ceramics

Review

Ceramic Tile Adhesives from the Producer's Perspective: A Literature Review

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Abstract: Ceramic tiles and ceramic tile adhesives (CTA) are two impressive materials that have changed construction history. Ceramic tiles could not provide their beauty and durability for buildings when used as a covering both for the inside and exterior finishing without CTA. Nowadays, they are complex multi-component systems. Among the various CTAs, cementitious products are the most commonly used. This article presents an extensive review of the literature, showing how they are perceived in the scientific literature today. In this paper, an attempt is made to review individual adhesives' ingredients' effects on their properties, with particular reference to redispersible polymer powders and methylcellulose ethers. The article presents the basics of the CTAs, assessing and verifying the constancy of their performance in force in European Union countries. Furthermore, it gives a critical review of CTA's normalized measurement methodologies. The study also draws attention to the need to consider measurement uncertainty in decision-making and conformity assessment, supported by an analysis of the results of multi-annual inter-laboratory studies and market surveillance tests. Future research suggestions are also made based on the review, mainly from the adhesive manufacturer's perspective.

Keywords: ceramic tile adhesive; ceramics; construction products

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1. Introduction

Ceramic tiles have been used for centuries as decorative elements inside and outside of buildings of all kinds, including residential homes, public buildings and places of worship. Their history goes back to antiquity: Egypt, Assyria and Babylonia (e.g., the Ishtar Gate, one of the most beautiful and impressive examples of glazed bricks). The Romans and Greeks also used decorative tiles. Their growing use was connected with the Islamic expansion. Finally, in the Middle Ages, they became popular in Europe. The industrial revolution made tiles widely available. Ceramic tiles have been valued for centuries due to their durability and exceptional resistance to external factors. The relative maintainability of their cleanliness is also essential [1]. Nowadays, ceramic tiles in many traditional applications have to compete with glass, metal, high-pressed laminates and other covering materials. This is especially true when building architecture requires features that go beyond beauty and durability. This is also because construction has already moved and is still moving forward to the era where productivity is the keyword.

It would be impossible to use ceramic tiles without the material to stick them to the substrate, i.e., the adhesive connecting these materials. For thousands of years, construction was associated with the use of mineral binders like gypsum, lime, pozzolans (volcanic ash), or cement [2]. It is precisely the mortars using the mineral binders that were also used for the installation of ceramic cladding.

In 2019, 12.673 billion square meters of ceramic tiles were produced worldwide (a decrease of 3.7% compared to the previous year, 2018), while the consumption of ceramic cladding was 12.375 billion m^2 (a decrease of 4.1% compared to 2018) [3]. Assuming an average consumption of 4 kg/m^2, this means the use of slightly less than 50 million tons of the commonly used cementitious adhesives for tiles. One of the global marketing research agencies, in 2020, estimated that the dry-mix mortar (renders and plasters, ceramic tiles adhesives, masonry mortars, joint and crack fillers, screeds, and flooring compounds) market size was over 260 million tons [4]. According to this study, ceramic tile adhesives (CTAs) had a share of slightly more than 25% in all types of dry-mix mortars, which means a little less than 70 million tons of manufactured products. The difference in these data is due to several reasons, including the different definitions/understanding of the term CTA, the different standards of works related to laying ceramic tiles, the different technologies and materials used, and the difficulty of obtaining reliable sales data. The latter is visible, for example, when comparing the data of two CTA market size surveys. According to one of them, the global CTA market was projected to be USD 8.23 billion in 2019, and to reach USD 13.98 billion by 2029 at a compound annual growth rate (CAGR) of 5.5%. [5]. According to another study, the global CTA market was valued at USD 15.08 billion in 2018, and is projected to reach USD 40.73 billion by 2026, growing at a CAGR of 13.3 from 2019 to 2026 [6]. Regardless of the difficulties in precisely defining the size of the CTA market, it is undeniable that it is an important group of building materials that are constantly developing [2,7,8].

