

OPTICAL HAZING IN POLISHED PORCELAIN TILES: MEASURING, THUS DEFINING, CONTROLLING AND DEFEATING A DEFECT

Richard Bowman⁽¹⁾ and Michele Lanzetta⁽²⁾

⁽¹⁾ Intertile Research Pty Ltd, Australia

⁽²⁾ Department of Civil and Industrial Engineering, University of Pisa, Italy

ABSTRACT

There has been much debate throughout Australia as to whether optical hazing of polished porcelain tiles is a defect or an effect. Independent tile experts consider it a defect.

What is optical hazing? Haze is light that has been reflected by small surface structures adjacent to the main specular component. Optical hazing is often only visible under low angle reflected light viewing conditions, but typically appears as a milky or cloudy finish where there is a loss of reflected image clarity and lights are reflected with multiple halos. When first observed, the overall impression is that a part of the floor has a smudge and is dirty. Cleaning is incapable of remedying the objectionable appearance of optical hazing, which can have multiple causes and manifestations.

Optical hazing of expensive technical porcelain tiles is principally caused by isolated problems in the industrial polishing process that often occur unexpectedly. As such, the percentage of affected packaged tiles depends on the time for the problem to be recognised and fixed. Quality control is unlikely to detect optical hazing as the viewing conditions are unsuitable. While only a small percentage of defective polished technical porcelain tiles might be packaged, they are unlikely to be detected until after they are installed. It is unrealistic to expect that whole batches of tiles can be laid out and very carefully inspected under appropriate viewing conditions before installation.

Optical hazing of cheaper residential porcelain tiles can also be due to its high porosity. Nanocoatings or waxes are typically used to provide stain protection, filling any pores opened by the polishing, as well as any microcracking induced by inappropriate processing conditions¹. Where tiles are covered by a waxy coating, any optical hazing is likely to remain undetectable until after the tiles have been installed. Whole batches of polished residential porcelain tiles may be defective.

Tile fixers cannot be made responsible for quality control as they will rarely install tiles under circumstances where the optical hazing will be detected.

Although some manufacturers use glossmeters as a quality control measure, these instruments are insufficiently precise: too much light is internally refracted within the glass component of the tile surface. The only realistic option is to install appropriate artificial vision equipment at the end of the polishing train in order to detect any problem as soon as it has occurred.

The University of Pisa has conducted extensive research into the optical phenomena associated with the polishing and surface modification of stones, using several different analytical techniques. This theoretical understanding has led to various prototype devices, and the granting of patents. A novel scanning reflectometer is now being commercially developed, with one production line model and another for use in the plant or laboratory.

Now that we can measure optical hazing, we should be able to reach a consensus as to what is unacceptable, so that we can develop acceptance standards, and adopt quality classifications. Since the reflectometer can be used to control and optimise polishing processes and effectively correlates surface roughness and reflectance, it might also have some potential applications with respect to slip resistance assessments.

1. INTRODUCTION

While polished porcelain tiles were first placed on the market in the mid 1980s, significant optical hazing problems only became apparent in the mid 2000s, when Chinese tile production boomed. Optical hazing has become quite an emotional topic for householders: the realisation that their floor will not look as they envisaged it can be an extreme disappointment, particularly when they have thought the tiles to be dirty. This delusion has sometimes been reinforced by merchants advising that the floor needs professional cleaning, or even suggesting that the floor has been improperly cleaned. Many householders have become quite distressed when they comprehend that no matter how many hours they spend on hands and knees trying to clean the floor, will never be achieved.

An important aspect of the appearance of some polished surfaces is the distinctness (clarity) of images reflected by them. Optical hazing is a collective term that has been used to describe aesthetic defects, where, in certain viewing conditions, parts of a polished porcelain tile look dirty or lack the reflective qualities of the remainder of the tile. While most instances of optical hazing are due to polishing problems, areas of high surface porosity and variable "nanoseal" application, complications can also arise due to other causes such as localised devitrification. Instances of grout haze and chemical etching have been misdiagnosed as optical hazing. In some instances, damage may have been induced by attempts to mechanically and chemically remove optical hazing. Some surfaces have become stained after such cleaning attempts. Some consumers believe that optical hazing defines tiles that can't be cleaned to provide the uniform glossy appearance they anticipated after viewing tiles in the showroom.

In 2010 Colin Cass² proposed a definition of optical hazing: "A fuzzy halo seen around certain types of reflected light, also seen as a milky pattern immediately beside low angle reflected natural light"; together with definitions for shadowing: "Permanent dark smudges only visible on tiles in low angle reflected natural light"; and sealer marks: "Regular factory processing marks only visible immediately beside low angle reflected natural light.

