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Microbial susceptibility of various polymers and evaluation of thermoplastic elastomers with antimicrobial additives

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Abstract

The incursion of microbial growth on polymeric products can deteriorate their performance and lead to the development of undesirable staining and odors. A growing trend in the industry has aimed to reduce microbial populations on high-touch surfaces via the use of antimicrobials to protect material aesthetics and durability or to prevent the spread of pathogenic microorganisms. In this study, a variety of plastic substrates (30 unique polymer compounds), including poly(acrylonitrile-*co*-butadiene-*co*-styrene), poly(butylene terephthalate), poly(etherimide), various thermoplastic elastomers (TPEs), poly(carbonates), and poly(amides), were screened for susceptibility to microbial attack using American Society for Testing and Materials (ASTM) G21 (fungi susceptibility), Japanese Industrial Standard (JIS) Z2801, and modified ASTM E1428-15a (bacterial susceptibility) test standards. TPEs were determined to be most susceptible to microbial attack under the appropriate environmental conditions. Subsequent studies assessed the use of an antimicrobial additive, zinc pyrithione (ZPT), for potential efficacy in a variety of TPE blends for diverse target market applications. ZPT proved to be very effective in protecting TPEs, reducing *Staphylococcus aureus* and *Escherichia coli* populations by 99.9% or more in JIS Z2801 testing and inhibiting fungal growth (rating = 0) according to the ASTM G21 standard.

KEYWORDS

additives, antimicrobial, biological applications of polymers, blends, elastomers, thermoplastics

1 | INTRODUCTION

The global consumption of specialty biocides at the manufacturing sales level was approximately 1.7 million metric tons with a value of about $7.5 billion.[1] However, the usage of these additives is quite nominal in plastics ($180 million USD) and other hard surfaces.[2] The SARS-CoV-2 pandemic has brought to the forefront the necessity for customers to protect themselves in the environment in which they live, leading to a greater appreciation for disinfectant products in professional hygiene settings (airports, hospitals, schools, etc.) as well as home disinfection applications, such as laundry sanitization. Accordingly, this has also increased awareness and acceptance of specialty biocides in industries where there was previously some hesitancy for adoption (e.g., plastics). This renewed awareness for

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antimicrobial products has also illuminated the additional benefits they may offer as an additive for material preservation.

Concurrently, there is rising market demand for plastic products treated with antimicrobial additives for applications in packaging, automotive, consumer goods, medical and healthcare, building and construction, sporting goods, and electronics markets. The global antimicrobial plastics market is forecasted to grow significantly from 36.9 billion to 59.8 billion USD during 2020–2025, a compound annual growth rate of 10.1%.[3] Similar to the specialty biocides market, the outbreak of COVID-19 has undoubtedly increased consumer cognizance of high-touch plastic surfaces (e.g., phone cases, point-of-purchase equipment, shopping carts, etc.). This realization coupled with a growing understanding of the practical benefits of antimicrobial-embedded plastics for extending the useful life of products are believed to be primary drivers for recent market growth.

Apart from pathogenic microbes and their apparent impact on human health, bacteria and fungi can also cause staining, unpleasant odors, and deterioration of polymeric product performance over time.[4,5] To reduce the spread of infection through casual contact with contaminated plastic surfaces, or to extend the useful life of polymer products by preventing the development of said staining or odors, antimicrobial technologies can be employed.[6] For the latter scenario, the use of Environmental Protection Agency (EPA)-registered biocides in plastic components is allowable under the "Treated Articles Exemption" set forth by The Federal Insecticide, Fungicide, and Rodenticide Act, which enables polymeric articles to be treated for the purposes of material preservation or protection without additional registration requirements.[7]

Within the plastics industry, there are certain applications and products where biocides have already found significant usage. From a product-type viewpoint, flexible polyvinyl chloride (PVC) and poly(urethane)-foam-based applications have used biocides for decades.[8,9] PVC is especially vulnerable to attack from fungi and bacteria due to extensive plasticizer usage in flexible applications.[10] Poly(urethane) foams are another notable consumer of biocides because of their porous nature, which provides an ideal environment for microbes to grow.[11,12] Therefore, it is not surprising that many applications based on these two materials have significant usage of biocides; commonly, oxybisphenoxarsine or lower toxicity alternatives such as zinc pyrithione (ZPT) antimicrobials are employed.[10] Specific example applications include kitchen and bath accessories, swimming pool liners, carpet backing, sleep solutions like mattresses and pillows, roofing membranes, and tiles.

