated FSS. The fine and coarse FSS were used to substitute the sand and stone aggregates, respectively in the grade 30 concrete admixtures. A mixture without any FSS was used as reference for both groups. The compressive strength of the concrete mixtures was measured at 7 and 28 days age.

Table 5
Percentage of Fine aggregates (sand), Coarse aggregates(stone), Unsegregated FSS, Coarse FSS and Fine FSS in concrete mixtures

Concrete Mixtures	Fine aggregates (Sand)	Coarse aggregates (Stone)	FSS	Coarse FSS	Fine FSS
		Direct			
Control (Grade 40)	100%	100%	-	-	-
S1	100%	83.2%	16.8%	-	-
S2	96.6%	87.0%	16.8%	-	-
S3	83.2%	100%	16.8%	-	-
		Segregation			
Control (Grade 30)	-	-	-	-	-
40/40%	60%	60%	-	40%	40%
50/50%	50%	50%	-	50%	50%
60/60%	40%	40%	-	60%	60%
60%	100%	40%	-	60%	-
80%	100%	20%	-	80%	-
100%	100%	-	-	100%	-

Direct use of FSS

Figure 5 shows the results of 7- and 28-day compressive strengths of grade 40 precast concrete where the percentage of sand or stone varied from 83.2%-100% while FSS percentage is kept at 16.8% in the mixture. As can be seen from the results, the compressive strengths of all the samples exhibited lower compressive strength as compared that to the control sample. This demonstrates that use of un-segregated FSS into concrete reduces compressive strength of concrete.

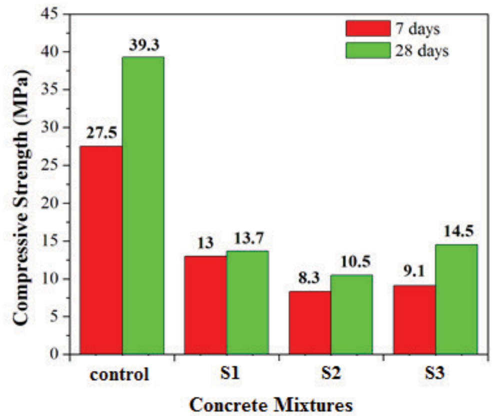

Figure 5
7- and 28 day compressive strength of mixtures made with unsegregated FSS

Segregation of FSS

As was discussed earlier, the particle size distribution of unseggregated FSS exceeded the recommended range especially for particle sizes less than 10mm, 4mm and 2mm. Therefore, the FSS was crushed and sieved into two parts namely fine FSS (<4 mm) and coarse FSS (>4 mm) . The fine and coarse FSS were used to replace sand and gravel, respectively in concrete mixtures. The 7- and 28-day compressive strength of mixtures made with different percentages of fine and coarse FSS are shown in Figure 6. The compressive strength of mixtures with 40% fine and coarse FSS substitution in the mixtures design was found to be comparable to that of control mixture. However, it was noticed that when the substitution of fine and coarse FSS was increased to 50%, the compressive strength of the concrete decreased by approximately 15-20% as compared to that of the control mixture. This concludes that substitution of fine and coarse FSS in grade 30 concrete should be limited to 40%. However, as it was shown earlier, the treatment of fine FSS for ASR is not effective. Therefore, in the subsequent experiments, only coarse FSS was used to replace the stone in the mixtures and the results are illustrated in Figure 7.

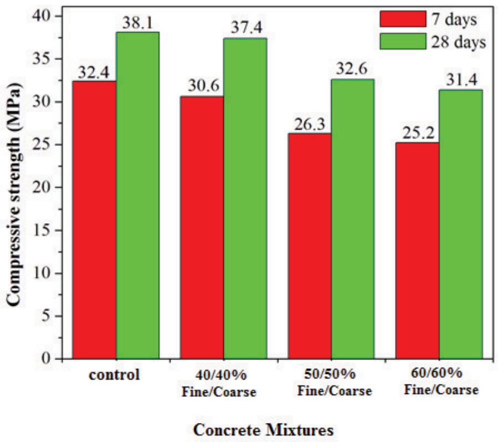

Figure 6
7- and 28-day compressive strength of mixture with fine and coarse aggregates substituted with different percentages of fine and coarse FSS

As can be seen in Figure 7, the 7- and 28-day compressive strength of concrete with 60-80% of coarse FSS are comparable with the strength of control mixture. Concrete with 60% substitution of coarse FSS has the highest compressive strength (37.4MPa (7-day and 42.1MPa (28-day) while concrete with 80% substitution of coarse FSS exhibits almost equivalent compressive strength to that of the control sample. The 7- and 28-day compressive strengths of the mixture with 100% stone replaced with coarse FSS are 27.8 MPa and 35.2 MPa, respectively, which marginally meet Grade 30 MPa. This demonstrates that the natural aggregate can be replaced from 60 to 100% by coarse FSS.

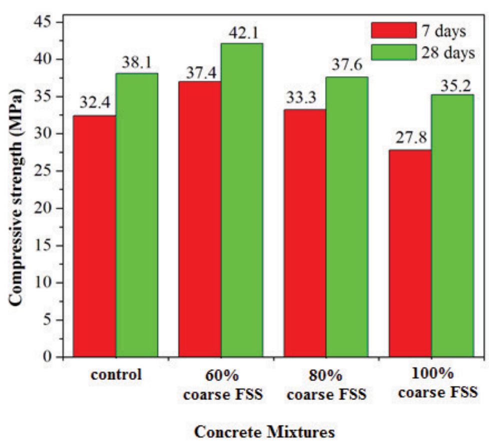

Figure 7
7 and 28-day compressive strength of mixtures with coarse aggregates substituted with different percentages of coarse FSS

Heavy metal leaching of concrete with FSS

To understand the potential heavy metal leaching of FSS, concrete with maximum percentage of recycled FSS (i.e., 60%of fine and coarse FSS) was selected as the worst-case scenario. The concrete sample was submerged in water for 64 days and the leachates were collected and tested based on EPA 6010B. There is no specific requirement from NEA (National Environment Agency) for heavy metal leaching of recycled steel slag. The heavy metals were compared with Dutch Standard for ground water and the results are illustrated in Table 6. As can be seen, most of the heavy metal elements found to be less than 10 ppb except Ba (690 ppb) which exceeded the intervention value by 65 ppb. Although the possibility of Ba to leach out from concrete with FSS is low, it is recommended not to use FSS in concrete structure that will be in contact with water sources.

Table 6

Heavy metal leaching of concrete with 60%coarseand fine FSS

Elements	Result EPA 1311/6010B (μg/L)	DUTCH STANDARDS 2000 (μg/L)	
		Target Value	Intervention Value
Ag	<10	Nil	Nil
As	<10	10	60
Cd	<10	0.4	6
Cr	<10	1	30
Cu	<10	15	75
Fe	10	Nil	Nil
Hg	<10	0.05	0.3
Mn	<10	Nil	Nil
Ni	<10	15	75
Pb	<10	15	75
Sb	<10	Nil	20
Se	<10	Nil	Nil
Zn	<10	65	800
Ba	690	50	625
Co	<10	20	100
Mo	<10	5	300

μg/L = ppb (part per billion)

CONCLUSION

In this study, properties of concrete made with different percentages of ladle steel slag were investigated. The results recommend that ladle furnace steel slag, which is the by-product from Natsteel steel making plant, can be reused as coarse aggregates in non-structural concrete. However, there are few important steps that should be taken into consideration. First, the FSS need to be crushed and segregated into coarse steel slag with the average diameter ranging from 4 mm to 20 mm, and fine steel slag with less than 4 mmm diameter. Use of fine FSS is not recommended due to its vulnerability to expansion. A steaming step is necessary to accelerate the expansion of coarse FSS due to ASR prior to its use in concrete.

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NUMERICAL STUDY OF A CONCRETE CORE TEMPERATURE CONTROL (CCTC) BUILDING FOR TROPICS

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ABSTRACT

In this paper, we investigated the performance of a specific type of radiant cooling system - Concrete Core Temperature Control (CCTC). The performance of the CCTC was measured in terms of indoor occupant comfort and annual energy consumption using transient thermal simulation models. The results were compared to a conventional cooling and ventilation system. Annual weather data of Singapore and heat load of a typical office were created to simulate the hypothetical building with and without CCTC using Transient System Simulation (TRNSYS) software. Variable conditions such as flow rate of the cooling water, and mass of concrete were considered during the simulation exercise. It was found that, while achieving the same indoor comfort level, the building with the CCTC system was able to achieve significant energy savings at the chiller plant and air-distribution levels. The percentage reduction for electricity consumption in air distribution and in chiller was about 30% and 20%, respectively.

INTRODUCTION

Due to the hot and humid weather conditions in Singapore, air conditioning is widely used in buildings. In most cases, the air conditioning system consumes up to 50% of the total electricity consumption. One of the biggest challenges in achieving energy efficiency in buildings is to achieve a good indoor comfort level, while reducing the amount of energy consumed by air conditioning. One possible solution is radiant cooling systems; a high temperature cooling system that transports cooling energy to the building space through water, which is a more efficient heat transfer agent compared to air. Concrete Core Temperature Control (CCTC) is the practice of pumping cooling water through polymer pipes that are embedded in concrete of the building mass. The CCTC system makes use of the concrete mass as a heat sink for the internal heat load in the building, hence cooling the building space. Originated in Europe and popular in temperate climates around the world, CCTC is yet to be validated and implemented in buildings in the tropics.

A radiant floor cooling/heating system transports energy by water which is a more efficient way compared to an air system due to larger heat capacity of water (Olesen, 2008). Monte (2000) studied the transient response of one-dimensional multi-layered composite conducting slabs to sudden variations of the temperature of the surrounding fluid, applying the method of separation of variables to the heat conduction partial differential equation. Lu and Tervola (2005) analysed a novel analytical approach to heat conduction in a composite slab subject to periodic temperature changes. The solutions for partial heating of rectangular solids are reported by Beck et al. (2004) and methods of separation of variables and time-partitioning were also analysed. Laouadi (2004), developed two-dimensional prediction model for radiant systems for integration in energy simulation software, and the model is validated using the numerical modelling approach. heat transfer in thermally activated building constructions using both simplified star network and triangular network are reported by Weber and Johannesson (2005). Holopainen et al. (2007), examines the use of an uneven nodal network in floor heating simulation with finite difference heat balance method, and shows the benefits of placing the densest gridding in steepest curvature of the temperature gradient. Larsen et al. (2010), develops 2-D transient solution of a slab with an embedded array of parallel circular pipes. Jin et al. (2010), builds a numerical model of radiant floor cooling system using finite volume method with composite grids, and shows the pipe has effect on the performance when the thermal conductivity of the pipe is low and the effect of the water velocity on the performance is not great.

SYSTEM DESCRIPTION

The cooling of office and management buildings with environmental energy from soil, groundwater and air are energetically and economically particularly interesting. Especially in today's office buildings, thermal comfort plays an increasingly larger role. Conventional ventilation and air-conditioning cooling systems require very low water temperatures (forward / reverse; 8°C/12°C) in fan coil units and are therefore not particularly interesting for the use of

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environmental energy. They need a conventional compression refrigeration system to supply these low temperatures to fan coil units. The thermal concrete core activation provides a much more favourable approach here: Water-carrying pipe systems for year-round temperature control of buildings over a large area integrated within solid components (concrete floors and concrete ceilings) with high heat storage capacity. With the circulation of water into solid components, these components are loaded with cold or heat energy depending on the flow temperature. Unlike the familiar 60 mm screed with a conventional under floor heating system the concrete core activation has a significantly higher heat loading potential. Due to activated building material, the thermal heat load is shifted. Today this effect can be seen in old buildings like churches or castles that were built with very thick outer walls without interior lining. These buildings always maintain a pleasant cool indoor room temperature even at high outside temperatures. As a result of the large heat transfer area, the system allows for slight over or under temperatures in comparison to the indoor air temperature, significant heating or cooling capacities. The pipe network for the concrete core activation is usually made out of polyethylene or aluminium multi-layer composite pipes with diameters of 16-20 mm (Figure 1). For installation, cable ties are used. Besides the exact mounting of the pipes, a precise hydraulic balance is an important point. For the only, way to ensure that water is uniformly distributed in all circuits a precise and high quality water distributor is required. Another important point is the energetic structure of the object. In recent decades, architects and designers have attached high importance to the primary energy consumption of buildings. Therefore, thermally very tight building envelopes with the resulting low U-values have been created. Because of the flow temperatures being nearly equal to the room temperatures (as opposed to a conventional refrigeration system), it is not possible to counteract extreme peak loads. Due to this, problem planners and architects need to take great care especially of the building's sun protection.

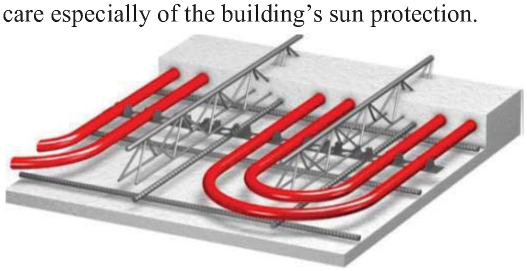

Figure 1: 3-D rendering of CCTC pipes embedded in concrete.

MODELLING AND SIMULATION

The purpose of using an energy-modelling tool, Transient System Simulation (TRNSYS) software, for this paper was to predict the behaviour of the CCTC system, as accurately as possible under different scenarios. Google Sketch-up Pro was used to create 3-D models of building spaces and fed into TRNSYS. After the building's 3-D geometry, zoning and construction types were defined and transferred to TRNBuild. Figure 2 and 3 is showing the simulation schematic for the building simulation and energy system in a building.

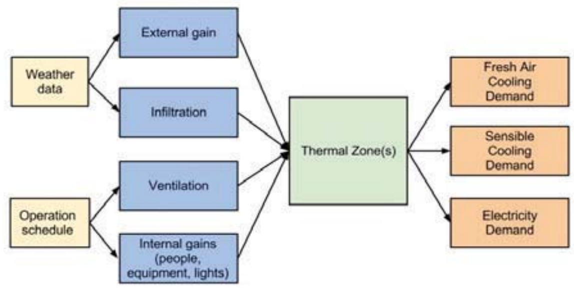

Figure 2: Simulation schematic for the building simulation.

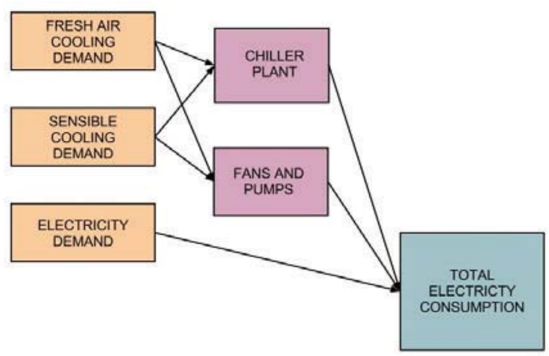

Figure 3: Simulation Schematic for the energy system in a building.

Two building spaces were modelled and simulated to measure the effectiveness and performance efficiency of the CCTC system. The Base Case (BC) is a building space with all the below mentioned parameters, without the CCTC system. In other words, it uses a conventional VAV system to handle the cooling and dehumidification requirements of the space(s). The Proposed Design (PD) has the same experimental parameters as the base-case, except that instead of cooling the space using the VAV system, part of the sensible load is handled by the CCTC system. Table 1 describes the input parameters that were used to create the building geometry and model and simulate the energy systems. The schematic and dimension of CCTC pipes embedded in concrete is shown in Figure 4. To model a radiant cooling CCTC, an "active layer" added to the wall, floor or ceiling definition. The layer is called "active" because it contains fluid filled pipes that remove heat from the surface. The active layer is described by five parameters:

- Specific heat coefficient of fluid in the pipes
- Pipe spacing
- Pipe outside diameter
- Pipe thickness
- Pipe wall conductivity

Table 1: Thermal Modeling parameters (System and Zone)

NO	PARAMETER	VALUE		UNIT
		BC	PD	
GEOMETRY				
1	Area	100	100	Sqm
2	Volume	300	300	Qm
3	Total Window Area	18	18	Sqm
LOADS				
4	Infiltration Rate	0.15	0.15	ACH/HR
5	People	25	25	--
6	Plug Load	1600	1600	W
7	Lighting Load	700	700	W
ZONE SET-POINTS				
8	Zone Temperature Set-point	23	23	C
9	Zone Relative Humidity Set-point	65	65	% RH
AIR-HANDLING UNIT SPECIFICATIONS				
10	Fresh Air Requirement	56	56	L/S
11	Fresh Air Temperature Set-point	20	20	0C
12	Fresh Air Relative Humidity Set-point	40	40	% RH
13	Fan Efficiency	0.45	0.45	W/CMH

For surfaces containing an active layer, the convective heat transfer coefficient between surface and zone air depends on the temperature of the active layer. Heat transfer coefficients depend heavily on the temperature difference between surface and fluid and the direction of heat flow. For example, the flow pattern evolved by a CCTC ceiling/floor is completely different to that of a vertical surface. The mathematical formula used for appropriate heat transfer coefficients is of the form;

$$\alpha_{conv} = const\,(T_{surf} - T_{air})^{exp}$$

For horizontal surfaces, the convective heat transfer coefficient due to the difference between the surface temperature and the temperature of the air right near the surface calculated by

$$\alpha_{conv} = 2.11\,(T_{surf} - T_{air})^{0.31}$$

The above relationship is valid assuming that the surface temperature is higher than the surrounding air temperature. If this is not the case, then the relationship given by

$$\alpha_{conv} = 1.87\,(T_{surf} - T_{air})^{0.25}$$

where;
α_{conv} = Convective heat transfer coefficient; T_{surf} = Surface temperature; T_{air} = Air temperature

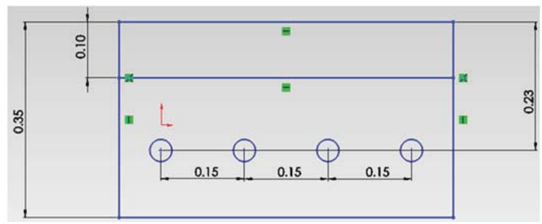

Figure 4: Schematic of CCTC pipes embedded in concrete

A specific minimum mass flow rate is necessary to assure that a linearization of the exponential curve between inlet and outlet temperature is possible. In most common cases, the specific mass flow rate has to be greater than 13 kg/hm² (the exact value is calculated for each active Layer). Therefore, two segments in series for most cases can model an ordinary piping system. The thickness of both layers adjacent to the active layer must be ≥ 0.3 × pipe spacing

Table 2: Energy benchmarking categories and parameters

Energy Systems	Sub-system	BC parameters	PD parameters
Air Conditioning	Electrical Chiller Plant	Plant efficiency: 0.58 kW_el / RT	Plant efficiency: 0.58 kW_el / RT
Air Distribution	Sensible Cooling	AHU Fan efficiency: 0.45 W/CMH	AHU Fan efficiency: 0.45 W/CMH
	Fresh Air supply	AHU Fan efficiency: 0.45 W/CMH	AHU Fan efficiency: 0.45 W/CMH
Water Distribution	CCTC pumps	N/A	Pump efficiency: W/CMH

Energy Benchmarking

Architects and eco-consultants use energy benchmarking to compare the improvements with baseline number. Energy benchmarking refers to the process of (i) creating the 'baseline' data – divided into several sub-systems and the overall annual total and (ii) comparison of respective sub-systems and overall total numbers of the proposed design against the baseline. In the case of these experiments, energy benchmarking refers to (i) collection of base-case simulated energy consumption results (BC) and classifying the data into several sub-systems as mentioned in Table 2, and (ii) comparison of respective subsystems and overall energy consumption numbers between PD and BC.

The Basic Model has considered with construction and flow rate properties of 0.15m concrete thickness of CCTC layer and mass flow rate of 1500 kg/hr. The paper has also measured the variation of the CCTC system performance under different parametric conditions. The three biggest factors that influence amount of energy transferred to the zone by the CCTC system are:

a) Temperature of the chilled water in the CCTC system,
b) Mass Flow rate of the chilled water in the CCTC system, and
c) Amount of concrete that is being cooled by the CCTC system

CCTC systems optimized has been done by varying the concrete thickness of CCTC layer from 0.1m, 0.125m, 0.175m, and 0.2m and mass flow rate from 1000 kg/h, 1250 kg/h, 1750 kg/h, and 2000 kg/h. The optimum chiller plant energy efficiency has been considered as 0.58 kW/RT for all the simulation models.

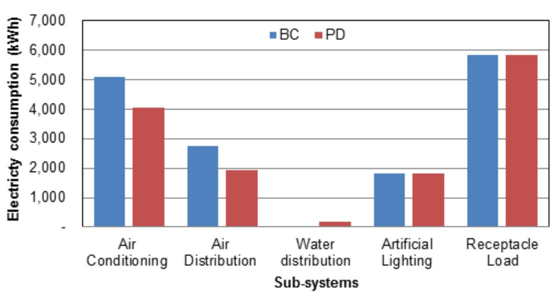

Figure 5: Comparison of subsystem energy consumption for base case and proposed design.

RESULTS AND DISCUSSIONS

Based on the models developed in TRNSYS, the reduction in energy consumption and sensible cooling requirement from air cooling system has been calculated. It can be seen from Figure 5 that the air distribution consumption is reduced by 30%, and the chiller electricity consumption reduces by 20%. Overall, there is 10.8% electricity saving for PD as compared to BC. The electricity consumption reduction for air-distribution is attributed to the reduction in air flow rate required to cool the building space (sensible cooling). The significant reduction in chiller plant consumption is attributed to the reduction in sensible cooling required by the CCTC system in PD as compared to the air cooled system in BC. The reduction in sensible cooling requirement from air cooling system is shown in Figure 6. It was observed that the cooling requirement of the air cooling system was reduced during the off-peak hours too along with reduction in cooling requirement during peak hours. Hence, it can be concluded that the thermal retention/storage property of concrete is an additional advantage to reduce cooling requiremnt.

