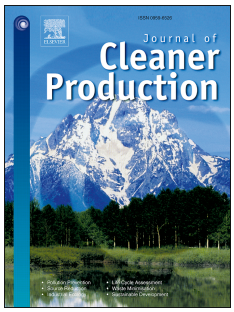
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Changing urban cement metabolism under rapid urbanization –A flow and stock perspective

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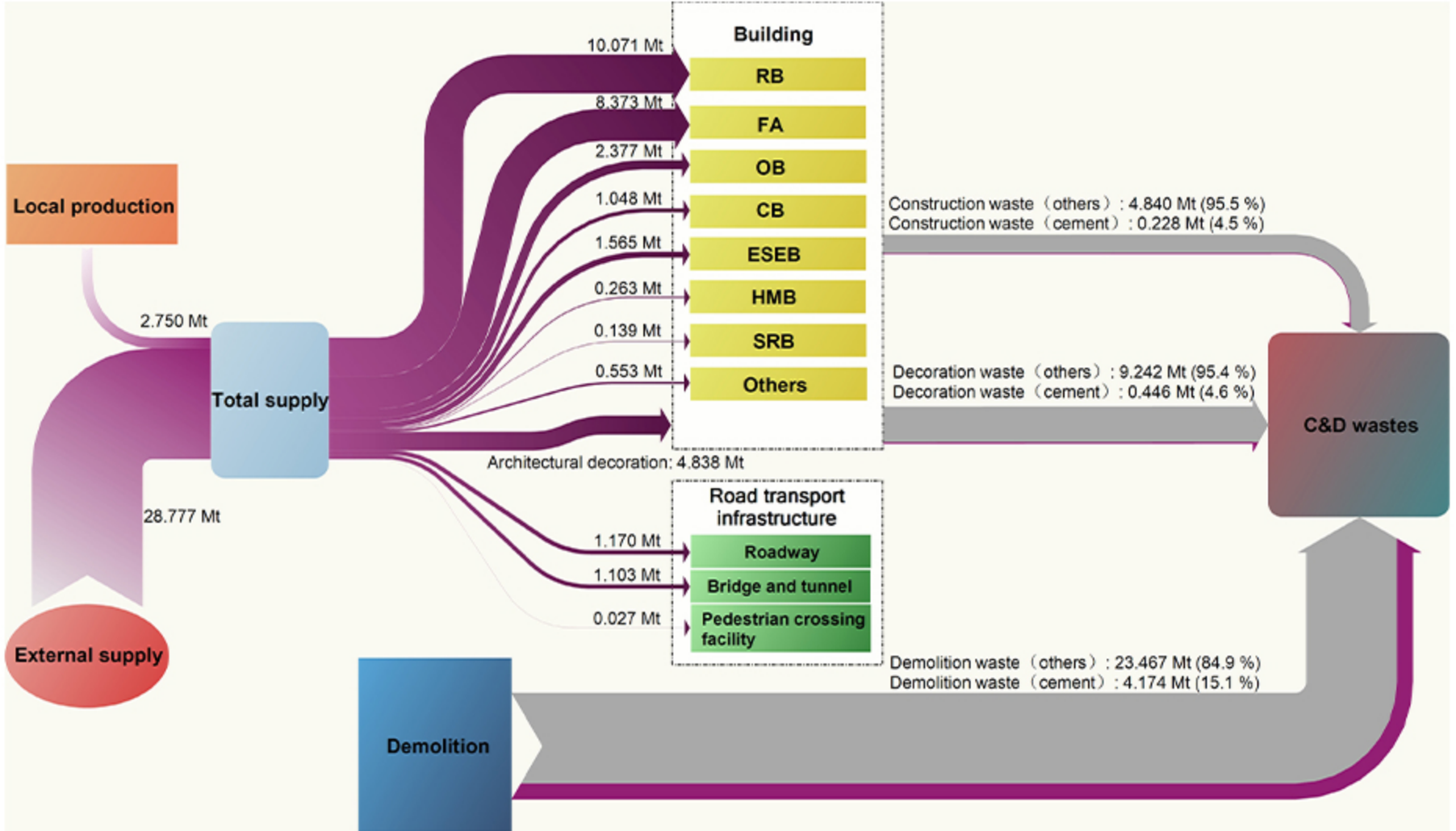
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Local production
2.750 Mt
External supply
28.777 Mt
Total supply
10.071 Mt
8.373 Mt
2.377 Mt
1.048 Mt
1.565 Mt
0.263 Mt
0.139 Mt
0.553 Mt
Building
RB
FA
OB
CB
ESEB
HMB
SRB
Others
Architectural decoration: 4.838 Mt
Road transport infrastructure
1.170 Mt
1.103 Mt
0.027 Mt
Roadway
Bridge and tunnel
Pedestrian crossing facility
Construction waste（others）: 4.840 Mt (95.5 %)
Construction waste（cement）: 0.228 Mt (4.5 %)
Decoration waste（others）: 9.242 Mt (95.4 %)
Decoration waste（cement）: 0.446 Mt (4.6 %)
Demolition waste（others）: 23.467 Mt (84.9 %)
Demolition waste（cement）: 4.174 Mt (15.1 %)
Demolition
C&D wastes

ACCEPTED MANUSCRIPT

Changing urban cement metabolism under rapid urbanization —a flow and stock perspective

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Abstract: China's rapid urbanization is characterized by large-scale construction activities which require enormous amounts of construction materials and induce a series of resource and environmental problems. However, few studies have paid serious attention to construction material metabolism within urban ecosystems in the Chinese urbanization hotspot. This study focuses on changes in cement metabolism in Xiamen from 2002 to 2012 and aims to elucidate its metabolic characteristics and mechanisms. The results show that, (1) residential buildings account for 1/3 of total cement use, with more and more accumulating as unused stock; (2) decoration is the second largest cement consumer after building and should be paid more attention in metabolism analyses; (3) road transport infrastructure is expected to maintain its growing potential for cement use; (4) increasing amounts of construction and demolition waste are hardly reused or recycled. To mitigate ecological pressures resulting from urban cement metabolism and foster sustainable construction, a multidimensional policy portfolio is proposed including development of improved real estate policies, optimization of urban spatial patterns, popularization of decoration-binding residential buildings and premixed mortar usage, establishment of a waste recycling system, industrialization of the construction industry and the promotion of sustainable consumption. This empirical research provides a reference template for future sustainable construction material management studies in rapidly urbanizing areas elsewhere.

Keywords: cement metabolism, flow and stock, bottom-up accounting, construction material management, rapid urbanization

1. Introduction

Urbanization is currently taking place at an unprecedented pace throughout the world. Urban societies have become the focus of global concern about sustainable

Abbreviation: UCMF, urban cement metabolism framework; RB, residential building; NRB, non-residential building; FA, factory; OB, office building; CB, commercial building; ESEB, entertainment, sports or educational building; HMB, healthcare or medical building; SRB, scientific research building; C&D, construction and demolition; BRT, bus rapid transit; TDM, transportation demand management; TOD, transit oriented development; BCO, Bulk-cement Office.

development (Grimm et al., 2008; Kennedy et al., 2015). As large numbers of people migrate from rural to urban areas, a large amount of production and consumption accompanied by massive material and energy flows are concentrated in urban areas. This gives rise to a host of resource and environmental problems: rapid urbanization causes water supply scarcity and often relies on inter-basin water transfer projects which aggravate the ecological risk to rivers (Liu, 2010; Zhao et al., 2015); the share of global energy consumed by urban areas is 67-76% and accounts for 71-76% of energy-related CO_2 emissions (Seto et al., 2014); many big cities suffer severe air pollution and subsequent public health problems (Parrish and Zhu, 2009). Whether cities can develop towards sustainability largely depend upon the way in which they manage their material and energy flows (Kennedy et al., 2015).

