

POLYMER-MODIFIED THIN-BED TILE ADHESIVES

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1. HISTORY

The fundamentals of cementitious tile adhesives were laid a few thousand years ago. At that time opus caementitium, a forerunner of modern Portland cement was introduced by the Romans [1]. Due to the high compressive strength of opus caementitium the Romans were able to erect huge aqueducts and giant cantilever cupolas such as the Pantheon in Rome with 43 meters diameter. From the early beginnings until the middle of last century cement based mortars p. e. tiling mortars were prepared by basically mixing cement, sand and water in the appropriate ratio by hand at the jobsite. The quality of the site-mixed mortar depended on the quality of the raw materials and on the correct batching ratio which could not be controlled easily. However, in the 1950s two major innovations revolutionized tiling mortar technology and tiling technique.

The first revolution was the development of so-called redispersible polymer powders. Polymers are added to cementitious tile adhesives in order to improve their elasticity and bonding to the substrate resp. to the back of the tile. The advent of this technology enabled the building chemical industry to introduce polymer-modified dry-mix adhesives. Since that time jobsite mixed mortars were increasingly substituted by the new type of ready-mix mortars. Since dry-mix tile adhesives are industrially produced the quality of raw materials is easier maintained at a homogeneous level and mixing errors of even multi-component mixtures may be avoided. Additionally tiling with pre-mixed and pre-packed tile adhesives allows high performance and application safety at the construction site.

The second quantum leap in the 1950s was the improvement of substrates. Due to modern plaster and dry construction technologies substrates got more and more even. Therefore the thick-bed technique for laying tiles which was necessary to level uneven substrates was replaced by the thin-bed method. Instead of up to 30 mm of thick-bed mortar which was basically a jobsite mixture of cement and sand (mixing ratio 1:4), 4 mm of polymer-modified pre-mixed tile adhesive were sufficient. During the change from the thick-bed to the thin-bed technique tilers were earning “good” money since at that time builders were not aware of the much lesser adhesive consumption.

Thin-bed (2 – 5 mm)

The thin-bed mortar is usually spread with a notched trowel onto the substrate resulting in a ribbed mortar bed of typically 2 to 5 mm thickness. Afterwards the tiles are laid into the ribbed adhesive with a slight twisting motion within the open time of the adhesive (floating technique). Due to the twisting action the contact between grout and tile is more intimate and the effective open time of the adhesive is increased. The execution of ceramic linings by hydraulic thin-bed mortar is described in DIN 18157-1[2].

Middle-bed (5 – 15 mm)

The middle-bed ranges from a thickness of 5 to 15 mm. It is used for floors and walls which do not fulfill the requirements of tolerances in building constructions according to DIN 18202:2005 [3]. Another field of application of middle-bed adhesives is the laying of uncalibrated natural stones. The deviation of the substrate resp. the natural stone from correct flatness resp. thickness is compensated by the higher applied thickness of the middle-bed mortar. The mortar is spread on the surface and tiles are laid according to the floating method. There are specially shaped trowels for the application of middle-bed adhesives.

Thick-bed (15 – 30 mm)

Tiling method used before the 1960s for earthenware tiles or still in use for not calibrated, big and heavy natural stones. Cement, sand and water are mixed at the building lot. The mortar is applied on the back of the tile in a thickness typically of 15 to mm (buttering technique). The “buttered” tile is pressed on the pre-wetted floor and then patted with a hammer until a homogeneously flat tile surface is obtained. This method became obsolete over time since it is time- and material-consuming and cannot be used for modern ceramic claddings such as porcelain stoneware.

Solid bed (void-free)

For ceramic claddings of industrial floors or tiling in wet or exterior areas (swimming pools, balconies, terraces, facades ...) a solid, void-free bedding of tiles is necessary. A solid bed reduces the likelihood of damage caused by the freezing of water trapped under the tiles, and enhances the ability of the tiles to withstand mechanical loads. There are two techniques for the solid bedding of tiles. Firstly, by combining the floating and buttering method. Tile adhesive is spread both on the background and on the back

side of the tile. The buttered tile is pressed into the mortar bed on the substrate with a twisting motion (buttering-floating technique). Secondly, more convenient, by the use of modern tile adhesives of thixotropic behavior. Such flowable mortars are poured onto the base and scratched over the surface with a trowel. Then mortar is combed onto the still wet scratch coat with a medium bed trowel or special trowel for flowable adhesives which guarantees void-free tiling. Complete bedding is achieved when the tile or stone is placed with a twist and slide motion in the thixotropic, deformable mortar bed.

Since a thin-bed amounts only 10 to 20 % to the thickness of a thick-bed, modern tile adhesives are upgraded with p. e. polymers in order to reduce shear stress in the composite substrate, tile adhesive and tile. There are numerous more additives for improving workability (open time, adjustability time, consistency, non-sag) and bonding (water-retention, elasticity) characteristics. The formulation of a modern cement-based thin-bed mortar may consist of more than fifteen components.

The production of tile adhesives is carried out in dry-mix mortar plants which basically consist of storage silos for the individual components, batching and dosing facilities, a high-speed blending unit, an automatic packaging unit and storage buildings for the finished dry-mix tiling mortar. Since this production process is automatized and computer-controlled dry-mix mortar products with well-defined quality and performance characteristics with a high degree of application reliability are obtained. The capacity of a modern production line is more than 100.000 tons of tile adhesive per annum. It is estimated that about 3 million tons of dry-blended, pre-bagged thin-bed tile adhesives are produced in Europe per annum.

2. COMPOSITION OF TILE ADHESIVES

2.1 Composition of Cementitious Tile Adhesives [4, 5, 6]

A thin-bed tile adhesive is composed of binder, aggregate and chemical admixtures.

2.1.1 Binder

The main tasks of the binder are to form a firm bond to background and tile (adhesion) and to bind aggregates together (cohesion). Hydraulic cements retain strength due to chemical reaction with the mixing water. This reaction is also known as hydration of cement. The increase of compressive strength depends on the quality of the cement, its grain size distribution, the water to cement (w/c) ratio, the formulation of the mortar and the climate conditions (temperature, relative humidity) and elapsed time.

Nowadays there are mainly three types of hydraulic cements used for tile adhesives Portland cement (PC), Portland Pozzolan cement (PPC) and high High-Alumina cement (HAC). The definition for these binders is found in DIN EN 197-1 "Cement. Composition, specifications and conformity criteria for common cements" [7].

PC is made by heating limestone with clay to 1450 °C in a kiln. PC can bind 40 % of its weight of water and are the binder of choice for standard tile adhesives. The setting time of PC is relatively long, alkalinity is permanent, and the content of free calcium hydroxide rather high. Therefore PC based tile adhesives cannot be used for sensitive natural stones since free water could transport soluble impurities into the pores of natural stones by diffusion. Irreparable staining can occur.

Portland Pozzolan Cement (PPC) also known as trass cement is a combination of PC (94 – 65 %) and Pozzolans (6 – 35 %). Pozzolans are present on earth's surface such as diatomaceous earth, volcanic ash, and tuff. Artificial Pozzolan sources are fly ash and fumed silica. The advantage of PPC is the content of water-soluble, free silica which neutralizes emerging calcium hydroxide during the hydration of Portland cement. Portland Pozzolan cements are part and parcel for dry-blend mortars used for laying of natural stones since the risk of efflorescence is reduced and the alkalinity content is rather low. The price for this is a longer setting time of PPC based tile adhesives.

Therefore such mortars cannot be used for deformation-sensitive natural stones, p. e. natural stones containing serpentine minerals or slate.

High-Alumina Cement (HAC) in combination with PC not only accelerates the setting and hardening of tile adhesives but also improves the shrinkage characteristics of mortars. Most of these qualities result from the perfect control of ettringite formation. Only a few hours after tiling such claddings may be stressed with maximum load [8].

Mortars based on HAC are often used for ultra-rapid mortars to stop water leakages, for mortars for concrete and road repair, non-shrink grouts, for anchoring of heavy pieces of machinery. Another field of application are self-leveling underlayments (SLU). Such products are used to level out minor substrates' unevenness before laying top-floorings such as tiles, carpets, linoleum etc. SLUs must not only show excellent flowing characteristics during their installation but also a good hardening profile and satisfy high mechanical demands during use (p. e. rolling chairs in offices, beds in hospitals). Excellent fluidity, long working-time, no bleeding, low shrinkage, no cracking, water-retention etc. can only be obtained by a blend of hydraulic binders (PC, CaSO_4 , $\text{Ca}(\text{OH})_2$) optimized with high-alumina cement (HAC). Due to their fast hardening of HAC, SLUs are walkable after two hours and can be tiled the next day.

There are other special cements. For instance, white Portland cement which is similar to ordinary, gray Portland cement in all respects except for its high degree of whiteness. The brown color of ordinary Portland cement derives from chromium, manganese, and iron oxide impurities. In white Portland cement the amount of Cr_2O_3 is reduced to 30 parts per million (ppm), Mn_2O_3 to maximum 300 ppm, and Fe_2O_3 below 0.35 % in the clinker. White Portland cement is used in tile adhesives for natural stones. Other special binders are geopolymer cements based on water-soluble alkali metal silicates, fly ash, metakaolin, expansive cements, or sulfate-resistant cements.

2.1.2 Aggregates

Aggregates serve as reinforcement and structural component to add strength to the tile mortar. They provide packing density, flexural strength and durability. Aggregate may be based on quartz, limestone and silica. Generally, silica sand (quartz) used for thin-bed tile adhesives has a grain size distribution in the range of 0.05 to 0.5 mm.

Nowadays, low-density aggregates like expanded glass granulates (granular density < 0.5 kg/l) substitute high-density silica sand (≈ 2.6 kg/l) in tile adhesives for creamier consistency and exceptionally smooth workability.

2.1.3 Chemical Admixtures

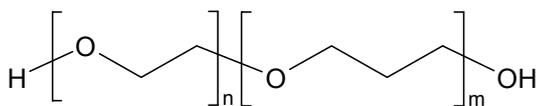
Chemical additives are the magic ingredients which give modern tile adhesives their unique properties. The content of such admixtures is usually below 1 %. Only redispersible polymers are added in higher concentrations. Chemical admixtures can only be added in powder form to the dry-mix blend. If several admixtures are used they have to be compatible with each other.

2.1.3.1 Accelerators

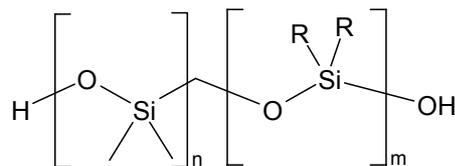
Accelerators are often used in cold weather applications to speed the rate of setting and/or the early strength of tile adhesives. Calcium chloride, calcium formate or lithium carbonate are commercially available accelerators. A typical addition dosage for these additives is in the range of 0.5 %.

2.1.3.2 Defoamers

The main purpose of dry powder antifoams is to reduce the entrainment of air when mixing the dry-mix powder blend with gauging water at high speed. Good performance show polyalkylene glycols or polysiloxanes placed on a silica carrier.



polyalkylene glycol



polysiloxane

2.1.3.3 Redispersible Polymer Powders [9]

The second generation of thin-bed tile adhesives, so-called flexible, polymer-modified tile adhesives were placed on the market in the beginning of the 1980s. They made possible the safe laying of tiles on floor heating systems, terraces and balconies. Even fully vitrified and glass tiles could be laid without problems due to excellent physical bonding of elasticized mortar to the reverse side of tiles. Redispersible, elasticizing

polymer powder invented by Wacker Chemie in 1953 was the key for this quantum leap in thin-bed technology.

Redispersible polymer powders are organic polymer materials produced from latex dispersions by spray-drying. Latex dispersions are manufactured by emulsion polymerization. The starting emulsion consists of water-insoluble monomers (p. e. vinyl acetate, vinyl versatate, ethylene, styrene, methacrylic acid esters etc.) and surfactant (emulgator) in a continuous phase of water. Water-soluble, so-called protective colloids (p. e. polyvinyl alcohol or cellulose ethers) are added to stabilize the emulsion micelles. The polymerization is started by addition of persulfates or peroxides (initiators) to the emulsion. At the end of the polymerization process a milky polymer dispersion containing 40 to 70 % of latex particles of diameter 0.1 to 20 μm is obtained. Lattices with particles above 1 μm are of milky-white appearance. Latex particles in the range of 0.1 to 1 μm give blue or brownish emulsions. Afterwards the emulsion is spray dried to obtain polymer powder. For that purpose, the latex emulsion is atomized into fine drops by a nozzle into the spray tower. At the same time, water of the emulsion droplets is removed by blowing heated air through the spray tower. An anti-caking agent (p. e. fumed silica, CaCO_3) is added during the spray-drying process in order to avoid the agglutination of the still sticky redispersible powder. The dried polymer powder is pneumatically carried out of the spray-tower and separated via a cyclone from the humid air. Redispersibility means that the dried polymer particles of 100 to 500 μm size disperse into the primary emulsion latex particles (0.1 to 20 μm) when stirred with water.

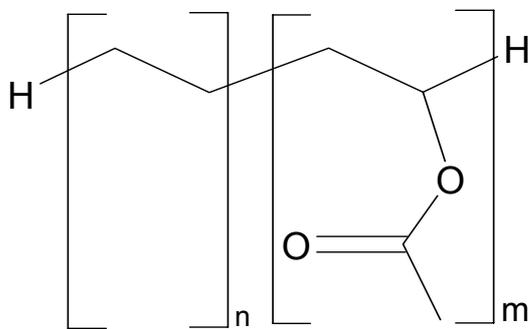
The polymer domains which work as an organic binder in the tile adhesive matrix develop after evaporation of water of the mortar by coalescence of the individual latex particles (see chapter 5.1.1). The polymer domains provide better adhesion at the mortar/substrate and the mortar/tile interface. The main benefits of redispersible polymer powders in thin-bed tile adhesives are:

- Better interlocking of adhesive and substrate resp. fully vitrified tiles improves tensile and shear strength
- Higher flexibility reduces shear stress in the composite substrate, tile adhesive and tile and allows tiling on young, still shrinking cement substrates

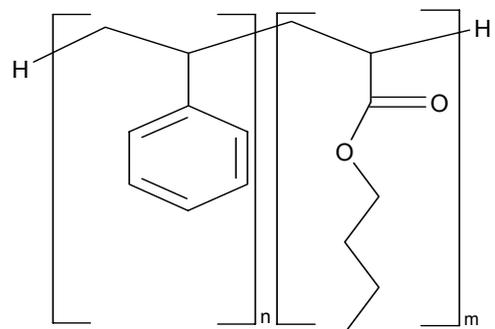
- Improved rheological properties result in easier mixing, smoother workability and good wetting of the tiles

Typical polymer emulsions used for tile adhesives are copolymers of ethylene and vinyl acetate (EVA) or styrene and butyl acrylate.

Dosages of redispersible polymer powder in cementitious thin-bed tile adhesives range from 0 to 5 %. The influence of redispersible polymer powders on important physical parameters of tile adhesives is discussed in chapter 5.2.



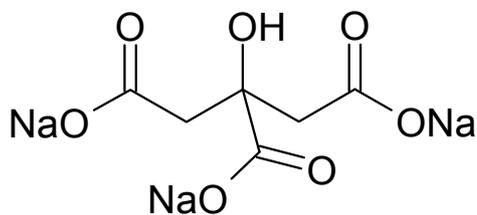
poly(ethylene-co-vinyl acetate) (EVA)



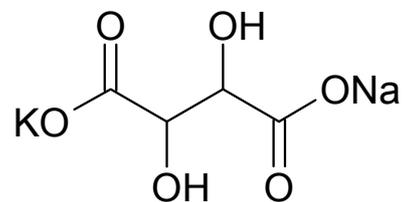
poly(styrene-co-butyl acrylate)

2.1.3.4 Retarders

Retarders are mainly used to allow for tiling in hot climates. They slow the rate of cement hydration and prolong the open time of the tile adhesive. Highly active retarders are the sodium salts of fruit acids (α -hydroxy carboxylic acids) like citric acid or tartaric acid. The usual content of retarders is not more than 0.25 %.



Citric Acid

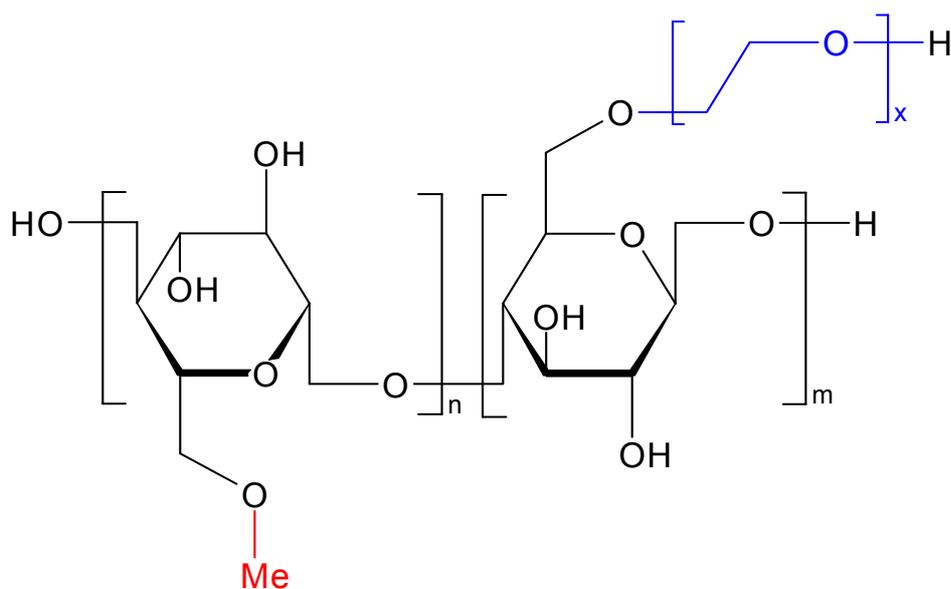


Tartaric Acid

2.1.3.5 Water-retention agents [10]

The main purpose of water-retention agents is to retain the water in the tile adhesive for a longer period of time so that there is enough water available for the cement to hydrate. Water acts also as a lubricant for easy workability and solvent during the hydration process. Water-retention became an issue when the technique for tiling changed from thick-bed to thin-bed since the decreasing thickness of the mortar bed causes increased dehydration. This is of especial importance when tiling porcelain stoneware or on absorbent backgrounds such as gas concrete or at unfavorable climate conditions (high ambient temperature, low humidity, wind). Water-retention is quantified according to DIN 18555-7:1987 by the filter plate method [11]. The water-absorbing substrate is simulated by water-absorbing filter plates. The tile adhesive is placed on the filter plates for a defined period of time. Subsequently the absorbed water is determined by weighing the filter plates and the water-retention is calculated in percentage.

The underlying mechanism of water-retention is the viscosification of interstitial water. Therefore filtration from fresh mortar into permeable substrates is reduced since the water is sucked to a lower degree into capillaries than non-viscosified water. Additionally, water loss of the fresh mortar is reduced by adsorption of water-retention agents on substrate and binder particles forming a thin filter cake of low permeability on the substrate.



methyl hydroxyethyl cellulose (MHEC)

The quantity of gauging water is also influenced by water-retention agents. The tiler is adding as much water until the mortar shows the right consistency. Increased water demand improves the yield of the dry-blend.

Other parameters changed by water-retention agents are open-time, wetting capability and non-sag characteristics of a tile adhesive.

High water-retention can be achieved by chemically modified methyl cellulose (MC). Modification of MC is carried out with ethylene oxide or propylene oxide. The correlating products are methyl hydroxyethyl cellulose (MHEC) or methyl hydroxypropyl cellulose (MHPC). Compared to methyl cellulose MHEC shows higher solubility and may be used at temperatures above 35 °C. Compared to methyl hydroxypropyl cellulose (MHPC) MHEC entrains less air which is preferred for tile adhesives. Therefore the mainly used cellulose ether in tile adhesives is MHEC.

The water-retention capacity of MHEC depends very much on the dosage and on the viscosity of a 2 % aqueous solution of MHEC. It has to be noticed that viscosity data of different producers often cannot be compared since they use different measurement methods. Viscosities data measured with two different methods can differ by up to several hundred per cents for the same concentration. Typically, dosage of MHEC in tile adhesives is not exceeding values of 0.5 %.

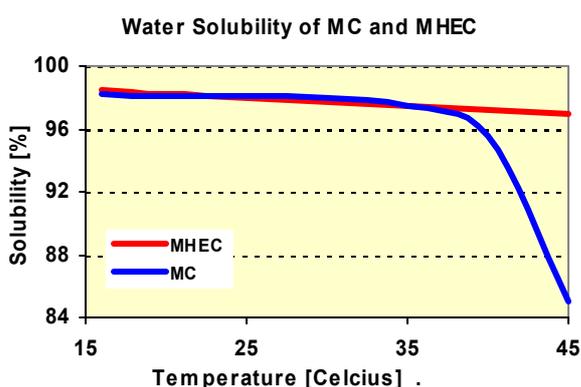


Figure 1: Solubility of MC and MHEC

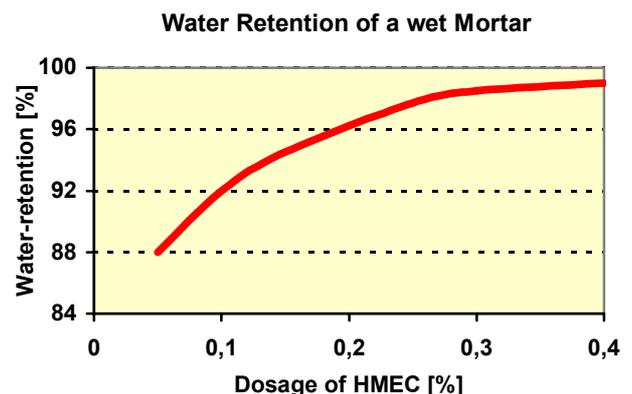


Figure 2: Water retention as a function of HMEC dosage

Figure 1 shows that MHEC has superior solubility characteristics at higher temperatures compared to MC. This is important if tile adhesives are used in hot countries such as Dubai. Water-retention is improved by dosage and viscosity of MHEC (figure 2 resp.

figure 3). However workability of tile adhesives may suffer if too much MHEC of high viscosity is used. Then the mortar is not properly sticking to the substrate any more and “rolls” off.

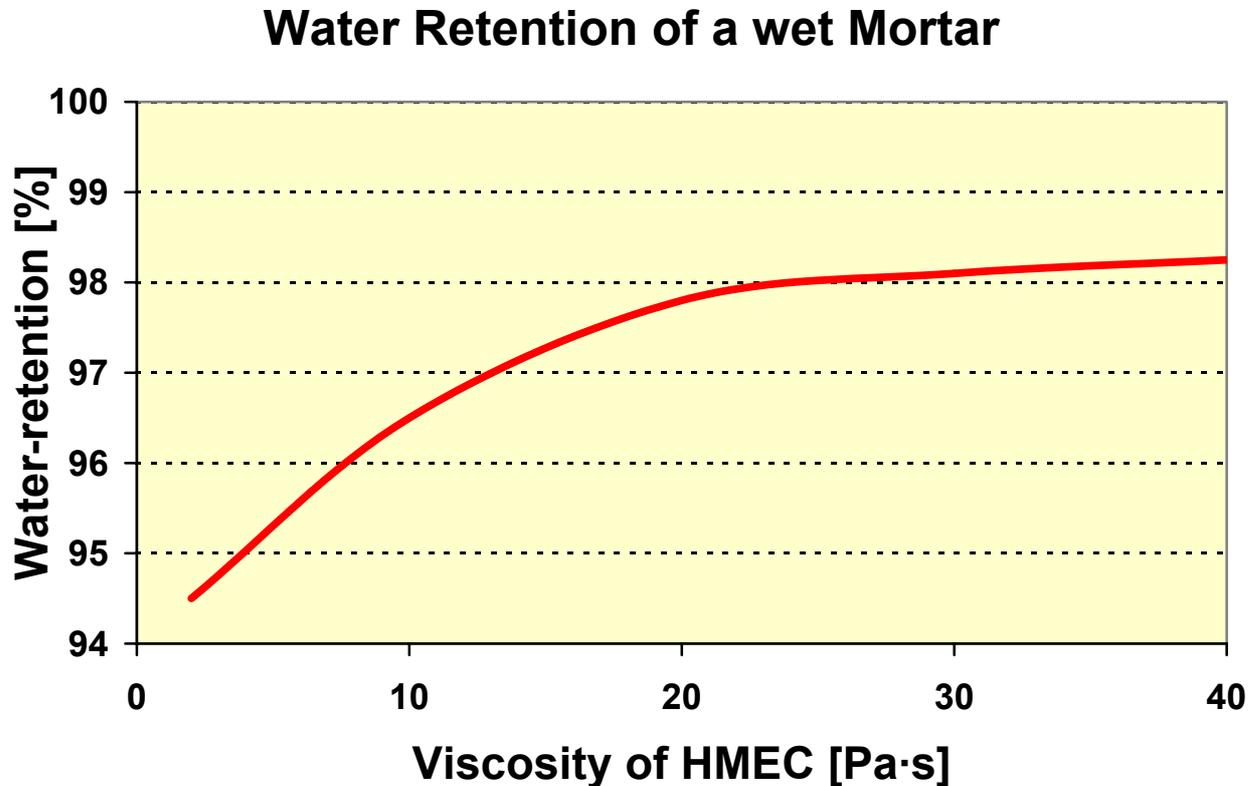


Figure 3: Water retention of a wet mortar as a function of viscosity of HMEC

2.1.4 Typical formulations for cementitious thin-bed tile adhesives

In literature or the World Wide Web typical formulations for standard tile adhesives (C1 class according to DIN EN 12004) and flexible tile adhesives (C2 class) can be found (table 1) [12]. Whereas C1 class tile mortars cannot be used for fully vitrified tiles and surfaces exposed to higher thermal stress (balconies, terraces, floor heating), C2 class adhesives may be used for all sizes of tiles, tile materials and substrates. The most important difference between C2 class and C1 class adhesives is the higher amount of redispersible polymer powder. Thus physical bonding by anchoring to the tile surface and substrate is assisted by polymer film adhesion.

Of course these formulations are only coarse guidelines since type of component, the exact dosage and raw material specifications are the key intellectual property of the manufacturers. Modern thin-bed tile adhesives can contain over 15 components.

Table 1: Formulations for standard and flexible tile adhesives

Component	Main Functions	Specification	Dosage [%]	
			C1 class	C2 class
Portland cement	binder for mortar matrix flexural and compressive strength	CEM I 42,5R/52.5R	30 - 50	30 - 40
Silica sand	aggregate, filler mortar matrix	0.1 – 0.5 mm	45 - 70	45 - 60
Calcium carbonate	co-filler consistency, workability	30 – 60 µm	5 - 10	5 - 10
Redispersible polymer powder	flexibility, open time rheology, adhesion	diverse	0 - 3	3 - 6
MHEC cellulose	water-retention sag, workability	40,000 mPa·s	0.2 - 0.5	0.2 - 0.5
Calcium formate	accelerator	< 0,4 mm, sieved	< 1	< 1

2.2 Resin-based Tile Adhesives

2.2.1 Dispersion Tile Adhesives

Dispersion tile adhesives are a mixture of organic binding agent(s) in the form of an aqueous polymer latex (see chapter 2.1.3.3, resp. 5.1.1), organic additives and mineral fillers. Dispersion adhesives allow the flexible laying of tiles and mosaic on flexible substrates such as plasterboards, gypsum fire boards, wooden panels etc. These adhesives compensate variations in temperature, shrinkage of the substrate and vibrations to some degree.

