Atmospheric Environment 245 (2021) 118014

Contents lists available at ScienceDirect

Atmospheric Environment

journal homepage: http://www.elsevier.com/locate/atmosenv

VOC emission inventory of architectural coatings and adhesives for new buildings in China based on investigated and measured data

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HIGHLIGHTS

- A VOC emission inventory for architectural decorations in 2017 in China was developed based on building area.
- A new database of corresponding emission factors and activity data was established.
- Floor coatings and solvent-based adhesives were key VOCs sources for architectural decorations.
- Emission contributor was subdivided into provincial level.

ARTICLE INFO

Keywords:
Architectural coatings and adhesives
VOCs
Building area
Emission inventory
Emission factors

ABSTRACT

Architectural decoration is one of the most important sources of anthropogenic volatile organic compound (VOC) emissions in China, as well as one of the major sources of indoor air pollution, which negatively affects the comfort, health, and productivity of residents. In this study, a VOC emission inventory of architectural coatings and adhesives for new buildings in China in 2017 was developed based on building area, using a new database established through a bottom-up activity level investigation and analysis of large number of samples. Our results show that the investigated coating ratio of exterior walls distinctly differed from the empirical value. The comprehensive VOC emission factors and total emissions for architectural coatings and adhesives in China in 2017 were 214.5 kg km^{-2} and 614 kt, respectively, with floor coatings (41.1%) and solvent-based adhesives (18.2%) being the highest contributors to emissions. Shandong, Jiangsu, Zhejiang, Sichuan, and Guangdong were the five largest emission contributors, accounting for 39.1% of VOC emissions from architectural coatings and adhesives for new buildings. Market access and supervision of architectural materials should be strengthened maximally, and gradual phasing out of solvent-based coatings and adhesives is advised in the future in China.

1. Introduction

China has made great efforts to reduce severe pollution, resulting in declines in annual fine particulate matter ($PM_{2.5}$) by 48%, 39%, and 32% in Beijing–Tianjin–Hebei (BTH), the Yangtze River Delta (YRD), and the Pearl River Delta (PRD), respectively, in 2018 compared with 2013 levels after implementation of the National Air Pollution Prevention and Control Action Plan (Ministry of Ecology and Environment; MEE, 2019a). Nonetheless, the maximum daily 8-h average ozone (O_3) concentration in China has increased continuously, from 139 mg m^{-3} in 2013 to 151 mg m^{-3} in 2018, with increased O_3 concentrations in BTH, YRD, and PRD of 28%, 16%, and 6%, respectively (MEE, 2014; MEE, 2019a). According to the monthly monitoring data of the China National Environmental Monitoring Centre during 2013–2019, the monthly characteristics of O_3 pollution vary among different regions, and the high O_3 concentrations in BTH, YRD, and PRD occur mainly in May–September, April–October, and July–October, respectively. Volatile organic compounds (VOCs) are crucial precursors in the formation of O_3 (Hao, 2012; Yuan et al., 2013; Zhao et al., 2013), especially in VOC-sensitive urban areas (Ran et al., 2009; Tang et al., 2012; Ding

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https://doi.org/10.1016/j.atmosenv.2020.118014
Received 23 June 2020; Received in revised form 14 October 2020; Accepted 15 October 2020
Available online 21 October 2020
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et al., 2013; Han et al., 2013; Lam et al., 2013).

Due to the rapid urbanization and nearly 3 billion square meters of completed buildings per year (Lin, 2019), the market demand for architectural coatings and adhesives has been strong. The outputs of architectural coatings and adhesives increased from 1940 kt and 950 kt in 2008 to 6300 kt and 2260 kt in 2017, showing 3.2- and 2.4-fold increases over a decade, respectively (Lin, 2011, 2017, 2018, 2019). Architectural decoration is one of the most important sources of anthropogenic VOC emissions in China (Wu et al., 2016; Liang et al., 2017a, b; Wu and Xie, 2017). In recent years, China issued a series of VOC governance requirements for architectural decoration, including promoting the use of architectural materials that meet environmental protection requirements, strictly implementing the limits of hazardous substances in architectural material products, and phasing out solvent-based coatings and adhesives (Peng, 2011; MEE, 2016; MEE, 2017; MEE, 2019b; Gao et al., 2017). Moreover, VOCs emitted from architectural materials are one of the major sources of indoor air pollution, which negatively affects comfort, health, and productivity (Campagnolo et al., 2017; Goodman et al., 2017; Zhou et al., 2017). Therefore, determination and characterization of VOC emissions from architectural decoration are critical to minimizing potential secondary pollutant formation and reducing the risk of human exposure.

Several studies have examined the VOC emission characteristics of architectural decoration in China (Wei et al., 2008; Qiu et al., 2014; Mei et al., 2016; Wu et al., 2016, 2017; Cao et al., 2017; Mu et al., 2017; Zheng et al., 2017; Deng et al., 2018; Gao et al., 2018, 2019); however, there were several limitations in those studies. First, architectural adhesives and several important categories of architectural coatings (e.g., waterproof coatings, floor coatings, anticorrosive coatings, and fire-retardant coatings) were not covered in most of the studies. Second, traditional methods based on the consumption of architectural materials were always restricted at the regional and city levels because the consumption data were exclusively available on the national scale. Mu et al. (2017) and Deng et al. (2018) developed VOC emission inventories of architectural coatings for Nanjing and Beijing, respectively, without considering floor, anticorrosive, or fire-retardant coatings, likely because of the lack of corresponding consumption data. Third, the empirical values for exterior wall coating ratios (i.e., 60–64%) adopted in previous studies are outdated due to the rapid development of markets for exterior wall tiles and glass curtain walls in China. This limitation inevitably led to uncertainties in corresponding consumption and VOC emission estimations of exterior wall coatings. Finally, most of the inventories were established using emission factors based on Chinese standard limits due to the lack of measured data, and with the improvement in health awareness, the innovation of architectural material structures, and the implementation of Chinese standards, the VOC contents of architectural materials may have changed.

