Science of the Total Environment 714 (2020) 136580

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Asbestos-containing materials in abandoned residential dwellings in Detroit

A. Franzblau [a], A.H. Demond [b], S.K. Sayler [a], H. D'Arcy [a], R.L. Neitzel [a,*]

[a] Department of Environmental Health Sciences, University of Michigan, 1415 Washington Heights, Ann Arbor, MI 48109-2029, United States of America
[b] Department of Civil and Environmental Engineering, University of Michigan, 1351 Beal Avenue, 120 EWRE, Ann Arbor, MI 48109, United States of America

HIGHLIGHTS

- The amount of asbestos in abandoned residential homes (ARDs) has not been characterized.
- We sampled a database of ARDs in Detroit to assess asbestos-containing material (ACM) and abatement costs.
- ACM was present in about 95% of the sampled ARDs.
- The majority of asbestos in the sampled ARDs was nonfriable chrysotile asbestos.
- Abatement accounted for about 20% of the total demolition cost of the sampled ARDs

GRAPHICAL ABSTRACT

ARTICLE INFO

Article history:
Received 18 October 2019
Received in revised form 3 January 2020
Accepted 6 January 2020
Available online 10 January 2020

Editor: Pavlos Kassomenos

Keywords:
Asbestos
Demolition
Health

ABSTRACT

Objective: The efforts of many municipalities to demolish abandoned residential dwellings (ARDs) are hampered by the presence of asbestos-containing materials (ACMs) in these structures. However, the extent of such materials is unknown. Our study sought to characterize ACMs present in ARDs demolished in Detroit.
Methods: Working with the City of Detroit, we obtained information on all ARDs demolished from 2014 to 2017. We randomly sampled 605 ARDs and analyzed the presence, type, and amount of ACM present, and the associated abatement and demolition costs.
Results: Asbestos was present in about 95% of the sampled ARDs. The most common types of ACMs were flooring, roofing, siding, and duct insulation. The material containing the greatest fraction of asbestos was duct insulation. The type of asbestos generally present was chrysotile. Only eight (1%) ARDs contained commercial amphibole asbestos; another 36 contained vermiculite. The total cost of demolition averaged $13,645 per home, of which 20.1% was asbestos abatement.
Conclusions: The majority of the ACM in the ARDs was nonfriable and consisted of chrysotile. This study contributes information about the nature and extent of ACM in ARDs, which can provide part of the foundation for making an assessment of possible asbestos-containing air emissions during the demolitions of ARDs, and the nature or extent of pre-demolition abatement that may be needed (if any) to protect the public's health.

Abbreviations: ACM, asbestos-containing material; ARD, abandoned residential dwelling; DBA, Detroit Building Authority; EPA, Environmental Protection Agency; NESHAP, National Emission Standards for Hazardous Air Pollutants; RACM, regulated asbestos-containing material.

* Corresponding author.
E-mail addresses: afranz@umich.edu (A. Franzblau), avery@umich.edu (A.H. Demond), sksayler@umich.edu (S.K. Sayler), hjsd@umich.edu (H. D'Arcy), rneitzel@umich.edu (R.L. Neitzel).

https://doi.org/10.1016/j.scitotenv.2020.136580
0048-9697/

1. Introduction

In 1950, the population in Detroit was 1.85 million, making the city the 5th most populous in the US (*Quick Facts: Detroit City, Michigan*, 2019). However, since that era, the city's population has declined by almost two-thirds, dropping to 673,000 in 2018 (MacDonald, 2016; *Quick Facts: Detroit City, Michigan*, 2019). Not surprisingly, this severe and rapid decline in population has resulted in a large number of abandoned residential dwellings (ARDs) in almost every neighborhood. As of February 2016, it was estimated that Detroit had almost 53,000 ARDs, which translated into the highest percentage (18.6%) of vacant residential dwellings of any city in the US (Abbey-Lambertz, 2016). Vacant, abandoned properties have been associated with a variety of urban problems, including fires, crime, and decreased property values (Accordino and Johnson, 2000; FEMA, 2015; Larson et al., 2019; Neavling, 2016). Additionally, ARDs are more common in low-income communities and communities of color, thus constituting an important environmental justice issue (Accordino and Johnson, 2000; Kotelchuck et al., 2006; Rauh et al., 2008). Many cities in the US (Farfel et al., 2003, 2005; Mucha et al., 2009), as well as in other countries (Advisor, 2015; Kakooei and Normohammadi, 2014), are engaged in demolition programs to remove ARDs (Accordino and Johnson, 2000; Keene and Ruel, 2013) as a means to resolve urban blight and revitalize city centers. From January 1, 2014 to July 3, 2019, the City of Detroit demolished 18,304 ARDs (Detroit Building Authority, 2019) at a cost of $310 million (City of Detroit, 2019).

The rapid removal of ARDs is complicated by the possible presence of asbestos. The primary diseases associated with exposure to asbestos are asbestosis, lung cancer and mesothelioma (EPA, 1986). However, asbestosis has generally been associated only with “higher levels of exposure commonly found in workplace settings and is not expected to contribute substantially to potential risks associated with environmental asbestos exposure” (EPA, 2003). Hence, lung cancer and mesothelioma are the most important risks associated with low levels of exposure to asbestos (EPA, 2003). And, while all forms of asbestos are capable of causing cancer, amphibole forms of asbestos have higher potency than chrysotile fibers, particularly in relation to mesothelioma (Berman and Crump, 2008; Garabrandt and Pastula, 2018; Hodgson and Darnton, 2000; Korchevskiy et al., 2019). For mesothelioma, the risk ratio for the most prevalent commercial fiber types has been estimated to be in the range of 1:100:500 for chrysotile, amosite and crocidolite, respectively (Hodgson and Darnton, 2000; Korchevskiy et al., 2019). For lung cancer, the risk differential between chrysotile and the two main commercial amphiboles (amosite and crocidolite) is between 1:10 and 1:50 (Hodgson and Darnton, 2000).