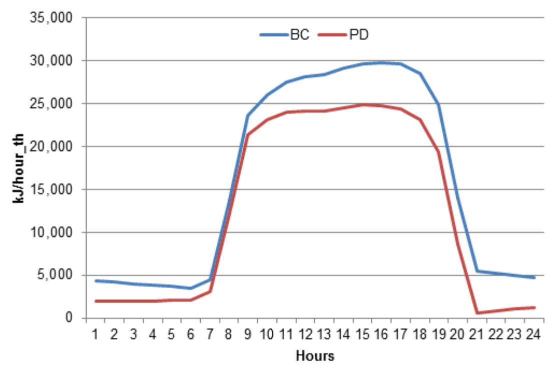

Figure 6: Comparison of sensible cooling for base case and proposed design.

The analysis of CCTC system has been optimized for various mass flow rates of CCTC water and concrete thicknesses of CCTC layer. The mass flow rate was varied from 1000 kg/h (A1), 1250 kg/h (A2), 1750 kg/h (A3), and 2000 kg/h (A4). The comparison of electricity consumption and sensible cooling demand for different mass flow rates are shown in Figure 7 and 8, respectively. As expected, the percentage savings is highest for the air-distribution system, second highest for the air-conditioning system and third highest for the total consumption. This is because the CCTC system directly affects the air-distribution system, which in turn affects the air-conditioning system and the total consumption. Hence, the effect of the CCTC system is significant on the air-distribution system.

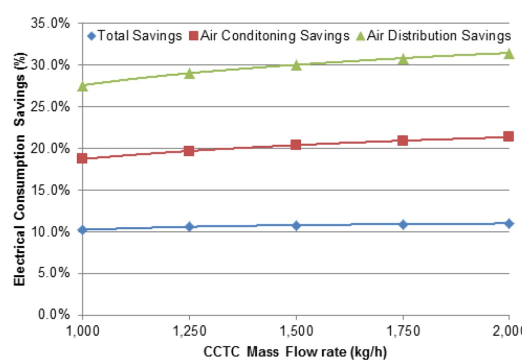

Figure 7: Consolidated comparison of electricity consumption for different mass flow rate of CCTC water.

It can be seen from Figure 8 that as the mass flow rate of the water in the system increases from 1000kg/h to 2000kg/h from A1 to A4, the amount of sensible cooling energy required from the air-cooling system is reduced. It was also noted that irrespective of the mass flow rate, it appears that the concrete retains cooling energy even after the CCTC system has been shut off. Another important observation is that the 'kick-in' time was the same for the mass flow rate range between 1000 to 2000 kg/h irrespective of the mass flow rate.

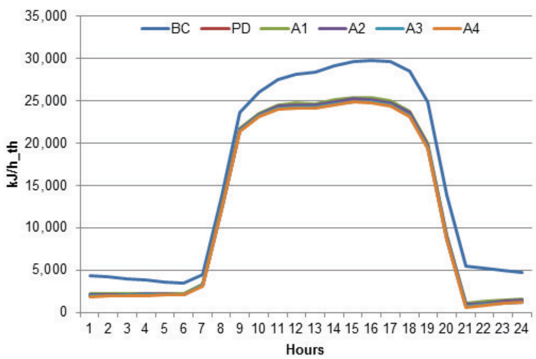

Figure 8: Consolidated comparison of sensible cooling demand for different mass flow rate of CCTC water.

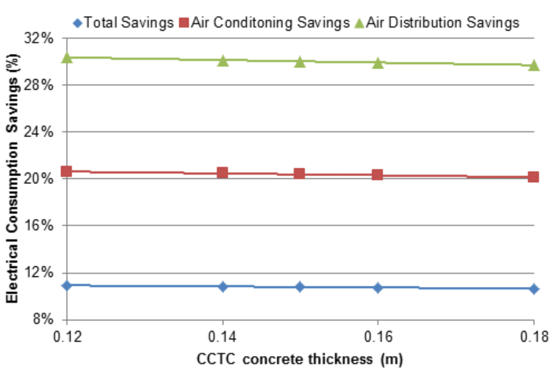

Figure 9: Consolidated comparison of electricity consumption savings for different concrete thickness of CCTC layer.

The concrete thickness of CCTC layer was varied from 0.12m (B1), 0.14m (B2), 0.16m (B3), and 0.18m (B4). The comparison of electricity consumption and sensible cooling demand for different mass flow rates are shown in Figure 9 and 10, respectively. As expected the electricity consumption (Figure 9) increased with increase in concrete thickness. It can be seen from Figure 10 that as the thickness of the concrete increases from 0.12m to 0.18m, the thermal resistance increases. Hence, with increase in the thickness of the concrete, the cooling energy supplied to the room decreases. It was also observed that during the peak hours (0700hrs-1900hrs) the amount of cooling provided by the CCTC system decreased as the amount of concrete increased.

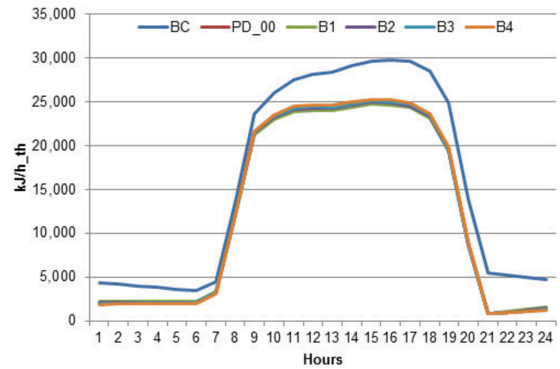

Figure 10: Consolidated comparison of sensible cooling demand for different concrete thickness of CCTC layer.

CONCLUSION

The performance of a specific type of radiant cooling system - Concrete Core Temperature Control (CCTC) has been investigated using TRNSYS software for variable mass flow rates and concrete thicknesses. The performance of the CCTC was measured in terms of indoor occupant comfort and annual energy consumption and compared to a conventional cooling and ventilation system. It was found that the as the mass flow rate of water increased the percentage saving of electricity consumption also increased. With the increase in mass flow rate, the amount of sensible cooling energy required from the air-cooling system reduced. It was also found that, the increased mass retains cooling energy and dissipates it more effectively during off-peak hours. However, it also increases the 'kick-in' time, which reduces the effectiveness of the CCTC system during the peak hours. The results from Category 'B' also clearly conclude that the electricity consumption increases with the increase in concrete mass.

ACKNOWLEDGEMENT

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SERVICE LIFE PREDICTION AND LCW OF WOODEN BUILDINGS

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ABSTRACT

A methodology was developed to calculate the service life of wooden buildings. The methodology is based on the ISO 15686-1 "factor method". The factor method can evaluate the expected service life of buildings. A methodology was also developed to calculate the amount of waste discharged during the life cycle of buildings with regard to the service life of the buildings.

A calculation tool that can calculate both the service life of wooden buildings and the life cycle waste of the buildings was developed. By giving the location of the building, the types of the materials and components, the weather protection design and the quality of the construction works and daily maintenance as an input the tool calculates the service life and the life cycle waste of the assessed building. The outline of the tool and the results of the case studies are reported in this paper.

INTRODUCTION

In Japan the service life of wooden residential houses is reported to be approximately thirty years. This service life is extremely short compared to that of the wooden residential houses in Europe and North America. Because of the short service life of wooden houses, a huge amount of resources is consumed and a huge amount of waste is produced.

The amount of the waste produced during the service life of wooden buildings depends of the durability of the buildings. The durability of wooden buildings is governed by the environment of the site where the buildings exist, the durability of the materials and components, the weather protection design of the buildings and the quality of the construction works and the quality of the daily maintenance.

From 1980 to 1984 a national research project was run to develop a calculation method to evaluate the service life of wooden buildings (Gihodo Shuppan Co.Ltd., 1986). This method is well known as the "Factor Method". The ISO Standard 15686-1: Buildings and constructed assets - Service life planning - Part 2, Service life prediction procedures (ISO, 2008) was standardized referring this Factor Method. And the evaluation standard for buildings' durability in the Japan Housing Labelling System (Ministry of Land Infrastructure and Transport, 2001) was standardized referring the service life prediction method developed in the national research project.

Recently many useful tools are proposed to calculate the amount of waste discharged and the amount of resource consumed during the life cycle of buildings (Koga et al., 2008). However, most of these tools do not have engines that can precisely determine the service life of the materials and components used in the buildings. Buildings with durability will have longer service life. In addition, building with longer service life can reduce waste production and resource consumption in comparison to the normally designed buildings.

The service life of building members and buildings depends on the following conditions:
1) the climate of the building sites
2) the durability of the composing materials
3) the design of the buildings
4) the quality of the construction works
5) the quality of the maintenance works

Buildings designed for durability have much more environmental benefit than normally designed buildings in terms of Life Cycle Waste (LCW) and Life Cycle Resource (LCR). Life cycle assessment tools with engines that precisely evaluate the service life of buildings and building members could encourage durable design and consequently promote low LCW and low LCR society.

SERVICE LIFE EVALUATION METHOD

Outline

The service life evaluation method was developed in 1984 (Gihodo Shuppan Co.Ltd., 1986) as a result of the national research project. Figure 1 gives the outline of the calculation of the evaluation method

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for wooden buildings. The service life of each unit can be calculated by giving the climate of the construction site, the service classes of the composing unit (walls, floors and roofs), the specification of the composing materials and components against durability, the design specification with regard to durability improvement, the quality control level for the construction works and the quality of the maintenance works. And the service life is classified into seven classes (see Table 1).

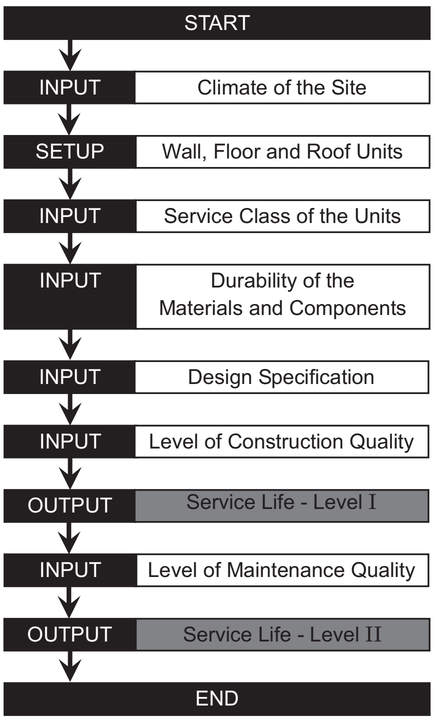


Figure 1 Outline of the service life evaluation method

Table 1 Service life classification

CLASS	SERVICE LIFE	REPRESENTATIVE SERVICE LIFE
Y-100	100 and more	100 years
Y-90	From 80 to 100	90 years
Y-75	From 70 to 80	75 years
Y-60	From 50 to 70	60 years
Y-45	From 40 to 50	45 years
Y-30	From 20 to 40	30 years
Y-15	From 10 to 20	15 years

Climate classes of the construction site
The climate classes of the construction sites are ranked according to the inhabitation of the termites and the wood-rotting fungi.

Service classes of the composing units
The service classes for the composing units are ranked according to the possibility of being exposed to water or humidity. For example, exterior walls and the interior walls have different service classes and walls of the bathroom and walls of the bedrooms have different service classes.

Durability of the materials and components
Durability of the materials and components is ranked according to the species and the cross section size of the columns and beams. The type of the sheathing materials and the specification of the chemical processing for the decay prevention are also taken into account.

Design specification
Design specification for durability improvement is ranked by the design taken to prevent degradation caused by the attack of water and humidity. For example wooden buildings with long projected eaves, highly ventilated under floor and attic, uncovered and ventilated structural members and high quality water proof paper have higher ranks for the design specification.

Quality control level for construction works
The quality control level for the construction works is ranked according to the quality of the inspection. The rank is classified to several classes according to the quality and quantity of the inspection.

Quality of the maintenance
The quality of the maintenance is ranked according to the quality and quantity of the daily inspection and routine inspection. The quantity of the operation of the chemical retreatment against termites and wood-rotting fungi is also considered.

Calculation method
The formula to calculation the service life is given in equation 1 and equation 2.

$$SL1 = C \times SC \times DMC \times DS \times CQ \qquad (1)$$

Where $SL1$ is the coefficient that represents the initial service life of buildings (i.e. with no regard to the effect of the maintenance quality),
C is the coefficient that represent the climate class of the construction sites,
SC is the coefficient that represent the service classes of the composing units,
DMC is the coefficient that represent the durability of the materials and components,
DS is the coefficient that represent the design specification for durability and,
CQ is the coefficient that represent the quality of the construction works.

$$SL2 = SL1 \times MQ \qquad (2)$$

Where $SL2$ is the coefficient that represents the possible service life of the building being maintained in a certain quality,
$SL1$ is the coefficient that represents the possible service life of the building without regard to the effect of the maintenance quality and,
MQ is the coefficient that represent the quality of maintenance works.

The service life is given according to the values of $SL1$ and $SL2$. The service life classes and the corresponding coefficient are as shown in table 2.

Table 2 Service life classes and corresponding coefficient

CLASS	*SL1*	*SL2*
Y-100	3.3≤x	3.3≤x
Y-90	2.8≤X<3.3	2.8≤X<3.3
Y-75	2.3≤x<2.8	2.3≤x<2.8
Y-60	1.8≤x<2.3	1.8≤x<2.3
Y-45	1.3≤x<1.8	1.3≤x<1.8
Y-30	0.8≤x<1.3	0.8≤x<1.3
Y-15	0.3≤x<0.8	0.3≤x<0.8

UPDATE OF THE SERVICE LIFE EVALUATION METHOD

Backgrounds

The evaluation method was developed in 1984 almost 30 years ago. New technologies and new knowledge for durability have been developed and found in these 30 years. Some parts of the evaluation method became old-fashioned because of the change of the life style. The evaluation method was updated with consideration to the latest knowledge and the newly collected data.

Outline of the updated service life evaluation method

The structure of the updated service life evaluation method is almost same to that of the former one. The outline for the calculation operated in the new method is given in figure 2. The difference between the former method and the new method can be summarized as follows:

1) Service life was classified into 4 classes as shown in table 3.
2) The climate classes of the construction site was given in advance for almost 900 areas in Japan.
3) More detail classification has been proposed for the service classes of the building units.
4) The knowledge for the durability of building materials and components have been updated.
5) Design specification against water protection was added as a new indicator.
6) The quality of maintenance was evaluated with regard to the maintenance operated by the builders and the maintenance operated by the owner.

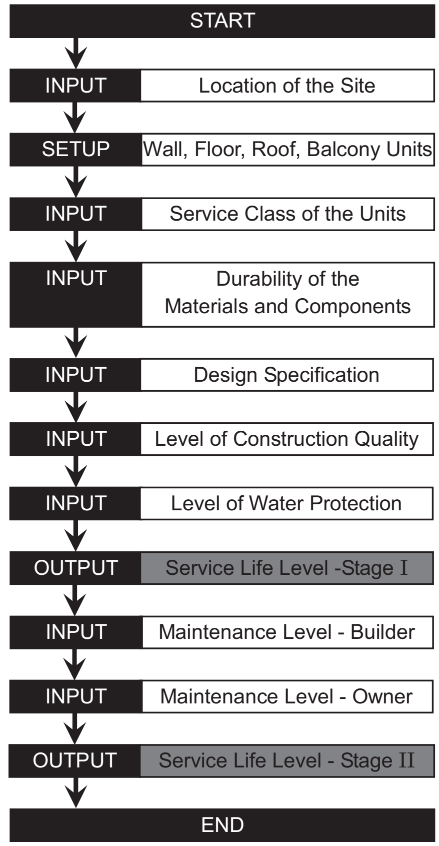


Figure 2 Outline of the updated service life evaluation method

Table 3 Service life classification

CLASS	SERVICE LIFE	REPRESENTATIVE SERVICE LIFE
3 Generation	90 and more	90 years
2 Generation	60 to 90	60 years
1 Generation	30 to 60	30 years
0 generation	Less than 30	10 years

Climate of the construction site

The climate classes of the construction sites were given for almost 900 areas in Japan. Climate classes for wood-rotting fungi attack and climate classes for termites attack were given respectively. The climate classes for wood-rotting fungi attack were classified into 3 classes according to the Scheffer Index (Scheffer, 1971) of the site. Scheffer Index is calculated by equation 3.

$$Scheffer \cdot Index = \sum_{Jan-Dec} \{(9/5 \times T - 3)(D - 3)\} \div 30 \quad (3)$$

Where T is the average temperature of the month and,
D is the amount of date in a month that have more than 0.1mm rain fall.

The climate classes for termites were classified into 3 classes according to the possible attack of the two major termites inhabiting in Japan. The classes are as follows:
Class 1: No attack.
Class 2: Attack of one specie.
Class 3: Attack of two species.

Service classes of the composing units
Followings are the units being concerned:
1) Exterior wall
2) Interior wall
3) Floor
4) Roof
5) Wall of balcony
6) Floor of balcony

The service classes for the composing units were classified according to the possible exposure of the structural members to water or humidity. For example the walls and floors of the bathroom and those of the bedrooms have different service classes. For example the coefficients the classes given for the exterior wall are shown in table 4.

Durability of the materials and components
Durability of the materials and components is classified according to the specification of the materials. The specification includes the material type, the lumber species, the adhesive types of glulam, LVL and sheathing materials and the method taken for the chemical processing for decay prevention. The coefficients are given in table 5 and table 6.

Design specification
Design specification was classified considering the design against water and humidity protection. For example high ranks were given to the specification such as long projected eaves, highly ventilated under floor and attic, uncovered and ventilated structural members. The classification are operated by counting the amount of good design being adopted.

Design specification against water protection
Specification of the facade against water protection was classified considering the design specifications of the facade. For example high ranks were given to high quality waterproof materials, high quality exterior sidings and water protection design. The classification are operated by counting the amount of good designs being adopted.

Quality of construction works
The quality of the construction works was classified according to the quality and quantity of the inspection. The classification is based on the content and number of inspection items.

Table 4 Service Class and Coefficient for Exterior Wall

ENVIRONMENT		ROOM TYPE THE EXTERIOR WALL FACES			POSSIBLITY OF WATER EXPOSURE		COEFFICIENT
DRY	WET	BATH-ROOM	WASH-ROOM / KITCHEN	OTHERS	DRAIN	DOOR/ WINDOW	
X		X					0.40
X		X			X		0.36
X		X				X	0.32
X		X			X	X	0.29
	X	X					0.36
	X	X			X		0.32
	X	X				X	0.29
	X	X			X	X	0.26
X			X				0.64
X			X		X		0.58
X			X			X	0.51
X			X		X	X	0.46
	X		X				0.58
	X		X		X		0.52
	X		X			X	0.46
	X		X		X	X	0.41
X				X			0.80
X				X	X		0.72
X				X		X	0.64
X				X	X	X	0.5
	X			X			0.65
	X			X	X		0.58
	X			X		X	0.58
	X			X	X	X	0.48

Quality of maintenance (builder)
The quality of the maintenance operated by the builders was classified according to the quantity and quality of the routine inspection and maintenance.

Quality of the maintenance (owner)
The quality of the maintenance operated by the owners was classified according to the quantity and quality of the daily inspection and maintenance.

Table 5 Material type, Specification and coefficient

MATERIAL	SPECIFICATION	COEFFICIENT
Lumber	Durable Species (Heart wood)	1.5
Lumber	Normal Species (Heartwood)	1.0
Lumber	Durable / Normal Species (Sapwood)	0.5
Glulam	Durable Type	1
Glulam	Normal Type	0.5
LVL	Durable Type	1
LVL	Normal Type	0.5
Plywood	Durable Type	0.8
Plywood	Normal Type	0.5
OSB	-	0.5
Particleboard and fiberbord	Durable Type	0.5
Particleboard and fiberbord	Normal Type	0.5

Table 6 Coefficient for chemical processing against the attack of termite attack and wood-rotting fungi

METHODS FOR CHEMICAL PROCESSING	COEFFICIENT
Pressure Injection	0.6
Adhesive Contamination	0.4
Field Application	0.2

Calculation method
The formula to calculation the service life is given in equation 3 and equation 4.

$$SL1 = C \times SC \times DMC \times DS \times WPS \times CQ \quad (3)$$

Where $C = (C1 + C2)/2$,
$DMC = D1 \times D2$,
$SL1$ is the coefficient that represents the initial service life of buildings (i.e. with no regard to the effect of the maintenance quality),
$C1$ is the coefficient that represent the inhabitation of wood-rotting fungi,
$C2$ is the coefficient that represent the inhabitation of termites,
SC is the coefficient that represent the service classes of the composing units,
$D1$ is the coefficient that represent the durability of the materials and components,
$D2$ is the coefficient that represent the method adopted for chemical processing,
DS is the coefficient that represent the design specification for durability and,
WPS is the coeeficient that represent the design specification for the water and humidity prevention,
CQ is the coefficient that represent the quality of the construction works.

$$SL2 = SL1 \times MQ \quad (4)$$

Where $MQ = M1 \times M2$,
$SL2$ is the coefficient that represents the possible service life of building being maintained in a certain quality,
$SL1$ is the coefficient that represents the initial service life of buildings (i.e. with no regard to the effect of the maintenance quality),
$M1$ is the coefficient that represent the quality of maintenance works of the builder and,
$M2$ is the coefficient that represent the quality of maintenance works of the owner.

The service life is classified into 4 classes in accordance with the values of $SL1$ and $SL2$ (see table 7).

Table 7 Service life and corresponding coefficient

CLASS	*SL1*	*SL2*
3 Generation	$2.2 \leq x$	$2.2 \leq x$
2 Generation	$1.2 \leq x < 2.2$	$1.2 \leq x < 2.2$
1 Generation	$0.3 \leq x < 1.2$	$0.3 \leq x < 1.2$
0 Generation	$0.0 \leq x < 0.3$	$0.0 \leq x < 0.3$

COMPUTER ASSISTED CALCULATION PROGRAM

Computer assisted service life calculation program for wooden buildings was developed. The summary of the program are as follows:

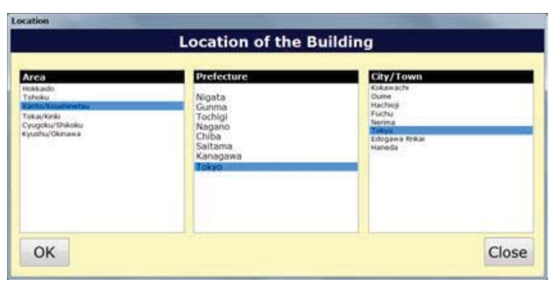


Figure 3 Operational screen to give input for the location of the building

Climate classes
Climate classes for the site can be set by choosing the location from almost 900 locations. The coefficients that represent the climate of the sites are

automatically given. Figure 3 is the operational screen to give input for the location of the site.

