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# The concentration and prevalence of asbestos fibres in Christchurch, New Zealand's drinking water supply

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## ABSTRACT

Asbestos cement was a common construction material for water pipes during the twentieth century, as a replacement for metal piping that was vulnerable to corrosion. We report on the presence of asbestos fibres in drinking water supply in Christchurch, New Zealand from ageing asbestos cement reticulated water supply. By sampling the mains water supply via hydrants, 19 of our 20 samples showed long asbestos fibres ($>10$ μm), with an average concentration 0.9 million fibres per litre (MFL). Short asbestos fibres ($>0.5$ μm) had an average concentration of 6.2 MFL. Sampling was targeted to pipes from 1930 to the 1960s and there was abundant evidence of fibres being released from pipes of this age. Municipalities cannot continue to rely on ageing asbestos-cement piping, as it appears to be releasing asbestos fibres into drinking water with uncertain health implications, and should prioritise replacing pipes greater than 50 years in age, especially where high water pressures or land disturbance occur, to reduce the risk of water-carried asbestos being released into urban environments, and mitigate any risk of asbestos from ingested contaminated water sources.

**Key words:** asbestos, asbestos cement, drinking water, piped network

## HIGHLIGHTS

- Municipalities should monitor for the presence of asbestos fibres as a strategy for detecting pipe corrosion.
- Asbestos cement piping is reaching its end-of-life stage and is releasing short and long asbestos fibres into the water supply.
- Municipalities with soft water supply are vulnerable to cement pipe decay and we observed high corrosion rates of 0.20 mm $a^{-1}$ averaged over a lifetime from asbestos pipes.

## GRAPHICAL ABSTRACT

## INTRODUCTION

Potable water piped networks installed from the 1930s to the 1980s were comprised of asbestos cement composites and significant lengths of these pipes remain in use (Brandt *et al.* 2017). Asbestos is a naturally occurring silicate with ultrafine fibrils, which, when bound together, substantially increase tensile strength, and are highly efficacious against thermal and chemical breakdown (Sporn 2013). Typical compositions of asbestos cement contain between 10 and 20 wt% of asbestos, principally chrysotile and crocidolite due to their high strength and chemical inertness (Benarde 2018; Kelly & Zweben 2000). Its utility

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in water mains, however, began to decline in favour of more flexible modern plastics at least in part due to health perceptions surrounding asbestos fibres in construction materials (Twort *et al.* 2001).

Despite global restrictions on the use of asbestos and its associated health concerns, approximately 20% of the piped network in the UK and 15% in the USA persist as the original asbestos cement (Brandt *et al.* 2017; Barton *et al.* 2019). In a review of the causal mechanisms for pipe failure in the UK, Barton *et al.* (2019) identified that the peak age for asbestos cement pipe failure is those installed approximately 60 to 80 years ago. Environmental ground factors further influence the rate of pipe breakage, principally land movement associated with intense summer drying or frost heave, where the brittle and rigid nature of asbestos cement causes joint failure or circumferential fractures (Mordak & Wheeler 1988; Wols & van Thienen 2014; Barton *et al.* 2019). Degradation of the asbestos cement mortar occurs in chemically aggressive water, causing binding failure and release of asbestos fibres (Gong *et al.* 2016; Punurai & Davis 2017). Such chemical degradation is not apparent without physically inspecting the pipe, but is a known factor in reducing the lifespan of cement piping when conveying water with an aggressive index $<10$ (AWWA 1998). It is well established, for example, that the processes of conveying very soft water (pH $>7$, and hardness $<10$ mg $L^{-1}$ of $CaCO_3$) leads to accelerated pipe corrosion due to a lack of calcium carbonate precipitate that forms an interior pipe scaling (Al-Adeeb & Matti 1984).

The outer skin of the pipe is also vulnerable to decay especially in conditions of high groundwater tables where sulfate attack may occur in acidic and low iron environments (Hu *et al.* 2013). Moreover, the degradation of asbestos cement pipes is chemically complex, and cannot be discerned from age alone (Zavanšnik *et al.* 2021). Chlorination of water, for example, can exacerbate the potential for pipe corrosion, but conditions conducive to scaling can be protective, so the only effective method for determining the potential rate of asbestos fibre release into the piped network is via direct pipe inspection (Zavanšnik *et al.* 2021). Thus, a confluence of conditions cause asbestos pipe deterioration – the age of the pipe, the manufacturing standards of the time and manufacturing defects, the chemical corrosivity from conveying soft water, fluctuating groundwater tables in acidic soil conditions, or the propensity for pipe bending through ground movement (either from poor installation, seasonal disturbance, or ground motion). Of particular concern is that asbestos fibres may be released from deteriorating pipes in abundance when the pipes are subject to intense vibrations like construction, transport networks or earthquakes (Ratnayaka *et al.* 2009).