Other categories of antimicrobial applications within the plastics family include medical devices and technologies for odor prevention and aesthetics preservation. To reduce the incidence of device-associated infections, antimicrobial technologies have been utilized in a variety of ways ranging from bulk-imbedded additives to surface grafting techniques.[13,14] In particular, silver-based additive technologies are frequently explored for healthcare applications due to their favorable toxicological profiles and broader regulatory approvals, while silver nanoparticles with controlled, long-term release profiles continue to be a very active and promising area of biomedical research.[15-19] In textile segments such as sports activewear, biocides are used to prevent the growth of odor-causing bacteria from perspiration.[20,21] Additionally, high-end recreational products such as boats utilize biocides to preserve the aesthetics of PVC products used for seat covers since bacterial growth may lead to pink staining caused by specific bacterial metabolites.[22,23] With respect to the mechanism of action, many antimicrobial products work by attacking enzymes common to a variety of microbes, interfering with membrane transport processes (e.g., importing environmental copper into the cells) as well as interfering with iron metabolism pathways.[24,25]

Herein, an assortment of both rigid and flexible resins/compounds will be evaluated for susceptibility to determine whether particular resin chemistries or compounds are inherently vulnerable to microbial growth and subsequent degradation or other deleterious effects. A discussion of the EPA-registered biocide ZPT will be included as well as a study to evaluate the antimicrobial efficacy and resulting material properties for a variety of commercial thermoplastic elastomer (TPE) compounds containing ZPT.

2 | EXPERIMENTS

Microbial susceptibility screening for 25 different commercially available polymers and/or compounds was performed on injection-molded samples using a BOY 90E, 100-ton press (Boy Ltd., Rushden, Northants). A subset of samples was prepared utilizing a 2 × 6″ (5.08 × 15.24 cm) mold, 0.125″ (3.175 mm) thickness containing light stipple texture (T-2102) on the A-side, and smooth surface on the B-side (Industrial Mold and Machine, Twinsburg, Ohio). TPE samples were prepared by injection molding of 5 × 6″ (12.7 × 15.24 cm) plaques, 0.125″ (3.175 mm) thickness using a Milacron™ Roboshot™ S2000i (Milacron, Batavia, Ohio) with a polished mold surface. Samples were cut to size as specified by test standards.

To prepare samples with an active ingredient, a linear low-density poly(ethylene) masterbatch "AMPE 143101"

(Avient Corp., Avon Lake, OH) containing ZPT (Lonza Group AG, Morristown, New Jersey) was formulated into select grades of Versaflex™ and OnFlex™ GLS™ TPEs. These various elastomers contain a propriety combination of base resins, processing aids, fillers, stabilization packages, and other additives. The loading level of ZPT ranged from 1000 ppm to 3000 ppm in the final formulation. Samples were prepared via extrusion utilizing a Leistritz ZSE 27 mm co-rotating twin-screw extruder (Leistritz Advanced Technologies Corp., Nuremberg, Germany), followed by injection molding of $5 \times 6''$ (12.7×15.24 cm) plaques, 0.125″ (3.175 mm) thickness using a Milacron™ Roboshot™ S2000i.[1] For antimicrobial testing, specified test specimens were prepared from the aforementioned plaques. Physical and mechanical property testing was also performed on extruded pellets and/or specimens prepared from injection molded plaques. Durometer hardness was measured in accordance with American Society for Testing and Materials (ASTM) D2240 and values were reported following a 10-s delay. Specific gravity measurements were recorded as specified by ASTM D792. Tensile bars were die-cut (type IV) from plaques and tested at 20 in./min, 23°C in accordance with ASTM D638. Capillary viscosity was measured at 200°C using a Dynisco™ 7000 series capillary rheometer (Dynisco Instruments LLC, Franklin, Massachusetts) with a 15:1 L/D, 120° die geometry; a Bagley correction was applied. Color and haze measurements were taken using a Datacolor 650™ dual-beam spectrophotometer (Datacolor Holding AG, Lawrenceville, New Jersey) in transmission mode. The lightness (L^*) values, green–red (a^*) opponent values, and blue–yellow (b^*) opponent values defined by the International Commission on Illumination (CIE) color space were used to identify differences in color, and the yellowness index (YI) was measured in accordance with ASTM D1925.