China's urbanization has made remarkable achievements in the past few decades, making it a global research hotspot (Normile, 2008). Other than rapid industrialization and lifestyle change, urbanization in China is particularly characterized by large-scale construction activities, which require an enormous amount of construction materials (Huang et al., 2015). China has become the top producer and consumer of both cement and steel in the world (Huang et al., 2013), and the production, use and disposal of these construction materials impacts on the depletion of raw materials, climate change, air contamination and solid waste generation. As Liu et al. (2015) pointed out, for instance, the rapid building of infrastructure in China has offset the CO_2 emission reductions achieved in the country through improved industrial efficiency and pilot regional carbon-emissions-trading schemes. Management of construction material metabolism (flows and stocks) within urban ecosystems is therefore of great importance for sustainable urban development in rapidly urbanizing economies such as China.

Previous studies of construction material metabolism have targeted different construction sub-systems at various spatial and temporal scales. These studies generally follow one of two analytical perspectives, material stock analysis (MSA) or material flow analysis (MFA). MSA aims to reveal, by quantifying material stock volumes, the physical infrastructure level of a geographically defined area and

understand its socioeconomic characteristics therein. National MSA is widely used for in-use stock accounting, historical trend analysis, and regional disparity examination on a macro scale (Han and Xiang, 2013; Kovanda et al., 2007; Liu and Muller, 2013). MSA has also been applied at the urban scale from the perspective of urban metabolism, which can help elucidate urban environmental issues, assess urban sustainability, and inform urban planning (Guo et al., 2014; Huang and Hsu, 2003; Tanikawa and Hashimoto, 2009). Methods employed by MSA range from traditional statistical methods using macroeconomic data to integration of geographical information systems and remote sensing techniques by incorporating multisource databases (Liang et al., 2014; van Beers and Graedel, 2007). MFA represents an analytical approach to quantitatively characterizing material flows in a well-defined system. Typically, MFA is categorized into retrospective MFA and prospective MFA depending on the research timescale. Retrospective MFA is able to understand the metabolic features of a system of interest, examine corresponding environmental and ecological impacts, and prepare the ground for future proactive work (Hu et al., 2010; McMillan et al., 2010). Prospective MFA, mostly using a dynamic modeling approach, is applicable for forecasting and evaluating prospective inflows and outflows of materials of concern, thus providing a scientific basis for policy development around resource and waste management (Bergsdal et al., 2007; Brattebo et al., 2009; Shi et al., 2012). However, there have been three main limitations to previous research: (1) relatively few studies have focused on urban scale in comparison to national-scale studies. Small scale studies concerning urban systems with local-specific policy implications have been rare, particularly for developing countries like China. This has hampered a better understanding of construction material metabolism in rapidly urbanizing jurisdictions; (2) decoration, an important metabolic unit in urban construction, has not received due attention, leading to an incomplete characterization of urban construction material metabolism; (3) countermeasures to improve the material cycle have been mainly discussed from a technical perspective (e.g. prolonging the lifetime of infrastructure, reducing material consumption intensity, and enhancing the recycling rate), while multi-dimensional policy instruments tailored to

local social, economic and administrative characteristics have been inadequately explored.

The main purpose of this paper is to provide an empirical study of urban cement metabolism in a rapidly developing country. Cement as a key construction material plays an indispensable role in rapid urban development. However, relevant research specifically on urban cement metabolism has been limited, and as previously discussed, cement was usually analyzed together with other construction materials (e.g. steel, sand and gravel) in urban systems (Hu et al., 2010; Huang et al., 2016; Tanikawa and Hashimoto, 2009; Wang et al., 2016). Therefore, in-depth investigations of socioeconomic metabolism and sustainable management of urban cement remain elusive. By taking Xiamen, a rapidly urbanizing city in China, as an example and elucidating its cement metabolic characteristics and mechanisms during the period from 2002 to 2012, this study aims to answer the following questions: (1) What is the distribution of cement use and waste and how does it evolve during the process of rapid urbanization? (2) What characteristics of urban development (e.g. varying infrastructure investment, life style change) are revealed by the historical dynamics of cement metabolism? (3) Where are the key points for policy interventions to reduce resource consumption and environmental load resulting from urban cement metabolism? Additionally, this study makes a preliminary effort to account for the cement metabolism of decoration that has been rarely available through previous research. This empirical research provides a reference template for sustainable construction material management studies in other areas of rapid urban development.

2. Study area and Methodology

2.1 Study area

Xiamen is situated on the southeast coast of China, with an area of 1573 km^2 and a population of 3.81 million. Being one of the “special economic zones” and “cities specifically designated in the state plan”, Xiamen has been in a period of rapid urbanization since the 1990s, and particularly since the 2000s, the process has been

even more rapid: the urbanization rate increased from 50.4% in 2000 to 81.2% in 2013 and the urban built-up area expanded from 81.9 to 281.6 km^2 over the same period.

2.2 Methodology

2.2.1 Urban cement metabolism framework (UCMF)

Fig. 1 presents the UCMF developed in this study. In the light of common end uses of cement within urban systems, building construction, civil infrastructure construction and decoration (referring to "interior decoration" here as "exterior decoration" is already included as part of building construction) are the three principal destinations considered in this study. The portion of cement consumed by non-construction activities is very small (e.g. ornamental statues), and is not addressed here given data availability. The outputs of cement within the urban system, mostly in the form of waste concrete, originate from newly-built construction (known as "construction waste"), obsolete construction (known as "demolition waste"), and decoration works (known as "decoration waste").

Fig. 1 UCMF.

Due to a lack of any statistics, a bottom-up accounting approach (Tanikawa and Hashimoto, 2009; Yuan et al., 2014) was adopted to develop an inventory of urban cement metabolism, in which cement consumption (inflow) and waste cement generation (outflow) were quantified for each urban construction component (grey box in Fig. 1) as an end user and simultaneously as an emission source. The flow quantities can be estimated using the following equation:

$$F_a^{in/out}(t) = P_a(t) \times I_a(t), \quad (1)$$

where $F_a^{in/out}(t)$ is the inflow of cement consumed by or outflow of waste cement generated by component a in year t; $P_a(t)$ is the physical quantity of component a in year t, indicating its activity level in volume or size (e.g. floor space of

buildings, area of roadways); and $I_a(t)$ denotes the cement use intensity (in reference to material inflows) or the waste generation rate (in reference to waste outflows) of component a in year t. Given data availability, the building category was divided into residential building (RB) and non-residential building (NRB) according to use function, with the latter further divided into factory (FA), office building (OB), commercial building (CB), entertainment, sports or educational building (ESEB), healthcare or medical building (HMB), scientific research building (SRB), and others; the civil infrastructure category primarily referred to road transport infrastructure and was divided into roadway (including expressway, classes Ⅰ~Ⅳ highways and subordinate highways), bridge, tunnel, and pedestrian crossing facilities (overpass and underpass); demolition was only addressed for buildings. The study did not account for construction waste from newly-built road transport infrastructure, because such waste can be mostly backfilled for use as a subgrade material. Additionally, the local cement production quantity was obtained directly from the Municipal Bureau of Economic and Information Technology.