Taking the above into consideration, the main objectives of this study were to (1) investigate coating ratio of exterior wall through a bottom-up method by region; (2) collect a large number of samples for VOC analysis for architectural coatings and adhesives; (3) establish comprehensive VOC emission factors based on building area; (4) compile VOC emission inventory of architectural coatings and adhesives for new buildings in China in 2017. We believe that our study will promote the estimation of VOC emissions from architectural decoration and facilitate policy making and implementation with respect to VOC emission control in China.

2. Methods and database

2.1. Emission estimation

Typically, emissions can be estimated by multiplying emission factors by the relevant activity data (United States Environmental Protection Agency, 1995), which is usually referred to as the emission factor method. In contrast to the traditional method based on activity data of architectural material consumption, in this study, a method based on building area was proposed to establish VOC emission inventories for architectural decorations, as building area activity data are more accessible. Meanwhile, a new database of corresponding emission factors and activity data was established through a bottom-up activity level investigation and analysis of large number of samples.

Table 1
Source classification and samples of VOC emission inventories for architectural decorations.

Architectural material	Subsector	Samples	
Architectural coatings	Interior wall coatings	Water-based	87
	Exterior wall coatings	Water-based	81
		Solvent-based	5
	Waterproof coatings	Water-based	155
		Reaction-based	60
		Solvent-based	–
	Floor coatings	Water-based	10
		Solvent-less	42
		Solvent-based	22
	Anticorrosive coatings	Water-based	20
		Solvent-based	25
	Fire-retardant coatings	Water-based	4
		Solvent-based	12
	Total coatings		523
Architectural adhesives	Water-based		68
	Solvent-based		73
	Bulk-based		32
	Total adhesives		173
	Total materials		696

As shown in Table 1, a total of 16 subcategories of architectural coatings and adhesives were considered, based on a decentralized system classification method. Currently, no relevant statistical data are available for estimating the renovation area of old buildings. Therefore, we exclusively estimated VOC emissions of architectural coatings and adhesives used to construct new buildings. Generally, VOCs from construction can be regarded as fugitive emissions, which can be calculated by Eq. (1):

$$E_i = \sum_i A \times EF_i \Big/ 1000000 \tag{1}$$

where i is the type of architectural coatings or adhesives; E (unit: kt) is VOC emissions, EF is the emission factor based on building area, and A is the activity data, that is, building area in each province.

2.2. Database for emission factors

2.2.1. Emission factor estimation

Comprehensive VOC emission factors based on building area (EF, kg·km^{-2}) were investigated and calculated according to Eqs. (2)–(4).

$$EF_i = \sum_i P_i \times N_i \tag{2}$$

where P (L·m^{-2} or kg·m^{-2}) is the consumption of architectural materials per unit building area. For interior/exterior wall coatings and other architectural materials, P can be calculated by Eqs. (3) and (4), respectively. N (g·L^{-1} or g·kg^{-1}) is the VOC content of each type of architectural material and is calculated by Eq. (5).

$$P_i = K_i \times L_i \times F_i \tag{3}$$

where K is the correlation coefficient between the building area and the area of the interior or exterior walls (2.5 for interior walls, 0.7 for exterior walls (Lin 2011; Gao et al., 2019)); L is the coating ratio of interior or exterior walls (78% for interior walls (Lin 2011; Gao et al., 2019), the investigated data conducted in Section 2.2.2 for exterior walls); and F (L·m^{-2}) is the paint consumption of interior or exterior

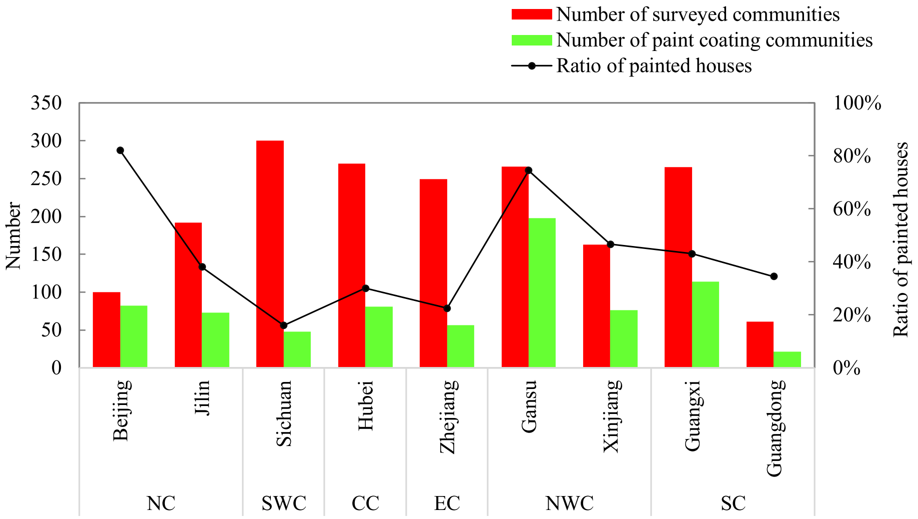

Fig. 1. Coating conditions of the exterior walls of residential buildings by region. NC, North China; SWC, Southwest China; CC, Central China; EC, East China; NWC, Northwest China; SC, South China.