Asbestos was used in a variety of common construction materials, including duct and pipe insulation, cement, siding, flooring, roofing, and in sealants, caulks, and glazes, throughout the 20th century, until it was partially banned in the 1970s (Allen et al., 2018). Asbestos may also be present in vermiculite insulation. Although not all vermiculite contains asbestiform amphibole fibers, nearly 80% of the vermiculite used world-wide came from Libby, Montana, which contained a variety of asbestiform amphibole fibers, including winchite, richterite and tremolite (collectively labeled ‘Libby amphibole’) (Hilbert et al., 2013; Lockey et al., 2015). Consequently, in 2004, the EPA issued a statement: “the EPA is informing the public to consider all vermiculite insulation as asbestos-containing material” (EPA, 2004).

In the initial asbestos NESHAP (National Emission Standards for Hazardous Air Pollutants) (U.S. Environmental Protection Agency (EPA), 1973) ruling, building materials were divided into two types, friable and nonfriable, based on the likelihood of the release of asbestos fibers. Friable materials were materials containing >1% asbestos (as determined by Polarized Light Microscopy (PLM)) that could be crumbled by hand. In contrast, nonfriable materials were materials containing >1% asbestos that could not be similarly crumbled. Nonfriable materials can be further subdivided into Category I and Category II materials. Category I includes packing, gasket, floor covering and roofing products, whereas Category II includes asbestos cement piping. Regulated asbestos-containing material (RACM) is friable material or nonfriable material (both Category I and II) that has become friable, or that has been or will be subjected to forces that crumble or pulverize it in the course of demolition or renovation operations. While many construction materials may contain asbestos, many are not friable or likely to become friable during manipulation or demolition; for example, asbestos-containing floor tiles (Lange, 2002) and roofing materials (Sheehan et al., 2010) have not been shown to create elevated levels of airborne asbestos during abatement and scraping, respectively. In fact, the use of respirators is not required during the abatement of floor tile and mastic, as the exposures remain well below that specified by OSHA (Lange and Thomulka, 2000). Furthermore, studies of airborne-asbestos emissions during demolition of several partially-abated structures did not show a significant increase in airborne-asbestos concentrations (Perkins et al., 2007; Wilmoth et al., 1994).

The NESHAP regulations require that all RACM be removed prior to demolition of all buildings with an exemption for residential buildings of four or fewer dwelling units, based on a National Academy of Sciences study stating “…single-family residential structures contain only small amounts of asbestos…” (National Research Council, 1971). However, in 1990, the US Environmental Protection Agency (EPA) issued a statement in which it said that it “does not consider residential structures that are demolished or renovated as part of a commercial or public project to be exempt from this rule” (EPA, 1990). Hence, cities have been required to comply with the full asbestos inspection and abatement requirements of NESHAP as part of their ARD demolition program, despite EPA's determination that the NESHAP requirements apply to buildings at a single demolition site (U.S. Environmental Protection Agency (EPA), 1995).

Missing from this discussion is information on the types and prevalence of ACM in ARDs. We are not aware of any previous reports that describe features of ARDs that have been demolished, and the ACM associated with such structures. Using publicly available data, the present study examined the nature of ARDs demolished in Detroit from 2014 to 2017, seeking to describe key features of these structures. Knowing the extent and types of ACM present can help in making an assessment of the possibility of asbestos-containing air emissions during the demolitions of ARDs, and the nature and extent of pre-demolition abatement that may be needed to protect the public's health.

2. Methods

The City of Detroit maintains an on-line, downloadable, publicly available database of all demolitions completed since January 1, 2014, which is updated on a daily basis (Detroit Building Authority, 2019). In addition, the Detroit Building Authority (DBA) maintains records of pre-demolition inspection reports that describe the results of EPA-mandated asbestos inspections and testing for RACM in the ARDs. The pre-demolition inspection reports and publicly-accessible database include a variety of details about each ARD, such as: address, date of demolition, total cost of the demolition, date of construction of the house, square footage of the house, the cost of asbestos inspection and abatement, and a description of the type and quantity of ACM in each ARD. However, not every ARD in the demolition database has a completed pre-demolition inspection report, usually because such structures were too unsafe or hazardous for inspectors and/or abatement workers to enter the premises. Such hazardous ARDs are considered “emergency demolitions”, and represent about 10% of all demolitions listed in the database. The remaining ARDs in the database (about 90%) generally have a completed pre-demolition inspection report of RACM and are the focus of this investigation.

On February 14, 2017, the on-line demolition database was downloaded; on this date, there were 11,043 ARDs in the database. After removing the emergency demolitions, each of the remaining 9811 ARDs was assigned a random decimal value between 0 and 1.

Starting from 0, the ARDs with the lowest-assigned random numbers were selected for inclusion until a total of 605 ARDs were identified. We initially targeted a sample size of 600, but oversampled slightly to account for potential missing data in the selected ARDs. With the cooperation and assistance of the City, the pre-demolition inspection reports were downloaded or requested for each.