As a result of the development of science, the development of the building material industry, the development of construction technologies, and the growing market expectations in the 1960s, the production of factory-mixed dry mortars started to grow [2]. Initially, the development of dry-mix mortar technology was related primarily to Germany and other Western European countries, and the USA. The primary factors that influenced the development of dry-mix mortar technology include the limited resources of skilled workers, the need to shorten construction operation times, and increasing labor costs. Furthermore, the growing number of specialized applications, the related need to use appropriate construction products, and users' rising expectations played an influential role. Factory-made dry mix mortars eliminated the possibility of errors that could occur when using job-site-mixed mortars. The development of dry-mix mortar technology in Germany in the years 1960–1995 allowed for a sixfold increase in the amount of render and plaster mortars used, while reducing employment by 25% [2]. The Polish system transformation of 1989 initiated a successful development of dry-mix mortar technology in Central and Eastern Europe [9]. The following years brought enormously growth to other new markets, including Russia and the Middle-East [8]. Today, dry-mix mortar technology is widely used. There are no precise data on the number of functioning dry-mix mortar plants. In 2007, in Europe, there existed about 790 plaster and mortar works, in which about 41.5 million tons of premixed dry mortars were produced [7]. However, there is no doubt that there are thousands of dry-mix mortar plants in the world in which mineral and polymer binders are mixed with fillers/aggregates and chemical additives, modifying the properties of mortars in a well-defined way (mixing method and time, automatic computer-controlled processes). Then, dry-mix mortars are packed in bags or silos and delivered to the sales places or construction sites. After adding a strictly defined amount of water at the construction site to the dry-mix mortar, they are applied.

2. Composition of Ceramic Tile Adhesives

Cementitious CTAs are the most commonly used type of thin-bed mortars for tiling ceramic tiles. The use of dispersion adhesives and adhesives based on reactive resins is significantly lower, and they are not discussed in this paper. Due to this reason, only the cementitious adhesives for ceramic tiles are the subject of consideration of this article.

Ceramic tiles can be installed inside (bathrooms, kitchens, offices and other rooms) and outside buildings (terraces, balconies and building facades). Today, a wide variety of ceramic tiles are offered, glued to various substrates, both on horizontal and vertical surfaces. The composition of the CTA should be designed so that the properties of the adhesive give the desired effect and meet the expectations of all of the participants in the construction process, i.e., the investor, contractor and construction inspector.

The CTAs used today are complex multi-component systems. Thin-bed ceramic tile adhesives are composed of binder/binders, aggregates and chemical additives. In most cases, meeting the requirements of modern users necessitates the use of two binders to produce CTAs, i.e., mineral, Portland types of cement, sometimes with the addition of high-alumina cement, and polymer, in the form of redispersible polymer powder (RPP). Aggregates serve as a reinforcing and structural element, increasing the strength of the CTA. Generally, aggregates ensure the packing density, flexural strength and durability. The most commonly used aggregates are quartz fillers with quartz sand granulation in the range of 0.05–0.50 mm. Apart from quartz, limestone, light and special fillers are also used. Among the chemical additives usually used up to 1% are water-retention agents/thickeners (mainly chemically modified cellulose derivatives), and sometimes modified starch derivatives and cellulose fibers, accelerators, retarders, and deformers play a unique role in CTA. In the following, we will discuss the influence of the components mentioned above on cementitious CTA properties.

2.1. The Specificity of Thin-Layer Mortars

In the case of construction mortars containing Portland cement, the reaction of the clinker components with water leads to the setting and hardening of the mortar. Water is needed in the mortar over a prolonged period for the cement setting processes to take place. In the case of thick-layer mortars, i.e., systems with a low surface area to volume ratio, the amount of water is usually sufficient for the setting processes. In thin-layer mortars, where the surface-to-volume ratio is much higher than in the case of thick-layer systems, there is typically a deficit of water, which evaporates on the surface or is pulled through the substrate by capillary forces. This leads to a reduction in the hydration processes (sometimes the hydration degree is below 30%), the rapid hardening of the mortar, and the deterioration of the properties of the hardened mortar, which can significantly affect the durability and service life of the mortar [10]. This is a common problem of the thin-layer mortar system. This problem was well demonstrated by Schulze et al., who compared the compressive and flexural strength for a mortar using two different specimens: the standard prism of 40 × 40 × 160 mm dimensions and a 10 × 40 × 160 mm prism [11]. The study compared the flexural and compressive strength for the cementitious mortar stored for 28 days in dry-air conditions (23 °C/50% r.h.) and after immersion in water for both measurement prisms. The samples' compressive strength and flexural strength after storage in water were higher for both measurement prisms than those for the pieces stored in dry-air conditions. In the case of the prism with dimensions of 10 × 40 × 160 mm, for which the surface-to-volume ratio was four times higher than in the case of the standard prism (40 ×40 × 160 mm), immersion in water led to a much higher increase in the compressive and flexural strength (the effect of a much higher degree of hydration caused by the greater water availability).