walls per unit coating area obtained by product recommendations and experienced usage.

$$P_i = Q_i \div S_N \times 1000 \tag{4}$$

where Q (kt), the apparent consumption of architectural materials nationwide, was adopted through industry associations and expert consultation. S_N (km^2) is the nationwide building area, originating from the Statistical Yearbook of the Chinese Investment in Fixed Assets (2018).

$$N_i = \sum_j N_j \times M_j \tag{5}$$

where j is the type decentralized system for each architectural material. Decentralized systems can generally be classified into the following four categories: water-based, reactive-based, solvent-free, and solvent-based. M is the market share of various decentralized systems for architectural materials and was obtained from Gao et al. (2019).

2.2.2. *Activity level survey*

As a key parameter for consumption estimation of exterior wall coatings, coating ratios of exterior walls were obtained through a bottom-up regional investigation in this study. Three types of architecture were involved: residential, public, and productive buildings. Taking the geographical administrative divisions, living environment, economic development level, and living habits into account, mainland China was divided into six typical geographical regions: North China (including Northeast China), Southwest China, Central China, East China, Northwest China, and South China. One or two representative provinces were considered from each region, and three representative cities were investigated in each province, including one provincial capital city, one moderately developed city, and one underdeveloped city. In addition, three districts with different levels of economic development were selected in each city.

For each city, the parameter survey for the coating ratios of exterior walls was based on 100 numbers of buildings newly constructed within the last 5 years. If the number of the buildings in survey areas failed to meet the above conditions, the actual number of buildings surveyed shall prevail. The main information investigated included community name, address, construction time, and type of exterior wall materials. Therefore, a total of 1866 communities in nine provinces of six regions were investigated for the coating ratios of residential exterior walls, including 292 in Beijing and Jilin in North China, 300 in Sichuan in Southwest China, 270 in Hubei in Central China, 249 in Zhejiang in East China, 429 in Gansu and Xinjiang in Northwest China, and 326 in Guangxi and Guangdong in South China.

2.2.3. *Sampling and analysis*

Representative samples of architectural coatings and adhesives were collected according to the market brands and shares of dispersed systems obtained from the China Coatings Industry Association, China Adhesives and Adhesive Tapes Industry Association, and market investigation. As shown in Table 1, a total of 523 samples of various architectural coatings were collected, including 87 interior wall coatings, 86 exterior wall coatings, 215 waterproof coatings, 74 floor coatings, 45 anticorrosive coatings, and 16 fire-retardant coatings. In addition, a total of 173 samples of architectural adhesives were also obtained, including 73 solvent-based adhesives, 68 water-based adhesives, and 32 bulk adhesives.

Samples of architectural coatings and adhesives were collected or purchased from construction sites, local manufacturing companies, and markets. We obtained representative samples in accordance with the following principles: (1) covering high-end building material supermarkets, wholesale markets, and personal sales; (2) selecting representative construction and the primary raw materials used; and (3) collecting the main products of companies.

The procedures of the VOC analysis followed relevant Chinese standards. Interior and exterior wall coatings were analyzed according to GB 18582–2008 and GB 24408–2009, respectively. Water-based and reactive-based waterproof coatings were measured according to GB 18582–2008 and JC 1066–2008. The evaluation of floor coating adopts the method in *Floor Coating Materials* (GB/T 22374–2008). Water-based and solvent-based anticorrosive coatings were tested using GB/T 23986–2009 and GB 30981–2014, respectively. The VOC contents of fire-retardant coatings were analyzed using JG/T 415–2013. The method in Appendix F of GB 18583–2008 was followed for architectural adhesives.

2.3. *Database for activity data*

China's reports on building area are derived mainly from two statistical reporting systems: the fixed asset investment statistical system and sampling survey, and the construction industry statistical system. Building area is referred to as "area of completed buildings" in both systems; however, the principles of the survey statistics for the two indicators are different. The building area in the fixed asset investment survey is based on the location of the construction project. It can truly

Table 2
VOC contents in architectural coatings.

Coating type	Subordinate		Number of samples	VOC content range (g·L−1)	VOC comprehensive content (g·L−1)	Standard limit (g·L−1)	
Interior wall coatings	Water-based	Dominant brands	25	33–95	35	120	GB 18582-2008
		Other brands	62	≤100			
Exterior wall coatings	Water-based	Dominant brands(Flat coatings)	22	36–68	41	120 [a]/150 [b]	GB 24408-2009
		Other brands(Flat coating)	39	≤100			
		Real stone or texture coating	20	≤7	2		
	Solvent-based		5	291–456	374	680 [c]/700 [d]/760 [e]	
Waterproof coatings	Water-based		149	≤10	5	120 [f]	JC 1066-2008
			6	>10			
	Reaction-based		60	≤140	116	200 [f]	
	Solvent-based		–	–	500	750 [f]	
Floor coatings	Water-based		10	89–120	103	120	GB/T 22374-2008
	Solvent-less		42	≤60	40	60	
	Solvent-based		22	126–600	448	500	
Anticorrosive coatings	Water-based		20	≤121	44	150	DB 11 3005-2017
	Solvent-based		25	261–693	529	420	
Fire-retardant coatings	Water-based		4	≤80	68	80	JG/T 415-2013
	Solvent-based		12	304–720	474	500	