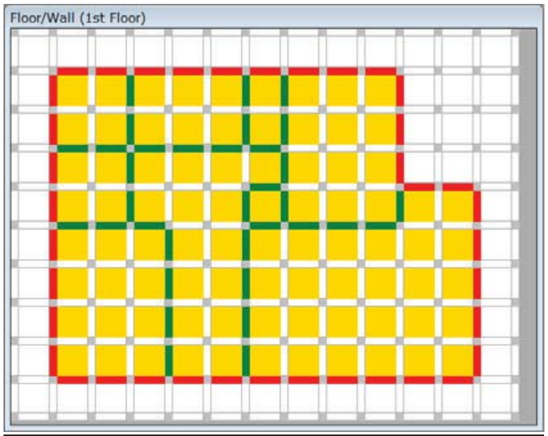
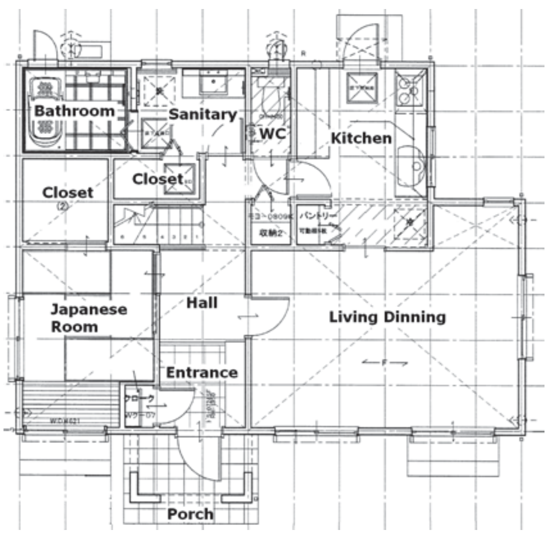
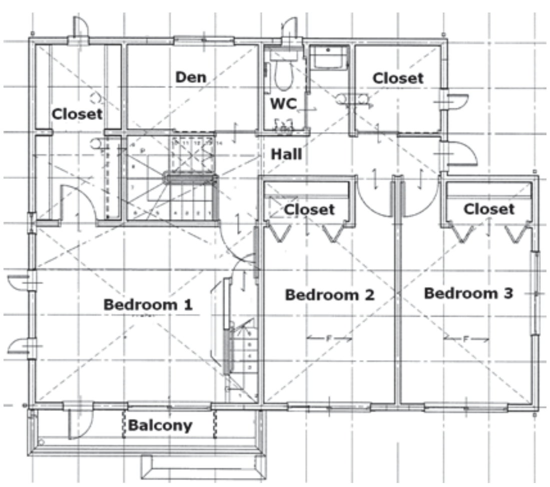


Figure 4 Example of the grid setting



(a) First floor



(b) Second floor

Figure 5 Floor plan of the case studied house

<u>Grids setting</u>

In the Tool one unit of the wall or one unit of the floor are expressed as one grid. Figure 4 gives an example of the grid setting. The grids those of the 1st floor of the house that the floor plans are given in figure 5. The red grids represent the exterior walls, the green grids represent the interior walls and the yellow grids represent the floor.

<u>Climate condition of the elements</u>

Figure 6 shows the operation screen to set the climate condition of each unit. By choosing the climate condition and clicking the corresponding grid the climate condition will be given to all units.

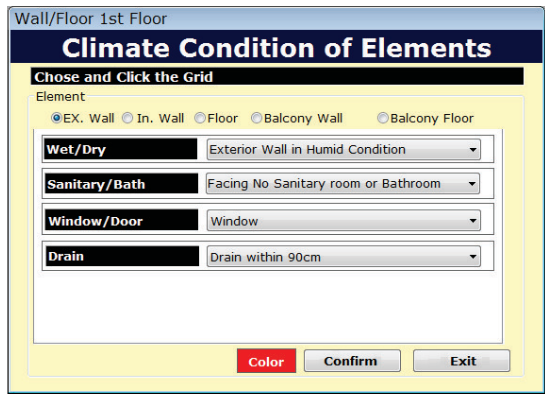


Figure 6 Input menu for the condition of the elements

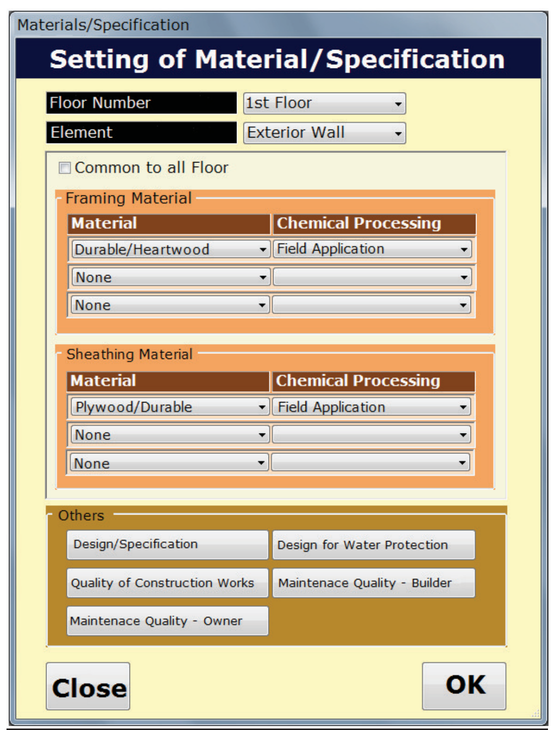


Figure 7 Input menu for materials and measurements

Durability of materials and components, design for durability and quality of construction and maintenance works

Figure 7 is the operation screen to set the following items:

1) Type and specification of materials and components
2) Design adopted to increase durability.

By choosing the type of the materials and components being used and the design measurements taken to improve durability for the corresponding grids the durability level will be set for the units.

PROGRAM TO CALCULATE THE AMOUNT OF WASTE

A program was developed to calculate the amount of waste being generated in the 90 years period (i.e. three generation). The summary of the program are as follows:

Grid setting

The grid shown in figure 8 will be automatically displayed. The composition of the layer of the materials and components has to be set for all units. The composition of the layer can be chosen from the material list (see figure 9).

Figure 8 Grid to set the composition of the layer of the units

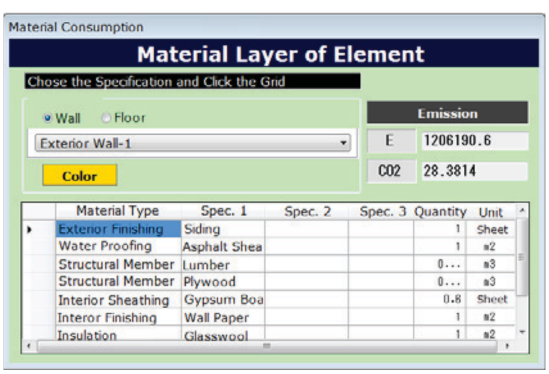


Figure 9 Menu to select the materials and components for the layer

CASE STUDY

A case study was operated to evaluate the contribution of long service life building for waste reduction. The case study was operated to a single detached house. The floor plan of the house is shown in figure 5. The house is a two story wood frame house and the total floor area is approximately 140m^2.

The estimated service life of the 1st floor is shown in figure 10. The estimated service calculated for the case with no measurement taken for long service is shown in figure 10(a). Almost all units of the house except some units of the interior walls were ranked as one generation or two generations. The estimated service life calculated for the case that measurements were taken for long service is shown in figure 10(b). The walls and floor of the bathroom were ranked as one or two generations and the floors of the sanitary room, toilet and kitchen were ranked as two generations. Other units such as the walls and floors of the living room, dinning room and Japanese room were ranked as three generations.

(a) Measurement not taken for long service life

(b) Measurements taken for long service life

Figure 10 Estimated service life

The waste being generated to keep the house in a good condition for 90 years was calculated for the both cases. The calculation was operated on the assumption that the all layers of the units will be replaced when the units come to the end of their service life. In the normally operated refurbishment the whole layer will not be replaced but to make things simple in this method was taken.

The results are shown in figure 11. The amount of the waste was reduced to one-fifth by adopting measurements to extend the service life. As mention above the whole layer will not be replaced in the actual refurbishment the result is considered to overestimated. Detail calculation method that can take into account the service live of each layer will be developed as the next step.

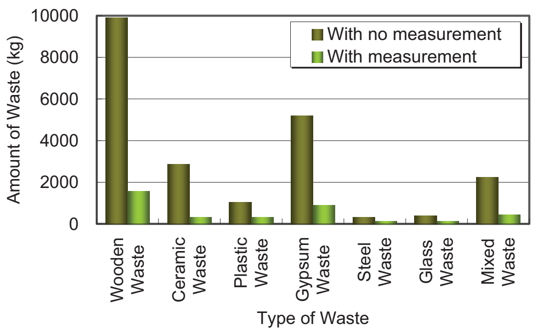


Figure 11 Comparison of the amount of the waste

CONCLUSION

A calculation tool that can calculate both the service life and the life cycle waste of wooden buildings was developed. A case study was operated to evaluate the contribution of long service life of the buildings to the waste reduction. As the result of the case study the amount of the waste was reduced to one-fifth by adopting measurements to extend the service life. As the case study was operated on the assumption that the all layers of the units will be replaced when the units come to the end of their service life detail calculation method that can take into account the service live of each layer should be developed as the next step.

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A MECHANICAL PROCESS FOR IN SITU RECYCLING OF EOL CONCRETE

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ABSTRACT

Recycling End of Life (EOL) concrete into high-grade aggregate for new concrete is a challenging prospect for the building sector because of the competing constraints of low recycling process cost and high aggregate product quality. A further complicating factor is that, from the perspective of the environment, there is a strong societal drive to reduce bulk transport of building materials in urban environments, and therefore, to apply more in situ recycling technologies for construction & demolition waste. The European C2CA project investigates a combination of smart demolition, grinding of the crushed concrete in an autogenous mill to increase the liberation of cement mortar from the surface of aggregates and a novel dry classification technology called ADR to remove the fines. The feasibility of this recycling process was examined in a demonstration project involving 20,000 tons of EOL concrete from two office towers in Groningen, the Netherlands. Results show that the +2 mm recycled aggregate compares favorably with natural aggregate in terms of workability and the compressive strength of the new concrete, showing 30% higher strength after 7 days.

Keywords: Recycling, Concrete, Recycled aggregate

INTRODUCTION

In the coming years, a strong increase of the amount of waste is expected in Europe because of the large number of constructions from the 1950's which are closing to their end of life. It is estimated that the annual generation of C&D waste in the EU could be as much as 450 million ton, which is the largest single waste stream apart from farm waste (Rao et al., 2007). At the same time, the demand for road foundation materials, an important outlet for the stony fraction of C&DW, is expected to decline with time, due to the reduction in the net growth of infrastructure. Government statistics of the Netherlands, for example, predict that whereas nearly 100% of the EOL concrete is absorbed by the Dutch road sector today, this number will have dropped to below 40% by 2025. By recycling part of the concrete fraction of C&DW into high quality construction materials like aggregate and cement for new concrete, it is possible to take advantage of the surplus of waste. However, so far as there are many unsolved problems associated with the quality of recycled aggregate, its application is limited.

In order to provide a sustainable solution, Recycled Aggregate Concrete (RAC) must be able to compete with primary materials in terms of workability, compressive strength and durability. To satisfy all these requirements, it is crucial to at least reduce the contents of (floating) contaminants and fines of the aggregate. The simplest option to realize this is to dilute recycled aggregate (RA) with natural aggregate (NA) down to levels of 20% replacement of total aggregate by RA (Paul and Van Zijl, 2012), but of course this is not a sustainable practice eventually. Removing fines, so far, has been practical only for fully dry crushed concrete by screening or by wet classification methods. Drying the materials to lower moisture content prior to screening is unattractive because it consumes a lot of energy while wet methods produce sludge which has to be treated or land-filled, often at considerable costs (de Vries and Rem, 2012). Another problem is that both drying and wet technologies are less suitable for in situ recycling in an urban environment.

The C2CA project aims at a cost-effective system approach for recycling high-volume EOL concrete streams into prime-grade aggregates and cement (see FIGURE 1).

The technologies considered are smart demolition to produce crushed concrete with low levels of contaminants, followed by mechanical upgrading of the material on-site into an aggregate product with sensor-based on-line quality assurance and a cement-paste concentrate that can be processed (off-site) into a low-CO2 input material for new cement. To achieve in situ recycling of the aggregate is one of the main goals of the C2CA project. Therefore liberation of the cement paste as well as the sorting and size classification of the aggregate is performed purely mechanically and in the moist state, i.e. without prior drying or wet screening. This choice reduces process complexity and avoids problems with dust or sludge. After crushing and sorting out big contaminants, liberation of the cement paste is promoted by several minutes of grinding in a small-diameter (D = 2.2m) autogenous mill while producing as little as possible new fine silica. A new low-cost classification technology, called advanced dry recovery (ADR) (de Vries and Rem, 2012) and (Berkhout and Rem, 2009) is then applied to remove

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the fines and light contaminants with an adjustable cut-point of between 1 and 4 mm for mineral particles. ADR uses kinetic energy to break the bonds that are formed by moisture and fine particles and is therefore able to classify materials almost independent of their moisture content. After breaking up the material into a jet, the fine particles are separated from the coarse particles. ADR separation has the effect that the aggregate is concentrated into a coarse aggregate product and a fine fraction including the cement paste and contaminants such as wood, plastics and foams. In order to reduce cost and make it possible to ship the recycled aggregate to a mortar facility immediately after production, The C2CA project develops two types of sensors for automatic on-line quality control and quality assurance. The concept is to avoid the need for laboratory analysis and intermediate storage, minimize transport of bulk materials and combine, if possible, quality and end-of-waste certification at the site, without human intervention. A schematic representation of the C2CA process is shown in FIGURE 2. A second major goal of the project, next to in situ processing and local reuse of the aggregate, is to help decrease CO2-emissions in cement production by concentrating part of the cement paste from EOL concrete into a separate fraction that can be reused as a low-CO2 feedstock replacing primary limestone. Already in 2000, world cement production amounted to 8.6% of global CO2-emissions from fossil fuels (Kleijn, 2012).

Perhaps the most challenging goal of the C2CA project is to understand how Europe may encourage the in-situ recycling of EOL buildings into high-grade new building materials. For this, the C2CA project focuses on projects in which construction companies take the lead both in demolishing and recycling EOL buildings as well as in constructing new buildings. Such a combination of activities in a single actor has important advantages in creating a circular economy for the building sector. For one, the construction company is in control of the quality of the recycled materials used in the new buildings and the costs associated with uncertainty about this quality is strongly reduced. Another strong point is that the construction company is both the supplier and the user of building materials, and so will tend to use its favorable negotiation position to enforce a maximum and optimal re-use of its own material.

MATERIALS AND METHODS

The first case study of the C2CA project involved demolition of a governmental complex in the province of Groningen in the Netherlands and the building of an underground garage from concrete with recycled aggregate. The scope of the demolition part of the project consisted of two identical high-rise towers (KB2 and KB6) and several low-rise buildings marked with the blue dotted line in FIGURE 3. In the 70's and 80's the Dutch construction sector used asbestos in the buildings. Therefore, prior to the dismantling asbestos was removed. The further strategy for the dismantling of the EOL-buildings in Groningen involved the detailed removing of all materials from the concrete skeleton before starting of the demolition: air-conditioners, radiators, lamps, piping systems of water and heating, electric cables, carpets, gypsum plates from ceilings and walls, window glass, frames of doors and windows etc.

For the demolition of the two towers (KB2 and KB6) three different methods were investigated from which two methods were applied: the top-down method to demolish the top 12 floors, and short-reach method to demolish the lowest 2 floors of the towers. Different types of concrete were used for structural floors, structural beams, pillars and façades in the two towers (see TABLE 1). The quality class of the parent concrete mixture was K-300 (325kg cement per m3). According to the visual evidence two types of cement, Portland and CEM III/B (historic name: blast furnace-A), exist in this EOL concrete.

Clean EOL concrete from the two towers was collected in two batches of 10000 ton each. Both batches were crushed applying an industrial jaw crusher (Kleemann: SSTR1400) to particle sizes smaller than 40 mm. Jaw crushers are reported to perform better than impact crushers in the case of aggregates recovery (Hansen, 1990), because they will crush only a small proportion of the original aggregate particles in the old concrete if they are set at 1.2 -1.5 times the maximum size of original aggregate. FIGURE 4 shows the particle size distribution of the crushed concrete according to norm EN 933-11:2009 for the first batch. A sample of circa 40 tons of this material was processed while varying the conditions of the milling process and samples were taken of the +2 mm ADR aggregate product for testing.

A floating test of the crushed EOL concrete of the first batch according to EN 12620 (for application of the material as coarse recycled aggregate) shows that the total amount of floating contaminations is less than 1 cm3/kg. This level of floats satisfies the FL2-specification of EN 12620. It confirms that the EOL concrete comes from a careful demolition procedure, and that sensor sorting to remove coarse contaminants was not necessary. The distribution of floating materials in the +4 mm fractions is shown in TABLE 2.

Crushed concrete was used to carry out experiments with a simplified version of the C2CA process. A mill (5.6 meter length, 2.2 meter diameter and 12RPM speed) with maximum internal capacity of 16 tons was installed. Milling of materials was followed by a rotating 16 mm screen and an ADR with a capacity of 60 tons per hour. FIGURE 5 shows the flowchart of the process. Experiments were conducted applying two different amounts of loading inside of the mill. In both experiments the residence time of the materials inside of the mill was 12 minutes and around 30 (wt%) of mill input was refluxing coarse fraction with the size of +16mm. TABLE 3 lists the amounts of loaded crushed concrete inside of the mill as well as the coding of the experiments and products.

PROPERTIES OF RECYCLE AGGREGATE

Laboratory tests were conducted on the coarse ADR product samples 3-BS2 and 4-BS2 to evaluate the properties of recycled aggregates (RA). TABLE 4 shows the used standards. ADR coarse product (3-BS2) was selected for testing into new concrete. The water absorption capacity of RA (3-BS2) is 5,4 (wt%) which is typical for C&DW coarse aggregates with density 2000-2400 kg/m3 originating from demolition of concrete constructions. The guideline prepared by RILEM (Hendricks and Pietersen, 1998) recommended recycled coarse aggregates for concrete production if their water absorption are between 3-10%.

Recycled aggregate tends to absorb more water in comparison with natural aggregates. Many researches attempt to address this issue by increasing the water and cement content in order to achieve the required workability at a constant water to cement (W/C) ratio (Nixon, 1978) and (NEVILLE, 2011). However, higher cement content can affect the properties of the hardened concrete like shrinkage beside being not economical.

PERFORMANCE OF RECYCLED AGGREGATE CONCRETE

Samples of recycled aggregate concrete (RAC) and natural aggregate concrete (NAC) were made separately with the same amount of cement and consistence. Based on the initial concrete recipes the fresh concrete mixes were prepared at the laboratory mixer (18dm3), afterward the properties of the first fresh concrete mixes were used as a basic information for modification of concrete recipes. The modified concrete recipes for both RCA and NCA can be seen in Table 5. Curing conditions after de-moulding of samples was according to EN 12390-2. FIGURE 6 shows the compressive strength with the standard errors resulting from the tests done in triple. Fresh and hardened concrete properties can be seen in Table 6.

Considering FIGURE 6, it is clear that recycled concrete aggregate achieved more compressive strength up to 30% at early ages and after aging this difference has become lower, to 5% at 90 days.

For normal concrete with typical aggregate the interfacial transition zone (ITZ) is composed of three layers: a film composed of sub-layer of Ca(OH)2 in direct contact with aggregate surface and C-S-H sub-layer with ettringite crystals backing it, large portlandite crystals and porous layer which are smoothly dense to normal bulk C-S-H paste. The thickness of this zone is different, usually about 30-100 μm (Pichór, 2006). This special structure of ITZ is a result of higher local water/cement ratio in the vicinity of aggregate surface because of wall effect. Also water which is absorbed on the aggregate surface plays an important role in this phenomena. In comparison with natural aggregates, C&DW aggregates usually are more porous. From this the ITZ microstructure of the concrete with addition of recycled aggregates are different from that of the concrete with natural aggregates. In the fresh concrete mix made with recycled aggregates the high porosity and water absorption capacity of these aggregates, usually coupled with its low initial water content, rendered the aggregate to take up a large amount of water during the initial mixing stage and lowered the initial W/C ratio in the ITZ at early hydration. Newly formed hydrates gradually filled this region. This process effectively improved the interfacial bond between the aggregate and cement, what could resulted in growing early strength development of the concrete. Additionally, in comparison with natural aggregates, C&DW aggregates are usually partially carbonated on the aggregates surface (old mortar or cement paste) what could increase growing of new hydration products in initial time of hydration.

According to earlier researches, the compressive strength of recycled aggregate concrete is somewhat lower (in some cases up to 20% lower) compared with the strength of control mixes (Nixon, 1978). However, there have been some unpublished researches indicating reaching higher compressive strength in recycled aggregate concrete.

An experimental study was performed in accordance with PN-B/88-06250 to check durability of RAC and NAC. Twelve cube samples with a size of 100*100*100 mm were stored for 56 days under condition with relative humidity greater than 95% (water) and at a temperature of 20°C ± 2ºC. After 56 days of ageing, 6 samples were placed in water with a temperature of 20°C ± 2ºC while the remaining six samples were subjected to cycles of freezing and thawing at a rate of 2–3 cycles per day. Freezing took place in air (-18oC ± 2ºC) and thawing in water (18oC ± 2ºC). Frost resistance was determined by a drop in compression strength and a loss of mass in the samples subjected to cyclic freezing compared to the control samples which were stored in water at 20oC. After 100 cycles, compressive strength and weight loss of samples were determined. According to the standard, frost resistant concrete should have a mass loss of less than 5% and a loss of compression strength smaller than 20%.