Since the bonding mechanism is related to evaporation of water (see chapter 5.1.1) it takes about 48 hours until the surface can be grouted or exposed to foot traffic. Dispersion tile adhesives have to dissipate the water to the substrate, tile or through the joints. When large-size tiles are laid on non-absorbent substrates this time period may be even larger. As a rule of thumb the time period for complete drying of the adhesive-bed increases by the 2nd power of tile length.

A big advantage of dispersion tile adhesives is that they are ready for use without any mixing activities. A guide formulation for a standard dispersion tile adhesive is given in the table below.

Table 2: Formulation of a standard dispersion tile adhesive

Component	Main Functions	Specification	Dosage [%]
Poly (styrene-co-acrylate)	binder, rheology, flexibility	50 %	10 %
Water	viscosity, workability		20 %
Hydroxy ethyl cellulose	sag, workability	30,000 mPa·s (Höppler)	0.5 %
Sheet silicate	viscosifier, rheology		1 %
Polypropylene-glycol	frost protection		1 %
Tenside	defoaming		0.25 %
Biocide	conservation		0.25 %
Calcite	filler	Ø 9 µm	10 %
Calcite	filler	Ø 29 µm	20 %
Calcite	filler	Ø 46 µm	37 %

The application of dispersion tile adhesives is very similar to cement-based thin bed tile adhesives. A thin scratch coat to the substrate with the straight edge of a steel trowel is applied first and then the adhesive is combed to the new scratch coat with the notched edge of the trowel.

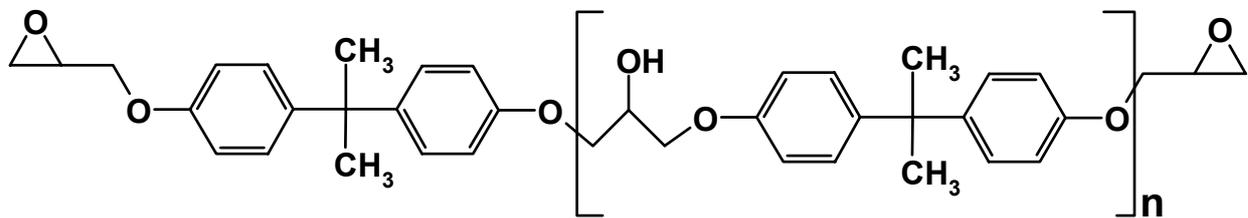
Before the tiles are placed in the adhesive bed with a twist and slide motion the open time is checked by touching the adhesive bed with the finger tip. Tools should be cleaned with water immediately after use. Once the product has cured it can only be removed by mechanical means.

For requirements, classification and designation of dispersion tile adhesives please refer to chapter 3.2.2.

2.2.2 Epoxy Tiling Products [13]

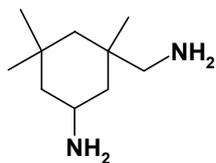
Epoxy adhesives are usually dual component products for laying and grouting tiles. Epoxy adhesives consist of a base component (resin) (A) and a hardener

component (B). The base component (A) is usually bisphenol-A-epichlorhydrin resin with a number average molecular weight below 700 Dalton ($n = 0, 1, 2$).

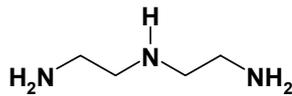


epoxy base component (A), bisphenol-A diglycidylether

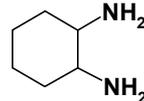
Combining the base component with the hardener component (B) they react with each other and form a tough and solid polymeric network. Typical hardeners are isophorondiamine (IPDA), diethylenetriamine (DETA), 1,2-cyclohexyldiamin or 4,4'-methylenedianiline (MDA).



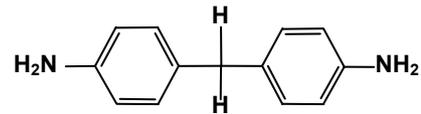
**isophorondiamine
(IPDA)**



**diethylenetriamine
(DETA)**



1,2-cyclohexyldiamine

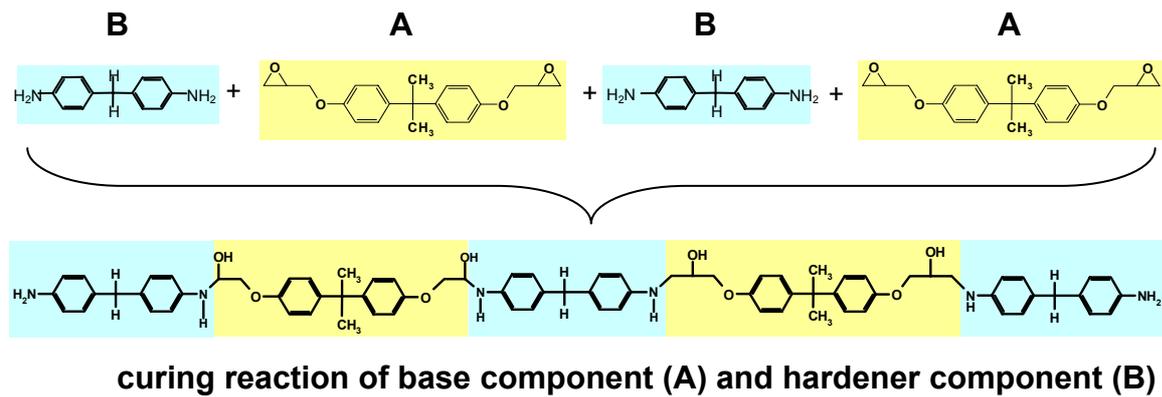


**4,4'-methylenedianiline
(MDA)**

epoxy hardener components (B)

Aromatic hardeners are normally avoided since they may be toxic and cannot be used for outdoor applications. Such adhesives yellow under the impact of sunlight and oxygen. During the curing process the base and hardener component form a polyadduct, the epoxy resin.

Since resin and hardener react in a stoichiometric ratio of one to one resp. two to one (the hardener molecule possesses two active hydrogen atoms per nitrogen atom) it is important to thoroughly mix base and hardener component in the appropriate mixing ratio in a clean container. Then aggregates are added according to the recommendations of the building chemical manufacturer and mixed until a homogeneous compound is obtained. Since the reaction of resin and hardener is exothermic only the recommended batch size of below 10 kg may be prepared otherwise the mixture gets too hot causing damage to the adhesive or even fire.



For tiling, a thin scratch coat is applied to the substrate with the straight edge of a trowel. Afterwards an adhesive bed is combed to the new scratch coat with the notched edge of a trowel. The tiles are placed with a twist and slide motion and adjusted to correct position. In order to achieve a non-sag characteristic suspending agent may be added to the epoxy tile adhesive. Heavy vitrified tiles can be pegged underneath to support their weight until the adhesive is set. The best temperature for using epoxy products is +20 °C. Laid floors are walkable and groutable after two days. Grouted floors are also walkable after two days.

If epoxy resins are used for tile grouting this could be carried out with a rubber float (elutriation method), caulking gun, by cartridge injection or joint iron. Especial care must be taken for washing grouted claddings. Usually a first wash with warm water and a hard epoxy sponge is made after 10 minutes. Then the surface is several times washed with a soft viscous sponge and fresh water. Special additives, recommended by the manufacturer, to the washing water allow removing hardened resins from the tile surface.

What are the advantages of epoxy tile adhesives compared to cementitious thin-bed tile adhesives?

The major advantage is their high-resistance to chemicals such as inorganic acids, many organic acids, lyes, salts, brines, fuels, oils and many organic materials. Epoxy tile adhesives are only short term resistant to organic solvents such as acetone, ethanol, petroleum ether etc. and to some organic acids, p. e. formic acid, acetic acid. Full chemical resistance of epoxy products is obtained after 7 days curing time at 20 °C.

Therefore swimming pools may be filled with water only after 7 days. Epoxy materials contain fine fillers therefore they produce smooth joint surfaces which are low in pores and easy to clean. Epoxy resins are highly wear resistant to rolling and grinding loads. Tensile bond strengths to substrate and claddings and to joint flanks are much higher compared to cementitious adhesives.

Epoxy tile adhesives and joint grouts are used for chemical-resistant and water-impermeable laying and grouting of wall and floor coverings in breweries, dairies, soft drink industries, canteen kitchens, butcheries, slaughter houses, fat processing industries, battery rooms, galvanizations, dye works, bleaching works, tanneries, paper mills, laboratories, swimming pools, spas, saunas, sewage plants, sewers, cattle stables and hospitals. Ceramic tiles or mosaics may be laid on renders, cement screeds, concrete and timber chipboards.

Major drawback of epoxy tiling products is their limited temperature stability. Steam jets for cleaning may be applied for short periods of time only. However, the main disadvantage is that epoxy products (epoxide groups) are highly irritating to the skin and strong sensitizers. Approximately 20 % of construction workers who use epoxys develop an allergic contact dermatitis (hand, arms, face). Workers allergic to epoxys will experience an even stronger skin reaction after each contact. To avoid any contact with epoxy products is the only option left. That means that the tiler has to change his profession.

When tiling with epoxy adhesives/grouts it is mandatory to wear protective cloths (gloves made of nitrile and safety goggles) during transportation, mixing and tiling activities.

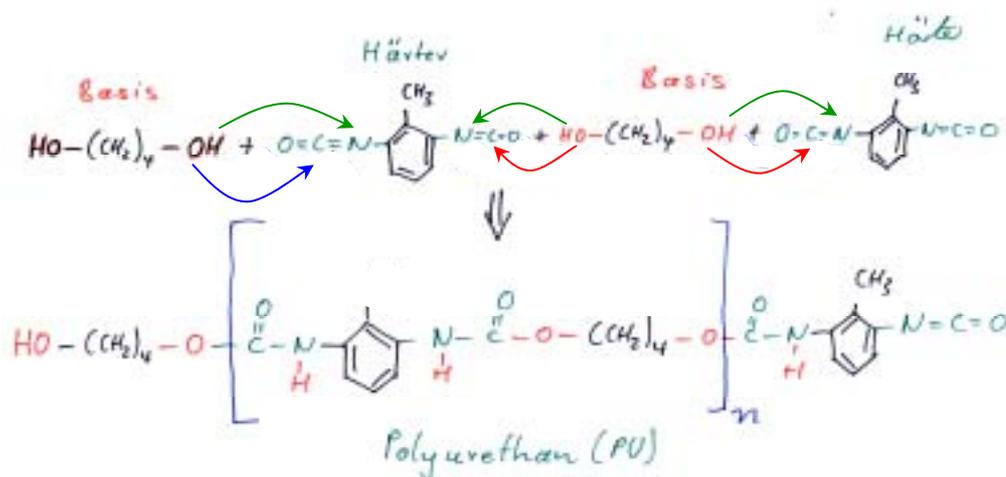
It is recommended to mix both components with a long-stemmed mixer with low rotation speed and not to fill the vessel within 20 cm of the brim. Use spreaders with handles, spatulas with relative long handles. Allow epoxy products on tools to cure and subsequently scratch it off, instead of cleaning with volatile solvent.

For requirements, classification and designation of epoxy-based tile adhesives please refer to chapter 3.2.2.

2.2.3 Polyurethane Tile Adhesives [13]

Polyurethanes commonly abbreviated PU are produced by the reaction of a monomer A containing at least two alcohol groups (dialcohol, base component) with a monomer B containing at least two isocyanate groups (diisocyanate, hardener component). Polyurethanes vary in an extremely wide range of elasticity, hardness, and density depending on the type of monomers. They can be elastomers, paints, foams, fibers, and adhesives.

Below scheme shows the polyaddition reaction of the two monomers. Since there are functional groups on both ends of each monomer a linear, polymeric backbone via so-called urethane (-NH-COO-) linkages is formed. Linear polyurethanes show elastic behavior. If the base or/and hardener component contains more than two functional groups cross-linked stiff thermosets are obtained. The higher the number of hydroxide functions in the base component the higher stiffness and stability toward chemicals of the resulting PU. The polymerization reaction is catalyzed by tertiary amines or organotin compounds.

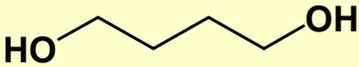
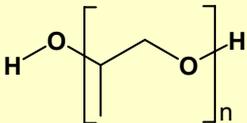
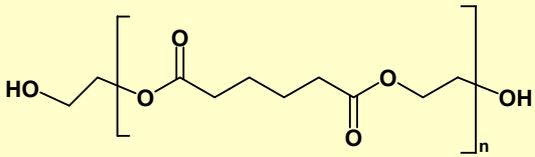
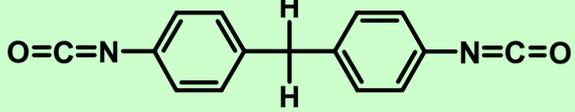
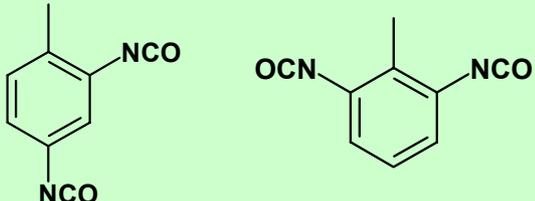
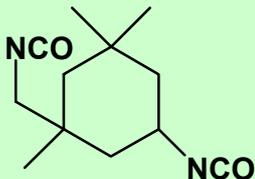
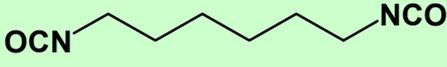


curing reaction of base component and hardener component

The table below shows commercially important diols and diisocyanates. There are short chain diols such as glycol, 1,4-butandiol and long chain polyols such as polypropylene glycol or poly adipic acid glycol esters. Polyols of molecular weight above 2,000 Dalton form soft, elastic and flexible PU. Polyols of molecular weight below 700 form more

rigid, stiff PU. Polyether polyols, p. e. polyethylene glycol, are less thermally stable than polyester polyols but less sensitive towards saponification.

Table 3: Base and hardener components for polyurethanes (PU)

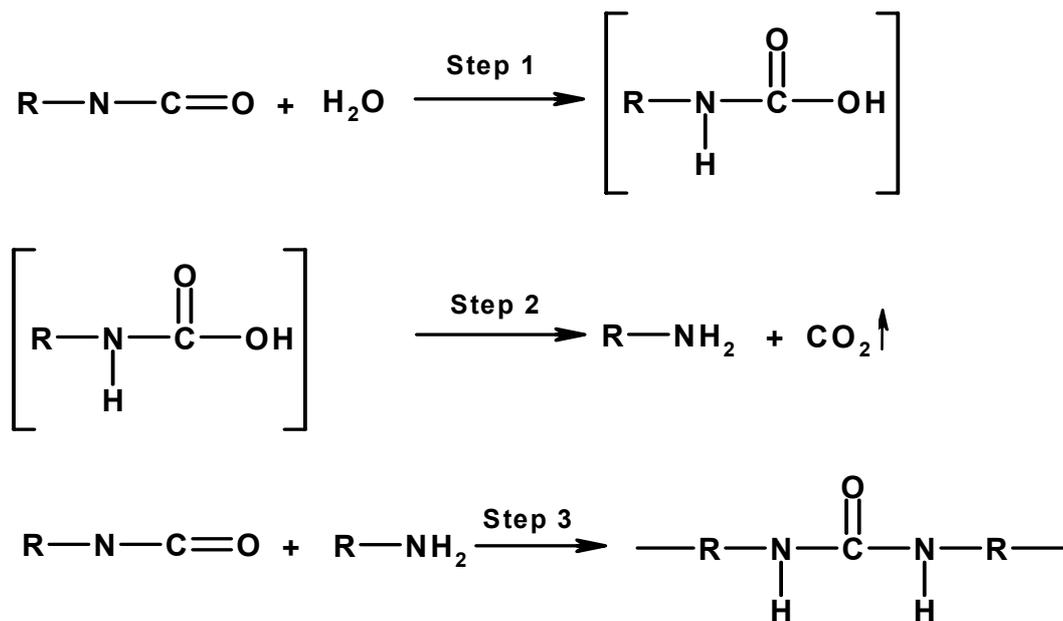
Base Component (A)	Hardener Component (B)
 <p>1,4-butanediol</p>  <p>polypropylene glycol</p>  <p>poly adipic acid glycol ester</p>	 <p>4,4'-methylene diphenyl diisocyanate (MDI)</p>  <p>2,4-/2,6-toluylene diisocyanate (TDI)</p>  <p>isophorone diisocyanate (IPDI)</p>  <p>1,6-hexamethylene diisocyanate (HDI)</p>

Although the properties of PU are mainly determined by the choice of polyol, the diisocyanate has also some influence and must fit to the application. For instance, the cure rate and stability upon exposure to light is determined by the hardener component.

The aromatic diisocyanates MDI and TDI are volume wise the most important hardener components. They are cheaper and more reactive than the aliphatic diisocyanates IPDI and HDI. Technically used TDI predominantly consists of a mixture of 80 % 2,4-TDI and 20 % 2,6-TDI isomer. This blend is called TDI-80 or TD-80. TD-100 and TD-65 are also used in industrial applications. Commercially sold MDI is either the pure 4,4'-MDI or a blend of 50 % 4,4'-MDI and 50 % 2,4'-MDI.

Light stable, not yellowing PU can only be obtained with aliphatic diisocyanates. Due to their toxicity, IPDI and HDI are transformed into less toxic oligomers. Prepolymers are formed by reacting diisocyanates with polyols in a stoichiometric ratio of 2 to 1. The prepolymers are not only less active and toxic than the “undiluted” diisocyanates but also influence the physical features of the final PU depending on the length of the polyol-bridge (long bridge = soft, elastic PU, short bridge = stiff, brittle PU).

Moisture curing 1K-PU go through a three step curing process. In the first step, a molecule water reacts with an isocyanate group to form a carbamic acid. Carbamic acids are unstable. In the second step, the carbamic acid decays into carbon dioxide and an amine. In the third step, the amine reacts with an isocyanate to form a poly urea. The carbon dioxide can cause bubbles during the curing process. Therefore it is recommended to use 1K-PU only for thin layer applications or to add calcium hydroxide to scavenge the developing carbon dioxide.



three step curing reaction of 1K-PU

Isocyanates are skin and respiratory sensitizers. Therefore gloves, goggles and special garments should be worn to prevent contact to isocyanate liquid and vapor especially during the mixing phase where there is risk of splashing. Fully cured polyurethanes are chemically inert and not toxic. However, in case of heating or fire, carbon monoxide, nitrogen oxides, hydrogen cyanide, methyl isocyanate etc. are set free. Therefore heating of PU must be avoided.

In the construction industry, PU are used as sealants p. e. for fire stopping applications, as an insulator, as paints and varnishes coats to protect or seal wood, as construction foams, as coatings to level irregularities of floors and walls especially in shipbuilding, and as waterproofing and tile adhesive.

2K-PU tile adhesives are used to fix ceramics, natural stones and mosaic for indoor and outdoor use, for walls and floors. They can be used especially for indoor substrates sensitive to moisture, such as chipboards, parquet flooring, plywood, plasterboards, gypsum fiber boards etc. 2K-PU tile adhesives show good bonding to impermeable, smooth and vibrating substrates such as old ceramics, natural stone coverings, aluminum, steel, PVC coverings and polyester based substrates. Due to the fast curing, 2K-PU are also used for fast track tiling work, such as renovation of natural stone and ceramic coverings in residential and commercial buildings, pre-fabricated houses, with only short interruptions in operation.

Due to the fast curing of 2K-PU tile adhesives, claddings are already groutable after 3 hours and able to bear weight the next day. The polyurethane adhesive builds a waterproof layer with adequate barrier properties against water vapor which prevents the absorption of moisture und thus the swelling of water-sensitive substrates. Compared to epoxy tile adhesives, polyurethanes show higher elasticity, so they can better compensate variations in temperature, expansions in the substrate and damp vibrations.

Some companies offer 1K-PU which can be used both for waterproofing and tiling. Such products are ideal for tiling bathrooms, kitchens, balconies and other areas exposed to water. Since these products are ready for use there is no mixing necessary. Compared to 2K-PU the curing time is much longer and the non-sag characteristic cannot compete since the product is also used for “self-leveling” waterproofing membranes.

For tiling a thin scratch coat is applied to the substrate with the straight edge of a trowel. Afterwards an adhesive bed is combed to the new scratch coat with the notched edge of a trowel. The tiles are placed with a twist and slide motion and adjusted to correct position. Heavy tiles should be wedged if necessary. The best temperature for using

polyurethane products is +20 °C. Laid floors are walkable and groutable after two days. Grouted floors are also walkable after two days.

For requirements, classification and designation of polyurethane-tile adhesives please refer to chapter 3.2.2.

2.2.4 Comparison of Tile Adhesives

Following table compares the characteristics of cement-, dispersion- and resin-based tile adhesives. Top performer for each parameter is highlighted.

Table 4: Comparison of cement-, dispersion- and resin-based tile adhesives

Parameter	Tile Adhesive		
	Cement-based (C)	Dispersion-based (D)	Resin-based (R)
Application Range	indoor, outdoor floor, wall	indoor wall	indoor, outdoor floor, wall
Mixing	good	ready to use	2K, exact mixing procedure necessary
Non-sag	very good	good	middle
Curing Time	middle	slow	PU fast, Epoxy slow
Washing Profile	very good	good	bad
Adhesion	good	good	excellent
Chemical Resistance	low	low	high
Temperature Resistance	middle	low	low
Toxicity	alkalinity	low	skin sensitizers
Price	low	middle	high

C = cement

D = dispersion

R = resin (epoxy/polyurethane)

3 STANDARDS AND TESTING

Standards are often seen as overregulation but in reality standards promote trade, improve security for end-users and applicators and simplify rationalization and communication.

In general, industry welcomes standards. Especially the idea that testing of physical parameters is carried out by uniform European test standards. Another advantage of the European approach is that classes (set of physical parameters) are specified for different levels of requirements in so-called harmonized product standards. It is up to national authorities or to constructors to choose which class of requirements is needed for a certain application.

Unfortunately reality shows that test results vary widely in different European laboratories despite of detailed test standards and that national authorities do not strictly follow the harmonized classification system if aspects of safety are touched. Industry, workmen and constructors hope that there will be a more harmonized European approach in the future in order to gain more market transparency.

Another point of criticism is that test and product standards produce resp. specify a set of data which are out of touch with reality. This is a general point of criticism against standardization work which will be discussed more explicit in this chapter.

For cementitious thin-bed tile adhesives following standards apply in Germany:

- Application standard DIN 18157-1:1979: „Execution of ceramic linings by thin mortar bed technique; hydraulic mortar” [2]
- Product standard DIN EN 12002:2003 “Adhesives for tiles – Determination of transverse deformation for cementitious adhesives and grouts” [14]
- Product standard DIN EN 12004:2007 resp. ISO 13007-1:2006 “Adhesives for tiles – Definitions and specifications” [12, 15]
- Test standard DIN EN 1308:2007 “Adhesives for tiles – Determination of slip” [16]
- Test standard DIN EN 1323:2007 “Adhesives for tiles – Concrete slabs for tests” [17]

- Test standard DIN EN 1346:2007 “Adhesives for tiles – Determination of open time” [18]
- Test standard DIN EN 1347:2007 “Adhesives for tiles – Determination of wetting capability” [19]
- Test standard DIN EN 1348:2007 “Adhesives for tiles – Determination of tensile adhesion strength for cementitious adhesives” [20]

Polymer-modified thin-bed mortars took off in the beginning of the 1980s. The tilers were easily convinced by the creamy workability, unique non-sag properties and the gained safety margin for tiling of porcelain tiles. Flexible thin-bed tile adhesives quickly gained market share and replaced standard cementitious tile adhesives by a higher price. Since there was no specification or even standard for what flexible means numerous me-too products overstocked the market and unsettled the tiling community.

It was the German Association of Building Chemical Industry (Deutsche Bau-chemie e. V.) which developed a specification for flexible thin-bed adhesives. According this guideline a cementitious thin-bed adhesive has to fulfill the raised specifications for tensile adhesion strength (C2, > 1 N/mm²) according to DIN EN 12004:2007 and at the same time a minimum transverse deformation of 2.5 mm according to DIN EN 12002:2003.

3.1 EN 12002 “Adhesives for Tiles – Determination of Transverse Deformation for Cementitious Adhesives and Grouts” [14]

EN 12002:2003 has been prepared by Technical Committee CEN/TC67 “Ceramic tiles”, the secretariat of which is held by UNI, Italia. The standard specifies a test method to measure the transverse deformation of cementitious tile adhesives when subjected to a 3-point bending load, performed on defined test specimens.

3.1.1 Testing

The adhesive is mixed with water in parts by mass as stated by the manufacturer. Mixing time is 30 s and another 60 s after mature time. Enough matured adhesive is placed on a flat polyethylene film. Two templates and a flow table are used to form a

test strip of 45 mm width, 3 mm thickness and 280 mm length. The test specimens are placed in an air-tight plastic container at 23 °C for 12 days and then conditioned at standard conditions (23 °C, 50 % R. H.) for another 14 days. After that, the thickness of the test specimens is determined using a caliper with 0.01 mm precision.

Samples which deviate more than 0.1 mm from 3 mm are discarded. The specimens are placed on the test jig with two cylindrical bearings of 10 mm diameter, 60 mm length and 200 mm distance. Eventually the test specimen is deformed with a transverse load applied by a defined anvil at a rate of 2 mm/min until failure occurs. The average deflection from the horizontal plane of three test specimens is recorded to 0.1 mm.

3.1.2 Classification

There are two classes depending on the measured transverse deformation data.

- S1 - cementitious tile adhesives with a transverse deformation in the range of 2.5 to 5 mm
- S2 - for highly deformable cementitious tile adhesives with a transverse deformation above 5 mm.

3.1.3 Reproducibility and Limits

The preparation of the testing specimens is sophisticated and takes some experience. Especially the thickness of the test specimens is important since it has a major influence

Table 5: Average transverse deformation [mm] – Round robin test

Tile Adhesive	Average Transverse Deformation [mm] Measured by Ten Different Industry Laboratories										∅	Δ
	1	2	3	4	5	6	7	8	9	10		
I	3.1	2.5	2.4	2.7	2.4	2.7	3.0	1.8	3.6	2.6	2.7	0.48
II	2.9	2.4	2.6	3.0	2.1	2.6	3.4	2.9	3.1	2.6	2.8	0.37
III	2.3	1.8	1.8	2.3	1.6	2.1	2.5	2.1	2.4	2.1	2.1	0.29
IV	2.5	1.8	2.2	2.6	1.8	2.3	2.8	2.3	2.4	2.3	2.3	0.32
V	1.8	1.3	1.3	1.6	1.1	1.4	1.7	1.6	1.4	1.5	1.5	0.21
VI	1.7	1.2	1.5	1.8	1.1	1.3	1.8	1.8	1.5	1.7	1.5	0.26
VII	1.8	1.1	1.6	1.8	1.2	1.5	1.7	1.7	1.6	1.6	1.6	0.24

on the transverse deformation value. In order to get a feeling about the reproducibility of results a round robin test was carried out by companies which are member of the German Association of Building Chemicals (DB e. V., Frankfurt). The data for transverse deformation of seven different thin-bed tile adhesives was measured according to EN12002:1997 at 10 different producer laboratories. Table 5 shows the most important data at one glance.

