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Quantitative Analysis Method for Corrosion and Patina Progression on Plumbing Components during Long-Term Connection Leaks from Potable Water Supply Systems

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Abstract

The modern field of Forensic Engineering evaluates the origin, cause, and duration of failed building components. As many failed components are subject to insurance claims and legal probes, a scientific methodology for evaluating such events is inherently valuable. Due to the potential for widespread interior finish damage, failed plumbing supply components are commonly encountered during forensic evaluations. Plumbing pipes themselves and properly soldered fittings rarely fail. Consequently, many failures correspond to mechanical fittings which form connections from pipes to plumbing fixtures. The results of this study provide a scientific methodology to evaluate the duration of connection leaks by quantifying the extent of corrosion, patina, and accumulated deposits on various components by creating and evaluating slow plumbing supply component connection leaks.

Keywords

Building Science, Forensic Engineer, Plumbing, Leaks, Corrosion, Patina

1. Introduction

This paper is arranged by providing a general explanation of plumbing supply and the significance of compression fittings, followed by a corresponding explanation and depiction of the study means and methods. A basis for color depth analysis is provided, before illustrating the application of color scale compared to actual specimen photos. Color depth data is graphed and plotted against time to provide a visual depiction for analysis. A comprehensive discussion of data trends accompanies the graph. Finally, definitive conclusions are presented, supported by the gathered data.

Potable water is supplied to buildings through a pressurized system of pipes, leading from municipal plants to end users in commercial and residential buildings. Elevated pressure ensures adequate distribution through this network. The pressurized system ensures that water will continuously exit pipes in the event of the failure of a plumbing supply component under constant pressure [1] [2] [3]. In the United States, materials must be approved by regional building codes to be utilized as plumbing supply pipes. Galvanized steel pipe was commonly utilized in the 1970's, while PEX, or crosslinked polyethylene, and CPVC, Chlorinated Polyvinyl Chloride, are currently approved by some states [4] [5]. Due to its reliability and durability, copper has historically been and currently is the most commonly utilized material for plumbing supply pipes in the United States.

Copper pipes connect to municipal service and extend through commercial and residential building interiors. Pipes are then connected to sink fixtures by way of a terminating supply valve and flexible supply lines. Multiple connections are found in a small area, thereby increasing the potential for failures. Many such connections rely on compression fittings. Compression fittings function by compressing an inner sleeve slid over the pipe against a tightened outer nut to provide a watertight seal [6]. Compression fittings may spontaneously, partially, or completely fail and release varying amounts of water, slowly or catastrophically.

Although corrosion may be moisture, chemically, or microbiologically induced, water exposure is the most common factor in corrosion within the built environment [7] [8] [9]. During a long-term leak, copper pipes and metal fittings commonly exhibit corrosion, patina, and accumulated deposits [10]. Corrosion reduces the service life of affected materials and necessitates costly repairs [11]. During typical Engineering analyses, corrosion is commonly analyzed by percentage of weight loss, scanning electron microscopy, pulsed eddy current, and mathematical estimations [12] [13] [14]. The previous methods prove costly and impractical for an evaluation of cause and duration of a simple plumbing leak.

The lack of readily applicable models for evaluating corrosion and patina demands a practical approach for daily application in the field of Forensic Engineering. This research inquiry directly translates commonly believed theoretical color depth advancement of corrosion and patina into an empirical model with tangible industry applications. Upon further data accrual by analyzing more specimens, the trendline equations will represent a prescriptive method for analyzing leak duration based on advancing color depth analysis. The trendline equations will accurately represent leak duration based on corrosion and patina color depth analysis, which will allow Forensic Engineers to assign a definite time frame to leaks observed in the field. Anticipated leak duration may be mathematically calculated by inputting the color depth into the trendline equation or simply graphically analyzed by following the field-recorded color depth to the trendline and projecting a line to the corresponding time value on the data graph.

2. Materials and Methods

2.1. Components

A mock sink supply configuration was created using commonly employed materials in United States residential construction. Each supply pipe was terminated with a compression supply valve and metal braided supply line, in an effort to simulate water supply connections to a common sink. The far end of the metal braided supply line was capped (**Figure 1**). Low-volume leaks were intentionally created at each copper pipe to supply valve connection and from each supply valve to supply line connection (**Figure 2**). Leaks were ensured by not tightening compression fittings entirely and not using thread sealant putty or tape between connections. Component specifications were provided for reference (**Table 1**).