Several standard test methods were employed to evaluate the microbial resistance of the polymer substrates, including Japanese Industrial Standard (JIS) Z2801, ASTM G21-15, and ASTM E1428-15a. The bacterial and fungal strains used in this study included *Escherichia coli* (American Type Culture Collection [ATCC] 8739), *Staphylococcus aureus* (ATCC 6538), *Aspergillus brasiliensis* (ATCC 9642), *Aureobasidium pullulans* (ATCC 15233), *Chaetomium globosum* (ATCC 6205), *Talaromyces pinophilus* (ATCC 11797), *Trichoderma virens* (ATCC 9645), and *Streptoverticillium reticulum* (ATCC 25607).

The JIS Z2801 for testing the antimicrobial activity of plastics quantifies the ability of the surface to kill bacteria; samples were inoculated with *S. aureus* and *E. coli*, which are commonly tested representatives for gram-positive and gram-negative bacteria, respectively. In brief, 3.8-cm^2 test pieces were prepared and placed in intimate contact with tryptic soy agar. The samples were then inoculated with nutrient broth containing $2–5.5 \times 10^5$ colony-forming units (CFUs) per milliliter of the organism of interest. After incubation for 24 h at 35°C/90% relative humidity, samples were plate counted, and the average number of CFU/sample was determined. Results are reported in mean CFU/sample over a 24-h period, and $\log_{10}$ reductions are calculated relative to a control substrate. A passing result for this method is >2 log reduction, indicating at least 99% of the bacteria on the surface were killed over the course of 24 h.

The ASTM G21-15 standard for determining the resistance of synthetic polymeric materials to fungi is a 28-day fungal test that qualifies the growth inhibition of a spore suspension containing five environmentally relevant fungal species: *A. brasiliensis*, *A. pullulans*, *C. globosum*, *T. pinophilus*, and *T. virens*. Test samples 3.8 cm^2 were placed in intimate contact with nutrient salts agar. The surface of both the agar and the sample was inoculated by spraying with the aforementioned spore suspension. Samples were incubated at 28–30°C and greater than 85% relative humidity for 28 days. Following the incubation period, samples were stained with methylene blue and examined for growth; a passing score for this test is not as strictly defined, but typically a rating of 0 or 1 is considered passing as this represents <10% sample coverage of visible fungal growth.

In addition, an internally modified version of the ASTM E1428-15a for evaluating the performance of antimicrobials in polymeric solids against staining by *Streptomyces* species (pink stain organism) was also used for susceptibility screening. This method tests the inhibition of growth of *S. reticulum*, which is a waterborne bacteria that secrete a pink-colored permanent stainant. To summarize, 3.8-cm^2 samples were sprayed with an inoculated agar slurry and incubated at 29°C for 14 days. Following the incubation period, the samples were examined for the presence of visible colonies in the inoculated agar slurry. The agar was rinsed from the surface, and the samples were reexamined for the presence of staining. Staining is reported as a percentage of sample surface exhibiting staining, wherein <10% stain coverage is typically considered a passing result.

3 | RESULTS AND DISCUSSION

Initial microbial susceptibility screening showed failures across nearly all substrates as it pertains to JIS Z2801 (Figure S1) and ASTM E1428-15a testing, which are both bacterial methods. The only exception to these results was the high-performance engineering resins polyetherimide (PEI) and poly(sulfone), which demonstrated

