United States
Consumer Product Safety Commission

May 2023

CPSC Staff[1] Statement on Forcon International report "Task II Report"

The voluntary standard ASTM F462 *Standard Consumer Safety Specification for Slip-Resistant Bathing Facilities* has been withdrawn since 2016. To support the work of CPSC staff in this area and the ASTM Subcommittee's consideration of a replacement standard, CPSC awarded contract 61320621P0035 to Arizona State University (ASU) to perform three tasks:

1) Conduct literature review of existing standards and studies and determine appropriate tribology method to evaluate bathing surfaces. (ASU subcontracted this task to Forcon International)
2) Develop test surfaces for tribometer measurement and human slip research to evaluate slip-resistance on bathing surfaces. (ASU subcontracted this task to Forcon International)
3) Conduct human research study to evaluate slip/fall on test surfaces developed in Task 2, with focus on older populations.

The report titled, "Task II Report," presents the results of work by Forcon International on Task 2. The contractor developed four types of exemplar reference bathing surfaces (porcelain-enamel, embossed plastic, polymer composite, and mosaic tile) for use in human research study to evaluate slip-resistance. Friction levels were measured using the Pendulum method described in the Task I report, generated for this contract. In general, friction data was obtained on small diameter prototypes, and then if the design was deemed appropriate for human testing, a larger version was created for the human slip tests.

This work will assist CPSC staff as they continue to work to improve the safety of bathing surfaces, including working with the ASTM F15.03 Subcommittee on Bathtub and Shower Structures and other interested parties.

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[1] This statement was prepared by the CPSC staff, and the attached report was produced by Forcon International for CPSC staff. The statement and report have not been reviewed or approved by, and do not necessarily represent the views of, the Commission.

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CPSC PROJECT 61320621Q0068

TASK II REPORT

October 13, 2022 – John Leffler, PE

1. Introduction

1.1. The goals of and context for this project are described in the Performance Work Specification (PWS) “Background” section. A key purpose for the project is to provide the technical foundations required for a modernized version of the obsolete and withdrawn ASTM F462 standard for bathing surface friction. This planned modernized version is referred to as “F462+”.

1.2. The PWS describes the overall scope of Task II, as delineated into two sections and seven subtasks. The Contractor responses to these subtasks incorporate qualifiers defined in the bid documents accepted by CPSC.

1.3. This report contains references to other reports; it is recommended that the **Task I Report** be reviewed as background. Other than the **Task I Report**, which is lengthy, references in bold type can be found by using the PDF bookmarks.

2. Background

2.1. The overall project’s work is split into two general technical fields as follows:

2.1.1. **Human testing**: Multi-subject human testing of the barefoot friction of “reference surfaces” (RSs) intended to represent typical bathing surface (bathtub and shower standing surface) environments. The human testing is intended to be conducted utilizing test subject populations representative of those more affected by bathing surface slip events. This work is conducted by Arizona State University (ASU).

2.1.2. **Tribometry methodology**: Development of the needed RSs in conjunction with development of a practicable friction test methodology suitable for evaluation of new and installed bathing surfaces without the need for convening scenario-specific human testing. The RSs and method are interrelated; neither can be standalone. This work is conducted by Forcon International.

2.2. Task II as stated in the PWS is focused on the development of four types of RSs: porcelain-enamel, embossed plastic (vacuum-formed sheet polymer), polymer composite (e.g., gelcoat/fiberglass), and mosaic tile – and on development of a tribometer test method for friction testing of RSs. A key concept of this project is to develop RSs that represent “threshold” surfaces that are just-adequate when it comes to frictional performance in human testing; in F462+, these threshold RSs would be the tribometer testing frictional benchmark, defining the minimum friction measurement value to be obtained on an acceptable bathing surface.

3. Methods

3.1. Task II-1a (Identification and development of ‘reference samples’ representative of surfaces involving adult slip/fall on bathing surfaces including: porcelain-enameled metal, polymer/composite, embossed plastic, and mosaic tiled surfaces representative of bathing surfaces): **Evaluation of feasible frictional homogeneity of “reference sample” surfaces from a manufacturing standpoint, and from the standpoint of relevance (of the reference surfaces) to bathtub/shower mass production.**

3.1.1. See section 2 of the **Task II Draft Plan** (dated October 2, 2021). The methods in that section were proposed before the actual work began; the Results section 4.2 below describes what actually happened.

3.2. Task II-1b: (Identification and development of “reference samples” representative of surfaces involving adult slip/fall on bathing surfaces including: porcelain-enameled metal, polymer/composite, embossed plastic, and mosaic tiled surfaces representative of bathing surfaces): **Evaluation of feasibility of cross-manufacturer standardization of certain geometric elements (e.g., pattern and size) of friction feature design.**

3.2.1. See section 3 of the **Task II Draft Plan**. The methods in that section were proposed before the actual work began; the Results section 4.3 below describes what actually happened.

3.3. Task II-1c: (Identification and development of “reference samples” representative of surfaces involving adult slip/fall on bathing surfaces including: porcelain-enameled metal, polymer/composite, embossed plastic, and mosaic tiled surfaces representative of bathing surfaces): **Providing a range of friction levels (through the use of different friction features) to facilitate informed conclusions about which surface(s) represent an adequate “minimum threshold” for surface friction.**

3.3.1. See section 4 of the **Task II Draft Plan**. The methods in that section were proposed before the actual work began; the Results section 4.4 below describes what actually happened.

3.4. Task II-2a: (Development [or adaptation] of a tribometry test method that can be used for standardized testing of bathing surfaces): **Evaluation of homogeneity of “reference sample” surfaces from a friction measurement standpoint.**

3.4.1. See section 5 of the **Task II Draft Plan**. The methods in that section were proposed before the actual work began; the Results section 4.5 below describes what actually happened.

3.5. Task II-2b: (Development [or adaptation] of a tribometry test method that can be used for standardized testing of bathing surfaces): **Correlation of testing slightly concave manufactured bathing surfaces to testing of flat reference surfaces.**

3.5.1. See section 6 of the **Task II Draft Plan**. The methods in that section were proposed before the actual work began; the Results section 4.6 below describes what actually happened.

3.6. Task II-2c: (Development [or adaptation] of a tribometry test method that can be used for standardized testing of bathing surfaces): **Method addressing tribometer testing of surfaces with variations in geometric elements (e.g., pattern and size) of friction feature design.**

3.6.1. Section 7 of the **Task II Draft Plan** addressed this subtask but not in a useful way. See Results section 4.7 below.

3.7. Task II-2d: (Development [or adaptation] of a tribometry test method that can be used for standardized testing of bathing surfaces): **Method for tribometer testing of 3D-profiled/patterned surfaces.**

3.7.1. Section 8 of the **Task II Draft Plan** addressed this subtask but not in a useful way. See Results section 4.7 below.

4. Results

4.1. As will be described below, in this project 12 porcelain-enamel “2Dxx” RS candidate designs were friction tested, as were 23 vacuum-formed sheet plastic “3Dxx” RS candidates, 5 gelcoat/fiberglass and simulated gelcoat/fiberglass “3DFxx” RS candidates, and 3 grooved ceramic tile “3DMxx” simulated mosaic tile RS candidates. Friction levels were measured using the Pendulum method described in **Task I Report** section 4.5.1.5.1 and 4.5.2.

4.1.1. As of the date of this report, ASU has been sent the following RSs. In general, friction data for designs was first obtained on ~152mm [6”] diameter prototypes, and then if the design was deemed appropriate for human testing, a larger version suitable for nearly covering a 457mm [18”] square RS backing board was created.