The Detroit Land Bank Authority (DLBA) contracts with accredited asbestos inspectors (State of Michigan, 1999), who visually inspect the inside and outside of the house to identify potential ACM, measure the approximate quantity of suspected ACM and take bulk samples of each type of material suspected of containing asbestos, and record all findings in a written report. Bulk samples are sent to a laboratory accredited by the National Voluntary Laboratory Accreditation Program (NVLAP) (National Institute of Standards and Technology, 2019) and analyzed using polarized light microscopy (PLM) to quantify the percent asbestos content, and to determine the type of asbestos (i.e., actinolite, amosite, anthophyllite, chrysotile, crocidolite, and/or tremolite asbestos) in accordance with NIOSH Method 9002 (National Institute for Occupational Safety and Health (NIOSH), 1994). The estimated limit of detection (LOD) for this method is 1% asbestos content of the bulk sample (National Institute for Occupational Safety and Health (NIOSH), 1994), as 1% is the minimum content necessary for a material to be designated as ACM. Pre-demolition inspection reports include the written summary of the inspector (with a listing of all suspected ACM), as well as the results of the analyses performed by the accredited laboratory. Pre-demolition abatement of ARDs involves removal of all RACM, identified on the basis of the inspection and laboratory confirmation of an asbestos content above 1% by PLM, by a licensed, certified, and registered asbestos abatement contractor, as required by the Occupational Safety and Health Administration (OSHA, 1994).

An exception to the above process involves vermiculite insulation. In 2004, the EPA noted that the PLM method "is not accurate and yields false negatives when used on vermiculite insulation" (EPA, 2004). Nevertheless, in the same memo the EPA stated that, if used correctly, the standard PLM method would "satisfy EPA's minimum requirement for the analysis of asbestos in vermiculite loose fill insulation." This assertion that PLM is not an accurate means of determining whether vermiculite is ACM, with the simultaneous endorsement of continued use of the PLM as the measurement method, was adopted as policy by the Michigan Department of Environmental Quality (MDEQ) in a memo addressed to asbestos inspectors (MDEQ, 2017). Hence, when vermiculite insulation was visually identified by inspectors working on behalf of the City of Detroit, some took samples for analysis (though none were actually analyzed by the labs), while others did not, simply assuming the vermiculite to be ACM.

From the on-line database and from the pre-demolition inspection reports, we abstracted data describing various features of ARDs that were demolished in the City of Detroit between January 1, 2014, and February 14, 2017, focusing on the types and quantity of major categories of ACM. To avoid the possibility of differential error in our abstraction process, all data abstractors were trained on the identification and the recording of information about ACM in the reports. We used scatterplots and histograms to examine trends and determine potential outliers. Pearson correlation coefficients were used to evaluate the associations between abatement, demolition, and total (i.e., abatement plus

Table 1
Characteristics of 605 abandoned residential dwellings in Detroit demolished after asbestos abatement.

Variable	Category	N (%)	Mean (SD) [range]
Number of floors	Single story	188 (31%)	–
	Two stories	417 (69%)	
Total square footage	<1000 sq ft	233 (39%)	1270 (732)
	1000 to 1499 sq ft	231 (38%)	[404–11,800]
	1500 to 1999 sq ft	71 (12%)	
	≥2000 sq ft	70 (12%)	
Year built	1885–1914	92 (15%)	1929 (15)
	1915–1919	75 (12%)	[1885–1974]
	1920–1924	127 (21%)	
	1925 or later	311 (51%)	
Occupied home to right?	Yes	74 (12%)	–
	No	207 (34%)	
	Unknown	324 (54%)	
Occupied home to left?	Yes	81 (13%)	–
	No	206 (34%)	
	Unknown	318 (53%)	
Limited access to areas/materials?	Yes	177 (31%)	–
	No	398 (69%)	
Asbestos present	Yes	566 (94%)[a]	–
	No	30 (5%)	
	No report in records	9 (1%)	
Amphibole asbestos present	Yes	8 (1%)	–
	No	587 (97%)	
	Missing	10 (2%)	
Vermiculite noted	Yes	36 (6%)	–
	No	569 (94%)	
Abatement cost	<$800	175 (29%)	$2740 ($3441)
	$800–$3000	196 (32%)	[$0–$18,400]
	>$3000	140 (23%)	
	Unknown	94 (16%)	
Demolition cost	<$9000	171 (28%)	$10,927 ($3418)
	$9000–$12,000	165 (27%)	[$3550–$30,030]
	>$12,000	175 (29%)	
	Unknown	94 (16%)	
Total cost	<$11,000	188 (31%)	$13,645 ($4758)
	$11,000–$15,000	212 (35%)	[$4722–$39,700]
	>$15,000	167 (28%)	
	Unknown	38 (6%)	

[a] One home contained vermiculite which was not analyzed, but was assumed to contain asbestos; otherwise, this home was free of ACM.

Table 2
Amount and type of asbestos containing materials found in 605 abandoned residential dwellings in Detroit.

Material type	Homes containing material N (%)	Amount among homes containing the material			Amount among all 605 homes		
		Mean (SD)	Median	Range [min, max]	Mean (SD)	Median	Range [min, max]
Flooring (sq ft)	310 (51%)	436 (621)	211	[4, 6600]	221 (493)	10	[0, 6600]
Roofing (sq ft)	291 (48%)	1350 (824)	1355	[3, 5000]	653 (890)	0	[0, 5000]
Siding (sq ft)	204 (34%)	2093 (1517)	1800	[1, 10,500]	610 (1244)	0	[0, 10,500]
Other[a] (sq or linear ft)	200 (33%)	–			–		
Duct insulation (sq ft)	192 (32%)	78 (167)	30	[1, 1650]	24 (99)	0	[0, 1650]
Window glaze (sq ft)	181 (30%)	270 (1092)	120	[1, 570]	19 (73)	0	[0, 570]
Caulk (linear ft)	171 (28%)	362 (276)	310	[25, 1700]	57 (171)	0	[0, 1700]
Cement (sq ft)	136 (22%)	4.1 (2.5)	4.0	[1, 10]		0	
Sealant (linear ft)	135 (22%)	210 (189)	200	[2, 1000]	34 (109)	0	[0, 1000]
Pipe insulation (sq ft)	115 (19%)	262 (339)	125	[1, 2000]	41 (162)	0	[0, 2000]
Plaster (sq ft)	91 (15%)	4398 (2432)	4400	[10, 11,300]	521 (1647)	0	[0, 11,300]

[a] "Other" category contains heat shield (n = 34), penetration mud (n = 28), millboard (n = 18), drywall joint compound (n = 17), wallboard system (n = 15), glue pods (n = 14), chimney wrap or mortar (n = 13), mastic (n = 12), construction adhesive (n = 11), vermiculite insulation (n = 36), and other miscellaneous materials.

demolition) costs by type of ACM-containing material. All analyses were conducted in SPSS version 25 (SPSS Inc., Chicago, IL) and SAS version 9.4 (SAS Institute Inc., Cary, NC).