Analyzing the results delivers insights as follows:

- The deformation of standard tile adhesives (V – VII) is lower than for polymer modified tile adhesives (I – IV).
- The standard deviation for the measured data for a single tile adhesive is about 15 % of the general average.
- In absolute numbers the average transverse deformations measured by the individual laboratories deviate about 20 % from the general average (the column before last) for a single tile adhesive. For instance the measured data for tile adhesive IV differ from 1.8 to 2.8 mm (mean value: 2.3 mm).

Table 6: Average thickness of test specimen [mm] – Round robin test

Tile Adhesive	Average Thickness of Test Specimen [mm] Measured by Ten Different Industry Laboratories										Ø	Δ
	1	2	3	4	5	6	7	8	9	10		
I	3.0	2.9	3.5	3.2	3.2	3.9	3.1	3.4	3.6	3.5	3.3	0.31
II	3.2	2.8	3.4	3.0	3.2	3.5	2.7	3.0	3.1	3.1	3.1	0.24
III	3.1	2.8	3.5	3.0	3.0	3.4	2.7	3.1	3.2	3.3	3.1	0.25
IV	3.1	2.8	3.4	3.0	3.3	3.6	2.9	3.0	3.2	3.3	3.2	0.25
V	2.9	2.9	3.2	3.0	2.9	3.5	2.6	3.1	3.2	3.2	3.1	0.25
VI	3.2	3.1	3.5	3.1	3.1	3.9	2.7	3.1	3.2	3.3	3.2	0.31
VII	3.3	3.1	3.3	3.0	2.9	3.3	2.8	2.9	3.3	3.3	3.1	0.20
Ø	3.1	2.9	3.4	3.0	3.1	3.6	2.8	3.1	3.3	3.3	3.2	0.26
Δ	0.13	0.13	0.12	0.08	0.16	0.23	0.17	0.16	0.16	0.12	0.15	0.26

Table 6 and figure 4 summarize resp. illustrate the measured thicknesses of the test specimens. In this case not only the data of the different testing labs for individual tile adhesives (lines) may be compared. But also data of individual labs for different tile adhesives (columns) under the assumption that the test specimen thickness is not influenced by different tile adhesives.

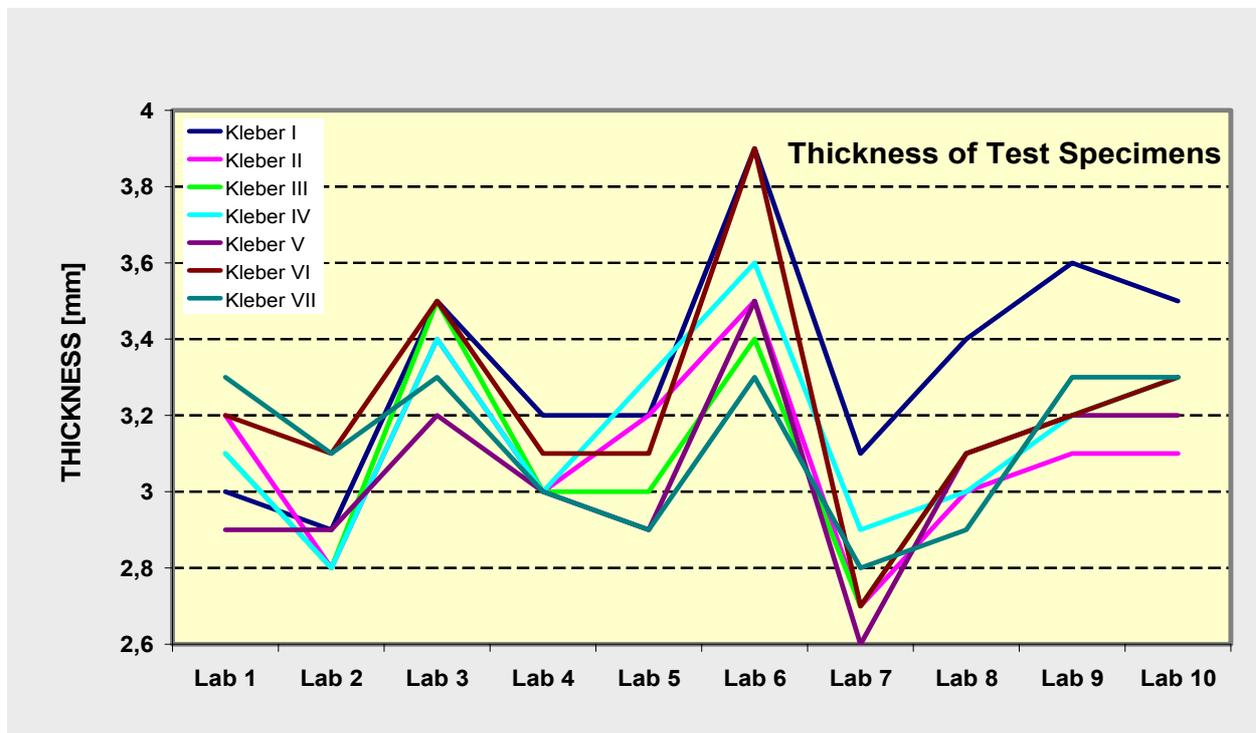


Figure 4: Thickness of test specimens – Round robin test

Results for test specimen thicknesses prepared according to DIN EN 12004:1997 are as follows:

- The standard deviation for the thickness of test specimens prepared in the same laboratory is about 5 % from the general average determined in this laboratory (column).
- The standard deviation for the thickness of test specimens of an individual tile adhesives prepared in different laboratories is about 10 % from the general average for this tile adhesive (line). For instance the measured data for tile adhesive of lab 5 differ from 2.9 to 3.3 mm (mean value 3.1 mm).
- Since the thickness has a big influence on the measurement data for deformation the spread of measured data is too big. Although all labs used the same test procedure the range of thickness of test specimens spreads from 2.6 to 3.9 mm.

The main conclusion of the round robin test was that the standard had to be specified in order to reduce spread of the thickness data for the test specimens. At the end of the day two templates were specified for the preparation of test specimens in the current edition of DIN EN 12002:2003. Besides this it was agreed that only test specimens of 2.9 to 3.1 mm thickness may be used for measuring the transverse deformation.

There was no further round robin test up to now by DB e. V. to verify that DIN EN 12002:2003 gives more precise results than DIN EN 12002:1997.

3.1.4 Critical Remarks

The testing method is well described but there are still inaccuracies in practical use. The importance and difficulties to obtain reproducible test specimen thicknesses were discussed above. Another problem is to unhinge the test specimen from the template after the specimen has cured. The higher the polymer content the catchier is the disentanglement of the test specimen since it heavily sticks to the template. Lubricating of the template with grease solves this problem. However, the influence on the deformation potential of the test specimen has not been studied yet.

The storage and drying conditions of the test specimen influence the elasticity of the test samples. Whether these conditions are comparable amongst the different testing laboratories is a pivotal question. Irrespective of the fact that real hardening conditions of a thin-bed tile adhesive in the composite background, adhesive and tile have nothing in common with the requirements of standard EN 12002:2003.

A fundamental point of criticism is the significance of a transverse deformation measurement for the practical use of such products. Normally thin-bed tile adhesives and flexible joint grouts are not exposed to flexural load but to shear stress. PCI Augsburg in Germany carried out lab experiments to correlate values for transverse deformation according to DIN EN 12002:2003 and absolute deformation by shearing of thin-bed tile adhesives. For the determination of the absolute value for deflection of the tile adhesive a 10 x 10 cm porcelain tile was glued to a concrete slab (9 x 10 cm) and then stressed by a vertical force parallel to the tile surface (see image 1).

The main problem is to measure the deflection of the tile from static condition as a function of force since the amplitude for maximum deflection is only in the range of micrometers. It takes some experience and preparation time to obtain reproducible results. As figure 5 shows, there is a good correlation of transverse deformation of a test specimen according to EN 12002:2003 and the absolute deflection of a fully vitrified tile with increasing force. That means the measurement of transverse deformation according to EN 12002:2003 gives the same information than the cumbersome shear experiment. By the way the higher the content of redispersible polymer powders the higher the transverse deformation according to DIN EN 12002:2003 resp. the absolute deflection.



Image 1: Device to determine the absolute deflection of a tile from static conditions

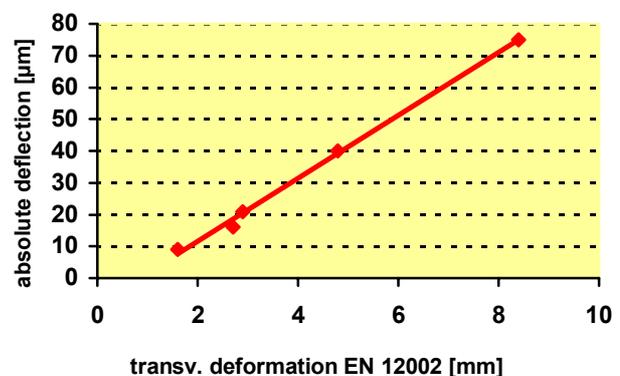


Figure 5: Transverse deformation versus absolute deflection of the tile for different thin-bed adhesives

Tiling adhesives with S2 specification are often recommended for balconies and terraces on polymer-modified cement-based waterproofing slurries. Since such slurries must have a crack-bridging capability of at least 0.4 mm the polymer content of such slurries is more than 10 %. Therefore waterproofing slurries are much more elastic than S2 tile adhesives. Waterproofing slurries show an absolute deflection according to above test method from more than 200 μm whereas cement-based S2 tile adhesives show values for this parameter of not more than 50 μm . Thus the contribution for the compensation of thermal stress is mainly coming from the elastic waterproofing membrane and far less from the tiling adhesive.

There is no real correlation of transverse deformation and tensile adhesion strength. There is an indication that increasing content of redispersible polymer powder improves both transverse deformation and tensile adhesion strength at least at standard storage conditions. Whether this applies for other storage regimes is still to verify. Anyway, there is no recommendation right now by technical committees, tiler communities or even official authorities to prefer S2 cementitious tile adhesives.

3.2 EN 12004:2007 “Adhesives for Tiles – Definitions and Specifications” [12]

EN 12004:2007 has also been prepared by Technical Committee CEN/TC67 “Ceramic tiles”, the secretariat of which is held by UNI, Italia. EN 12004:2007 is a product standard which defines and specifies essential requirements for tile adhesives based on cement, polymer dispersions or reaction resins.

Basic definitions of tiling techniques, tools, application properties, final properties and failure patterns for thin-bed adhesives are defined in chapter 3 of EN 12004:2007. Some definitions for application and final properties are cited here:

- Shelf life: Time of storage under stated conditions during which an adhesive may be expected to maintain its working properties.
- Maturing time: Interval between the time when the cementitious adhesive is mixed and the time when it is ready for use
- Pot-life: Maximum time interval during which the adhesive can be used after mixing.
- Open time: Maximum interval after application at which tiles can be embedded in the applied adhesive and meet the specified tensile adhesion strength requirement according to EN 1346:2007 [18].
- Wetting capability: Ability of a combed adhesive layer to wet the tile according to EN 1347:2007 [19].
- Slip: Downward movement of a tile applied to a combed adhesive layer on a vertical or inclined surface according to EN 1308:2007 [16].
- Adjustability: Maximum time interval after which the tile position in the adhesive layer can be adjusted without significant loss of adhesion strength.
- Adhesion strength: Maximum strength per unit surface area which can be measured by shear (EN 1324:2007, EN 12003:1997) or tensile strength (EN 1348:2007) [21, 20, 22].

- Transverse deformation: Deflection recorded at the centre when a mortar strip of hardened adhesive is subjected to three point loading. It is used to evaluate the deformability of the adhesive according to EN 12002:2003 [14].

3.2.1 Testing of Tensile Adhesion Strength

The dry blend is mixed (mixer type see 4.4 of EN 196-1:2005) with water in parts by mass as stated by the manufacturer. Mixing time is 30 s and another 15 s after mature time [22]. A thin layer of matured adhesive is applied to the concrete slab with a straight edge trowel. Then additional adhesive is combed with a 6 x 6 mm notched trowel (60° angle to the substrate). After 5 min V1 tiles, dry pressed in accordance with EN 14411:2007, group BI_a [23], with a water absorption < 0.5 % with facial dimensions of 5 x 5 cm are placed in the mortar bed. Each tile is loaded with 2 kg for 30 s. Measurements for 4 different storage regimes are carried out.

- Storage at room temperature (28 d RT)
The slabs are stored under standard conditions (23 °C, 50 % R. H.) for 27 days. Then the pull-head plates are bonded to the tiles and the slabs are stored for another day.
- Storage with water immersion (7 d RT + 21 d W)
The slab is stored for 7 days under standard conditions (23 °C, 50 % R. H.) and afterwards immersed in water for 20 d. The pull-head plates are bonded to the tiles and the tiles are immersed for further 7 hours. Then the test units are removed from water and the bond strength measurement is immediately carried out.
- Heat aging (14 d RT + 14 d 70°C + 1 d RT)
The slabs are stored for 14 days under standard conditions (23 °C, 50 % R. H.) and then at 70 °C in an air-circulating oven for a further 14 days. After removal of the test units from the oven the pull-head plates are bonded to the tiles and the test units are stored at standard conditions for further 24 hours.
- Freeze-thaw cycles (7 d RT + 21 d W + 25 FTC)
The tiles are covered with a 1 mm thick layer of adhesive before placed on the slab (buttering-floating technique). After the slabs have been stored for 7 days under standard conditions (23 °C, 50 % R. H.) and immersed in water for another 21 days, 25 freeze-thaw cycles are carried out. One freeze-thaw cycle consists of storing the

slab test unit for 4 h in a cold chamber at -15 °C and afterwards for 2 hours in a water quench. This cycle is repeated 25 times. After the last cycle the test unit is removed from the water quench, wiped with a cloth and the pull-head plates bonded to the tiles. The test units are stored another 24 h at standard conditions before testing.

- Measurement

The tensile testing machine for direct pull shall be able to apply the load to the pull-head plates (metal, 50 x 50 x 10 mm) at a rate of 250 Newton per second, through a suitable fitting that does not exert any bending force. The data for the individual tensile adhesion strengths are calculated and reported to an accuracy of 0.1 N/mm² (mean of ten values).

3.2.2 Classification

A set of basic requirements (see table 7) with associated test standards are defined for cement-based thin-bed tile adhesives in the product standard EN 12004:2007. Furthermore, definitions and testing methods for optional requirements such as fast setting, non-sag, and extended open time are given. For the transverse deformation measured in accordance with EN 12002:2003 there are no requirements, but it is up to the producer to declare this parameter.

If a tile adhesive is labeled C2FTE such a mortar is cement based (C) and fulfills the increased requirements for tensile adhesion strengths of at least 1 N/mm² for the four storage schemes (dry, wet, warm, freeze-thawing = C2). Additionally, such a tile adhesive is not only fast setting (F) but shows at the same time an extended open time (E) and non-sag characteristic (T). PCI Augsburg in Germany was the first building chemical manufacturer which introduced such a product (PCI-Nanolight[®]) into the market in 2001.

Table 7: Basic requirements for cement-based thin-bed tile adhesives according to the product standard EN 12004:2007

	Classification	Characteristic	Requirement	Test Method
Normal setting adhesives, class 1	C1	Initial tensile adhesion strength (28 d RT)	> 0.5 N/mm ²	EN 1348, 8.2
		Tensile adhesion strength after water immersion (7 d RT + 21 d W)	> 0.5 N/mm ²	EN 1348, 8.3
		Tensile adhesion strength after heat aging (14 d RT + 14 d 70 °C + 1 d RT)	> 0.5 N/mm ²	EN 1348, 8.4
		Tensile adhesion strength after freeze thaw-cycles (7 d RT + 21 d W + 25 FTC)	> 0.5 N/mm ²	EN 1348, 8.5
		Open time	> 20 min	EN 1346
Normal setting adhesives, class 2	C2	Initial tensile adhesion strength (28 d RT)	> 1 N/mm ²	EN 1348, 8.2
		Tensile adhesion strength after water immersion (7 d RT + 21 d W)	> 1 N/mm ²	EN 1348, 8.3
		Tensile adhesion strength after heat aging (14 d RT + 14 d 70 °C + 1 d RT)	> 1 N/mm ²	EN 1348, 8.4
		Tensile adhesion strength after freeze thaw-cycles (7 d RT + 21 d W + 25 FTC)	> 1 N/mm ²	EN 1348, 8.5
		Open time	> 20 min	EN 1346
Special characteristics				
Slip	T	Non sag characteristic	< 0.5 mm	EN 1308
Fast setting adhesives	F	Early tensile adhesion strength	> 0.5 N/mm ² after 6 h	EN 1348, 8.2
		Open time	> 10 min	EN 1346
Extended open time	E	Open time	> 30 min	EN 1346

Data for basic and special requirements for dispersion-based (D) and reaction resin-based tile adhesives are given in table 8. The term reaction-resin summarizes both epoxy-resins and polyurethane-resins.

Table 8: Basic requirements for dispersion/resin tile thin-bed tile adhesives according to the product standard EN 12004

	Classification	Characteristic	Requirement D/R	Test Method D/R
Normal setting adhesives, class 1	D1/R1	Initial shear adhesion strength (28 d RT)	> 1/>2 N/mm ²	EN 1324, 7.2/ EN 12003, 7.3
		Shear adhesion strength after water immersion (7 d RT + 21 d W)	> n. a./>2 N/mm ²	n. a./ EN12003, 7.4
		Shear adhesion strength after heat aging (14 d RT + 14 d 70 °C + 1 d RT)	> 1 N/mm ² /n. a.	EN 1324, 7.4/ n. a.
		Open time	> 20/> 20 min.	EN 1346/ EN 1346
Normal setting adhesives, class 2	D2/R2	Tensile adhesion strength after water immersion (7 d RT + 21 d W)	> 0.5 N/mm ² /n. a.	EN 1324, 7.3/ n. a.
		Shear adhesion strength after thermal shock	n. a./> 2 N/mm ²	n. a./ EN 12003, 7.5
Special characteristics				
Slip	T	Non sag characteristic	< 0.5/< 0.5 mm	EN 1308/ EN 1308
Extended open time	E	Open time	> 30/n. a. min	EN 1346/ n. a.

D = dispersion tile adhesive

R = reaction resin tile adhesive

3.2.3 Reproducibility and Limits

Since the determination of tensile adhesion strength for cementitious adhesives is crucial for their classification a round robin test was carried out by the same test labs which already participated in the round robin test for EN 12002:1997. The tests were carried out according to test standard DIN EN 1348:1997 "Adhesives for tiles – Determination of tensile adhesion strength for cementitious adhesives". The tests were carried out with two different concrete slabs. Slab 1, normally available by the individual companies to determine the tensile adhesion strength for cementitious thin-bed mortar. That means slab 1 differed for every lab taking part in the round robin test. In order to eliminate differences in the porosity and balance capillarity differences the same concrete slab (slab 2) was provided to all testing laboratories for the round robin test.

Tile adhesion strength was measured of ten samples after dry storage at 23 °C for 28 days. Studying the data (table 9) following conclusions are obtained:

Table 9: Average tensile adhesion strength [N/mm²] – Round robin test

Tile Adhesive	Average Tensile Adhesion Strength [N/mm ²] Measured by Ten Different Industry Laboratories										Ø	Δ
	1	2	3	4	5	6	7	8	9	10		
I-Slab1	1.4	1.7	1.7	2	1.3	1.5	1.3	1,1	1.5	1.4	1.51	0.23
I-Slab2	1.6	1.3	1.7	1.7	1.3	1.3	1.3	1.2	1.3	1.2	1.39	0.20
II-Slab1	1.5	1.8	1.6	1.5	1	1.7	1.6	1.2	1,5	1.4	1.48	0.23
II-Sub2	1.6	1.4	1.7	1.7	1.2	1.5	1.5	1.2	1.5	1.5	1.48	0.18
III-Slab1	1.1	1.5	1.4	1.6	1.2	1.2	1.2	1	1.6	1.2	1.30	0.21
III-Slab2	1.2	0.9	1.3	1.6	1.2	1	1.3	1	1.7	1.4	1.26	0.26
IV-Slab1	1	1	1.2	1.3	0.9	1.3	1.2	0.8	1.3	1	1.10	0.18
IV-Sub2	1.1	0.8	1.3	1.1	0.9	0.9	1.3	0.7	1	1	1.01	0.20
V-Slab1	1.4	1.1	0.9	1.3	1	1	1	0.9	0.9	1.1	1.06	0.17
V-Slab2	1.2	0.7	0.9	1	0.8	0.8	1	0.9	1.1	1.1	0.95	0.16
VI-Slab1	0.5	0.7	0.7	1	0.8	1	1	0.4	1.2	0.8	0.81	0.25
VI-Slab2	0.7	0.6	0.6	1	0.9	0.4	0.9	0.5	1.1	0.8	0.75	0.23
VII-Slab1	0.9	0.8	0.7	0.8	0.6	0.7	0.9	0.7	1	0.9	0.80	0.12
VII-Slab2	0.8	0.5	0.8	0.9	0.5	0.5	0.8	0.7	0.8	0.7	0.70	0.15

Slab 1: individual slab

Slab 2: common slab

- The standard deviation for the tensile adhesion tests of the different laboratories are in the range of 15 to 20 %.
- There is an influence of the slab on the values however, less than suspected.
- The variation of values is especially high for simple tile adhesives with low values for tensile adhesion strengths. For instance the average data for tile adhesive VI varies in the range from 0.5 to 1.2. The higher the average tensile adhesion strength for a tile adhesive the less variation is observed between the different test labs (compare data for tile adhesive 1 and 6)
- The higher the polymer content the higher the tensile adhesion strengths. Polymer content increases from tile adhesive VII to I.

3.2.4 Critical Remarks

Again, the testing method is well described but there are many oversimplifications under conditions of practice. For instance, there is only one standardized substrate defined for testing. Of course this is essential to make results of different labs comparable and to use them for the classification of tile adhesives. On the other hand such a single well-defined substrate has not much significance for the job site. There are hundreds of substrates in practice p. e. concrete, cement-/gypsum-based screeds, precast concrete units, plasterboards, expanded plastic slabs, etc.

For reasons of homogenization it would be of advantage to prime the test slab before applying the tile adhesive and laying the test tiles. Priming would not only homogenize the absorptive capacity of concrete slabs and make the experimental data for tensile adhesion strengths better comparable but would also be nearer to reality.

Many critics question the significance of tensile adhesion strength measurements since in real life the usual strain of ceramic claddings is parallel shear force and not vertical tensile force. Shear stress in the composite tile, tile adhesive and substrate may come from thermal expansion of the ceramic cladding (p. e. balconies, terraces) or from shrinkage of the substrate (p. e. young concrete or cement-based screed). It is regardless for the absolute value of shear stress whether the relative movement of tile to substrate stems from expansion or shrinkage. Tensile adhesion strength measurements are standardized and relatively easy to carry out. In contrast determination of shear stress is rather sophisticated. Measurement of shear force and especially shear displacement needs not only experience but also delicate fine mechanical complexity. The results for shear stress often vary in a wide range and reproducibility is restricted. Therefore shear stress determination – although from a physical standpoint more sensible – did not find wide application for cement-based tile adhesives (see also chapter 5.2).

Another critical point of EN 12004:2007 is that determination of tensile adhesion strength allows at least 7 days curing time at standard conditions (23 °C, 50 % relative humidity and less than 0.2 m/s airflow) regardless of the storage regime. From the standpoint of the redispersible polymer powder this is an ideal situation since it has time and temperature enough for the irreversible formation of polymer domains (details see

chapter 5.1). However, real life climate is often quite different. Balconies and terraces are often carried out late in the year. The tiles are laid on a sunny September day and suddenly temperatures may fall below 10 °C or even below 5 °C not only during night time. The hydration process of the cement and the film formation process are disturbed or not occurring at all. If on top of that rain fall sets in the redispersible polymer may be washed out. The tile adhesive will never reach its regular mechanical properties any more. After only one winter season loose tiles may be observed. Testing according to EN 12004:2007 after water immersion or freeze/thaw cycles is of irrelevance because before these conditioning regimes were carried out the specimens were prepared and stored for 7 days at standard climate.

Test series show that at 5 °C even fast curing cementitious thin-bed tile adhesives may take 7 days until they achieve tensile adhesion strengths above 0.5 N/mm². At standard climate this threshold value is already exceeded after 1 hour. The other extreme is tiling in hot and dry countries such as Saudi Arabia or United Arab Emirates. Temperatures may rise to 45 °C and above. Air-conditioning may cause high air convection or wind may blow through the structurally incomplete buildings. Both high temperature and wind may dramatically reduce open time of cementitious thin-bed mortar. Again, open time according to EN 1346:2007 is determined at standard climate (23 °C, 50 % relative humidity and less than 0.2 m/s airflow). On top of it, the substrate may be much more water absorbent than the concrete slabs used when testing open time according to EN 1346:2007.

Laboratory tests demonstrate that increased temperatures dramatically reduce open time of cementitious thin-bed tile adhesives. Open time may drop from over 30 minutes at 23 °C below 10 minutes at 45 °C. That means at higher temperature the tiler must not spread much tile adhesive on the substrate since after a few minutes the adhesive already forms a skin and cannot get in adhesion with the tile any more. Porous substrates and air condition may deteriorate the situation. Again, heat-aging according to EN 12004:2007 and determination of open time give no hint about the behavior of the adhesive at higher temperatures since specimen preparation and storage is done at 23 °C. Some thin-bed adhesives do not perform at all at desert climate since the redispersible polymer powder flocculates under these conditions. Cooling the gauging water with ice cubes may save the day.

3.3 EN 13888:2002 “Grouts for Tiles – Definitions and Specifications” [24]

EN 13888:2002 has also been prepared by Technical Committee CEN/TC67 “Ceramic tiles”, the secretariat of which is held by UNI, Italy. EN 13888:2002 is a product standard which defines and specifies essential requirements for ceramic tile grouts based on cement or reaction resins.

Basic definitions of terminology concerning the products, working methods, application properties and final properties for ceramic tile grouts for internal and external tile installations on walls and floors are defined.

An excerpt of definitions important for tile grouts is cited here.

- Grouting a tile surface: Process of filling the joints between all types of tiles, with the exception of movement joints.
- Grouting time: Minimum time interval after installation of tiles, after which the grout can be applied into the joints.
- Cleaning time: Time interval between filling the joints and starting to clean the tiles.
- Flexural strength: Maximum value of a grout prism failure determined by exerting a force in flexure at three points. It is measured according to EN 12808-3:2002 [25].
- Compressive strength: Maximum value of a grout prism failure determined by exerting a force in compression on two opposite points. It is measured according to EN 12808-3:2002.
- Water absorption: Amount of water absorbed by capillary action when the surface of the grout prism is in contact with water without any pressure. It is measured according to EN 12808-2:2002 [26].
- Abrasion resistance: Capability of the grout surface to resist wear. It is measured according to EN 12808-5:2002 [27].
- Shrinkage: Reduction in length of a grout prism during hardening. It is measured according to EN 12808-4:2002 [28].
- Chemical resistance: Capability of a grout to resist chemical agents. It is measured according to EN 12808-1:1999 [29].