[a] Standard limit for primer.
[b] Standard limit for topcoat.
[c] Standard limit for colored paint.
[d] Standard limit for varnish.
[e] Standard limit for glitter paint.
[f] Standard limit for Class B.

reflect the situation of newly built houses in the region during that year. In the construction industry survey system, the building area is based on the registration location of the construction industry. It will include the cross-regional housing construction of the company and cannot reflect the specific situation of the region. Therefore, we chose the building area indicator in the fixed asset investment as the activity data for this study. It should be noted that the building area of rural households in the fixed asset investment is obtained by the sampling survey method, and this part must be included when using this index. The total building area covering rural households (km^2) can be obtained from the Statistical Yearbook of the Chinese Investment in Fixed Assets (2018) and is shown in Table S1 in the Supplemental Materials.

3. Results and discussion

3.1. *Coating ratio of exterior walls*

Residential, public, and productive buildings were considered in this study. According to the Statistical Yearbook of the Chinese Investment in Fixed Assets (2018), residential buildings contributed 54.2% of China's total building area in 2017, with an area of 1.5 billion square meters. Public and productive buildings had a total area of 1.3 billion square meters, accounting for 45.8% of the total area. The exterior walls of public and productive buildings were mostly decorated with paint-free materials such as glass curtain or tiles. Therefore, an industry and market empirical value of 10% was proposed for the coating ratio. For residential buildings, the coating ratio was based on our regional survey and is discussed in detail below. Additionally, flat coating and real stone or texture coating were the two coating markets for exterior walls, accounting for 69% and 31%, respectively, of which the consumption per unit of exterior wall area varied greatly.

Fig. 1 illustrates that the coating ratio of exterior walls for residential buildings varied significantly by region (Table S2). The ratios in North China (60%) and Northwest China (61%) were higher than those in other regions. Southwest China and East China were the two regions with the most ceramic tile applications for exterior walls, with low coating ratios of 16% and 22%, respectively. The coating ratios in Central China (30%) and South China (39%) were moderate among the six regions. The coating ratio is not only related to the local living environment (e.g., better thermal insulation for coatings compared with ceramic tiles) and rainfall, but is also associated with the level of economic development and community construction planning. Large differences were also observed in different provinces of the same region (such as Beijing and Jilin). The government advocated the promotion of architectural coatings rather than ceramic tiles, since coatings save more energy and have better safety standards. Therefore, in restoration centers and developed cities such as Beijing, coatings might be promoted more. However, in Jilin, the choice of exterior wall materials might be greatly affected by building developers, who usually prioritize the advantages of high-grade, beautiful, and easy-to-clean ceramic tiles. As a result, this paper proposes a national arithmetic average coating ratio of residential exterior walls of 43% [coefficient of variation (CV), ±49%], which is quite different from the empirical value (60–64%) (Gao et al., 2019). This indicates that previous studies may have overestimated the consumption of exterior coatings.

3.2. *VOC contents*

3.2.1. *Architectural coatings*

In general, VOC contents in water-based and solvent-free coatings were lower than those in solvent-based coatings and VOC contents exceeding Chinese standard limits was obvious in solvent-based architectural coatings (Table 2).

Wall coatings, including interior and exterior wall coatings, were the dominant architectural coatings. The VOC contents of dominant brand water-based interior coatings ranged from 33 to 95 g L^{-1}. For other

Table 3
VOC contents in architectural adhesives.

Adhesive type	Subordinate	Number of samples	VOC content range (g·L−1 or g·kg−1)	VOC comprehensive content (g·L^{-1} or g·kg^{-1})	Standard limit (g·L^{-1} or g·kg^{-1})	
					GB 30982-2014	GB 18583-2008
Solvent-based adhesives	Neoprene	41	483–840	621	680	700
	Styrene–butadiene–styrene (SBS) block copolymer	12	451–731	593	630	650
	Polyurethane	12	395–691	550	680	700
	Acrylic	8	412–775	539	600	700
	Others	–	690	690	680	700
Water-based adhesives	Polyvinyl acetate	40	9–84	43	100	110
	Formal	18	58–179	107	150	350
	Polyurethane	10	12–63	37	100	100
	Acrylic	–	225	225	100	350
	Rubber	–	200	200	150	250
	Vinyl acetate ethylene (VAE) emulsion	–	225	225	100	350
	Others	–	250	250	150	350
Bulk-based adhesives	Silicone	18	11–195	74	100	100
	Polyurethane	14	18–87	47	50	100
	Polysulfide	–	75	75	50	100
	Epoxy	–	75	75	50	100
	Others	–	100	100	–	100

brands, contents were below 100 g L^{-1}, and VOC contents in more than 80% of the samples were below 35 g L^{-1}, the majority of which were even below the method detection limit (MDL) (2 g L^{-1}). Similar to interior coatings, more than 80% of the water-based exterior wall flat coatings for other brands contained less than 34 g L^{-1}, and most were also below the MDL (2 g L^{-1}). Latex paint was made of mainly VOC-containing synthetic resin emulsions as film-forming materials, water as a dispersion medium, and then appropriate pigments and additives. To reduce costs, the production of other brands reduced the amount of emulsion, thereby reducing the VOC contents in their products. Real stone or texture paints of exterior wall generally contained no more than 7 g L^{-1} VOCs, and most were below the MDL (2 g L^{-1}). The average VOC content of solvent-based wall coatings was 374 g L^{-1}, ranging from 291 to 456 g L^{-1}. VOC contents of interior and exterior wall coatings were far below China's standard limits.