Asbestos fibres in drinking water and beverages have been reported since the 1970s (Cunningham & Pontefract 1971; Levy *et al.* 1976; Murr & Kloska 1976; Harrington *et al.* 1978; Illette *et al.* 1980; Kanarek *et al.* 1980; Meigs *et al.* 1980; Millette *et al.* 1980; Conforti *et al.* 1981; Toft *et al.* 1981; Webber & Covey 1991) but are generally regarded by the World Health Organization as not of prominent concern (Hanley 2011; WHO 2011; Cheng *et al.* 2020). Applying a precautionary principle the USA regulations within the Clean Water Act of 1977 enacted a regulatory threshold of 7 MFL of long asbestos fibres (i.e., $>10$ μm in length), but this does not restrict the amount of short asbestos fibres (i.e., $>0.5$ μm in length). Some recent studies have suggested a correlation between ingested asbestos and prevalence of gastric and colorectal cancers (Andersen *et al.* 1993; Varga 2000; Kjaerheim *et al.* 2005; Bunderson-Schelvan *et al.* 2011; David Williams 2013; Di Ciaula 2017), as well as evidence of asbestos enmeshed in gastrointestinal tissue (Kim *et al.* 2013), although in a recent meta-analysis Cheng *et al.* (2020) identified that no epidemiological links could be established.

Since the 1980s few studies have reported asbestos fibre concentrations in drinking water supplies. A small study showed evidence of chrysotile, amosite, and crocidolite fibres (42–483 fibres per litre) across 14 households in Korea and Japan (Ma & Kang 2017). By comparison, Tuscany, Italy, reported asbestos fibres in drinking water of 700,000 fibres per litre (0.7 MFL) (Di Ciaula & Gennaro 2016). Reports of asbestos fibres in drinking water are rare, since it is not part of regular monitoring of drinking water supply, but reports of asbestos fibres detected in water supplies consistently emerge in the news media.[1] Thus, the deterioration of asbestos cement piping presents a challenge for local authorities especially prioritising infrastructure replacement and remediation, as well as mitigating any risk, or perceived risk, of releasing asbestos from decaying pipes.

In New Zealand, asbestos cement piping is widespread as the principal material of the potable water supply, and was used extensively until the mid-1980s. The serviceable lifespan of asbestos cement piping is estimated at 70 years, but strongly depends on the ambient environment (Davis *et al.* 2008; Punurai & Davis 2017), so that models of pipe age and deterioration in New Zealand range from 20 to 60 years (Water NZ 2017a, 2017b). Furthermore, in New Zealand, the piped network

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[1] High levels of asbestos found in Arp drinking water (Rivers, 2017), Asbestos on tap: Water customers warned, mayor says 'we don't know what caused it' (Locklear, 2016), Asbestos in water supply caused by old pipe (RNZ, 2016), Whakatāne residents fear asbestos in drinking water (Jones, 2020)

intersects three important vectors for deterioration of asbestos cement pressure piping: 1) extensive and expansive use of asbestos cement piping occurs throughout the country, and significant lengths of ageing pipe remain in use; 2) the potable water supply is moderately aggressive promoting internal decay; and 3) tectonic instability leads to frequent ground disturbance and pipe strain through seismic shaking and land displacement. In particular, we are interested in the state of Christchurch's potable water supply. Christchurch experienced significant land deformation and intensive liquefaction associated with earthquakes in 2011 (Cubrinovski *et al.* 2011) and as such, has experienced considerable ground vibrations that may adversely affect the integrity of the pipe network. In the decade since the earthquake, much repair work has been undertaken on the infrastructure, but 789 km of asbestos cement piped network remains in use. To discern the condition of these pipes, and whether there is any evidence of asbestos fibres being transported through the piped network, we undertook sampling at 35 locations across the city to investigate whether asbestos fibres could be detected in the drinking water supply.

## METHODS

### Study location

Christchurch/Otautahi is situated on the east coast of New Zealand with a population of 369,000 with 153,000 private dwellings (Statistics New Zealand 2018). Drinking water is drawn from deep bores that are recharged by percolation from the Waimakariri River (Taylor *et al.* 1989). The mains water network is comprised of 1,814 km of pipe, 789 km of which are asbestos cement. The network consists of 1,681 km of sub-mains pipe; however, only 15 km of these are asbestos cement. Since 2018 the local water supply has been treated with sodium hypochlorite while wellhead maintenance and upgrades are undertaken. Between 1937 and 1955 asbestos cement pipes were imported pre-coated from the UK and lined with bitumen (Everite), and locally manufactured Fibrolite since the 1950s. Production of asbestos cement piping was discontinued in 1986 when it ceased being an industry compliant standard in response to UN Conventions restricting its use (Water NZ 2017a, 2017b; Cheng *et al.* 2020). Prior to 2010, 52.7% of the water mains network was comprised of fibrolite asbestos cement piping (O'Callaghan 2015). Christchurch experienced unusually large ground motions during an Mw 6.2 earthquake in 2011, with 11,000 aftershocks in the years following the main earthquake (Cubrinovski *et al.* 2011; GNS Science 2021). Coincident with the February 2011 $M_w$ 6.2 earthquake and its aftershocks, extensive liquefaction occurred in central and eastern Christchurch (Cubrinovski *et al.* 2011), which required substantial investment in land remediation, building, and infrastructure repair. In particular, the eastern suburbs were severely damaged by the initial earthquake and 630 ha of residential land, including over 8000 dwellings, were classified as unfit for redevelopment.