2.2. Configuration

Five individual plumbing pipes were placed in a linear configuration along a common incoming pipe, and consequently subjected to the same internal pressure. The five specimens were numbered 1 through 5 from left to right, with Specimen 4 serving as the control (**Figure 3**). The control sample was subjected to the same internal pressures and external temperature and humidity exposure, in an effort to separate normal weathering from usage and moisture induced conditions. The specimens were mounted on a wood frame with 100 to 150 mm between specimens, above a clear, plastic container, measuring 40.1 cm wide by 65.5 long by 17.5 cm deep. The container retained the leaked water and was manually emptied on a daily basis. Suspended supply line components were never submerged below the water line.

Water supply was provided by the Town of Davie, Florida municipal water supply, under common city service conditions. Water temperature ranged from

Table 1. Material specifications.

Copper Pipe Mueller Streamline Brand Type L Hard-Temper [15]			
Pressure Max (kPa)	Temp Max (C)	Diameter Interior (mm)	Diameter Exterior (mm)
6797	204.4	12.7	15.75

1/4 Turn Angle Stop Compression Brass Craft Brand with Brass Body [16]				
Temp Min (C)	Temp Max (C)	Diameter Inlet (mm)	Diameter Outlet (mm)	Pressure Max (kPa)
4.4	60	15.75	9.53	861.8

Braided Stainless Steel Faucet Supply Line Home Works Worldwide Brand With Brass Fitting Material and Stainless Steel Tube Material [17]			
Diameter Inlet (mm)	Diameter Outlet (mm)	Diameter Inlet (mm)	Pressure Max (kPa)
9.53	12.7	9.5	850

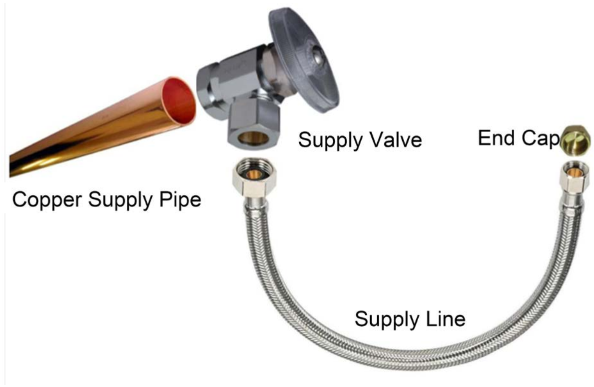

Figure 1. Supply pipe and line configuration [15] [16] [17].

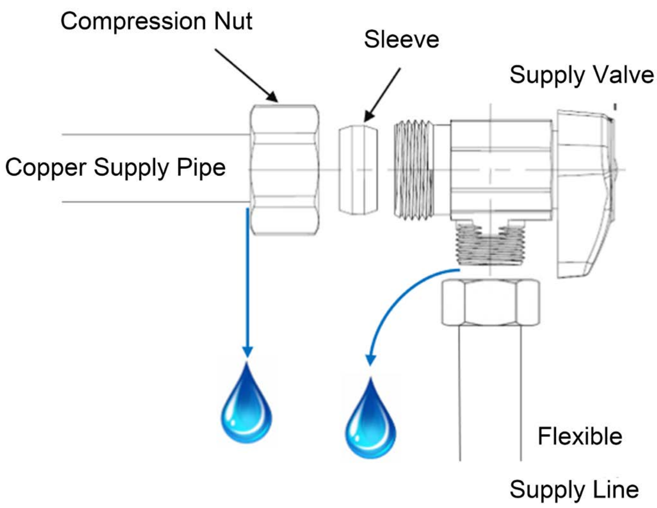

Figure 2. Supply valve and line leak locations [18].

Figure 3. Specimen and experimental setup [19].

21.1˚C to 25˚Celcius (˚C). Ambient room temperature in the conditioned environment ranged from 23.3˚C to 25.8˚C. Ambient relative humidity (RH) ranged from 52 to 79 percent. Internal water pressure remained a constant 482 kilopascals (kPa) throughout the study.