2.2. Influence of Cellulose Derivatives (CDs) on the Properties of CTAs

Among the ingredients modifying the properties of CTAs, so that they meet the requirements facing them today, a special place is occupied by chemically modified cellulose derivatives (CDs). The properties of CDs or other water-retention agents should always match the specific purpose of the construction mortar. Among the various CDs, the following are mostly used in CTA applications: methyl hydroxyethyl cellulose (MHEC), methyl hydroxypropyl cellulose (MHPC) and hydroxyethyl cellulose (HEC). Their addition to any construction mortar, including CTA, causes the retardation of the cement hydration. It creates changes in the microstructure of the adhesive. It increases plasticity, affects the viscosity and workability, and ensures higher water retention in the mortar. The presence of CD influences the properties of both fresh and hardened adhesive [2,12].

Although CDs in the form of cellulose ethers have been used since the beginning of the 1960s for mortar modification [13], and the construction sector held the largest market share among all CD applications [14], not many papers have been published on the mechanisms by which CDs affect cement hydration [15–22]. This is due to the complexity of the cement hydration process, during which the reactions of different clinker phases with water overlap. The poly-mineral composition of cement grains additionally complicates the whole process. From the CTA formulator's point of view, research concerned with CDs' influence on various selected properties of building mortars is more important [13,23–26].

Cellulose ethers allow the increase of the adhesion of fresh mortar to the substrate, which also positively affects the adhesion of the mortar after it has hardened. CDs (MHEC and MHPC) also stabilize the air pores in the mortar [24,27]. CDs stabilize the air bubbles introduced into the mortar during mixing, which in most cases is a desired phenomenon and affects the application parameters of the mortar, including its workability. On the other hand, too much air affects the mechanical properties: adhesion, compressive and flexural strength depend on the density exponentially. Moreover, the ability to stabilize the introduced air affects the efficiency of the mortar's application, which depends on the maximum water-to-binder ratio and the total air volume. The most desirable effect of using cellulose ethers in building mortars is their strong affinity for water and its retention [25,28]. The water stored by the cellulose ether provides the appropriate conditions for the setting and hardening of the cementitious binders. Cellulose ether, due to the specific function of the water storage, has a positive effect on the strength parameters of the mortars, including their adhesion to the substrate [10].

Cellulose ethers are often not the only rheology modifiers/thickeners in formulations of the CTA. Today, they are commonly mixed in the CTA with other water-retention agents, such as starch ethers, polyacrylamide, or inorganic (bentonite, sepiolite) modifiers [29].