Griese³ considered optical hazing to describe inconsistencies observed in the reflective properties of polished surfaces, encompassing a broad range of observations. Notably, these inconsistencies are typically imperceptible under normal lighting and when viewed from above; only becoming obvious when viewed at a low angle (oblique) illumination conditions.

In optics, the angle of incidence is measured as the angle between a ray and the line perpendicular to the surface; consequently low critical angle illumination conditions have high angles of incidence. With low angles of incidence (viewing almost perpendicularly), there is dominant specular reflection and relatively little refraction. With increasingly higher angles of incidence, more light is refracted, and total internal reflection of some light may occur. When the light is partially reflected, refracted and diffused, the merged light contains an overlapping of different types of light that deceives the eye (and glossmeter instruments).

We all recognise haze as an atmospheric phenomenon where dust, smoke and other dry particles obscure the clarity of the sky. Thus, **optical hazing of polished porcelain (natural and agglomerated stone) tiles might best be considered as an aesthetic phenomenon where flatness deviations, scratching, voids, and material composition variations obscure the clarity of surface reflections.** *Reflection haze* is produced by irregularities in the reflecting surface that affect the distribution of flux reflected around the specular angle. Hazing can either be regular, where it manifests consistently across a surface, or as irregular, where an inconsistent part of a tile surface has a distinctly different appearance under certain viewing conditions.

The surface texture of the polished tile will be a function of the number, size and shape of the pores; the size, depth, orientation and distribution of the scratches associated with the polishing process; and the extent and characteristics of any cracking or quartz particle losses that are induced by the relief of residual stresses during the grinding and polishing processes. Sousa et al is the most recent of a series of papers considering the theoretical surface texture distribution of porcelain stoneware tiles due to the kinematics imposed by industrial polishing, together with supplementary experimental work. Polished porcelain is produced using a "polishing train", where the amount of material removed from the surface of the tile is typically of the order of 0.5 to 1.5 mm, depending mainly on the curvature of the fired tile. This process creates a new tile surface that features several open pores due to the existence of initially closed pores within the body of the fired tile.

Shadowing is an (optical hazing) phenomenon that has been observed at night in shopping centres (in the absence of natural lighting). Sousa *et al*⁴ refer to polishing shadows that are left after the polishing process. Areas close to tile edges (at the edge of the polishing train) are most likely to have preferential textures that give rise to anisotropic glossiness (irregular hazing).

Without becoming too fixated on definitions, there are several devices and procedures that might be used to confirm the causes of various optical hazing phenomena that might lead to more appropriate definitions, together with potential associated remedial measures. We thus propose optical hazing be used as a collective term for various optical manifestations of disparate appearance within polished tiles, broadly in line with past indiscriminate industry usage. Optical hazing might also describe polished porcelain tiles that have a finished appearance that is inconsistent with expectations based on viewing appropriately displayed tile samples.

Such a broad interpretation of optical hazing is inconsistent with the pseudo-physical analyses promoted by merchants' interests seeking to avoid liability for tile batches where optical hazing may be present. Where objectionable optical hazing is present, there may only be a few tiles involved, as a polishing line problem may have been spotted and corrected. However, in some cases the whole batch may be more marginal. In some instances one or more cartons containing quarantined tiles with optical hazing have been mistakenly dispatched.

Polishing line problems are generally due to unexpected failures of the grinding stones rather than resulting from manufacturing (process control⁵) parameters. Such unpredictable failures require inspection of every tile. Although Chinese manufacturers

use intense fluorescent lighting and employ many people to visually assess polished porcelain tile quality, low incident viewing conditions are not used, so 'optical hazing' and 'shadowing' are unlikely to be detected. Given the viewing difficulties and the human error associated with the poor existing inspection practices, automated inspection is to be preferred. Such devices should enable immediate identification of processing line failures, as well as identifying when tiles have more marginal hazing characteristics.

Cass has observed⁶ that some polished porcelain tiles reflect like mirrors, while some don't. Some tile merchants (as the de facto manufacturer) have sought to decrease their liability by choosing to advise potential customers about the physics of surface reflectivity, avoiding, wherever possible, use of the negatively perceived term optical hazing⁷. Polished porcelain tiles may not be perfect mirrors, but consumers form impressions of tiles and expectations of performance based on showroom displays. In most countries customers have the right to expect that the goods they will receive will be of the same quality and appearance as those that are displayed. Would a reasonable person have purchased tiles affected by optical hazing if they had known about (or been able to see) the defect? Tiles should not be displayed under viewing conditions that will disguise any optical hazing.