### Sampling and analytical methods

Hydrants and taps were sampled across the main water supply zones from differently aged pipe networks with consideration of the different aged piped networks across the city. Samples were collected following standard methods in 500 mL plastic low-density polyethylene (LDPE) bottles that were 5% $HNO_3$ acid washed, rinsed twice with distilled water, and air-dried prior to sampling (Standards NZ 1998). Twenty samples were collected from mains water supply via fire hydrants and within households from domestic water taps (15 locations, 11 of which had first draw and flush duplicate samples). Hydrant sample locations were specified to target lengths of older asbestos cement pipes. A standpipe was used to connect to hydrants for drawing water. An initial flush emptied stagnant water from within the hydrant connection, and flow was immediately brought back down to low prior to a minute flush that was used to mitigate potential fibre release from high-pressure hydrant extraction. Flow reduction meant that sampling could meet water quality-sampling protocols (Standards NZ 1998). Household taps were sampled as a 'first draw' and then flushed for 2 minutes and resampled to discern any variations in water holding period within domestic pipes. All sampling was undertaken from 4 to 9 June 2021. *In situ* measurements of specific electrical conductance, temperature, and pH were recorded using an YSI multisensor probe, and samples were cool stored at $\leq$4 °C ($\leq$ 39.2 °F) prior to laboratory transfer.

Water samples were pre-treated with ozone gas and ultraviolet light and filtered through a 0.1 μm capillary polycarbonate filter and analysed using transmission electron microscopy (TEM) according to the US-EPA methods 100.1 and 100.2 at International Asbestos Testing Laboratories (IATL) in the USA (Millette *et al.* 1999; Millette 2005). The laboratory reported results of total asbestos concentration in MFL, the concentration of fibres $>$10 μm and 0.5 μm in size, and the asbestos mineral type (e.g. chrysotile, amosite, and crocidolite). The TEM has a detection limit of 0.062 MFL

The water aggressive index (AI) was calculated for all hydrant samples and is a general indicator of the tendency for calcium carbonate precipitate formation, which can form a protective deposit (scaling) on the interior of asbestos cement pipes

(Mirzabeygi *et al.* 2016). Although AI is not a quantitative measure of corrosion, it is a general indicator of the tendency for corrosion to occur on asbestos cement pipes (Water NZ 2017a, 2017b). An AI $<10$ is considered very aggressive, whereas $>12$ is non-aggressive.

## RESULTS

### Pipe deterioration due to age and manufacturer specifications

Data collected by the Christchurch City Council as a part of their piped network asset management catalogued 180 asbestos cement pipe sections that have been repaired or inspected since 2013. Of these data, 42% of the records are Everite pipes from the 1930s to the early 1960s, 43% were Fibrolite from 1957 to 1996, and the remaining 15% the manufacturer was unknown and date from the 1950s. Less than 6% of the inspected pipe sections were older than 1950, with most inspected pipes from the 1950s (39%) and the 1960s (32%).

Of the asset database, 123 pipe sections were measured to determine total deterioration as a corrosion depth (in mm) (Figure 1). The average corrosion depth of asbestos pipes in Christchurch was 11.0 ± 0.5 mm across the asset database of inspected, repaired, or replaced piping. There was a slight difference in the corrosion depth with manufacturer type, 12.8 ± 0.8 mm for Everite compared to 9.8 ± 0.5 mm for Fibrolite; however, this may in part reflect an age-bias, as Everite does not have any pipes from the mid-1960s onwards.

When expressed as a rate of corrosion (i.e., depth/pipe age), there was no difference related to pipe diameter, and was 0.21 mm $a^{-1}$ on average. Corrosion depth is similar for pipes laid from the 1960s to the 1980s (Figure 2) and the higher rate of decay in the youngest pipes may be anomalous as only 5% of the pipes were laid from 1980 to 1986 and have a higher uncertainty due to fewer observations (Figure 2). The greatest depth of corrosion was observed in 150 mm diameter