4.1.1.1. Porcelain-enamel ASU RSs: 2D11, 2D13, 2D14, 2D17

4.1.1.2. Vacuum-formed ASU RSs: 3D27, 3D31, 3D35

4.1.1.3. Gelcoat/fiberglass ASU RS: 3DF08

4.1.1.4. Simulated gelcoat/fiberglass ASU RSs: 3DF02, 3DF04

4.1.1.5. Simulated mosaic tile ASU RSs: 3DM01, 3DM02

4.1.1.5.1. Additional design 3DM03 is being re-fabricated and will be delivered to ASU in the near future. The original one was delayed due to the supplier shipping to the wrong address, it was also broken in transit, and obtaining a replacement tile (as a basis for the re-fabrication) has been time-consuming.

4.1.2. The compiled friction test data (for all designs) is posted on Watchdox as “DataCompilation.xlsx” and in attached PDF printouts **2D-DataCompilation.pdf**, **3D-DataCompilation.pdf**, **3DF-DataCompilation.pdf**, and **3DM-DataCompilation.pdf**. The documented friction data for ASU RSs 2D11, 2D13, 2D14, 3D31, and 3DF02 was obtained on smaller prototype versions. Friction data for ASU RS 3D27 was obtained on the smaller 3D28 prototype which had the same geometry.

4.1.3. In a CPSC Watchdox folder entitled “Forcon\Task II\High speed MP4 video files” are the high-frame-rate video MP4 files associated with certain friction tests (as tabulated in DataCompilation.xlsx). In a Watchdox folder entitled “Forcon\Task II\Photos” are photos taken in association with the project.

4.2. Task II-1a (Identification and development of ‘reference samples’ representative of surfaces involving adult slip/fall on bathing surfaces including: porcelain-enameled metal, polymer/composite, embossed plastic, and mosaic tiled surfaces representative of bathing surfaces): **Evaluation of feasible frictional homogeneity of “reference sample” surfaces from a manufacturing standpoint, and from the standpoint of relevance (of the reference surfaces) to bathtub/shower mass production.**

4.2.1. Any understanding of the feasible and achievable frictional homogeneity of prospective F462+ RSs is almost entirely dependent upon the cooperation of bathing surface manufacturers. It is their processes that facilitate whatever homogeneity there is to be, and their industry that needs to have processes in place that could feasibly manufacture RSs to be used in an F462+ standard[1].

4.2.1.1. One manufacturer of bathing surfaces provided general input on their vacuum-forming and porcelain-enameling manufacturing processes. The engineer from this company was not able to state whether their processes were representative of what other manufacturers in the industry use. This manufacturer provided a supply of the ~2mm [0.08”] thick acrylic sheet they use for their bathtubs; this material was used for Forcon’s initial vacuum forming of prototype RSs.

4.2.1.2. Beyond this, multiple presentations were made to bathing surface manufacturers at three American Society of Mechanical Engineers (ASME) A112 / Canadian Standards Association (CSA) B45 conferences and at two special meetings of Plumbing Manufacturers International (PMI) regarding the project goals. The ASME A112 / CSA B45 committee writes the codified standards for porcelain-enameled plumbing fixtures including bathtubs and shower bases. The PMI meetings contained more technical details of the scientific challenges, the confidentiality that Forcon could provide, the benefits (to manufacturers) in cooperating, and the key questions that were going to be most useful in developing RSs. See the attached presentation slides **A112presentation011820.pdf**, **PMIpresentation062021.pdf**, **PMIpresentation101421.pdf**, and **A112presentation011322.pdf**. All presentations included time for attendees to ask questions. However, no other manufacturer responded in any way outside of the presentations.

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[1] An informative parallel is with the tile industry and the production of ASTM F2508 RSs – the tile industry is not one that has typically needed to produce particularly homogenous products.

4.2.1.3. In the absence of manufacturer cooperation, characterizations of the frictional homogeneity of existing products from existing manufacturers could be done, but these would be lacking in foundation unless large cross-sections of sample sizes were analyzed – and such information would only be empirical.

4.2.1.4. On the topic of manufacturer cooperation, of the four types of bathing surfaces that were to be evaluated in this project, only porcelain-enamel has a manufacturing process that is basically unachievable without very specialized equipment. Qualified porcelain-enamel vendors and job shops were sought out when it became apparent that no manufacturer cooperation was forthcoming. Consultation with the Porcelain Enamel Institute and the contacting of most all listed members resulted in no job shops interested in assisting with the creation of reference surfaces. As such there has been no input from even a job shop about what sort of homogeneity this enameling process is likely to result in.

4.2.1.5. In the **Task II Draft Plan** it was surmised that for porcelain-enamel surfaces, surface roughness could be used for homogeneity characterization, but further inquiry revealed that such measurements would not be effective on surfaces that have disparate friction features; some production porcelain-enamel bathing surfaces have a comparatively scant scattering of particles on an otherwise “smooth” vitrified surface. This would not lend itself to 2D profilometry-based surface roughness characterization. The use of 3D noncontact surface roughness characterization is possible but requires very expensive equipment, and as such, testing is expensive. In the absence of manufacturer cooperation, in the form of production-achievable surface exemplars, there was basically nothing to test for homogeneity. It is also worth noting that underfoot surface roughness has a debatable correlation to human slip experiences[2]; the use of surface roughness in this project would be limited to homogeneity characterization.

4.2.1.6. As for the homogeneity of 3D-profiled polymer composite and embossed plastic bathing surfaces, these are simultaneously more challenging and less important to characterize. With 3D bathing surface friction features in general, it is a grosser mechanical interlocking with the human foot that provides friction, and as such, fine details of localized surface microroughness or feature pattern amplitude/period consistency will be comparatively less important because of the millimeter-scale height of typical friction features on such surfaces. Indeed, the one manufacturer that provided some input stated that

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[2] Chang WR et al. The role of surface roughness in the measurement of slipperiness. *Ergonomics* 2001, vol. 44, no. 13, 1200-1216.

close tolerance control of vacuum-formed bathing surface friction feature geometry is not something that they focus on too much. Further, the opportunities for creating shapes and patterns of 3D features are effectively unlimited for polymer composite bathing surfaces, and it is only somewhat limited by the peculiarities of vacuum forming for embossed plastic bathing surfaces. And the plastic bathing surface industry has never adopted a friction standard, so a significant limitation on what patterns they could produce would likely be a non-starter. It is possible that given some plastic RS designs that appear to be good threshold surfaces (based on human testing), the friction feature designs could be varied slightly, to simulate inhomogeneity and explore the effects on tribometer measurements. However, due to the aforementioned unlimited range of feature design options, knowledge gained about the effect of moving one design's features some small distance will not be generalizable to other designs. As well, human slip research results sufficient to identify a project plastic RS as a candidate threshold surface were not provided in time to conduct such a dimensional inhomogeneity study for discussion in this report.