2.2.2 Physical quantity of urban construction

Physical quantities $P_a(t)$ of various components concerned in this study (e.g. construction/demolition amount) were obtained from government statistics and enquiries to public agencies. Table 1 gives the detailed specification of this parameter in terms of different components. For road transport infrastructure, note that $P_a(t)$ of roadways, bridges and tunnels are originally in length units which needed to be converted into area units to match corresponding intensity parameters discussed below. This study thus referred to Guo et al. (2014) on statistical width of roadways for different road classes and derived the incremental areas for roadways, bridges and tunnels included in the study area. For decoration, floor work and wall space work where cement is mainly consumed (as compared to ceiling work, doors and windows work, paintwork etc.) were taken into account in this research.

Table 1 Specification of physical quantities of urban construction components.

Component		Physical quantity	Remark	Source
Building		Finished floor area (m^2)	Not use floor area under construction to avoid double counting (as construction period usually lasting more than one year)	Yearbook of Xiamen Special Economic Zone, Xiamen Construction Bureau
Road transport infrastructure	Roadway, bridge, tunnel Pedestrian crossing facility	Incremental length (km or m) Incremental area (m^2)	Conversion into incremental areas needed	Xiamen Transportation Bureau Xiamen Municipal Works and Gardens Administration Bureau
Decoration	Floor work	Floor area decorated (m^2)	Assuming all finished floor area of buildings undergo decoration in the same year	Assumption of this study
	Wall space work	Wall space area decorated (m^2)	Calculated from 3×80%×floor area	Budgeting Handbook for Building Decoration Engineering (Zhu, 2004)
Demolition		Demolished floor area (m^2)		Xiamen Municipal Bureau of Land Resources and Real Estate Management

191

192 *2.2.3 Cement use intensity and waste generation rate*

193 Data on material intensity (or waste generation rate) are quite limited for developing
194 countries, particularly at a local level, and relevant literature was reviewed to collect
195 empirical values for $I_a(t)$. It is generally recognized that $I_a(t)$ is significantly
196 determined by structure, construction technology and level of management, and all
197 these influencing factors are spatially, temporally and socio-economically related.
198 Therefore, the research specifically focused on recent literature on built structures in
199 China to account for contextual relevance.

200 As to building and road transport infrastructure, literature on cement use intensity was
201 compiled by construction type and structure as per Table S1. In addition, the study
202 collected project information from 190 individual buildings of various use types
203 constructed locally during the study period (from Xiamen Construction Project Cost
204 Management Station), with reinforced-concrete being the dominant structure
205 (accounting for over 90%) for every building use type. It was therefore reasonable to
206 screen out (from Table S1) those intensities of buildings with reinforced-concrete
207 structures to be referred to in the following analysis. For road transport infrastructure
208 in the study area, no information was available on structures. Intensities of bridge and
209 pedestrian overpass were also applied respectively to tunnel and pedestrian underpass
210 for their similarity in reinforced-concrete consumption (Guo et al., 2014).

As to decoration, a variety of technological selections are alternatives for both floor work and wall space work (such as cement mortar flooring, rubber tile flooring, carpet flooring etc., according to different functional requirements or decoration styles). The research only chose those commonly used in the study area—namely, "stone flooring" or "ground tile flooring" for floor work, and "concrete wall plastering" or "brick wall plastering" for wall space work—as the basis for preliminary estimation of cement consumption in decoration. An "additive pavement layer" approach was developed to derive cement use intensity for decoration, which is unavailable from previous studies. The formula is as follows:

$$I_{ts} = A_{unit} \times \sum_{i=1}^{n} thk_i \times C_i^{prop} . \quad (2)$$

Firstly, procedures related to cement use were listed, on the basis of locally issued "Engineering Quantities Inventory for Decoration", for each chosen technological selection (see Table 2); secondly, the volume of the pavement layer (i=1,…n) corresponding to each specific procedure (e.g. crushed stone concrete layer, cement mortar layer) was calculated for a unit area (A_{unit}=1 m^2) according to the thickness (*thk*) specification of that procedure (in Table 2); thirdly, by referring to the mix proportion of cement for different pavement materials (C_i^{prop} as Table S2), the cement requirement per unit area could be derived for a given technological selection (I_{ts}) (results shown in Table S3).

Table 2 Procedures for common technological selections used in floor and wall space works.

Decoration work	Technological selection	Specific procedure
Floor work	Stone flooring	(1) C15 crushed stone concrete cushion layer, 70 mm thick
		(2) 1:3 cement mortar layer (bonding layer), 25 mm thick
		(3) neat cement grout, 2 mm thick
	Ground tile flooring	(1) C15 crushed stone concrete cushion layer, 70 mm thick
		(2) 1:3 cement mortar layer (bonding layer), 18 mm thick
		(3) neat cement grout, 2 mm thick
Wall space work	Concrete wall plastering	(1) 1:3 cement mortar, 13 mm thick (bed course)
		(2) 1:2.5 cement mortar, 6 mm thick (surface course)
	Brick wall plastering	(1) 1:3 cement mortar, 16 mm thick (bed course)
		(2) 1:2.5 cement mortar, 6 mm thick (surface course)

Source: Xiamen Construction Project Cost Management Station (2013)

Regarding $I_a(t)$ on the output side, a step-wise approach was taken by deriving general waste generation rates (without differentiating between materials) of construction, demolition and decoration works at first, and then examining the mass ratio of waste concrete by waste types as well as structures (if possible), and finally referring to the mix proportion of cement within concrete. Relevant literature was compiled as Table S4.

Once the account of inflows and outflows was established, the substance flow model of urban cement metabolism in Xiamen was developed on the basis of the mass conservation principle.

2.2.4 Uncertainty analysis

Given multiple data sources for $I_a(t)$ as cited in Table S1 and S4 (for decoration different technological selections were treated as different data sources), an uncertainty analysis was performed using the Monte Carlo simulation to investigate the impact from variation of $I_a(t)$ caused by regional disparities, technical innovation, and/or managerial differences. A symmetric triangular distribution was assumed for this parameter with the range obtained from a selection of literature (and from calculated results (shown in Table S3) for decoration) and the most likely value being the average of the minimum and maximum values (see Table S5 for cement use intensities and Table S6 for waste generation rates). Where only one reference could be traced for a parameter, it is not included in the uncertainty analysis and is marked with an asterisk in Tables S5 and S6. Uncertainties from $P_a(t)$ were not considered here as government statistics are the only data sources. 100,000 trials were run and the mean and 95% confidence intervals are reported.

