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CASE HISTORY—PEER-REVIEWED

Premature Failure of CPVC Drainpipes

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Abstract Water leaks were noticed from a chlorinated polyvinyl chloride (CPVC) drainpipe system used in a cafeteria only 3 months after the commissioning of the building. The drainpipe was used to recover food waste using various systems installed directly in the kitchen. The leak was caused by the presence of numerous cracks in some of the elbows from the drainpipe system. Scanning electron microscopy showed the presence of mud cracking, which is generally associated with environmental stress cracking. Chemical analyses revealed the presence of incompatible products with the CPVC, coming from the chemical transformations in the composting process and from excess cement used to assemble the various sections of the drainpipe system.

Keywords CPVC · ESC · Food residue · Failure analysis

Background

Following the discovery of their premature failure, pipes-and-elbow assemblies from the drain system were submitted to us for investigation. The specimens were cut on site before being shipped to our office. The assemblies were made of CPVC parts (pipes and elbows) (Fig. 1).

To assemble CPVC piping parts, the most common technique is to use solvent cement welding. This technique uses solvents and resin to chemically fuse the pipe and fitting together at a molecular level, essentially creating one continuous piece of plastic [1].

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We were mandated to determine the probable cause of the premature failure of the drainpipes. We thus proceeded with a full failure analysis of the submitted parts.

Approach

The specimens were visually inspected and photographed. To conduct a general visual and low-magnification examination of the cracks on the specimens, several cuts were made. This approach allowed the examination of the internal surface of the pipe-and-elbow assemblies and the identification of the location and the orientation of the cracks within the walls of elbows. The cracks were then opened to examine the fracture surfaces and proceeded to a scanning electron microscopy (SEM) analysis.

Chemical analyses of the content of the pipe were conducted to determine the presence of incompatible products with CPVC. In order to detect the presence of alcohols, a sample was submitted to a gas chromatography coupled with flame-ionization detection (GC-FID) analysis. The presence of volatile organic compounds, oil and grease was analyzed using a gas chromatography–mass spectrometry (GC–MS).

The Investigation

Visual Examination

Figure 1 shows one pipe-and-elbow assembly as received. The elbow exhibited three cracks on the outer surface. They were on average of 10 cm long and mostly parallel to each other. On the inner surface of the assembly, traces of

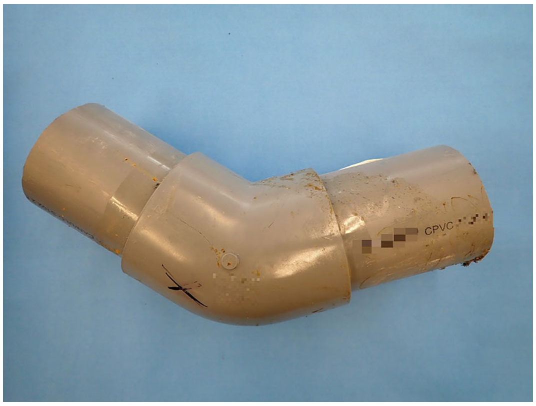

Fig. 1 Two pipes inserted into a 45° elbow. The pipes were cut during sampling. The elbow exhibited three longitudinal cracks

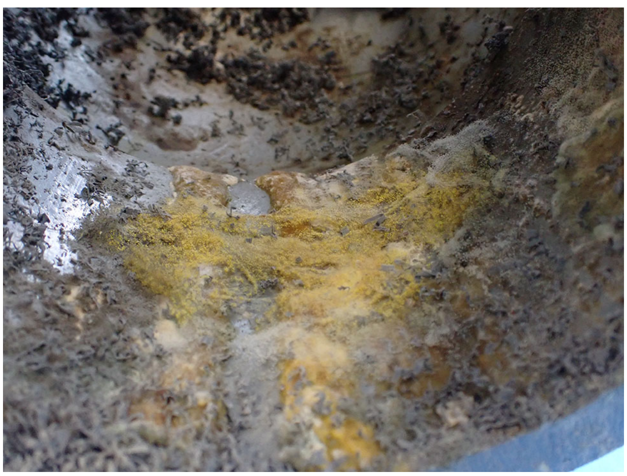

Fig. 2 Mold formation on the inner surface of the pipe-and-elbow assembly

mold were apparent (Fig. 2). Upon the cleaning of the part, we could observe that the cracks were propagating on both sides on the elbow. They seemed to initiate from the cement weld between the pipe and elbow, on the inner surface of the assembly (Fig. 3). Examination at higher magnification revealed microcracks on the fracture. On the internal surface of the elbow, mud cracking was apparent (Fig. 4).