0% stain coverage following a post-wash of the inoculated agar slurry (see Figure 1; Table S1). However, it should be noted that these resins still exhibited bacterial growth (>100 visible colonies) prior to the washing and did not reduce bacterial growth during JIS Z2801 testing (Figure S1). The initial screening also included an evaluation of whether a stipple texture (T-2102) on the part surface plays any role in susceptibility to microbial growth. Textured surfaces are commonplace in the injection molding industry, and the increased surface area contributed by the irregular microscale topologies of a textured mold was hypothesized to promote microbial growth based on previous literature.[26-28] Interestingly, when testing smooth versus textured samples in direct comparison using JIS Z2801 method with *E. coli*, no significant differences ($p < 0.05$) or obvious trends were perceived (Table S2). For ASTM G21-15, most polymer compounds also exhibited marginal or no change in fungal growth with the added texture, except for nylon-6; trace growth (rating = 1) was observed on the smooth surface while heavy growth (rating = 4) occurred on the textured surface. Overall, the most notable distinctions were observed during ASTM G21-15 fungal resistance testing on smooth plaque surfaces, which exhibited variable growth ratings for the polymer substrates, as shown in Table 1.

The various susceptibility tests performed herein clearly showed the vulnerability of TPE formulations; all six formulations exhibited heavy fungal growth, in addition to failing JIS Z2801 (with higher median bacterial growth relative to the control film) and modified ASTM E1428 testing with complete pink stain coverage. These results made TPEs an attractive candidate for modification with antimicrobial additives for the preservation of the TPEs in their end product use and for further efficacy studies.

Among commercially available biocidal additives, ZPT and 2-butyl-1,2-benzisothiazolin-3-one (BBIT) were considered for use to reduce the microbial susceptibility of TPE compounds. While BBIT possesses higher thermal stability (ca. 300°C) than ZPT ($T_{d,5\%\ loss} = 260$°C), it also becomes increasingly volatile at temperatures in excess of 175°C (Figure S2). Without proper engineering controls, this would challenge the applicability for TPEs under normal thermal processing conditions for extrusion and molding. Furthermore, zinc-based antimicrobials tend to

TABLE 1 Summary of ASTM G21 results for initial susceptibility screening of untreated resins/compounds

Fungal growth	Resin/compound
4 = Heavy growth (61%–100% coverage, fail)	TPE, 6 formulations
3 = Moderate growth (31%–60% coverage, fail)	Poly(urethane), 2 formulations
2 = Light growth (11%–30% coverage, fail)	Nylon-6,10, PBT, poly(amide) elastomer, ABS, 3 formulations, reinforced Nylon, 2 formulations
1 = Trace growth (<10% coverage, pass)	CoPET, 2 formulations, Nylon-6, Nylon-12, PEI, poly(sulfone), poly(carbonate), 2 formulations

Abbreviations: ABS, acrylonitrile-*co*-butadiene-*co*-styrene; ASTM, American Society for Testing and Materials; CoPET, copolyester; PBT, poly(butylene terephthalate); PEI, poly(etherimide); TPE, thermoplastic elastomer.

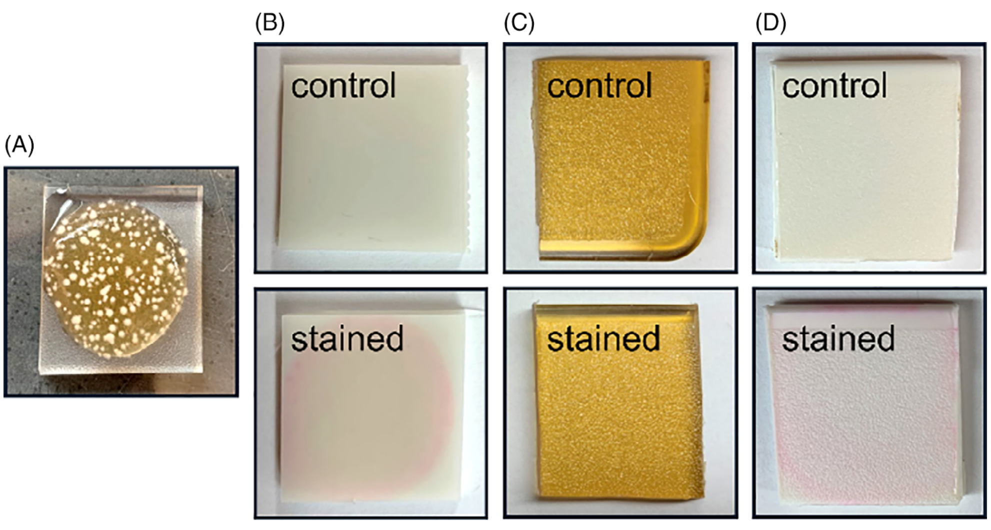

FIGURE 1 Representative images for American Society for Testing and Materials E1428-15a testing wherein (A) demonstrates bacterial growth on a polymer substrate prewash and comparative images exhibiting varying levels of pink stainant caused by bacterial growth and secondary metabolites for substrates including column (B) a thermoplastic elastomer blend, (C) poly(etherimide), and (D) poly(butylene terephthalate). Control samples (top row) are shown for comparison to samples post-incubation and washing (bottom row)