4.2.1.7. As for mosaic surfaces, which are being simulated through the use of grooving of USC3 Tile E ceramic tiles[3], there is data on the top surface homogeneity of such tiles, though the homogeneity of the grooving will not be something that is readily characterized – nor is it relevant to actual production mosaic tile mesh-backed sheets. Here again, it is the grosser deformation of the bare foot bottom into the grooves that provides frictional resistance, meaning that the geometric consistency of groove widths and depths will be less important. Further, in production use, grout gaps are filled to varying degrees with grout, using a manual process, and the grout is available in different formulations (e.g., some contain gritty sand). The homogeneity (for tribometry) of the simulated mosaic surfaces has two elements: the homogeneity of the top surface, and the homogeneity of the simulated grout joints (grooves). The former has been studied by Carl Strautins though he used water instead of the SLS solution used in this project; he reported an uncertainty of approximately 3 PTV. The homogeneity of the grout grooves bears additional discussion. As cut, these grooves have a sharp top edge (that would contact the slider); it is necessary for both tribometry and human safety to grind the sharp edge so that it is not sharp. Forcon used a grinding stone to smooth the sharp top edges of RSs 3DM01 and 3DM02, to the point of passing the UL 1439 sharp edge test[4]. Grinding of a hard and brittle ceramic edge (just to the point where it is not sharp) is not a precise process, however, in the absence of automated machinery. The only way to potentially characterize the

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[3] M. G. Blanchette, J. Lee-Confer, J. R. Brault, B. Rutledge, B. S. Elkin, and G. P. Siegmund. Human Slip Assessment of Candidate Reference Surfaces for Walkway Tribometer Validation: An Update to Standard ASTM F2508. *Journal of Testing and Evaluation*. https://doi.org/10.1520/JTE20210240.

[4] UL1439-2015. Standard For Tests For Sharpness Of Edges On Equipment. Northbrook, Illinois; Underwriters Laboratories

homogeneity of the grooves would be through tribometry. But because the groove-slider contact represents such a small fraction of the RS-slider contact trajectory overall, and because the friction measurements will be position-specific, homogeneity of the grooves defies straightforward evaluation.

4.2.2. Given the lack of manufacturer or job shop cooperation, Forcon had to fabricate all the RSs used in this project - except for the simulated mosaic surfaces. The homogeneity of the RSs Forcon created is irrelevant to production bathing surfaces.

4.2.3. The only evidence of mass-produced bathing surface product homogeneity may be when the eventually chosen threshold RSs are produced in quantity – which is separate from this project scope. Then when the threshold homogeneity data is documented within the standards development process, the manufacturers will be free to comment on the homogeneity of these RSs. Under the ASTM consensus process (and standards development processes in general) the manufacturers are free to choose not to participate in the solution and then to later approve or reject the solution.

4.3. Task II-1b: (Identification and development of “reference samples” representative of surfaces involving adult slip/fall on bathing surfaces including: porcelain-enameled metal, polymer/composite, embossed plastic, and mosaic tiled surfaces representative of bathing surfaces): **Evaluation of feasibility of cross-manufacturer standardization of certain geometric elements (e.g., pattern and size) of friction feature design.**

4.3.1. The *necessity* for standardization of friction feature geometric elements would arise (in the context of F462+) if reliable friction testing requires such standardization; the *feasibility* of standardization is a related question. The concept of any standardization of friction feature geometry and characteristics has been strongly resisted in discussions with bathing surface manufacturers. It has always been Forcon's goal, in this project and back to 2017, to avoid suggesting any more constraints on the manufacturers than is necessary. However, the unique characteristics of 3D friction features in particular are such that reliable methods may require certain limitations on pattern feature geometry. Nevertheless, the “standardize first” approach of **Task II Draft Plan** section 3.1 changed over time based on the project’s evolution.

4.3.2. Different types of surfaces have been revealed to have different concerns when it comes to patterns and feature proportions, as discussed below.

4.3.3. Porcelain-enamel:

4.3.3.1. Production bathtubs are available that have patterns of “gritty” friction features (polygons, ovals, circles) separated by untextured vitrified porcelain, or they have un-patterned “continuous” applications of grit across the bathing surface floor. Testing was done on a total of 12 porcelain-enamel surface patterns consisting of rectangles or circles of gritty surface features with polished vitrified porcelain between those features. To create these patterns, bathtubs from one manufacturer were cut to obtain square test panels; the bathtub floors from this manufacturer had a continuous distribution of un-patterned grit. After cutting the blank panels, the nominal friction level was measured using the Pendulum method described in **Task I Report** section 4.5.1.5.1 and 4.5.2.[5] Then abrasive polymer disks and buffing wheels were used to polish away areas of the grit to leave a pattern of the remaining grit – at which point the panels were friction tested again. See **2DxxPatterns.pdf** and **2DxxImages.pdf**. Panels from two units of other manufacturers' products were cut and used for early testing but additional units (from these manufacturers) revealed unacceptably inconsistent applications of "continuous" grit on their surfaces.

4.3.3.2. Early in the project it was surmised that patterns would need to be limited to certain geometry, for example see **Image 1** which shows hypothetical patterns that fit uniformly into the 125x75mm Pendulum contact area. However, the main limitation Forcon now supports for testing porcelain-enamel is indeed on the *testing* side versus the *manufacturing* side: the limitation is to center the Pendulum's slider swept trajectory midpoint on the center of a gritty feature as opposed to centering on a gap between gritty features – see the images for 2D08 in **2DxxPatterns.pdf**. Geometrically, centering on a feature should typically result in a smaller area of gritty features swept by the slider. This was proven out (through CAD analysis) by the fact that 9 out of 10 patterns in this project have less gritty area contacted by the slider when the slider is "feature centered". See **Image 2**. In turn, less grit contacted should result in a lower measurement. Given a choice between a lower friction measurement and a higher one, in the interest of safety, the lower "worser case" measurement should be the one that is recorded. As an aside, when testing patterned 3D-profiled plastic RSs, centering the slider trajectory on a 3D friction feature should also result in lower friction for most patterns – as fewer friction features in the pattern will be traversed by the slider.

4.3.3.3. In preparation for the friction testing, which (except for early patterns 2D01 – 2D07) was done at multiple angles of orientation relative to the pattern, calculations were done of the swept surface area percentage of the gritty features at those different orientations. As a baseline, the area traversed by the Pendulum slider trajectory is 9,375 mm^2. See **Image 3**. This analysis revealed that some patterns had a greater degree of variability in gritty surface area relative to testing orientation. For example, Pattern 2D10 has a much higher standard deviation of 334mm^2 (of gritty surface) compared to 2D14 with 135mm^2. These standard deviations can be normalized to the overall grit surface area (for the pattern) by dividing by the pattern's mean grit area, resulting in the *coefficient of variance*. It seems reasonable that a superior pattern would minimize the orientation-dependent variability in grit surface

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[5] The data for these blank panels is documented in the first 24 columns of the 2Dxx tab in DataCompilation.xlsx, and the blank panel used for each design is documented in the subsequent columns.

area, i.e., 2D14 is superior to 2D10. And in turn, hypothetically the greater the amount of gritty surface area, the greater amount of friction. This will be discussed in Section 4.4.4.6. It is noted that friction testing could be done at any position and orientation on the patterns, and results would vary – but the goal of the project is to arrive at a repeatable and reproducible test methodology.

4.3.3.4. In the context of potential standardization of porcelain-enamel friction feature patterns, there are several conclusions offered.

4.3.3.4.1. The lack of manufacturer input precludes a decision about which pattern/feature standardizations would be technically feasible in mass production. The characterization of the grit application itself (particle sizes, distribution densities, and localized variations by position) will be manufacturer-specific

4.3.3.4.2. There is a continuum of performance, where “lightly-gritty” friction features must cover a greater percentage of the bathing surface floor area, and “heavily-gritty” friction features may cover less of a percentage. There will be a point on this continuum where even coarsely gritty features are too far apart (separated by untextured porcelain) to result in adequate friction for humans. Determining the minimum percentage of bathing surface floor to be covered by friction features would be a worthwhile research project in itself. ASTM F462-1979 had requirements for this but the foundations for the percentage are undocumented. To put such a requirement in F462+ would require a sound technical foundation.