3. Results

Based on the 605 ARDs examined in this study, the typical ARD in Detroit was a single-family house consisting of two stories, with almost 90% comprising <2000 square feet (Table 1). The year of construction ranged from 1885 to 1974, with the mean being 1929. Whether there was an occupied dwelling adjacent to the ARD was not recorded in over 50% of the cases. Where such information was recorded, over half of ARDs (51%) were not adjacent to an occupied dwelling on either side, while a third (34%) were adjacent to only one occupied dwelling. Information about the presence of asbestos was missing for only 9 of the 605 ARDs, or 1.5% of the sample in this study. Asbestos was documented to be present in 95% of the ARDs, with the vast bulk of asbestos consisting of chrysotile; commercial amphibole was found in only 8, or 1%. In addition, vermiculite was found in 36 ARDs, or 6%. The estimated or bid cost for the demolition of these ARDs ranged from about $3500 to $30,000, with the mean just under $11,000. The mean abatement cost was $2740 (Table 1), and the mean total cost, including abatement and demolition, was $13,645, with a range of $4722 to $39,700.

The ten most prevalent types of ACM found in these ARDs are summarized in Table 2, including flooring (51% of homes), roofing (48%), siding (34%), and duct insulation (32%). In addition to these ACMs, 200 of the ARDs contained other ACM including: mastic or glue; chimney mortar; drywall/joint compound or tape; textured ceiling; unspecified debris; heat shield; stair tread; chimney wrap; and stucco. Each of these other forms of ACM was found in <6% of ARDs. The total amount of each of the major types of ACM found in homes varied considerably, with many homes containing multiple types of ACM. For example, the mean square footage of asbestos-containing plaster in homes found to have this material (n = 95) was nearly 4400 square feet, while the mean square footage in homes found to have asbestos-containing cement (n = 106) was only 4.1 square feet. When all homes were considered, mean and median amounts were lower by a factor of 2–5, depending on the specific ACM considered (Table 2).

Chrysotile was found in the vast majority of samples; a summary of the percent chrysotile content of the major types of ACM found in the ARDs is shown in Table 3. The mean percent chrysotile content varied considerably, from to 54.9% (duct insulation) to 1.6% (plaster), with a similar, though not identical, pattern for the medians. The characteristics of the eight ARDs found to have commercial (i.e., amosite or crocidolite) amphibole asbestos are given in Table 4. The range of year of construction was 1924–1969, with 1937 as the mean. Each ARD with commercial amphibole had only one type of ACM that contained such amphibole, with the content ranging from 2% to 40%. Generally, the amphibole was only amosite; in one case both amosite and crocidolite were identified. In four of the five cases in which the location was described, the ACM was located in the basement, and the amount was relatively small (up to 23 square feet). The exception was one ARD that had 1400 square feet of exterior transite siding containing 2% amosite.

Table 5 shows the characteristics of the 36 ARDs found to contain vermiculite. These ARDs were slightly smaller and older than the overall sample, and more likely to be single story. Of these 36 homes, 28 had reports which noted, "roof system and vermiculite insulation material not sampled," while another eight reports stated that the vermiculite was sampled. For these eight homes, the labs did not actually test for asbestos, but simply noted, "Assumed." Abatement costs in the homes with vermiculite were slightly lower than the overall sample, while total demolition costs were slightly higher.

Table 3
Percent chrysotile content in samples collected from 605 abated abandoned residential dwellings in Detroit, by type of material.

Material type	Number of samples containing chrysotile	Mean (SD)	Median	Range [min, max]
Duct insulation	195	54.9% (18.5)	65%	[(4, 98)]
Pipe insulation	146	49.1% (21.0)	55%	[(1.25, 95)]
Siding	158	19.0% (9.3)	20%	[(0, 43)]
Cement	104	15.8% (18.5)	9%	[(1.5, 75)]
Flooring	530	9.9% (11.1)	5%	[(0, 75)]
Roofing	60	9.0% (3.8)	10%	[(0, 20)]
Sealant	181	6.1% (3.7)	5%	[(0, 20)]
Caulk	205	6.0% (4.5)	5%	[(0, 25)]
Window glaze	212	2.7% (2.0)	2%	[(0, 15)]
Plaster	94	1.6% (1.2)	2%	[(0, 6.25)]
Other[a]	252	25.9% (27.5)	10%	[(0, 98)]

[a] "Other" category contains heat shield, penetration mud, millboard, drywall joint compound, wallboard system, glue pods, chimney wrap or mortar, mastic, construction adhesive, vermiculite insulation, and other miscellaneous materials.

Table 4
Characteristics of eight abandoned residential dwellings found to contain amphibole asbestos.