Scanning Electron Microscopy (SEM)

Our SEM examination of selected fracture surfaces did not reveal any material or manufacturing defects (i.e., voids, inclusion, processing defects, etc.).

Figure 5 shows a SEM image of the inner surface of the elbow. On this surface, evidence of mud cracking was apparently close to the fracture. Mud cracking is a visual clue of multiple fracture initiations with an easy diffusion

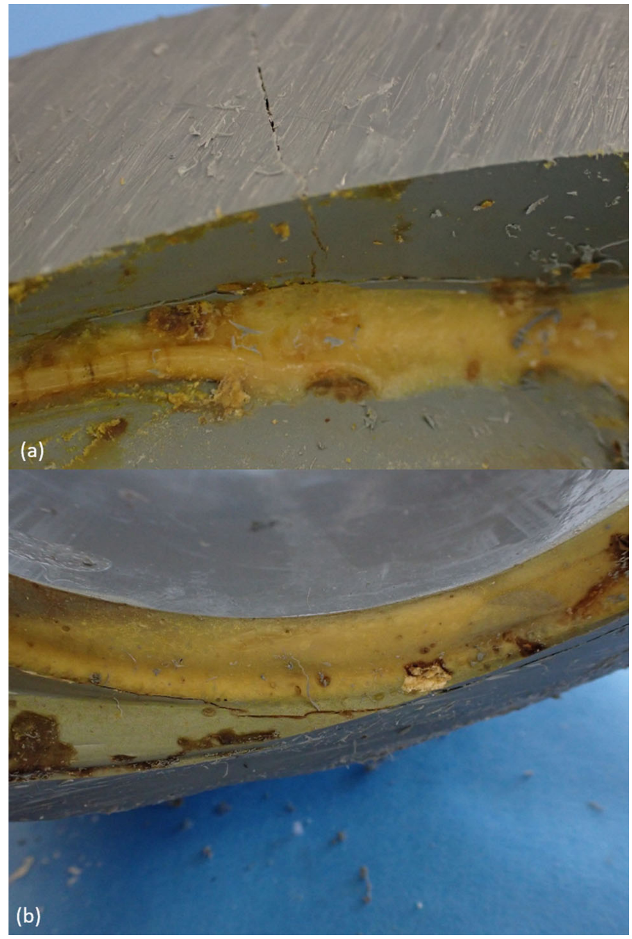

Fig. 3 Inner surface of the assembly showing crack visible on (**a**) both sides of the elbow and along the cement weld and (**b**) the internal side of the assembly along the cement weld

path, in closely spaced locations. This is a phenomenon, in plastics, generally associated with environmental stress cracking (ESC), a typical failure mode in plastics [2].

Figure 6 shows evidence of a progressive brittle fracture. This type of failure is characteristic of high localized stress. The ESC agent reduces the level of stress required to initiate the failure by a mechanism of localized plasticization, through stress enhanced fluid absorption, causing a slow-crack-growth mechanism [3].

Figure 7 shows the origin of the crack. Our observations indicate that the crack originated from the inner face of the elbow and propagated toward the outer face (Fig. 7). The origin is in a location of high localized stress and in direct contact with the ESC agent.

Chemical Analysis

The content of the pipes was analyzed. We detected the presence of oils and greases, volatile organic compounds (VOCs) and alcohols (Table 1).