Results show that NAC had a reduction in compressive strength about 0,6%, and loss of weight below 5%. Simultaneously, RAC samples showed a decrease in compressive strength of 10,4%, and loss of weight below 5%. Considering PN-B/88-06250 both concretes fulfill requirements for F100 class of freeze-thaw resistance (see Table 7). Differences in compressive strength after cycles of freezing and thawing between RAC and NAC could result from many factors, e.g. the higher water absorption of recycled aggregates, mineralogical types of aggregates, porosity and concrete recipe parameters like: W/C ratio, air content.

CONCLUSION

A new process is being developed in the context of the European C2CA project, which aims to reduce the environmental impact of Construction & Demolition waste by in-situ mechanical recycling of EOL concrete into high-grade aggregate and low-CO_2 raw material for cement. The process applies autogenous milling and ADR to extract 2-16 mm recycle aggregate from crushed concrete. Among the various mechanical liberation routes, attrition milling at low to medium compression appears to produce aggregate of particularly high quality. This type of attrition milling offers low-complexity (mobile) and low-cost technology. After milling, ADR efficiently separates the moist material into fine and coarse fractions. In the course of the first demonstration case of the new technology, recycle aggregate was tested into new concrete (RAC) to investigate the workability, compressive strength and durability compared to concrete made from natural aggregate. The RAC showed 30% higher compressive strength after 7 days. It is believed that the favorable development of strength of the recycle aggregate is caused by changes in the surface porosity of the particles as a result of the intensive liberation process. The results of the freeze-thaw resistance showed that the recycled concrete performed less well than NAC but fulfilled the requirements for F100 class.

AKNOWLEDGEMENT

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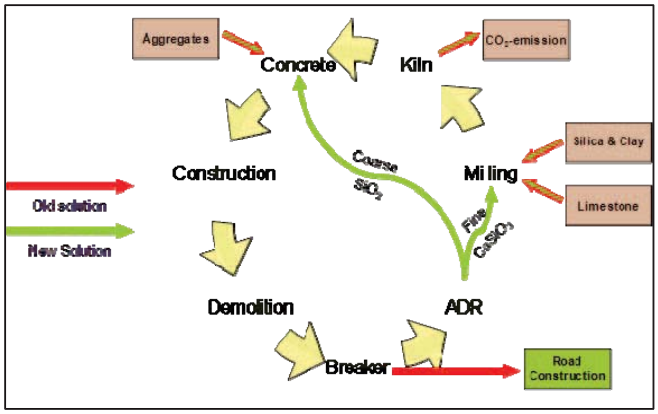

FIGURE 1: Existing vs. proposed novel closed cycle for C&D wastes.

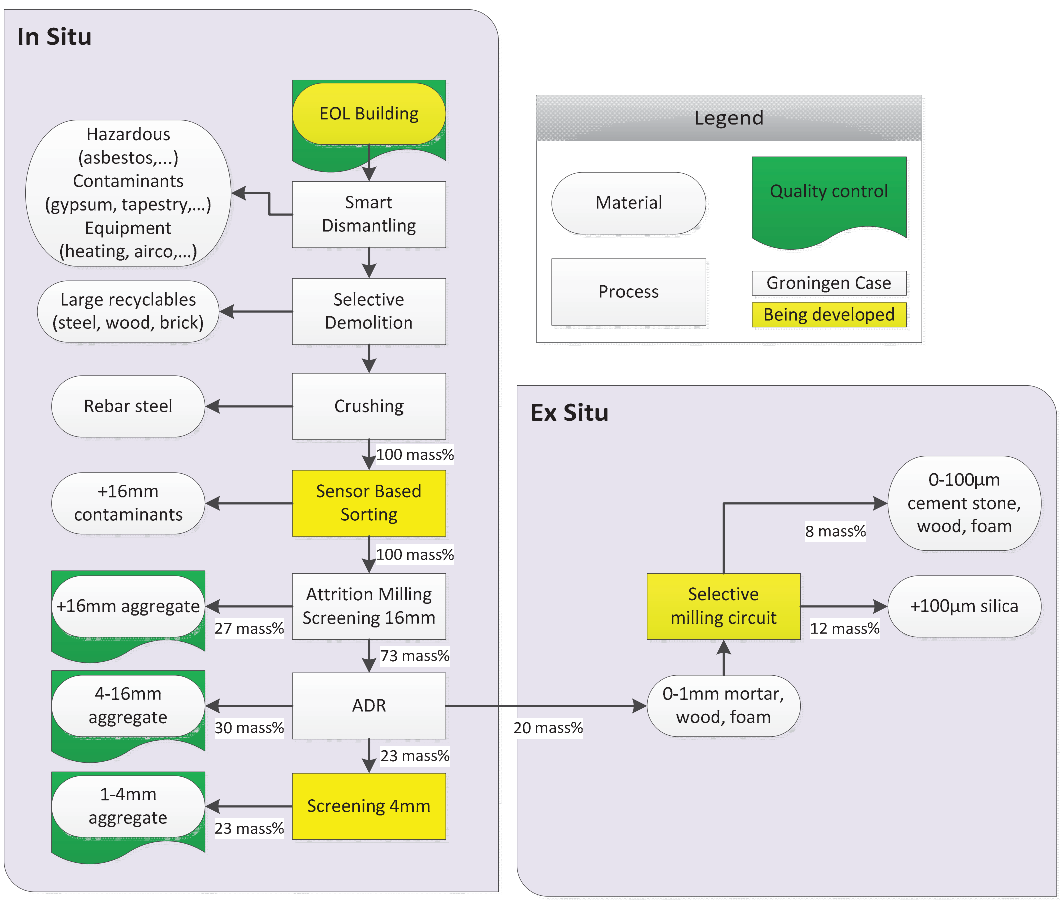

FIGURE 2: General layout of the C2CA technology showing the mass flow distribution for the concrete fraction. Mechanical process steps and quality assessment steps that were not yet implemented in the first demonstration case are shown in dark colour.

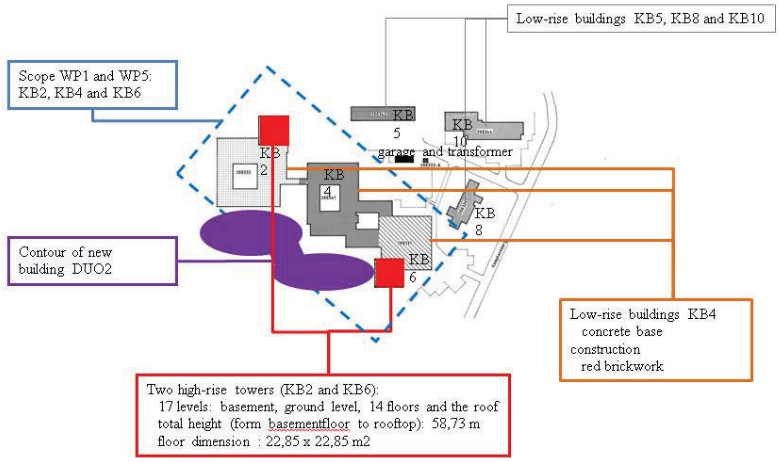

FIGURE 3: Overview of the end of life buildings.

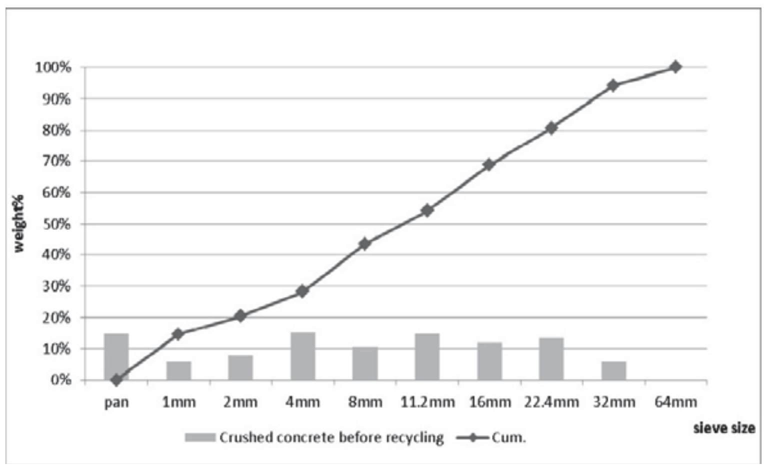

FIGURE 4: Particle size distribution of the crushed concrete.

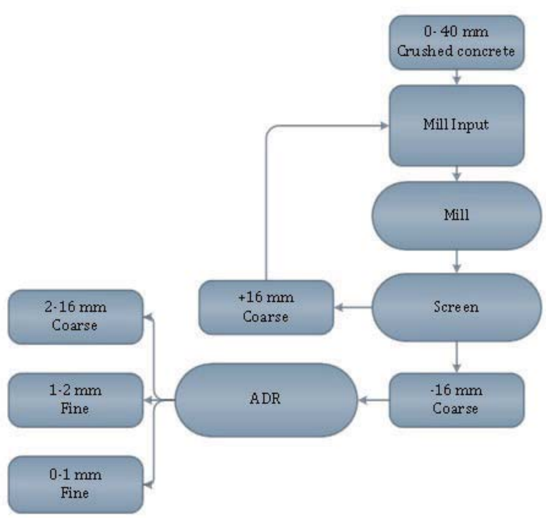

FIGURE 5: Flowchart of the recycling process.

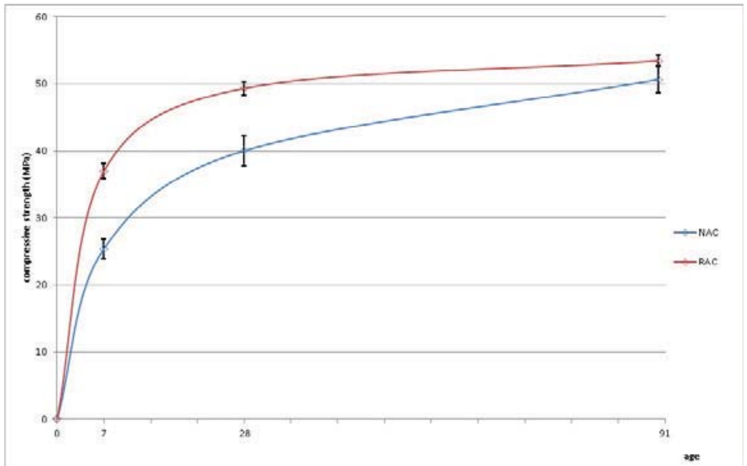

FIGURE 6: Comparison between compressive strength of RCA and NCA in different ages .

TABLE 1: Overview of the amounts of clean EOL concrete recovered from each tower.

storey	structural floor		structural beam		pillar		facade		storey total	
-1	915	m3	0	m3	44	m3	0	m3	959	m3
0	104	m3	51	m3	93	m3	0	m3	248	m3
1	104	m3	51	m3	44	m3	24	m3	222	m3
2	104	m3	51	m3	44	m3	24	m3	222	m3
3	104	m3	51	m3	44	m3	24	m3	222	m3
4	104	m3	51	m3	44	m3	24	m3	222	m3
5	104	m3	51	m3	44	m3	24	m3	222	m3
6	104	m3	51	m3	44	m3	24	m3	222	m3
7	104	m3	51	m3	44	m3	24	m3	222	m3
8	104	m3	51	m3	44	m3	24	m3	222	m3
9	104	m3	51	m3	44	m3	24	m3	222	m3
10	104	m3	51	m3	44	m3	24	m3	222	m3
11	104	m3	51	m3	44	m3	24	m3	222	m3
12	104	m3	51	m3	44	m3	24	m3	222	m3
13	104	m3	51	m3	50	m3	24	m3	228	m3
14	104	m3	51	m3	52	m3	24	m3	230	m3
roof	126	m3	51	m3	0	m3	20	m3	197	m3
imtem total	2599	m3	813	m3	770	m3	351	m3	**4532**	**m3**

TABLE 2: Floating materials in crushed concrete.

Size of crushed aggregates(mm)	floating materials [cm^3/ per kg of crushed concrete]
4-8	0.38
8-11.2	0.09
11.2-16	0.05
16-22.4	0.08
22.4-31.5	0.14
Total	**0.74**

TABLE 3: Recycling experiments coding and amount of loading inside of the mill.

experiment code	total mill input (ton)	Reflux of +16 mm into the mill	ADR products codes		
			coarse (2-16 mm)	fine (1-2 mm)	fine (0-1mm)
3-BS	8.7	yes	3-BS2	3-BS3	3-BS4
4-BS	15.1	yes	4-BS2	4-BS3	4-BS4

TABLE 4: Standards used for determining properties of recycled aggregate

Test	Standards
particle shape (flakiness index)	EN 933-3
particle shape(shape index)	EN 933-4
Resistance to fragmentation (LA coefficient)	EN 1097-2
resistance to crushing according to Polish National Standard	PN-B-06714-40

TABLE 5: Modified mix composition of RAC and NAC.

Component	RAC		NAC	
	Mass [kg]	Volume [dm^3]	Mass [kg]	Volume [dm^3]
Cement – CEM I 42,5R	380	123	380	123
Water	167	167	137	137
Coarse	1162	445	1063	439
Sand	508	192	603	227
Superplasticizer	0,8% of cement mass			
Air entraining admixture	0,4% of cement mass			
Initial W/C ratio	0,44		0,36	

TABLE 6: properties of fresh and hardened concrete.

Type of concrete	Fresh concrete		Hardened concrete	
	Slump(mm)	Air content Vol.%	Abrasion resistance (mm)	water absorption [% wt.]
NAC	130	6.5	22.5	5.7
RAC	140	6.5	23	6.4

Table 7: Compressive strength of samples after freeze-thaw cycle and control samples in water.

Type of concrete	compressive strength (Mpa) control samples in water	standard error	compressive strength (Mpa) after freeze-thaw cycles	standard error	Loss of weight [%]
NAC	61,9	1,3	61,5	1,2	< 5
RAC	56,4	0,5	50,6	1,6	< 5

CONSTRUCTION AND DEMOLITION WASTE MANAGEMENT IN HONG KONG

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ABSTRACT

This paper provides an overview of the current practice of construction and demolition waste management in Hong Kong and formulates strategies for waste minimization. The data for this paper came from a survey questionnaire, interviews and a case study. The results of the survey showed that companies mainly reused metal, wood, wires, paper and bamboo in their sites. The mains reasons the responding companies were not reusing other waste materials are the high recovery costs, lack of space for storage and lack of special contractors to recover the waste materials. Most of the responding companies did not have a construction and demolition waste management plan. This would indeed be the biggest barrier in implementing the construction and demolition waste management in Hong Kong. The paper also provides recommendations to different parties involved in construction projects, including the government, developers, designers and contractors.

INTRODUCTION

Hong Kong is one of the most densely populated cities in the world with an overall density of approximately 6,300 people per square kilometer. The city's population has increased sharply since the late 1980s, and reached 7 million in 2010. The population, however, is continuing to grow due to the influx of annual 45,000 immigrants from mainland China. In order to cope with this huge population, redevelopment of old urban districts is imperative and inevitable.

Due to the rapid redevelopment programs, a large amount of construction and demolition waste (C&D) is being generated every year. In 2009, Hong Kong generated approximately 6.4 million tonnes of municipal solid waste of which 51% was landfilled (Wong et al. 2011). According to the Hong Kong Environment Protection Department (EDP 2011) in 2011 C&D solid waste disposed at landfills was 1.22 million tonnes and accounted for 25% of all solid waste disposed to the landfills (Table 1). Despite the fact that reusing, recycling and reducing waste have been encouraged by the Hong Kong government, disposal in landfills is still the most common method used in the construction industry for the disposal of C&D waste (Hao et al. 2008). With the current rate of solid waste disposal the landfills in Hong Kong will be filled up by 2015 (Poon 2007). Thus, C&D waste control is an essential element of sustainable development in Hong Kong. The amount of waste required to be disposed would be greatly reduced if there is a better C&D waste management system on construction sites.

Table 1. Disposal of solid waste at landfills in 2011 (Adopted from: EDP 2011)

	Waste type	Average daily quantity (tpd)
a	Domestic waste	5,973
b	Commercial waste	2,360
c	Industrial waste	663
d	Municipal solid waste (a+b+c)	8,996
e	Overall construction waste	3,331
f	Special waste	1,131
g	All waste received at landfills (d+e+f) Total	13,458

This paper provides an overview of the current situations of C&D waste management practice in Hong Kong and suggests few strategies to minimize C&D waste.

DEFINTIONS

The following are definitions of key words used in this paper
.

CONSTRUCTION AND DEMOLITION WASTE. Waste arising from any land excavation or formation, civil or building construction, roadwork, building renovation or demolition activities. It includes various types of building waste, rubble, earth, concrete, timber and mixed site clearance materials (EPD 2007).

RECYCLING. Recycling includes collecting recyclable materials that would otherwise be considered waste, sorting and processing recyclables into raw materials such as fibers, manufacturing raw materials into new products, and purchasing recycled products.

REUSE. Reuse involves putting an item to another use after its original function has been fulfilled. The products are used a number of times before they are discarded.

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COMPOSITION OF C&D WASTE IN HONG KONG

Figure 1 shows that over 85% of C&D waste in 2000 came from renovations and construction works (Li 2002).

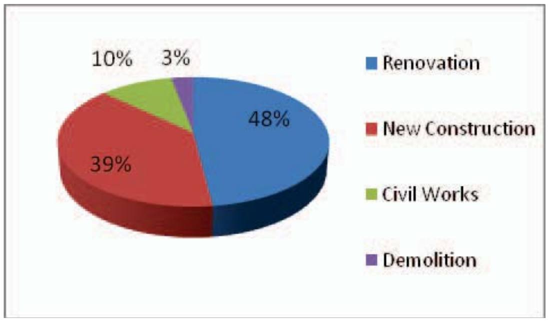

Figure 1. The percentage of waste from different kinds of C&D activities. The percentage of waste is based on volume. (Adopted from: Li 2002)

The renovation works are usually conducted by small contractors employed by individual households. In general, it is difficult to sort waste due to renovation because it is broken into fine pieces and mixed together. This reduces the possibility of recycling or reusing and the waste is inevitably disposed to landfills. Almost 80% of C&D waste came from private projects. Table 2 shows that concrete was the most common construction material received in the public landfills in Hong Kong. This is because most of buildings in Hong Kong are made of reinforced concrete.

Table 2. Composition of C&D waste received in the public landfills in Hong Kong. The percentages are based on volume. (Adopted from: Li 2002)

	CON	DEM	CIV	REN
METAL	4%	5%	10%	5%
WOOD	5%	7%	0%	5%
PLASTIC	2%	3%	0%	5%
CONCRETE	75%	70%	40%	70%
ROCK/RUBBLE	2%	1%	5%	0%
SOIL/SAND	5%	0%	40%	0%
GLASS/TILE	3%	2%	0%	10%
OTHERS	4%	12%	5%	5%

CON: construction, DEM: demolition, CIV: civil work, and REN: renovation

A more recent survey by Yuan et al. Showed that concrete is the most common construction waste on site followed by timber board, brick and block, plaster, tiles, and ready mixed concrete (Yuan et al., 2011).

GOVERNMENT INCENTIVES FOR C&D WASTE MANAGEMENT IN HONG KONG

The Hong Kong government introduced the Construction Waste Disposal Charging Scheme (CWDCS) in December 2005. The scheme is a waste reduction measure based on the polluter pays principle (EPD 2007). The objective of this principle is to shift responsibility for processing or dealing with the C&D waste from the government to the parties who produce such waste. This charging scheme is not only intended to provide an economic incentive for contractors and developers to reduce waste but is also to encourage reuse and recycling of waste materials thereby slowing down the depletion of limited landfill and public filling capacities (Hao et al. 2008).

The scheme applies different charge rates for various types of construction waste and requires construction contractors to open an account with the government for payment of the waste disposal charges (EPD 2007). According to the CWDSC, disposal of construction waste is subject to a charge of HK$125/tonne if sent to landfills, HK$100/tonne if sent to sorting facilities, and HK$17/tonne if sent to public fill reception facilities.

A survey by Poon et al. showed that three years after implementation of CWDSC there was no consensus among the construction participants on its effectiveness. Close to 40% of the survey respondents believed that waste reduction is less than 5% after CWDCS was implemented. Almost 30% of survey respondents believed that the savings to contractors through CWDCS was not high enough to raise awareness about waste management on construction sites (Poon et al. 2013).

In addition, the Environmental and Other Obligations Assessment category requires contractors undertaking public residential construction works to submit a waste management plan to the Housing Department. It also encourages them to sort and segregate C&D waste generated in their construction site for reuse and recycling. However, this system is still only used in public residential projects.

The Hong Kong Government also introduced a new requirement in December 2005 requiring contractors of all public works to prepare and implement an Environmental Management Plan (EMP). Arrangement for, and conducting on-site sorting of construction waste are mandatory under the relevant contractual provisions and payment items (EPD 2007). These efforts contributed to the reduction of construction waste disposed of at the waste disposal facilities.

SURVEY

A survey was conducted to find out what C&D waste materials are commonly reused or recycled and explore the views of industrial participants towards different waste management strategies. A total of 350 questionnaires were sent via email and fax to the members of the Hong Kong Construction Association and the management teams of construction projects with high demand for C&D waste management. The respondents were consultants, engineers, project managers and environmental, health and safety officers. The overall response rate of the survey was about 10% (35 responses were received). The response rate was relatively low but is understandable considering the typical responding rate in the construction industry. As shown in Figure 2 major types of work performed by the respondents included: alteration and additions (34%), commercial (20%), civil works (11%), building services (9%), and educational (6%).

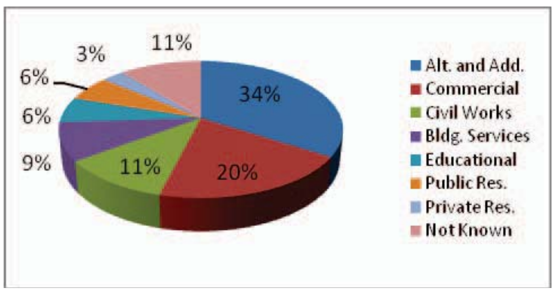

Figure 2. The percentage of the types of work being performed by the respondents

The purposes of the questionnaire were to find out:

- which kinds of waste materials have been reused;
- the main reasons for not reusing the waste materials;
- which kinds of waste materials have been recycled;
- the main reasons for not recycling the waste materials;
- if the responding companies have a plan designated for construction waste management; and
- the views of industrial participants towards different waste management strategies.