4.3.3.4.3. For patterned porcelain-enamel, the most likely candidate for F462+ design limitations would be a merging of a maximum coefficient of variance and a minimum surface area of friction features. If there a high percentage of surface area covered, the directional sensitivity of the pattern to orientation is less important and less likely to lead to slips in one orientation versus another – and vice versa. This project was unable to explore these factors to any significant depth.

4.3.4. Embossed plastic or polymer composite RSs with 3D friction features:

4.3.4.1. The floors of production plastic bathing surfaces are typically made of vacuum-formed sheet acrylic, or gelcoat (polyester resin with colored solid fill) reinforced with fiberglass, or “solid surface” molded thermoset resin. In this project, solid surface RS were not created because their potential geometry is basically identical to that of gelcoat/fiberglass. Vacuum-formed surfaces have design peculiarities that gelcoat/fiberglass and solid surface products do not have, but regardless, the ready *feasibility* of creating nearly any 3D feature pattern in plastic means that any *necessity* to standardize plastic bathing surface design would be based on facilitating reliable tribometry. Testing of 22 different embossed plastic (vacuum-formed) RS candidates was conducted, as well as testing of 5 different polymer composite (gelcoat/fiberglass) and simulated polymer composite (coated 3D printed plastic) RS candidates. See images of these designs in **3DxxImages.pdf** and **3DFxxImages.pdf**.

4.3.4.2. For the purposes of this project, uniform 3D patterns were created. There is uniformity in the Z amplitude of the features and uniformity in the XY positioning of the features. This uniformity becomes a bit moot once the orientation of friction testing (relative to the pattern) is changed, as will be discussed. **Task I Report** section 4.5.1.5.1 describes the general mechanical characteristics of the Pendulum tribometer. High-frame-rate video (960 fps) of Pendulum testing of numerous vacuum-formed 3D pattern designs shows that given the damped natural frequency of the spring-loaded slider (whatever that is), there are friction feature patterns for which the slider bounces (due to the 3D feature "excitation") over groups of friction features without contacting them. Whether this causes significant resonance or attenuation, it is not a desirable situation; consultation with Pendulum experts in the UK Slip Resistance Group (UKSRG) supports this. See https://youtu.be/ooou7Vqc9-8 and https://youtu.be/bk0ZmDXuuVo and https://youtu.be/4M-t4w9WQnA.

4.3.4.3. As described in **Task I Report** sections 4.5.1.5.1 and 4.5.2.2, the Pendulum slider can rotate about two different axes; 1) the lateral axis of the slider carriage, and 2) the longitudinal axis of the slider mounting pivot. See Image 11. Both of these degrees of freedom can affect slider motions during testing. Assuming 3D patterns can be expressed in terms of rows and columns with separation distances, if they are uniform, the more closely spaced the 3D features are, the less likely it is that the slider will sink down into a trough between the features and experience the full excitation of the feature amplitude. Also, as the longitudinal axis for the slider allows it to rock clockwise or counterclockwise, a friction feature that causes the slider to rock away from it won't really be "measured" by the tribometer as the slider polymer will not adhere or deform as much. It is foreseeable that to have 3D features in contact with the slider polymer on both sides of the longitudinal pivot will reduce this rocking; this speaks to a certain minimum density and size of 3D features. The alternative is to restrain the slider from rocking around its longitudinal pivot. Forcon developed a "conditioning clip" to aid in the pre-testing conditioning (sanding) of the slider polymer; if sanding without this clip the slider can get into a stick/slip oscillation that damages the contact edge. The clip reduces the free pivoting of the slider about the longitudinal axis – see **Image 4** and also **MethodImages.pdf** for all images of method-related work. The clip design is sufficient to solve the stick/slip oscillation problem during conditioning, it only weighs about 8 grams, and it can be printed by anyone with a 3D printer. This design isn't rigid enough to eliminate all rotation, but for conditioning use it doesn't need to. One might use this clip (as is) to reduce the slider rocking during friction testing, or it could be stiffened, but the stiffer it is, the heavier it will be. More importantly, unlike conditioning use of the clip (which is not friction measurement), the use of the clip during measurement would raise questions about the effects of the clip mass and moments of inertia on the overall mass, balance, and kinematics of the Pendulum arm and slider carriage; it is possible that the clip could be fitted and the device still be within the calibration tolerances, but this would vary tribometer to tribometer. Nevertheless it is of interest to look at the data results for pattern 3D36 tested on 7/24/22, conducted with and without the conditioning clip; measurements are higher and more inconsistent without the clip than with it (standard deviation of 4 PTV versus 1 PTV) at a test orientation of 0, and higher without the clip at an orientation of 45°. At this point Forcon does not consider conditioning clip use during testing to be well supported, but further study is warranted if the clip (or equivalent stiffener) will reduce the necessity to standardize 3D features for reliable tribometry.

4.3.4.4. As described above for 3D36, the test orientation relative to the pattern affects these interactions between the slider and the 3D features. High-frame-rate video (see 3D18 and 3D24 videos) shows skipping of features when tested square to the patterns but not when tested at a bias angle of 15 or 30°. Square symmetric patterns (in terms of XY coordinates) can have resonance, attenuation, or some other form of skipping of the slider at 0°, 45°, and 90° of test orientation. A rectangular pattern will be unlikely to have skipping at orientations other than 0° and 90°. A pattern that is effectively untestable due to resonance at 0° or 45° or 90° may be fine for testing at a bias angle of 15° or 22.5° or 30°; patterns 3D08, 3D18, 3D24, 3D27/3D28 and 3D36 are this way. Indeed, the 3D27 ASU RS has the friction features at a 30° bias angle to the human. The same untestable pattern may be better if the friction features have a lower height (Z amplitude) or different 3D profile.

4.3.4.5. As to the consistency of 3D feature height, there could be effective designs that have varying 3D feature height. For example, from a tribometry standpoint, there will be designs that test well with every other row or feature an alternating height. This was not explored; proving a necessity for manufacturers to limit 3D feature height would have required a baseline comparison to be tested by humans, for example, 3D35 versus a version of 3D35 where every other row's features are 0.3mm [0.012"] higher.

4.3.4.6. As to the difference in 3D feature design between vacuum-formed and gelcoat/fiberglass surfaces, the draping effect of sheet acrylic (or other polymer) on the vacuum forming "positive" form will cause any vacuum-formed features to be more rounded and less distinct than for gelcoat/fiberglass where a "negative" mold is used, in that the gelcoat simply conforms to whatever the negative mold geometry is. There are no sharp corners to vacuum-formed 3D features while there can be sharp corners with gelcoat/fiberglass. Because of this, gelcoat/fiberglass features can be smaller in profile volume/height and still provide interlocking with the foot. Also, the sheet polymer used for vacuum-formed bathing surfaces is nominally glossy and slick while the gelcoat surface exposed to the bather may not be, depending upon how highly polished the negative mold is. But again the vacuum-formed surface is likely to be slipperier than the gelcoat/fiberglass surface not only because of the characteristics of 3D feature definition but also because of the draping effect and the fact that the sheet polymer is slippery. So, for the more “problematic” surface that is vacuum-formed, the mechanical interlocking (with the bare foot) to be provided for with the 3D features comes down to questions of feature height and profile. As discussed in Task I Report section 4.5.4.2.3, a profile (e.g., 3D35) with steeper and more vertical side flanks will be expected to provide more mechanical interlocking with the bare foot – just as cleated boots provide more traction on loose underfoot materials – and such designs will be more likely to overcome the draping-related smoothness of vacuum-formed surfaces.