EN 13888:2002 also describes a scheme for the evaluation of conformity including initial type testing, factory production control, registration, and traceability. Equipment, test

methods, frequency of testing for initial testing and factory production control (raw materials, production process, and finished products) and statistical techniques are specified. In chapter 6 and 7 of the standard requirements for classification, designation, marking and labeling are defined.

3.3.1 Testing

The dry blend of cement-based joint grout is mixed (mixer type see 4.4 of EN 196-1:2005) at slow speed settings (140 rpm) with water in parts by mass as stated by the manufacturer. Mixing time is 90 s and another 15 s after mature time. After mixing the test specimens are prepared immediately.

- Determination of resistance to abrasion (EN 12808-2:2002) [26]
The template, a smooth, square, rigid frame of PE or PTFE with internal dimensions of 100 x 100 x 10 mm is placed over a PE film. The template is filled with mixed tile grout and after 24 h the template is carefully removed and the test specimen is conditioned for another 27 days at standard conditions. The test specimen is placed in the abrasion apparatus (see standard EN 12808-2:2002) with the trowelled face against the wheel, so that it is tangential against the rotating disc of the abrasion apparatus. The steel disc of the abrasion apparatus is rotated for 50 revolutions. Abrasive material is fed into the feeding zone at a homogeneous rate of 1 g per revolution. At the end the chord length of the groove caused by the steel disc is measured to the nearest 0.5 mm and the volume of material removed is determined according to the table given on page 7 of the standard.
- Determination of flexural and compressive strength (EN 12808-3:2002) [25]
The joint grout mortar is poured into a three-gang mould to form prisms of 160 x 40 x 40 mm. After 24 hours the specimens are removed from the mould and then conditioned for another 27 days at standard conditions.

For determining the flexural strength the test specimens are placed on the test jig with two cylindrical bearings of 10 mm diameter 60 mm length and 100 mm distance. Eventually the test specimen is deformed with a transverse load according to 9.2 of EN 196-1:2005. The prism halves broken in flexion are used to determine compressive strength described in 9.3 of EN 196-1:2005 [22-1].

For determination of flexural and compressive strength after freeze-thaw cycles the prisms are stored for 6 days under standard conditions (23 °C, 50 % R. H.) and immersed in water for another 21 days. Afterwards 25 freeze-thaw cycles are carried out. One freeze-thaw cycle consists of storing the specimen for 4 h in a cold chamber at -15 °C and for 2 hours in a water quench. This cycle is repeated 25 times. After the last cycle, the test unit is removed from the water quench, wiped and stored for another 3 days at standard conditions. After that flexural and compressive strengths are determined according to 9.2 resp. 9.3 of EN 196-1:2005.

- Determination of shrinkage (EN 12808-4:2002) [28]

The joint grout mortar is poured into a three-gang mould to form prisms of 160 x 40 x 40 mm. After 24 hours the specimens are removed from the mould and the length of the prisms are measured (initial length). After another 27 days the length of the shrunk prisms are measured again (final length). The linear shrinkage is calculated in mm/m from the initial and final length as the mean of three values based on the initial length.

- Determination of water absorption (EN 12808-5:2002) [27]

The joint grout mortar is poured into a three-gang mould to form prisms of 160 x 40 x 40 mm. After 24 hours the specimens are removed from the mould and then conditioned for another 27 days at standard conditions. After 21 days from manufacture of the prisms the side faces of the prisms are sealed with neutral curing silicone sealant. After 28 days from manufacture the prisms are weighed to 0.1 g precision and then immersed 5 to 10 mm deep upright in water. The water level in the tray is maintained constant by adding water when necessary. After 20 min the test samples are removed from water, excess water on the prism removed and weighed. The procedure is repeated after another 210 minutes. The water absorption is calculated by the difference of weight of wet prism and dry test sample.

3.3.2 Classification

A set of basic requirements (see table 10) with associated test standards are defined for tile grouts based on cement (CG1) or reaction resin (RG) in the product standard EN 13888:2002. Furthermore, definitions for improved cementitious tile grouts (CG2) such as high abrasion resistance, reduced water absorption after 30 and 240 min are

also given. For the transverse deformation measured in accordance with EN 12002:2003 there are no requirements, but it is up to the producer to declare this parameter for cementitious grouts.

If a tile grout is labeled CG2 S1, such a dry-blend is cement based and fulfills the increased requirements for high abrasion resistance of less than 1000 mm³ and reduced water absorption after 240 min of less than 5 g. S1 stands for a transverse deformation of at least 2.5 mm determined according to EN 12002:2003. About the purpose of S1/S2 classes and labels see chapter 3.1.4.

3.3.3 Critical Remarks

EN 13888:2002 describes a well-defined set of requirements and testing methods. The main question is how reasonable this set is for every-day demands of tile grouts. In our opinion the determination of abrasion resistance is the most meaningful parameter of all. Since abrasion of tile grouts may occur due to cleaning devices or pedestrian traffic. The harder the joints the less abrasion should be observed. Low shrinkage of joint mortars should also be beneficial to reduce adhesion bond failures of tile grouts to joint flanks. In general, the lower the shrinkage of a joint mortar the less risk of adhesion bond failures. The meaning of the parameters compressive strength and flexural strength for daily life is not transparent to the author.

Especially when laid on balconies and terraces the bonding of the tile grout to the joint edge of the tile is of interest. Cracks at this critical interface allow water to penetrate into the tile adhesive mortar bed. In the cold season this infiltration may cause damage due to frost. Since water expands by 10 % when it passes over to the solid state the composite tile, adhesive and substrate delaminates. The pressure of ice is above 1000 N/mm², whereas tensile and shear adhesion between tile grout and joint edge is only below 5 N/mm². Therefore a parameter for the evaluation of the quality of the bonding of tile grout and joint flank would be more interesting than values for flexural or compressive strength.

In our opinion it is not enough to label tile grouts as S1 or S2 products according to EN 12002:2003 since this flexibility is not sufficient to compensate stress caused by temperature changes or shrinkage of substrate and cannot avoid cracks at joint flanks.

Table 10: Basic requirements for tile grouts according to EN 13888:2002

	Class	Characteristic	Requirement CG/RG	Test Method
Standard cementitious grout/ reaction resin grout	CG1/RG	Abrasion resistance (28 d RT)	< 2000/250 mm ³	EN 12808-2
		Flexural strength after dry storage (28 d RT)	> 3.5/30 N/mm ²	EN 12808-3
		Flexural strength after freeze-thaw cycles (7 d RT + 21 d W+25 FTC+ 3 d RT)	> 3.5/n. a. N/mm ²	EN 12808-3
		Compressive strength after dry storage (28 d RT)	> 15/45 N/mm ²	EN 12808-3
		Compressive strength after freeze- thaw cycles (7 d RT + 21 d W+25 FTC+ 3 d RT)	> 15/n. a. N/mm ²	EN 12808-3
		Shrinkage	< 2 mm/m	EN 12808-4
		Water absorption after 30 min	< 5/n. a. g	EN 12808-5
		Water absorption after 240 min	< 10/0.1 g	EN 12808-5
Improved cementitious grout	CG2	High abrasion resistance (28 d RT)	< 1000 mm ³	EN 12808-2
		Reduced water absorption after 30 min	< 2 g	EN 12808-5
		Reduced water absorption after 240 min	< 5 g	EN 12808-5

One major drawback of EN 13888:2002 is that the testing is only carried out with one specified tile. In practice there are numerous tiles such as glazed or unglazed porcelain tiles, stoneware tiles, quarry tiles, mosaic, terracotta, natural stone products etc.

A new test method “drop effect” for hydrophoby is discussed right now in the technical committee CEN/TC 67. Parameter is the time interval between the placing of a waterdrop on the hardened joint grout specimen and its disappearance due to absorption by the grout mortar. The longer the time interval the higher the hydrophoby of the tile grout. This parameter should be a key figure for cleanability of the surface of the joint grout. Whether this parameter really correlates to practice has to be seen.

3.4 CE-Marking

3.4.1 Scope

The aim of the Construction Products Directive (CPD) [30] is to open the EC-market for the manufacturers of building chemicals. CE-marking shall help to achieve this important goal. CE-marking refers to harmonized European standards (hEN) or technical approvals (ETA). They specify minimum technical requirements and the attestation of the conformity system. The harmonized standards state which tests must be carried out, and how sampling, testing and evaluation of the test results must be carried out.

3.4.2 Requirements for Tile Adhesives

Ceramic tile adhesives can be CE-marked against the CPD (Directive 89/106/EEC, 21st December 1988) of the European Commission [30], providing they meet the essential safety requirements defined in Annex ZA of DIN EN 12004:2007 [12].

Table 11: Requirements for thin-bed tile adhesives according to DIN EN 12004:2007

Parameter	Test Method	Requirement for Thin-bed Tile Adhesives		
		C Cement	D Dispersion	R Resin
Initial Tensile Adhesion Strength	EN 1348, 8.2	> 0.5	not applicable (n. a.)	n. a.
Tensile Adhesion Strength after Water Immersion	EN 1348, 8.3	> 0.5	n. a.	n. a.
Initial Shear Adhesion Strength	EN 1324, 7.2	n. a.	> 1.0	n. a.
Shear Adhesion Strength after Heat Aging	EN 1324, 7.4	n. a.	> 1.0	n. a.
Initial Shear Adhesion Strength	EN 12003, 7.3	n. a.	n. a.	> 2.0
Durability against Water Humidity Action	EN 12003, 7.4	n. a.	n. a.	> 2.0
Reaction to Fire	EN 11925-2 EN 13823	A1 to F A1 _{fl} to F _{fl}	A1 to F A1 _{fl} to F _{fl}	A1 to F A1 _{fl} to F _{fl}

In order that the tile adhesive really fulfills the minimum requirements for CE-marking, the system of attestation of conformity consists of an initial type testing carried out by a notified test laboratory and in setting up a factory quality control by the manufacturer supervised by the notified body.

When appliance both initial type testing and of production control is achieved, the manufacturer will obtain a declaration of conformity by the notified test laboratory which authorizes the manufacturer the affixing of the CE-marking on the packaging and on accompanying commercial documents. The factory production control may be carried out by the manufacturer.

The following information shall be given together with the CE-label:



- name of manufacturer
- address of manufacturer
- production date
- reference to EN 12004:2007
- intended end use
- product description
- information to the relevant parameters

3.4.3 Reaction to Fire

For CE-Marking with respect of the essential requirement of safety in the event of fire, reaction to fire of the building product must be declared. The classification of the reaction to fire is according to DIN EN 13501-1:2007 “Fire Classification of Construction Products and Building Elements – Part 1: Classification using Data from Reaction to Fire Tests” [31]. EN 13501-1:2007 defines a harmonized procedure for the classification of reaction to fire of construction products in general. The classification is based on testing procedures such as non-combustibility test (EN ISO 1182:2002) [32] heat of combustion test (EN ISO 1716:2002) [33], single burning item test

(EN ISO 13823:2002) [34], ignitability test (EN ISO (EN ISO 11925-2:2002) [35] and determination of the behavior of floorings, using a radiant source (EN ISO 9239-1:2002) [36].

Certain products can be classified in a particular fire classification without the need for testing. Such products show well characterized reaction to fire performance. Agreements for products to be classified without further testing (CWFT) are issued by the Standing Committee on Construction in the Official Journal of the EC, and in the internet (<http://europa.eu.int/comm/enterprise/construction>). Deutsche Bauchemie e. V. (German Association of Building Chemicals Manufacturer, Frankfurt) carried out large test series together with the Materialprüfungsamt (MPA) Dresden to verify that cementitious tile adhesives containing less than 20 % organic content, dispersion tile adhesives containing less than 40 % organic content and reaction resin tile adhesive containing less than 50 % organic content mounted on any substrate are of at least class E of reaction to fire performance according to DIN EN 13501-1:2007. The testing results were presented to the Standing Committee on Construction of the European Commission at the end of 2006. The Fire Expert Group of the Standing Committee discussed the test results and decided in December 2007 that tile adhesives with formulations as follows:

Table 12: Classes of reaction to fire performance for adhesives for ceramic tiles

Type od Adhesive	C Cement	D Dispersion	R Resin	Class
Binder - Cement - Aqueous Polymer - Synthetic Resin	30 - 70 n. a. n. a.	n. a. < 30 n. a.	n. a. n. a. > 40	E
Further Organic Additives (cellulose ether, starch, siloxane)	< 20	< 10	< 10	
Mineral Fillers (sand, limestone, ...)	60 - 30	40 - 80	30 - 80	
Water	< 5	< 10	n. a.	

can be classified to class E as provided for in Table 1 of the Annex to Commission Decision 2000/147/EC without further testing. The publication of this adjudication will occur in the next months.

If the tile adhesive does not meet above requirements or a higher classification (A-D) is desired, the tile adhesive has to be tested in accordance with EN 13501-1:2007.

General test parameters are as follows:

- Substrate consists of paper-faced gypsum plaster board.
- Test specimens are stored for 28 days at standard climate.
- For testing of class E/E_{fl} test specimens are prepared according to EN ISO 11925-2:2002 (15 s exposure time to fire).
- For class A/B/C/D-testing additional test specimens are prepared according to EN 13823:2002 resp. EN 1182:2002 (class A).
- Tiles of 50 x 50 mm of ceramic type BI_a (EN 14411:2007) are placed on the substrate with a joint width of 5 mm.

If the content of organic is less than 1 %, tile adhesives are considered to fulfill requirements of fire class A1/A1_{fl} without further testing according to EN 12004:2007.

4 STRESSES IN THE COMPOSITE SYSTEM TILE – ADHESIVE – SUBSTRATE

4.1 Demands on Tile Adhesives in Practice

In the 1970s, it was discovered that thin-bed tile installation, with the use of a purely cement-based adhesive, could lead to damage in the ceramic tiling if, owing to longitudinal modifications of the substrate or of the ceramic tiling, excessively high stresses formed in the fixing mortar [37, 38]. When gluing the complete surface of a tile to the base, the forces resulting from the deformations of the substrate can be transmitted through the adhesive to the tiling and vice versa.



*Image 2, 3
Detachment of ceramic tiles due to high stresses*

What can cause the relative movements between base and ceramic tiling?

4.1.1 Thermal Stress

On the one hand are the different expansions (Δl) that materials undergo with variation in temperature. This longitudinal modification, in absolute form, depends on the variation of temperature (ΔT), the initial length of the piece (l_0) and the specific thermal coefficient of linear expansion (α) of the material [39].

$$\Delta l = l_0 * \alpha * \Delta T$$

Table 13: Coefficients of thermal expansion [40]

	α [mm/mK]			
Ceramic tile	0.006	Δl	Absolute length change	[mm]
Anhydrite	0.008	l_0	Initial length	[m]
Concrete	0.012	α	Coefficient of linear expansion	[mm/mK]
Chipboard	0.030	ΔT	Variation of temperature	[K]

When, for example, the midday sun raises the temperature by 40 °C (ΔT) of the ceramic cladding of a 5 m (l_0) wide terrace, this tiling tends to expand 1.2 mm (Δl). Owing to the composite construction and since, if the base is heated at all, it does so more slowly, the tiling, adhesive and the base will need to absorb the resulting stresses.

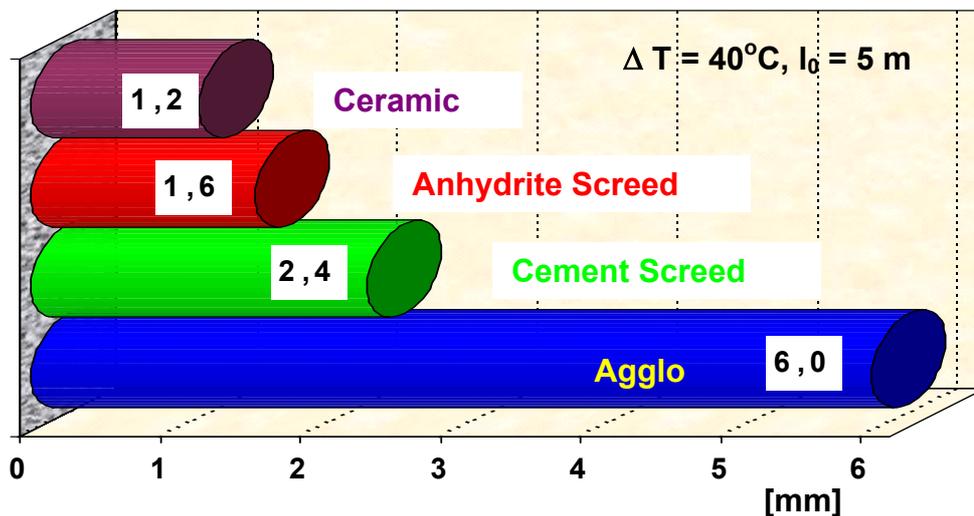


Figure 6: Absolute length change of a terrace cladding

4.1.2 Shrinkage of Substrate

A second group of causes of the relative movements between cladding and substrate are time-dependent shrinkage processes, caused by the setting of the screed or the concrete base. Depending on the composition of the concrete and on the environment, this residual shrinkage can, over the years, reach approximately 1 mm per meter [41]. The magnitude of deformation of the base is indicated in the literature as a non-dimensional measurement index (ϵ_s), which establishes a relation between the longitudinal modification of the base (Δl) and its initial length (l_0).

$$(1) \quad \epsilon_s = \frac{\Delta l}{l_0}$$

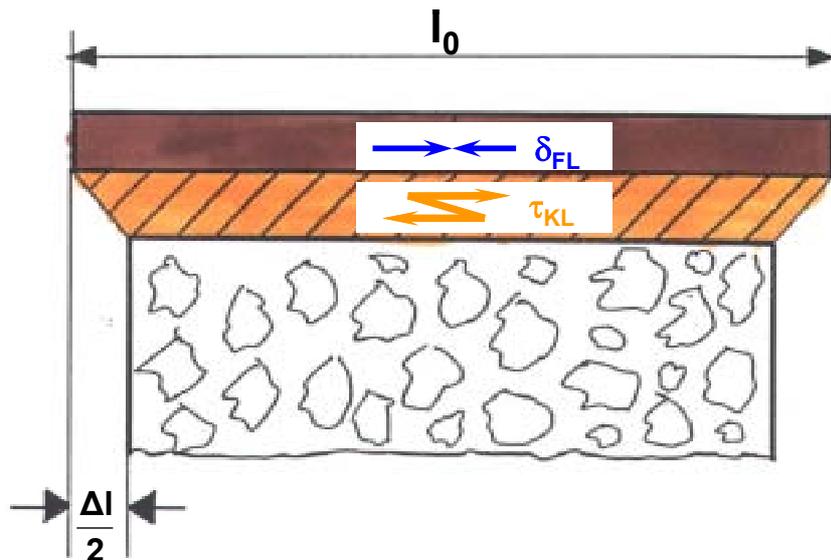


Image 4: Shortening of the base due to cement hydration

Δl	Absolute shrinkage	[mm]
l_0	Initial length of base	[mm]
ε_S	Deformation of base	[mm/mm]

4.1.3 Influence of Water on Tile Dimension

Sometimes moisture expansion for tiles is discussed as additional source of stress. It is claimed, that after a heavy rain shower the ceramic cladding of a facade, balcony or terrace is expanding due to water adsorption by the ceramic tiles. Let us have a closer look at that.

EN 14411:2007 defines and specifies requirements and marking criteria for ceramic tiles produced by extrusion or dry-pressing techniques. Tiles are made of clays and other inorganic materials. The clays are washed, homogenized and milled. If the tile body is shaped from a paste made of milled clay and water by an extruder, the resulting tiles are called extruded tiles (traditionally split tiles or quarry tiles). In the case finely milled clay is pressed with high pressure to the tile body one refers to dry-pressed tiles.

For classification of tiles into groups besides their method of manufacture their water absorption E according to EN 10545-3:1997 is used [42].

Table 14: Specification of tiles according to EN 10545-3:1997 subject to water absorption

Production Process	I E < 3 %	Water Absorption		
		II _a 3 – 6 %	II _b 6 – 10 %	III > 10 %
A (Extruded)	AI _a E < 0.5 %	AII _a	AII _b	AIII
	AI _b 0.5 < E < 3 %			
B (Dry-pressed)	BI _a E < 0.5 %	BII _a	BII _b	BIII
	BI _b 0.5 < E < 3 %			

The moisture expansion coefficient according to DIN EN ISO 10545-10:1995 [43] was determined and compared with the thermal expansion if the tiles are warming up by 40 °C. The results are summarized in table 15.

Table 15: Important parameters of commercial tiles

Tile	Product Process	Classification EN 14411	Water Absorption [%]	Moisture expansion EN 10545-10 [µm/m]	Linear Thermal Coefficient [µm/mK]
Fully Vitrified Tile	Dry-pressed	BI _a	< 0.4	< 1	6
Stoneware Tile	Extruded	AI _b	0.7	< 1	5.2
Split Tile	Extruded	AII _a	4.5	< 1	4.0
Earthware Tile	Dry-Pressed	BIII	15 %	12	7

The data supplied by courtesy of Deutsche Steinzeug/Agrob Buchtal show that the moisture expansion is insignificant compared to the thermal expansion for tiles of classes BI_a, AI_b and AII_a. These tiles show a moisture expansion of less than 1 µm per meter. Warming up these tiles by only 1 °C expands the tile by 5 to 7 µm. Only in the case of tiles of class BIII of very high water absorption (E = 15 %) the expansion due to the water saturation of the tile is measurable. However, the value of 12 µm expansion per meter of such tiles is only about 5 % of the thermal expansion if the terrace is heating up by 40 °C.

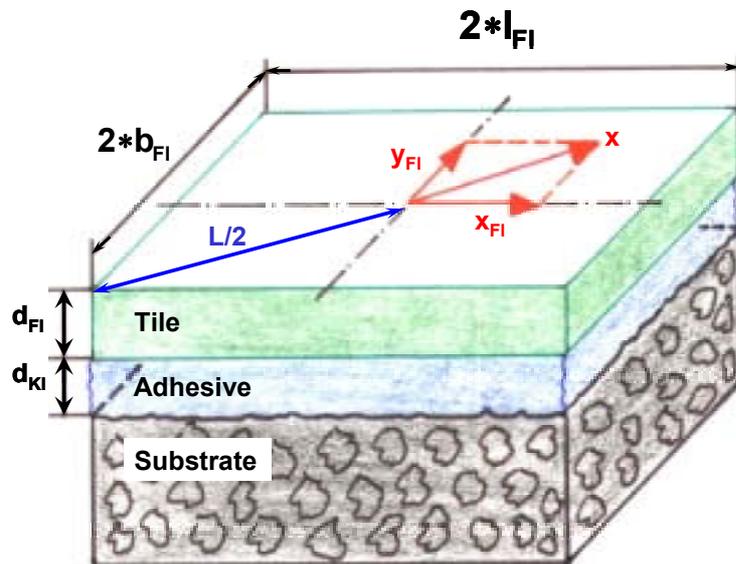
In summary the comparison for maximum typical deformations

- concrete shrinkage = 1 mm/m
- thermal expansion = 0.3 mm/m
- moisture expansion < 0.01 mm/m

show that the effect of moisture expansion of tiles is negligible.

4.2 Theoretical Considerations

4.2.1 Mathematical Model



$$0 \leq x \leq l_{Ti} \quad 0 \leq y_{Ti} \leq b_{Ti} \quad 0 \leq x \leq L$$

Image 5: Geometrical parameters of the composite tile-adhesive-substrate

d_{Ti}	Thickness of tile	[mm]
d_{Ad}	Thickness of tile adhesive	[mm]
x	Radial distance from the centre of tile	[mm]
x_{Ti}	Distance from the centre of tile in longitudinal direction	[mm]
y_{Ti}	Distance from the centre of tile in transverse direction	[mm]
$L/2$	Maximum radial distance from the centre of tile	[mm]
l_{Ti}	Half tile length	[mm]
b_{Ti}	Half tile width	[mm]

A step by step deduction of the mathematical relations would exceed the frame of the present paper and can be consulted in [44]. In this fundamental deduction it is possible to set out from equilibrium between the compression force in the tile (F_{Ti}) and the shear force in the tile adhesive (F_{Ad}).

$$(2) \quad F_{TI}(x) = -F_{Ad}(x)$$

Expressing the compression force in the tile and the shear force in the fixing mortar in relation to the compressive stress (σ_{TI}) and the shear stress (τ_{Ad}), respectively, gives equation (3) [45].

$$(3) \quad 2 * b_{TI} * d_{TI} * \sigma_{TI}(x) = -2 * b_{Ad} * \tau_{Ad}(x) * x$$

Taking into account the differential modifications of the shear stress, of the compressive stress and of the compression of the tile by means of differentiation in accordance with the radial distance x from the centre of tile and after some transformations, gives the following non-homogeneous second-order differential equation with constant coefficients:

$$(4) \quad \frac{d_{TI} * d_{TI} * E_{TI}}{G_{Ad}} * \frac{d^2}{dx^2} \sigma_{TI}(x) - \sigma_{TI}(x) = -\epsilon_S * E_{TI}$$

As a closed solution of the system of differential equations for the shear stress, distribution equation (5) is obtained [46]:

$$(5) \quad \tau_{TI}(x_{TI}, y_{TI}) = \epsilon_S * \sqrt{\frac{E_{TI} * d_{TI} * G_{Ad}}{d_{Ad}}} * \frac{\sinh \sqrt{\frac{(x_{TI}^2 + y_{TI}^2) * G_{Ad}}{d_{Ad} * d_{TI} * E_{TI}}}}{\cosh \sqrt{\frac{(l_{TI}^2 + b_{TI}^2) * G_{Ad}}{d_{TI} * d_{TI} * E_{TI}}}}$$

4.2.2 Discussion of Shear Stress Formula (5)

- General

In the corners of the tile, the shear stress must acquire maximum values, since the value of the relative movement between the ceramic slab and the substrate maximizes there. Setting x_{TI} and y_{TI} equal to l_{TI} and b_{TI} , i. e. positioning oneself in the corner of the tile, expression (6) is obtained for the maximum shear stress in the corners of the slab:

$$(6) \quad \tau_{Ad-max}(l_{TI}, b_{TI}) = \epsilon_S * \sqrt{\frac{E_{TI} * d_{TI} * G_{Ad}}{d_{Ad}}} * \tanh \sqrt{\frac{(l_{TI}^2 + b_{TI}^2) * G_{Ad}}{d_{Ad} * d_{TI} * E_{TI}}}$$

Therefore, the maximum shear stress in the fixing mortar in the corners of the tiles (τ_{Ad-max}) depends exclusively on the geometric factors tile length (l_{TI}), tile width (b_{TI}), tile thickness (d_{TI}), adhesive layer thickness (d_{Ad}), on the material properties modulus of elasticity of the tile (E_{TI}), shear strength of the fixing mortar (G_{Ad}) and on the relative movement of the ceramic tiles with regard to the substrate (ϵ_S).