present broad-spectrum efficacy, a more favorable economic position relative to alternative transition metal counterparts (i.e., silver and copper-based antimicrobials), and have a long history of use in anti-dandruff shampoo and soaps.[29,30] For these reasons, ZPT was elected for further study.

In the evaluation of ZPT-containing compounds, 34 distinct TPE formulations were produced, with each group being represented by various commercially active grades of Versaflex™ or OnFlex™ GLS™ elastomers. These grades are differentiated by market application, formulation, and processing parameters. They represent a wide variety of resins and/or resin mixtures, processing aids, and stabilization packages used in current TPE technologies. Products manufactured on different compounding lines also have unique processing conditions, including but not limited to variations in screw design, residence time, and processing temperatures. For a baseline understanding, ZPT was compounded into these aforementioned products at nominal loading levels ranging from 1000–3000 ppm. It can be seen in Table 2 that even at lower loadings (i.e., 1000–1500 ppm) ZPT was quite effective at limiting fungal growth; most experimental groups demonstrated no observable growth (rating = 0), whereas control samples (i.e., ZPT loading = 0 ppm) generally exhibited heavy fungal growth (rating = 4). Thus, the robust antifungal activity of ZPT was confirmed for the various TPE compounds in this study and is in agreement with previous reports which have demonstrated efficacy via zone of inhibition assays for ZPT-containing polymeric substrates.[31-33]

In addition to antifungal activity, bacterial resistance properties were tested. Two of the most common gram-negative (*E. coli*) and gram-positive (*S. aureus*) bacteria were tested using JIS Z2801 method for insight to bactericidal properties of ZPT-containing TPEs. Figure 2 shows the performance of a select series of Versaflex™ and OnFlex™ GLS™ TPEs with a range of ZPT additive (1000–3000 ppm). In general, it can be seen that untreated control compounds provided a favorable growth substrate for bacteria under the environmental conditions specified by the test method. More notably, however, ZPT-loaded samples demonstrated a clear reduction in the average number of CFUs after 24 h. Although statistical significance could not be determined, a large effect size ($d > 1$) as described by Cohen's d was observed for all treatment groups relative to their respective controls. For TPE compounds tested containing 1000–1500 ppm of ZPT, all exhibited ≥3-log reductions (99.9%) in *E. coli* and ≥4-log reductions (99.99%) in

TABLE 2 ASTM G21 results for control and ZPT-loaded Versaflex™ and OnFlex™ TPE line products

Sample	Market application	ZPT loading (ppm)	28-day rating[a]
GP 2810-40N	Consumer overmold	0	4
		1000	0
		3000	0
CE 3120-65	Consumer electronics	0	4
		1500	0
		3000	0
LO 7120-45B	Automotive and HVAC	0	4
		1500	0
		3000	0
CL2242	Medical	0	4
		1500	2
		3000	0
HC BT218	Medical	0	2
		1500	0
		3000	0
G2705N	Consumer health/medical	0	4
		1500	0
		3000	0

Abbreviations: ASTM, American Society for Testing and Materials; HVAC, heating, ventilating, and air-conditioning; TPE, thermoplastic elastomer; ZPT, zinc pyrithione.
[a]Numerical rating according to ASTM G21-15 where 0 indicates no growth and 4 indicates heavy growth (61%–100% sample coverage).