As a follow up to the survey two interviews were conducted. One of the interviewees was an environmental engineer while the other one was an environmental, health and safety officer. Each of the interviews lasted for approximately twenty minutes and was conducted via telephone conversations. The main purpose of interviews was to find out the limitations in reusing or recycling the waste of various categories.

<u>REUSE</u>

As shown in Figure 3, the responding companies mainly reuse metal, wood, paper and bamboo. The percentages of companies which have reused these materials are 74%, 74%, 54% and 60% respectively.

Metal. According to the interviewees, metal price has appreciated more than thirty percent during the past decade. The engineer would firstly inspect the condition of the metal. If the metal elements were suitable for new construction work, those elements would usually be reused. The most common metal elements which had been reused include the following items: metal formworks, steel columns, steel piles, metal pipes (e.g. cast iron, copper), metal railings, and metal doors. However, in some cases, the condition of the metal elements might not be suitable for new construction works. For instance, the metals were rusted due to aging of the elements and the dimensions of the existing materials did not suit the new works.

Concrete. Reusing the existing concrete elements in the new building structures is not common in Hong Kong. The main reason is that the existing elements do not dimensionally match with the new building designs. In addition, due to the aging of the concrete, it may not be able to support the structures and the loading of the new buildings.

Glass and Tiles. These kinds of materials are fragile and easily break during demolition. In addition, the recovering cost is expensive. Thus, they are usually disposed rather than reused.

Wood. The most common wood elements which had been reused included the following items: formwork timber, wood floor, and wood door. Due to the prevalence of in-situ reinforced concrete in buildings, extensive use of formwork is needed. Most of the formwork timbers are used more than once. However, this depends on the workmanship and the formwork stripping process. Some high quality wood flooring and doors would also be recovered and reused.

Rock, Rubbles and Sand. These materials could be used in sub-bases of piling structures or ground slabs and backfilling. However, this would require extra labor hours and extensive space for sorting, screening, jack-hammering and storing the aggregates. In most cases, it requires engineers to inspect if the rocks, rubbles and sand were free from contaminations for the purpose of using them as backfilling. Some builders would prefer to use imported materials for backfilling, in order to save time.

Wires. Due to aging of the wires, the wires in the existing buildings may not be safe and suitable to be reused in the new construction work. According to the interviewees, the cost of recovering the wires would not be much cheaper than buying new ones. Thus, most of the builders would prefer to dispose the wires rather than recover them.

Plastics. Most of the builders would reuse the plastic tools, like buckets, during the construction. However, the builder usually does not reuse the plastics from the existing structures, since the cost of virgin materials is low when compared with the cost of recovery.

Toilet Pans. Many owners do not accept used toilet pans in their properties, because they consider such toilet cups unhygienic. Furthermore, according to the interviewees, the recovery cost of toilet is high.

Paper Cloth and Textiles. Paper includes packaging waste, office paper, cardboard and newspaper. Cloth and textile includes carpets, towels, wiping cloth and canvas. Some of these materials might be contaminated during the construction and demolition or be wet due to exposure to the weather. These materials would not be suitable for reuse in such situations.

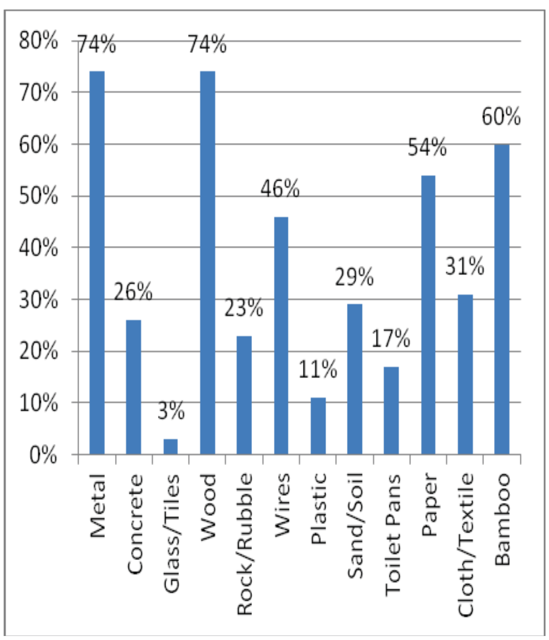

Figure 3. The mean percentage of companies which have reused different kinds of materials

Bamboo. Bamboo is widely used for scaffolding in Hong Kong, due to its stiffness, low cost and flexibility. Most bamboos are used more than once. However, bamboo becomes brittle when exposed to the weather and may not be suitable for reuse.

These companies listed high recovery costs of waste materials, lack of space for storage, and lack of specialty contractors to recover waste materials as main obstacles for reuse of waste materials. Other reasons mentioned were: tight schedule, lack of standards, and contract requirements.

<u>RECYCLE</u>
The results also showed that the responding companies mainly recycle metal, paper, wood, and plastic (Figure 4).

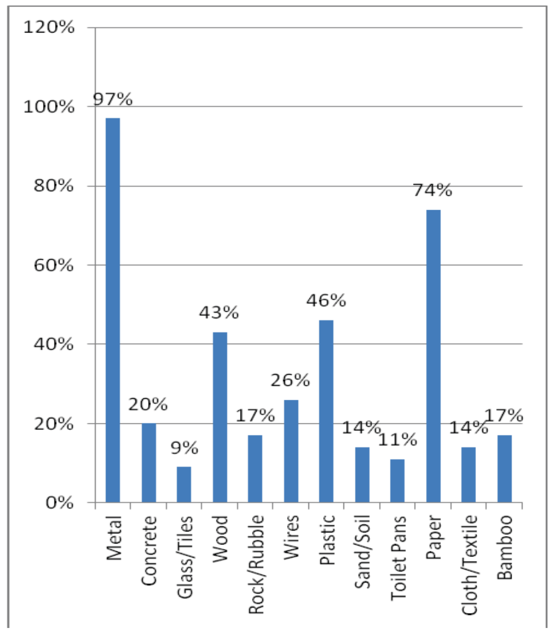

Figure 4. The mean percentage of companies which have recycled different kinds of materials

Figure 5 shows that the main reasons for low recycling rate for other materials include: tight schedule, lack of demand, and lack of space for sorting.

Tight Schedule. The land prices in Hong Kong are very expensive. Owners of the construction project often squeeze the construction time, so that they get the return from their investment (e.g. rental income, profit from selling the properties) and pay back the loans earlier. Therefore, project schedules are tight. Most of the construction companies are not able to afford extra time and man hours in sorting and storing recyclable materials. They would rather allocate budget and resources in the real progress of the projects.

Lack of Demand for Recyclable Materials in the Market. The recovering market is immature. Construction companies are not able to find recycling companies to recover the waste materials, even though there are suitable materials for recycling.

Lack of Space for Sorting. Retrieving recyclable materials requires extensive space for sorting. The site areas of the projects in Hong Kong are very limited, due to the high land prices. Construction company might not be able to allocate sorting area for retrieving recyclable materials. Such materials have to be disposed in such cases.

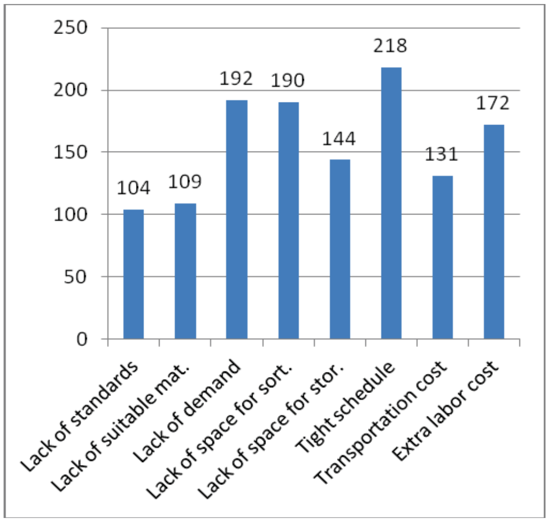

Figure 5. The scores of the reasons for not recycling the waste materials

MANAGEMENT PLAN

About 94% of the responding companies did not have a formal waste management plan; a plan that specifies the goals for waste management and identifies strategies and procedures to accomplish the goals. The current legislations do not mandate construction companies to have such plans before commencement of their works. Indeed, such planning is critical to the success of waste management.

The responding companies had favorable opinions towards government advocacy for reduction of C&D waste and increase of reuse/recycling rates. These could be in the form of mandating a minimum recycling rate or providing incentives for effective waste management plan.

CASE STUDY

A HK$100 million high-rise construction project was studied to demonstrate the strategies adopted by Hong Kong leading construction companies in managing C&D waste. The company in charge of the construction was certified to ISO 14001:2004 Environment Management System Standard by Hong Kong Quality Assurance Agency, and has also attained several awards related to the aspects of environmental protection in recent years. With annual turnover of approximately HK$1,000 million, the company is included in the List of Hong Kong Special Administrative Region (HKSAR) Approved General Building Contractors, List of Building Contractors for Housing Authority. The company is also in the list of HKSAR Approved Contractors for Public Works (Group C) for Categories of Buildings, Roads and Drainage, Site Formation, and Water Works.

For this project, the company established a plan for C&D waste management and provided details of the means and measures for reducing the environmental impact of the construction waste generated during construction. It also provided comprehensive guidelines for subcontractors and employees to follow.

The plan included the following items:

- Goals
- Organization structure for waste management
- Types and quantities of wastes that would be generated during the execution of the work
- Timing of waste arising
- Procedures of handling different kinds of waste
- Layout plan for on-site waste sorting
- Areas for waste storage
- Monitoring and auditing program

All C&D materials were sorted on-site and separated into the following categories for disposal at landfills, public filling areas, or reuse and recycling as appropriate:

- Non-inert portion (Landfill)
- Inert C&D waste(Public Fill)
- Chemical Waste
- Recyclable materials (e.g. metal)

The sorting was conducted immediately at designated points or at the source on each floor to avoid loss or leakage during handling. Different kinds of C&D materials (i.e. general C&D waste, inert waste, etc.) placed separately next to the refuse chute at each floor (Figure 6).

Figure 6. The refuse chute

To avoid contamination, different kinds of C&D materials were disposed separately via the refuse chute to the refuse collection point at ground level. The waste collected on the refuse collection point at ground level was removed promptly so that different kinds of wastes were not mixed together (Figure 7).

Metal formwork and scaffolding systems were used to reduce the amount of bamboo and timber waste disposed at landfills and public filling areas.

Waste generation was significantly reduced by use of a prefabricated concrete façade system (Figure 8). Yuan et al. examined the ways prefabrication can minimize construction waste in Hong Kong through a survey and concluded that although prefabrication is used mainly to reduce the construction time and improve quality, it also reduces waste by employing higher skilled labor force and over ordering (Yuan et al. 2011).

Recycling boxes for collecting recyclable wastes were placed at proper locations to increase efficiency of collecting and delivering wastes and promote environmental awareness among all working staff on site.

Figure 7. Refuse collection point at ground level

SUMMARY AND RECOMMENDATIONS

This research found that currently construction companied in Hong Kong reuse only a limited amount of recovered metal, wood, paper and bamboo. The mains reasons for low reuse rate are high recovery costs, lack of space for storage, and lack of special contractors to recover the waste materials. The research also found that construction companies are only interested in recycling materials with high value such as metal and paper. Most of the companies that responded to the survey did not have a C&D waste management plan, which seems to be the biggest barrier in reducing waste and maximizing reuse/recycling.

Figure 8. Prefabricated facade system

Based on the findings of this research, the following recommendations are made to minimize C&D waste and maximize reuse/recycling in Hong Kong:

- The government shall mandate contractors to reuse and/or recycle a minimum percentage of C&D waste in any construction project. Since such mandate requires a mature industry for recovery, reuse, and recycling that currently does not exist, the government should start with a relatively low rate and increase it gradually.

- Government shall provide incentives to encourage implementation of C&D waste management systems. These could be in the form of allowing higher floor area to site area ratio, lower tax rate, or lower charge fee in using public filling areas.

- Currently recovering or recycling companies are only interested in wastes with high recycling values, such as metals. The main difficulty for these companies is finding a suitable space for sorting and handling the waste due to the high cost of land. The government could lease out some land to these companies with rates lower than the current market.

- The developers shall include a clause in their construction contract requiring the contractors to develop and implement a C&D waste management plan for any private or public project. The contract may also include a penalty/bonus clause if the amount of waste is higher/lower than a specified limit.

- Major developers shall adopt an assessment system for selecting contractors in their procurement. Such assessment shall include the contractor's effectiveness in implementing C&D waste management plan.

- Designers shall consider waste minimization in their design by using modular size and prefabricated elements. They shall specify materials with recycled contents and allow contractor to select reused elements.

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CASE STUDY OF A HOUSING REFURBISHMENT AND MATERIAL REVITALIZATION

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ABSTRACT

Based on the 2011 American Housing Survey by the US Census Bureau, over 60% of the housing inventory in the US is more than 30 years old. According to the survey, the median construction date for homes is 1974. When considering methods to conserve energy and natural resources, the refurbishment of the existing homes would play a significant role. The University of New Mexico Schools of Engineering and Architecture in conjunction with the New Mexico Home Builders Association has undertaken a research project to evaluate the methods for remodeling homes that are more than 25 years old. The Civil Engineering Department at the University of New Mexico was endowed by the Association of General Contractors (AGC) with a 1960's era, 3 bedroom, 2 bath, 140 square meters home. The construction materials and energy usage for this facility is typical for the region. The primary objectives of the refurbishment are to convert the house to a low energy facility, analyse the deconstruction techniques, and evaluate the alternatives for installing reused/recycled materials. To accomplish this goal, the project will evaluate the cost effectiveness of material replacements, examine the options for reuse of salvaged materials, analyse the functionality of retrofitting building information systems, and perform a cost analysis that includes the impact of government incentives on the feasibility of home owner's implementation of these programs. The lessons learned from this project will provide valuable data to assist state legislation in assessing tax incentive programs and serve as a resource for environmental remodelling.

INTRODUCTION

Background
The United States Department of Energy estimates that over 41% of the energy demand (DOE, 2011) can be attributed to the built environment. The US Environmental Protection Agency has contracted numerous research projects that have shown that the amount of Municipal Solid Waste that can be attributed to the built environment vary depending on the particular state from 25 - 70%. Amid this group, residential construction, comprising of new construction, renovation, and demolition accounts for 39% of the overall buildings life cycle waste (EPA, 2009). As reported by the Department of Housing and Urban Development (HUD), the majority of residences in the US are greater than 36 years old and would require significant modifications to bring them up to current building standards (HUD, 2010). As the housing stock is remodelled, a greater amount of waste is generated and more natural resources are consumed.

In the US, the federal government only establishes regulations regarding recycling waste for government departments (EO, 2007). It is up to the individual states and local regions to develop and enforce their own goals for recycling programs. Although several states and cities have established energy saving objectives or recycling programs; numerous programs are being considered to encourage greater participation by the public in C&D waste recovery options for residential housing (Chini and Goyal, 2011). However, few home owners are willing to spend the extra revenue to provide for an energy efficient system or even provide for the extra labor to reduce waste streams unless it can be demonstrated to have a significant payback in either reduced energy bills, tax savings, or increased property values. This case study aims to address these issues and find means to encourage individual participation in energy and waste savings.

Low Energy Facilities
Ideally a residence should be designed such that it can produce at least as much energy as the facility uses. When the energy efficiency of the building increases, the owner may be able to recognize some revenue as a result of the home producing more energy than is used and thus the owner is able to sell back extra energy to the grid. With new homes, the ability to install the appropriate thermal barriers and insulation to attain this level of building performance can be built into the initial structure. However, with a remodelling situation in which the building was constructed using minimal insulation or the home has settled and cracks and openings have compromised the building thermal barriers, the ability to obtain a satisfactory envelope to conserve energy use can be far more challenging.

A 2009 retrofit of a 1970's era ranch house in New Hampshire had the objective of creating a net zero energy facility from a 3000 square foot Northeastern home. To reduce the PV array to a manageable size for the building, the first criteria was to reduce thermal losses by establishing passivhaus levels of

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insulation for the structural envelope. Although the finished home was able to provide 1,732 kWh more energy than it was consuming, the added cost was significant. Overall, the completed project cost was an additional $400 per square foot or over $1.2 million for the total remodelling. Based on an energy income of $0.15 per kWh, the revenue generated from the home would be an estimated $260 per year. Unfortunately, these kind of costs are well beyond the means of the average home owner. More practical applications need to be found and compromises may be required to obtain a balance of energy performance to remodelling cost (Green Building Advisor, 2009).

Waste Reduction

Numerous papers have been published on some of the new developments regarding the recycling of construction and demolition waste. Peter Erkelens development of the Zero Waste Model is useful in establishing a framework in which the materials encountered during construction and remodelling can be evaluated for recycling potential (Erkelens, 2003). His explanation of the five types of materials is useful in evaluating construction materials to assist in the decision process to determine what can be done with waste material and selection of the more environmentally friendly new products. As Erkelens explained, salvaged materials can fall into the following five sets: A) Materials for reuse, B) Materials for reuse in lower grade applications C) Materials to be recycled D) Waste to be discarded and E) Renewable materials.

For markets in which the waste has a high need in the industry, such as metals, they could be classified as category C materials in the Zero-Waste model. For these type of products, the primary concern is proper sorting of the materials during the remodelling process such that the waste streams maintain the highest quality. Therefore, for materials such as rebar, the recycling potential is strong; but it will require added time to remove the material from the debris to minimize the amount of collateral waste that would be generated if the recycle stream is effectively contaminated from undesirable by-products such as excessive concrete attached to the rebar.

One of the primary concerns is how to address the materials that are classified as category B or D. The category B materials, reused in lower grade applications, are typically items that have been ground up and used as aggregate or soil additives. In future remodelling efforts, it may become difficult to extract these elements and apply a more beneficial use to the material. For category D materials, items to be discarded, an alternative solution needs to be developed instead of landfill or incineration. Some of the most common category B and D materials are gypsum and concrete.

Townsend and Cochran have performed extensive research into the recycling potential for gypsum (Townsend and Cochran, 2003). As a common product in drywall or sheet rock, it can comprise up to 25% of the overall waste from a construction project. Since there are a limited number of gypsum recycling companies, alternative methods of reusing the material on site need to be determined in advance. Because the transportation of the drywall material to recycling centers can significantly increase the Life Cycle carbon uses, depending on the quantity of gypsum to be recycled it may be beneficial to have a grinder at the construction site to process the excess gypsum and directly apply the material as a soil additive or augment the concrete aggregate.

Another of the common category B type materials is concrete that is being removed for construction or remodelling. As one of the heavier of the waste materials from a remodelling project, the transporting of the concrete can significantly increase the life cycle carbon quantities for the project. Similar to Gypsum, a preferred alternative may be to perform on site grinding of the materials once the rebar has been salvaged. Therefore, although there may be a viable market for using the concrete off site, the first option from a life cycle stand point should be to find a means to apply the material as either aggregate in other concrete uses or as soil enhancements (Estevez, B. et al., 2003).

As explained in a paper by Brad Guy, one of the primary factors impacting the waste stream quality is the lead time for planning the material removal from the buildings (Guy, 2001). When there is adequate time to evaluate the material being removed in addition to analysing the new product installations as part of the remodelling, then adequate resources can be applied to evaluate the quantities and future uses of the debris. Likewise, if the remodelling process is paced at a rate that the labor force can properly sort the material and reduce the impurities in the waste stream, then again a greater percent of the material can be recycled and thereby reduce the products that downgraded to a reduced recycled quality or diverted to landfill. Overall, it seems that the best control for recycled materials is by on site reuse as it can be directly controlled and verified that the substances have been properly diverted from landfill waste.

Government Incentives

The payback period for investments in energy and waste savings plays a significant role in homeowners decisions to purchase more environmentally friendly materials. As much of the technology for improved performance is relatively new, there is often not enough of a market for the industry to remain economically viable on its own and the cost for "green" products may be noticeably higher than those of conventional products. Government incentives for these programs can play a substantial role in both encouraging new developments through research and in providing tax incentives for industry and home owners to install the environmentally preferred equipment. However, there is a tremendous amount of controversy within legislatures to develop new or continue to use existing tax incentives programs for residential housing. Since these programs result in reduced taxes collected for the government, they are often seen as an expense in the legislature's budget. Naturally, this results in significant debates concerning the reduction of government spending and what programs should be funded by taxes.

From a homeowners perspective, tax incentives or rebate programs need to be closely evaluated since many of these programs have time limits and restrictions pertaining to their use. Effectively there are four categories relating to tax incentives. The groups can be considered based on taxes and age of the property. Thus there are Federal tax incentives for new homes and Federal tax incentives for remodelling. The other two categories would be based on local taxes for new construction and local taxes for remodelling. Other than tax incentives, there are also rebates that are offered by utility companies and refunds provided by individual product manufacturers. Fortunately, from websites such as the Department of Energy Tax, Rebates, and Savings website (http://energy.gov/savings) and RESNET (http://www.resnet.us/), many of these programs can be evaluated to determine which apply to a particular location and product.

Another method that the national and local governments have been able to promote more energy and waste efficient homes is through educational outreach programs. Both the US Environmental Protection Agency (EPA) and the US Department of Energy (DOE) have developed websites, training brochures, and computer programs to assist home owners in selecting energy and waste efficient products. The Home Builders Association has taken this information and created site specific outreach programs in which they will go to local communities to educate the residents on things they can do on an individual level to reduce energy use and promote waste reduction.

The EPA has identified several national organizations that have established a priority to reduce waste within the construction industry. Some of the most notable of the organizations due to their planned participation in this case study are:

a. Associated General Contractors (AGC) which has included 4 goals that directly relate to materials management as part of the 2006 Environmental Agenda. Those goals are:
    1. Encourage environmental stewardship through education, awareness and outreach.
    2. Recognize environmentally responsible construction practices.
    3. Identify opportunities to reduce the impact that construction practices have on the environment, including
        a. Facilitating members' efforts to recycle or reduce construction and demolition debris.
        b. Identifying and maximizing the contractor's role in "green" construction.
    4. Identify ways to measure and report environmental trends and performance indicators of such trends.

b. The National Association of Home Builders (NAHB; http://www.nahb.org) issued the 2012 National Green Building Standard ICC 700-2012 as guidance on how to construct and remodel homes in a sustainable manner. These guides include specific requirements to reduce, reuse, and recycle construction waste. The NAHB also holds an annual conference to specifically address new developments in Green Building technology. In addition, the NAHB Research Center performs research on the recycling of C&D waste and options for on-site material reuse.