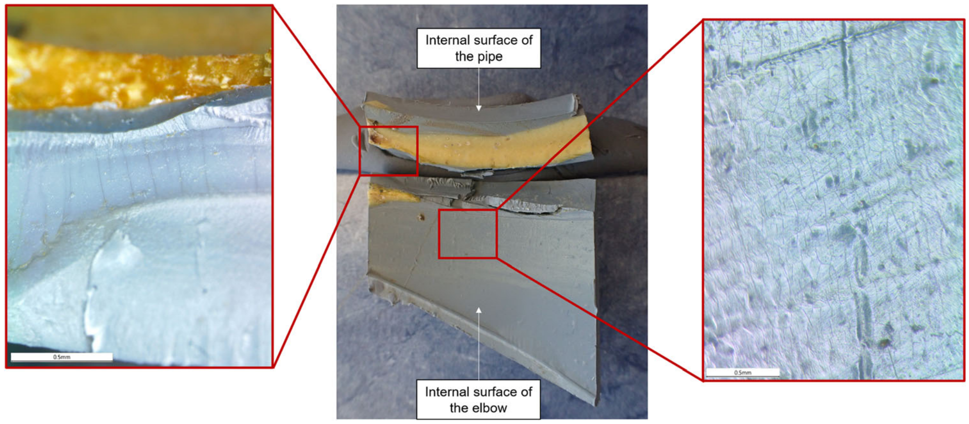

Fig. 4 Crack opened with close-up view of microcracks originating from the internal surface (left-side picture) and craze formation (right-side picture)

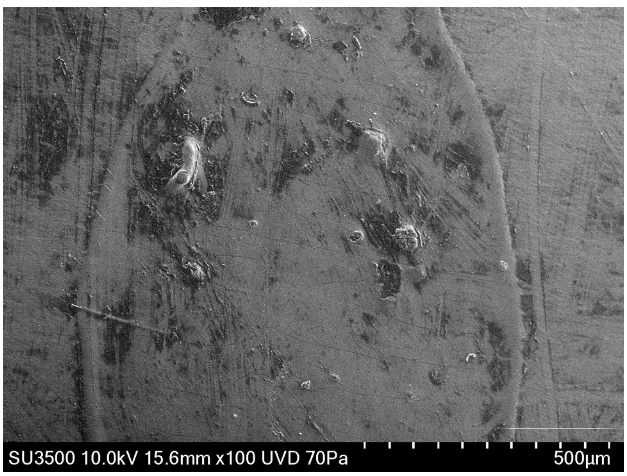

Fig. 5 SEM image of the internal surface of the pipe showing mud cracking

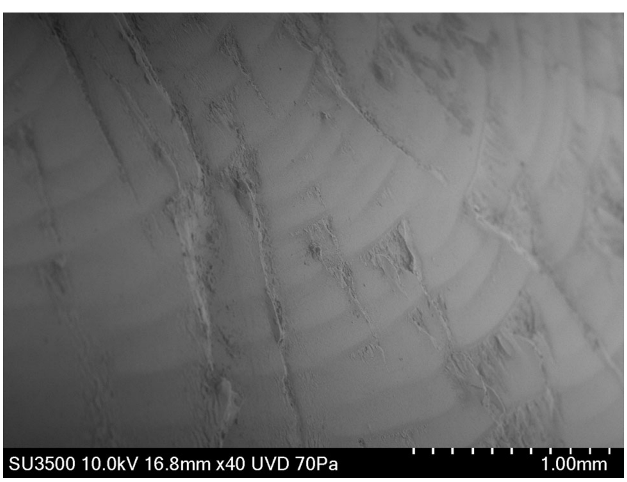

Fig. 6 SEM image of the fracture surface showing a progressive brittle fracture

Oils and grease are commonly found in food residues and were expected in this case. VOCs are carbon compounds with high vapor pressure at room temperature. There is a wide variety of VOCs. They can be released through human action or through natural reactions. Most scents or odors are of VOCs [1].

Mold, which is a fungal species, will emit blends of VOCs during its development. The composition and quantity of the VOCs will vary with the fungal species. These fungal species can produce mixtures composed of alcohols, aldehydes, acids, ethers, esters, ketones, terpenes, thiols and their derivatives. They are responsible for the characteristic moldy odors [4].

Alcohol would be produced during composting. Chemical transformations in the composting process are mediated by microorganisms, primarily bacteria and fungi (mold) [5]. The main components of compost are degradation products which can be alcohols. For example, alcohols (R–OH) can be produced during the decomposition of proteins (Fig. 8) [6].

According to the manufacturer of the part, almost all products detected were incompatible with CPVC (Table 2). Incompatible chemicals can disentangle the CPVC molecular chain through a physical change in the polymer. Indeed, the weak intermolecular bonds (hydrogen bonding, Van der Waals forces, etc.) are broken by the ESC agent. When those bonds are broken, the mobility of the polymer chain increases, and the disentanglement is accelerated. This results in a local softening of the material that promotes brittle crack formation and propagation [7].