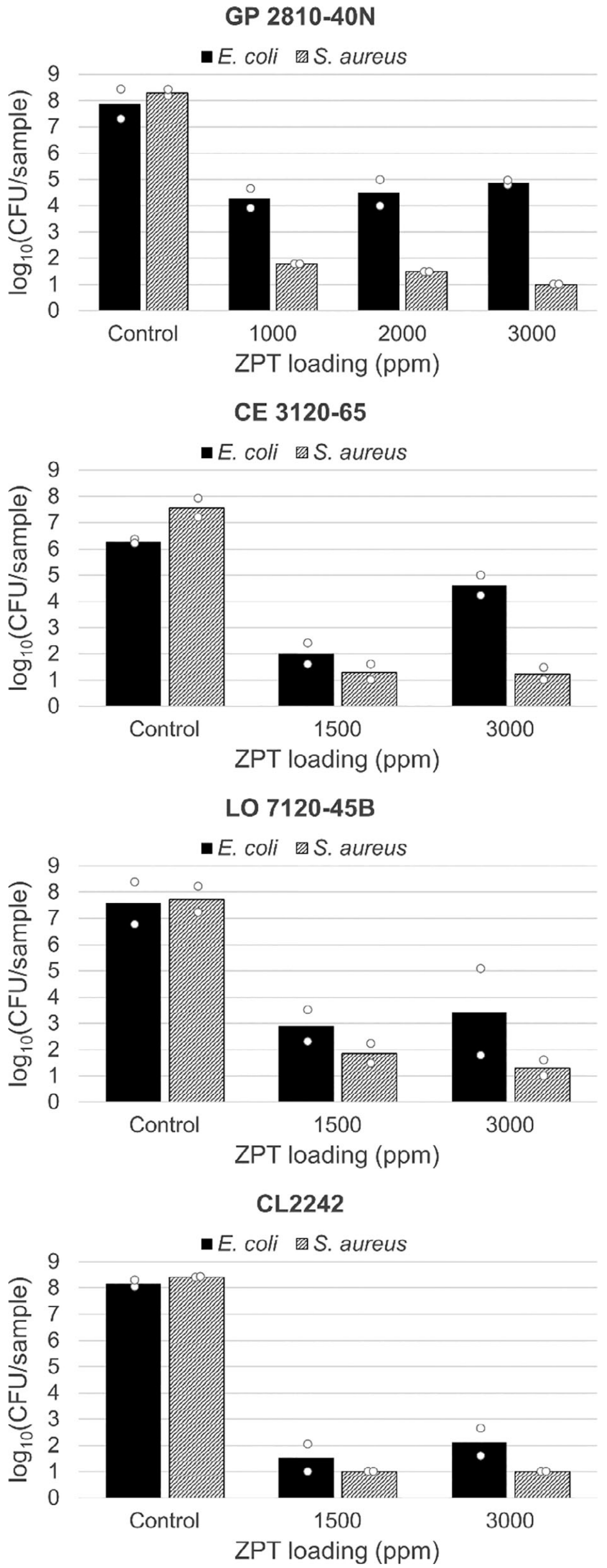

FIGURE 2 Results of Japanese Industrial Standard Z2801 testing for various GLS™ thermoplastic elastomer line products; 24-h bacteria viability reported in mean CFU/sample is plotted for a series of samples with increased ZPT loading. All samples were tested in duplicate ($n = 2$); the bar graph represents the average, and the open circles represent the $\log_{10}$-transformed raw data. CFU, colony-forming unit; ZPT, zinc pyrithione

S. aureus. Interestingly, increased loadings of ZPT did not appear to consistently reduce microbial growth further; for *E. coli*, the higher loadings (nominally 2000 and 3000 ppm) appear to have exhibited the same activity or less. It is possible that increased efficacy was not seen with increased loadings due to an activity threshold for ZPT (potentially limited by environmental copper availability) in which no significant trend truly exists upon increasing the active content in the sample beyond 1000–1500 ppm.[18,24] Furthermore, it appears from Figure 2 that the ZPT-containing samples may have shown slightly enhanced activity toward *S. aureus*. This is in contrast to literature reports wherein various silver and zinc-based antimicrobial compounds tend to demonstrate higher efficacy toward *E. coli* than *S. aureus*; however, several reports have also observed an enhancement in efficacy toward *S. aureus* for ZPT, and it should be noted that the minimum inhibitory concentration of ZPT in solution is comparable for these two bacteria.[18,19,31-34]