Samples with VOC contents below 10 g L^{-1} contributed the most in water-based waterproof coatings, accounting for 96% of the total. For reaction-based waterproof coatings, the average VOC content was 116 g L^{-1}. Although VOC contents in solvent-based waterproof coatings were not measured in this study, the estimated result from a related study (Gao et al., 2018) was proposed. Solvent-based coatings exceeded the standard obviously, and 23%, 40% and 17% of the samples from floor coatings, anticorrosive coatings, and fire-resistant coatings exceeded the VOC limits, respectively. The VOC contents of other coatings were all in compliance with standard limits.

3.2.2. *Architectural adhesives*

Among the three types of adhesives, solvent-based adhesives generally had higher VOC contents than those of water-based and bulk adhesives (Table 3). The average VOC contents in all architectural adhesives complied with the relevant Chinese standard limits (GB 30982–2014; GB, 18583–2008), but samples exceeded the standards still existed.

The content of VOCs in solvent-based adhesives ranged from 395 to 840 g L^{-1} and 30% of the samples exceeded the VOC limits. Eleven samples from neoprene adhesives exceeded the Chinese standard limit in GB 30982–2014, and six exceeded the limit in GB 18583–2008. For styrene–butadiene–styrene (SBS) block copolymer adhesives and solvent-based acrylate adhesives, three and one samples exceeded the corresponding VOC limits, respectively. One sample from solvent-based

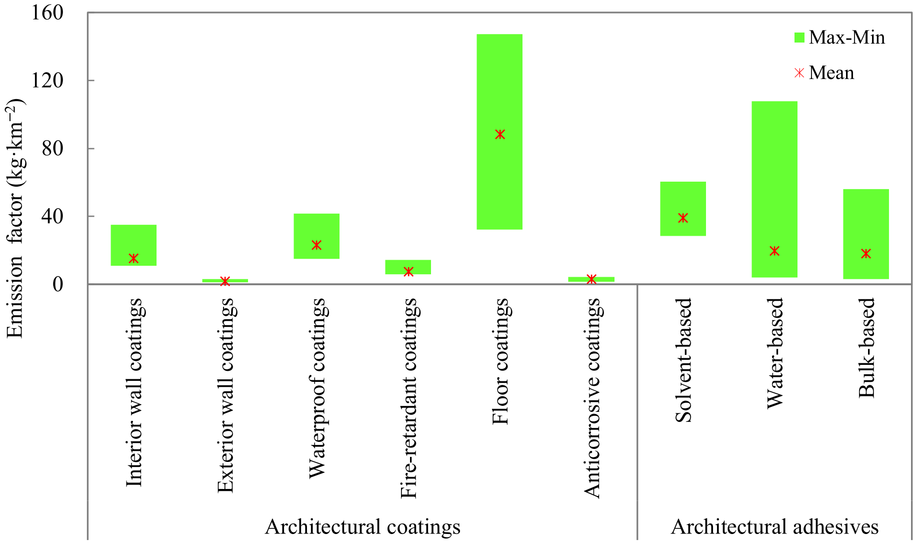

Fig. 2. VOC emission factors of architectural coating and adhesive usage.

Table 4
VOC emission factors and key indicators of architectural coating and adhesive usage.

Architectural materials		*P*	Unit	*N*	Unit	*EF* kg·km^{-2}
Architectural coatings	Interior wall coatings	0.437	L·m^{-2}	35	g·L^{-1}	15.1
	Exterior wall coatings (Flat coatings)	0.036	L·m^{-2}	41	g·L^{-1}	1.7
	Exterior wall coatings(Real stone or texture coatings)	0.141	L·m^{-2}	2	g·L^{-1}	
	Waterproof coatings	0.290	kg·m^{-2}	79	g·kg^{-1}	22.8
	Fire-retardant coatings	0.024	kg·m^{-2}	293	g·kg^{-1}	7.2
	Floor coatings	0.332	kg·m^{-2}	266	g·kg^{-1}	88.1
	Anticorrosive coatings	0.007	kg·m^{-2}	429	g·kg^{-1}	3.0
	Total	–	–	–	–	138.0
Architectural adhesives	Solvent-based	0.072	kg·m^{-2}	543	g·kg^{-1}	38.9
	Water-based	0.431	kg·m^{-2}	45	g·kg^{-1}	19.5
	Bulk-based	0.287	kg·m^{-2}	63	g·kg^{-1}	18.1
	Total	–	–	–	–	76.5

polyurethane adhesives exceeded the limit in GB 30982–2014. The VOC contents of water-based adhesives ranged from 12 to 179 g L^{-1} and 3% of the samples exceeded the VOC limits. Two samples from formal adhesives exceeded the limit of 150 g L^{-1} in GB 30982–2014. Bulk adhesives had VOC contents in the range of 11–195 g kg^{-1} and 3% of the samples exceeded the VOC limits. Four samples from silicone-based adhesives exceeded the limit in GB 18583–2008 and GB 30982–2014. Five samples from bulk polyurethane adhesives exceeded the limit in GB 30982–2014. The VOC contents of uncollected architectural adhesives all referred to the average limits in GB 30982–2014 and GB 18583–2008.