What do the ceramic tiling standards say?

The ISO 13006⁸ ceramic tile product standard and the ISO 10545.1⁹ test methods do not refer to optical hazing as it is a phenomenon that has not traditionally been associated with ceramic tiles. However, a study of the standards can be illuminating.

A first quality tile is one which conforms with ISO 13006, where the characteristics of polished porcelain tiles are defined by Annex G for dry-pressed ceramic tiles with low water absorption ($\leq 0.5\%$). In terms of surface quality, this requires "A minimum of 95 % of the tiles are to be free from visible defects which can impair the appearance of a major area of tiles" in accordance with ISO 10545.2¹⁰, which was first published in 1995.

ISO 10545.2 identifies and defines 13 types of surface defects. It also has note "In order to judge whether an intentional decorative effect is acceptable or there is a defect, the relevant clause of the product standard should be referred to. Cracks, nipped edges and nipped corners cannot be intentional effects". Since nipped edges and nipped corners are not included in the ISO 10545-2 list of defects, this note establishes the principle that other unintentional defects (which are not included in the ISO 10545-2 list of defects) can be deemed to be surface defects.

The Working Group of the Italian Ceramic Society on Ceramic Tile Defects produced a book that classified¹¹ and illustrated over 70 different types of surface defects, providing pictures of the defects as well as descriptions and possible causes. However, this book is not exhaustive: it does not include sulphuring, feathering and starring, and it explicitly excludes geometrical anomalies, such as warpage. Optical hazing and shadowing were not included as defects. Although incomplete polishing was included in the category of alterations to the surface quality (widespread, localised), there were no further details. Does incomplete polishing represent shadowing or optical hazing? Perhaps it signifies inconsistent polishing, consistent polishing with inconsistent results, or a failure to polish a surface to the expected level of gloss?

Standards writers recognise that it is impossible for standards to identify all known surface defects, as well as anticipating other defects that might occur with the introduction of new technological production methods. One cannot sensibly test tiles with all chemicals in order to determine that tiles are chemically resistant; however, the standards provide protocols that can be used to assess the performance of tiles with specific chemicals. Many test methods are optional or by agreement.

Merchants expect minimum shade variation within batches, but accept that variations will occur between batches. First class tiles can be considered second class if they fail to comply with agreed small colour difference requirements.

The standards also extend to a consideration of intentional and unintentional effects. For example, there are some partly polished tiles that are intentionally produced. crazing is a surface defect that can be an intentional effect. ISO 13006 includes a note that states "Certain decorative effects may have a tendency to craze. They shall be identified by the manufacturer, in which case the crazing test given in ISO 10545-11 is not applicable".

Glaze devitrification could be a deliberate intentional effect, for example if a manufacturer sought to replicate the Sung Dynasty Chinese oil-spot glazes as an intentional effect. This would seemingly require that the manufacturer declare glaze devitrification as an intentional defect on the packaging. Since manufacturers have yet to declare optical hazing or incomplete polishing as an intentional effect, it must be an unintentional defect.

When surface quality is assessed according to ISO 10545-2, the procedure requires viewing the tiles perpendicularly at a distance of 1 m under even illumination of 300 lx intensity. Such viewing conditions emanate from at least 1974 (in BS 1281). It was intended that the conditions only permit the identification of objectionable defects that might be most readily seen in completed buildings. The specified viewing conditions predate the modern use of floor to ceiling windows where tiling may be used for passive heating in prestigious environmentally designed projects.

The ISO 10545-2 test procedure will not reveal the presence of optical hazing, oriented sheen, darkened glazed tile edges, variable reflectance patterns, or any other anomalous aesthetic defect that requires the tiles be viewed under low angle reflected light conditions. While tiles may comply with the ISO surface quality requirements, the standards still provide grounds for experts to declare tiles defective and the standards to be in need of revision.

In Australia, some State Governments collectively produced a non-prescriptive Guide to Standards and Tolerances¹², a convenient reference to the minimum quality of expected building work. This promotes the use of 1.5 m or greater as a distance for floors, viewing the surface at an angle, using "non-critical light" illumination, which means diffused light that is not glancing or parallel to the floor. This might be interpreted as low (angle) incident light, but how low an angle is the issue. While overall tiling appearance will always be affected by glancing light, and self-levelling screeds will assist in minimising any deviations from planarity between tiles, the failure of a very small percentage of the tiles to reflect light in the same way as the other tiles is not excusable.