House	Multi-story?	Year built	Total sq ft	Type of ACM	Location in house	Amount of ACM	Asbestos content
1	Yes	1950	1250	Transite siding	Exterior	1400 sq ft	18% chrysotile 2% amosite
2	Yes	1924	1800	Pipe joint insulation		23 sq ft[a]	20% chrysotile 5% amosite 10% crocidolite
3	Yes	1939	1800	Penetration mud	Basement; vent covers	20 sq ft	5% chrysotile 40% amosite
4	No	1938	901	Heat shield		10 sq ft	5% chrysotile 15% amosite
5	Yes	1941	1000	Millboard	Basement at vents	8 sq ft	8% chrysotile 12% amosite
6	Yes	1969	1000	Stack cement		6 sq ft	15% chrysotile 5% amosite
7	Yes	1926	2278	Cement patch	Basement	2 sq ft	60% chrysotile 5% amosite
8	No	1912	966	Cement patch	Basement	1 sq ft	10% chrysotile 10% amosite

[a] Report indicates “metric ft”, but value assumed to be square ft.

Fig. 1 shows the relationship between total cost and abatement cost (1a), and between abatement cost and square footage (1b), for the 605 ARDs in the sample. There was a positive correlation between total cost and abatement cost (Fig. 1a, $r = 0.71$, $p < 0.001$); however, only a marginal association was observed between abatement cost and total square footage (Fig. 1b) ($r = 0.09$, $p = 0.054$). We also examined the associations between age of ARD and total cost, and between age of ARD and abatement cost (data not shown). Correlation coefficients for both associations were negative (approximately −0.09) and marginally significant ($p = 0.03$–0.04). Table 6 provides a summary of Pearson correlations of the total amount of ACM by type, with abatement costs and with total costs. Four types of ACM, flooring, siding, plaster and the “other” category, were each significantly correlated with abatement costs and the total cost of the removal of the ARD. In addition, asbestos-containing roofing was significantly correlated with total cost, but not abatement cost.

4. Discussion

To our knowledge, this is the first study to document the nature and extent of ACM in ARDs in any city in the US. Based on the large sample of 605 ARDs in Detroit that we analyzed, one or more types of ACM (and usually multiple types of ACM) were present in 95% of demolished ARDs. The materials most often found to contain asbestos included flooring and roofing – both of which were the ACM in approximately one-half of the sampled ARDs – as well as siding and duct insulation, which were both found in approximately one-third of the ARDs. The material containing the greatest fraction of chrysotile asbestos was duct insulation. In almost 99% of ARDs in which asbestos was found to be present, the asbestos consisted of chrysotile. Commercial amphibole-containing material was found in only eight ARDs. For these occurrences, there was no clear pattern in terms of age of dwelling or type of material; however, the amount of material was small, with the basement being the prevalent location. Vermiculite was identified in another 36 ARDs (6%), but the amount of vermiculite present was not characterized.

Our finding that the vast majority (99%) of the 605 sampled ARDs did not contain commercial amphiboles, but rather the substantially less-hazardous chrysotile, reduces potential public health risk associated with ARD demolition. Disease risk for chrysotile in relation to mesothelioma and lung cancer is much lower than for commercial amphibole forms of asbestos. Vermiculite was noted to be present in another 6% of ARDs. In each of these ARDs, the vermiculite was presumed to contain asbestos. This suggests that amphibole material

Table 5
Characteristics of 36 abandoned residential dwellings in Detroit found to contain vermiculite.

Variable	Category	N (%)	Mean (SD) [range]
Number of floors	Single story	9 (25%)	–
	Two stories	27 (75%)	
Total square footage	<1000 sq ft	16 (44%)	1215 (489)
	1000 to 1499 sq ft	9 (25%)	[404–2326]
	1500 to 1999 sq ft	7 (19%)	
	≥2000 sq ft	4 (11%)	
Year built	1885–1914	5 (14%)	1924 (12)
	1915–1919	3 (8%)	[1900–1951]
	1920–1924	12 (33%)	
	1925 or later	16 (44%)	
Abatement cost	<$800	12 (33%)	$2543 ($2779)
	$800–$3000	8 (22%)	[$300–$11,000]
	>$3000	10 (28%)	
	Unknown	6 (17%)	
Demolition cost	<$9000	9 (25%)	$11,209 ($3261)
	$9000–$12,000	10 (28%)	[$6503–$21,545]
	>$12,000	11 (31%)	
	Unknown	6 (17%)	
Total cost	<$11,000	6 (17%)	$14,261 ($4022)
	$11,000–$15,000	15 (42%)	[$7642–$22,925]
	>$15,000	14 (39%)	
	Unknown	1 (3%)	