- Influence of the Shear Modulus of the Tile Adhesive (G_{Ad})

If typical values are set for the individual parameters and the shear stress is calculated for increasing distances from the centre of the tile, the shear stress distribution represented in figure 7 is obtained.

While a fully vitrified tile has a modulus of elasticity of 35,000 N/mm² [47], the shear modulus of the fixing mortar G_{Ad} must be chosen freely since no values are available in the literature. A cementitious tile adhesive would not indefinitely withstand a maximum shear stress peak of 2 N/mm² indefinitely in the corners of the tile.

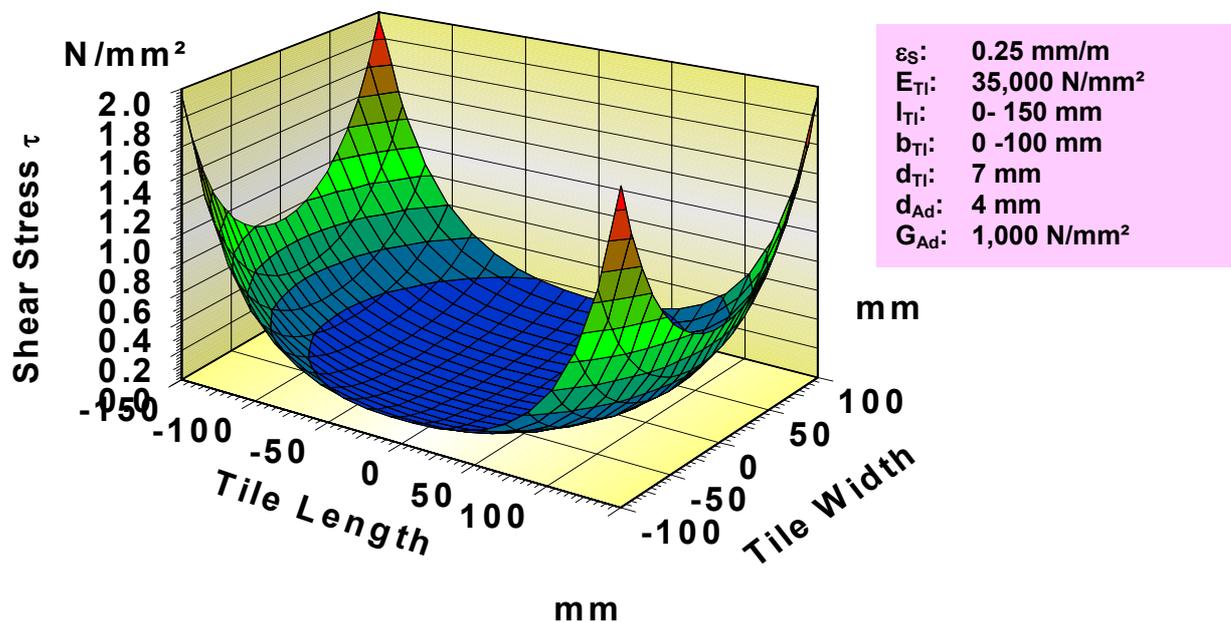
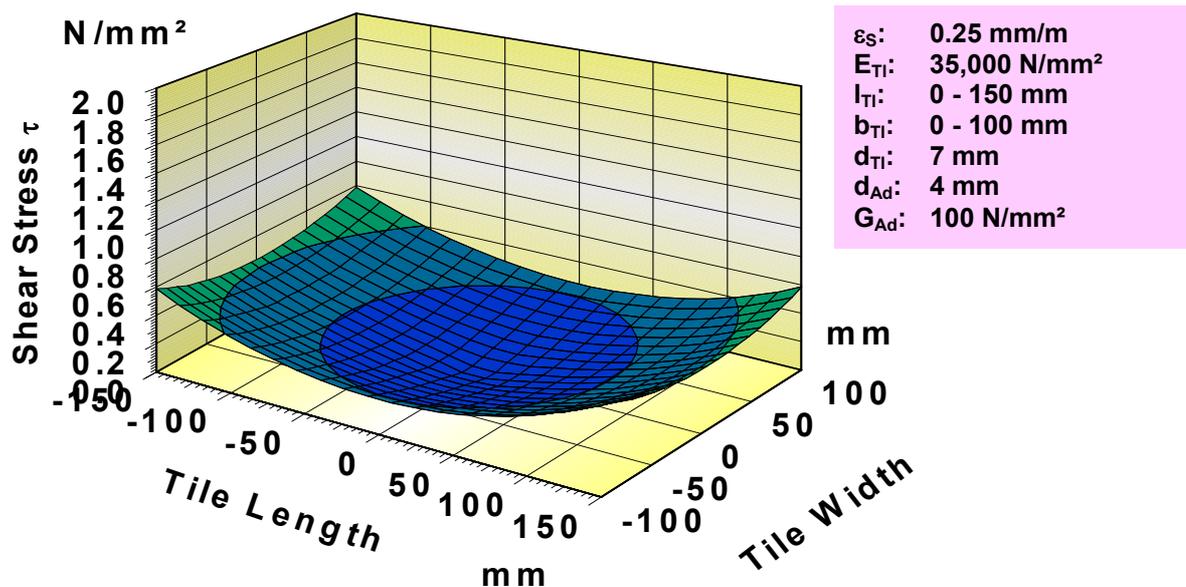


Figure 7: Radial distribution of the shear stress for a rigid tile adhesive

The adhesive would disaggregate beginning in the corners and detachments of the ceramic tiling would occur. The detachments would propagate inwards until the radial shear stress has a value below 0.5 N/mm². If the adhesive was extremely rigid, it might then be left with just a single central adhesion point in the centre,

whose adhesion surface area might then be insufficient to support the tile's own weight on a vertical wall. The reduction of the shear modulus from 1,000 to 100 N/mm² leads to a significantly smaller shear stress in the mortar, since it is more flexible. Owing to the low internal strength of the adhesive, a significantly smaller stress is generated (figure 8).

Figure 8: Radial distribution of the shear stress for a flexible tile adhesive



- Influence of the relative Movement between Tile and Substrate (ϵ_S)

The following diagram displays the maximum shear stress peaks for a porcelain tile of 20 x 30 cm, simultaneously varying the shear modulus of the adhesive (G_{Ad}) and the relative movement between the ceramic tile and the base (ϵ_S).

Two borderline cases of figure 9 need to be discussed. In the case that the adhesive is infinitely elastic, i. e. $G_{Ad} = 0$, no shear stress forms in the adhesive, even at great deformations of the base, since the adhesive acts in a certain sense as an ideal separation layer.

In the case that there is no relative movement between the base and the ceramic tile ($\epsilon_S = 0$), no shear stress develops either, independently of the stiffness of the fixing mortar. Especially critical shear stress peaks form in the corners of the tile when high residual shrinkage in the base occurs and a very rigid fixing mortar is

used (low dispersion powder content). In this case, the stress peaks in the corners of the tiles are in the red area of the diagram, which inevitably leads to the destruction of the cementitious adhesive.

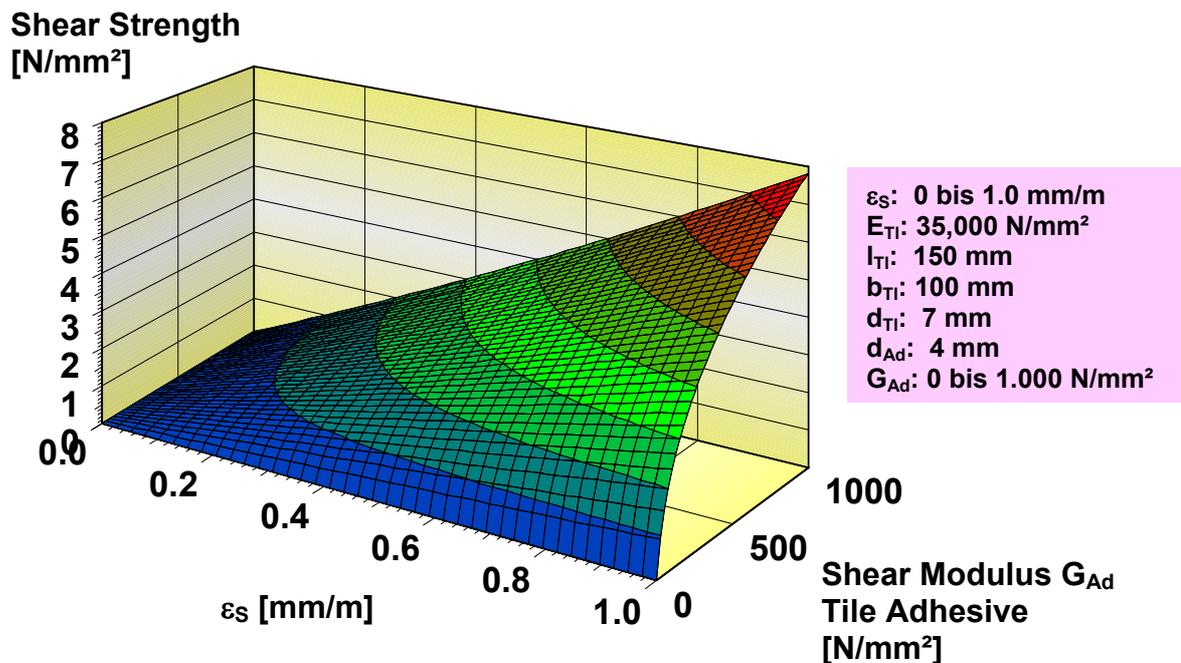


Figure 9: Influence of base deformation and shear modulus of the tile adhesive on the maximum shear stress

In the case that there is no relative movement between the base and the ceramic tile ($\epsilon_S = 0$), no shear stress develops either, independently of the stiffness of the fixing mortar. Especially critical shear stress peaks form in the corners of the tile when high residual shrinkage in the base occurs and a very rigid fixing mortar is used (low dispersion powder content). In this case, the stress peaks in the corners of the tiles are in the red area of the diagram, which inevitably leads to the destruction of the cementitious adhesive.

- Influence of Tile Size (l_{Tl} , b_{Tl})

Professionals often allege that shear stress rises considerably when tile size increases. Equation 6 shows that this is only relatively true. For the extreme case of an infinitely large tile the subradical expression converges as argument of the

hyperbolic tangent towards infinite. The hyperbolic tangent of an infinite number is 1, so that the maximum shear stress in the corners of an infinite tile can be calculated from equation 7. It is interesting that this maximum value no longer depends on the dimension of the tile, but exclusively on the natural strength of the tile, on the shear modulus of the adhesive, on the thickness of the tile, on the thickness of the adhesive layer and on the relative movement (shrinkage of the base, thermal expansion of the ceramic tile) of the cladding relative to the base.

$$(7) \tau_{Ad-max}(\infty, \infty) = \epsilon_S * \sqrt{\frac{E_{TI} * d_{TI} * G_{Ad}}{d_{Ad}}}$$

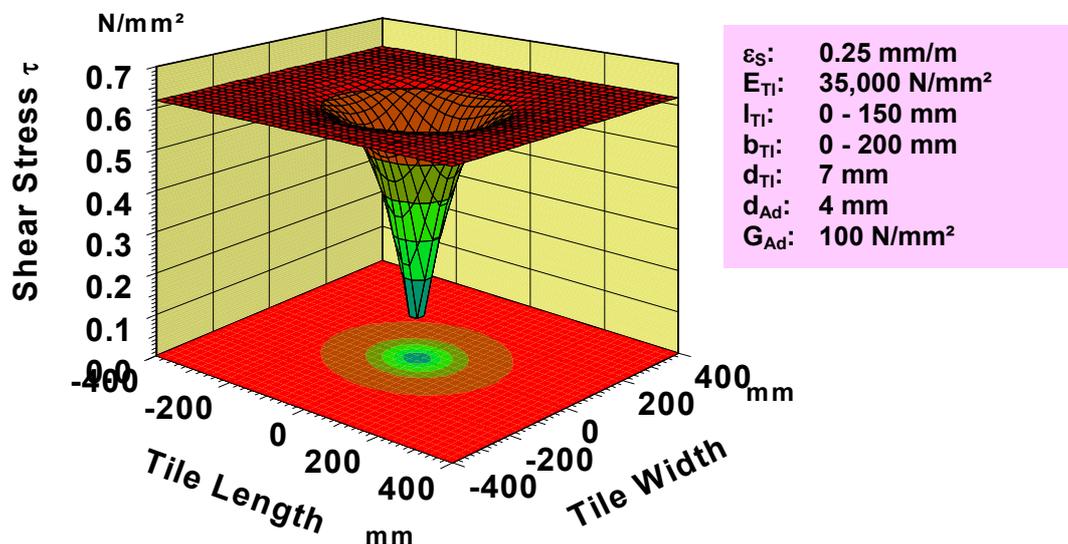


Figure 10: Maximum shear stress as a function of tile size

Figure 10 shows how the maximum shear stress rises when tile size increases (l_{TI} , b_{TI}) in accordance with equation 7. In the given case, for a mosaic of 4.5 cm edge length, maximum shear stress peaks of 0.2 N/mm² would form. At a tile size of more than 40 cm in edge length, the maximum shear stress is 0.62 N/mm². This value is limited by the shear modulus of the adhesive. For a large-sized tile areas, at a distance of more than 20 cm from the centre of the tile maximum shear stress would not exceed 0.62 N/mm².

Figure 11 depicts another representation of the same circumstance. The curve indicates up to which tile size, as a function of the adhesive shear modulus (G_{Ad}),

the shear stress peaks in the corners of the tiles will not exceed a value of 0.5 N/mm², at which a safe and lasting tile installation may be assumed. As deformation

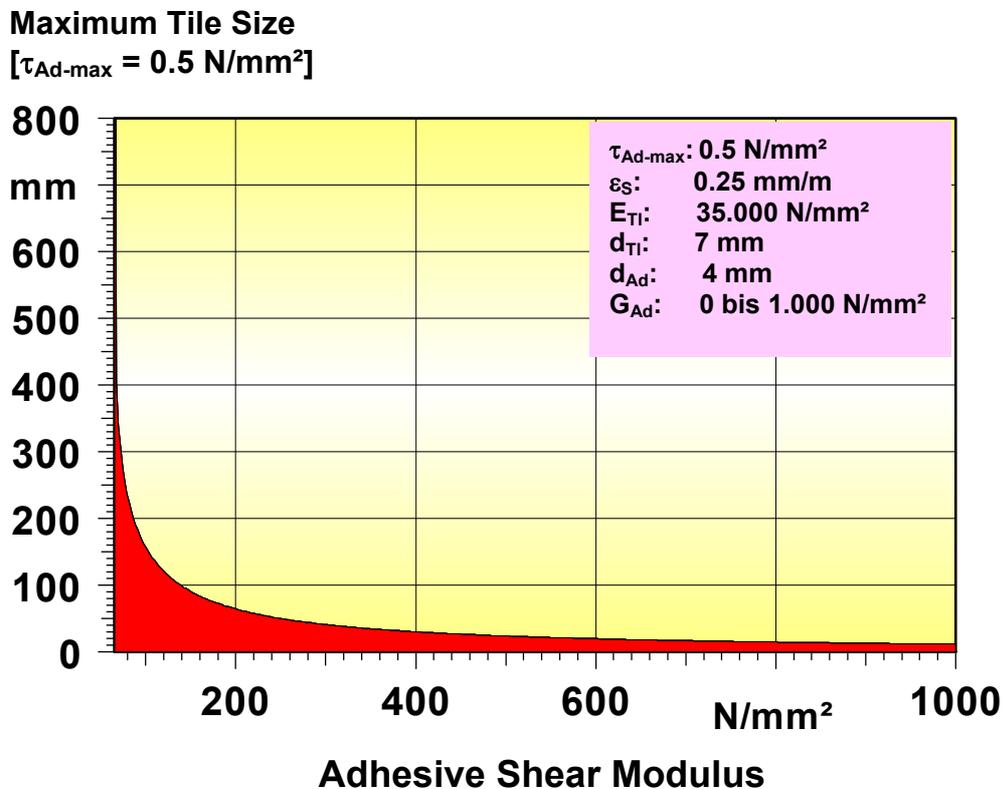


Figure 11: Maximum tile size as a function of adhesive shear modulus, if the maximum shear stress shall not exceed 0.5 N/mm²

of the base a value of 0.25 mm per meter base has been assumed. In the case of high shear modules, i. e. in the case of rigid, inflexible, adhesives ($G_{Ad} = 1000 \text{ N/mm}^2$), this value is already exceeded for edge lengths above 12 mm. In the case of soft, deformable adhesives, with a G modulus below 65 N/mm², the critical value of 0.5 N/mm² is not even reached for an infinite tile. The development of the curve was calculated from equation (8):

$$(8) \quad l_{Tl-max} = \epsilon_S * \sqrt{\frac{E_{Tl} * d_{Tl} * d_{Ad}}{2 * G_{Ad}}} * \operatorname{artanh} \left[\frac{\tau_{Ad-max}}{\epsilon_S * \sqrt{\frac{E_{Tl} * d_{Tl} * G_{Ad}}{d_{Tl}}}} \right]$$

- Influence of Joints

The magnitude of the maximum shear stress in the corners of the tile for an infinitely large tile is obtained from equation (7). However, since tiles have a finite size equation (6) must be used for the calculation of the maximum shear stress.

Claddings can be considered to be made up of tiles and a grid of joints. The case is assumed, in which the grid of joints is filled with a mortar grout that has the same stiffness, i. e. the same modulus of elasticity as the ceramic tiles. From a physical point of view, this would mean there was no joint at all, i. e. that the entire tiling was solely made up of one almost infinitely large ceramic slab. If the joints have not been filled or if this has been done with a very elastic joint filling, the actual dimensions of the tiles can be inserted in equation (6). The reason is, that in the case of shrinkage of the base or of thermal heating of the tiling, the individual ceramic tiles can move relatively to each other without “disturbing” each other. Thus, the presence of the joints reduces the maximum shear stress compared with a cladding without any joints. The absolute value of the reduction in shear stress in the corners of the tiles as a result of the joints, in comparison with a tiling without any joints, is calculated by subtracting equation (6) from equation (7).

$$(9) \quad \Delta \tau_{Ad-max}(l_{TI}, b_{TI}) = \varepsilon_S * \sqrt{\frac{E_{TI} * d_{TI} * G_{Ad}}{d_{Ad}}} * \left[1 - \tanh \sqrt{\frac{(l_{TI}^2 + b_{TI}^2) * G_{Ad}}{d_{Ad} * d_{TI} * E_{TI}}} \right]$$

For a very small mosaic piece, i. e. l_{TI} and b_{TI} equal to zero, the hyperbolic tangent has a value equal to zero. In this way, the reduction in shear stress is maximum, i. e. no shear stress develops. In contrast, for an infinitely large tile, $l_{TI} = b_{TI} = \infty$, the hyperbolic tangent adopts the value 1, i. e. no reduction in shear stress takes place. Thus, the expression between parentheses $1 - \tanh$ practically represents a reduction factor (r) of the maximum shear stress in the corners of the tiles, caused by the joints and the finite size of the tiles linked to these joints.

$$(10) \quad r = 1 - \tanh \sqrt{\frac{(l_{TI}^2 + b_{TI}^2) * G_{Ad}}{d_{Ad} * d_{TI} * E_{TI}}}$$

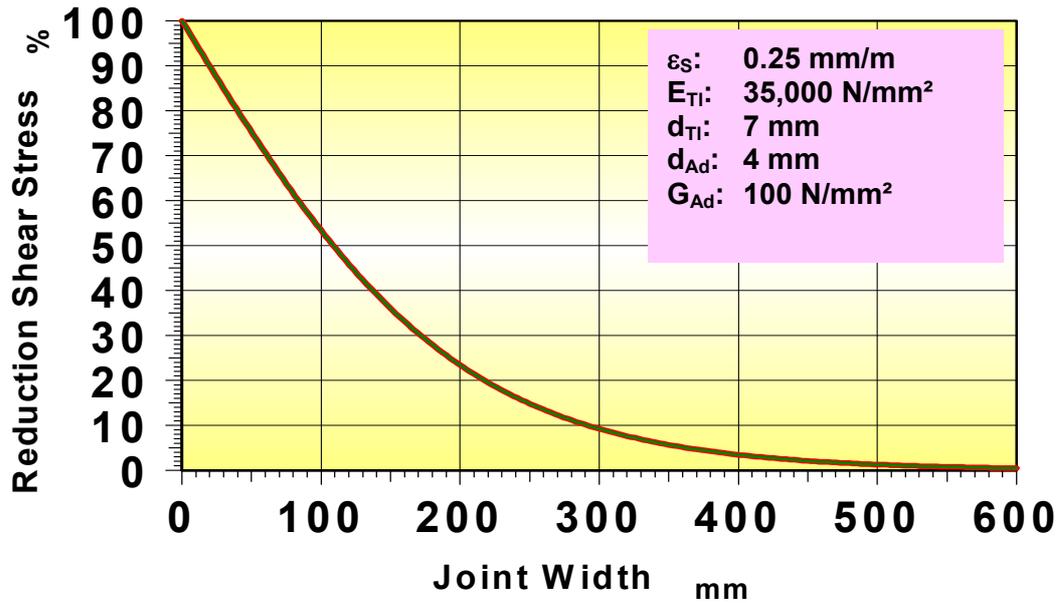


Figure 12: Reduction of maximum shear stress by joints distance

Figure 12 graphically represents the behavior for a given tile and a defined fixing mortar. At a joint distance of 5 cm (large mosaic), the maximum shear forces are reduced by 75 % in the corners of the tiles due to the joints. In the case of a joint distance of 20 cm, the reduction in stress is still approximately 25 %. Beyond a tile size of 50 cm there is no reduction any more in the maximum shear stress in the corners of the tiles.

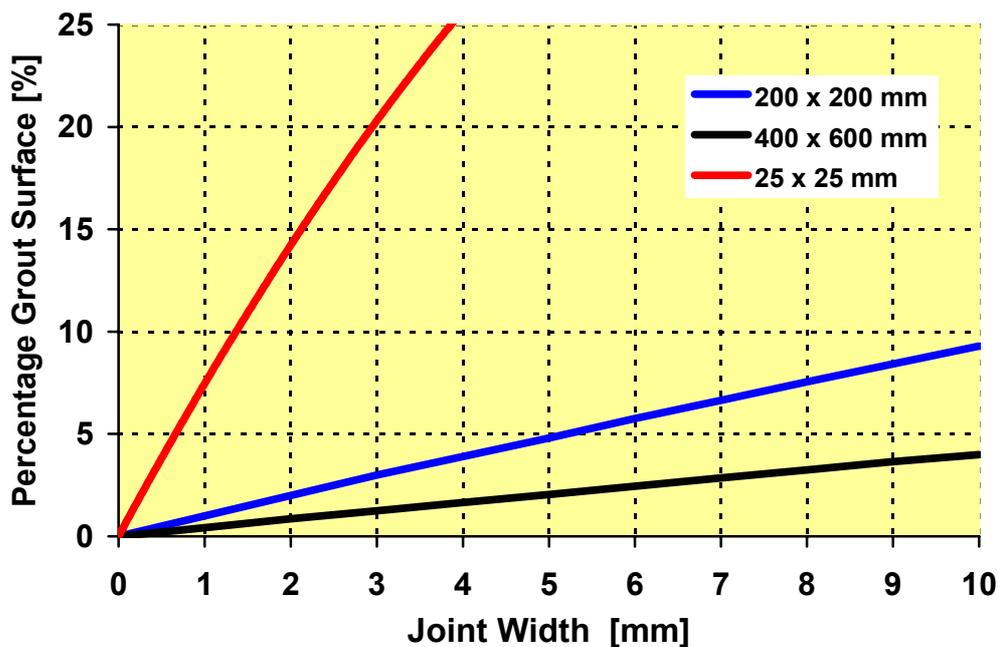


Figure 13: Percentage of grout surface as a function of joint width

By the way, the percentage of grouted surface of a cladding should not be underestimated. It is calculated as follows:

$$(11) \text{ Percentage of Grouted Area} = 100 * \left[1 - \frac{l_{TI} * b_{TI}}{(l_{TI} + jw) * (b_{TI} + jw)} \right]$$

Illustration 13 shows that for a mosaic the grout surface may exceed 15 % of the total surface whereas for a 40 x 60 cm tile this portion is typically around 2 %.

- Influence of Adhesive Layer Thickness (d_{Ad})

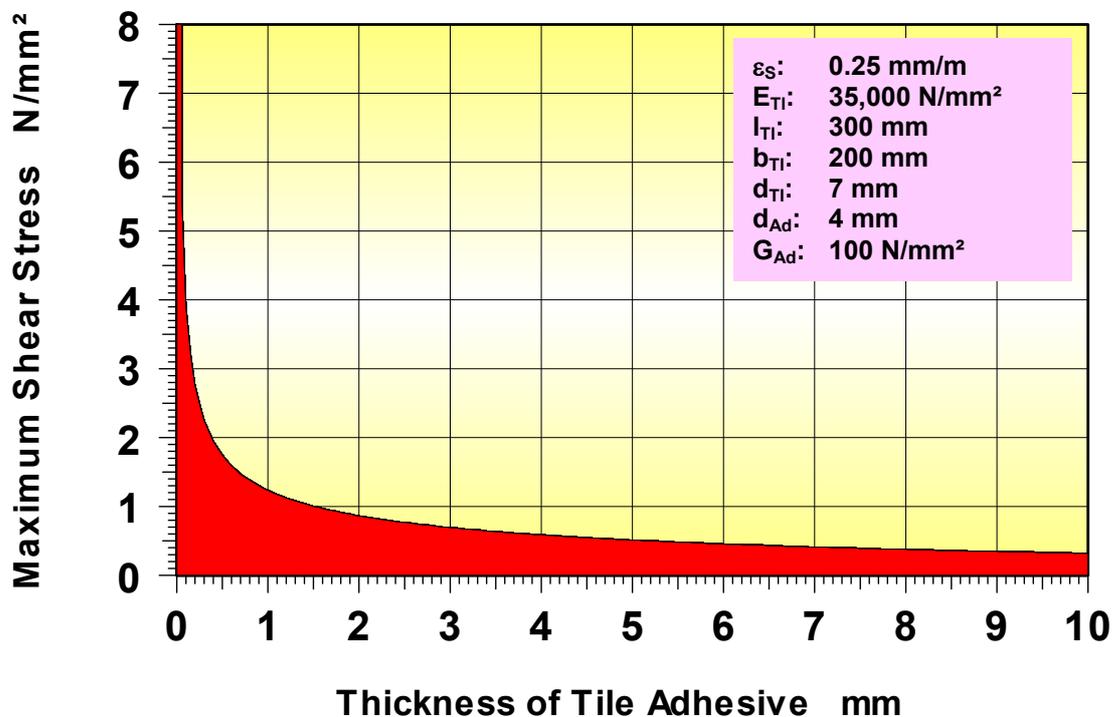


Figure 14: Maximum shear stress as a function of mortar layer thickness

Experience shows that the thickness of the adhesive layer can contribute significantly to reducing shear stress. If in equation (6) only the thickness of the adhesive layer (d_{Ad}) is varied, then, in accordance with figure 14, this patently obvious truth is confirmed. The shear stress in the fixing mortar increases exponentially for an adhesive layer thickness below 1 mm. For an adhesive layer thickness exceeding 4 mm only a low reduction in shear stress is obtained.