3.3. *VOC emission factors*

Fig. 2 shows the VOC emission factors and their maximum, minimum, and mean for architectural coatings and adhesives based on building area. The comprehensive emission factor of VOCs was 214.5 kg km^{-2}, of which 138.0 kg km^{-2} was from architectural coatings and 76.5 kg km^{-2} from architectural adhesives. For architectural coatings, floor coatings had the highest VOC emission factor, accounting for 63.9% of the total emission factors for coatings. For architectural adhesives, solvent-based adhesives were the largest contributor to adhesive emission factors, contributing 50.9%. The emission factor of water-based adhesives was similar to that of bulk adhesives, contributing 25.5% and 23.6%, respectively.

The consumption of architectural materials per unit area of completed building (*P*) and the content of VOCs (*N*) were two crucial indicators of the comprehensive VOC emission factors. As shown in Table 4, among the six architectural coatings, floor coatings had the highest VOC emission factors. Both decisive indicators of floor coatings were higher than others, at 0.332 kg m^{-2} and 266 g kg^{-1}, respectively. The VOC emission factor for interior wall coatings was significantly higher, by approximately nine times, than that for exterior walls. This was mainly caused by their different coating consumptions, 0.437 versus 0.036–0.141 L m^{-2}. To be precise, the difference in consumption was partly due to their correlation coefficients for building area, 2.5 for interior walls and 0.7 for exterior walls (Lin 2011; Gao et al., 2019), as well as the coating ratio, 78% for interior walls and 10% or 43% for exterior walls. Although the consumption of anticorrosive coatings (0.007 kg m^{-2}) and fire-resistant coatings (0.024 kg m^{-2}) was much less than that of exterior wall coatings (0.036–0.141 L m^{-2}), their VOCs emission factors were still higher due to their higher VOC contents. Their abundant VOC contents were related to the market share of solvent-based coatings for the two types of coatings, 90% and 80%, respectively. Among the three architectural adhesives, solvent-based adhesives had the highest emission factors, apparently due to the higher VOC contents. Water-based and bulk adhesives had similar emission factors due to their comparable indicators.

3.4. *VOC emission inventory*

3.4.1. *Source characteristics*

A VOC emission inventory for architectural coatings and adhesives in China in 2017 was compiled based on building area. The total VOC

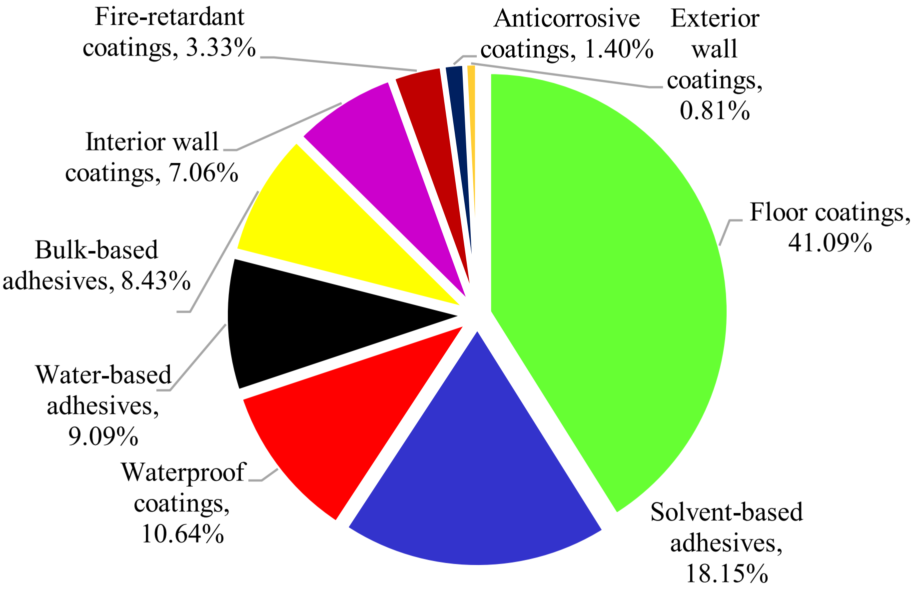

Fig. 3. Proportion of VOC emissions of architectural coatings and adhesives according to source in China in 2017.

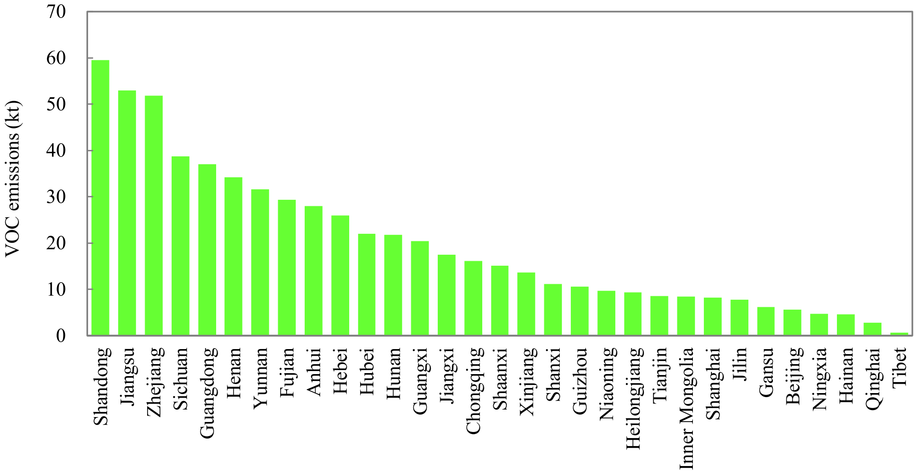

Fig. 4. VOC emissions from architectural coatings and adhesives for each province in China in 2017.

emission was 614 kt, of which 395 kt was from architectural coatings and 219 kt from architectural adhesives.