Several physical and mechanical properties were evaluated to detect variations when compounding ZPT into the various Versaflex™ and OnFlex™ TPE products. In brief, minimal to no changes were observed as exemplified by the results shown for GP 2810-40N in Table 3. Specific gravity and tensile properties remained mostly unchanged. An observable increase in Shore A durometer hardness occurred relative to the control with increased ZPT loading. For some products, the capillary viscosity was slightly affected by the presence of antimicrobial; however, viscosity changes were not consistent across sample groups. It should be noted that some property deviations may also be contributed in part by the carrier used to deliver the ZPT as well as experimental error. The most notable physical change that occurs when incorporating ZPT to TPE compounds is a loss in sample transparency accompanied by a slight yellow color shift. YI and opacity are increased as ZPT loading increases, and processing at high temperatures or extensive residence times appear to result in further yellow-shifting (Figure S3). Clarity and yellowness remains an industry challenge for thermoplastics with bulk-imbedded antimicrobial additives.

Lastly, a brief study was performed to address clarity and yellowness in a clear TPE product (Versaflex™ CL3000-80). The loading of ZPT was reduced from 1500 to 1250, and 750 ppm, and a blue tint colorant masterbatch was added at two levels, 3% and 6% by weight of the final compound. It was determined that haze and YI increased in roughly linear fashion with increased ZPT loading level (Figure 3A). It can also be seen in Figure 3B that the reasonable contact clarity is achievable, but the haze is very apparent (ca. 30%) when the sample is not directly in contact with the desired substrate. Notably, the addition of blue tint can effectively decrease the YI to a level below

TABLE 3 Typical physical and mechanical properties observed for Versaflex™ GP 2810-40N thermoplastic elastomer with increasing zinc pyrithione (ZPT) loading levels

		ZPT loading (ppm)		
Property	**Control**	**1000**	**2000**	**3000**
Specific gravity (g/cm^3)	0.877 ± 0.001	0.877 ± 0.001	0.878 ± 0.001	0.879 ± 0.001
Hardness, Shore A	37.2 ± 1.7	39.0 ± 1.2	40.2 ± 1.4	41.1 ± 1.9
Tensile strength (MPa)	3.45 ± 0.14	3.58 ± 0.19	3.63 ± 0.16	3.57 ± 0.26
Tensile elongation (%)	712 ± 22	696 ± 24	667 ± 16	679 ± 31
300% modulus (MPa)	1.65 ± 0.12	1.73 ± 0.10	1.86 ± 0.12	1.78 ± 0.12
Viscosity at 1340 s^{-1} (Pa s)	38.5 ± 2.5	40.1 ± 1.6	38.9 ± 1.3	39.8 ± 0.9
Viscosity at 11 170 s^{-1} (Pa s)	7.8 ± 0.3	8.1 ± 0.4	8.0 ± 0.4	8.5 ± 0.4