3. Results

3.1 Cement consumption

During the period from 2002 to 2012, the cement consumption in urban construction

of Xiamen city was estimated to have reached 31.53 Mt, which approximated the entire production for the entire Fujian province (where Xiamen city is located) in 2006. Building accounted for about 78% of the total cement use and was definitely the dominant consumer during that period, followed by decoration (15%) and road transport infrastructure (7%) illustrated as Fig. 2. In terms of cement used in building, RBs consumed 10.07 Mt, while NRBs consumed 14.32 Mt; in terms of cement used in decoration, floor works consumed 2.96 Mt, and wall space works consumed 1.87 Mt; in terms of cement used in road transport infrastructure, roadways consumed 1.17 Mt, bridges and tunnels consumed 1.10 Mt, and pedestrian crossing facilities consumed only 0.03 Mt. One phenomenon contrary to intuition is that, although the physical quantities and material consumption of each individual decoration project are small (roughly 5 tons for a 100 m^2 apartment based on the calculation, which is also recognized by decoration professionals), decoration in total was the second largest consumer of cement, even outweighing road transport infrastructure. This is because the overall activity level of decoration was much larger than that of road transport infrastructures during the study period, even though the cement use intensities of decoration are relatively small when compared to those of infrastructure (see Table S5). Under normal circumstances, decoration works are mostly managed by individual property owners and tend to be dissipated, rendering material use in these activities difficult to include in sectoral statistics and thus easily neglected at the macro scale. Nevertheless, the results from this bottom-up analysis show that cement consumption in decoration accounted for a substantial proportion, important information for urban planners and resource and environmental managers. Another point of concern is that even though the total constructed mileage of bridges and tunnels was far smaller than that of roadways during the study period, the amount of cement consumed in bridges and tunnels, because of their spanning and supporting structural requirements, was a very close counterpart to that consumed in roadways. This highlights that three-dimensional transport infrastructure is much more material-intensive than plane transport infrastructure.

Fig. 2 Distribution of cement consumption in Xiamen, 2002 to 2012.

Fig. 3(a) shows the temporal variation of estimated cement consumption in different urban construction components from 2002 to 2012. Before 2005, annual cement consumption was around 2 Mt; then starting in 2006, it took a sharp increase until peaking at 4.77 Mt in 2008; since then, it has fallen back and fluctuates around 3 Mt per annum. Building together with decoration accounted for more than 90% of cement use for most years. In terms of building cement consumption, the proportion of buildings of various use functions is shown as Fig. 3(b). It is clear that RBs and FAs have been the main consumers and their sum constituted 66% to 83% of building cement use during the study period. Also note that the aggregate proportion of ESEB, HMB and SRB—all used as public service facilities—has risen ever since 2005, implying that more attention has been paid to development of urban public services in recent years. As to infrastructural cement consumption, its temporal variation is shown as Fig. 3(c). It can be seen that annual cement consumption in road transport infrastructure ever since 2008 is generally higher than that before 2008 (79% of infrastructural consumption occurred between 2008 and 2012), particularly for that amount consumed in bridges and tunnels. This trend could also be reflected in the proportion of road transport infrastructure in the annual total cement consumption, which has increased since 2008. The driving force underlying the shift is basically attributable to the urban integrated traffic planning promulgated in 2006, in response to increasing deterioration of traffic conditions caused by accelerated automobile unit growth, cross-island traffic jams, slow-developing public transit etc. The planning formulated a series of key projects such as bay-city cross-sea passages, an urban expressway system and a bus rapid transit (BRT) system (Xiamen Municipal Commission of Urban Planning, 2006). The integrated traffic planning in 2006 induced considerable road transport infrastructure investment (Xiamen Municipal Statistics Bureau, 2013) and corresponding cement use in the subsequent few years.

Fig. 3 Temporal variation of cement consumption in (a) urban construction

components, (b) buildings (in percentage terms), and (c) road transport infrastructures in Xiamen. Error bars represent 95% confidence intervals.

3.2 Waste cement generation

Annual general waste generation and the waste cement component are shown as Fig. 4. During the study period, the estimated amount of total waste generated from urban construction and demolition (C&D) activities in Xiamen city was roughly 42.40 Mt, of which 65% was demolition waste, 23% was decoration waste, and only 12% was construction waste. Waste cement accounted for 11% of the total waste, about 4.85 Mt, and 86% of waste cement came from demolition waste. It is evident from the figure that demolition waste constituted the largest fraction for most years and therefore dominated the trend in variation. Except for the last two years, Fig. 4 exhibits an obviously increasing slope for demolition waste, indicating expanding redevelopment of old city districts and the removal of old buildings (partially resulting from frequently revised urban plans (Shi and Lin, 2013)). The annual average generation of C&D waste was about 3.85 Mt, while according to the Xiamen Constructive Waste Management Station, only 0.3~0.6 Mt of wastes were disposed annually under its supervision in an appropriate way. This means that a large amount of waste is still out of the control of the regulating department, and illegal dumping of this waste may lead to negative environmental impacts and even raise public health and security concerns.

Fig. 4 Temporal variation of (a) general waste and (b) waste cement from urban C&D in Xiamen. Error bars represent 95% confidence intervals.

3.3 Stock analysis and substance flow model

Since most newly-input construction materials are transformed and accumulated into structural components once they are consumed by urban construction activities, this research carried out a stock analysis of cement within the urban system as follows:

$$S(t) = S(t-1) + F^{in}(t) - F^{out}(t), \quad (3)$$

$$\Delta S(t) = S(t) - S(t-1), \quad (4)$$

where $S(t)$ denotes the stock of cement in urban system by the end of year *t*, $S(t-1)$ denotes the stock by the end of year $t-1$, $F^{in}(t)$ is the total inflow of cement in year *t*, $F^{out}(t)$ is the total outflow of waste cement in year *t*, and $\Delta S(t)$ is the newly-added stock in year *t*. The results show that, the cement stock in Xiamen city displays a steady growth from 2.02 Mt in 2002 to 26.68 Mt in 2012 with an average annual growth rate of 29%.

The urban cement metabolism of Xiamen city is shown as Fig. 5. During the whole study period, more than 90% of cement consumed in urban construction had to be supplied from areas outside the city through internal trade. Such overreliance on exogenous construction material resources might imply unsustainability of urban construction if external supplies are interrupted. RB alone contributed 32% of the total cement use. The vast majority of input cement became urban stock and lasted for decades, and only a small fraction of that turned into waste cement because of design change, removal of temporary structures, on-site scattering and spill-over etc. In terms of general C&D waste (not just waste cement), however, their total output was even larger than the total cement input in the same period. Unfortunately, hardly any of this C&D waste can be reused or recycled under current circumstances, and ends in legal landfill or illegal dumping. This disables the internal circulation of construction materials within the urban system and results in huge resource waste and negative environmental impacts.

Fig. 5 Urban cement metabolism in Xiamen, 2002 to 2012. For waste output arrows, pink arrows (lower portion) represent waste cement; grey arrows (upper portion) represent other waste components, such as steel, wood, sand and gravel.

3.4 Metabolism efficiency assessment

Fig. 6 shows the efficiencies of urban cement metabolism from the perspective of cement as a resource input. A downward trend in cement consumption per unit GDP and per unit fixed investment can be observed during the study period. This demonstrates the declining dependence of local GDP and fixed investment on cement input and the emergence of a weak decoupling of cement use from local economic growth. Viewed from a different angle, there was a slight increase in cumulative cement consumption per capita, indicating the relatively slow growth of the urban resident population when compared to growth in cumulative cement consumption. A logical perception is that people's lifestyle is associated with more and more cement-containing physical assets, for instance bigger apartments, longer travel distances (roads) and more public services (public buildings). Based on the analyses above, it appears relevant to proceed from human demand management so as to reduce cement input into the urban system. Efficiencies from the waste output side were not evaluated here, given the fact that waste generated in any one year (mostly demolition waste from the obsolete construction of previous decades) were not directly linked to the socioeconomic outputs of that specific year.

Fig. 6 Metabolism efficiency of cement as a resource input.

4. Policy implications

To sum up, the challenges facing the urban cement metabolism and associated construction sector of Xiamen city include: (1) continuous input and an ever-increasing stock of cement as a key material within the urban system; (2) soaring generation of C&D waste (including waste cement) with most waste types being out of control; (3) overreliance for cement on external supply; and (4) a lack of recycling mechanisms leading to resource waste and negative environmental impacts. To ameliorate the resource and environmental pressures of urban cement metabolism and foster sustainable urban construction, a series of policy recommendations are proposed for different phases of cement metabolism in legislative, administrative, economic and technological dimensions.