Due to manufacturing variations and hand assembled components, the multiple drips did not have the same flow rates. Additionally, flow rates diminished with time and leaks continuously self-sealed, necessitating drips to be manually re-created on a weekly basis. The average flow rate was taken weekly by collecting and measuring the retained water for one hour and dividing by eight, the number of individual leaks. Due to the inability to provide uniform leaks, the average flow rate varied widely from 1.1 to 23.75 milliliters per hour.

2.3. Basis for Analysis

On a weekly basis, specimens were analyzed for corrosion and patina, and the locations were noted. Observed corrosion and patina were rated on a 1 through 10 color scale, with higher numbers corresponding to deepening shades of orange and green, respectively (Figure 4). Pipes and supply components were measured initially with a micrometer and measurements were recorded. Measurements were recorded at the same locations periodically to assess dimensional changes associated with corrosion and/or deposits.

3. Results and Discussion

3.1. Control—Specimen #4

3.1.1. Patina

Minute, faint patina spots of color depth 2 (Figure 5) were first observed on week 2 and increased to depth 3 by week 7. Minute spots further increased to depth 4 on week 11 and depth 5 by week 15. Spots remained at depth 5 for the duration of the study at week 15 (Figure 6). The observed minute spots were

Figure 4. Patina (green) and corrosion (orange) color scales from 1 to 10 [19].

Figure 5. Control—Minute faint patina spots on week 2 [19].

Figure 6. Control—Small spots with a color depth #5 on week 15 (end of study) [19].

located randomly over the pipe surface and were not concentrated in a local area. Consequently, the widespread minute spots represented the patina induced by atmospheric humidity and general usage.

3.1.2. Corrosion

Very light corrosion with a color depth #1 was first observed on week 2 around the base of the upper supply line nut (**Figure 7**). The color depth increased to depth 2 by week 3. On week 8, corrosion finally increased to depth 4 with no appreciable increase in area and remained a similar color through the end of the study on week 15 (**Figure 8**).

The corrosion orientation followed a tool mark or mating surface where the surface layer was absent and did not extend past the area of absent surface layer. Consequently, the observed corrosion may have represented the initial oxidative reaction during which the outer metal layer slightly corrodes and served to inhibit further corrosion and protect the underlying metal layer. The fact that the corrosion color depth remained steady and did not increase after week 8 supported this interpretation.

Figure 7. Control—Very light corrosion of color depth #2 on week 2 at supply line nut [19].

Figure 8. Control—Corrosion with color depth #4 on week 15 (end of study) [19].

3.2. Patina

By week 3, all specimens exhibited light widespread patina spots with an average of color depth 3.25 (**Figure 9**). Specimens 1 and 3 first exhibited minute specks of patina on the pipe adjacent to the supply valve connection leak on week 8, with color depths of 6 and 4, respectively (**Figure 10**). By week 16, the widespread, minute spots circularly increased slightly in area and deepened in color. Patina at the leaking connections progressed to an average of 6.25 by the end of the study on week 15 and remained locally concentrated around the leaks (**Figure 11** & **Figure 12**).

Widespread patina spots represented atmospheric and usage induced patina and were also observed on the control specimen. This is a vital observation, as detailed observations distinguished patina caused by a leak from that which is caused by general service conditions.

The localized patina on the supply pipe was largely concentrated adjacent to the engineered leak from the angle stop compression fitting. The concentrated area represented the surface which was directly wetted by the leak and did not greatly expand outside of this limited area.

Figure 9. Patina—Widespread spots on week 3 [19].

Figure 10. Patina—Specimen 3 first exhibited minute specks (color depth 4) at a leak on week 8 [19].

Figure 11. Patina—By week 16, the minute spots increased slightly in area and deepened in color [19].

Figure 12. Patina at the engineered leak Specimen 1 on week 15, concentrated around the leak [19].

Figure 13 depicts the control specimen and data average with corresponding trendlines. The solid green line represents the increase in color depth plotted against time, while the dotted green line provides the best fit trendline data average. The best fit equation is depicted above. The corresponding R^2 value depicts the accuracy of the best fit equation as compared to the recorded data. Generally, above 0.9 is considered an accurate fit, while above 0.99 is considered ideal.