4.3.4.7. In conclusion, it is readily *feasible* to standardize 3D plastic bathing surface patterns, because of the characteristics of the involved technologies. Standardization is not desirable, though, from a market standpoint. The different 3D designs studied reveal that vacuum-formed surfaces need steeper flanks, and molded plastic surfaces (e.g., gelcoat/fiberglass and solid surface) can have enough friction using smaller-profile 3D features because of the ability to have sharper corners. With these inputs, it will take significant additional research to determine if it is *necessary* to standardize feature patterns for the purposes of reliable tribometry. It is possible that something like the conditioning clip may prove to be a useful quasi-equater of RS designs. The eventual human test data on the performance of the plastic ASU RSs may inform decisions about which RSs approach being a threshold surface, at which point those designs can be varied slightly to further explore how minor changes in design details will affect tribometry. In general, there is questionable benefit in basing such research on RS designs that are significant outliers from the friction ranges needed by humans.

4.3.5. Mosaic surfaces:

4.3.5.1. As was discussed in Forcon’s Terms Of Bid, the relative position and orientation of any two adjacent individual mosaic units’ surfaces are effectively random (in typical mesh-backed mosaic sheets), precluding reliable friction testing. This is why Forcon created simulated mosaic RSs using partial-depth grooving of USC3 Tile E ceramic tiles. Two RS designs were provided to ASU for human testing, and a third is currently being re-fabricated. See images of these designs in **3DMxxImages.pdf**. Human testing at the University of Southern California shows that Tile E’s top surface is very slippery, so the grooving provides the mechanical interlocking for the ASU human subjects' bare feet. The use of grooving limited the RSs to designs that can be grooved using cutting/grinding equipment – such as squares or diamonds. Actual mosaic tile products used in bathing surfaces have designs that may be circles, hexagons, triangles, squares, rectangles, and combinations thereof, in various sizes. The surfaces of such mosaics may be pressed from ceramic or cut from dimension stone (e.g., marble, granite). The grooved tiles used in this project are similar to cut dimension stone in mosaic edge profile. Testing was done on two grooved designs, one of which (3DM02) was meant to partially simulate the geometry of common 50mm [2"] hexagonal mosaics. As mentioned previously, a third design (3DM03) is being re-fabricated and will be delivered in the future. The original one was delayed due to the supplier shipping to the wrong address, and it was also broken in transit. As for pressed ceramic tiles, these typically have an edge radius, and despite consultation with the Tile Council of North America and with several tile fabricators, no option for cutting/grinding a consistent edge radius on the USC3 Tile E simulated mosaic patterns was found. Edge-radiused mosaics will provide less mechanical interlocking that a square-cut mosaic edge, so this remains an avenue of research that needs to be pursued.

4.3.5.2. The ASU human testing is continuing until perhaps December 2022; testing of the pending 3DM03 design may reveal information about to the sensitivity of slip performance to groove orientation. In the F462+ standard, the results of the current project could manifest themselves as a requirement for a maximum anisotropy ratio of grout grooves. As an example, for a fixed grout groove width, the anisotropy ratio can be no greater than 3:5 – for every 10 grout grooves in one direction there must be 6 that are perpendicular. It is unlikely, however, that conclusive evidence of the need for such standardization will result from the current project. Mosaic tile pattern standardization would be a different type of pursuit, within F462+, because it is contractors and installers that assemble mosaic bathing surfaces, typically onsite. The standardization would manifest itself as something that affects these people (and design professionals) more than the mosaic manufacturers.

4.4. Task II-1c: (Identification and development of "reference samples" representative of surfaces involving adult slip/fall on bathing surfaces including: porcelain-enameled metal, polymer/composite, embossed plastic, and mosaic tiled surfaces representative of bathing surfaces): **Providing a range of friction levels (through the use of different friction features) to facilitate informed conclusions about which surface(s) represent an adequate "minimum threshold" for surface friction.**

4.4.1. This is a project topic that is intimately intertwined with ASU's human testing. Past interactions with ASU identified a threshold RS as one where some of the human subjects (that test that particular RS) have experienced low-velocity or short-distance slips but few or none have experienced high-velocity or long slips, nor have they experienced no slips at all. This determination is further subject to nuance because certain of the RSs have anisotropy, and may have more human-utilizable friction in one orientation than another.

4.4.2. Each of the four RS types had quite dissimilar fabrication techniques and the leads time for creation (and associated costs) varied between the four types. It would not have been beneficial to drown ASU in dozens of different candidate RS designs within each type because the effort that it takes for a human to test just one of them (and for ASU to process the data) is significant. At the same time, significant delays in ASU's human testing and release of data reduced Forcon's ability to efficiently "iterate" RS designs to focus in on threshold candidates. The ASU testing may continue until December 2022, so all the data still is not in such that conclusive decisions can be made about threshold RSs. The human test population demographics for the project are rather broad, and the different demands placed upon the RSs by younger and healthier versus older and weaker test subjects are important. This Task II Report will not discuss much in the way of specific human test data, because the testing (after a month-long technical hiatus) is ongoing, and because to date the human testing has had a younger-subject emphasis despite an elderly-subject emphasis having been planned. If decisions are made about choosing threshold RSs and eliminating non-obvious RS outliers (too slippery or grippy) and those decisions are made without a sufficiently diverse (or numerous) cross-section of humans having tested them, that would be disadvantageous. Where data is cited below, it is from an ASU spreadsheet entitled "CPSC_data_report_9_7_22_v2.xlsx", provided to Forcon on September 7, 2022.

4.4.3. The following is a discussion of the various RS friction feature design evolutions, with some context from the human testing. The **Task II Draft Plan** section 4.1 estimated that 8 porcelain-enamel, 12 vacuum-formed, 8 gelcoat/fiberglass and 6 simulated mosaic RSs would be needed – a total of 34. The actual numbers (as mentioned) ended up with 12, 23, 5, and 3 designs respectively – a total of 43. **Task II Draft Plan** section 4.2 was quite optimistic in planning on manufacturer cooperation; basically, almost none was received. Even the "backup plan" section 4.3 anticipated external supplier support that did not happen. Even where vendors existed (e.g., for vacuum forming), virtually all vendors contacted had 6-8 week lead times (due to COVID-related staffing shortages) or the project wasn't big enough to interest them in quoting. In reviewing the information below, it is important to note that basically none of this type of research appeared to have been done before, so the learning curve was steep and bumpy.

4.4.4. Porcelain-enamel "2Dxx" RSs

4.4.4.1. This entire section is perhaps academic, because for porcelain-enamel RSs, the lack of cooperation from manufacturers in this highly specialized industry means that none of the RS designs sent to ASU could be considered threshold RSs due purely to the inability to reproduce them, or even thoroughly understand their manufacture, as will be discussed.