4.1 Resource conservation

The realty industry proves to be a key sector for focus, in the sense that almost one third of cement was used in RBs and the added value of this sector took up an increasing proportion (from 6% to 9%) of local GDP (Xiamen Municipal Statistics Bureau, 2013) during the study period. It needs to be noted, however, that bubbles and risks have been accumulating for this sector behind the scenes of apparent booming growth (Pi, 2013; Xiong, 2009). According to the statistics, the "ratio of investment in real estate to local fixed investment" displays a rising trend and has been over 30%, which is regarded as the warning level for a fast developing economy (Pi, 2013), for most of the years since 2002. Meanwhile, the "area of RBs for sale" has significantly increased since 2008 (up to 2.59 million m^2 in 2013), indicating increasing stock and sales pressure. Be aware that the "area for sale" does not include areas that have been sold but actually left vacant (e.g. for increase in value and resale). If these areas were counted as well, the total vacant area would be even larger. The existence of newly constructed vacant buildings is quite prevalent at present in rapidly urbanizing China. Particularly in some newly planned urban areas, scores of vacant buildings and underpopulated districts have developed into an extreme phenomenon known as "ghost towns". This means that, from a material metabolism perspective, large amounts of construction materials (cement included) have been consumed and stocked in RBs that stay unused and depreciating, representing a potentially huge resource waste. At least 28 ghost towns have been recorded between 2008 and 2012 (He et al., 2016), and about 22.4% of newly-built RBs in urban areas stood vacant in 2013 (Southwestern University of Finance and Economics, 2014). Note that the "ghost town" phenomenon is not unique to China but occurs in other emerging economies (Murray, 2016). The development of improved real estate policies, through the regulation of land supply (e.g. by reducing the overreliance of local governments on land sales for their fiscal expenditures), improvements in financial credit mechanisms and reforms in the property tax system, is an effective way to deal with the housing bubble (Cao et al., 2013; He et al., 2016). Not only does it contribute to the reduction of risk from overreliance of local economies on the realty industry, but it

helps avoid as much as possible excessive cement input into an overheated realty industry.

Road transport infrastructure has become one of the major factors driving cement consumption in recent years as discussed in section 3.1. Moreover, this component is expected to maintain its considerable demand for cement input in the near future along with the integration process of Xiamen Island and the areas beyond. According to the municipal commission of urban planning (2014), a new round of integrated traffic planning has been issued which involves, inter alia, a metro network of about 246 km length, an expanded urban expressway system (2 loops and 8 radiations), and an expanded cross-sea corridor system (13 passages), and some projects are already underway. Nevertheless, the truth is that large amounts of capital and resource inputs do not make local traffic condition improve greatly. The mismatch between limited supply of traffic resources and fast-growing transportation demand brought about by urban expansion and socioeconomic development is the main reason behind this. There has been a mere 17% increase in the "road area per capita" from 2002 to 2013, an increase rate which is far behind the growth rate for car ownership (171%) and "proportion of transportation expenditure in consumption expenditure per capita" (250% for urban residents and 67% for rural residents) during the same period (Xiamen Municipal Statistics Bureau, 2014). Meng et al. (2010) also found increased trip volume and distance based on a large-scale resident trip survey. Therefore, emphasis and implementation of transportation demand management (TDM), rather than sole dependency on reactive increases in supply of transport infrastructure, is a fundamental solution to sustainable urban transportation and reduction of cement input to transport infrastructure in the long run. The idea of TDM also applies to other rapidly urbanizing areas worldwide, where development of transport infrastructure is thriving and requires a large amount of capital and construction materials (World Bank, 2016). From an administrative point of view, optimizing urban spatial patterns through integrated land-use and transportation planning is considered a useful approach to TDM. Urban form and infrastructure are strongly linked to transportation demand, thus affecting the throughput of materials and energy and the accompanying

long-run GHG emission trajectories of a city (Seto et al., 2014). To be specific, a two-prong planning strategy is suggested to optimize the spatial pattern of Xiamen city: (1) facilitation of the transition from a single-centered to multi-centered urban form, by means of preferential development of city clusters beyond Xiamen Island, co-location of high residential and employment densities, and achievement of high land use mixes; (2) advocating transit oriented development (TOD)—via construction of metro and BRT systems for example—and promoting intensive land use along the mass rapid transit routes.

Besides, the "sustainable consumption" paradigm deserves more attention given the result of increased cement consumption per capita (section 3.4). With life style change, more and more natural resources (including construction materials like cement) are required and an increasing trend of per capita material footprint in emerging economies is noteworthy (Wu et al., 2016). However, limited global resources are unable to support large populations in those countries (e.g. China, India, Brazil) to live a resource-intensive lifestyle equal to developed economies. In this sense, concentration on sustainable production alone cannot solve the problem of resource conservation, sustainable consumption should also be vigorously advocated for and adopted. Along with economic levers such as taxation, environmental awareness needs to be enhanced through public outreach, though behavioral change may be slow and difficult.

4.2 Waste reduction

Legislative measures need to be in place for the reduction of C&D waste (including waste cement) in different aspects. Other than old buildings that have reached the end of their lifetimes, irrational urban plans (causing short-lived buildings/infrastructure) are also responsible for the generation of massive demolition waste volumes across China (Wu et al., 2016). Consolidating the legal status of urban planning to make land use consideration more proactive and durable could help with this problem. As for the decoration waste that constitutes the second largest fraction of C&D waste, attention should be paid to individually-managed decoration works (related to undecorated RBs) which are still prevailing in most cities of China. Relevant research (Chen et al., 2012;

Shi and Lin, 2013) showed that individually-managed decoration work generates 0.02 t more waste per square meter than batch decoration work does (related to decoration-binding RBs), generally because of arbitrary structural change and poor on-site management. Recently, less than 25% of newly-built RBs in Xiamen are decoration-binding (NBS Survey Office in Xiamen, 2011). Therefore, popularizing decoration-binding RBs through legislation (e.g. proposals brought forward by the construction department) contributes to curtailing decoration waste substantially. As for construction waste, specifically for reducing waste cement, a promising instrument is to mandate use of premixed mortar by applying bulk cement. According to the Xiamen Bulk-cement Office (BCO), the majority of local construction works still use on-site mixed mortar by applying bagged cement. Such techniques inevitably lead to loss and waste during on-site mixing, loading and unloading, transportation and so on. Promoting legislation on premixed mortar can reduce the loss and waste of corresponding materials, while improving construction quality and decreasing engineering costs (Xiamen BCO, 2011).