2.3. Influence of Redispersible Polymer Powders on the Properties of CTAs

The CTAs used today would not meet the expectations of users and the requirements resulting from the regulations on the placement of a construction product on the market without the modification of their properties through the use of redispersible polymer powders (RPPs). Polymers have been used to modify mortars since ancient times. Egyptians and Romans modified lime plasters using natural polymers, such as Arabic gum, glutin glues produced from animal skins or bones, and fig juice. They and others also used egg yolks, casein, milk protein, proteins from horns, and the claws of wild and farm animals to modify building mortars [30]. Before the "era" of RPPs in the 1950s and 1960s, polymers were widely used as water dispersion to improve cementitious mortars. The use of two-component systems—cementitious dry-mix and dispersion—was associated with the possibility of using the incorrect proportions as a result of human error on the construction site. In addition, the liquid component in the system was sensitive to the action of microorganisms. These inconveniences were eliminated by the fact that, in the 1950s, RPP was obtained (RPP is an organic polymer material obtained in the spray-drying process from dispersion); the fact that, in 1970, RPP was a copolymer containing ethylene in its composition was an important factor in the development of CTAs with increased parameters (class C2) [2,12]. RPPs, similarly to cellulose ethers, affect both the properties of fresh and set mortars [31–36]. An undesirable side effect of polymeric additives (both RPPs and cellulose ethers) in the CTA formulation is the formation of a dry skin on the mortar surface [33,37]. This is created due to water drying from the surface layer. The dry external layer (skin) has different properties to the bulk body underneath. The thickness of the skin (the external surface layer) ranges from 0.1 mm (initial) to 1 mm about 30 min after applying fresh CTA [37]. The skin's formation on the CTA's surface limits its application, mainly when the skin is formed before the ceramic tile is applied [38].

For CTAs, adhesion to the substrate is the most desirable feature. The presence of RPP in the CTA significantly increases the value of this parameter [31–33,39–42]. RPPs increase the tensile strength of cementitious mortars. This is crucial in the case of thin-layer mortars [31,32,42]. The increase in tensile strength is related to the positive effect on the ability to bridge cracks, and to the transverse deformation (also known as elasticity) of polymer-modified mortar [43]. The vast majority of studies on the influence of RPPs on the compressive strength in cement systems showed that the value of this property is reduced [31–34,44]. Independent research by Sakai et al. [31] and Schultze et al. [45] showed that the decrease in compressive strength is directly proportional to the polymer additive's concentration. Additionally, both researchers showed that the amount of powder used does not affect the durability of the mortar. All of the tests proved the increase in the flexural strength of cement systems modified by RPPs [31,32,34,44,46,47]. In addition, it was observed that the increase in flexural strength is significantly influenced by the maturation conditions of the mortar samples for testing [47]. The studies by Sakai et al. showed that the maximum increase in flexural strength was observed after adding 10% by weight RPP to the cement, and a further increase in the amount of RPP in the system did not cause any changes. Another important aspect of RPP-modified cement systems is their durability. Durability is an important aspect when considering the system of mixed binders based on mineral-polymer binders and their environmental performance. Research by Mirza et al. showed that the modification of cement mortars with polymers increases the resistance of the mortar to freeze–thaw cycles [48]. Studies made by Schulze and Killermann of polymer-modified mortars subjected to outdoor and indoor exposure, using scanning electron microscopy, showed no changes in the morphology of the polymers in the mortars over the ten years of exploitation [45].

Other properties that are the subject of research on polymer-modified mortars include, among other things, the aeration of the mixture [35], the ability to reduce the amount of water to needed to prepare fresh mortar [44], and the increase of the water retention capacity of the system [34]. Of course, in mortars, the water retention capacity is mainly due to the use of cellulose ethers [49]. Wang et al. showed that RPPs have such properties; the concentrations for which similar effects are observed for cellulose ethers are at least one order of magnitude higher [34].

RPPs are characterized by the ability to inhibit cement hydration processes [34,50,51]. Despite the many years of research carried out in many centers around the world, it is not possible to indicate whether the interactions between the clinker phases undergoing hydration, the products of hydration of the clinker phases and the produced cement matrix, and the polymer contained in the system are only physical, or whether the observed modification effects are the result of synergistic coexisting physical and chemical interactions [52–56]. Various conclusions are drawn about the nature of the cement–polymer interaction [33,35,36,57–60].

3. Formulation of the CTAs

Modern CTAs contain a dozen components. Such an amount of ingredients in an appropriate composition is necessary to meet the requirements of modern CTAs given by their users. Many sample CTA recipes are available, but the producers' compositions are their key intellectual property.