The control specimen data and trendline is also depicted by the solid and dotted blue lines, respectively. The intent and effect of the control sample data was to separate normal humidity or usage induced patina from the patina created by the direct water exposure.

As both specimen and control data trends gradually increased with time, one may conclude that the difference in color depth between the exposed specimens and data specimen reflects the direct water exposure. This is an erroneous assumption, as in actual practice, the patina induced from direct water exposure occurred concentrated to the limited area of contact with water leaks, while the control specimen patina formed over the general surface area of the pipe. Wetted specimens also exhibited similar patina over the surface area of the pipe, but patina was not accurately represented by data as the area exposed to direct water exhibited a deeper color and was consequently recorded as the deeper shade.

3.3. Corrosion

Notable corrosion of average color depth 2.25 first appeared on the copper pipe adjacent to the supply valve connection on week 2 (Figure 14). Corrosion gradually advanced to an average color depth of 6.75 by the end of the study, remaining concentrated around the supply line connection, while streaking downward onto the supply line on one specimen (Figure 15). The area of downward streaking denoted the surface of the supply line wetted by the engineered leak.

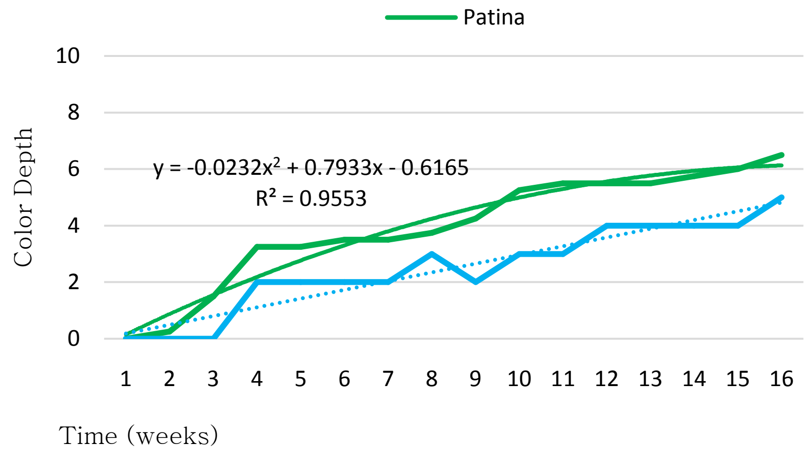

Figure 13. Patina progression time vs Color depth.

Figure 14. Corrosion—Average color depth 2.25 first appeared at the supply line connection on week 2 [19].

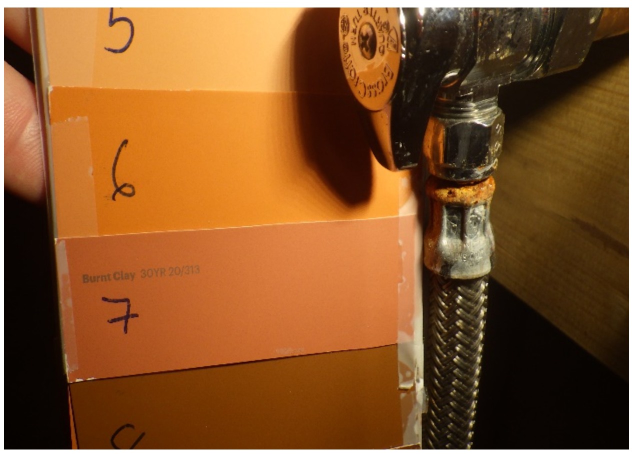

Figure 15. Corrosion—Average color depth of 6.75 at the end of the study, concentrated around the supply line connection [19].

The angle stop valve itself was in contact with both leaks and did not itself exhibit corrosion or patina, while adjacent components exhibited progressive corrosion and patina. Please refer to Table 1 and note that the angle stop valve body is brass which may exhibit patina as a copper containing metal alloy.

Figure 16 illustrates the physical data gathered depicted as the solid orange line, and corresponding trendline as the dotted orange line. The color depth was plotted against time and illustrates a gradual increase, which correlated to length of exposure time. A scaled logarithmic equation offered the best fit equation, which indicated that the data followed an initial sharp increase in color depth followed by a period of tapering toward asymptotic behavior. A longer period of data gathering would further illustrate this trend. Consequently, it may be concluded that deepening colors of corrosion require extremely extended time periods to occur and the ultimate color depth of 10 may never be reached.