4.3 Recycling improvement

On the one hand, support is needed for the recycling industry of C&D wastes by adopting the administration of a permit system combined with government procurement agreements. This mode could efficiently deal with the constraints of recycling of C&D waste, which has relatively high operating costs (due to long distance transport, large land use demand and expensive investment in capital equipment) and inadequate market demand (due to a lack of widespread social recognition) but not technology accessibility. Furthermore, the government should impose higher royalties on the exploitation of naturally-sourced construction materials (such as sand and gravel) to enhance the competitiveness of recycled products. The final purpose is to build up a secondary resource reserve, decreasing overdependence of urban construction on exogenous resources and improving the resilience of the city. On the other hand, advancing industrialization of the construction industry through technical innovation is highly recommended. Industrialization of the construction industry, which allows mass production, on-site assembly and whole-piece

529 dismantlement (when buildings reach the end of their lifespan) of precast structural
530 elements, represents a fundamental shift from the traditional construction paradigm.
531 This shift enables modularization of building construction, realizing substantial reuse
532 and recycling of construction materials (Cao et al., 2015). Xiamen has been approved
533 as a pilot city for housing industrialization, and the municipal construction bureau has
534 developed an action plan stipulating that pre-fabricated buildings account for 50% of
535 newly-built floor area by 2020 (Xiamen Construction Bureau, 2014). This provides a
536 good opportunity for technology research and development, standard formulation and
537 incubation of emerging industries in relevant fields.
538
539 **5. Conclusions**
540 Using Xiamen as a case study, this research develops a comprehensive UCMF
541 consisting of four major urban construction components for characterizing cement
542 metabolism in rapidly urbanizing areas of developing countries, namely building
543 construction, civil infrastructure construction, decoration and demolition. A bottom-up
544 accounting approach was employed to quantify the cement consumption and waste
545 generation (including waste cement) of each applicable component, and a cement
546 metabolism model for Xiamen city has finally been established.
547 In terms of resource use, building accounted for about 78% of the total cement
548 consumption, from which the largest fraction came from RB. More and more cement
549 has been stocked in newly-built vacant RBs caused by an overheated realty industry.
550 Road transport infrastructure has played a more important role in annual cement
551 consumption over recent years and is expected to continue growing in the foreseeable
552 future, due to the integration process of Xiamen Island and the areas beyond and
553 development of three-dimensional transportation. A significant finding based on the
554 “additive pavement layer” approach developed by this study is that, decoration turned
555 out to be the second largest cement consumer, even outweighing road transport
556 infrastructure surprisingly. This finding suggests the necessity of incorporating
557 decoration into accounts of urban cement metabolism and material cycling, especially
558 in areas where most newly-built RBs are undecorated. In terms of waste generation,

559 waste from demolition activities dominated total C&D waste and basically showed an
560 upward trend, indicating expanding redevelopment of old city districts and the
561 removal of old buildings in the process of rapid urbanization. Hardly any C&D waste
562 could be reused or recycled under current circumstances. In terms of metabolism
563 efficiency, ascending cement consumption per capita was observed in opposition to
564 the descending cement consumption per unit GDP and the per unit fixed investment,
565 suggesting that it might be more relevant to reduce cement input through human
566 demand management.

567 By coupling physical metabolic analysis with some socio-economic indicators, a
568 multi-dimensional policy portfolio is proposed in order to reduce the resource and
569 environmental pressures of urban cement metabolism and foster sustainable urban
570 construction: (1) economically, develop improved real estate policies to avoid
571 excessive resource inputs into an overheated realty market; (2) administratively,
572 optimize urban spatial patterns to reduce long-term cement use in transport
573 infrastructure, and adopt a permit system to support the recycling industry of C&D
574 waste and build up a secondary resource reserve; (3) legislatively, consolidate the
575 legal status of urban planning, popularize decoration-binding RBs and mandate the
576 use of premixed mortar to curtail demolition, decoration and construction waste; (4)
577 technologically, advance industrialization of the construction industry to achieve
578 internal circulation of construction materials; (5) furthermore, promote sustainable
579 consumption to alleviate resource pressures. Such policy instruments do not only fit
580 this local study but have wider generalizability in terms of sustainable construction
581 material management to rapidly urbanizing areas elsewhere (e.g. in BRICS countries),
582 that are suffering or likely to suffer similar issues like vacant buildings, transport
583 infrastructure booms, irrational urban plans, lack of recycling mechanisms and
584 transition to consumer societies.

585 Further research is still needed. First of all, the accuracy of cement accounting can be
586 improved by investigating localized $I_a(t)$ through in-depth sectoral enquiries and
587 expert consultation. Second, the scope of urban cement metabolism can be more

588 comprehensive by taking airports, harbors, railways and municipal pipe networks into
589 consideration when corresponding data became available. Thirdly, the deployment of
590 life-cycle analysis can help trace back and evaluate transboundary resource and
591 environmental pressures of cement consumption (mostly occurring at the production
592 stage), which will facilitate the revelation of regional impacts from rapid urbanization
593 and optimization of production technology in the cement industry. Last, to develop a
594 dynamic model on an urban scale, by considering local resource and environmental
595 endowment, will contribute to simulation of future resource demand and waste
596 generation scenarios and decision support for resource and waste management.
597