Cementitious CTAs are produced in plants that typically supply customers with their products within a radius of 120–200 km. Manufacturers try not to deliver their products over 200 km because CTAs are relatively cheap construction materials (especially C1 class CTAs), and the influence of the transport costs of the final product and raw materials is noticeable. Manufacturers of CTAs, when formulating the recipes of their products, must take into account many aspects, among which the following should be considered:

- compliance with the minimum classification requirements specified in the relevant standards, including:
  - (a) the variability of the raw materials of local origin (cement, aggregates, other inert ingredients);
  - (b) in the case of producers offering the product from different production locations, the need to optimize (average) the product quality;
  - (c) the variability resulting from the measurement uncertainty of the test methods used;
- the real conditions of use on the construction site;

- fulfilling the expectations of tile fixers (appreciation) in terms of product friendliness in the broad sense, i.e., the ease of application, fresh-state application properties, and parameters not specified in the standards constituting the basis for the assessment of the product resulting from legal provisions;
- the competitiveness against other products intended for similar uses, including:
  (a) technical dimensions;
  (b) manufacturing costs;
- the competitiveness of the CTAs against other products: defining the ability of CTAs to compete with substitutional goods towards downstream clients.

4. Testing of the CTAs

4.1. Assessment and Verification of the Constancy of the Performance of the CTAs

In 2001, as a result of CEN/TC 67/WG 3 activity, the European Standard EN 12004:2001 [61] was established, which specified the requirements for CTAs. So far, the standard has been amended several times: EN 12004:2001/A1:2002/AC:2002, EN 12004:2007, EN 12004:2007+A1:2012 and EN 12004–1:2017. The latest version of the standard with the requirements for CTAs published in the list of European harmonized standards [62] is EN 12004:2007+A1:2012 [63]. The next version of the standard published by CEN in 2017, EN 12004–1:2017 [64], has not yet been included in the list of harmonized standards published in the Official Journal of the European Union, and therefore cannot be the basis for the assessment and verification of the constancy of performance. Although the CPR rules have been in force for seven years [65], the document used in the process of assessing and verifying the constancy of the performance of tile adhesives is a standard from the old legal order, i.e., from the time of Directive 89/106/EEC Construction products [66]. Before 2001, various national standards operated in EU countries. The lack of requirements which were applicable to all of the participants of the construction market in the EU countries made it difficult and often impossible to evaluate the product objectively compared to other competing products, not to mention the free movement of goods between the Member States [67].

The EN 12004 standard, apart from cementitious adhesives, also applies to dispersion adhesives and adhesives based on reactive resins for ceramic tiles. The EN 12004 standard divided cement adhesives for ceramic tiles into two main classes (groups): those with basic properties, marked as C1, and those with enhanced parameters, marked as C2. Table 1 shows the requirements for cementitious CTAs under EN 12004: 2007+A1:2012.

Table 1. Requirements for cementitious (C) adhesives for ceramic tiles (CTA) according to EN 12004:2007+A1:2012 [63].

Fundamental Characteristics		
Characteristics	**Requirement**	**Test Method**
Normal setting adhesives (C1)		
Initial tensile adhesion strength	$\geq$0.5 N/mm^2	8.2 of EN 1348
Tensile adhesion strength after water immersion	$\geq$0.5 N/mm^2	8.3 of EN 1348
Tensile adhesion strength after heat aging	$\geq$0.5 N/mm^2	8.4 of EN 1348
Tensile adhesion strength after freeze-thaw cycles	$\geq$0.5 N/mm^2	8.5 of EN 1348
Open time: tensile adhesion strength	$\geq$0.5 N/mm^2	EN 1346
Fast setting adhesives (C1F)		
Early tensile adhesion strength	$\geq$0.5 N/mm^2	8.2 of EN 1348
Open time: tensile adhesion strength	$\geq$0.5 N/mm^2	EN 1346
All other requirements as in Table 1a of EN 1348		EN 1348