As shown in Fig. 3, floor coatings were the largest contributor, with VOC emissions of 252 kt, accounting for 41.1% of the total emissions. This was mainly associated with the relatively large consumption of solvent-based coatings (accounting for 70%). Solvent-based adhesives followed, with emissions of 112 kt, accounting for 18.2% of the total emissions. Waterproof coatings, water-based adhesives, bulk-based adhesives, and interior wall coatings had emission contributions in the range of 7–11%, accounting for 10.6%, 9.1%, 8.4%, and 7.1% of the total emissions, respectively. Together, fire-retardant coatings, anticorrosive coatings, and exterior wall coatings contributed ~5%, accounting for 3.3%, 1.4%, and 0.8% of total emissions, respectively. Exterior wall coatings had the lowest VOC emissions, contributing less than 1% of the total emissions, as consumption was greatly affected by the coating ratio of exterior walls, and the VOC content was low.

3.4.2. Provincial characteristics

A 2017 provincial VOC emission inventory for architectural coatings and adhesives in China was compiled. As shown in Fig. 4, the five largest emission contributors were Shandong (59 kt), Jiangsu (53 kt), Zhejiang (52 kt), Sichuan (39 kt), and Guangdong (37 kt), accounting for 39.1% of total emissions. Beijing, Ningxia, Hainan, Qinghai, and Tibet were the five smallest emission contributors, each contributing less than 1% and together accounting for 3.0% of total emissions. The remaining provinces each had emission contributions of 1–6%.

Provincial VOC emissions from architectural coatings and adhesives directly depend on their building area activity data, which are closely related to the permanent population, economic development, urban planning, urbanization rate, and other factors. As shown in Fig. 4, large VOC emissions usually appeared in densely populated provinces, such as Shandong, Jiangsu, Sichuan, Guangdong, and Henan. Due to their large populations, the demand for housing and auxiliary construction facilities was high, which resulted in relatively large building areas. In some provinces with medium populations, such as Zhejiang, Yunnan, and Fujian, in addition to population, the high VOC contribution was probably related to their construction demands for rich tourism resources. Guangdong, the province with the largest population and gross domestic product (GDP) in China in 2017, ranked fifth in terms of VOC emissions, most likely due to the saturation of new building construction in some urban planning areas (e.g., Guangzhou and Shenzhen), and the refurbishment of second-hand buildings occupying a certain proportion, resulting in a relatively low new building area in the province. Ningxia, Hainan, Qinghai, and Tibet were the four provinces with the lowest emissions, which was closely related to these provinces having the smallest populations and GDP in China in 2017, according to statistical data from the National Bureau of Statistics.

Table 5
Comparison of architectural coating VOC emissions from this study and Gao et al. (2019).

Coating type	Emission factor ($g\cdot kg^{-1}$)		Activity data (kt)		VOC emissions (kt)	
	This work	Gao et al. (2019)	This work	Gao et al. (2019)	This work	Gao et al. (2019)
Total	–	–	4298.8	5833.3	395.0	348.0
Interior wall coatings	24.91	24.63	1738.0	1747.1	43.3	43.0
Exterior wall coatings	30.7 (Flat)1.3 (Real stone and texture)	23.13	690.8	2807.2	4.9	64.9
Waterproof coatings	78.71	76.52	830.0	602.7	65.3	46.1
Floor coatings	265.62	235.57	950.0	333.8	252.4	78.7
Anticorrosive coatings	428.62	421.34	20.0	120.0	8.6	50.8
Fire-retardant coatings	293.14	289.70	70.0	222.5	20.5	64.5

3.4.3. Comparison

Several studies have reported VOC emissions of architectural decorations in China (Wei et al., 2008; Qiu et al., 2014; Wu et al., 2016, 2017; Zheng et al., 2017; Gao et al., 2019). However, most were established earlier (e.g., 2005 and 2010) without a breakdown of emissions from different architectural building materials, and using emission factors based on Chinese standard limits due to the lack of measured data. Therefore, we compared the VOC emission inventory for architectural coatings in this study with that developed by Gao et al. (2019), which was relatively refined and based on recent measured data for 2016. To make a clear comparison, we integrated emission factors and activity data with corresponding parameters based on coating consumptions. Table 5 compares the estimated VOC emissions, emission factors, and activity data of our study with those of Gao et al. (2019). Overall, the VOC emissions for architectural coatings in our study were slightly larger than those of Gao et al. (2019). Except for interior coatings, the VOC emissions of other coatings in both studies were quite different. These discrepancies were mainly due to the differences in activity data of coating consumption, since the emission factors of each coating in the two studies were similar. For exterior wall coatings, the discrepancy in consumption was caused mainly by the coating ratio of exterior walls:

Table 6
Uncertainties in activity data, emission factors, and emissions for architectural coatings and adhesives in China in 2017.