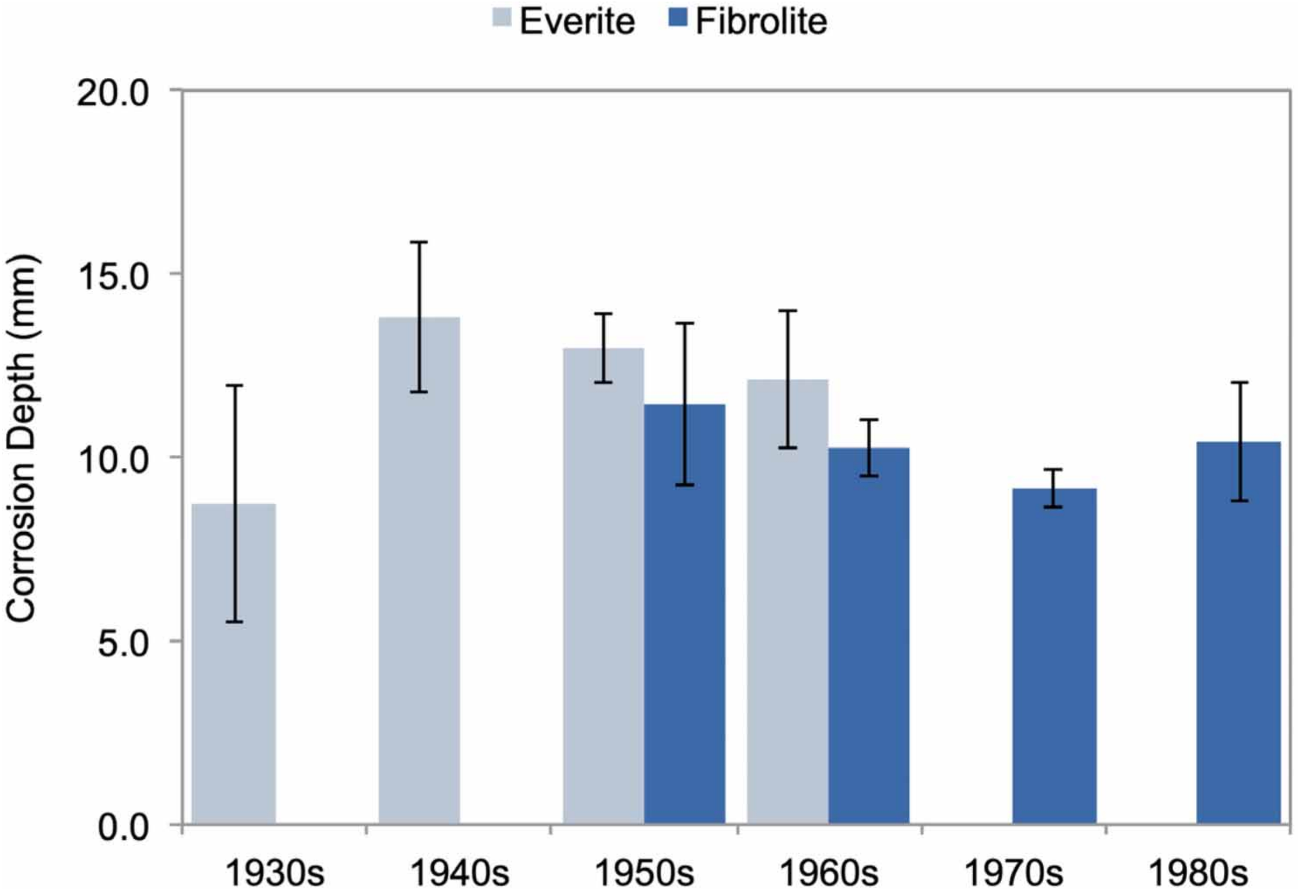

**Figure 1** | Comparison of corrosion depths in asbestos piping in Christchurch plotted relative to decade of installation and manufacturing brand (Everite, UK and Fibrolite, NZ).