Table 1. *Cont.*

Optional Characteristics		
Special Characteristics		
Slip	≤0.5 mm	EN 1308
Extended open time: tensile adhesion strength	≥0.5 N/mm^2	EN 1346
Deformable adhesive: transverse deformation	≥2.5 mm and <5 mm	EN 12002
Highly deformable adhesive: transverse deformation	≥5 mm	EN 12002
Additional characteristics (C2)		
High initial tensile adhesion strength	≥1 N/mm^2	8.2 of EN 1348
High initial adhesion strength after water immersion	≥1 N/mm^2	8.3 of EN 1348
High tensile adhesion strength after heat aging	≥1 N/mm^2	8.4 of EN 1348
High tensile adhesion strength after freeze-thaw cycles	≥1 N/mm^2	8.5 of EN 1348
Fundamental Characteristics		
Characteristics	**Requirement**	**Test Method**
Normal setting adhesives (C1)		
Initial tensile adhesion strength	≥0.5 N/mm^2	8.2 of EN 1348
Tensile adhesion strength after water immersion	≥0.5 N/mm^2	8.3 of EN 1348
Tensile adhesion strength after heat aging	≥0.5 N/mm^2	8.4 of EN 1348
Tensile adhesion strength after freeze-thaw cycles	≥0.5 N/mm^2	8.5 of EN 1348
Open time: tensile adhesion strength	≥0.5 N/mm^2	EN 1346
Fast setting adhesives (C1F)		
Early tensile adhesion strength	≥0.5 N/mm^2	8.2 of EN 1348
Open time: tensile adhesion strength	≥0.5 N/mm^2	EN 1346
All other requirements as in Table 1a EN 1348		EN 1348
Optional Characteristics		
Special Characteristics		
Slip	≤0.5 mm	EN 1308
Extended open time: tensile adhesion strength	≥0.5 N/mm^2	EN 1346
Deformable adhesive: transverse deformation	≥2.5 mm and <5 mm	EN 12002
Highly deformable adhesive: transverse deformation	≥5 mm	EN 12002
Additional characteristics (C2)		
High initial tensile adhesion strength	≥1 N/mm^2	8.2 of EN 1348
High initial adhesion strength after water immersion	≥1 N/mm^2	8.3 of EN 1348
High tensile adhesion strength after heat aging	≥1 N/mm^2	8.4 of EN 1348
High tensile adhesion strength after freeze-thaw cycles	≥1 N/mm^2	8.5 of EN 1348

In terms of the deformability of cementitious CTAs, there are two types of products according to the EN 12004: deformable adhesives (S1) with transverse deformation ≥2.5 mm and ≤5.0 mm, and highly deformable adhesives (S2) with transverse deformation ≥5.0 mm.

The authors of the EN 12004 standard (CEN/TC 67/WG 3) adopted as the essential characteristics of cementitious CTAs the adhesion and open time, i.e., the maximum time after applying the CTA when the tiles can be embedded into the adhesive layer to obtain the required adhesion. The adhesion measurement is performed after the mortar has been stored in various laboratory conditions, simulating the real conditions in which cementitious CTAs are used. In the initial stage of the development of EN 12004, the authors also considered shear strength as one of the characteristics of cementitious CTAs. Due to the slight differences in the measured offset (in tenths of a millimeter), the authors rejected the possibility of using the shear strength to characterize cementitious CTAs.

EN 12004:2007 + A1:2012 is a standard established by the Comité Européen de Normalization (CEN), and it is valid in the EU and European Free Trade Association (EFTA) countries. Taking into account that, in 2019, the consumption of ceramic tiles in 28 countries belonging to the EU amounted to 920 million square meters [3], and that the EFTA includes only four countries (Iceland, Liechtenstein, Norway, and Sweden), the coverage of EN 12004 is slightly over 7.4%. However, it is worth noting that the requirements for AVCP for cementitious adhesives in force in EU countries since 2001 were implemented in 2004 by the International Organization for Standardization (ISO), which established the ISO 13007 series of standards [68]. Thus, the requirements for cementitious CTAs are standardized in most countries of the world.

4.2. Critical Remarks on the Laboratory Test Methods According to EN 12004

As mentioned before, the key to the classification of cementitious CTAs is their adhesion determined by the tensile strength. In this aspect, it is worth looking into the measurement methodology. From a practical point of view, perhaps the most interesting point for the manufacturers of CTAs is the reproducibility of the results, i.e., the degree of agreement between the results obtained by different analysts in different laboratories using a given measurement procedure.