4.4.4.2. The early 2D porcelain-enamel designs like 2D01, 2D02, 2D04, and 2D05 measured as having low friction, due to a combination of the designs polishing away too much of the grit, and because the cut-up shower pan blanks (from the first two manufacturers) had a low and inconsistent amount of grit in the first place. There are three manufacturers of porcelain-enamel bathing surfaces that have “continuously” gritty surfaces (as opposed to a designed grit pattern); this project cannot use a manufactured design pattern because of CPSC requirements. Later 2D designs have more residual grit, are on grittier and more consistent panels from a third manufacturer, and are testable at any orientation. Regarding porcelain-enamel RS homogeneity, the necessary reliance on cut-up bathtub bottoms for RSs is not something for which there is an alternative given Forcon’s lack of success in interesting a job shop in creating surfaces. Panels cut from the third manufacturer’s products (for the current RSs), though more consistent, had significant tribometer-measured PTV variation in grit distribution. Testing of 4 panels (before patterning) in 4 quadrants each revealed the following friction data:

	Zone A	**Zone B**	**Zone C**	**Zone D**
Blank X3	20	22	28	29
Blank X4	30	28	23	20
Blank X5	24	32	31	31
Blank X6	32	31	31	34

But the whole topic becomes further academic given that homogeneity of such gritty surfaces may not be something that the manufacturers aim for to any measurement-relevant degree. This is a similar discussion to those involving ASTM F2508 reference surfaces of ceramic and vinyl; the manufacturers of those surfaces also did not target a level of homogeneity that was precise enough to become irrelevant to friction measurement. This is one of the main reasons F2508 is being redone with new RSs and more emphasis on RS homogeneity. For the cut-up bathtub bottoms in this project, inter-panel and intra-panel friction measurements could be done, but it is unknown whether the next bathtub bought will be similar to the ones already tested, in the absence of manufacturer input. Methods such as ISO 35[6] specify that homogeneity determinations are to be based on a quantity-dependent stratified randomization of the “samples”, which means that given the quantity of bathtubs that manufacturer #3 produces, many would need to be obtained (from different timeframes of production) and cut up for testing. This is not feasible for F462+, let alone this project. The homogeneity (if proper stratified sampling was done) can be evaluated with the use of 3D non-contact profilometry (at a high

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[6] ISO Guide 35-2017. Reference materials — Guidance for characterization and assessment of homogeneity and stability. Geneva, Switzerland: International Organization for Standardization.

cost) based on the work of Marcel Engels and the European SlipSTD project (see attached presentation) but there remain no published thresholds or metrics to target as “goal” values. Pursual of such advanced methods could be justifiable if there was information on the homogeneity practices of different manufacturers, but there is no such information. The effects of porcelain-enamel homogeneity on reliable tribometry, and (in turn) on the defensible selection of designs as threshold RSs, appears to be a topic that cannot be explored until RSs can be custom-manufactured in volume for F462+.

4.4.4.3. Referring back to section 4.3.3.3, much effort was made to design 2D patterns with a low coefficient of variance, but the designs by necessity were those that could be created by Forcon using polishing wheels or abrasive discs – meaning circular or rectangular friction features. An actual manufacturer could create ovals, obrounds, or more complex gritty features.

4.4.4.4. The file **2DxxPatterns.pdf** shows the different gritty surface areas of the different ASU 2D RS designs, and **Image 2** and **Image 3** chart this data. Design 2D13 has the highest gritty surface area and also has an anisotropic design – it has been human-tested in 0 and 90 degree orientations. Of interest is that the friction measurements at the different angles are quite similar – and this is reflected in the human testing, where 11 of 112 people slipped in one orientation and 9 of 111 slipped in the other.

4.4.4.5. The ASU human research data to date reflects that slips occur on all of the 2D RSs. Design 2D14, the only circular-feature pattern, was retired several months ago because it had a lot of slips (9 of 55 humans), and because two key measures used by ASU didn’t agree. Briefly, for a slip, the Peak Sliding Heel Velocity (PSHV) should be proportionate to the Slip Distance of the foot during that sliding (SDII). Design 2D14 had the worst performance for this proportionality: PSHV was high while SDII was not. The retirement of 2D14 led to the development of 2D17, a design also intended to provide more frictional area than 2D11.

4.4.4.6. It was hypothesized that the greater the gritty feature surface area (e.g., 2D11 versus 2D13 versus 2D17), the higher the measured friction would be. This is not uniformly observed in the friction test data; there are several factors that could be affecting this:

4.4.4.6.1. Changes in friction test method: switching from 0.05% sodium lauryl sulfate to 0.1%, and switching from Pink Lapping Film to Green Lapping Film (see **Task I Report** section 4.5.22) without going back and redoing the prior testing.

4.4.4.6.2. Inconsistencies in the grit distribution on the RS panels (see 4.4.4.2).

4.4.4.6.3. Potential wearing away of grit on the RS panels during handling.

4.4.4.7. Of interest also (with the preliminary human test data) is that fewer people slip on the 54% gritty 2D17 than on the 60% gritty 2D13. But 2D17 friction-tested higher than 2D13.

4.4.4.8. In summary, the 2Dxx RS testing provided useful information on pattern designs, orientations, and preliminary frictional tendencies of three manufacturers' products. And the pattern coefficient of variance could be a useful metric for future work. The 2Dxx friction testing helped to refine the friction test methodology developed in this project. But due to the lack of manufacturer/supplier cooperation on the unique porcelain-enamel manufacturing process, the 2Dxx work has not resulted in threshold RS candidates.

4.4.5. Vacuum-formed sheet plastic “3Dxx” designs:

4.4.5.1. An extensive description of the evolution of Forcon's RS vacuum forming efforts is in **Task I Report** section 4.5.4.2.3. Generally, the majority of 3D pattern designs (up through 3D26) were formed using low vacuum from a shop vacuum and had low friction values due to low delineation of the 3D profile features. The high vacuum setup first used on March 5, 2022 was a milestone that obsoleted the earlier work. Forcon's smaller vacuum box had small holes every 1.3cm [0.50”] while the large box had large holes every 2.5cm [1.0”]; this affected how vacuum would reach the form features between holes, and it also drove the pattern dimensions and periods. See the photos in **3DxxImages.pdf**.There was no point in placing a 3D form feature where it would overlap a vacuum hole in the box.

4.4.5.1.1. Vacuum forming has different sources of variability; unless a production-grade vacuum apparatus and custom-designed form are used, there can be differentials in the vacuum “flow” in one area of the vacuum box versus another – higher at the outlet and lower away from the outlet. And with the polymer draping (over the form features) that occurs with vacuum forming, an area of lower vacuum will not conform to the form features as well as an area that has higher vacuum. There can also be variability due to the heating of the polymer sheet before forming. The process is finicky in that the polymer sheet sags and slumps as it is getting up to temperature, and there is transition time between when the floppy sheet exits the oven and when it encounters the surface of the form (with vacuum). Localized cooling and general differences in polymer temperature can also affect the draping and conformance to form features. Though these effects can be reduced by using an automated and well-refined process with commercial-grade equipment, each formed sheet will be slightly different in terms of friction feature profile geometry. Of benefit is that the feature peaks (which are what the tribometer slider primarily encounters) will have the best draping and conformance; the variation in polymer sheet draping and feature conformance will manifest itself instead around the flanks and bottoms of the friction features. Numerous vacuum-formed sheets were discarded because of uneven forming across the surface, but friction measurement deviations across uneven surfaces would not necessarily be discernable from the nominal repeatability of the Pendulum testing process. Testing of pattern 3D28 at 15, 30, and 45° resulted in all values within 1 PTV, and testing of pattern 3D30 tested at 0, 15, 30, and 45° had the same result. Three different samples of 3D35 all tested within 1 PTV of each other. Admittedly, again, these were made from subjectively “evenly-formed” samples. Forcon did not take the time to mount and test unevenly-formed samples for the purpose of seeing the effect of the unevenness.