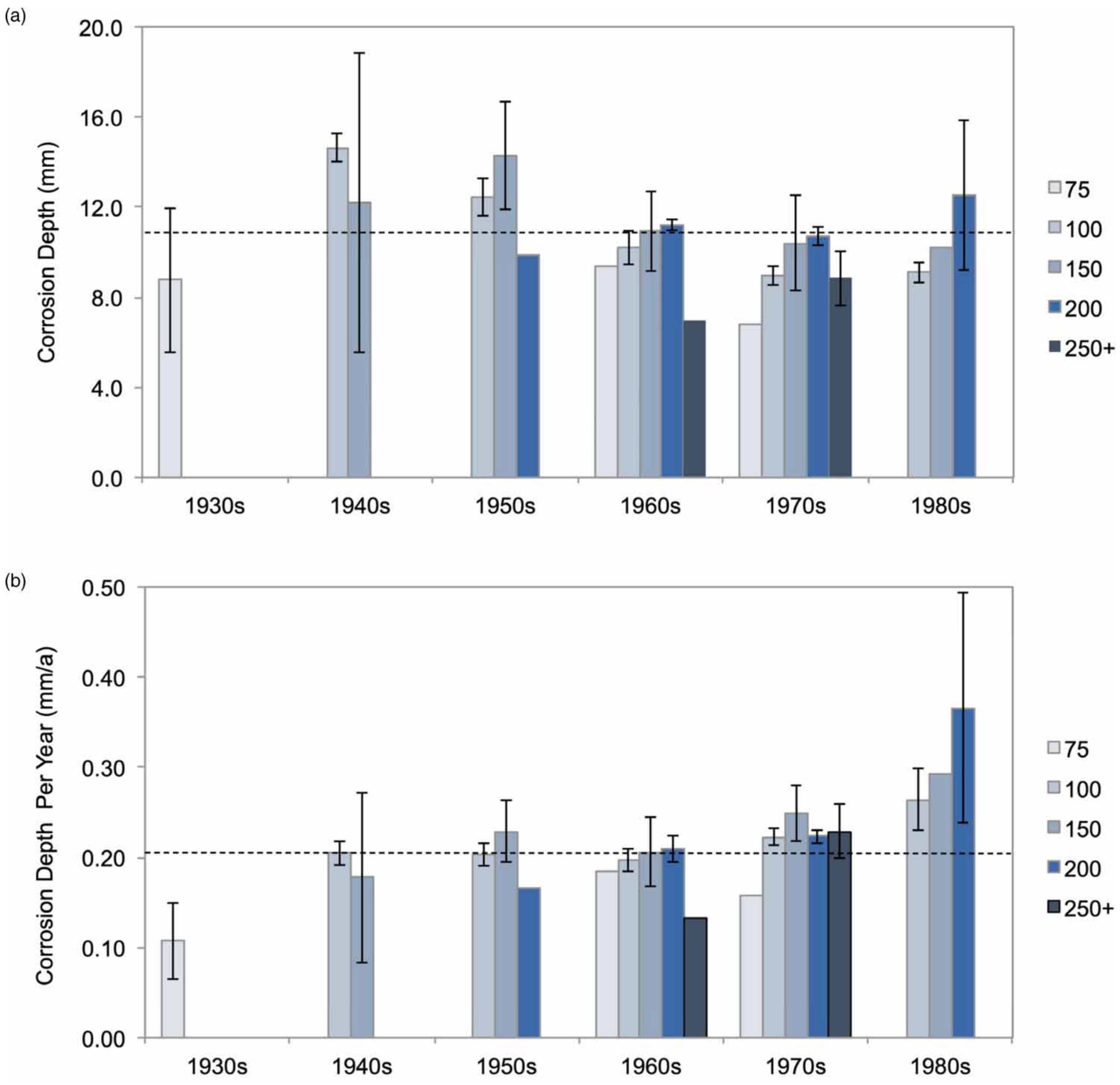

**Figure 2** | Reported corrosion depth (a) and mean rate of corrosion (b) measured from damaged asbestos pipes from Christchurch City's water mains. Data on pipe diameter and corrosion damage provided by Christchurch City Council for 123 pipe sections where corrosion depth and pipe age is known. Dashed line indicates the arithmetic mean. Individual bars are for pipe diameter classes (in mm).

pipes, averaging 12.2 ± 1.4 mm but this is not significantly different from the majority of pipes examined that have a 100 mm diameter, which averaged a corrosion depth of 11.0 ± 0.5 mm.

## Evidence of asbestos fibres in mains water supply

Asbestos fibres were detected in hydrant samples across Christchurch in all sampled pressure zones. The highest concentrations of fibres (as short asbestos fibres, SAF) that exceeded 7 MFL were spread across the city, and there is no discernable clustering at this scale of sampling. There was no obvious spatial clustering to the positive detections in household water taps. Long asbestos fibres (>10 μm) were detected in all hydrant water mains samples within central Christchurch. All samples were positive for the presence of chrysotile fibres, two also detected amosite, and a third location was positive for crocidolite. Short asbestos fibres accounted for the highest concentrations in drinking water, with five hydrant samples exceeding 5 MFL, with the highest concentration reported as 56 MFL (Table 1). The hydrant sampling sampled all water supply zones within Christchurch, except for the recent development of Kainga. Long asbestos fibres (LAF), which are pathogenic when aerosolized, were detected in 19 out of 20 hydrant sampling locations, with a mean concentration of 1 MFL. Asbestos fibres (LAF and SAF) were detected in pipes of all age classes, ranging from the late 1930s to the 1970s. The concentration of SAF is highly correlated with the concentration of LAF (Pearson's $r=0.78$, $p=0.000$, $n=24$).

Long chrysotile fibres were also detected in 3 of 15 household tap samples, averaging 0.3 MFL. Short asbestos fibres were also detected in these same locations, but were considerably higher with an average concentration of 3.5 MFL. These samples were detected in three different pressure zones (Hackthorne, Rawhiti, and North West), and the SAF from Rawhiti was a notable outlier at 8.1 MFL (Table 2). The remaining household taps did not show any presence of asbestos fibres, even though some samples came from similar pressure zones as the locations where asbestos was detected. Due to limitations on access to household taps, the households sampled do not relate to hydrant sample pipes.

The average calculated water aggressive index (Table 1) from hydrant samples was 11. This indicates that Christchurch's water supply is classified as 'moderately aggressive' to cement pipe infrastructure. The age of the mains pipes was extracted using geospatial data provided by the Christchurch City Council. The highest concentrations of LAF and SAF were detected in pipes laid during the 1940s and 1950s (Figure 3), with an extreme outlier of 56 MFL detected in a 100-mm diameter pipe laid in 1958. The oldest pipes we sampled dated from 1930 and 1936 and had lower concentrations of asbestos relative to later pipes, although this was not statistically significant as one sample had a LAF concentration at the method detection (0.062 MFL) and the other was 1.8 MFL (Figure 3).

**Table 1** | Concentration of asbestos fibres detected in Christchurch water mains from hydrant sampled in June 2021

| Pressure Zone | Pipe Age (Years) | Water Pressure (kPa) | Water Age (Hours) | LAF > 10 μm (MFL) | SAF > 0.5 μm (MFL) | AI |
|---|---|---|---|---|---|---|
| Central | 72 | 550 | 10–30 | 0.1 | 0.3 | 11.0 |
| Clifton 3 | 73 | 700 | > 50 | 2 | 5.7 | - |
| Hackthorne | 91 | 700 | < 10 | 1.8 | 4.1 | 10.9 |
| Halswell 2 | 81 | N.S. | > 50 | 0.1 | 0.2 | |
| Lyttleton High | 85 | N.S. | > 50 | 0.1 | 0.4 | 11.3 |
| Lyttleton Low | 54 | N.S. | N.S. | BDL | 0.1 | 11.3 |
| Mt Pleasant 2 | 73 | N.S. | > 50 | 1 | 3.8 | 11.5 |
| North West | 76 | 400 | 10–30 | 0.9 | 2.8 | 10.5 |
| North West | 72 | 400 | < 10 | 1.9 | 7.6 | 10.6 |
| North West | 64 | 400 | < 10 | 2 | 13 | 10.7 |
| North West | 66 | 400 | < 10 | 0.3 | 1.6 | 10.7 |
| North West | 61 | 400 | < 10 | 0.1 | 2 | 10.8 |
| Parklands | 54 | 420 | 10–30 | 0.5 | 3.6 | 11.2 |
| Rawhiti | 72 | 500 | < 10 | 0.4 | 3 | 11.0 |
| Rawhiti | 63 | 500 | > 50 | 3.7 | 56 | 11.2 |
| Rawhiti | 76 | 500 | > 50 | 0.4 | 1.5 | 11.0 |
| Rawhiti | 73 | 500 | < 10 | 0.2 | 0.9 | 11.0 |
| Riccarton | 81 | 450 | < 10 | 0.1 | 1 | 10.7 |
| West | 73 | 450 | 10–30 | 3.5 | 14 | 10.7 |
| West | 57 | 450 | N.S. | 0.3 | 2.3 | 12.0 |