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604

605 **Appendix A. Supplementary data**
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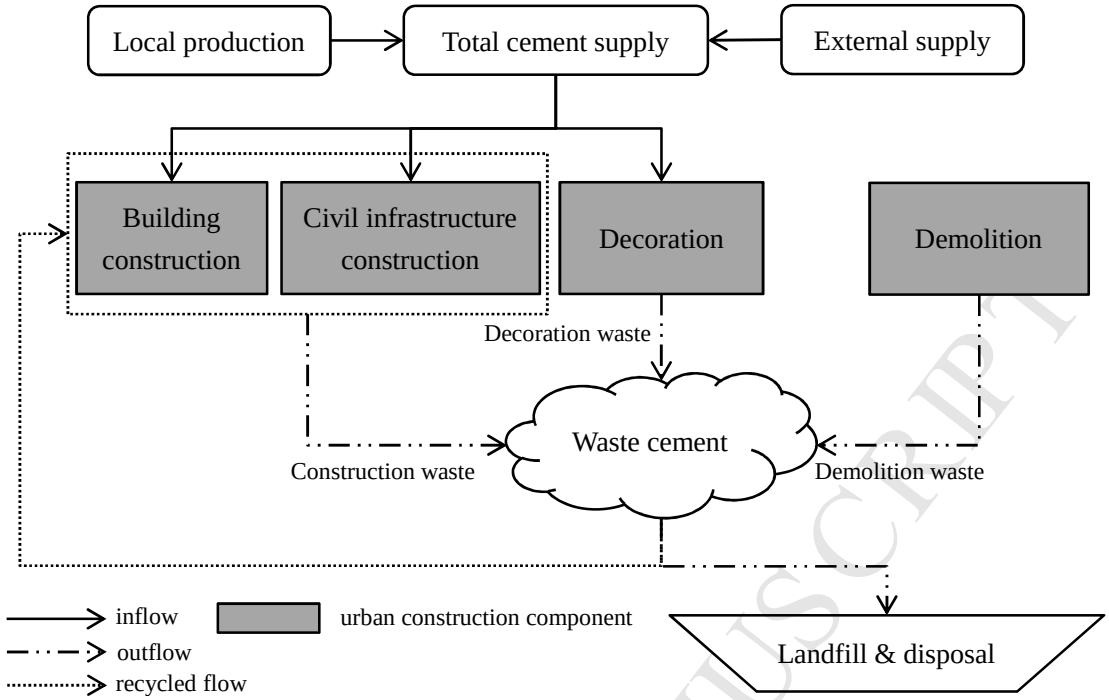
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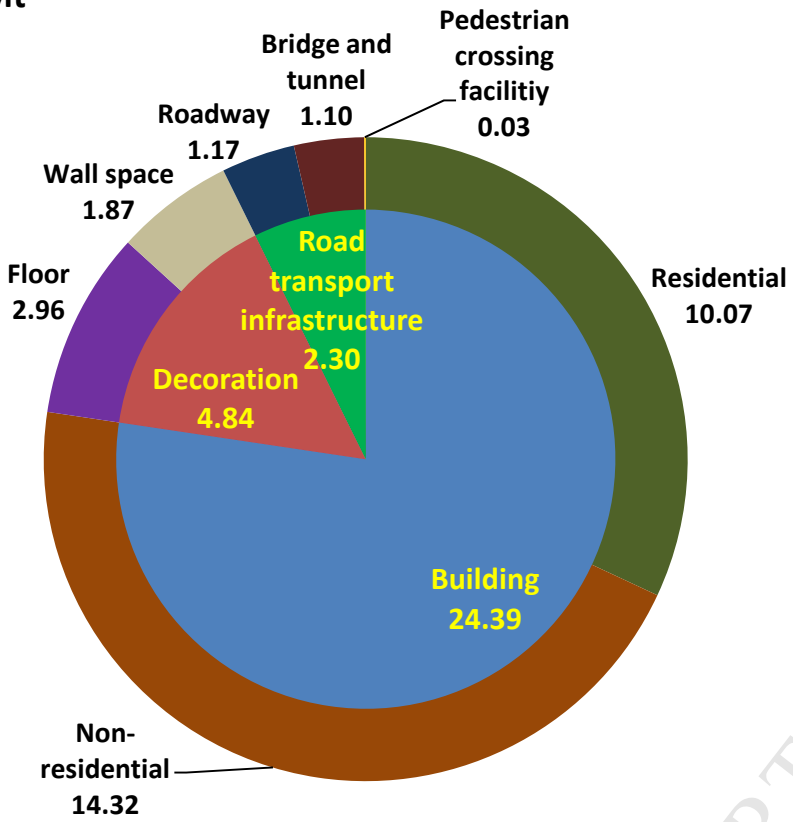
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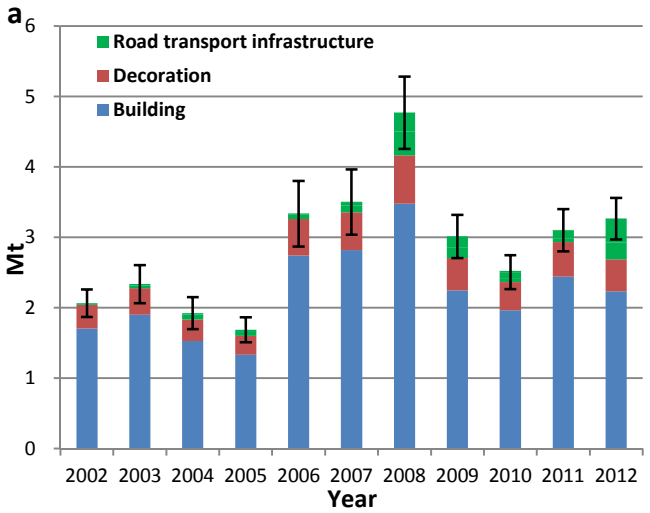
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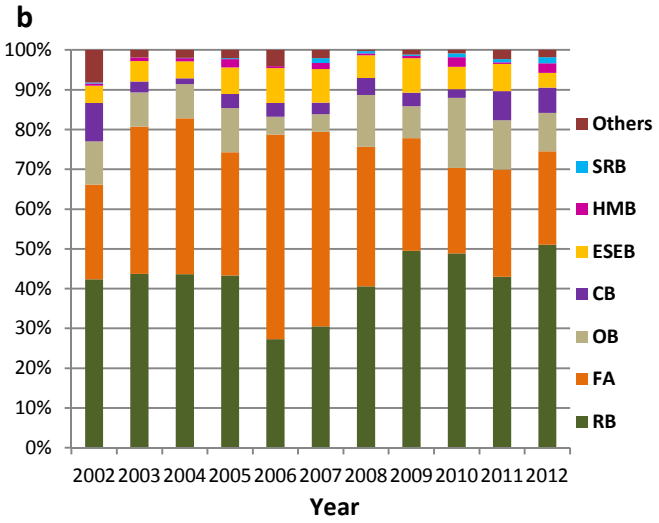
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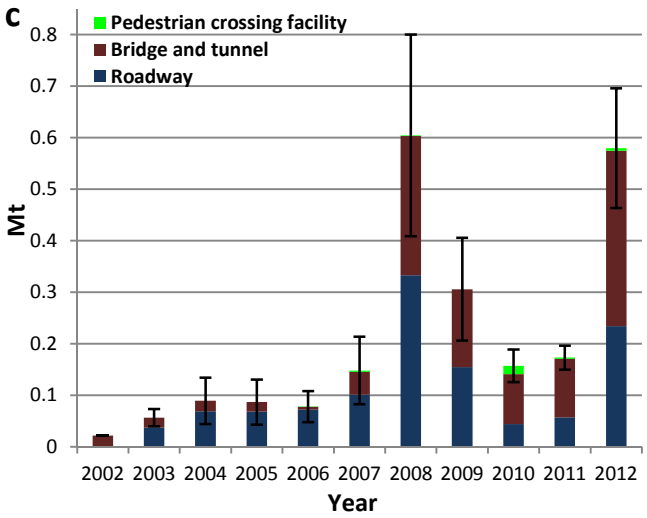
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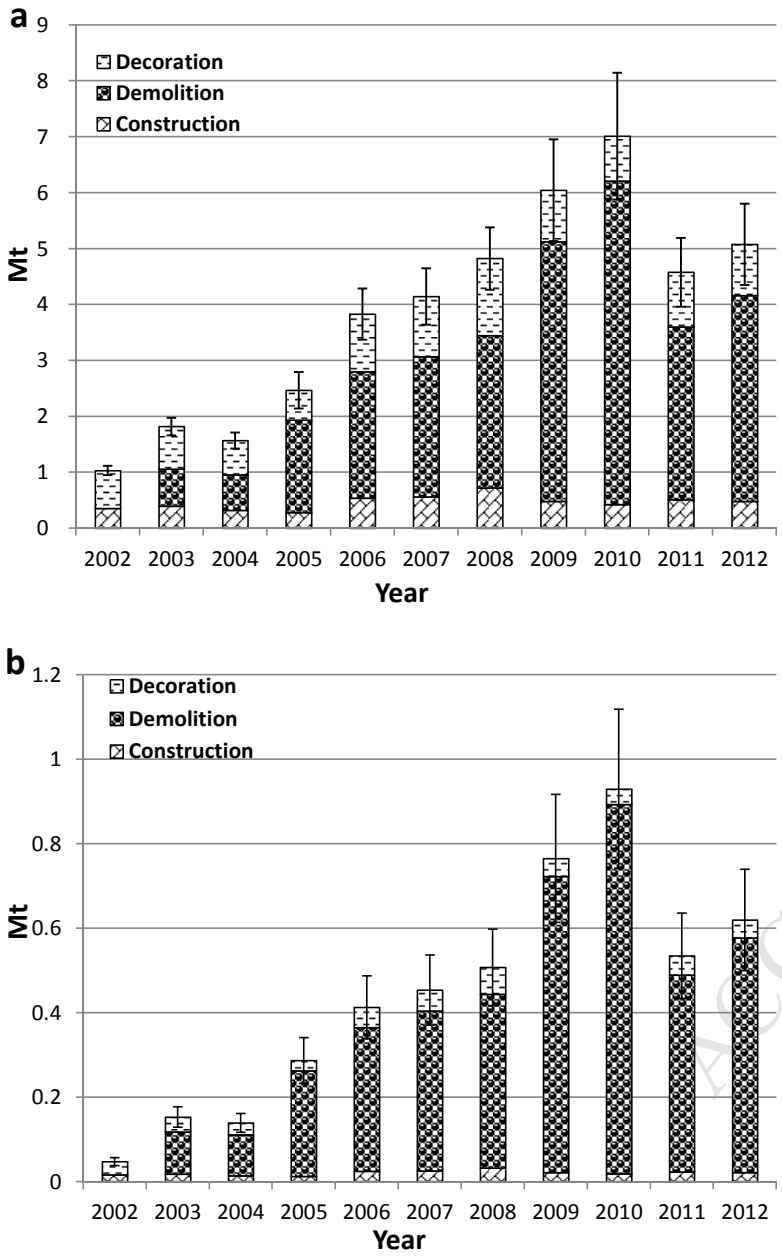