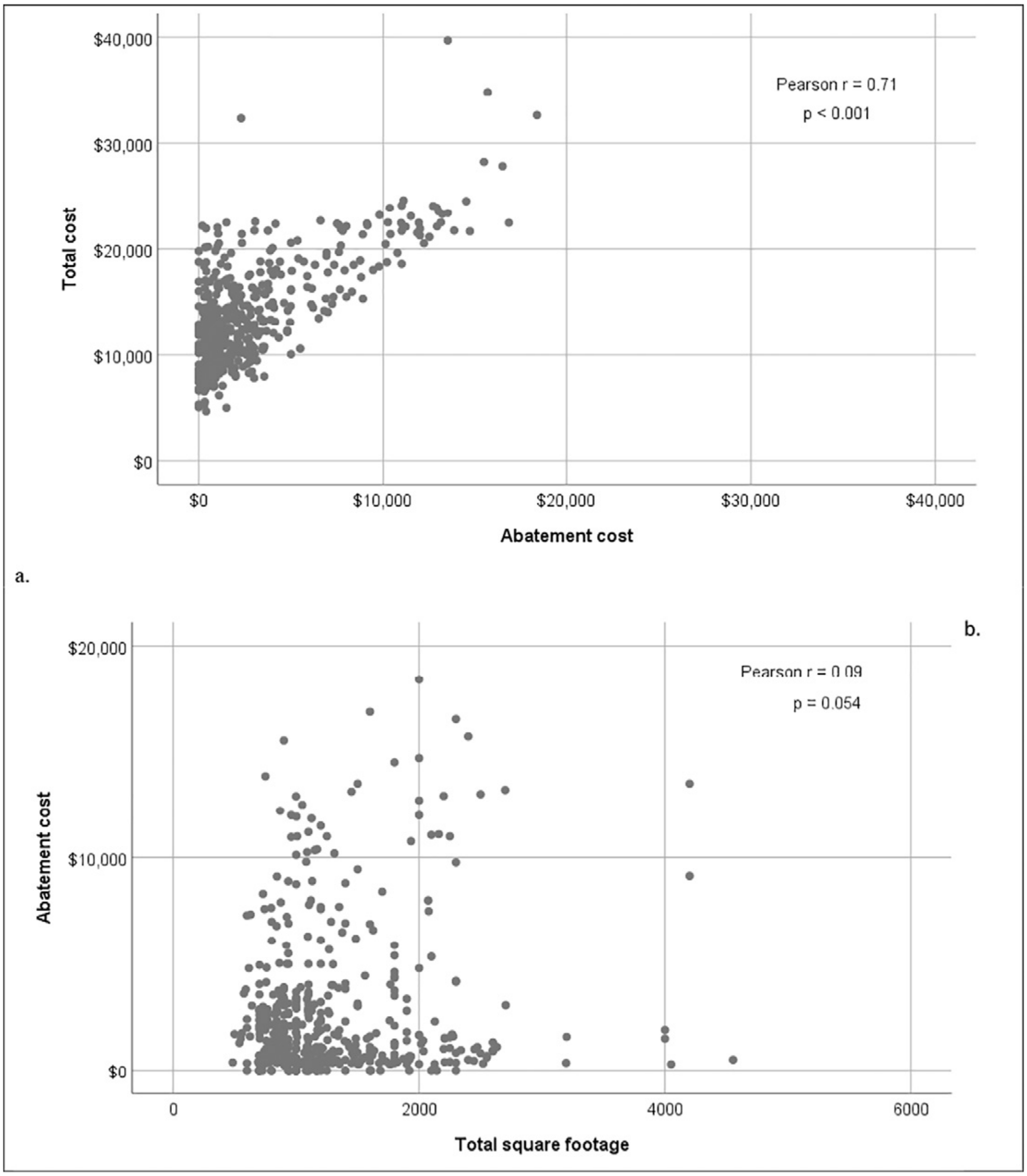

Fig. 1. Relationship between a) total cost and abatement cost and b) abatement cost and square footage of 605 abandoned residential dwellings. [1]One observation at nearly 12,000 sq ft and nearly $0 abatement cost has been omitted for better visibility of the majority of the data, but is included in the correlation coefficient.

(i.e., commercial amphibole and/or Libby amphibole) is present in about 7% of ARDs in Detroit (assuming that, if tested, all of the vermiculite in ARDs actually contained amphibole asbestos and/or asbestiform amphiboles).

ARD removal costs, either abatement and/or total, were positively correlated with the predominant categories of ACM materials, flooring (both abatement and total costs), siding (both abatement and total costs), roofing (total costs), other (both abatement and total costs). Many of these materials are considered to be Category I nonfriable, for example, flooring tiles, siding and roofing. The only additional category that shows a positive correlation with cost is asbestos- containing plaster, which occurs in 15% of the homes. If such plaster is present, the amount tends to be large, with a mean value of 4398 square feet. Asbestos-containing plaster may be a Category II ACM meaning that it may contain >1% asbestos and may become friable if deteriorated.

The costs associated with abating asbestos in ARDs are not trivial. The cost of asbestos inspections and abatement among the 605 sampled ARDs was $2740 on average, or 20.1% of the $13,645 average total cost to remove an ARD. If this percentage holds true for all ARDs in Detroit that have been demolished after asbestos abatement (roughly 90% of the total), the cost of abatement would be roughly $56 million.

While the sample size of 605 demolished ARDs is relatively large, and was from among >10,000 ARDs removed in Detroit over a three-year period, it is nevertheless possible that these results are biased in some way. We believe this to be unlikely, as the homes included in our analysis were randomly sampled, were located throughout the City of Detroit, and represent a wide range of construction dates, building styles, and quality of construction. Asbestos samples from the 605 homes we examined were collected by inspectors from different companies and analyzed by a number of different laboratories. Consequently, the reports summarizing the ACM inspections were characterized by different formats, styles, and ordering and presentation of ACM-related findings. While these differences could introduce bias into our findings, the fact that all inspectors were licensed and

Table 6
Pearson correlations of total ACM material amount in 605 abandoned residential dwellings, by ACM type, with abatement and total costs.

ACM type	Abatement cost	Total cost
Flooring	0.18**	0.28***
Pipe insulation	0.04	0.11
Siding	0.38***	0.24**
Caulk	0.16	0.16
Cement	−0.18	0.12
Sealant	0.24*	0.16
Duct insulation	0.00	0.05
Plaster	0.62***	0.52***
Roofing	0.05	0.21***
Window glaze	−0.04	0.09
Other[a]	0.50***	0.38***

* $p < 0.05$.
** $p < 0.01$.
*** $p < 0.001$.
[a] "Other" category contains heat shield, penetration mud, millboard, drywall joint compound, wallboard system, glue pods, chimney wrap or mortar, mastic, construction adhesive, vermiculite insulation, and other miscellaneous materials.

trained in a consistent manner, and that the labs were all externally accredited, we believe any errors introduced by the different inspectors and laboratories would be random and most likely bias our results towards the null. Finally, it is possible that vermiculite was more prevalent than was noted in the ARD inspection reports. Some inspectors may not have recorded vermiculite systematically (though we have no evidence to suggest this), which would introduce bias into our estimates of the presence of vermiculite and the associated potential for ACM. The guidelines for inspection do call for recording the presence of vermiculite, so we believe this to be a relatively low likelihood.