BDL=below detection limit, N.S.=not specified.

**Table 2** | Concentration of asbestos fibres detected in Christchurch water mains from households or public taps sampled in June 2021

| Pressure Zone | Pipe Age | Pressure (kPa) | Water Age (Hours) | LAF $> 10\ \mu$m (MFL) | SAF $> 0.5\ \mu$m (MFL) |
|---|---|---|---|---|---|
| Central | 73 | 550 | <10 | – | – |
| Central | 77 | 550 |  | – | – |
| Central | 69 | 550 | <10 | – | – |
| Hackthorne | 91 | 700 | <10 | 6 | 2.2 |
| McCormacks Bay | 41 | 700 | 10–30 | – | – |
| North West | 51 | 400 | <10 | BDL | 0.062 |
| North West | 56 | 400 | N.S. | – | – |
| North west | 50 | 400 | N.S. | – | – |
| Rawhiti | 72 | 500 | >50 | – | – |
| Rawhiti | 73 | 500 | N.S. | – | – |
| Rawhiti | 63 | 500 | N.S. | 5 | 8.1 |
| Riccarton | 71 | 450 | 10–30 | – | – |
| Riccarton | 81 | 450 | N.S. | – | – |
| West | 61 | 450 | <10 | – | – |
| West | 73 | 450 | N.S. | – | – |