Discussion

Based on the results obtained during our investigation, we determined that the submitted parts failed due to environmental stress cracking (ESC), because of their physical contact with incompatible products (cement solvent and food residue).

ESC is the result of an interaction of the polymer with certain chemicals (ESC agents). The chemical agents do

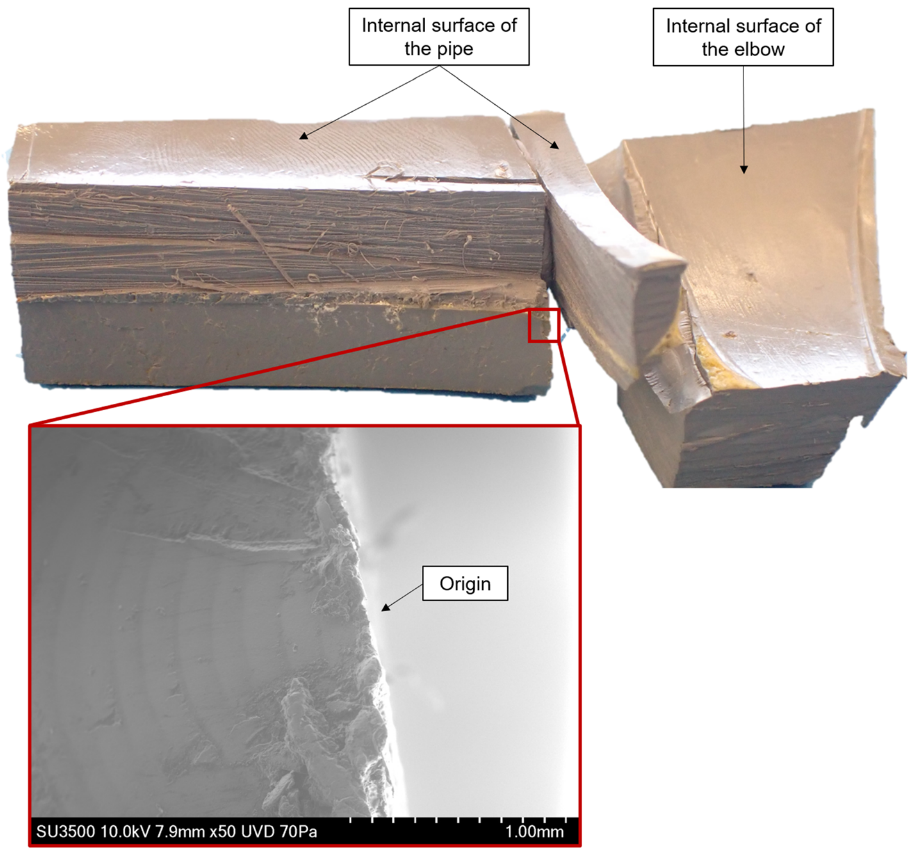

Fig. 7 Crack origin at the junction between the cement weld and the internal surface of the elbow

Table 1 Results of chemical analyses performed on the content of the pipes

	Product	Concentration
VOCs		
Ethyl acetate	1200	μg/L
Acetone	180	μg/L
Hydrocarbons		
Mineral oil and grease	4	mg/L
Total oil and grease	52	mg/L
Alcohols		
Isobutanol	3.4	mg/L
Methanol	79	mg/L
n-Propanol	29	mg/L

$$\text{Protein} \xrightarrow{O_2} \underbrace{CO_2 + \text{R-OH} + NH_4}_{\text{Humus-like substance formation}}$$

Fig. 8 Chemical reaction of decomposition of proteins

Table 2 Compatibility chart of CPVC

Product	Compatibility with CPVC at ambient temperature [13]
Ethyl acetate	Not recommended
Acetone	Not recommended
Mineral oil and grease	Recommended
Total oil and grease	Not recommended
Isobutanol	N/A
Methanol	Not recommended
n-Propanol	Caution, further testing suggested

not cause chemical degradation of the polymer, but they accelerate the process of macroscopic brittle crack formation [8]. Physical change in the polymer occurs on a microscopic level, during which the ESC agent acts as a plasticizer. Therefore, the mobility of the polymer chain will increase. Intermolecular forces such as Van der Waal's forces and hydrogen bonding are overcome. As a result, the molecular disentanglement will be accelerated, thus facilitating the development and growth of brittle cracks [8].