5. Conclusions

Our study appears to be the first to summarize the characteristics of abandoned residential dwellings targeted in a large-scale urban demolition effort. Our results indicate that asbestos is likely present in about 95% of ARDs in the City of Detroit. A similar fraction of ARDs in other US cities that experienced substantial growth and development in the late 19th to mid 20th century may contain asbestos. The predominant form of asbestos was chrysotile asbestos and, in fact, it was the only type of asbestos present in over 92% of the sampled homes (again, assuming that, if tested, all of the vermiculite in ARDs actually contained amphibole asbestos and/or asbestiform amphiboles). This form of asbestos is much less potent than amphiboles in inducing lung cancer or mesothelioma, the health outcomes of primary concern (Berman and Crump, 2008; Garabrandt and Pastula, 2018; Hodgson and Darnton, 2000; Korchevskiy et al., 2019). Previous research has shown a low probability of elevated exposures to asbestos after abatement and scraping of nonfriable materials such as asbestos-containing floor tiles (Lange, 2002) and roofing materials (Sheehan et al., 2010). Our study showed that the majority of the potentially friable asbestos was inside the home, with the few commercial amphibole ACMs located in the basement. Furthermore, the homes are collapsed inward, and usually sprayed with water during demolition, reducing the possibility of asbestos airborne emissions. Published measurements of airborne asbestos emissions during the demolition of partially-abated commercial or non-residential structures showed minimal increases above background (Perkins et al., 2007; Wilmoth et al., 1994). However, there have been no studies to assess asbestos emissions during demolition of ARDs. To provide more conclusive evidence about the nature and extent of asbestos emissions during demolition of ARDs, it would be critical to make air measurements during the process. This study contributes information about the nature and extent of ACM in ARDs, which can provide part of the foundation for making an assessment of possible asbestos-containing air emissions during the demolitions of ARDs, and the nature or extent of pre-demolition abatement that may be needed (if any) to protect the public's health.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Dr. Franzblau has served as an expert witness in asbestos-related litigation.

None of the other authors have any financial interests/personal relationships which may be considered as potential competing interests.

Acknowledgements

The authors wish to acknowledge Brian Farkas of the Detroit Land Bank Authority (DLBA) for his assistance and support. Additionally, we wish to thank the following individuals for their assistance with data collection and entry: Xenia Chan, Katherine Galen, Emily Nash, Michael Sacchetti, and Taylor Tarpey. This study was supported by a pilot grant from the University of Michigan Center on Lifestage Environmental Exposures and Disease, funded by grant P30ES017885 from the National Institute of Environmental Health Sciences, National Institutes of Health. The DLBA provided assistance in accessing data, but the DLBA provided no funding. Neither the NIH nor the DLBA had any role in the study design, data analyses or interpretation, manuscript preparation, conclusions, or the decision to submit the manuscript for publication. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health or the DLBA.

References

Abbey-Lambertz, K., 2016. These are the American cities with the most abandoned houses. Retrieved January 30, 2019, from Huffington Post website. https://www.huffingtonpost.com/entry/cities-with-most-abandoned-houses-flint_us_56be4e9ae4b0c3c5505171e7.
Accordino, J., Johnson, G.T., 2000. Addressing the vacant and abandoned property problem. J. Urban Aff. https://doi.org/10.1111/0735-2166.00058.
Advisor, R. S. of N. Z. and O. of the P. M. C. S, 2015. Asbestos Exposure in New Zealand: Review of the Scientific Evidence of Non-occupational Risks. A Report on Behalf of the Royal Society of New Zealand and the Office of the Prime Minister's Chief Science Advisor. Auckland, NZ.
Allen, L.P., Baez, J., Stern, M.E.C., Takahashi, K., George, F., 2018. Trends and the economic effect of asbestos bans and decline in asbestos consumption and production worldwide. Int. J. Environ. Res. Public Health https://doi.org/10.3390/ijerph15030531.
Berman, D.W., Crump, K.S., 2008. Update of potency factors for asbestos-related lung cancer and mesothelioma. Crit. Rev. Toxicol. 38 (Suppl. 1), 1–47. https://doi.org/10.1080/10408440802276167 September.
City of Detroit, 2019. Demolition Price by Month.
Detroit Building Authority, C. of D, 2019. City of Detroit demolitions data lens. Retrieved January 30, 2019, from. https://data.detroitmi.gov/Government/Demolitions-Data-Lens/xhif-khyv.
EPA, 1986. Airborne Asbestos Health Assessment Update (Report 600/8-84-003F. Washington, D.C).
EPA, 1990. National emission standards for hazardous air pollutants; asbestos NESHAP revision. Fed. Regist. 55 (224) (48496–48433).
EPA, 2003. Final Draft: Technical Support Document for a Protocol to Assess Asbestos-related Risk (Washington, D.C.).
EPA, 2004. PLM and Point Count Methods for Vermiculite Insulation (Report by Martin Hestmark, April 1, 2004).
Farfel, M.R., Orlova, A.O., Lees, P.S.J., Rohde, C., Ashley, P.J., Chisolm, J.J., 2003. A study of urban housing demolitions as sources of lead in ambient dust: demolition practices and exterior dust fall. Environ. Health Perspect. 111 (9), 1228–1234. https://doi.org/10.1289/ehp.5861.
Farfel, M.R., Orlova, A.O., Lees, P.S.J., Rohde, C., Ashley, P.J., Julian Chisolm, J., 2005. A study of urban housing demolition as a source of lead in ambient dust on sidewalks, streets, and alleys. Environ. Res. 99 (2), 204–213. https://doi.org/10.1016/j.envres.2004.10.005.
FEMA, 2015. Vacant residential building fires (2010–2012). Top. Fire Rep. Ser. 15 (11), 1–11.
Garabrandt, D., Pastula, S., 2018. A comparison of asbestos fiber potency and elongate mineral particle (EMP) potency for mesothelioma in humans. Toxicol. Appl. Pharmacol. 15 (361), 127–136.
Hilbert, T., Franzblau, A., Dunning, K., Borton, E., Rohs, A., Lockey, J., 2013. Asbestos-related radiographic findings among household contacts of workers exposed to Libby vermiculite. J. Occup. Environ. Med. 55 (11), 1300–1304.