4.2.3 Significance of the Model in Practice

Equation (6) describes the maximum shear stress that develops in the corners of the tiles. If τ_{Ad-max} has a value exceeding 0.5 N/mm^2 , the fixing mortar disaggregates over time. Thus, beginning in the corners of the tiles, detachments take place that propagate concentrically towards the centre of the tile, reducing the values of l_{TI} and b_{TI} . The detachment advances until, owing to the reduced values of l_{TI} and b_{TI} , the value of τ_{Ad-max} falls below 0.5 N/mm^2 . Depending on how much of the fixing mortar surface area remains in contact, the own weight of the tile may be sufficient to cause it to fall off the wall. In outside environments, water can penetrate into the detached areas and destroy the ceramic tiling as a result of the pressure that builds up with frost (crystallization pressure of ice is above 1000 N/mm^2). Who can contribute to keeping the shear stress from growing too much?

- Constructor

Equation (6) indicates that the maximum shear stress increases with tile size, elasticity module of the tile (E_{TI}) and tile thickness (d_{TI}). A thicker tile is more difficult to compress than a thin one, as a result of which, at a given shrinkage of the base, a higher shear stress is generated. The thickness and modulus of elasticity of a tile are determined by the manufacturing process. The constructor chooses the type and size of tiles. Fully vitrified tiles, chosen gladly for aesthetic reasons, at $35,000 \text{ N/mm}^2$ has a greater internal stiffness than stoneware tiles ($E_{TI} = 15,000 \text{ N/mm}^2$).

Essentially, the magnitude of the shrinkage of base or, in general, of the relative potential movement between the base and the ceramic tiling (ϵ_S) can also be influenced by the constructor. The greater this relative movement, the greater will be τ_{Ad-max} . The potential deformation of a cement-based screed depends essentially on its residual moisture content, established by the CM method, and on the advance of cement hydration. For safe tile installation on a cement base, the literature requires a residual moisture content of 2 % (CM method). For a cement base, this residual moisture content is presumed to be reached in the case of normal climate ($20 \text{ }^\circ\text{C}$, 50% relative humidity) after 28 days [48, 49]. If this period of time is unavailable or, as is observed frequently in practice, a moisture content of 2 % is not reached according to the CM method even after 28 days, the progress of

the building work can be accelerated by using fixing mortars modified with redispersible polymer powder. The selection of the tiling to be installed also influences the possible relative movement between the tiling and the base. Figure 6 shows that aggro-marble displays a coefficient of thermal expansion five times greater than that of stoneware tiles [50]. In addition, it should be taken into account that black tiles heat and expand considerably more due to solar radiation than light-colored tiles.

- Tiler

The tile fixer essentially has an influence on the parameters adhesive layer thickness (d_{Ad}) and fixing mortar shear modulus (G_{Ad}). Below a certain adhesive layer thickness, the maximum shear stress increases exponentially. For this reason, it is important that the minimum quantities recommended by the mortar manufacturer should be used with regard to primers, bonding bridges and fixing mortar over the entire surface.

The tile fixer can influence the stiffness, i. e. the shear modulus of the fixing mortar (G_{Ad}), by selection of the fixing mortar or, respectively, by the addition of polymer latex. Mortars modified with liquid dispersions display a smaller resistance to deformation by shear than the purely cement-based adhesives. Thus, shear stresses can effectively be reduced (figures 7, 8 and 9). The use of fixing mortars modified with polymers is especially advantageous in the case of: fixing large-sized slabs on fresh cement bases, of tile installation on radiant flooring or for surfaces subject to strong solar radiation.

In practice, it is often forgotten that by filling joints with a hard grout mortar, the length (l_{TI}) and the width (b_{TI}) of the tile becomes practically identical to the dimensions of the whole tiled area. If the possibility exists of carrying out the grouting some weeks after the tile installation, parameters l_{TI} and b_{TI} in equation (6) would really be limited to the boundaries of the tile. The base could dry quickly through the open joints and the individual tiles could move freely and, therefore, generate smaller shear stresses (fig. 12).

- Building Chemical Manufacturer

The manufacturers of fixing mortars can only influence the shear modulus (G_{Ad}) of the tile adhesive. Specifically, the resistance to deformation by shear of the cementitious fixing mortar can be varied by the appropriate selection of polymer dispersion or of redispersible polymer powder and their quantities (figs. 7, 8, 9). At present, few or no data are published for shear modulus of cementitious fixing mortars because the measurement of the shear modulus is relatively complicated and inexact [51].

4.2.4 Limits of the Model

The most decisive limitation of the model resides in the fact that it is only valid for the Hook elastic area. Therefore, the reduction of stresses due to plastic deformation of the tile adhesive cannot be described. However, in practice it is known that due to the permanent action of the shear forces, beyond a certain magnitude, concrete slab, bases or screeds, fixing mortars, etc. can reduce stresses by means of creep [52, 53, 54]. Therefore, the present elastic consideration of the composite bond represents a worst-case scenario. The model enables describing how each parameter tends to influence the composite system in an individual way.

5 INFLUENCE OF POLYMERS ON MECHANICAL PARAMETERS OF TILE ADHESIVES

Theory shows that the shear modulus of the tile adhesive (G_{Ad}) is the crucial parameter for the maximum shear stress in the composite tile – adhesive – substrate (see 4.2.2 and formula 6 and 7). The higher the shear modulus of a tile adhesive the less elastic is the mortar. The shear modulus of a tile adhesive depends on the formulation of the mortar and especially on the quantity and type of redispersible polymer powder resp. polymer emulsion added.

5.1 Film Formation

5.1.1 Mechanism of Formation

Redispersible spray-dried polymer powder is dispersed again into discrete latex particles during the mixing of the dry-blend and gauging water. After a slake time of three minutes the mortar is usually re-mixed in order to complete the re-dispersion process.

In the first stage (particle concentration) after spreading the tile adhesive on the substrate and lying of tiles, the mortar loses water due to hydration of the cement, capillary suction of substrate and tile, and evaporation of excess water into the atmosphere. The more water disappears the more concentrated and closer the latex particles. A closed packed array of hexagonal particles is formed. In the second step (particle deformation), due to progress drying, the latex particles get deformed and coalesce irreversibly. Coalescence only occurs when the temperature is above the minimum film-forming temperature (MFFT). Only then the latex particles are deformable enough to form a void-free film which is still mechanically weak. In the third stage (complete coalescence) polymer interdiffusion between adjacent particles occurs which gives the polymer domains its final elasticity and strength [55, 56, 57].

The polymer domains effect a significant enhancement of the mechanical properties of the cured mortar. They depend on the selected redispersible polymer powder and the concentration of the polymer in the cement matrix. The characteristics of the redispersible powder are defined by the selected monomers, their respective concentration, and the polymerization process.

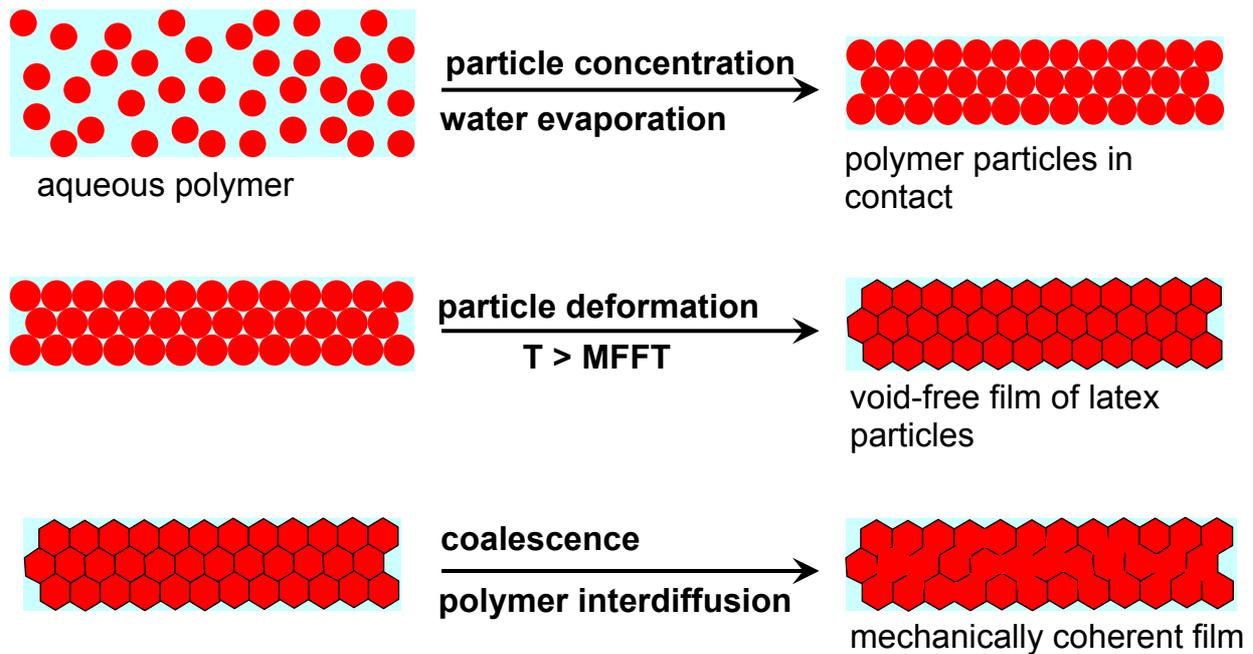


Image 6: Polymer film-forming process

It takes time and temperature that the polymer domains can form in the cementitious matrix. When tiling a balcony or terrace for an undisturbed polymer film formation there must be temperatures above the minimum film-forming temperature of the redispersible polymer powder (also during night time) and no rain fall for at least five days. After the polymer domains have formed they are not sensitive to rain any more (besides saponification, see chapter 5.1.3).

The lower the glass transition temperature (see chapter 5.1.2) the softer, the more flexible the polymer. There is some discussion whether soft polymers ($T_g < \text{application temperature}$) or hard polymers ($T_g > \text{application temperature}$) should be used in tile adhesives. Cement-based waterproofing slurries must form a continuous, flexible film of 2 mm thickness. Flexibility and bonding to substrate and tile adhesive must be guaranteed even at winter time and cold nights. Therefore, polymers used in such waterproofing products usually have a glass transition temperature of $-15\text{ }^\circ\text{C}$. Cement based thin-bed tile adhesives consist not of a continuous polymer film but of a cement matrix interspersed with polymer domains. These polymer domains make the matrix a little bit more elastic but not elastic per se. Another important point is that these polymer domains improve the bonding to non-porous and smooth surfaces and tiles. Therefore the polymer must not be too soft otherwise the bonding would be too weak, too elastic.

Glass transition temperatures for redispersible polymer powders used in tile adhesives are about +10 °C. This relatively high glass transition temperature does not put the elasticity of the adhesive as a whole at risk since there are only domains interspersed in the cement matrix and no homogeneous polymer film. The MFFT of the polymer powders is about 0 - 5 °C. MFFT is always below T_g .

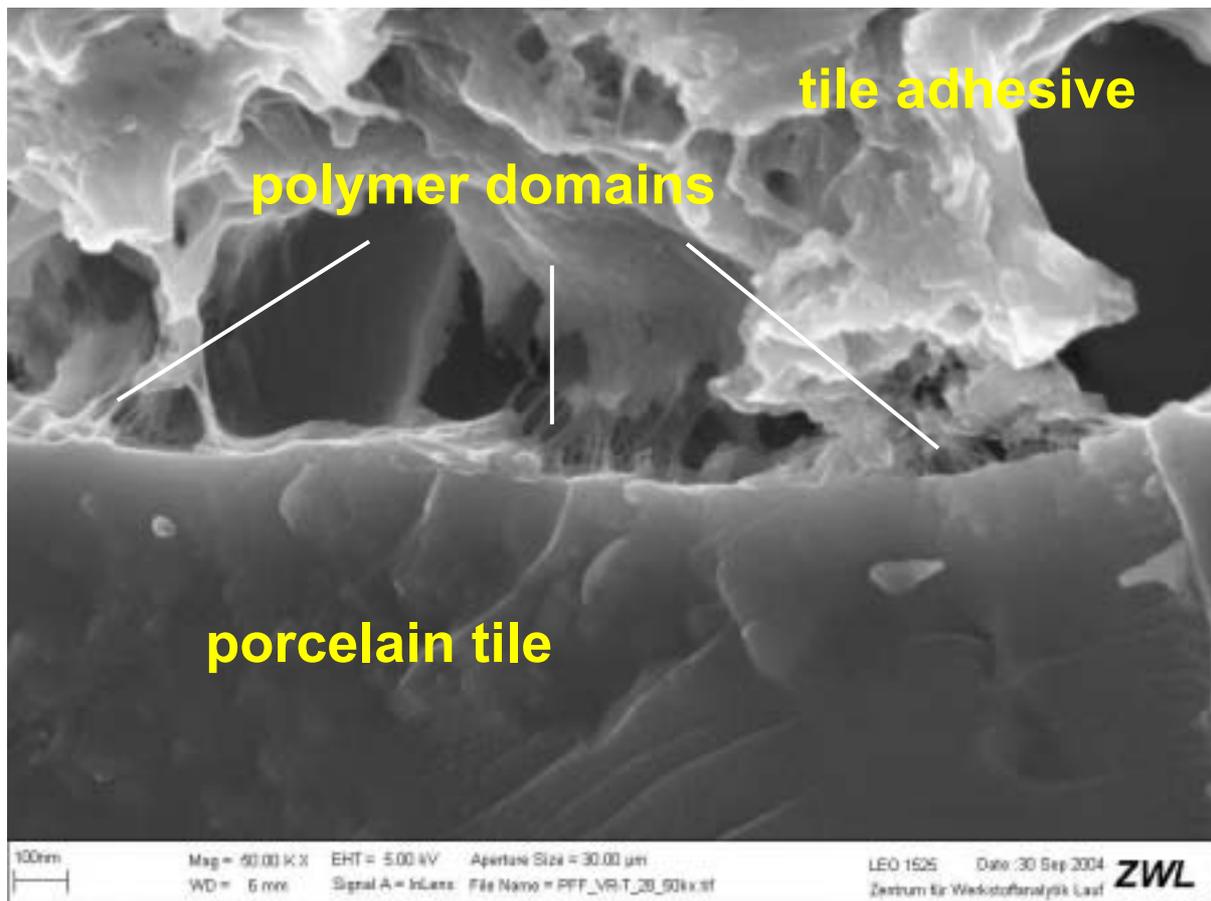


Image 7: Physical bonding between polymer domains of the tile adhesive and a porcelain tile

The polymer domains improve mechanical parameters of the cured tile adhesive p. e. elasticity and the bonding of the mortar to the substrate and the tile by polymer bridges. This is especially of importance in the case of non-porous substrates or tiles since the mechanical interlocking adhesion of the concrete crystallites with the few pores is possibly not enough for permanent adhesion.

In general the properties of a cement based thin-bed tile adhesive are influenced by the amount of redispersible polymer powder as follows:

- < 0.5 %: improvement of workability and adhesion
- 0.5 to 2.0 %: improvement of flexibility and tensile adhesion strength
- 2.0 to 5.0 %: highly improvement of flexibility, transverse deformation and adhesion to critical substrates and fully vitrified tiles
- > 5.0 %: increasing role as co-binder together with cement, highly flexible

Literature research verifies the positive effect of redispersible polymer powder on tensile adhesion strengths and flexibility of cement-based thin-bed tile adhesives. Typical results are shown and discussed in chapter 5.2.

5.1.2 Influence of Temperature

Thermoplastic polymers are semi-crystalline solids consisting of both crystalline and amorphous regions. The ratio of crystallinity to amorphous regions depends on the primary structure of the polymer and on the production process parameters.

The amorphous areas of the solid polymer can be either in the glassy or rubbery state depending on the ambient temperature. The temperature at which the transition from the glassy to the rubbery state occurs and vice versa is called the glass transition temperature (T_g). Below T_g the polymers are stiff and brittle. On warming they soften at

Table 16: Glass transition temperature (T_g) of some polymers

Polymer	T_g [°C]	MFFT [°C]
poly styrene	95	
poly (butadiene-co-styrene)	18	
poly vinyl acetate	30	10-30
poly (ethylene-co-vinyl acetate)	12	4
poly (ethylene-co-vinyl alcohol)	5	10
poly vinyl alcohol	85	
poly (styrene-co-butyl acrylate)		1-30
poly (styrene-co-acrylic acid)		12
poly acrylic acid	-10	
poly ethylene	-105	

the glass transition state. The polymers get flexible, elastic, and rubbery. At T_g the E-module of the polymer changes drastically. :

The minimum film-forming temperature (MFFT) depends on latex particle size, drying time etc. but mainly on the glass transition temperature of the polymer. It is known that polymer emulsions drying way below MFFT form no film at all but white polymer powder. Polymer lattices drying at temperatures slightly below MFFT form white, opaque films of low strength. Only above MFFT the deformation and coalescence of the latex particles is high enough to result in a continuous, crack-free film.

So-called coalescing agents, plasticizers, solvents can lower the MFFT well below the T_g of the dry polymer. Therefore the choice of the coalescing agent is an interesting topic of research to assure that polymer lattices in mortars form a film even when applied at +5 °C. Examples of coalescing agents are ethylene glycol ethers, phthalates and organic solvents. The MFFT of a polymer can be lowered by 20 °C and more.

What does all that mean for the tiling community?

- It is important to apply polymer-modified thin-bed tile adhesives above MFFT.
- MFFT for polymer-modified tile adhesives are typically +5 °C.
- Only above +5 °C the latex particles are soft and sticky enough to get close to each other (stage 1 of drying process) and to coalesce with each other (stage 2) to form polymer domains within the cement matrix.
- Since the drying process (evaporation of water!) takes time, the tiler must make sure that during that period of time (~ 5 days) the climate is not disturbing the film formation process. That means frost, temperatures below MFFT, rain showers or mechanical impact could irreversibly destroy the developing polymer domains. Afterwards, damaged films do not recover any more and the tile adhesive does not gain full elasticity and tensile adhesion strength especially to fully vitrified tiles.
- The cured of the boundaries (interlocking) of the adjacent coalescent polymer particles in the polymer film occurs via polymer diffusion between adjacent particles. Only after this the polymer particles are interlocked to tough polymer domains which are practically not water-soluble any more.

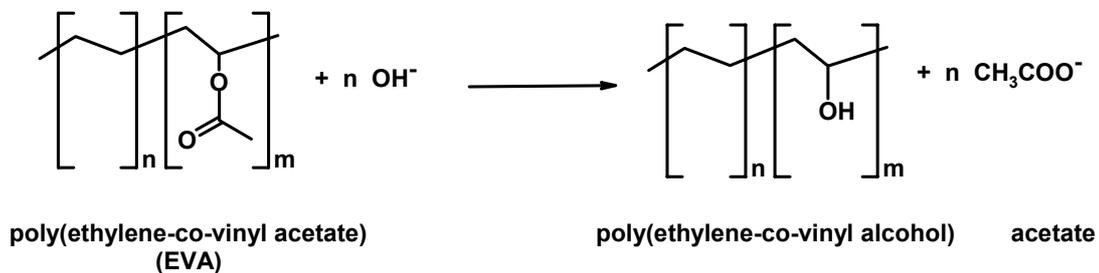
In summary polymer-modified cementitious tile adhesives need sufficient time and temperature to develop their unique characteristics. The author recommends five days depending on tile size, joint width, tile porosity, substrate capillarity ... at temperatures above 10 °C to allow the redispersible polymer to form continuous and water-insoluble polymer domains in the cement matrix.

5.1.3 Stability toward Water

After the polymer interdiffusion of adjacent particles is finished polymer domains are formed (stage 3) which are not water-soluble any more. However, the film still contains the highly water-soluble protective colloid which readily absorbs water so that the polymer domains may hydrate and swell which can disturb tensile adhesion strength of the tile adhesive.

Depending on the chemical nature of the polymer film there is still the possibility of so-called saponification reactions of the polymer.

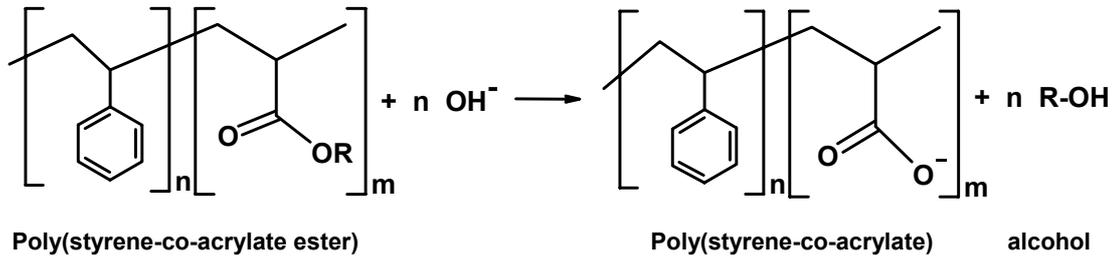
- Polymers containing Vinyl Acetate (VA)



Vinyl acetate p. e. in poly(ethylene-co-vinyl acetate) (EVA) is hydrolyzed (= saponified) in the presence of alkalinity to acetate and polyvinyl alcohol. Alkalinity (pH > 12) is present in cementitious tile adhesives when in contact with water. High alkalinity catalyzes the hydrolysis of EVA.

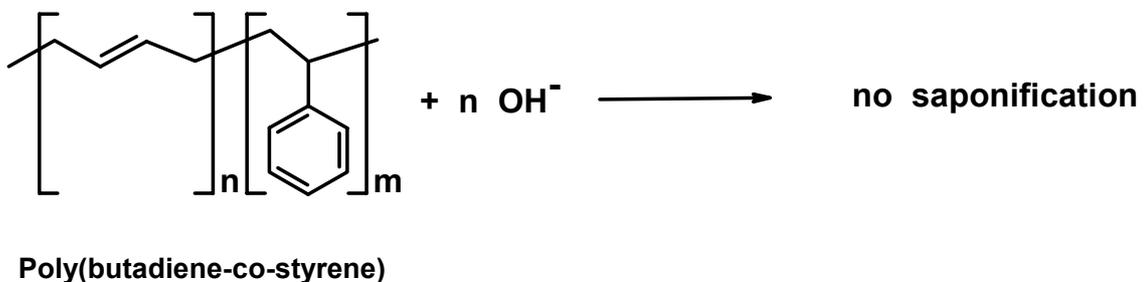
Whether the resulting backbone molecule poly(ethylene-co-vinyl alcohol) has comparable characteristics regarding elasticity and tensile bonding strength as EVA, is not known to the author. The by-product acetate could be corrosive and weaken to some extent the cement matrix.

- Polymers containing Acrylate Esters



Polymers containing acrylate esters saponify in the presence of alkalinity to poly(styrene-co-acrylate) and the corresponding alcohol (R-OH). Examples for acrylate esters monomers are butylacrylate, ethylacrylate and 2-ethylhexylacrylate. The resulting alcohols are n-butanol, ethanol resp. 2-ethylhexanol. They can be recognized by their specific smell. Again, the backbone of the polymer is not destroyed by saponification. However, it must be assumed that the characteristics of the saponified polymer are different than the ones of the original polymer.

- Polymers containing only Apolar Monomers



Polymer dispersions containing only apolar monomers such as styrene, ethylene, butadiene etc. do not saponify at all.

In summary only lattices containing polar monomers (p. e. vinyl acetate, acrylate esters ...) hydrolyze in alkaline milieu. Acetate resp. alcohol is set free during the saponification process. The polymer backbone stays intact however its polarity increases with increasing degree of saponification. The higher the polarity of the backbone, the higher its water-solubility. The water-solubility can be increasing so much that the polymer can be washed out of the mortar matrix by a strong rain shower.

Polymers containing only apolar monomers (ethene, butadiene, styrene ...) are not sensitive to saponification.

There is proof that saponification is really taking place in tile adhesives containing redispersible polymer powder when permanently saturated with water. The saponification is enhanced with diminishing integrity of the joint mortar. If there are many cracks in the grout mortar water seeps into the bed of the tile adhesive. This process is pandered if there is no void-free solid bed.

Studies of a Brazilian research group [58] on tiled facades show that tensile bond strength and transversal deformation are reduced dramatically when polymer-modified test specimens are immersed in water. For examining the effect of water on transversal deformation test specimens were prepared according to EN 12002:2003. The mortar consisted of 30 % PC, 40 % lime stone, 20 % redispersible polymer powder (Vinnapas® 5010) and 1 % Culminal® 4051 (cellulose). Storage conditions of the test specimens were 28 days at room temperature and 10 days in a water quench. Transversal deformation was measured after different periods of time after removal of the test specimens from the water quench.

The main results were as follows:

- Transversal deformation according to EN 12002:2003 decreased from 10 mm before immersion to only 2 mm directly after removal of the test specimens from the water quench. The transversal deformation recovered to about 8 mm after drying the specimens for 56 days at room temperature.
- The ultimate load also decreased from 5 N (dry storage) to only 3 N (directly after immersion) but exceeded the original value after 25 days drying period at room temperature (8 N).
- Tensile bond strength decreased from 1.2 N/mm² before immersion to about 0.4 N/mm² directly after immersion and recovered to about 0.8 N/mm² after 25 days at room temperature.

In summary transversal deformation, ultimate load and tensile bond strength are strongly influenced by the moisture content of the test specimens. A moisture content of 8 % decreased transversal deformation and tensile bond strength by 50 %.

The authors of [56] make the point that the decrease is caused by reversible swelling (hydration) of the polymer. The increase in ultimate load is due to irreversible late hydration of the cement matrix changing the mortar porous system. They do not interpret the irreversible decrease in flexibility and tensile bond strength of about 20 % after complete drying of the test specimens compared to the data for the test specimens before water immersion. Whether this decrease is caused by saponification of the polymer or the late hydration effect of the cement matrix has still to be investigated.

5.2 Influence on Tensile Adhesion and Shear Strength [59]

Determination of tensile adhesion strength according to DIN EN 1348:2007 is carried out with stoneware tiles (Bl_a – EN 14411:2007) with a water absorption below 0.5 %. Figure 15 shows that after 28 days storage at room temperature the tensile adhesion strengths increase with the amount of redispersible polymer powder. There is an almost linear correlation of tensile adhesion strength and amount of polymer.