4.4.5.2. The ASU RSs were 3D27, 3D31, and 3D35. The first two were formed of 1mm [0.04”] thick PETG, and 3D35 was formed of 0.5mm [0.02”] thick PETG. The 3D27 RS was fabricated at a 30° bias angle, because the nominal pattern has undesirable resonance at 0° and 45° friction test orientation (see 4.3.2.2 – 4.3.2.4). The 3D27 RS was an exploration of the concept that if a pattern causes resonance/attenuation at certain orientations, a bathing surface with that pattern would need to be manufactured with pattern at a non-resonant bias angle to the product’s long axis (e.g., the bathtub midline), because that is the axis along which Pendulum testing would occur. The Pendulum and most all other common tribometer designs do not lend themselves to testing in another orientation. In retrospect, the need for a bias angle should be a last resort, and another pattern chosen. Pattern 3D31 has a more continuous square-rib pattern without the wider gaps of 3D27, and 3D35 has a denser array of cylindrical 3D features, also without wide gaps. Many of the 3Dxx designs (including 3D27) had 3D form features (3D printed) that were semi-hemispheres or pyramids, where the flanks of these features were relatively “flat” – and the designs had low measured friction. Designs 3D30, 3D31, 3D35, and 3D36, in contrast, had form features with vertical flanks and un-radiused edges; such features on a molded RS (e.g., gelcoat/fiberglass) would be too “sharp”, but the draping of the vacuum-formed sheet polymer softened these edges and allowed more vertical 3D feature flanks.

4.4.5.3. Due to the 2.5cm [1”] grid spacing of Forcon’s large vacuum box, and the need to design for that spacing, there was no way to bias 3D27’s surface without first forming it “squarely” to the vacuum box then rotating the formed polymer sheet on the backing board. In turn, this necessitated the 3D27 pattern have a round perimeter. See the 3D27 images. The net effect of facilitating the 30° degree bias angle was that the pattern covered a reduced area of the RS backing board, making a smaller “target” for humans to land on and potentially affecting how carefully they felt they needed to be in placing their trailing foot after stepping with the leading foot. Additionally, there was a human subject that found 3D27 uncomfortable under their foot. Given these factors, 3D27 was retired in mid-July 2022.

4.4.5.4. In summary, only the later high-vacuum, thinner plastic RS candidates approached providing adequate friction for the humans. Pattern 3D31 has had 24 slips out of 176 tests (as of 9/7/2022); it was formed from 1mm [0.04”] plastic. It would be of interest to see how a 0.5mm [0.02”] thick plastic version of 3D31 performs with humans, but the schedule and budget do not support the creation and testing of a thinner 3D31. Pattern 3D35 performs consistently in friction testing, sample to sample and at different orientations. The human testing of 3D35 is still underway; whether it performs as a threshold RS remains to be seen.

4.4.6. Gelcoat/fiberglass “3DFxx” RSs (polymer composite)

4.4.6.1. The first two “polymer composite” RSs sent to ASU (in February of 2022) were not actually gelcoat/fiberglass, they were simulated using 3D printed feature patterns that had been spray coated with bathtub refinishing epoxy; this is a similar resin/hardener thermoset polymer to gelcoat. See **3DFxxImages.pdf**. Pilot testing was to be used to choose good designs that approach the median threshold (as determined by the humans) prior to incurring the 6-8 week leadtime and high cost of computer-numerically-controlled (CNC) machining of negative molds for use in gelcoat/fiberglass fabrication. Human testing on the simulated fiberglass RSs at ASU, however, did not commence for some time, and human test data adequate for making RS design decisions was not received by Forcon until July 30, 2022. Earlier, in April 2022, Forcon (despite the data vacuum) designed negative molds for Pattern 3DF08, because it was a “finer” pattern that could not be created with epoxy-coated 3D prints. The molds were CNC machined (which took 6 weeks) and stored until data was received at the end of July. A key reason to only make good candidates from gelcoat/fiberglass is that the gelcoat/fiberglass fabrication process involves a lot of high-VOC airborne solvents, primarily acetone, as well as polyester resins, mold releases, methylethylketone, specialized spray equipment, and respiratory protection. The ramp-up to fabricate 3DF08 began in early August and the challenging gelcoating process was finally resolved such that the RS was sent to ASU a month later. Pattern 3DF08 friction-tested relatively high given that its 3D features are small. It will be interesting to see the ASU human test results on it as the design may show the effect of the “sharper” feature definition of a molded RS (versus vacuum forming). The simulated patterns 3DF02 and 3DF04 show a lower number of slips (through 9/7/2022) compared to other RSs. But ultimately these two could not become threshold RS candidates unless they were first re-created in gelcoat/fiberglass. This may be a worthwhile task (though not under the current schedule or budget); the friction of design 3DF02 was tested at 0, 15, 30, and 45°, and all values were within 1 PTV of each other. Values for design 3DF04, tested at 0, 22.5 and 45°, were within 2 PTV.

4.4.6.2. In summary, the polymer composite RS candidate development suffered from a lack of timely human test data compounding an inherently time-consuming, expensive and environmentally unfriendly fabrication process. The remaining ASU human testing should inform decisions about whether the 3 designs submitted may form the basis for future threshold RS candidates.

4.4.7. Simulated mosaic “3DMxx” RSs

4.4.7.1. Here the concept of a mosaic threshold RS gets lost in the realities of mosaic tiles. The purpose of a threshold RS is to provide a friction benchmark for the testing of similar mass-produced products. Given that actual mosaic tile arrays have minimally controlled spacing and no substantive position/orientation control, to compare the frictional performance of an actual mosaic product with that of the project’s simulated mosaic RSs would require someone to manually position the individual mosaics precisely into a consistent array, top-down on a planar surface, then bond the mosaics together, and then grout the assembly for testing. Because of the (desirable) sensitivity of tribometry, there will be too many variables introduced by the inconsistencies in actual mosaic geometry to be able to take advantage of a consistently manufactured threshold RS.

4.4.7.2. The benefit in this project to the inclusion of simulated mosaics is that as fabricated from slippery-topped ASTM F2508 RS tiles, the ASU human testing explores the friction derived from grout gaps by humans. Once the ASU human testing is done, the three designs may provide enough information to construct a preliminary *minimum groove area* versus *top surface friction* formula for use in F462+. This was described in the **Task II Draft Plan** section 4.4.2.2.3 and its Attachment B. Before this is finalized, however, human testing will need to be done (see 4.3.5.1) on simulated mosaics that have edge radii.

4.4.7.3. As to the usefulness of a mosaic threshold surface for tribometry (not only with the Pendulum), basically the tribometer slider is presented with two very different friction mechanisms during every test; the friction of the top surface, and the friction of the far edge of each grout gap the slider passes over. If the grout gap is as wide as the slider and parallel to its edge, the slider will descend into the gap, impact the far edge and pop back up. If the grout gap is narrower than the slider or non-aligned , areas of the slider may deform into the grout gap while the rest of the slider is supported by the top surface. Here, variations in test orientation can make a large difference; with 3DM03 the friction measurement is 23 PTV at an orientation of 0° (slider edge parallel to grout gaps) and drops to 15 PTV at an orientation of 15°. See **3DMxxImages.pdf**. There is too much of a dichotomy between these friction mechanisms for such measurements to be useful.