Hodgson, J.T., Darnton, A., 2000. The quantitative risks of mesothelioma and lung cancer in relation to asbestos exposure. Ann. Occup. Hyg. 44 (8), 565–601. https://doi.org/10.1093/annhyg/44.8.565.
Kakooei, H., Normohammadi, M., 2014. Asbestos exposure among construction workers during demolition of old houses in Tehran, Iran. Ind. Health 52 (1), 71–77. https://doi.org/10.2486/indhealth.2012-0118.
Keene, D.E., Ruel, E., 2013. "Everyone called me grandma": public housing demolition and relocation among older adults in Atlanta. Cities 35, 359–364. https://doi.org/10.1016/j.cities.2012.10.011.
Korchevskiy, A., Rasmuson, J.O., Rasmuson, E.J., 2019. Empirical model of mesothelioma potency factors for different mineral fibers based on their chemical composition and dimensionality. Inhal. Toxicol. https://doi.org/10.1080/08958378.2019.1640320.
Kotelchuck, D., Queen, D., Bullard, R.D., 2006. Unequal protection: environmental justice and communities of color. J. Public Health Policy https://doi.org/10.2307/3342865.
Lange, J., 2002. Impact of asbestos concentrations in floor tiles on exposure during removal. Int. J. Environ. Health Res. https://doi.org/10.1080/0960312021000056401.
Lange, J., Thomulka, K., 2000. An evaluation of personal airborne asbestos exposure measurements during abatement of dry wall and floor tile/mastic. Int. J. Environ. Health Res. 10, 5–19.
Larson, M., Xu, Y., Ouellet, L., Klahm, C.F., 2019. Exploring the impact of 9398 demolitions on neighborhood-level crime in Detroit, Michigan. J. Crim. Just. https://doi.org/10.1016/j.jcrimjus.2018.11.002.
Lockey, J., Dunning, K., Hilbert, T., Borton, E., Levin, L., Rice, C., ... GK, L., 2015. HRCT/CT and Associated Spirometric Effects of Low Libby Amphibole Asbestos Exposure. J Occup Environ Med 57 (1), 6–13.
MacDonald, C., 2016. Detroit Population Rank Is Lowest Since 1850.
MDEQ, 2017. Vermiculite. Memorandum to Inspectors.
Mucha, A.P., Stites, N., Evens, A., MacRoy, P.M., Persky, V.W., Jacobs, D.E., 2009. Lead dustfall from demolition of scattered site family housing: developing a sampling methodology. Environ. Res. 109 (2), 143–148. https://doi.org/10.1016/j.envres.2008.10.010.
National Institute for Occupational Safety and Health (NIOSH), 1994. Method 9002: asbestos (bulk) by PLM. In NIOSH Manual of Analytical Methods (NMAM). 4th ed. Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, Cincinnati, OH.
National Institute of Standards and Technology, 2019. National Voluntary Laboratory Accreditation Program (NVLAP) (Washington, DC).
National Research Council, 1971. Biologic Effects of Atmospheric Pollutants: Asbestos - The Need for and Feasibility of Air Pollution Controls (Washington DC).
Neavling, S., 2016. How 10,000+ fires devoured Detroit neighborhoods over the past 3 years. Retrieved January 30, 2019, from Motor City Muckraker website. http://motorcitymuckraker.com/2016/03/17/how10000firesdevoureddetroitneighborhoodsoverthepast3years/ (March 3).
OSHA, 1994. Safety and health regulations for construction, 1926.1101 occupational exposure to asbestos. Fed. Regist. 59, 40964–41162.
Perkins, R., Hargesheimer, J., Fourie, W., 2007. Asbestos release from whole-building demolition of buildings with asbestos-containing material. J. Occup. Environ. Hyg. 4 (768371016), 889–894. https://doi.org/10.1080/15459620701691023.
Quick Facts: Detroit City, Michigan (Washington, D.C.).
Rauh, V.A., Landrigan, P.J., Claudio, L., 2008. Housing and health: intersection of poverty and environmental exposures. Ann. N. Y. Acad. Sci. https://doi.org/10.1196/annals.1425.032.
Sheehan, P., Mowat, F., Weidling, R., Floyd, M., 2010. Simulation tests to assess occupational exposure to airborne asbestos from artificially weathered asphalt-based roofing products. Ann. Occup. Hyg. https://doi.org/10.1093/annhyg/meq058.
State of Michigan, Department of Licensing and Regulatory Affairs, 1999. Asbestos accreditation. Retrieved July 2, 2019, from Michigan Occupational Safety and Health Administration Asbestos Program website. https://www.michigan.gov/lara/0,4601,7-154-89334_11407_15333_15369-36200–,00.html.
U.S. Environmental Protection Agency (EPA), 1973. Part 61 - national emission standards for hazardous air pollutants: asbestos, beryllium, and mercury. Fed. Regist. 38 (66), 8820.
U.S. Environmental Protection Agency (EPA), 1995. Asbestos NESHAP clarification of intent. Fed. Regist. 60 (145), 38725.
Wilmoth, R.C., Taylor, M.S., Meyer, B.E., 1994. Asbestos release from the demolition of two schools in Fairbanks, Alaska. Appl. Occup. Environ. Hyg. 9 (6), 409–417.