The failure under study only occurred in the elbows. Indeed, the submitted elbows were found cracked at the interface between the pipe and the elbow, at the location of the cement weld. This is an area of mechanical stress concentration, which is, moreover, covered in cement residue. In addition, according to the installation layout, it was also an area facilitating the accumulation of food residues (Fig. 9). The accumulation of food residues will increase the duration and the frequency of exposure to incompatible products which will affect the resistance of CPVC.

Mud cracking, which is typically found in ESC, was visible close to the area covered by cement residue, inside the elbows. Mud cracking, also known as crazing, is identifiable by its visual aspect composed of a network of fine cracks on the surface of a material. Crack formation due to ESC is often preceded by craze formation [8]. Crazes are expanded regions held together by highly drawn fibrils which bridge these microcracks [9]. Crazes form and grow within the chemically affected zone. Eventually, the crazes rupture to form a crack [3]. Cement itself is an ESC agent for CPVC. When too much cement is applied, it can run down the inside of the pipes. While trapped inside the pipes, the solvent contained in the cement cannot evaporate and will attack the CPVC.

The contents of the drainpipes were a mixture of food residues. The presence of mold in the submitted pipe-and-elbow assembly suggested that the organic matter (food residues) was broken down by microorganisms (fungi) to produce compost.

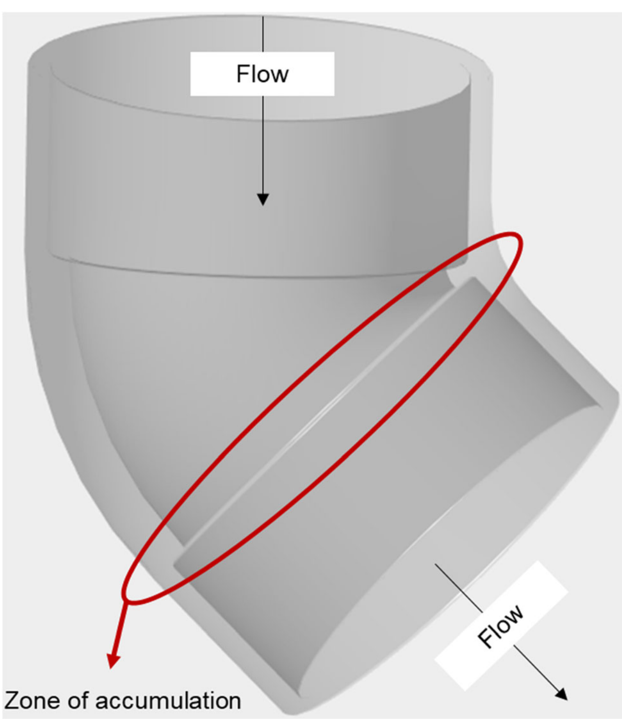

Fig. 9 Diagram representing accumulation zones in an elbow fitting in the assembly

In fresh composting or in mold growth substrate, nitrogen (N) is mainly present in ammonium form or relatives of ammonium such as amines in protein, urea and uric acid. As these proteins break down, the by-product of protein degradation such as organic acids and ammonia (NH_3) builds up [10]. In immature compost, we often see high ammonia level, which is not recommended in CPVC pipes according to the chemical resistant chart of the manufacturer. CPVC is not designed for compost exhaust's low acidity filled with moisture, ammonia and organic acids [11, 12].

Finally, as the cement residue is a spongy material, it can absorb contaminants and trap them. In the case under study, the cement “trap” inside the elbow was in constant contact with food residues flowing inside the pipes and thus became impregnated with products which are incompatible with the CPVC and can induce their failure.

Conclusion

Our investigation revealed that numerous cracks were initiated in the elbow, from the cement weld between pipe and elbow. The rupture propagated from the inner surface of the assembly to the outer surface, in a brittle manner.

The phenomenon that caused the failures was environmental stress cracking (ESC), which is caused by the combined and simultaneous effect of three factors:

- A material susceptible to ESC;
- A tensile stress, inherent from the manufacturing process or induced from installation;
- An ESC agent, which in this case was a combination of chemicals from the decomposition of food residue and solvent from the cement weld.

An inadequate material choice for the pipes and elbows was used for the drainpipes. The accumulation of food residue in the assembly contributed to a premature failure. We believe that without the accumulation factor, the failure would have still occurred, but probably after a longer period of operation.

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