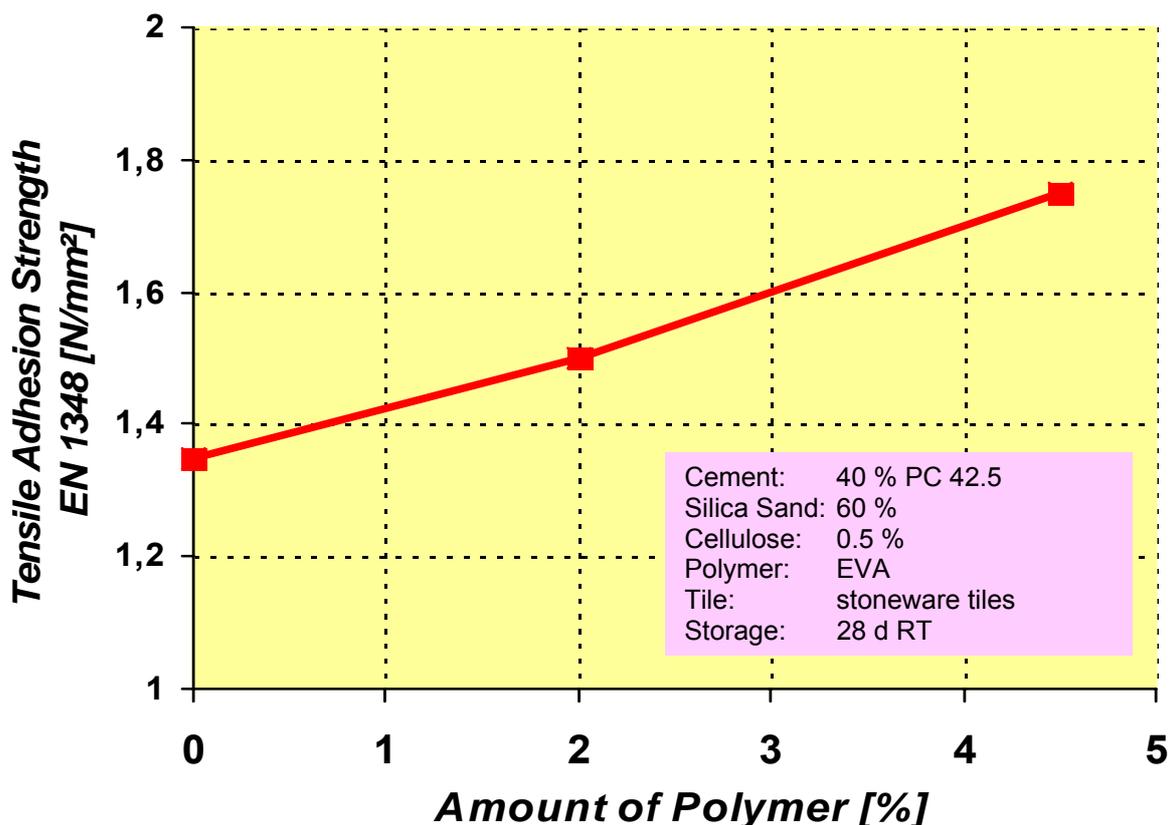


Figure 15: Tensile adhesion strength after conditioning at standard conditions

The tensile adhesion strength depends not only on the amount of polymer but also on the specification of the substrate. Especially the porosity of the substrate is crucial.

Therefore DIN EN 1348:2007 defines the water absorption for concrete slabs used for testing. Substrates with a certain macroscopic porosity such as concrete slabs allow a mechanical anchoring of the cementitious mortar. The denser the substrate the more important is the additional bonding caused by physical interaction of the polymer domains in the cured tile adhesive with the non-porous substrate. Figure 16 shows that

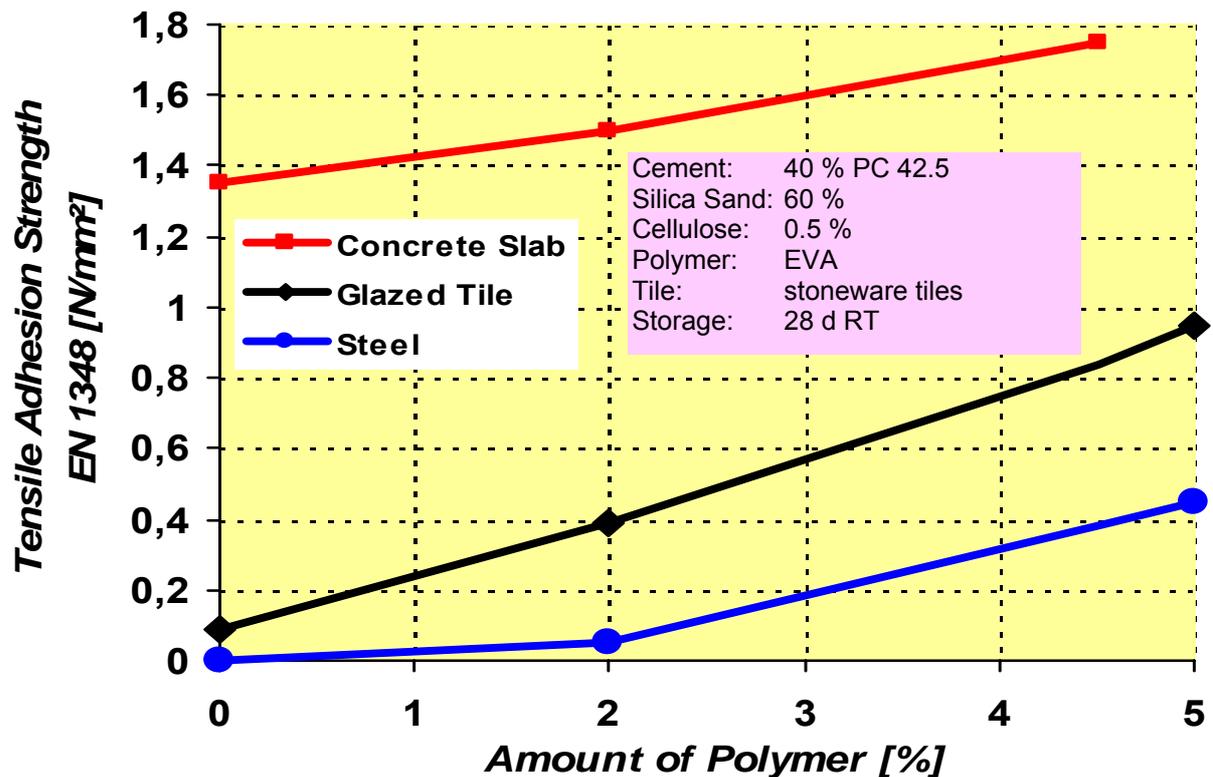


Figure 16: Tensile adhesion strength for different substrates

when lying on steel or glazed tile substrates the use of standard tile adhesives with no polymers is not sufficient. Application of flexible C2 thin-bed adhesives with a polymer dosage above 3 % for glazed tile substrates and above 5 % for steel substrates is necessary to achieve a durable bonding between tile, adhesive and substrate.

The next test series compares the influence of polymer on tensile adhesion strengths after different storing conditions according to DIN EN 12004:2007. Figure 17 clearly demonstrates that after heat aging a secure fixation of stoneware tiles is only achieved if enough polymer powder is added to the cement. This is due to the stress built up by the different thermal expansion of substrate, adhesive and tiles. Only flexible cementitious tile adhesives are elastic enough to compensate the different thermal

elongations of the materials. On the other hand there is a 20 % decline of tensile adhesion strengths after water storage and after freeze-thaw cycles. This could be due to a hydration effect of the polymer domains weakening the cement matrix. In order to

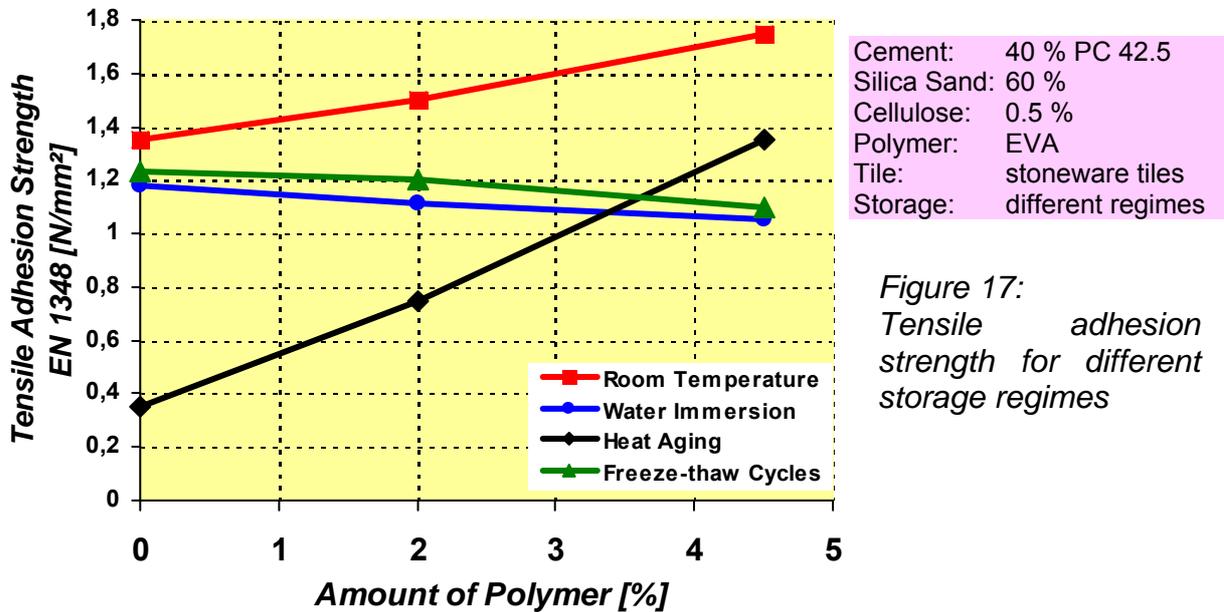


Figure 17:
Tensile adhesion strength for different storage regimes

achieve the C1 requirements of EN 12004:2007 for all four storage regimes the tile adhesive must contain at least 1 % of redispersible polymer powder. A C2 tile adhesive (> 1 N/mm²) shows optimum performance according to EN 12004:2007 in a polymer dosage range of 3 to 4 %. Above this range there are difficulties for the storage regimes water immersion and freeze-thaw, below the range heat aging is a problem.

The absolute values for tensile adhesion according to EN 1348:2007 depend on the type of tile used for the measurements. Therefore EN 1348 also specifies them.

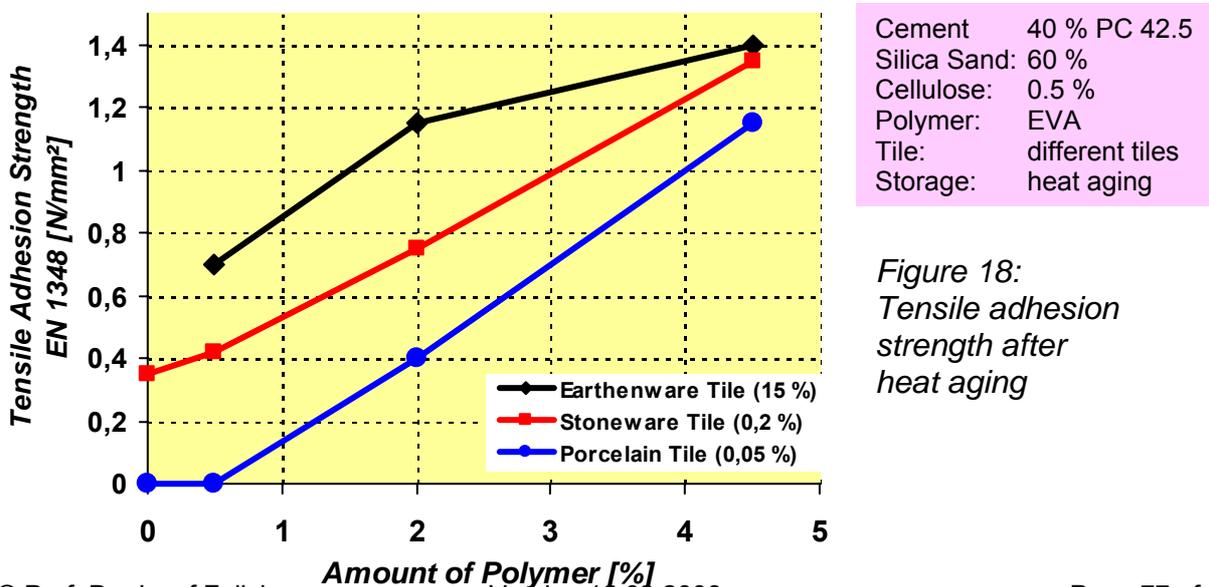
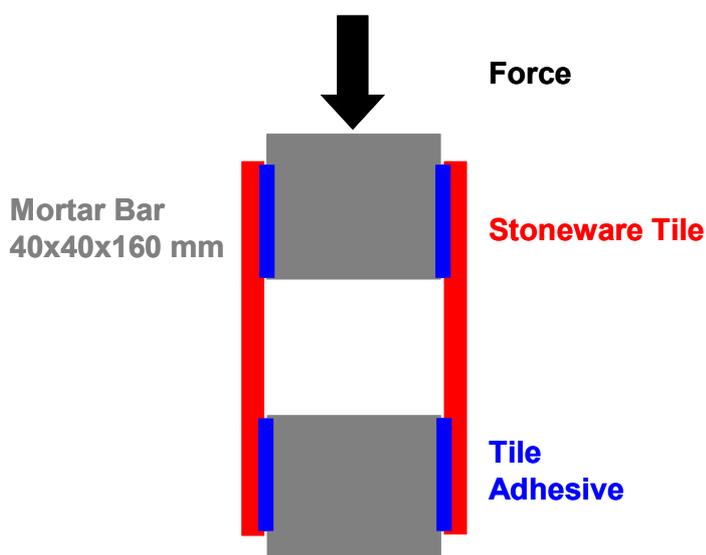


Figure 18:
Tensile adhesion strength after heat aging

Figure 18 shows the influence of tile quality on the tensile adhesion strength after heat aging. It can be seen that tensile adhesion strengths for earthenware tiles with high porosity are relatively high even at low amounts of redispersible polymer powder since there is a strong mechanical interlocking of cement crystallites of the tile adhesive and the pores of the earthenware tile. The other extreme are fully vitrified, porcelain tiles. Because of absent mechanical interlocking there is only physical bonding between polymer domains of the tile adhesive and porcelain tile. Therefore there is a certain amount ($> 2\%$) of redispersible polymer powder necessary to achieve reasonable tensile adhesion strengths after heat aging.

There is a long history of discussion whether tensile adhesion strengths have any significance in regards of the stress a thin-bed mortar is exposed under real life conditions. Eventually the pull-head plates are pulled off by an increasing vertical tensile force. Critics say it would have much more significance for the composite tile-adhesive-base if a shear force would act parallel to the surface of the tile. This is closer to reality since shrinkage of basement or expansion of tiles causes shear forces parallel to the composite.



*Image 8: Test specimen for shear strength
DIN 18156-3 [51]*

Mr. Wesseling proposed in the 1970s a test procedure for the determination of shear strength (DIN 18156-3:1980) [51]. Two mortar bars are connected with two stoneware tiles. The thickness of the tile adhesive bed is 3 mm. After storage of the specimen a force is applied vertical to the bars. Force is recorded as a function of deformation until tile adhesive failure.

On the other hand supporters of the tensile adhesion strength method claim that it does not really matter how the forces are orientated. More important is the final result, how strong the tiles are still bonded to the substrate after having suffered conditioning.

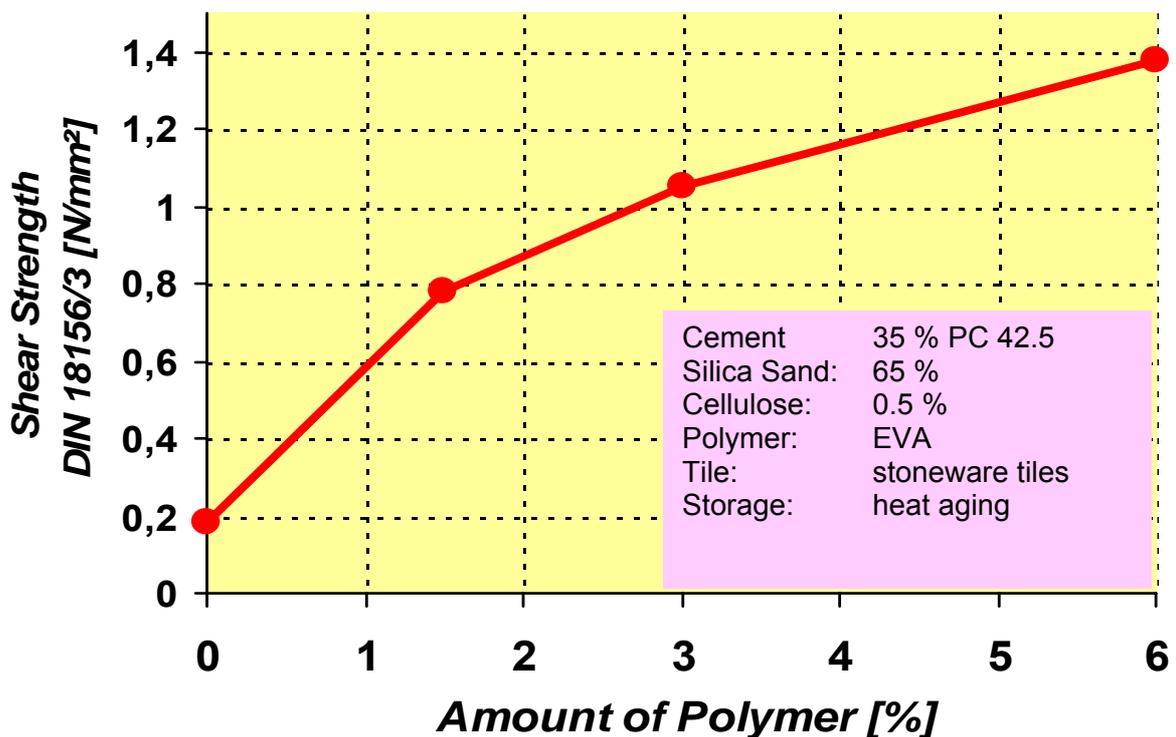


Figure 19: Shear strength after heat aging – DIN 18156

Figure 19 shows data for shear strengths determined according to DIN 18156-3:1980 after heat aging. It clearly can be seen that the higher the amount of redispersible polymer powder in the adhesive, the higher is the shear strength. Even more interesting, the values for shear strengths (DIN 18156-3:1980) and tensile adhesion strength show more or less the same curve progression. Therefore it is not necessary to determine shear strengths since tensile adhesion strengths give the same quality in results. This possibility to prefer tensile adhesion strengths is of practical advantage since sample preparation according to DIN 18156-3:1980 is not only time-consuming but also not very reproducible, p. e. thickness of mortar bed or parallelism of substrate bars. Additionally, preparation of the testing machine is cumbersome and the monitoring of deformation and shear forces is also very sophisticated.

There is also the possibility to measure the shear strength of tile adhesives according to EN 1324:2007 [21]. This standard normally applies to dispersion-based tile adhesives. Two earthenware tiles with 108 mm edge length are directly clued together with the tile mortar in such a way that they do not completely overlap.

The mortar is applied with a 6 x 6 x 6 mm notched trowel resulting in a mortar bed of 3 mm thickness between the two tiles. Afterwards the specimen is stored for 28 days at room temperature. After conditioning the absolute deformation as a function of shear force is determined and monitored and the respectively shear strength calculated. Figure 20 shows that shear strength increases with the amount of polymer in the formulation. In full analogy to the comments on the shear strength method according to DIN 18156-3:1980, the shear strength according to EN 1324:2007 is comparable with

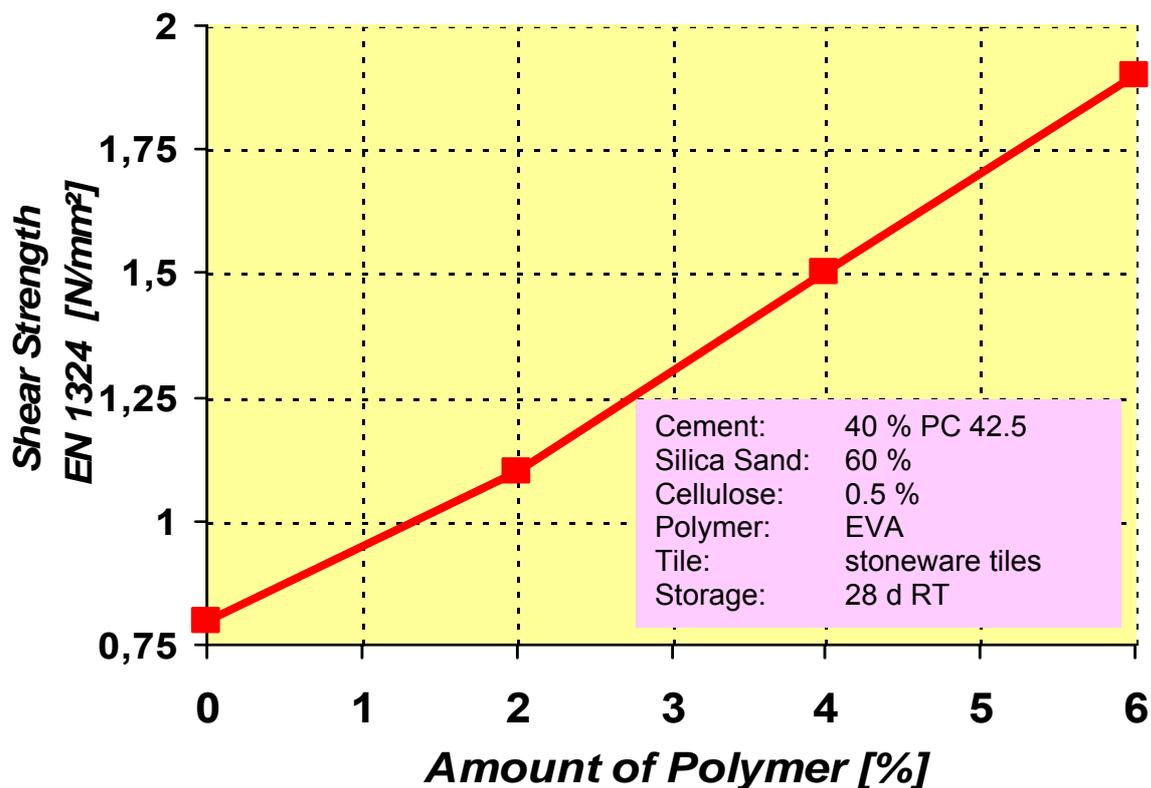


Figure 20: Shear strength after storage at standard conditions EN 1324

the data for tensile adhesion strengths. Therefore, it is enough to determine tensile shear strengths according to EN 1348:2007 [20].

5.3 Influence on Elasticity [59]

As we have seen before (chapter 4.2, 5.2) the flexibility, deformability of a tile adhesive is of utmost importance for cement-based, dry-blend thin-bed tile adhesives. Elastic deformation allows them to compensate shrinkage of the substrate, thermal elongation of the ceramic cladding and to avoid destructive shear stress in the composite tile-adhesive-substrate. Therefore a simple and fast test for the determination of

transverse deformation for cementitious adhesives was introduced by EN 12002:2003. For details of the testing procedure, its reproducibility and limits, and critical remarks see chapter 3.1.

Three different copolymers were added as redispersible powders to thin-bed tile adhesives for preparation of mortar strips according to EN 12002:2003 [14].

- EVA copolymer of vinyl acetate and ethylene $T_g = 10\text{ }^\circ\text{C}$
- MMA/BA copolymer of methylmethacrylate and butylacrylate $T_g = 10\text{ }^\circ\text{C}$
- S/A copolymer of styrene and acrylate $T_g = 12\text{ }^\circ\text{C}$

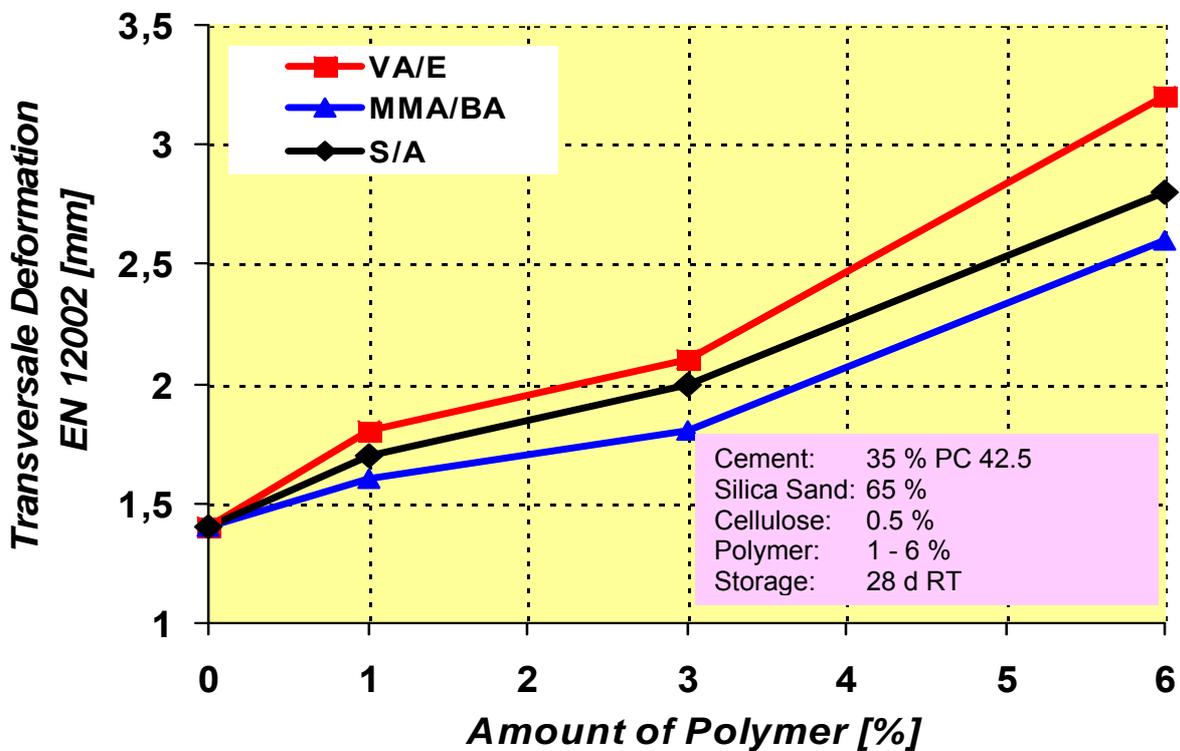


Figure 21: Transversal deformation according to EN 12002 for different polymers EN 12002

The glass transition temperature (T_g) for all three copolymer dispersions is around $10\text{ }^\circ\text{C}$. Generally speaking is the glass transition temperature, the temperature at which a polymer becomes brittle on cooling, or soft on heating. Figure 21 demonstrates that the deformability according to EN 12002:2007 is a function of the amount of polymer. The higher the polymer content the more flexible the mortar. Depending on the polymer

about 4 to 6 % are needed to achieve the S1 classification (transverse deformability of at least 2.5 mm). A transverse deformation of at least 2.5 mm is also necessary to classify a cement-based thin-bed tile adhesive as flexible according to the Guideline of Flexible Mortars of the German Association of Building Chemical Manufacturers. The curves for all three polymers show more or less the same behavior varying only to a certain degree in absolute numbers.

Determinations of shear deformation according to EN 1324:2007 [21] or 18156-3:1980 [51] is also possible. Shear deformation is apparently closer to real life conditions than a bending strain. Since the deflections are very small it takes a lot of experience and preparation time to obtain half-decent reproducible results.