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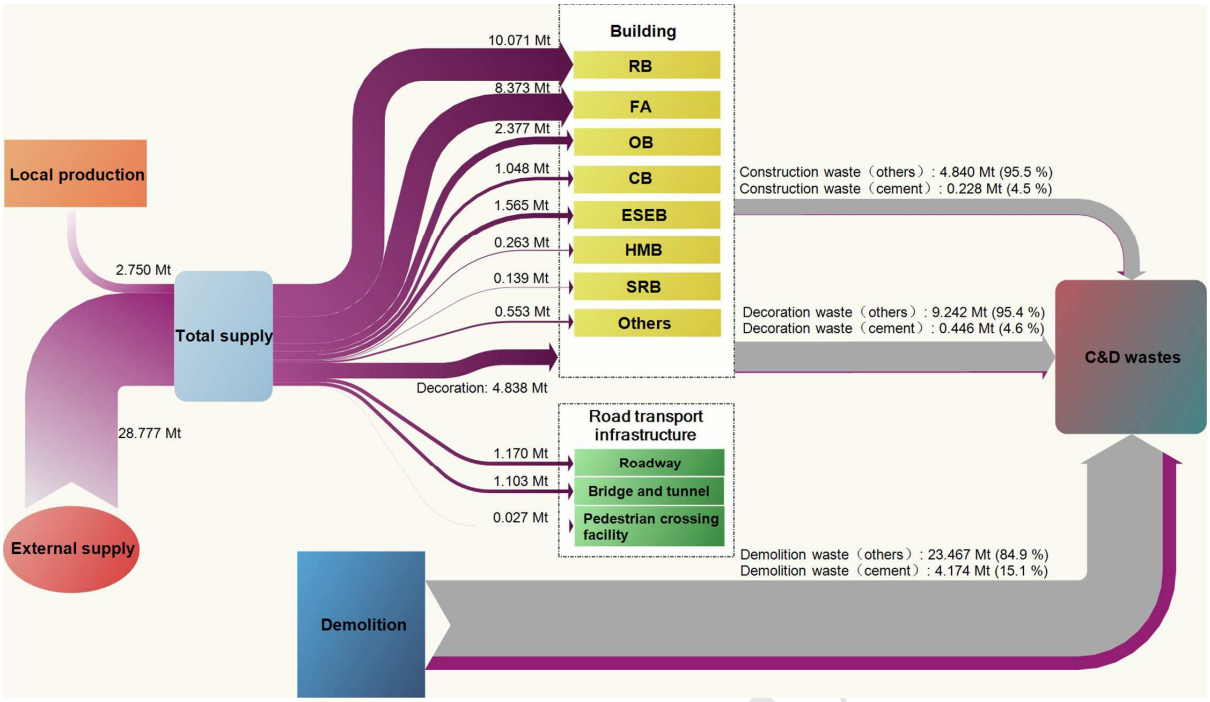
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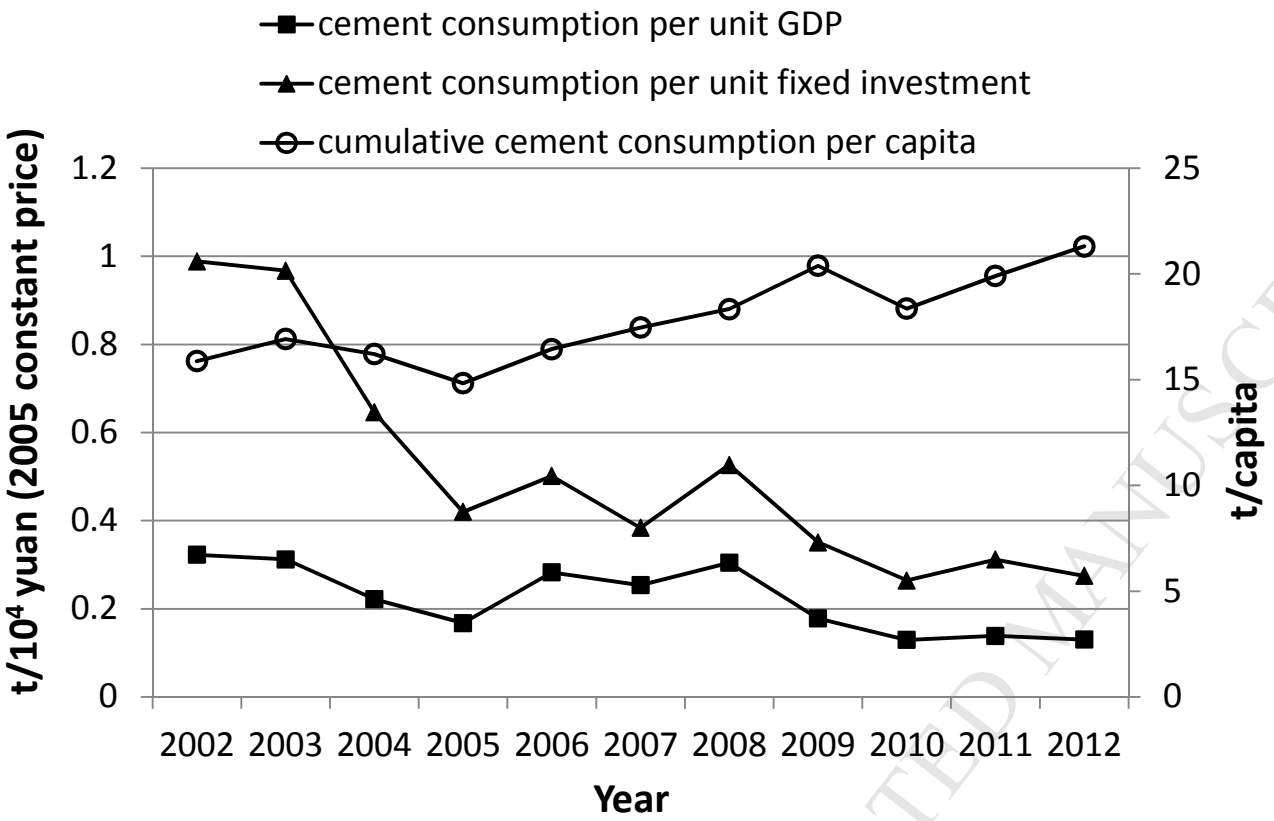
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- A comprehensive urban cement metabolism framework is established.
- Residential buildings accounted for 1/3 of total cement use.
- Cement use in architectural decoration is substantial and should not be neglected.
- Increasing construction and demolition waste is hardly reused or recycled.
- A multidimensional policy portfolio is proposed for sustainable urban construction.

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