<u>Evaluating Sustainability</u>

There are numerous rating systems to evaluate the effectiveness of the sustainability of a facility. For new construction, the UK's Building Research Establishment based BREEAM program is one of the earliest recognized programs, with subsequent programs being offered by rating systems such as LEED, Green Globes, and Energy Star. For building remodelling, many of the rating systems have a similar tool for evaluating the sustainable principles that were applied during the refurbishment. In addition, numerous local authorities have developed their own rating system that is geared to reflect the specific challenges of a certain location or demographic region. In New Mexico, the predominant rating system used for residential construction and remodelling is the Build Green New Mexico criteria which is based on the ICC 700-2012 National Green Building Standard (BGNM, 2012).

CASE STUDY

The University of New Mexico is working with the Associated General Contractors of New Mexico and the Central New Mexico Home Builders Association to remodel an existing home as a demonstration project. The project is intended to gather data and demonstrate the effectiveness of various remodelling techniques. As a collaboration of industry leaders in research, construction, and residential building; it is envisioned that this partnership will develop a synergy for future benefits to the community.

Existing Conditions

The house being studied was originally constructed in 1964 as a ranch home in Albuquerque, New Mexico. In 1986, the facility was donated by the Associated General Contractors of New Mexico (AGC-NM) to the University of New Mexico as part of an endowment package for the Construction Management Program in the Civil Engineering Department. Since that time, numerous visiting professors and occasionally new hired professors have lived in the home. Most of the minor repairs on the home have been conducted by funds as part of the endowment and from volunteer labour of the faculty and students. Essentially, all of the repairs on the home were intended only to keep the facility habitable and no major energy conserving features have been added.

The home is a 140 square meters 3 bedroom 2 bath concrete block facility constructed on a crawlspace (Figure 1). There is a relatively flat gable roof with a 1:12 pitch. The ridge of the roof runs through the middle of the building in a north south direction. Roofing construction is a ballasted built up roof system using bituminous material. The current heating is by gas furnace and cooling is provided by an evaporative cooling (swamp cooler) system. The building site is a 1,133 square meter lot that has a grass lawn and several planted landscaped areas. There is a covered carport and external storage shed.

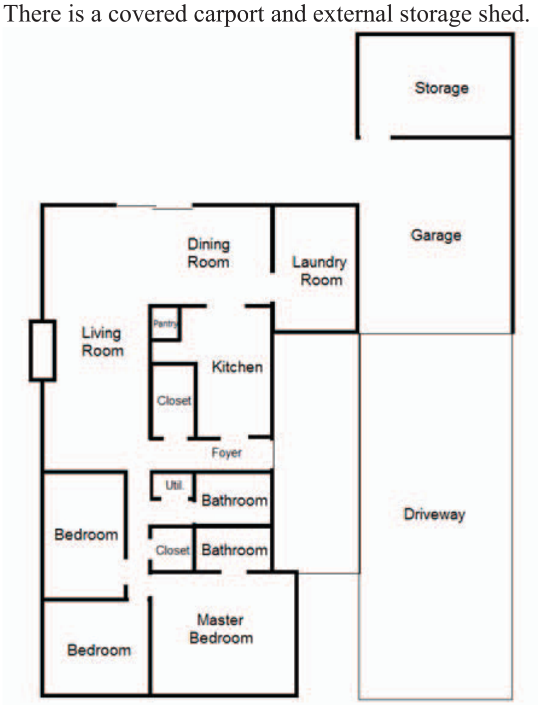

Figure 1. House layout

Currently, the performance and features of the electrical system of the house can be described as follows: There are ceiling fans on the bedrooms. The living room and dining room areas do not have ceiling lighting and lamps are not enough for providing appropriate lighting to these large spaces. The electricity provided through the electric outlets does not provide adequate power for a single portable heater or 2 small kitchen appliances working at the same time.

The building has been occupied by a family of three for the last two years. During that time, the annual utility usage has been 9,000 kWh of electricity, 387,000 litres of water, and 70 MBtu of gas. The average Albuquerque, New Mexico utility usage provided by PNM, the local utility company, for a similar size and age of home is: 9307 kWh per year and 75.5 MBTU of natural gas (PNM, 2013). The Albuquerque Bernalillo Water Utility Authority reports that the average daily water use per capita is 600 litres per day (ABCWUA, 2012). This would equate to approximately 438,000 litres for a similar household. Therefore the actual usage of utilities for the home is directly in line with the average Albuquerque utility usage for a similar constructed and age of facility.

During and subsequent to the home remodelling, the facility will be used as an educational facility, an office space, and temporary housing for visiting professors. The primary purpose for the house is to test out various sustainable techniques and allow students to verify their effectiveness. In addition, the facility is intended to provide a showcase for the general public in which they will be able to witness the various techniques in a real life situation and receive added information from applicable sustainability experts and contractors. As a research based facility, the home will be used to collect data regarding the full life cycle of building materials and evaluate their impact on the general economy and society.

Plan for Renovation

As there are numerous resources for providing advice on how to renovate a facility, it was determined to develop the restoration plan by using a multi-tiered approach. In determining the priority of renovations, the environmental pyramid was used to determine the sequence of areas to be remodelled. As shown in figure 2: the environmental pyramid starts with the basic least expensive items from the building and works up through more complex items to finish with on-site renewable energy systems. Since this provides a general overview based on critical elements and cost factors, it establishes the initial priority of what can be accomplished by the average home owner on a limited budget. The next document that was used to evaluate the steps that could be taken to renovate the facility was the Build Green New Mexico criteria for a Green Building. By evaluating the home based on each of these criteria, it is felt that the majority of factors that would ensure the building was operating to the most efficient level had been captured. The Build Green New Mexico guidance has the added advantage of taking the National Code for green buildings and applying the region specific criteria for New Mexico. Finally, the list of applicable rebates and tax incentives was evaluated to determine the most cost effective alternatives for rehabbing the building. The intent is to simulate the steps that would be taken by an average home owner and to analyse how effective these measures are to obtain the most effective sustainable level.

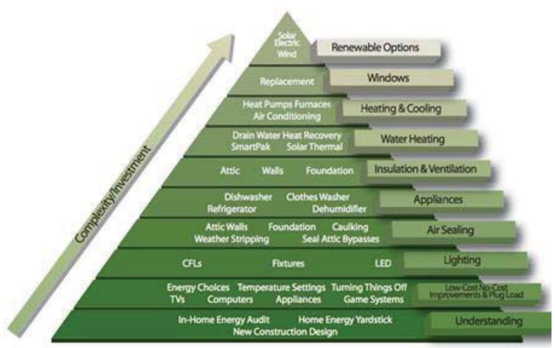

Figure 2: Environmental Pyramid from Central New Mexico Home Builders Association (BGNM, 2012).

Table 1 (Appendix A) provides a summary of the planned activities for renovating the house. Cost estimates were obtained from the HUD Energy Efficient Rehab Advisor and the RS Means Green Building Cost Data (HUD,2009)(RS Means, 2012).

Construction and Demolition Waste

The New Mexico Recycling Coalition has provided an overview of the recommended activities to be conducted during construction operations to reduce waste destined for the landfill (NMRC, 2010). Additionally, Build Green New Mexico Guidelines Sections 2.3 and 2.5 provide a sample C&D Waste Management Plan that was developed from the NAHB Resource Center research and numerous associated organizations. This guidance provides New Mexico specific advice on how waste can be handled in order to improve the potential for recycling in addition to giving resources for the location of recycling centers. This document is designed to be used as an addendum to construction contracts so that these policies can be enforced on any construction project. Compliance with the C&D Waste Management Plan will be a requirement for all contractors working on the remodelling of the AGC house. (BGNM, 2006)

Budget

Based on table 1, the budget for the overall project is $140,000. However, as the project intends to demonstrate the effectiveness of homeowners investing various ranges of funds to remodel their homes, the expenses will be incurred in a phased manner. As the facility is a three bedroom house, it is planned that one bedroom will be preserved at each funding level to be used as a demonstration for the general public. In other words, one room will receive only the modifications relative to the $25,000 level, another bedroom will retain only the benefits of the $75,000 level, and the third bedroom will be created to reflect the higher cost remodelling.

Phase I of the project will incur the basic costs of the project necessary to perform research and collect the monitoring data. These are costs that would not normally be incurred by an average homeowner; but are necessary to communicate with the public and acquire accurate data. The estimated cost for this phase is $9,000 and will be derived from University of New Mexico grants, the AGC endowment, and matching funds from sponsors.

Phase II of the project is geared to the average homeowner that has up to $25,000 available to remodel their home. This phase of renovation will commence shortly after the monitoring equipment from phase I has been installed. Funds for this phase of the project are planned to come from "in-kind" donations by material suppliers, local municipal grants, and state research funding.

Phase III of the project is geared to the homeowner that has up to $75,000 available for remodelling. Since all of the additions from Phase II would be considered as part of this budget, there would be an additional $50,000 needed to commence this part of the work. Work on this phase would commence following the completion of Phase II and upon confirmation of materials and funds for this portion of work. Similar to Phase II, it is anticipated that funds will originate from "in-kind" donations by material suppliers, local municipal grants, and state research funding.

Phase IV of the project is intended to demonstrate how the house can be modified to obtain net-zero energy and waste standards. As this will require a larger budget, it is anticipated that Federal Grants and research projects will be pursued to fund this work. Additionally, "in-kind" donations from local contractors will be used to promote their products and off-set the costs of expensive equipment. This portion of the work will commence shortly after the completion of Phase III and validation that funds and material are available.

ANALYSIS

Prior to commencing remodelling, monitoring equipment for local weather, temperature, humidity, electrical sub-metering, water sub-metering, and gas usage will be installed. This will establish the baseline conditions to which all of the subsequent data can be compared. As a facility that is being designed to collect data and provide evidence of impacts on changing the building systems, it is critical that every phase of the renovation is properly documented. One of the overall goals of the project is to provide a demonstration of the savings that can be created based on an average homeowner spending $25,000, $75,000, and more on renovations. To accurately reflect these impacts, all primary living spaces of the house will need to be monitored and simultaneous time lines developed that reflects how the house has been adjusted and what are the differences with respect to external weather conditions.

Students from the Civil Engineering Department will be used to help collect data and monitor the project. From the beginning of the refurbishment, the waste generated due to demolition and additions will be quantified by the students and tables will be created that reflect the type of waste, quantity, final disposition, estimated cost for landfilling, and actual cost for recycling. For portions of the waste, such as gypsum wallboard, that do not have a standard recycling program in New Mexico, material will be stock piled either on site or at the University of New Mexico so that research may be conducted to find suitable uses for the recycled material in the Southwest climate.

CONCLUSION

The lessons learned from this kind of research can play an invaluable role in advising policy makers on the advantages for tax incentives and educating the public on effective measures for remodelling homes while conserving natural resources. With the combined efforts of the University of New Mexico, Associated General Contractors of New Mexico, and Central New Mexico Home Builders Association, a collaboration of influential and innovative organizations can enhance their cooperation and provide a valuable resource for the public. Additionally, as an educational facility, it is intended to help train future engineers and architects on the application of sustainable technologies and demonstrate the methods and procedures to save energy while reducing waste generation.

Future Research

As a home remodelling project, there are innumerable areas in which future research can be addressed. Currently the planning committee is considering expanding the data collection to include other types of construction and various ages of facilities. Additionally, as more data is obtained on the actual utility use for this facility, more comprehensive trends can be developed that would lead to a realistic indication of the cost/benefit analysis and validate the assumptions used during the planning phase.

As an indicator of the sustainability of the facility a comprehensive Life Cycle Assessment (LCA) of the remodelling process would be useful in quantifying the overall environmental impacts associated with this project. It is planned to keep accurate records of the material used and the distances travelled to facilitate these calculations in the future.

As mentioned above, a concern with many legislators is the amount of tax incentives that are provided for energy and waste saving initiatives. Further research could play a significant role in demonstrating the added jobs and trickle down cost benefits that would be associated with these programs.

As new technology is developed it is anticipated the facility will be used as a test bed for application and analysis of the improved remodelling techniques. By offering a public demonstration site such as this, retailers will have an opportunity to analyse their products and evaluate the opinions of potential customers prior to a full scale production.

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Table 1Projects including cost and waste estimates for AGC House Remodelling

	Remodeling of AGC House						
Phases	**Priority Area**	**National Green Building Standard items**	**Project**	**Estimated cost ($)**	**Estimated Waste (lbs)**	**Means to recover waste**	**Cummulative Cost ($)**
Phase I	**Case Study Preperation**						
			Develop Architectural Renderings of finished project	2000	0		2000
			Construct scale models	1000	0		3000
			Prepare detailed plans and specs for remodeling	2000	0		5000
			Perform site survey	500	0		5500
			Grant and Proposal development	2000	0		7500
			Permitting	500	0		8000
			Community Impact Study	1000	0		9000
Total							9000
	Understanding						
Phase II			HEERs rating	500	0		500
		12.1(A).610.1	Life Cycle Assessment (Athena Eco Calculator)	500	0		1000
	Low-Cost / No-Cost						
			Programmable Thermostat	100.5	0		1100.5
			HVAC tune up	208	10	return parts to manufacturer	1308.5
	Lighting						
		12.1.701.4.4	Replace all lighting with CFLs	40	10	Recycle glass and electrical components	1348.5
			Install Energy efficient fixtures	840	20	Recycle electrical componenets	2188.5
	Air Sealing						
		12.1.701.4.3.2	Install weathter stripping around all windows and doors	550	0		2738.5
			Seal air leaks in attic, walls, and attic bypasses	604	0		3342.5
			Apply caulking to all air leaks in foundation	350	0		3692.5
	Appliances						
		12.1.703.5.3	Replace major appliances with Energy Star				
			Refrigerator	765	100	Return to manufacturer	4457.5
			Clothes Washer	675	100	Return to manufacturer	5132.5
			Dishwasher	555	50	Return to manufacturer	5687.5
	Insulation & Ventilation						
		12.1.701.4.2.1	Seal duct Leaks	483	0		6170.5
			Caulk foundation	500	0		6670.5
		12.701.4.3.1	Insulate Ceilings	1453	0		8123.5
			Insulate Walls	17600	1000	Reuse wood siding on site in garden and as window shading	25723.5
Phase III			Insulate Attic	1023	0		26746.5
			Install high albedo roof (TPO)	27900	23000	Recycled by paving contractor	54646.5
			Replace flooring with bamboo	11325	500	Provide carpet to recycler	65971.5
			Attic Radiant Barriers	3600	0		69571.5
	Water Heating						
			Solar Thermal	4150	50	recycle pipes,	73721.5
Phase IV	Heating & Cooling						
			Install ground source heat exchanger	20000	500	Reuse soil on site. Reuse crushed concrete as aggregate	93721.5
		12.1.701.4.1.1	Evaporative Cooler	895	150	Recyle metal and electronic components	94616.5
			Energy efficient or Bio-fuel furnace	4775	0	Recyle metal and electronic components	99391.5
	Windows						
			Replace doors with insulated core	880	20	Recycle wood from doors to be used as shelving	100271.5
			Replace windows with energy efficient glass	6000	320	Disassembe and send to appropriate glass and aluminum recylers	106271.5
	Renewable Options						
			Solar electric	25000	0		131271.5
	Total				25830		

A WHOLE OF LIFE APPROACH TO IMPROVE THE ENVIRONMENTAL SUSTAINABILITY OF THE RETAIL SECTOR: AN AUSTRALIAN CASE STUDY

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ABSTRACT

The retail sector in Australia is a major consumer of energy and water. It accounts for about 50% of the commercial property sector's energy use. This paper reports a whole-of-life study undertaken for a telecommunications company in Australia, with a view to changing their retail store fit-outs. Using a detailed construction and operational performance study of one retail fit-out, this study found that to lower overall environmental impact, a complex set of factors need to be considered. Design, construction and operation are all significant.

Ongoing operation needs to consider not just the physical use of the space, but also management policies/practices/processes that impact on the environment. While short term targets for energy reductions focus on careful product selection, medium to long term targets focus on setting benchmarks for continuous improvement and working with the base-building providers and supply chains to innovate and drive improved performance.

INTRODUCTION

The retail sector has increased by 15% globally over the last two years, particularly in emerging markets such as China and India, spurred largely by the buying power of an increasingly wealthy middle class (Nevill 2013).

In 2009, a report on the energy use of Canada's retail sector showed it to be the second highest consumer of energy, accounting for 14% of total energy consumption in Canada. Only the education sector was higher than retail sector at 22%, while offices accounted for 13% (Blundell 2009). The same author reported that in Australia, the retail sector is also a high-end user of both energy and water, accounting for around 50% of the commercial property sector's energy use and 4-5% of Australia's total greenhouse gas emissions.

In a recent article by the Property Council of Australia (Nevill 2013), it was reported that the retail sector in most States across Australia showed an expansion. In the 2012-13 year, there was a 19% increase in the value of work compared to the 2011-12 period and it is expected that there will be an increase of 10.5% over the next financial period. This puts the retail sector in second place, after the multi-residential sector.

Reports by Carbon Trust and Climate Works (2010) show that projected to 2020, the retail sector will contribute up to 28% of total greenhouse gas emissions from the buildings sector, in a business as usual scenario. The retail sector is estimated to produce approximately 2.52% of Australia's total greenhouse gas emissions in 2020 (ClimateWorks Australia 2011). Therefore, the retail sector has the potential to make significant savings in overall greenhouse gas emissions in Australia and internationally.

In particular, the greenhouse gas emissions from the retail sector are strongly associated with energy consumed in heating and cooling, lighting, and appliances. This includes a mix of fuel types such as gas, wood, oil and electricity. Just energy savings alone in the retail sector offers an untapped potential of 79% of total opportunities available in the business as usual scenario (Carbon Trust Australia and ClimateWorks Australia 2010). With use of more energy efficient appliances and use of renewables, the figure may be even higher.

LOW CARBON AUSTRALIA

The Australian parliament passed legislation in November 2011 to deliver a comprehensive plan for Australia to move to a clean energy future. Three main pieces of legislation were introduced: Clean Energy Act 2011, which implements the carbon pricing mechanism for Australia, Clean Energy Regulator Act 2011 and the Climate Change Authority Act 2011, which implement key elements of the governance arrangements for the carbon pricing mechanism. Central to this plan was the focus on cutting carbon pollution (Statement by the Honourable Greg Combet - Minister for Climate Change and Energy Efficiency 2012). A range of

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businesses has been supported to move to a clean energy future.

In the immediate past, due to its multi-faceted nature and complex tenant/landlord boundaries, the retail sector had ‘fallen through the cracks’ of energy efficiency policies, at least until NABERS (National Australian Built Environment Rating Scheme) Rating was introduced in Australia in 2009, and further through the Building Energy Efficiency Disclosure Act (Australian Government Department of Climate Change and Energy Efficiency (DCCEE) 2010) .

Traditionally, Australia has not led global changes for a low carbon Australia. Whether mandatory, through legislation or voluntary through industry peak bodies, Australia has followed what other countries have been doing to reduce their carbon emissions, largely, studying the roll out of policies in the UK, European Union and the USA. Due to the volumes involved, the focus has largely been on residential, followed by commercial- mainly office buildings.

Compared to the domestic sector, there is limited research in understanding the energy and water use in Australia in the non-domestic sector. Overseas, in the UK for example (Bruhns, Steadman et al. 2000), databases for modelling energy use in England and Wales has been developed to assist in estimating the national floor area and the exposed wall, glazing and roof areas to enable understanding the trends associated with fuel and energy usage. In the US, energy consultants are advocating the need to benchmark buildings first to determine which measure or suite of measures are to be used for reducing energy and water use (Skolnik 2011).

In a study to increase the adoption of energy-efficient investments and behaviours in buildings, Schwarz (2009) reported that the most effective, and widely used policies are through mandatory approaches, such as through Building Code legislation, followed by enrolling proactive measures to market energy efficiency directly to the consumers, and working with municipalities. For best results, all measures should feed off each other, and work towards a common goal of reducing energy use.

Similarly, Climate Works Australia identified three distinct ways to reduce energy use in the retail sector in Australia (ClimateWorks Australia 2011). These are:

- Retrofitting buildings with technology that have higher efficiency rating compared to existing buildings. This will involve for example, replacing existing light globes with energy efficient ones.
- Changing the use of energy consuming equipment, such as boilers or changing the number of light fittings in the space.
- Construction of new or refurbishing existing buildings to higher energy efficiency standard than current requirements.

Recent Climate Works Reports (Climate Works Australia 2010a, 2010b) show that buildings offer economically attractive opportunities for net savings in CO_2e (Carbon dioxide equivalent) emissions. With the federal regulatory requirements currently now in place in Australia, new retail buildings are becoming more energy efficient. With the Building Energy Efficiency Disclosure Act (Australian Government 2010), buildings also need to declare their energy and water use, and may involve a combination of the first two dot points stated above.

Specific jurisdictions in Australia have also spurred energy saving measures in the commercial, and some retail sectors. Examples are Melbourne’s 1200 Buildings program (City of Melbourne 2012) and Sydney’s Energy Efficiency Small Business program (NSW-OEH 2012). The City of Melbourne has developed the 1200 Buildings program, which aims to retrofit two thirds of the commercial building stock in the municipality. The program specifically targets improving energy and water efficiency and is a significant part of the transition to a carbon neutral city.

However, focusing on technology alone is only part of the solution. The links between behaviour change and energy to make lasting changes in reducing energy use have been documented (Shove 2003, Rohdin and Thollander 2006, Owens and Driffill 2008, Skea 2012). Therefore, while recommendations for energy use may be suggested, it is worth noting that behaviour change practices also need to follow.

Following from this background on the state of play, this paper presents the findings of a study undertaken for a major telecommunications company in Australia to achieve best practice for lower environmental impact towards achieving TBL (triple bottom line) sustainability needs for the company. A whole of life approach has been taken to understand environmental impacts, leading to recommendations that can be taken on board for roll out across the country for all the retail stores for this telecommunications company.