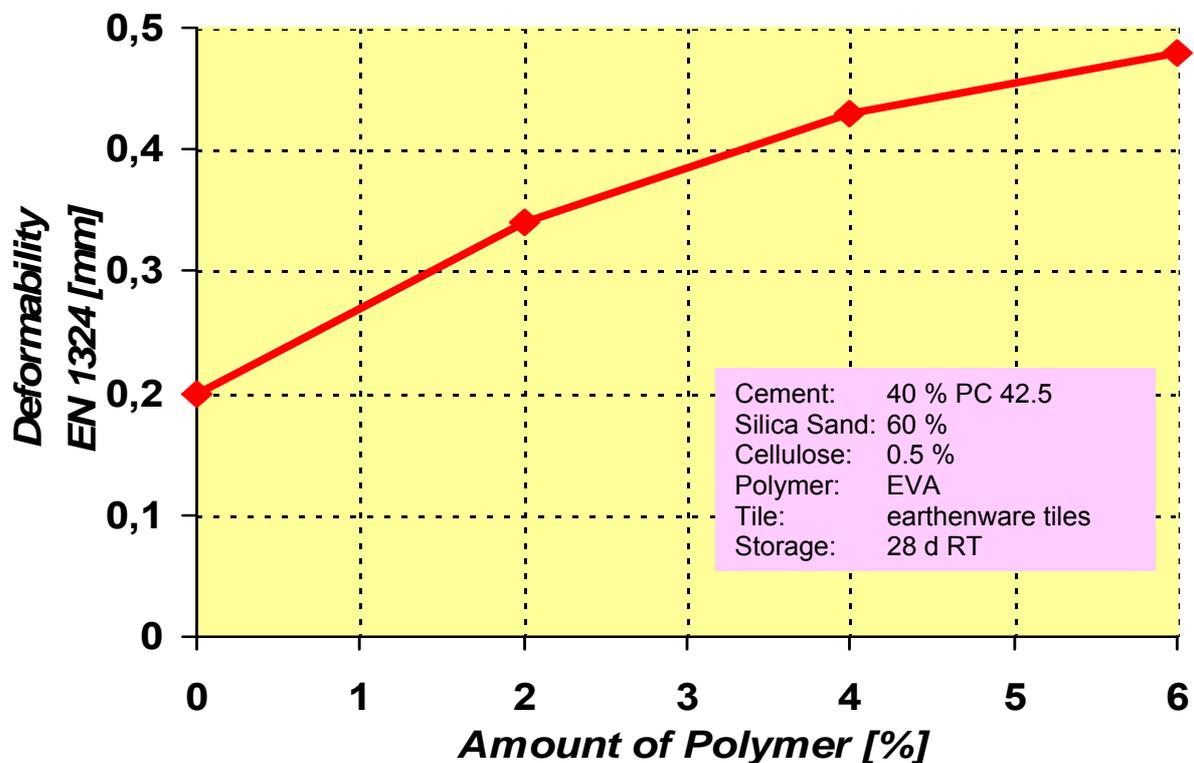


Figure 22: Deformability according to EN 1324:2007

Figure 22 shows that there is an increase of deformability with greater amount of redispersible polymer powder. Taking into account, that the differences are rather small (< 50 µm for one percent of polymer) and the poor reproducibility of the method, the results should not be over-interpreted. The determination of transversal deformation according to DIN EN 12002:2003 is less extensive, better reproducible and gives the same quality of information.

5.4 External Thermal Insulation Composite Systems (ETICS) [60]

In the days of shortage of fossil fuels and exploding oil prices the saving of energy is the topic par excellence. In Germany 75 % of the energy consumption in the residential sector is used for space conditioning, mainly for heating. Since the introduction of the “Federal Energy Savings Regulations” in 2001, every new building must meet certain energy savings standards. The quickest and most efficient way for saving heating costs and improving the climate inside buildings is thermal insulation of the outer walls of the building. The expert is talking about external thermal insulation composite systems (ETICS). There are different designs of ETICS. A typical ETICS consists of a polymer-modified cementitious adhesive, insulation panels made of expanded polystyrene (EPS) or mineral wool, a polymer-modified mineral base coat for embedding the reinforcement mesh on top of the thermal insulation panels, components for fixing (p. e. insulation anchors), one or more layers of mineral finishing coat and in some cases additionally of tile adhesive, tiles and grout mortar. The different components form a system which has to be tested as a whole system. It is not allowed to combine components of different tested ETICS to form a new ETICS.

Ceramic cladding on ETICS is exposed to extreme strain. During summer and especially in regions such as the Middle East they can heat up to 70 °C during daytime. Shock cooling of the hot tiles may occur if a rain shower pours against the façade. In colder regions the cladding may cool down to minus 20 °C especially during night time. Only if there is not too much water absorption by the ETICS, damage is avoided.

The verification of fitness for the intended use for ETICS is specified in an European Technical Approval Guideline (ETAG 004:2000) “External Thermal Insulation Composite Systems with Rendering” [61]. The combination of hydrothermal and freeze/thaw test cycles allows to simulate 10 years real life time exposure by only 4 weeks climate chamber testing. The testing regime is as follows:

A) 80 Hydrothermal cycles à 6 h ($\Sigma = 20$ d)

- Warming of the wall to 70 °C at 10 % R. H. in a time period of 1 h and maintaining this climate for 2 h
- 1 h sprinkling of the wall with water of 15 °C at a rate of 1 l/(m² x min)
- 2 hours waiting time
- Inspection of the wall after each 4 hydrothermal cycles for debonding, cracks, efflorescence, etc.

B) Regeneration Period

- Conditioning of the wall for two days at 10 to 25 °C and at least 50 % R. H.

C) 5 Freeze/Thaw cycles à 24 h ($\Sigma = 5$ d)

- Warming of the wall to 50 °C at 10 % R. H. in a time period of 1 h and maintaining this climate for 7 h
- Cooling of the wall to -20 °C in a time period of 2 h and maintaining this temperature for 14 h
- Inspection of the wall after each freeze/thaw cycle for debonding, cracks, efflorescence, etc.



Image 9: Example of a typical EOTA-Wall before and after tiling before weathering (Courtesy of Wacker Chemie AG)

The test was carried out for a rigid system (render, tile adhesive, and joint grout with low polymer content) and a soft system (render, tile adhesive, and joint grout with high polymer content). The EOTA-wall was subdivided into two areas. The left sector was covered with the rigid ETICS, the right one with the soft ETICS. Subsequently the complete testing (80 hydrothermal cycles + 5 freeze/thaw cycles) was carried out. The differences of optical appearance of the two ETICS were striking (image 10). The rigid ETICS showed strong efflorescence and even a few cracks at all. Opposite to this, the surface of the soft ETICS shows no efflorescence and cracks. The higher water content of the insulating core of the rigid ETICS compared to the insulating core of the soft ETICS is in agreement with these observations and the theory.



*Image 10: Joint grout surfaces after weathering.
Efflorescence on the rigid ETICS (left), unchanged visual appearance of the soft ETICS (right) (Courtesy of Wacker Chemistry)*

How to interpret these results? Due to the weathering of the EOTA wall, the wall itself and the cladding perform oscillating (breathing) movements. Only the soft ETICS is able to follow these movements without getting damaged. Therefore no cracks form in the joint grout and the weathering water can penetrate only at a very low level into the system. The rigid ETICS is not able to perform such breathing movements. Tile adhesive and joint grout form micro fissures through which higher amounts of weathering water seep into the ETICS. The trapped water behind the tiles dissolves calcium hydroxide from the tile adhesive and transports it on the surface when

squeezed out during a heating cycle. On the surface the calcium hydroxide reacts with carbon dioxide of the atmosphere resulting in white efflorescence.

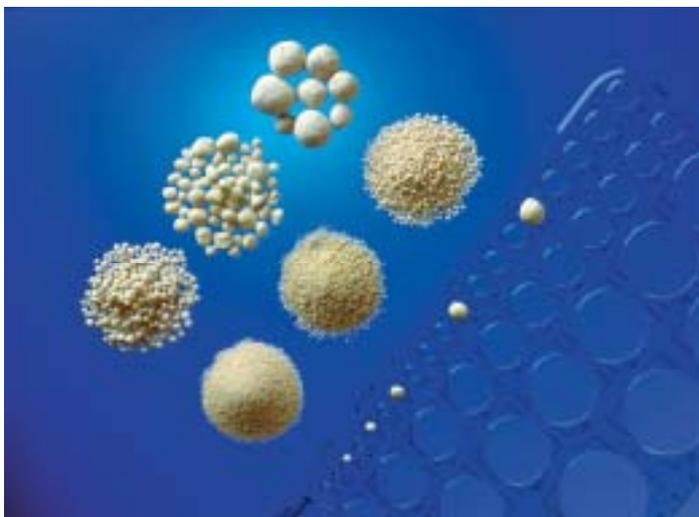
Therefore it is crucial for the job-site to use a tested, certified ETICS to ensure proper workability (p. e. open time, sag-resistance) and long-time performance. In Germany, all components (adhesive for insulation panels, finishing coat, tile adhesive, tiles, grout mortar) have to be tested in the system and certified by the Deutsches Institut für Bautechnik (DIBt, Berlin) before such systems may be applied on facades.

6 PROGRESS AND CHALLENGES

6.1 Lightweight Tile Adhesives

In this decade the third generation of thin-bed tile adhesives entered the market. Partial or total substitution of silica sand by lightweight aggregates gives them a light, creamy consistency to ensure smooth and easy workability, setting them apart from other adhesives.

There are lightweight aggregates based on different materials such as expanded clay, rubber granulate, polystyrene or expanded glass granulates. A suitable lightweight aggregate for tile adhesives has to meet numerous demands. Low water absorption and frost resistance is a must for exterior use. The additive must not show any elastic behavior or moisture expansion when the dry-blend is mixed with water. Otherwise the hydration process of the binder would be disturbed. The higher the content of lightweight aggregates the lower the mortar density and compressive strength of the cured mortar. Therefore the lightweight additive itself must have a reasonable mechanical stability.



Source: www.poraver.de

Image 11: Different fractions of expanded glass granulates

Table 17: Characteristics of expanded glass granulates:

• granular density	430 g/l
• compressive strength	2 N/mm ²
• moisture content	< 0.5 %
• softening point	700 °C
• thermal conductivity	0.07 W/mK
• water absorption	25 %
• color	white

Empirical testing showed that expanded glass granulates is best for the use in cementitious adhesives. They combine very low weight with high compressive strength.

They are weather-resistant, inflammable and not affected by high alkalinity of cement. The raw material for glass granulates is recycled glass. The glass is ground to a fine glass powder in large mills. Then the glass mixture is given its round shape in the granulating dish. The granulate is expanded in a rotating furnace at approx. 900 °C giving a fine pored, creamy white, round granulate. After cooling the round granulate is sieved and sorted into different granular sizes.

Due to the lightweight additives thin-bed mortars of the third generation have at least 30 % higher coverage per kg adhesive than conventional cementitious thin-bed tile adhesives. Therefore 15 kg of third generation thin-bed mortars cover the same area as 25 kg of conventional tile adhesive. Thus, these high-tech adhesives are available in 15 kg sacks equipped with a handle for easy transportation. Besides high coverage these mortars show unique non-sag characteristics and low-shrinkage. The unique creamy workability characteristics are immediately evident for the tiler. Due to the lower fresh mortar density the mortar is creamy and fluffy. Spreading of the material is much easier since 30 % less material has to be applied per square meter of substrate. Also 30 % less of material has to be transported to the construction site. This can be of importance when refurbishment on the eight floor has to be carried out without elevator.

6.2 Dry Tiling – Clipping versus Gluing

For the last 10 years there are serious efforts to introduce factory-made tile systems which can be laid as a floating floor in a similar way as laminate. Some of them come even with integrated joint profiles. The floor is usually laid on an underlayment of cork, foam or similar product to cushion the floor and absorb sound. Beneath the impact sound insulation a membrane of PE is placed as a vapor barrier. The tiles are laid above the impact sound insulation layer without gluing or jointing and are held in place by a locking mechanism. The main advantages of such click-in dry tiling systems are:

- quick progress of work
- immediately walkable after laying
- factory-integrated impact sound insulation (depending on manufacturer)
- installation on new and already existing floors possible
- no gluing and jointing

- easy installing procedure depending on the floor plan

Such tiling systems will find their way into areas such as showrooms, exhibition halls etc. where often floors are changed. Another area of application could be the renovation of floors in private houses for reasons of time saving and cleanness. When conventionally tiling, the whole room has to be cleared before tiling work can be started. In dry tiling, it is for instance enough to dislocate the wardrobe first and then to tile the area where the wardrobe will be located. The wardrobe is brought into position again and finally the remaining floor area is dry-tiled. By mixing different tile designs and formats a variety of patterns can be prepared with click-tiles.

The still relatively high price of more than 60 €/m² for dry tiling systems has to put into perspective to the price of not only tiles, but also for the tile adhesive and grouting mortar and the necessary tools of the trade. Other disadvantages of dry tiling systems are there still limited availability and the restricted variety of designs and sizes. The under-surface must have an optimal evenness. Uneven spots may amount to a maximum of 2 mm. Larger uneven spots must be leveled prior to dry-tiling. Since there is no long-time experience with dry-tiling, consumers are not aware of these systems or still show a lack of acceptance.

Suppliers of dry-tiling systems are:

- Quick Stone, Germany, www.quickstone.de, trade name “Quick Stone”
- ICF Industrie Ceramiche di Faenza, Italy, www.faenzacliptile.com, “Faenza Clip Tile”
- Edge Flooring, USA, www.edgeflooring.com, “Edge”
- A&M Ceramica Azulindas&Marti, Spain, www.easykersystem.com, “Easyker”
- KellRim, Germany, www.terraclit.de, “TerraClic”
- Aloha Imports, Germany, www.teakholzland.de, “Click-Stone”
- Eurosaxa, Germany, www.eurosaxa.de, “Flocoflex”
- Natursteinwerk Rinsche, Germany, www.click-and-stone.com, “Click-and-Stone”
- Hamberger, Germany, www.celenio.de, “Celenio”
- Witex International Flooring, Germany, www.ceraclit.com, “Ceraclit”

6.3 Fast Track Building

Time is money. This is especially true at construction sites. The construction industry is always pressed for time. New buildings earn nothing until they are occupied. Refurbishment must be carried out in the shortest time period possible to keep the annoyance of owners, tenants or landlords at a minimum. Looking up the expression fast-track in an encyclopedia one can find definitions as a) adj. "taking the quickest route to the desired result" or b) "materials that allow projects to be completed in the shortest time". The next chapter will describe a fast-setting screed which allows tiling only one day after installation of the screed.

PCI Novoment Z1 is a fast setting screed cement for fast track screeds installed on separation or insulation layers or bonded screeds. The recommended mixing ratio of binder to sand is 1 to 5 parts by weight or 1 to 4 parts by volume. Water is added while the blade-type concrete mixer is running until a stiff-plastic consistency is obtained. After that the mortar is spread with a shovel, trowelled and rubbed down with a wooden board and smoothed if necessary. Following these instructions cementitious screeds of class CT-C25-F4 and better according to DIN EN 13813:2002 can be achieved [62]. It is also possible to use a standard screed mixing pump to transfer the screed over longer distances. Layer thicknesses of 10 mm to 65 mm and more can be realized depending on the grading curve of the aggregate.

The main advantage of fast-setting screeds is their short curing time. Only 3 hours after installation it is possible to walk on the screed and tiles may be already laid the next day. Wall-to-wall carpets, parquet floorings and vapor-tight coverings can be installed if the residual moisture content is not more than 3 CM-%. This is a tremendous saving of time since conventional cementitious screeds need 28 days until they are ready for tiling. Only after that time the remaining shrinking potential of a conventional screed is low enough that secure tiling can be carried out.

In combination with fast curing tile adhesives big surface areas can be covered with tiles in a short period of time. Fast setting cement is responsible that surfaces tiled with rapid set tile adhesives are walkable only after 3 hours. Grouting of such areas can be carried out after 3 hours and may be exposed to full mechanical load after 24 hours.

The production hall of AMG-Mercedes at Affalterbach near Stuttgart is a perfect example to demonstrate what fast track tile laying systems are capable of. The world press conference for the opening ceremony of this prestigious complex of show rooms and production hall for state-of-the-art sports car engines was scheduled in time. The CEO of Mercedes was the host for the press. There was only one problem. Two weeks



Image 12: Production hall for tuned AMG Mercedes cars near to completion

before the grand opening there was no floor in the premises. The constructor insisted on the promised 1400 m² fully vitrified tile cladding. The contractor felt an unpleasant feeling slowly rising inside him. Or to put it in other words poor panic. The solution to this problem, fast-setting screed in combination with fast acting flowable tiling mortar came from the building chemical industry. The concrete slab was shot-peened first and brushed then with a mortar bonding agent for bonded screeds. The fast-setting screed mortar was applied on the still fresh bonding agent in an average thickness of 20 to 30 mm. After three days, the required compression strength of more than

30 N/mm² was achieved. 28 days old prisms showed compressive strengths even up to 70 N/mm². After three days, the residual moisture content of the screed was below 3 CM-%, so the screed was primed with acrylic resin dispersion. Large-sized fully vitrified tiles were laid into a flowable tiling mortar to avoid voids beneath the tiles. Due to excellent teamwork of composition floor layer and tiler in combination with high-performing building materials the CEO was able to welcome without worries journalists from all over the world. Polished cars glittered on a shiny ceramic floor. Was there any problem?

6.4 Tiling on Critical Substrates

Renovating floors in older buildings often involves laying of new ceramic floors. Many times the background consists of a combination of materials that expand to differing degrees in response to temperature and humidity. Often joints or borderlines of different screeds should be ignored for optical reasons. Under this circumstances cracks can easily appear in freshly laid tiled floors and have to be prevented by mechanically isolating the cladding from the substrate. Footstep sound insulation has to be installed especially when substituting carpet floors by claddings.

The traditional procedure is cumbersome and time-consuming. Cracks have to be expanded, stabilized and filled. Irregularities have to be eliminated by applying a leveling compound. Only then the sheets for thermal and sound insulation can be laid. The craftsman has to cut them precisely to shape and stick them onto the substrate. When the adhesive has set, he has to seal the joints between the sheets with adhesive tape before the tile adhesive can be applied on top. This takes days mainly because of the long waiting periods for the leveling course and adhesive to set.

Leveling, decoupling and sound reduction in one step is possible with state-of-the-art, cementitious, self-leveling compounds (p. e. PCI Nanosilent[®]). The special properties derive from special polymers and rubber particles. The rubber granules are responsible for the high flexibility, decoupling characteristics, and sound insulation properties of the cured leveling compound. The shear modulus G_{Ad} is very low due to the elastic rubber particles in the mortar and therefore the mortar compensates potentially upcoming shear movements between substrate and cladding (see chapter 4.2.2). Shear stress is reduced by 86 % according to a study of the Munich Technical University. By

comparison: 100 percent would represent a non-stuck tile that can move completely freely ($G_{Ad} = 0$). Footfall sound reduction was determined to 11 dB at a layer thickness of 10 mm by the Leipzig Material Research and Testing Institute. This is halving the perceived footfall sound and is in the same range as for conventional sound insulating boards. Irregularities in the old substrate are no problem since the self-leveling product flows smoothly into every irregularity of the substrate. 5 to 15 millimeters, and in some cases as much as 20 mm, may be leveled with ease. All you need do is pour, spread, deaerate. The next day the underground is ready for tiling.



Image 13:

Left Irregularities, different materials a common situation in renovating

Right Even substrate after applying the self-leveling product

7 SUMMARY

It was a long way for tiling technology to arrive at state-of-the-art polymer-modified, dry-blend, cementitious thin-bed tile adhesives. The development of redispersible polymer powders was one of the most important milestones to make it happen. The main benefits of redispersible polymer additives are improved workability, higher flexibility, and better adhesion. Thus, safe tiling in demanding applications, p. e. tiling of terraces, balconies, or on floor heating systems and of critical tiles such as fully vitrified and glass tiles is nowadays possible.

Theoretical considerations show that shear stress in the composite tile-adhesive-base does not occur if the tile adhesive is elastic enough to compensate relative movements between substrate and tile. Such relative movements may originate from the shrinkage of young screeds or from a temperature variation of the cladding due to changing climate situations. Physically speaking, tile adhesives must possess a low shear modulus (G_{Ad}) to be elastic enough. This can only be achieved by the addition of redispersible polymer powder. During the curing process of polymer-modified cementitious thin-bed tile adhesives so-called polymer domains are formed which elasticize the cement matrix and form physical bonds to even fully vitrified surfaces. It is important to know that these polymer domains can only irreversibly form if the temperature is above 10 °C and there is no rain-fall for five days. Chapter 5 shows that tensile adhesion strength, shear strength and transversal deformation strongly improve with increasing amount of redispersible polymer powder in the formulation. Unfortunately, there is not much data available about the shear modulus of cementitious tile adhesives. This is mainly due to the fact, that shear experiments are difficult to set up. The preparation of test specimen is cumbersome and sophisticated fine mechanic is necessary to obtain reproducible results. Effort is still necessary to design an industrial standard for easy and reliable shear stress measurements for cementitious thin-bed adhesives.

At present the testing of elasticity is done by measurement of transverse deformation of a cured mortar sample according to EN 12002:2003. Although there are some difficulties in test specimen preparation the test method is reasonably reproducible. Fundamental criticism claims that thin-bed tile adhesives are not exposed to flexural load but to shear stress. Own tests arrive at the conclusion, that there is a good

correlation of transverse deformation according to EN 12002:2003 and the absolute deflection of a tile if shear-stressed. In Germany, a thin-bed tile adhesive has to fulfill the raised requirements for a C2 adhesive according to DIN EN 12004:2007 (tensile adhesion strength $> 1 \text{ N/mm}^2$ for all four storage regimes) and at the same time a transverse deformation of minimum 2.5 mm according to DIN EN 12002:2003 to be labeled “flexible”.

Determination of tensile adhesion strength is described in EN 12004:2007 resp. EN 1348:2007. Reproducibility of the test is reasonably although the standard deviation is about 15 % of the real average tensile adhesion strength what was verified by round robin testing. Tensile adhesion strengths are measured after four different storing regimes: room temperature, water immersion, heat aging, and freeze-thaw cycles. The intention is to simulate real life conditions. A good idea, but badly realized since testing allows at least seven days storage time at room temperature for all four storage regimes. Especially the first seven days are important for cement hydration and polymer film formation. In reality, there are often temperatures below $10 \text{ }^\circ\text{C}$, rain falls or desert climate. These weather conditions cause disturbances during the cement hydration process and in the formation of polymer domains and have a big impact on workability characteristics such as open time. It has to be concluded that EN 12004:2007 has only a limited significance for real life conditions.

Although innovations such as pre-fabricated dry tile systems are on the horizon, the flexibility of polymer-modified dry-blend thin-bed tile adhesives in both senses of the word will guarantee them a bright future.

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10 ABBREVIATIONS

1K	one-component
2K	two-component
AG	Aktiengesellschaft
C	cement-based/compressive strength
CEM	cement
CEN	Comité Européen de Normalisation
CEO	Chief Executive Officer
CG	cementitious grout
CM	carbide method
cm	centimeter
CPD	Construction Products Directive
CT	cementitious
CWT	classified without further testing
D	dispersion-based
d	day
DB	Deutsche Bauchemie
DETA	diethylene triamine
DIBt	Deutsches Institut für Bautechnik
DIN	Deutsches Institut für Normung
E	extended open time/fire class/water absorption
EN	European Norm
EOTA	European Organization of Technical Approval
EPS	expanded polystyrene
ETA	European Technical Approval
ETAG	European Technical Approval Guideline
ETICS	External Thermal Insulation Composite Systems
e.V.	eingetragener Verein
EVA	poly (ethylene-co-vinyl acetate)
F	fast setting/flexural strength
FTC	freeze-thaw-cycle
GmbH	Gesellschaft mit beschränkter Haftung
HAC	high-alumina cement
HDI	1,6-Hexanediamine

hen	harmonized European standard
IDPA	isophorone diamine
IPDI	isophorone diisocyanate
ISO	International Standard Organisation
MC	methyl cellulose
MDA	methylene dianiline
MDI	methylene diphenyl diisocyanate
MFFT	minimum film-forming temperature
MHEC	methyl hydroxyethyl cellulose
MHPC	methyl hydroxypropyl cellulose
MMA/BA	copolymer of methylmethacrylate and butylacrylate
MPA	Materialprüfanstalt
n. a.	not applicable
PC	Portland cement
P.	page
p. e.	par example
PE	polyethylene
PPC	Portland pozzolan cement
PTFE	polytetrafluorethylene
PU	polyurethane
R	resin-based/aliphatic group
RG	resin grout
R. H.	relative humidity
rpm	revolutions per minute
RT	room temperature
S/A	copolymer of styrene and acrylate
SLU	self-leveling-underlayment
T	thixotropy, non-sag
TDI	toluene diisocyanate
TC	Technical Committee
UNI	Ente Nazionale di Unificazione
VA	vinyl acetate
W	water

11 SYMBOLS, UNITS

b_{TI}	half tile width	[mm]
d_{Ad}	thickness of tile adhesive	[mm]
d_{TI}	thickness of tile	[mm]
E_{TI}	elasticity modulus of tile	[N/mm ²]
F_{Ad}	force in tile adhesive	[N]
F_{TI}	force in tile	[N]
G_{Ad}	shear modulus of tile adhesive	[N/mm ²]
jw	joint width	[mm]
l_{TI}	half tile length	[mm]
l_0	initial length	[m]
$L/2$	maximum radial distance from centre of tile	[mm]
pH	pondus hydrogenii	
r	reduction factor for shear/stress due to joints	
T_g	glass transition temperature	[°C]
w/c	water to cement ratio	
x	radial distance from centre of tile	[mm]
x_{TI}	distance from centre of tile in longitudinal direction	[mm]
y_{TI}	distance from centre of tile in transverse direction	[mm]
α	thermal coefficient of linear expansion	[mm/mK]
Δ	root mean square deviation	
Δl	variation of longitudinal modification	[mm]
Δl	absolute length change	[mm]
ΔT	variation of temperature	[K]
ε_s	deformation of substrate	[mm/mm]
\emptyset	average, mean	
σ_T	compressive stress in tile	[N/mm ²]
τ_{Ad}	shear stress in tile adhesive	[N/mm ²]
τ_{Ad-max}	maximum shear stress	[N/mm ²]
μm	micrometer	
°C	degree Celsius	
€	Euro	
g	gram	

h	hour
K	Kelvin
kg	kilogram
m	meter
m ²	square meter
mm	millimeter
mm ²	square millimeter
mPas	milli Pascal seconds
N	Newton
Pas	Pascal seconds
ppm	parts per million
s	second
W	Watt

12 STANDARDS, DIRECTIVES AND GUIDELINES

CPD 89/106/EEC:1988	Council directive 89/106/EEC on the approximation of laws, regulations and administrative provisions of the member states relating to construction products
DIN 18156-3:1980	Materials for ceramic linings by thin mortar bed technique; dispersion adhesives
DIN 18157-1:1979	Execution of ceramic linings by thin mortar bed technique; hydraulic mortar
DIN 18202:2005	Tolerances in building construction - Structures
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