Felixberger [12] described the results of the initial adhesion tests of seven cementitious CTAs carried out in ten laboratories using two different test slabs. As the first test slab, each of the participating laboratories used a standard test slab that met the EN 1323:2007 requirements [69]. The second concrete slab was purchased by the research organizer and delivered to all of the participating laboratories. The standard deviation of the measurement ranged from 15 to 20%. The tests organized by Felixberger showed the influence of the slab on the value of the determined adhesion. It was also found that more significant differences between individual measurements were present for cementitious CTAs with a lower adhesion value (C1 class) than for adhesives with higher adhesion (C2 class).

According to Felixberger [12], priming the surface of the concrete slab for testing would unify the surface of the slab in terms of its absorption properties, and would create a situation closer to the actual use, in which the manufacturers of cementitious CTAs recommend the use of a primer before laying ceramic tiles.

In 2007, the Romanian notified laboratory in the scope of EN 12004 initiated interlaboratory measurements of the initial adhesion of CTAs. Nine laboratories, mainly Romanian, participated in the first edition of the study (2008–2009), and five years later they were joined by 27 laboratories of research institutes and manufacturers of CTAs from the following nine countries: Austria, Bulgaria, Croatia, Czech Republic, Germany, Poland, Portugal, Romania and Slovenia [70]. Proficiency tests/interlaboratory comparisons, as mentioned above, were carried out according to uniform rules and under the requirements of EN ISO/IEC 17043 [71]. The initial tensile adhesion strength of four different cementitious CTAs (C2FTE, C2TE, C2TES1 and C2TS1) was tested. All of the laboratories used identical concrete slabs and the same ceramic tiles provided by the test organizer for the tests. According to the authors of the study, more than 90% of the test results obtained by the participating laboratories can be described as "satisfactory" having ($|z| \leq 2$), according to EN ISO/IEC 17043; the remaining results were questionable or unsatisfactory [70]. In 2014, the study was extended to the second characteristic, i.e., adhesion strength after immersion in water. In 2018, three characteristics were measured during the tenth jubilee edition of the study: initial adhesion, adhesion after immersion in water, and open time [72]. Sixty-seven laboratories from 25 European countries and Asia participated in the tenth edition of the research. In total, 94% of the obtained test results were qualified as satisfactory ($|z| \leq 2$) under EN ISO/IEC 17043. One of the Romanian project's objectives was to show that continuous participation in laboratory proficiency testing programs improves the participants' work quality. In this respect, the organizers' research achieved the intended goal.

In meeting the standard requirements of cementitious CTAs, it is worth mentioning the research on the effect of the seasoning water on the adhesion of adhesive mortars [73]. Nosal et al. stored samples of cementitious CTAs in three types of water: in distilled water (pH = 7.09, specific conductivity = 0.040 mS/cm), in tap water (pH = 8.25, specific conductivity =

0.805 mS/cm) and in softened water (pH = 8.63, specific conductivity = 1.228 mS/cm). It was found in the study that the origin and type of the water used to condition the samples has a great influence on the adhesion of CTAs. Samples stored in distilled water were characterized by higher adhesion than those stored in tap water or softened water. As emphasized by the authors of the research, in some cases, the difference between the test results was so significant that it determined whether the standard requirements were met. This observation is important in various respects. It seems appropriate to determine, in the future, the type of water used to condition the samples.

The adhesion of the cementitious CTAs is determined in the following system: concrete substrate (slab)–adhesive–ceramic tile. The properties of ceramic tiles approved for use during adhesion tests are specified in the standards referred to for a given test method in EN 12004. However, not all of the parameters that should be characterized by ceramic tiles used for the testing of the adhesion of cementitious CTAs are specified. Niziurska assessed the influence of ceramic tiles' chemical compositions and surface structures on the adhesion of cementitious CTAs [74]. The results obtained in the tests confirmed the impact of the quality of the auxiliary materials (ceramic tiles) used in the tests on their compliance with the standard (threshold value) requirements of the tested CTAs.