THE RETAIL PROJECT

The main aim of the study was to understand the environmental impact of the telecommunication company’s ‘typical’ retail store and find ways to reduce, if not completely eliminate, these environmental impacts. The following specific sub-aims were identified as part of this overall aim:

1. Identifying leading edge practice in Australia and internationally in understanding the embodied and operational environmental impacts of telecommunication retail stores.
2. Identifying appropriate targets and benchmarks (criteria, indicators, rating tools).
3. Identifying appropriate reporting opportunities to communicate credibly and transparently project objectives and achievements.
4. Benchmarking the environmental performance of existing 'typical' retail designs for the telecommunications company against identified metrics and undertaking a gap analysis of design concepts against target criteria and indicators.
5. Recommending strategies and working with other parties as appropriate, to resolve and achieve detailed targets including product and materials selection.

The work was undertaken in two stages. The first stage was a literature review to understand best practice, so that the stretch targets may be identified. The literature review focused on both case studies and the individual elements of the case study that contributed to lowering environmental impact. The second stage was undertaking a full environmental impact of current stores to identify gaps and then determining what needs to be done to meet the stretch targets, and what aspect/s of these may be practical.

<u>Stage 1: Understanding best practice of the elements</u>
There are a number of exemplar shopping centres emerging, both in Australia and internationally, which are drawing upon recent understanding of sustainability features. For example, Aeon LakeTown in Japan has over 550 shops in an eco-friendly shopping centre (AEON 2008). Opened in late 2008, this shopping centre aimed to achieve a 20% carbon reduction through a number of sustainability strategies such as solar panels and a hybrid eco-gas system. Included in the overall eco approach are internal plant walls, interactive sustainability engagement with consumers and electric vehicle recharging stations.

Another example is City Square Mall in Singapore, where sustainability elements added an additional 5% to capital costs. The design includes solar panels on the roof, a rain-water harvesting system, smart lighting, indoor plants, high performance glazing and an eco-playground in addition to in-mall education graphics and messages about the environment. The mall uses 39% less energy compared to standard industry practice. It was awarded the BCA Green mark Platinum Award in 2007 (Tay 2011).

In Australia, Stocklands Forster shopping centre in the mid-north coast of NSW was the first shopping centre in NSW to be awarded a 6 star NABERS energy rating. In 2005 the original centre underwent a renovation, which resulted in a doubling of floor area. A focus on sustainability through elements such as natural ventilation resulted in a 30% reduction in overall energy use being achieved. Another shopping centre to receive a 6 star NABERS energy rating is the Orion Spingfield shopping centre in south-east Queensland (Office of Environment and Heritage 2013).

The state of play directed the research team to various components making up the retail fit-out. Various components that may contribute to the environmental impact of a retail store were categorised into flooring, ceiling, furniture and shop fitting, joinery and fit-out items, and partitions and wall coverings. The environmental impacts of the products and materials comprising these main elements were then considered across a number of life-cycle stages including:

- Production (extraction of raw materials, manufacture of finished products);
- Installation and construction (emissions from glues, wastes generated during construction);
- Use phase (emissions from products and ongoing operation); and
- End of life (emissions to landfill or the broader environment, opportunities for reuse or recycling, etc).

The academic literature review proved to be quite difficult as there are no examples of exemplary telecommunication retail stores designed that also are *documented and peer reviewed* for understanding low environmental impact. There are stores that have advanced technology used for appliances and other equipment. However, it was possible to source information on specific elements in a retail store such as exemplary flooring, ceiling, wall covering and appliance use.

As a general rule therefore, the focus was on cradle-cradle (McDonough and Braungart 2002) approach in the selection of materials and products. Materials and products made from reused or recycled materials; materials and products that have none or very little use of virgin materials; materials that had little or no impact both in terms of energy use and water use during manufacture on local and global ecosystems; materials and products that considered social issues in their manufacture and were therefore, socially sustainable; materials and products that used renewable energy and recycled water in their production systems and at the end of their useful life, were the broad principles through which selection of materials and products needed to be made. This ensured that in the future, when new products/materials come into the market, they could be vetted against these basic criteria to determine appropriateness in use. This was the stretch target for product and material selection. Each of the elements identified: flooring, ceiling, furniture and shop fitting, joinery and fit-out items, and partitions and wall coverings therefore had to be matched against these basic criteria.

Flooring products, like any other product, impact both human health and the environment. In the case of retail stores, specifically, premature end of life may result due to the high rates of retail churn, or sections needing replacement due to high traffic use, even when other sections may not need to be replaced. Replacing the entire floor therefore, contributes to environmental impacts even more so. There are companies now in the market place that recycle old flooring, so as to reduce overall environmental impacts.

Similarly, ceiling products, like flooring products need to be made of products that do not emit toxins. Again, there are products in the market place that maintain acoustic performance while being made of environmentally friendly materials that also decrease issues associated with moisture, mould and bacterial growth.

In a medium size office building, it is possible that furniture can contribute up to 31% of the life cycle energy of the total building environmental impact over a 40 year period (Taylor and Langenberg 2003). Again, like flooring and ceiling, materials that emit toxins such as formaldehyde and volatile organic compounds should be completely avoided. Joinery items are often tailor-made for retail shops. Here again, use of materials such as timber from sustainable plantations may be preferable to the use of materials that may not be. Understanding the supply chain is therefore critical.

Partitions and wall coverings made of timber, paint, fabric, vinyl and many such other materials may continue to emit toxins during manufacture, installation, post-installation and maintenance. There are very few opportunities for recycling and reusing wall coverings at the end of life.

Careful selection of appliances within the retail store will assist in reducing operational energy and water consumption. Lighting, reduced air conditioning, waterless urinals and use of rainwater tanks are common practices that can be observed in most commercial buildings.

With this background information, the next stage was undertaking the life cycle assessment.

<u>Stage 2: Life Cycle Assessment (LCA)</u>

The LCA of a 'typical' retail store was undertaken to identify environmental impacts as these stores were rolled out across the country, and lowering the environmental impact in the 'typical' store therefore, had the potential to lower environmental impact of all the stores operated by the telecommunications company.

The International Standards Organisation (ISO) has defined LCA as (ISO 2006): "A technique for assessing the environmental aspects and potential impacts associated with a product by:

- Compiling an inventory of relevant inputs and outputs of a product system;
- Evaluating the potential environmental impacts associated with those inputs and outputs; and
- Interpreting the results of the inventory analysis and impact assessment phases in relation to the objectives of this research".

The technical framework for life cycle assessment consists of four components, each having a very important role in the assessment. They are interrelated throughout the entire assessment and are in accordance with the current terminology of the International Standardisation Organisation (ISO 2006).

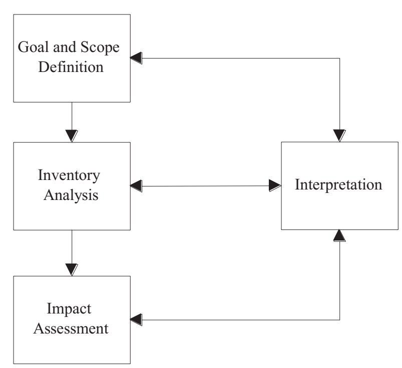

Figure 1: Components of an LCA. Source: (ISO 2006)

As shown in Figure 1, the components are goal and scope definition, inventory analysis, impact assessment and interpretation. The goal of the LCA was to model a 'typical' telecommunications store, to determine the environmental performance including operational energy and water, and material impacts. The scope was limited to the fit-out, operation and end of life of this typical retail store. The components were energy use, raw material use, waste, and any emissions to air, soil and water. The functional unit was the construction, operation and end of life of this typical store.

Some of the characteristics of the 'typical store' modelled include a rectangle floor area of 67.2m2, a multi-purpose staff area out the back of the shop (office/storage/kitchen), floor to ceiling storage/displays along both side internal walls, a service/sales counter along the back wall of the shop and a number of smaller counters in the middle of the floor area. Due to confidentiality issues, the layout of the store has not been provided.

Bills of quantities and drawings were used to source the amount of materials. Where information was not known or able to be tracked, assumptions were made. This was clearly stated so that the client was aware of assumed data. This also flagged to the client to try and source the data in the future, so that a clearer picture of environmental impact emerges. The data was segregated into the shop front, shop space, walls, sales counter and other joinery, office space including kitchenette, floor, ceiling and the electronic equipment in the shop.

As the study was of a retail store, a life cycle of 6 years was considered, a common practice in Australian commercial tenancy churn rate, unlike a standard residential or commercial building fit out of 50 or 100 years. It also needs to be noted that the retail outlet/shopping shell in which the telecommunications or any other store may be tenanted from may well be in the order of 50 years, but the actual tenancy periods vary widely, depending on a number of issues, including market conditions and tenancy agreements. SimaPro software (PRé Consultants 2007) was used to understand the LCA impacts of the retail store for this telecommunications company.

SimaPro is the most widely used LCA software in the world. Introduced in 1990 in response to industry needs, the SimaPro product family facilitates the application of LCA using transparent analysis tools (process trees, graphs and inventory tables). SimaPro allows use of standard data provided and/or specific data to carry out environmental analysis and pinpoint where the main environmental priority areas are and look for possible improvements.

Indicators used to describe the impact assessments included:

- Global warming potential (GWP), expressed as a single kg CO2 equivalent over a 100 year timeframe, was expressed as kg CO_2e. Intergovernmental panel for climate change (IPCC 1996) reference values for GWP of greenhouse gases were applied.
- Total energy inputs per unit of production. This provided the cumulative energy demand in the lifecycle of the materials, expressed as MJ LHV. This included energy utilised and energy incorporated into products and in particular polymers. It also included non-fossil energy sources such as bio mass and renewable energy inputs.
- Minerals and fuels that included only fossil fuels and other non-energy mineral depletions, expressed in MJ.
- Eutrophication, expressed as Kg $PO_{4,}$ dealing with the enrichment of soil or water with mineral nutrients. These nutrients cause heightened biological productivity, resulting in unstable ecosystems. Photo oxidants (VOCs) are the result of the reactions between nitrous oxides and volatile organic substances under the influence of ultra violet light.
- Water use, expressed in KL deal with the gross amount of water extracted from the environment. The water that is released back to the environment is not subtracted from this value.
- Land use, considering all the land uses over the entire life cycle, without any specific reference to the intensity of the land use expressed in m2.
- Solid waste expressed in Kg, referring to the total mass of materials discarded, predominantly to landfill. Mining and mineral waste are also included, whether they are disposed to landfill or not.
- Carcinogens, measuring the human health impacts associated with exposure to known carcinogenic agents, and based on modelling of the levels of exposure predicted and the effects of exposure limits on morbidity and mortality. Impacts are measured in disability-adjusted life years (DALY), which measures the equivalent years of "healthy" life lost due to ill-health.
- Respirator organics measuring the human health impacts associated with exposure to respiratory organics Impacts are also measured in DALY.

IMPACTS OF FIT OUT AND OPERATION

Table 1 and Figure 2 show the overall impacts of the fit out and 6 years of operation for the various indicators described above. Where negative impacts are shown, these refer to credits.

It is clear from the data presented, that energy use during operation dominates all indicators, except for land use and carcinogens. For land use the shop fit-out (materials) is the predominant phase, while the electronic fit-out dominates the carcinogenic impact. Credits arise due to the recycling of materials, avoiding the production of virgin material.

The operation phase of the retail shop is dominated by the building heating, ventilation and air conditioning system, followed by the Sensormatic gate and lighting, with these values being 59.35%, 10.07% and 8% respectively. It is not surprising that HVAC has such as high impact, as it does tend to dominate. That said, the power usage calculated was based on the power rating of the HVAC system and the operating hours of the shop, while in practise the actual power consumed can vary based on factors such as sizing of the HVAC system, ambient temperature and heat load. This figure is however, close to the typical contribution of HVAC systems in the retail (and commercial) sector of 40 – 60% of total energy use as determined by federal government department (AGO 1999).

However, what is surprising is the Sensormatic gate. This contributed to a rather high impact, even higher than lighting (8%), as the second highest impact. The electronic fit out overall was also high. A mixture of published LCA data and input/output data that characterises environmental impacts based on monetary values purchased from different economic sectors was used to calculate the impacts of electronic equipment. The results therefore, are an indication of the greenhouse impacts of the equipment, rather than being the actual values. Taken as a whole unit, the personal computers (base plus monitor) produce the greatest impact in the overall electronic fit-out (36.6%), followed by the MFD unit (21.4%) and the receipt printer (10.6%).

In relation to material fit-out, the greatest impact was from aluminium (18.1%), followed by steel used in the wall and ceiling system (16.7%) and plasterboard used in the ceiling (13%). Assuming that the vinyl flooring is not replaced over a six year time frame, the impact attributed to this is 10.5%. Recycling some or all of these materials will reduce environmental impacts further.

DISCUSSION

The literature review demonstrates that compared to a number of other countries, Australia has a long way to go to reduce the environmental impact of its shopping centres, and retail tenancies within shopping centres. It is not unusual to see exemplars in Australia of energy efficiency of operation or reduction in water and energy use, but almost no studies considering a whole of life approach.

Design, construction and ongoing operation are all significant, in reducing overall environment impact of retail stores. Ongoing operation needs to consider not just the physical use of the space, but also management policies/practices/processes that impact on the environment, whether it is a day to day waste generation practice or a policy regarding the churn rate of flooring or equipment. Waste reduction; particularly, reduction in management practices related to waste reduction should be encouraged as much as possible. For example, recycling phones, which is now emerging as a common practise.

While there are increasing number of rating tools entering the market place, and tracking/monitoring of energy and water use through smart meters and the like, it is still essential to set up benchmarks and aim for ongoing targets for lowering environmental impact. Good design, use of new technology, and using energy from renewables will assist greatly in reducing energy use. Likwise, water use should be minimised and low flow technology should be used.

Using local materials may lower environmental impacts, cutting out the energy and emissions associated with transportation. Materials that emit toxins harmful to the environment and to human health should be completely avoided. Products manufactured from recycled materials and recycled or reused at the end of their life reduce waste going to landfill. Minimising use of metals, and recovering metals at the end of life should be considered as part and policy of design brief and specifications.

In terms of specific findings related to the LCA, energy management needs to focus on the sensor gate, lighting, heating and cooling energy. With respect to electronic products, extending product use whenever possible (but this may conflict with fiscal accountabilities) and reducing the overall numbers of equipment used will assist in reducing energy use and reduce cooling loads in the space.

CONCLUSION

Based on the findings from this study, there are clear directions that telecommunications companies can focus on from short term, medium term and long term perspectives. Focusing on energy efficiency and greening the supply chain, selecting the right products and materials are quite straight-forward and easily do-able. In the medium to long term, benchmarking and monitoring will assist in setting targets and working with base building suppliers to identify areas for improvement and innovation, such as water recycling. So also, tracking the supply chain and influencing the supply chain to innovate and drive improved performance. Developing programs for carbon offsets, phone collections, and the like will also raise the Corporate Social Responsibility.

For tropical countries, the focus for most buildings, including shopping centres are on cooling. Recreating designs of glass and steel in the new urban growth areas of South East Asia needs to re considered and innovative approaches sought for reducing energy and water use.

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Table 1
Overall impacts of fit-out, 6 years use, and end of life

Impact Category	Unit	Total	Shop fit-out	Electronic fit-out	6 years energy use	Disposal and recycling
Global Warming	kg CO_2 eq	750,461	5863.8	12,030.5	736,266	-3699.4
Cumulative energy demand	MJ LHV	7,952,140	97,288.3	170,691	7,690,750	-6588.96
Minerals & fuel	MJ surplus	349.45	201.8	32.40	217.29	-102.04
Eutrophication	kg PO_4---eq	256.43	6.03	5.59	245.06	-0.25
Photochemical oxidation	kg C_2H_2eq	138.64	6.83	25.64	105.90	0.27
Land use	Ha a	1.12	0.81	0.07	0.24	0.004
Water Use	KL H_2O	1206.11	52.34		1161.72	-7.95
Solid waste	kg	34,636	1070.3		29,223.50	4342.23
Carcinogens	DALY	0.009	0.00068	0.0044	0.003	0.0029
Respiratory organics	DALY	0.0001	1.11E-5	3.78E-5	6.62E-5	-1.38E-7

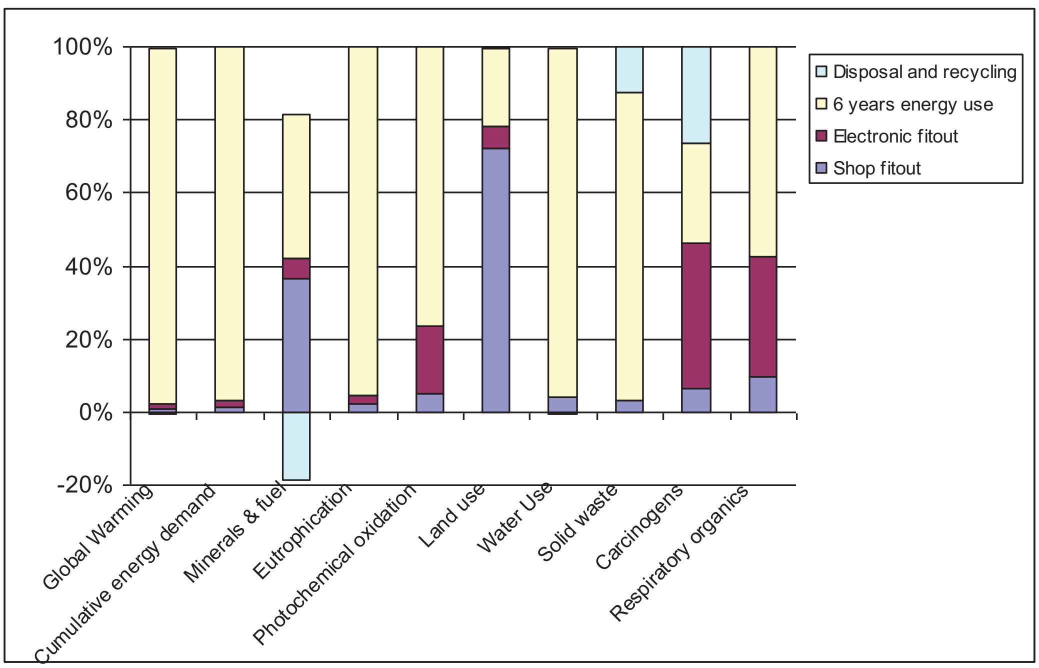

Figure 2: Relative impacts of fit-out, 6 years uses and disposal

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CARBON FOOTPRINT ASSESSMENT OF A FOUR STOREY INDUSTRIAL BUILDING CONSTRUCTED IN SINGAPORE

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ABSTRACT

This paper presents the environmental assessment using carbon footprint as an indicator to quantify the environmental impact generated from "cradle-to-grave" of a four storey industrial building. The carbon footprint assessment adopted methodologies include ISO 14040/44, ISO/DIS 14067 and PAS 2050. The results obtained from the study reflect that materials contributed were approximately 25% of the overall carbon emissions generated from the raw material stage (cradle) to demolition stage (grave). The top ten materials' carbon footprint contributed approximately 75% of emissions in the raw material stage. The usage stage of the building generated 73% of the overall carbon footprint. The environmental impact resulted from the materials embodied emissions was a major contributor but high emissions were dominated by the usage stage where electrical consumption was the major cause in the high carbon footprint. The total carbon emissions could be 16% higher if energy efficient devices and equipment were not implemented.

INTRODUCTION

The construction sector's activities globally consumed approximately 40% of the total global natural resources and generate approximately 40%-50% greenhouse gases (GHGs) [1]. In recent years in Singapore, environmental sustainability has been one of the major focuses in the construction sector. Different approaches to reduce environmental impact have been studied and indicators to quantify environmental sustainability have been investigated by many in local and overseas research arenas. The objectives are to lower energy usage and environmental impacts contributed by buildings in both the construction and operational stages. Life Cycle Assessment (LCA) has been widely used by many to assess the impacts to the environment due to the construction of buildings. LCA is used to quantify the emissions and resources that are involved in the entire life cycle a building. The impact categories covered in LCA include global warming potential (GWP), acidification and eutrophication potential, energy used, land used change, toxicity, biodiversity, resource depletion and others [2]. LCA is used as a tool to analyse energy consumption in the processing of materials. Jönsson et al. [3] is one example who use LCA to compare construction materials like concrete and steel frames. Bribián et al. [4] also conducted an analysis based on LCA methodology on building eco-materials. Blengini et al. [5] and Kofoworola et al. [1] employed LCA to study the environmental impact in the entire life cycle of a building. LCA is a comprehensive tool to evaluate the environmental impacts for the built environment. To complete an LCA, an LCA practitioner is required and locally, there are few practitioners. The study conducted by Saunder et al. [6] identified barriers to LCA. Long duration and difficulties in collecting of relevant data, complex methodology, and low demand from the clients are some of the setbacks to the use of LCA to quantify environment impacts. In the recent years, climate change has increased in awareness and popularity of carbon footprinting. To an LCA practitioner, climate change is only one of the many environmental impact indicators in an environmental assessment. The question commonly asked by many is: Is carbon footprint (CFP) sufficient to evaluate the environmental impacts? The debate on this topic will always be there but the objectives is to get all to participate in some form of environmental reduction activities that will bring benefit to the environment in general. As presented by Röö et al. [7] there is an availability of standards and guidelines for calculating carbon footprint. The World Resource Institute (WRI) and World Business Council for Sustainable Development (WBCSD) have developed the Greenhouse Green Protocol [8] and Intergovernmental Panel on Climate Change (IPCC) [9] for accounting of carbon footprint has made available standards and methodology in carbon footprint calculations. IPCC [10] has made carbon emission factors easily available for tabulation of carbon footprint. One of the advantages mentioned by Röö et al. [7], based on IPCC methodology, the anthropogenic substances that caused global warming can be calculated and expressed in one score, CO_2 equivalent (CO_2e) making it much easier to compute as compared to other impact categories. Other impact categories like acidification, eutrophication and biodiversity are sites dependence whereas CFP is the same on matter where it is being assessed. The simplicity of CFP and the wide separate of data for the calculation made CFP an attractive indicator to use. Although more work and knowledge are required to justify the completeness of CFP as the one indicator to represent all, CFP will continue to be the indicator used by many to evaluate environmental impacts as it is easy to understand and communicate.