4.5. Task II-2a: (Development [or adaptation] of a tribometry test method that can be used for standardized testing of bathing surfaces): **Evaluation of homogeneity of “reference sample” surfaces from a friction measurement standpoint.**

4.5.1. There are many similarities between the topic of RS homogeneity for friction measurement and the homogeneity of production bathing surfaces (discussed earlier in section 4.2). Once there are duplicate RSs to test, methods of homogeneity analysis based on ISO Guide 35[7] could be performed utilizing the Pendulum test method developed in this research. Homogeneity analysis is time- and resource-intensive and as such should be focused only on threshold RS candidates. In this project, sufficient human test data was not obtained in time to identify and duplicate threshold RSs, and ASU human test research is in process, but if threshold RSs are eventually produced, the steps of such a homogeneity analysis would be generally as follows:

4.5.1.1. Select multiple samples using stratified random sampling.

4.5.1.2. Mark two perpendicular test directions randomly on each sample.

4.5.1.3. Use a randomized sequencing of which order to test samples, and which test direction to test.

4.5.1.4. Utilizing a holding fixture to prevent relative movement, follow the project's Pendulum test method to obtain a single test result in each test location.

4.5.1.5. Calculate repeatability standard deviation utilizing ASTM E691 section 15.6.1 (formula 6).

4.5.1.6. Evaluate outliers using Grubb's test or similar strategy, per ISO Guide 35 section 7.7.1.2.

4.5.1.7. Determine the significance of outliers to the practicable use of the subject RS.

4.5.1.8. Evaluate the between-sample homogeneity of the reference surface type using ISO Guide 35 section 7.7.4.

4.5.1.9. Evaluate the within-sample homogeneity of the reference surface type using ISO Guide 35 section 7.9.

4.5.1.10. Check for sufficient homogeneity of the reference surface type using ISO Guide 35 section 7.10.

4.6. Task II-2b: (Development [or adaptation] of a tribometry test method that can be used for standardized testing of bathing surfaces): **Correlation of testing slightly concave manufactured bathing surfaces to testing of flat reference surfaces.**

4.6.1. See **Task I Report** section 4.5.3. Additionally, ASU human testing had a month-long hiatus in September 2022 due to technical issues requiring Forcon's assistance; testing of 3D concave surfaces has not been performed as of this writing. A supplement to this Task II Report regarding concave surface testing will be provided before the project ends in December 2022.

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[7] ISO Guide 35:2017. Reference materials — Guidance for characterization and assessment of homogeneity and stability. Geneva; International Organization for Standardization.

4.7. Task II-2c: (Development [or adaptation] of a tribometry test method that can be used for standardized testing of bathing surfaces): **Method addressing tribometer testing of surfaces with variations in geometric elements (e.g., pattern and size) of friction feature design.**
AND
Task II-2d: (Development [or adaptation] of a tribometry test method that can be used for standardized testing of bathing surfaces): **Method for tribometer testing of 3D-profiled/patterned surfaces.**

4.7.1. These two PWS subtasks are somewhat redundant to each other, as profile, pattern, and size of friction features is common to both. As such, these both will be addressed in this one section 4.7. Sections 7 and 8 of the **Task II Draft Plan** addressed these subtasks but not in a useful way.

4.7.2. The evolution of the Pendulum friction test method in place since February 5, 2022 was described in detail in **Task I Report** sections 4.5.1.5 and 4.5.2. The Shim Method developed by Forcon is used only for 3D RSs, but all other elements described in these sections are used for both 2D and 3D surfaces. In addition to the Task I discussion, the preceding section 4.3.3.2 in this report described another method focus – centering the slider swept trajectory on a friction feature. The compiled method is in **method101022.pdf**, and method development-related photos are shown in **MethodImages.pdf**.

4.7.3. The Shim Method proved to be quite consistent in Forcon’s testing. A dial indicator was affixed between the Pendulum base and arm pivot (see Image 16) and typically, repeated use of the Shim Method resulted in the base-to-pivot distance differing by no more than 0.1–0.15mm [0.004-0.006”] each time. If the Shim Method was inconsistent this distance would vary more significantly.

4.7.4. Furthering the discussion on the broad design freedom that plastic bathtub manufacturers have enjoyed, the frictional performance of any tribometer on one particular 3D design may be different from that of another 3D design that looks quite similar. In Forcon’s testing, the wider-spaced 3D friction feature patterns have more measurement dependency on orientation and the closer-together patterns have less, but these are for Forcon’s generic patterns; many commercial patterns have fewer discrete features, and many are simply random. Friction testing of 3D30 versus 3D31, and 3D35 versus 3D36, revealed that there may be a certain point where adding 20% more friction features (for example) may not significantly affect the Pendulum measurement value. As has been discussed, there is very little rigorous research in the tribometry world for patterned 3D profiled surfaces. Methodologically, there is a limit to the deviations from accepted methods (EN 16165, AS 4586, UKSRG Guidelines) that should be explored for testing 3D patterns, because there should be some recognizable tie to the accepted base of knowledge regarding Pendulum testing. Forcon’s Shim Method and conditioning clip are currently on a trajectory to acceptance within the Pendulum user community, and they address two key issues with testing 3D profiled and patterned surfaces. The use of Slider 55 and Green Lapping Film are other method improvements (for this testing). But the generally unrestricted world of 3D friction feature design means that this project will primarily result in a useful tribometry method for the threshold RSs and other very similar designs. The method will be translatable to an F462+ standard. But it is unlikely that the method can be made to reliably distinguish the friction of 3D profiled surfaces that differ much from the RSs. Here will be the opportunity to let not the *perfect* be the enemy of the *good enough*.

5. Conclusions

5.1. The goals of this project are appropriate and necessary for the eventual creation of F462+. As with any new standard that would guide private industry, there will be the inertia of the way things have been in the past. It is not unforeseeable that manufacturers would choose not to assist with the subject research, and developing an interaction with manufacturers is an iterative process. The support of manufacturers is important to F462+, however, so hopefully the subject research can be an iteration that brings manufacturer cooperation closer to being achieved. The need for Forcon to fabricate nearly all the RS candidates was not anticipated, and this affected the completion of certain Task I and II subtasks. The timing of events on the human testing side was not the timing anticipated by Forcon, and this also affected the completion of certain Task I and II subtasks. This project has resulted in a well-developed and technically sound friction test method in place of ASTM F462-1979's unreliable and irrelevant-to-humans method. The project has explored and articulated specific complexities that exist for F462+ or any other bathing surface friction standard – and these complexities can be further explored by other researchers.

5.2. Apart from topics requiring manufacturer input, numerous opportunities for future work (after the completion of ASU's human testing) are highlighted throughout this report. These include:

5.2.1. Explore the use of a coefficient of variance as potential guidance for improving the orientation independence of friction testing and human use of 2D friction feature patterns on porcelain-enamel bathing surfaces.

5.2.2. Explore the maximum distance there should be between friction features on an otherwise-smooth bathing surface.

5.2.3. For friction testing 3D profiled surfaces, explore the use of Forcon's conditioning clip (or similar means) for reducing the oscillation of the Pendulum slider about its longitudinal pivot axis.

5.2.4. Explore further the effects of RS anisotropy in human testing.

5.2.5. Develop and test simulated mosaic surfaces that have edge radii.

5.2.6. Develop guidelines for mosaic surface minimum grout joint areas and orientations.

5.3. Forcon's remaining work in this project includes:

5.3.1. Once the lab data is in, provide a supplement to the Task I Report regarding InterLaboratory Study results addressing the conditioning clip use, the Shim Method, and 3D35.

5.3.2. Provide a supplement to the Task I Report and this report regarding the effect of 3D RS concavity on Pendulum measurements.

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