The control specimen data and trendline were also depicted for comparison, by the solid and dotted blue lines, respectively. Corrosion on the control specimen may have been limited to initial oxidation of the outer protective layer of metal. The fact that the corrosion color depth leveled off at week 8 illustrated this phenomenon.

3.4. Accumulated Deposits

No accumulated deposits were observed nor measured throughout the duration of the study.

4. Conclusions

1) Patina and corrosion are accurate indicators of length of time of moisture exposure as colors progressively deepened upon extended water exposure.

2) Low-volume supply leaks are self-sealing over time. All of the leaks diminished with time and some of the drips were spontaneously sealed completely, on a weekly basis. It was theorized that minute, solid particles suspended within the water progressively lodged in the thread spaces and sealed the low-volume

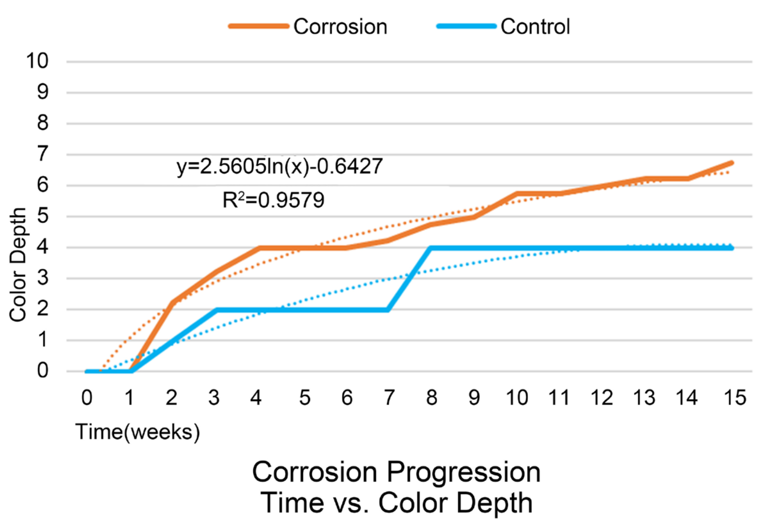

Figure 16. Corrosion Progression Time vs Color Depth.

drips. Secondly, thermal expansion and contraction of metal supply components likely played a role in spontaneously sealing the leaks, as metals expanded and contracted with daily and seasonal thermal cycles.

3) Corrosion first occurred and the most severe corrosion was noted on the supply line at the factory crimped connection below the upper nut. The surface was in direct contact with descending water from drips. Corrosion was first observed on supply line components on week 2. Consequently, it was logically concluded that wetted steel surfaces from plumbing leaks contained the most inherent potential risk to exhibit corrosion.

4) Patina occurred as faint spots over the surface of the pipe and not to the portion of the pipe that was in direct contact with water. Ambient moisture and/or humidity progressively caused the patina spots, as evidenced by the control sample which was not directly exposed to water and similarly exhibited patina spots.

5) Patina on the copper pipe adjacent to the supply valve compression nut was first noted to specimens 1 and 3 on week 7 of the experiment. The first attempt at measuring patina with the micrometer disturbed the patina. Consequently, in order to avoid affecting data, measurements were further taken only at the end of the experiment.

6) Minute accumulated patina was physically observed on the copper pipe directly below the drip location. When measured to the tenth of a millimeter, no appreciable built-up patina or accumulated deposits were able to be quantified, though.

7) Corrosion and patina on common angle stop supply valves necessarily takes very long time periods. No corrosion or patina was observed on the angle stop valve components although the valves were directly exposed to water from leaks.

8) Accumulated deposits were not observed, nor were appreciable changes in component dimensions noted throughout the 16-week length of the study which indicated that extremely prolonged time periods are required for deposits to accumulate.

9) Future repetitions of the same experiment and setup are necessary to provide a precise trendline equation which can be utilized in the field to analyze the duration of plumbing supply line leaks based on corrosion and patina color depth.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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