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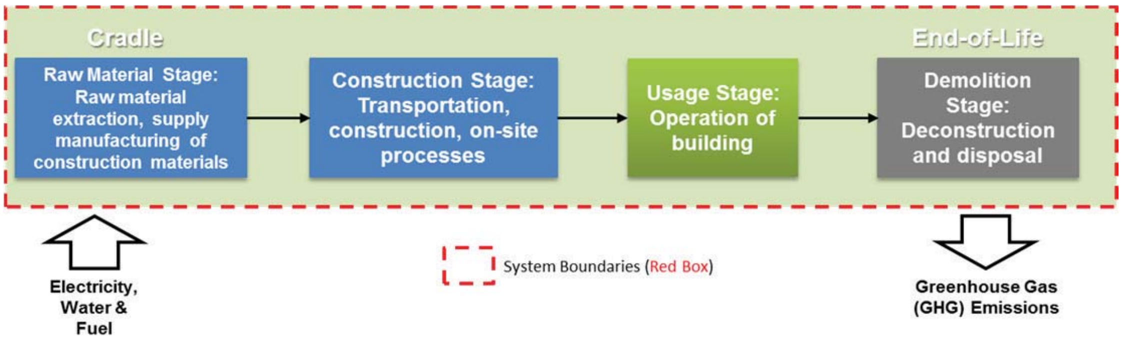

Figure 1 – System boundary for carbon footprint assessment for the four storey building

This paper explores the use of CFP as an indicator for environmental assessment of a four storey industrial building. The owner Greenpac (Singapore) Pte Ltd is the first local Small Medium Enterprise (SME) to calculate CFP for the entire life cycle of their building. The calculation of the CFP is part of their corporate social responsibility (CSR) contribution to ensure that their building is built as sustainable as possible.

METHODOLOGY

Guidelines

LCA has a number of environmental indicators and one of which is the GWP or CFP. CFP has been an effective indicator to quantify the environmental impacts based on a life cycle approach. This indicator is defined as a measurement of the six greenhouse gases GHGs, namely carbon dioxide (CO_2), nitrous oxide (N_2O), sulphur hexafluoride (SF_6), hydrofluorocarbon (HFCs) and perfluorocarbons (PFCs). Other than carbon dioxide, the remaining five GHGs are converted into the weight measurement of carbon dioxide equivalent (CO_2e) by multiply a CO_2 conversion factor based on a 100-year time scale, using the GWP recommended by the IPCC [9]. The total CFP is tabulated by summing up the all the GHGs to attain a final CO_2e. The commonly used standard, to quantify CFP, is the Publicly Available Specification 2050 (PAS 2050) [11] which is based on the developed standard by the British Standards Institution (BSI) in partnership with Carbon Trust [12] and Department for Environmental, Food and Rural Affairs (Defra) [13]. The assessment conducted in this study follows closely PAS 2050 and guidelines in the International Standard Organisation (ISO) 14040 [14] and 14044 [15] that is a well-established framework in LCA. To quantify CFP effectively, the conventional approach is based on LCA. The much talked about ISO/DIS 14067 [16] product carbon footprint standard, is also used as a reference in this study. The outcome of this standard is converted into a technical specification, ISO/TS 14067 [17] due to the lack of support among the participating countries.

Goal and Scope of Study

The main objective of this study is not only to quantify the carbon emissions generated from the typical four storey industry building but also to generate a life cycle inventory of the different stages in the construction of the building. The results of the study should address the following two questions:

1. What is the carbon footprint of the building from raw material extraction stage, transportation of materials and workers, construction of the building, usage of the building to end-of-life of the four storey building?
2. Where and what are the major carbon footprint contributors in the life cycle of the building?

The results of the study would help the construction company and building owner to have a better knowledge in carbon emissions involved in building and operating an industry complex and the choice of materials, processes and energy usage to ensure that future projects and operation are more environmentally sound.

Functional Unit

ISO 14040/44 [14, 15] defines functional unit as the quantified performance of a product system. The functional unit for this study is a four storey industrial building of approximately 18,000 m^2 of gross floor area. The company building the four storey building would like to know the total amount of carbon emissions generated throughout the life cycle of the building.

System Boundaries

Figure 1 shows the system boundary of the CFP assessment for the four storey building. System boundary refers to all processes and activities in each life cycle stages that are required in the construction of the four storey building and are included in the carbon footprint assessment [11]. The study takes into account of four major stages (raw material, construction, usage and demolition stages) in the construction of the industry building. The raw material stage, the material extraction, transportation, manufacturing and processing are included in the assessment. In the construction stage, the transportation of workers to site, equipment used in construction and on-site processes are considered in the study. The operations of the building is the only consideration when it comes to the usage stage. Lastly, the demolition stage includes the deconstruction and the disposal of the demolished building.

LIFE CYCLE INVENTORY (LCI)

Life cycle stages defined in the system boundary are from cradle to grave. The Life Cycle Inventory (LCI) for the study system boundary is defined by the collection of inventory data required for the carbon footprint assessment of the building. The inventory data can be classified into two main types: activity data and emission data [11]. Activity data refers to resources consumptions and activities revolving around these consumptions. Emission data are data of air pollutants, in this case is GHGs emissions, in relative to the level of activities involved that produces these air pollutants. The carbon footprint of the four storey building is based on these inventory data collected from a variety of sources. Activity data can be easily attained from the bill of materials and design drawings which can easily obtained from the construction company that is tasked to build the building. A large percentage of the activity data is primary data – data gathered either through direct measurement or calculation based on information collected directly from the original sources [16]. An example of an activity data is the total amount of concrete or steel bars required to build the four story building. As for the emissions data, most of them are obtained from peer-reviewed sources, publically available model, reports and commercial life cycle databases including GaBi [18] and SimaPro [19]. These emissions data are generally classified as secondary data. Secondary data refers to data that is collected other than direct measurement or calculation based on information collected directly from the original sources [16]. Some examples of secondary data include electricity generation from the grid, manufacturing processes, production of the construction materials, and transportation emissions. Each life cycle stages is further discussed in the following sections.

<u>Raw Material Stage</u>

Being a country with very limited resources, all construction materials for this building were purchased from overseas. Data, for the raw material stage, used in this assessment is highly dependent on secondary data. This stage focuses on the embodied emissions and the transportation of materials from country of origin to the site in Singapore.

<u>Construction Stage</u>

During the construction, number equipment on-site is used in the construction processes. The on-site equipment is powered mainly by diesel. Beside equipment, the construction site office is powered by diesel generators and water is purchase from the water company. These consumptions are defined as on-site utilities. The amount of diesel and water used can be collected from the on-site which monitors their consumption. As for emissions generated, data collected when from secondary sources. The transportation of worker to and from the site is also taken into account for this assessment.

<u>Usage Stage</u>

In this stage, the data collection for the assessment only includes the operation of the building. Maintenance is not taken into account due to the uncertainty of manufacturing processes that would be located in the building at this point of time. The building might be leased out to other manufacturing companies either as office space or for light manufacturing productions. The only contributor at this stage would be the heating furnaces that are situated in the building's first storey. One of Greenpac's roles is to heat treat wooden pallets that are to be ship out of Singapore. A large amount of wooden pallets are heat treated each day and the energy consumption is substantially high. The carbon footprint assessment conducted for this stage is based on 30 years of operation of the building.

<u>Demolition Stage</u>

The focuses for this stage are based on deconstruction and disposal of two types of materials – concrete and steel frames. There is limited information in the area of demolition. Reference for this stage based on the work done by P. Winistorfer et al. [20]. The data used for the assessment takes into the consideration of recycling of materials, landfill, energy used for transportation and energy used in the process of demolition. Uncertainty analysis is conducted for this stage to ensure that the results obtained are as reliable as possible.

RESULTS AND DISCUSSION

From the assessment, the total CFP for the four stages defined in the system boundary are present in this section. This section also presents over embodied emissions generated by the different materials that are used in the construction of the building. A detailed result showing emissions breakdown of different materials used in the concrete are also presented in this section.

<u>Carbon Footprint for the Life Cycle Stages</u>

The raw material extraction, manufacturing of building materials, transporting of materials and workers, construction, operation and demolition are the different stages that are being evaluated in this study. The results of the CFP are shown in Figure 2.

It is clear that the usage stage has the highest carbon emissions followed by the raw material stage. The construction and the demolition stages have relatively low carbon emissions. The usage stage contributes approximately 73% of the total carbon footprint. This is calculated based on the operation of the building and its equipment for a span of 30 years. 25% is contributed by the embodied emission of the materials used and transportation of these materials that are used in this construction project.

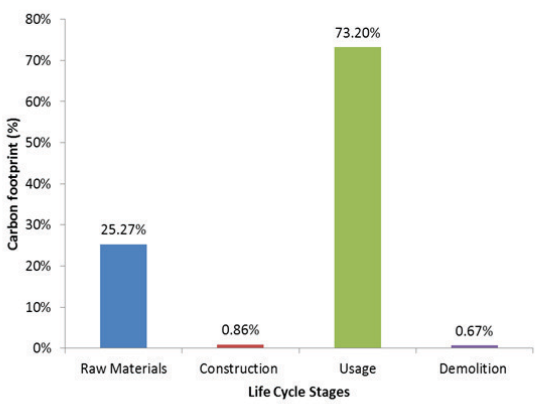

Figure 2 – Carbon footprint for the four different life cycle stages

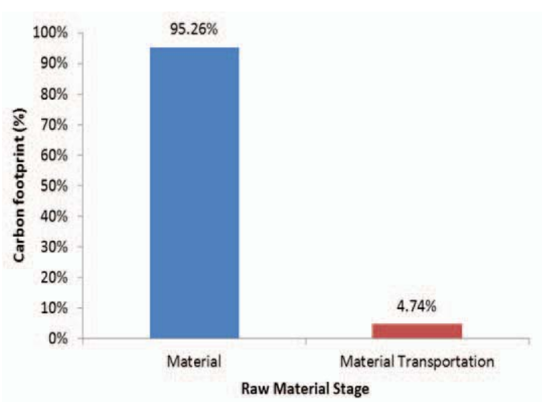

Figure 3 – Carbon footprint for the raw material stage

Carbon Footprint for the Raw Material Stage

In the raw material stage, it can be categories into two sections. These sections include embodied material emissions and the transportation emissions of materials. 27% of the total carbon footprint is contributed by the raw material stage and approximately 95% of the 27% is contributed by the embodied material carbon footprint emissions whereas the transporting of these materials to site is at approximately the remaining 5%. Figure 3 shows the breakdown results of this first stage.

Carbon Footprint for the Construction Stage

In this stage, the emissions are divided into three sections, namely energy used by construction equipment on site, on-site utilities and transportation of workers to site and back. The materials that are transported to site are processed and used to construct the building. Construction equipment on the site is powered by mainly by diesel. The overall emission for the construction stage is approximately 0.86% of the total carbon footprint generated in the lifetime of the building. Approximately 31% of the 0.86% is the total emissions generated by the equipment used on site. 37% comes from the on-site utilities. Electrical power and water consumed the temporary office on-site. Approximately 31% of the 0.86% is attributed to the transportation emissions of the workers from their dormitories to the site and back. The total carbon footprint is extremely low and shadowed by the usage and raw material stages. Figure 4 shows the breakdown of emissions for the construction stage.

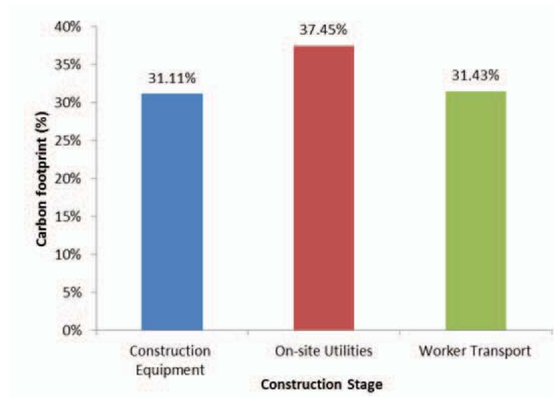

Figure 4 – Carbon footprint for the construction stage

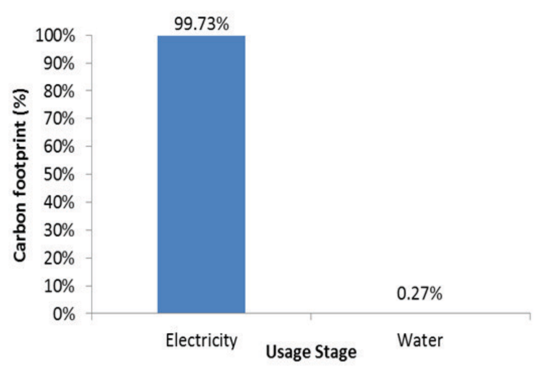

Figure 5 – Carbon footprint for the usage stage

Carbon Footprint for the Usage Stage

The usage stage emissions are contributed by the operation of the building in the use of electricity and water. A large amount of the emissions is contributed by the generation of energy. The building has a large heater that is used in its manufacturing processes. This heat equipment consumed approximately 90% of the total electricity required by the company. Figure 5 shows the usage stage and its breakdown. From the results, electricity used by the building to power its facilities and equipment has the highest emissions. 99% out of the 73% of the total carbon

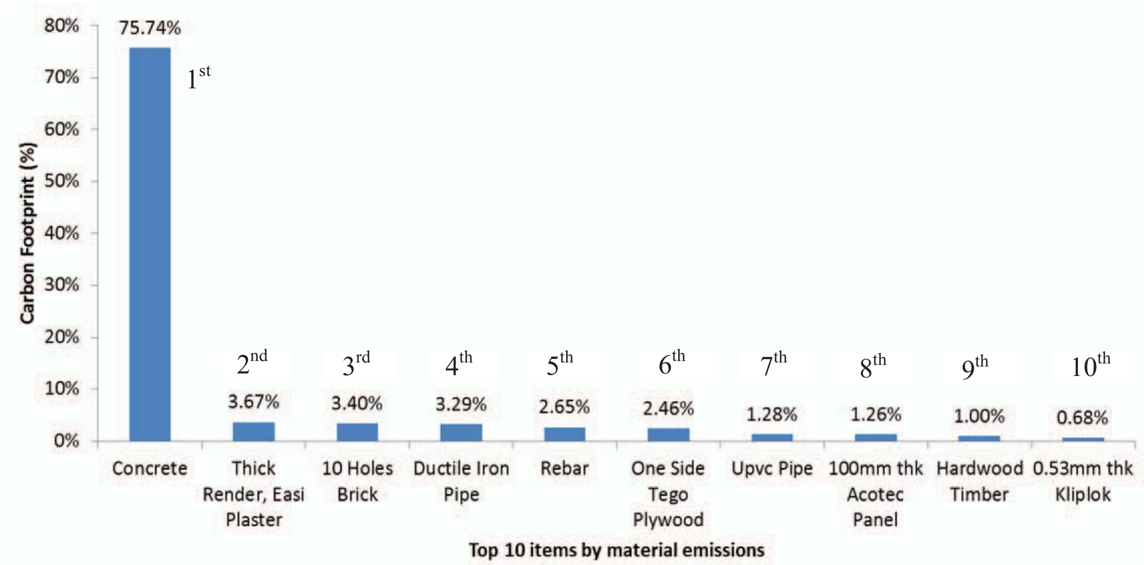

Figure 6 – Top ten highest embodied emission materials used in the building

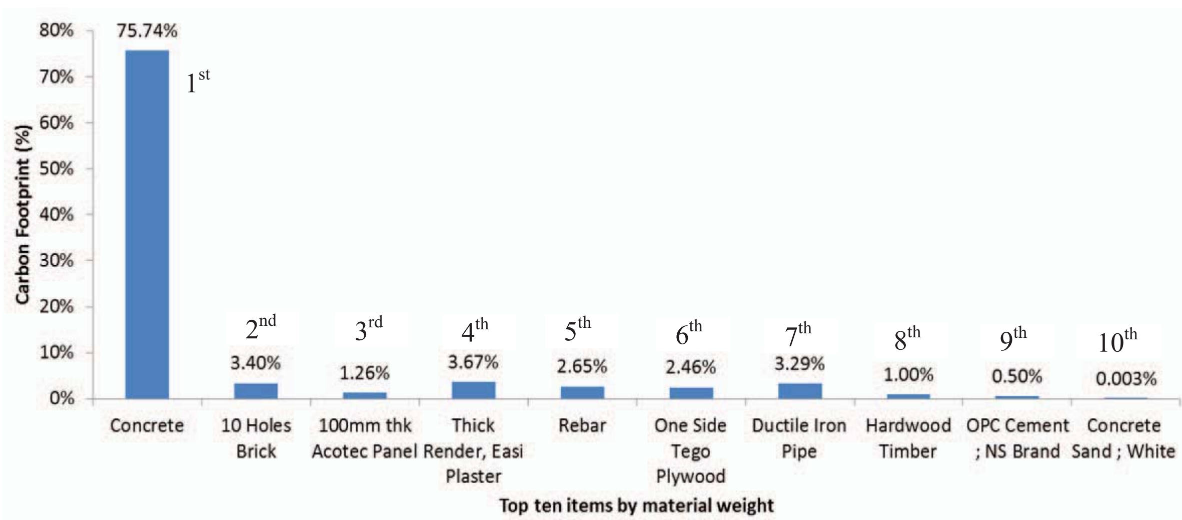

Figure 7 – Top ten heaviest materials used in the building

footprint assessed are emissions produced by the generation of electricity and only 0.27% of the emissions is from water consumed.

Carbon Footprint for the Demolition Stage

The carbon emission for the demolition stage is approximately 0.67% of the total carbon footprint of the total life cycle of the building. Due to the lack of data, reference has been made based on Winistorfer et al. [20] to ensure the assumption made for this stage is as close to the correct emission. The uncertainty calculated, at 95% confidence interval, for this stage ranges from 0.49% to 0.92%. The median at 0.67% is chosen for this assessment. The carbon emission impact of this stage is low even when the upper range is chosen to compute the total carbon footprint emissions. When upper limit is chosen, less than 1% of the emission is attributed to the overall carbon emissions. This value is relatively too low to cause any large changes in the overall carbon footprint emissions of the building.

Carbon Footprint for the Materials

Numerous materials are used to construct a building and each has an embodied emission. The choice of materials and the amount used will greatly affect the overall carbon footprint. Although the overall carbon footprint is dominated by the usage stage, choosing low carbon emission materials will help to reduce the overall emission. In the assessment, the top ten materials by embodied emissions and weight are identified and ranked. The objective is to determine which material used has largest impact to the overall carbon footprint in the raw material stage. The results have shown material used in large amount does not always contribute to high carbon emissions.

Figure 6 shows the top ten materials that generated the highest carbon emissions. Due to the emission factor and large of material amount used, concrete contributed to the highest emissions amount compared to all the materials used. 95.26% in the raw material stage is contributed by embodied emissions and concrete contributed 75% of the overall material embodied emissions. The top ten materials by embodied emission contributed 94% of the overall materials used in the construction of the four storey building. If the top ten heaviest materials were ranked, the carbon footprint emission would not be similar to that rank by embodied emissions. Figure 7 shows the material ranked by weight. The top ten materials ranked by weight contribute approximately 95% if the total material used in the construction of the building. Concrete remains at the top of the list as the amounted used and the embodied emissions are high for concrete. The remaining 9 materials used are large but the carbon footprint varied due to the emissions factor. The emission factors rebar and 10 holes brick are 1.01 kg CO_2e/kg and 0.24 kg CO_2e/kg, respectively. Rebar has higher emissions but the amount used for the 10 holes brick is 81% more than rebar, therefore the total carbon footprint for 10 holes brick is higher than rebar. The difference in carbon footprint between the two is relatively smaller as rebar has a very high emissions factor.

Emission breakdown for Concrete

Concrete, with approximately 76% of the overall material emissions, is the highest carbon emissions contributor in the raw material stage. It is made of a number of materials and these materials include aggregate, sand, cement and water. This assessment looks into the breakdown emissions of concrete and assessed the emissions of each materials found in concrete and their contribution to the overall material emissions. Figure 8 shows emissions and the weight proportion of the materials make up. Weight proportion of Portland Cement is approximately 15% in weight but the carbon footprint contributed to the overall concrete is about 95%. Aggregate used in concrete is the highest with an approximately 45% in weight but its emission is approximately only 4% in the overall concrete emissions.

Manufacturing Equipment

The manufacturing processes in a manufacturing plant contributed a large amount of energy. The installation of energy efficiency equipment would reduce the overall energy consumed. The building owner has decided to design and build their new equipment with energy efficiency devices and features that are able to use less electricity for efficient production. The overall carbon emission for the usage stage has improved by approximately 16% as compared to using the old equipment.

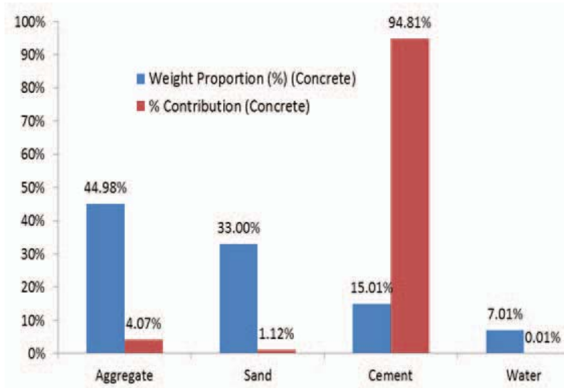

Figure 8 – Carbon footprint of materials used in concrete

CONCLUSION

The carbon footprint is used successfully as an indicator to evaluate the environmental impact of the entire life cycle of the four industry storey building. Approximately 73% of the total carbon footprint is contributed by the usage stage, 25% is by the raw material stage and the remaining goes to the construction and demolition stages. 95% of the emissions in the raw material stage are accounted for by embodied emissions of the construction materials. The electricity consumption is the major contribution of carbon emissions in the usage stage. 99% of the 73% of the overall carbon emission is generated by the used of electricity. The installation of energy efficiency equipment and devices in the building has resulted in a 16% reduction in the overall carbon emissions.

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