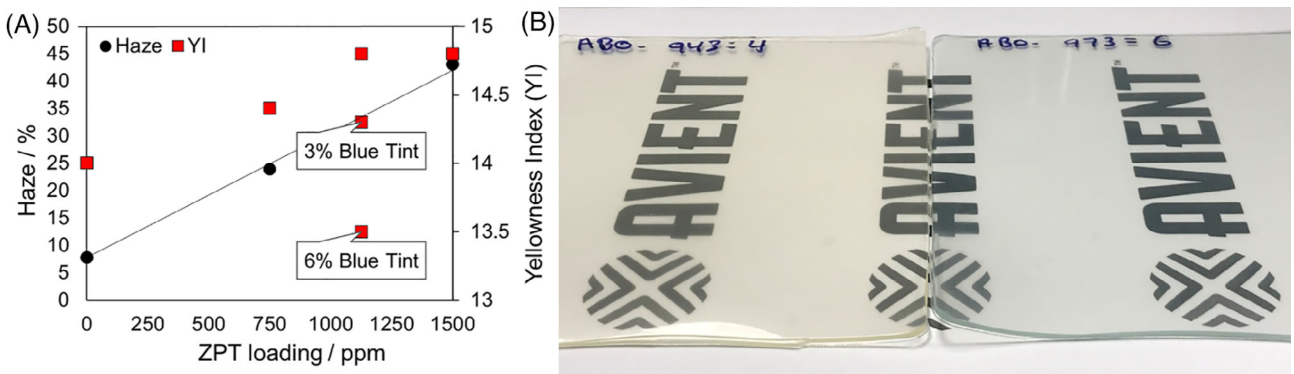

FIGURE 3 (A) A plot of haze and yellowness index as a function of zinc pyrithione (ZPT) loading level shows a relatively monotonic relationship as well as a clear reduction in yellowness index with the addition of blue tint. (B) Photograph comparing samples containing equivalent loadings of ZPT; natural color plaque (left) and a plaque containing blue tint masterbatch (right)

that seen for the control TPE (i.e., ZPT loading = 0 ppm), further improving the aesthetics of the sample.

4 | CONCLUSIONS

In this investigation, an evaluation of microbial susceptibility using antifungal (ASTM G21-15) and antibacterial (ASTM E1428-15a and JIS Z2801) test methods was performed for a wide variety of thermoplastic resins and compounds. The bacterial assays demonstrated that *E. coli*, *S. aureus*, and *S. reticulum* were able to survive on all thermoplastic substrates tested herein; no statistically relevant reductions during JIS Z2801 testing were observed for the untreated polymer compounds (Figure S1). All substrates also exhibited heavy bacterial growth (>100 colonies) prior to washing during ASTM E1428-15a pink stain testing, with only PEI and polysulfone demonstrating resistance to staining (Figure 1; Table S1). Furthermore, an investigation of smooth versus textured surfaces containing a light stipple texture (T-2102) was performed but did not demonstrate significant differences ($p < 0.05$) in JIS Z2801 testing with *E. coli* (Table S2). Only polyamide-6 exhibited a notable change in fungal growth from trace (rating = 1) to heavy (rating = 4) when comparing smooth and textured surfaces, respectively. Overall, the most prominent differences between polymer substrates were observed during ASTM G21-15 antifungal testing of smooth surface samples, in which all six TPE formulations suffered from heavy fungal growth (rating = 4). TPE formulations also exhibited higher median growth than the control film in JIS Z2801 (Figure S1) testing and full stain coverage in ASTM E1428-15a (Table S1), which exemplified their vulnerability to microbial attack and prompted additional experiments to screen the antimicrobial efficacy of ZPT in TPEs.

A case study for various commercial Versaflex™ and OnFlex™ TPEs formulated with 1000–3000 ppm of ZPT demonstrated the ability to reduce microbial growth via the incorporation of antimicrobial additives. ZPT-containing TPEs inhibited the growth (rating = 0) for a mixture of environmentally relevant fungal species during ASTM G21-15 testing (Table 2) and also yielded ≥3-log reductions (99.9%) in *E. coli* and ≥4-log reductions

(99.99%) in *S. aureus* at ZPT loadings of 1000–1500 ppm (Figure 2). While physical and mechanical properties were generally retained (Table 3), clarity and YI were impacted by the addition of ZPT biocide; reasonable contact clarity can be achieved for thin-walled parts, and yellowness can be compensated for through the use of blue tint additives (Figure 3), but achieving high clarity and non-yellowing antimicrobial formulations remains a challenge in this field. All in all, ZPT proved to be a highly effective additive in protecting various TPEs from fungal and bacterial growth, and it is expected that this can extend the useful life of TPE products by preventing microbiological degradation and the development of staining, odors, and unsightly growth.[4,5,34] However, it should be noted that leaching of bulk-imbedded biocides from the polymer substrate is required to exert antimicrobial action, and the long-term effectiveness and release of ZPT from these compounds are currently unknown.[16,31,35-37] Future studies are required in order to determine the true durability of the compounds when exposed to the specific environmental conditions of the end-use target applications (e.g., surfactant washes, humidity cycling, fluid contact, weathering).

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ENDNOTE

[1] Milicron™ is a registered trademark of Cincinnati Milacron Inc.; Roboshot™ is a registered trademark of Fanuc Corporation; Versaflex™, OnFlex™, and GLS™ are registered trademarks of Avient Corporation; Dynisco™ is a registered trademark of Dynisco LLC; Datacolor 650™ is a registered trademark of Datacolor Holding AG.

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