Dawn and dusk will produce the most pronounced natural 'glancing light', but reflections from outside surfaces can extend the duration considerably. Lighting design can minimise adverse effects of a lack of tile or tiling planarity, but higher than normal standards of workmanship to optimise the reflection of uniform tile surfaces.

ISO 13006 defines a polished surface as "surface of glazed and unglazed tile which has been given a glossy finish by mechanical polishing as the last stage of manufacture". ISO 13006 Clause 8.1f has required (since 2012) that the marking on tile packaging must include details of any surface treatment applied after firing. This should logically include the fact that the tiles have been polished, as well as whether any wax or nanocoating has been applied during or after the polishing process. Such coatings might initially have been used to protect the polished finish of the tile during the tile installation phase, but some products were used to enhance the stain resistance of the tiles, and others have been used to disguise any variability in surface reflectivity (due to variations in surface texture and porosity). Where manufacturers fail to state that such coatings have been applied, the tile is technically not a first quality product. From a practical perspective, it is important for independent laboratories to be aware of such coatings when undertaking tests: it may sometimes be necessary to modify the test protocol in order to obtain relevant results. It is also necessary for merchants and property owners and managers to understand the nature of the surface in order to select appropriate maintenance regimes and maximise economical tile life cycle performance.

The Australian Tile Council has recommended¹³ that polished porcelain tiles should be sealed unless otherwise advised (which perhaps recognises that many tiles have already been factory sealed). Any failure to remove cementitious and wax residues from the tiles before sealing will result in these contaminants being trapped below the sealer surface. While some merchants may consider that "Optical hazing is not considered a fault in the tile", such an attitude does not conciliate traumatised consumers. Neither does the suggestion that "The effects of optical hazing can be minimised by careful design planning, such as, the use of curtains and blinds, and the careful placement of furniture". If there was no optical hazing, there would be no need to suggest to consumers that they use rugs, furniture and unwanted planning measures to hide defective tiles. Merchants are entitled to gamble on tile quality: they can alert consumers to potential optical hazing problems, but have no right to try to transfer the liability of any losing wagers to consumers. The merchants who chose not to retail cheap polished porcelain have been somewhat bemused by the controversy.

While various bodies may seek to prepare guidance, the fundamental question is, "Are the variations readily discernible or not?" In inspecting some Chinese showrooms, there were instances of mild ubiquitous regular optical hazing. Haze was evident and the clarity of reflection was less than perfect, probably due to the inherent porosity of the porcelain or its polishing. Are such tiles acceptable? If the merchant receives the same tiles that he has been shown, and if consumers receive the same tiles that they observe, there would appear to be no problems. However, if an architect specifies polished porcelain tiles based on seeing other batches of porcelain tiles, the matter is not so clear. A reliable means of classifying the surface reflectivity is obviously required.

Chinese manufacturers often use glossmeters for measuring the reflectance of polished porcelain. Specular gloss is one of several related appearance attributes that

produce the sensation of glossiness. Thus, specular gloss measurements may not always correlate well with subjective visual rankings of glossiness. Since specular reflectance depends on the surface refractive index of the specimen, the measured gloss ratings change as the surface refractive index changes. Improved correlations with visual judgments can sometimes be achieved by using different glossmeter geometries, but fixed geometry glossmeters will generally be incapable of detecting optical hazing.

Polished porcelain is a translucent material that experiences mixed diffused reflection, i.e., both specular reflected radiation and anisotropic diffused radiation. The reflections are dependent on the heterogeneity of the surface and the internal composition of the tile. Even where polished porcelain visually has uniform gloss, glossmeters can give variable results depending on the position, size, shape and orientation of any crystalline matter, cracks and voids, as well as significant differences in the refractive indices of the vitreous phases, where there can be considerable localised compositional changes.

Variable gloss measurements on acceptable low porosity polished porcelain tile led to the following Brazilian definition¹⁴ for polished technical porcelain tile: Technical porcelain tile that receives mechanical polishing, which results in a polished surface with variable intensity of gloss, in all of the surface or part of it, in accordance with the desired aesthetic effect.