4.3. Manufacturers' Risk Related to the Assessment and Verification of the Constancy of the Performance of the CTAs

The introduction of any product to the market is associated with risk. The manufacturer's risk is also that his product will be negatively assessed by market surveillance authorities, which will order the manufacturer's product to be tested. In a situation where the product's actual performance is close to the threshold value resulting from the standard's requirements, a situation may arise in which the manufacturer's product is negatively assessed, and his product will have to be removed from the market. This is the case for construction products due to the EU's surveillance and inspection system for construction products [75]. In order to prevent the possibility of such a situation, the manufacturer should carry out an analysis of the measurement uncertainty [76,77]. Not taking the risk resulting from the variability of the measurement uncertainty of the test method may create a situation in which the product assessed as compliant by the manufacturer will be assessed as non-compliant in the market surveillance authorities' test. It may also happen that the product found by the manufacturer to be non-compliant meets the threshold value [78].

For this reason, the knowledge of the measurement uncertainty in the testing of a given property is essential for the manufacturer. A risk-aware manufacturer can increase product parameters (colloquially speaking, improve product quality) and minimize the risk. In most cases, however, this means an increase in the production costs of the construction product.

Research carried out in 2016–2020 by the Polish construction supervision authorities of cementitious CTAs showed that many products did not meet the threshold value of adhesion strength [79]. However, it is essential to note that when assessing the compliance of the obtained results with the criteria, the market surveillance authorities applied a simple acceptance rule [80]. The simple acceptance rule means that the product is compliant or non-compliant concerning the result if this result met or did not meet the threshold requirements without considering the variability resulting from the measurement uncertainty.

4.4. A Few Remarks on the CTAs' Exploitation Conditions

Many critical comments are made in connection with the adoption in the EN 12004 of adhesion as being crucial for the classification of cementitious adhesives for ceramic tiles. These comments result from the fact that this parameter is determined by measuring the tensile strength (vertical force) and not the parallel shear force [12,81]. Shear stresses in the substrate—CTA—ceramic cladding system may arise due to thermal expansion of the ceramic cladding (for example, on balconies or terraces) or as a result of subsoil contraction (for example, fresh concrete or unsealed cement floor) [82,83]. Unfortunately, shear strength measurements are somewhat complex, unlike the relatively simple tensile adhesion strength measurements. For this reason, the shear strength of cementitious CTAs is not ordinarily determined. Fritze and Feichtner described a test method in which the tensile strength of the tile adhesive was determined after a sample was subjected to a controlled shear force [81]. According to the authors, their proposed research method corresponds well to the real-life impacts of cementitious CTA under operating conditions.

It should also be noted that the evaluation and classification of cementitious CTAs are usually carried out relatively shortly after the production of CTAs under laboratory conditions. Many centers dealing with CTAs indicate [84] the need to develop research methods related to the long-term operation of cementitious CTAs.

A constant challenge for the producers of CTAs is the continuous development of ceramic tiles' technology, including large-format ceramic tiles [85,86].

The most crucial challenge facing building material producers is sustainable development, which is a global challenge for construction. The environmental impact of CTAs should be considered in different dimensions. One is to consider CTAs along with ceramic tiles. Shohet and Laufer showed that external ceramic coverings last longer than other covering materials, except for stone [87]. Their environmental performance is influenced by the service life of the building itself and the building materials used. Construction materials' replacement intervals are important in the life cycle assessment of buildings. Ceramic tiles and terracotta tiles have a much longer life than plasterboards, plaster, or renders [88]. CTAs, considered in the aspect of waste materials deriving from demolition, are construction products that can be reused without special treatments. Ceramic tiles can be reused as inert materials for buildings.

Today, CTAs are not assessed in terms of their environmental impact, and voluntary Environmental Product Declarations for CTAs are rare. However, this situation will change. Producers and users must consider the further progress of CTAs through the prism of sustainable development and the sustainable use of materials for their production. Recently, one of the RPP manufacturers introduced vinyl acetate co- and terpolymer produced from renewable, and therefore non-fossil, raw materials [89]. Adding alternative binders to Portland cement can reduce its negative impact on the environment, such as sulfoaluminate cement (CSA), the production of which emits half the amount of carbon dioxide compared to Portland cement [90].

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