BDL = below detection limit, N.S. = not specified

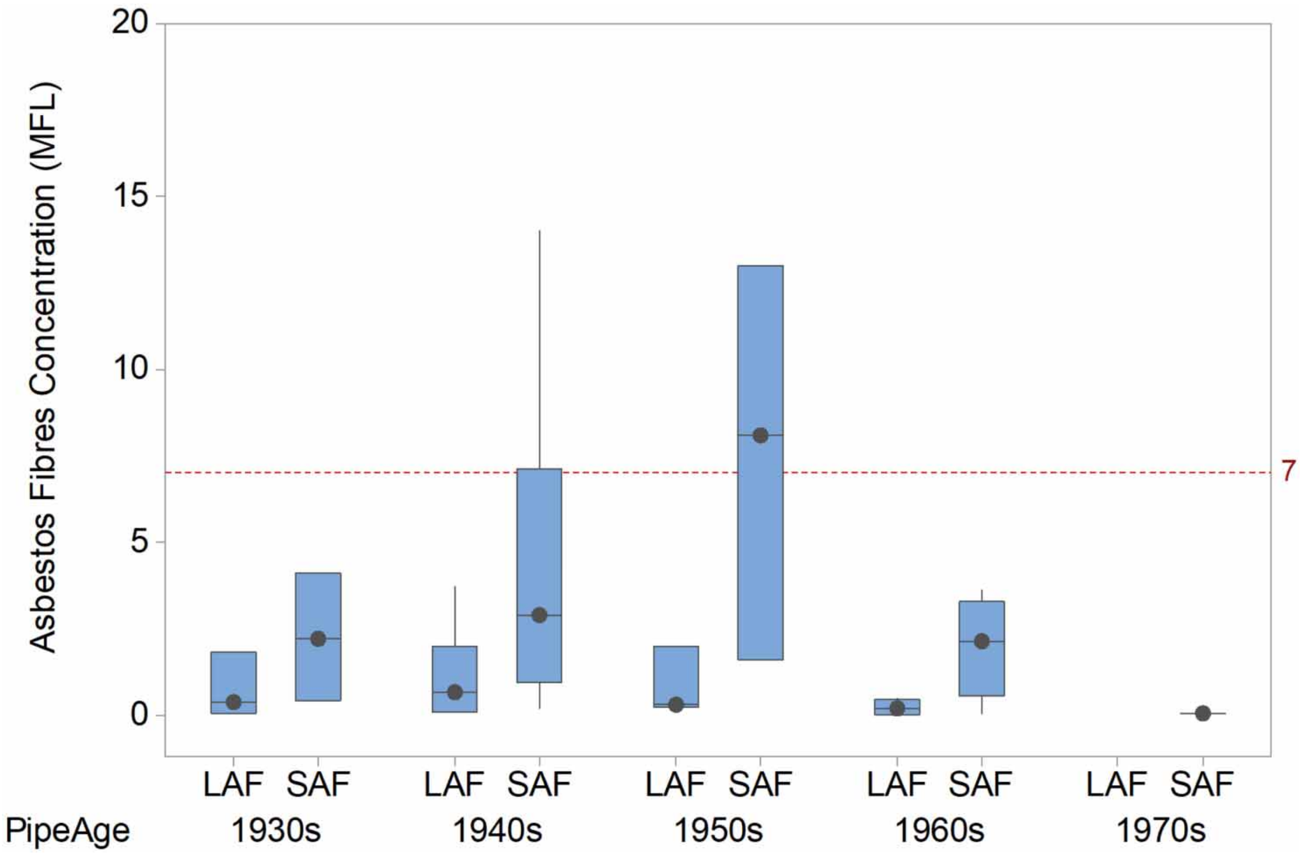

**Figure 3** | Box and whisker plots of the concentration of asbestos fibres detected in Christchurch's water mains and household taps ($n$=24). Data are plotted relative to estimated age of pipe installation and size of detected fibres for long asbestos fibres (LAF) and short asbestos fibres (SAF). Note an extreme outlier of 56 MFL or SAF from the 1950s has been omitted from the plots for clarity. Dots indicate the median value, and the dashed horizontal line marks the US-EPA regulatory threshold for LAF of 7 MFL.

## DISCUSSION

### Previous evidence of asbestos fibres in Christchurch

The Christchurch City Council sampled 17 hydrants for asbestos fibres in 2017 using a membrane filtering method using polarizing light microscopy (PLM). Chrysotile was detected in one hydrant sample; however, the PLM method does not report the concentration of fibres, nor the length of fibres detected and the laboratory report did not contain any specific information about detection limits or uncertainties of this method when used on water samples. This contrasts with the high incidence of asbestos detected in our study (20 out of 20 hydrants). Our sampling occurred approximately 43 months after the study undertaken by the Christchurch City Council. We cannot discount that there have been changes to the drinking water aggressiveness since the water chemistry was altered by the introduction of chlorination in 2018. On balance, however, differences between the 2017 study and our study are most likely attributable to the different analytical methods for detecting asbestos fibres. The previous study used PLM, which is a method commonly used in bulk building materials, but it requires considerable skill to identify asbestos fibres and may yield false negatives especially when fibres are in low concentration (Ham *et al.* 2019; OSHA 2021). Rather, the only US-EPA approved standard methods for detecting asbestos in water samples use TEM, which has a resolution that can readily detect fibres as small as 0.02 μm (Millette 2005). Thus, it is likely, that the previous PLM-based study may not have had sufficient analytical precision to detect the asbestos fibres in drinking water.

### Differences in asbestos concentration between hydrants and household taps

The occurrence of positive samples and high fibre counts in our hydrants is significantly greater than what was observed in our end-use samples collected from household taps. There are no filters that occur between mains or sub-main water pipes and household supply that would be effective at intercepting asbestos fibres. Our supposition is that sampling water from hydrants could mobilise fibres from asbestos cement pipe walls due to the high flow rates that are used to initially purge any standing water and the standpipe. Further research is required to quantify the number of fibres reaching consumer taps, specifically in suburbs where hydrant samples have high fibre counts, and to systematically sample household water supply directly connected to these piped networks. For our sampling strategy, we selected households across Christchurch where permission to enter premises could be obtained. The hydrants sampled in this study may not be a direct supply to the end-use samples collected in the same supply zone. However, two hydrants that are connected to direct supply can be compared with end users taps. Hydrant 3597 accessed the same water supply as delivered to a household. In this example we measured SAF of 1 MFL from the hydrant but no fibres were detected within the household. For the other paired example, we measured SAF of 4.1 MFL from hydrant 4061 and detected 2.2 MFL within the household taps. Further sampling work is required to assess how representative hydrant sampling counts are relative to end-user asbestos concentrations.

### Manufacturing and age considerations of asbestos pipe decay

If pipe ages were the principal determinant of fibre release from asbestos cement then it would be expected that the greatest concentrations of asbestos fibres would occur in pipes laid in the 1930s. There remain only two streets in Christchurch with active water supply from 1930s piped networks (a total of 15 pipes). A hydrant from each street supplied with 1930s aged piped networks were sampled (0.062 and 1.8 MFL $>10$ μm), with a mean 0.9 MFL, which is lower than the twelve 1940s aged pipes ($1.8 \pm 1.3$ MFL). From our preliminary study our sampling size from 1930s pipes is too small to determine whether these pipes are more vulnerable to degradation and the release of asbestos fibres, since the range of concentrations observed in the 1940s pipe is high (0.062 to 3.7 MFL $>10$ μm). Only 1.1% of the pipes within the inspected pipe database related to pipes dating back to the 1930s, which showed evidence of pipe corrosion of $8.8 \pm 3.2$ mm, compared to $13.8 \pm 2.0$ mm for pipes from the 1940s. It appears as though the pipes laid in the 1940s (1143 active pipes) are showing greater production of asbestos fibres and have greater corrosion depths, and given that these pipes are far more widespread throughout Christchurch, they should be prioritised for replacement. The corrosion depth data also shows that some 1980s pipes are also corroded to depths of $10.4 \pm 1.6$ mm, equivalent to decay rates of 0.30 mm $a^{-1}$, which is substantially faster than the mean of 0.20 mm $a^{-1}$ for pipes aged mostly from the 1950s (2304 active pipes) and 1960s (9154 active pipes). The corrosion rates observed in Christchurch are higher than those observed in Korea (Chung *et al.* 2004), with reported corrosion rates of 0.05–0.15 mm $a^{-1}$ for 7–25 year old pipes. The highly corrosive water in the Korean study examined 35 discrete samples of asbestos cement piping and reported a few unusually high corrosion rates of 0.23 and 0.5 mm $a^{-1}$ (Chung *et al.* 2004). There are scant other reported corrosion rates of cement piping for water mains, but it appears that the rates in Christchurch are high due to the soft source water and its chemical aggressiveness. More directed and targeted work would be required to resolve these patterns, but age is generally a poor indicator of pipe decay (Barton *et al.* 2019), and may be better approximated using probabilistic modelling related to internal and external pressure loading (Davis *et al.* 2008).