2. GLOSS, HAZE AND DISTINCTNESS-OF-IMAGE (DOI) STANDARDS

Gloss only provides a quantitative measure of how much light is reflected from a surface. Additional measurement functions are required to describe the effects of texture and surface contamination that may detract from appearance without reducing the gloss. Since glossmeters are not sensitive to most surface textures, two surfaces can have identical gloss values but very different levels of perceived quality. Haze is a measurement of light scattered close to the specular direction. Haze problems give surfaces a shallow 'milky' look and cause haloes to be present around the reflection of strong light sources. Gloss provides no indication of distinctness of image. Goniophotometric curves are the profile of reflected light plotted against angle. The most subtle differences in surface texture can be identified and understood by examining and comparing goniophotometric curves.

ASTM C584¹⁵ covers the determination of 60° specular gloss for glazed ceramic tiles. ASTM International has several other test methods for measuring gloss and haze, where some specifically relate to plastics, other materials and coatings. Although ASTM D523¹⁶, and D4039¹⁷, may be useful in characterising some aspects of glossy appearance, they do not provide satisfactory ratings for image clarity and are more suitable for other products like polished or galvanized metal and varnishes. ASTM D5767¹⁸ uses three different electro-optical measuring techniques to determine the DOI gloss of coating surfaces, including two goniophotometric techniques. However, is image clarity the appropriate characteristic for gauging consumer satisfaction when optical hazing is the problem? The challenge is more to measure a more elusive characteristic, the inconsistent manifestations that are only observed under some viewing conditions.

3. DEVELOPING A NEW REFLECTOMETER

Lanzetta et al¹⁹ recognised the limitations of glossmeters and identified the need for a reflectometer that could be used to control the polishing of stones. Some rocks can take an almost perfect polish, depending on the type of minerals they contain, the format and density of their crystals, cutting direction with respect to crystallization and the fill-in of any micro/macro discontinuities. Stone polishing commences by grinding the surfaces, sequentially decreasing abrasive grain size, and is completed by applying a number of chemical products to the smoothed surfaces to improve their shine. Controlling the efficacy of the polishing process is an important requisite. Inspections are usually made off-line, at the end of the process, but it would be best for them to be done on-line, following the process step by step in order to be able to intervene as soon as anomalies appear.

Lanzetta and Tantussi²⁰ have acknowledged the large team that has contributed to the development of a new type of reflectometer through many research phases, involving the construction of several devices, making numerous different types of measurements to characterise surface roughness and other properties, and developing integrated contact, optical and vision systems to enable automated production processing. This work has involved a series of progressive studies with various prototype devices that have reconciled performance with theoretical modelling, while acquiring data and evaluating controllable processes. The evolutionary testing campaign has enabled a configuration that maximises instrumental sensitivity while extending the operational range of surface roughness capability. These studies resulted in patent PI/2007/A/000105 due to industrial interest in the innovative potential for three different types of reflectometer. The artificial vision and engineered versions have potential for industrial process control. The near infrared range version is essentially a laboratory analytical device.

The laboratory device enables both the wavelength of the incident light and the angle of its incidence to be varied. The reflectometer uses the basic glossmeter principle of catching the light that is reflected off a surface from a source (usually a led). However, it differs in two major aspects: coherent (laser) monochrome light is used in conjunction with spot size control. These two parameters allow significant extrapolation of the reflected specular light component, using the widest range of wavelengths, angles of incidence and lighting input power.

4. PRODUCTION TESTING OF THE REFLECTOMETER

As glossmeters are the de facto standard devices for stone polishing quality control, initial experimental testing has focused on finding a correlation between glossmeters and an engineered prototype reflectometer, prior to making a more versatile instrument commercially available. Figure 1 shows that correlation has been found over the wide range of commonly polished tile materials. The ability to convert the reflectance to equivalent gloss units is a benefit that will assist commercial acceptance of the reflectometer.

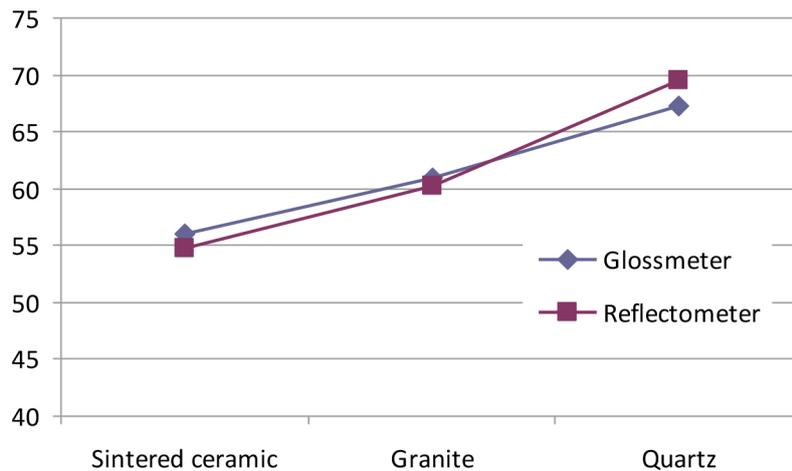


Fig. 1 Comparison of the normalised gloss and reflectance values of common polished tile materials.