Coating and adhesive type		Activity data	Emission factor	Emission		
		CV	CV	Inventory (kt)	95% confidence interval (kt)	CV
Coatings	Interior wall	±30%	±80%	395.0	[147.2, 748.2]	[−63%, +86%]
	Exterior wall	±30%	±80%			
	Waterproof	±30%	±50%			
	Floor	±30%	±50%			
	Anticorrosive	±30%	±50%			
	Fire-retardant	±30%	±50%			
Adhesives	Solvent-based	±30%	±50%	219.0	[85.0, 391.6]	[−61%, +78%]
	Water-based	±30%	±50%			
	Bulk-based	±30%	±50%			
Total		–	–	614.0	[318.7, 1000.5]	[−49%, +61%]

43% for residential building and 10% for others in this work, compared with 64% in Gao et al. (2019). For other coatings, the consumption of each coating in Gao et al. (2019) was estimated based on historical data from industry, relevant research, and growth rates of architectural coatings, in which there is great uncertainty. In this work, the consumption of other coatings was obtained from the China Coatings Industry Association and evaluated by industry experts, which could better reflect the current status of industry production and consumption of architectural coatings.

3.4.4. *Uncertainties*

Generally, the uncertainty of VOC emission inventories is due mainly to insufficient representations and the lack of activity data and emission factors (Zhong et al., 2007; Qiu et al., 2014; Wu et al., 2016). In this study, Monte Carlo simulation was adopted to quantitatively assess the uncertainty of the VOC emission inventory for architectural coatings and adhesives in China in 2017. The activity data and emission factors were assumed to be normally distributed, and the mean and standard deviation of each source were subsequently determined. We assumed that the basic data of each source was the mean, and the standard deviation was estimated by combining the CVs.

The activity level of the building area was collected directly from the Statistical Yearbook of the Chinese Investment in Fixed Assets (2018). It can be classified as level I in the evaluation system for uncertainty in activity data developed by Wei et al. (2011) and had a minimum CV of ±30%. The VOC emission factor based on the area of completed buildings was a comprehensive coefficient. It was calculated by combining the consumption and VOC content from architectural materials. Consumption was calculated by formulas based on market investigation, and the VOC content was obtained based on a large number of analyzed samples, which were well representative of the average source level in China. Therefore, the uncertainty of emission factors was divided into level II (CV: ± 80%) and level I (CV: ± 50%) of the evaluation system coefficient for wall coatings and others, respectively.

The results of the Monte Carlo simulation are shown in Table 6. The uncertainty for the total emissions of architectural coatings and adhesives in China in 2017, based on the 95% confidence interval, was −49% to +61%.

As mentioned above, uncertainties are present in our emission inventory, but by using the authoritative activity data and the latest measured emission factors, this study potentially provides a reliable and reasonable inventory of VOC emissions for architectural coatings and adhesives in China in 2017.

4. Summary and conclusions

In this study, a VOC emission inventory of architectural coatings and adhesives for new buildings in China in 2017 was developed based on building area, using a new database established through a bottom-up activity level investigation and analysis of large number of samples.

The investigated coating ratios of exterior walls were 43% for residential buildings and 10% for other buildings, which differ greatly from the empirical value (60–64%). The VOC contents of solvent-based architectural materials are generally significantly higher than types of architectural materials, and VOC contents exceeding Chinese standard limits was relatively obvious in solvent-based architectural materials. The comprehensive emission factor of VOCs was 214.5 kg km^{-2}, of which 138.0 kg km^{-2} was from architectural coatings and 76.5 kg km^{-2} from architectural adhesives. Floor coatings and solvent-based adhesives had the highest VOC emission factors for architectural coatings and adhesives, respectively. In 2017, the total emission of VOCs from architectural coatings and adhesives in China was 614 kt, of which 395 kt came from architectural coatings and 219 kt from architectural adhesives. Floor coatings and solvent-based adhesives were the largest sources, accounting for 41.1% and 18.2% of the total VOC emissions, respectively. Shandong, Jiangsu, Zhejiang, Sichuan, and Guangdong were the five largest emitters, contributing 39.1% of the total VOC emissions.

Our study will promote the estimation of VOC emissions from architectural coatings and adhesives. Meanwhile, according to the emission factor and inventory in this study, floor coatings and solvent-based adhesives were the key contributors. We recommend strictly controlling market access and strengthening market supervision for architectural materials while gradually phasing out solvent-based coatings and adhesives.

CRediT authorship contribution statement

Xiaoming Liang: Conceptualization, Investigation, Writing - original draft, Methodology. **Xibo Sun:** Visualization, Validation. **Qing Lu:** Investigation. **Lu Ren:** Investigation. **Ming Liu:** Investigation. **Yanhua Su:** Investigation. **Shuo Wang:** Investigation. **Haitao Lu:** Investigation. **Bo Gao:** Investigation. **Wei Zhao:** Investigation. **Jiaren Sun:** Investigation. **Zhiqiang Gao:** Writing - review & editing. **Laiguo Chen:** Supervision, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This study was funded by the National Key Research and Development Program of China (No. 2017YFC0212606), the National Natural Science Foundation of China (Nos. 41773130, 41573123, 41773127), the Second National Survey on Pollution Sources, and Central Public-interest Scientific Institution Basal Research Fund of South China Institute of Environmental Sciences, MEE (No. PM-zx703-201903-037, PM-zx703-202002-018).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.atmosenv.2020.118014.

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