### Network influences on pipe condition: water age, pipe length, and pressure zones

Samples with concentrations exceeding 7 MFL of SAF from hydrants and household taps were generally observed in pipes with flow lengths >1 km. Pressure zones across Christchurch vary from 400 to 750 kPa, but no correlation between pressure zones and asbestos concentration could be discerned from our small dataset. There was limited opportunity to compare the effects of water pressure on asbestos fibres detected in hydrant water samples. A comparison of similarly aged pipes (1940s–1950s) between North West and Rawhiti shows that there are greater fibres detected in the Rawhiti pressure zone (Table 3). These data suggest that conditions within Rawhiti are likely yielding greater amounts of SAF despite being from pipes of a similar age. These differences could be attributable to slightly higher water pressures in Rawhiti, but comparison to the two samples from pressure zones that operate at 700 kPa (Clifton and Hackthorne) from similarly aged 1940s pipes only yielded 4.9 MFL SAF on average. With limited data across different pressure zones, this study cannot determine what effect, if any, water pressure has on asbestos pipe degradation. The degradation of Rawhiti pipes is, however, congruent with areas of moderate liquefaction from the 2011 earthquake, and may indicate vibrational damage has occurred to these pipes and is a contributory factor to their decay.

Previous work by Cubrinovski *et al.* (2014) investigated the relationship between pipe repair rates and trench backfill characteristics, as well as the role of liquefaction and earthquake damage across Christchurch City. Their data showed that trench backfill supporting the piped network is spatially variable across Christchurch and may contribute to pipe deterioration. Asbestos cement pipes in liquefaction resistance index (LRI) Zones 0–3 were found to have higher repair rates when seated in native soil backfills compared to gravels or AP40 mix following the Canterbury Earthquake sequence. Data collected from our asbestos in drinking water investigation shows that locations of high fibre release rates also occurred in areas with native soil trench backfill characteristics. It is possible that pipe lengths in trenches backfilled with native fill in zones concomitant with areas of strong observed soil liquefaction (low LRI zones 1, 2 and 3) have experienced greater rates of degradation which may contribute to higher asbestos fibre count releases. For example, in the Rawhiti water supply zone, in aged asbestos cement pipes seated in native soil backfill, we observed the highest concentration of asbestos fibres reported in this study (56 MFL SAF).

## CONCLUSIONS

The drinking water supply of Christchurch, New Zealand has an ageing asbestos cement piped network that is leaching short (i.e., >0.5 μm) and long (i.e., >10 μm) asbestos fibres into the water supply. These data when combined with the corrosion rates of 0.20 mm $a^{-1}$ from failing pipe sections show that the asbestos cement pipes are being corroded by the soft and highly aggressive municipal water supply. We suggest that monitoring the presence of asbestos fibres in hydrant mains is an effective indicator of pipe decay and could be used to prioritise and direct the schedule of pipe replacement.

Epidemiological links between asbestos fibres in drinking water and incidence of cancers can only be established if data on asbestos fibres exists: which is not regularly collected. The previous attempt to discern whether asbestos fibres were present in the Christchurch potable water supply used a PLM method, which is not suitable for detecting asbestos fibres in water. In our study we used the TEM, which is the only suitable method for detecting asbestos fibres in water. Using TEM showed asbestos fibres were present in all samples collected from hydrants in Christchurch. If authorities want to determine whether asbestos is present in drinking water supplies they must use a TEM certified laboratory method.

Water supply should be regularly monitored to assess the concentration of both long and short asbestos fibres within drinking water supplies. Many industrialised developed countries continue to rely on asbestos-cement piping for municipal

**Table 3** | Comparison of pressure zones and asbestos fibre concentration in drinking water

| Pressure Zone | Pipe Installation | Mean Water Age (Hours) | LAF (MFL) | SAF (MFL) |
|---|---|---|---|---|
| North West (400 kPa) | 1940s, 1950s | 14 | 1.27 | 6.25 |
| Rawhiti (500 kPa) | 1940s | 30 | 1.18 | 15.36 |

Each pressure zone has four hydrant samples collected from pipes installed in the 1940s–1950s.

drinking water that are increasingly beyond their expected lifespan – and implementing directed and strategic water sampling and testing for asbestos fibres should be part of a long term strategy for monitoring network integrity. We recommend that all municipalities adopt monitoring of asbestos fibres from the reticulated water supply, especially as these pipes reach end-of-life, to detect pipe deterioration and prioritise pipe sections for replacement. Any future monitoring must ensure that samples are analysed using one of the standard TEM methods for the detection of asbestos fibres in drinking water to mitigate against false negative tests that are associated with other methods that are more suitable for bulk material assessment.

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## DISCLOSURE STATEMENT

The authors declare no conflicts of interest.

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## DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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