However the reflectometer has intrinsically different behaviour: it can measure individual spots on surfaces that are only 0.1 mm in size, whereas commercial glossmeters are limited to a minimum dimension of 10 mm. The multiple (diffuse lighting) reflections that occur in large measuring areas reduce the ability of the glossmeter to discriminate: it cannot determine the contribution of the specular reflection - the cited low angle component - amongst the total light captured by the sensor. Comparative experimental testing on a composite ceramic tile has confirmed the reflectometer is more capable of detecting variability in measurements.

The ability to measure smaller surface areas allows a better discrimination of surface variations, allowing identification of optical haze and other surface defects. Since light wavelength is a fundamental reflectometer parameter, it can be fine tuned to be more sensitive to various materials variations, as opposed to the “white” glossmeter light.

5. A BRIGHTER FUTURE?

Development of the industrial processing reflectometer should enable the prompt identification of production problems and minimise the packaging of any tiles that display optical hazing. The reflectometer should also assist in maximising the productivity of the polishing train, helping to maximise gloss and minimise regular hazing. It will be unable to improve the quality of the porcelain body, where porosity and stressed quartz particles may be at the heart of some hazing problems.

The laboratory reflectometer should enable tiles to be classified according to their gloss/haze levels, where this should allow identification of the highest quality polished porcelain. It should also be possible to establish criteria that can determine when portions of tiles have unacceptable irregular optical hazing. Such limits can then be incorporated into standards.

6. IN THE INTERIM

In the case of disputes, in order for expert opinion evidence to be admissible, one must demonstrate that there is a field of “specialised knowledge”, and that the witness has become an expert by reason of specified training, study or experience. The proffered expert opinion must be “wholly or substantially based on the witness’s expert knowledge”, where “observed” facts must be identified and admissibly proved, and “assumed” or “accepted” facts must be identified and proved in some other way. There are too many reputed experts who rely upon papers such as this as the principal basis for their expertise in a specific area. This paper is not exhaustive and only touches on some aspects of optical hazing, its manifestations and causes, and a few other pertinent matters.

The statement “If I take the trouble to view the premises, and I see something that I would be unhappy with in my house, somebody will regret their decision not to settle”, might best be considered as hearsay attributed to a judge faced with the prospect of a lengthy journey to view an optical hazing problem at an inopportune time such as dawn or dusk. Pronounced irregular hazing is almost certainly a major manufacturing defect. Mild regular hazing may or may not be a defect, depending on what might have been on display and how it was displayed. The sooner that novel reflectometers are used to control the processing of polished porcelain tiles, and relevant product standards are developed, the sooner that experts can direct their attention to more productive pursuits.

Designers, installers and consumers should appreciate the effects of lighting on tiles and tiling workmanship, and particularly the effects of glancing critical light. Merchants can seek to manage consumer expectations, but should not presume that esoteric subjective guidance on such issues will absolve them of responsibility for tiles that have pronounced aesthetic irregularities, particularly where tiles have been polished to provide a specific appearance. Use of the same guidance across a tile category fails to differentiate between those of the desired appearance, and those where a warning should be issued because they are unlikely to fulfil consumer expectations. Cass has stated²¹ “The industry’s catch phrase should be: Know your product and market it honestly or pay the penalty”. The only way to ensure acceptable polished porcelain tile quality is for manufacturers to adopt automated inspection and classification systems. Until then, merchants would best be advised to deal with manufacturers that will compensate for any losses due to the supply of defective tiles. Expert tiling consultants are likely to be early adopters of the new reflectometer.

The reflectometer developmental process has revealed that the two dimensional hybrid Rk (core depth) roughness parameter provides a more reliable contact roughness sample measure than the classic Ra and Rz roughness parameters. Rk is fairly uninfluenced by the very pronounced valleys that remain when the polishing process creates a plateau finish in granite and some other rocks. Since the reflectometer can be used to control and optimise polishing processes, and effectively correlates surface roughness and reflectance, further developments might lead to potential inspection applications with respect to slip resistance assessments of some products.

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